Study into the Power Loss Reduction and Voltage Profile Improvement in Radial Distribution System by Optimal Placement of DSTATCOM Using PSO and GA Methods a case of Bishoftu Substation II

Tesfaye Girma Tadesse

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

College of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Electrical Power System Engineering

Office of Graduate Studies

Adama Science and Technology University

June, 2025

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DECLARATION

I declare that this thesis entitled "**Study in to the Power Loss Reduction and Voltage Profile Improvement in Radial Distribution System by Optimal Placement of DSTATCOM Using PSO and GA Methods a case of Bishoftu Substation II**" is my own work and has not been submitted to any university for a similar purpose. Proper citations duly recognize the references used in this proposal.

Tesfaye Girma Tadesse	____________________	10/06/2025 G.C
Name of student	Signature	Date

APPROVAL PAGE

We hereby certify that the recommendation and suggestion given by the proposal review committee are appropriately incorporated into the final thesis proposal entitled “**Study in to the Power Loss Reduction and Voltage Profile Improvement in Radial Distribution System by Optimal Placement of DSTATCOM Using PSO and GA Methods a case of Bishoftu Substation II**” by Tesfaye Girma Tadesse.

Dr.Kena Likassa__	________________	10/06/2025 G.C
Major Advisor	Signature	Date

APPROVAL OF BOARD OF REVIEWERS

We, the undersigned, members of the board of reviewers of the thesis, open defense by Tesfaye Girma Tadesse, have read and evaluated the thesis entitled "**Study in to the Power Loss Reduction and Voltage Profile Improvement of in Radial Distribution System by Optimal Placement of DSTATCOM Using PSO and GA Methods a case of Bishoftu Substation II**" and assessed the understanding of the candidate about the proposed research. This is, therefore, to certify that the thesis proposal is accepted, and we recommend the implementation of the proposal.

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

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LIST OF ABBREVIATIONS

AI	Artificial Intelligence
ASTU	Adama Science and Technology University
BFOA	Bacterial Foraging Optimization Algorithm
DG	Distributed Generation
DSTATCOM	Distribution Static Compensator
EEU	Ethiopian Electric Utility
EEP	Ethiopian Electrical Power
FACTS	Flexible Alternating Current Transmission System
GA	Genetic Algorithm
LSF	Loss Sensitivity Factor
PSI	Power Stability Index
PSO	Particle Swarm Optimization
PV	Photovoltaic
RDS	Radial Distribution System
STATCOM	Static Synchronous Compensator
VSI	Voltage Stability Index
PSO-GA	Particle Swarm optimization-Genetic Algorithm

ABSTRACT

With the rapid increase in electrical energy demand, optimizing distribution networks through advanced technologies has become a critical necessity, particularly in developing regions where infrastructure is under pressure. The radial distribution system of Bishoftu Substation II has been identified as a critical zone due to its high-power demand, wide coverage, and low voltage profile, which has led to considerable power losses and reliability issues. The primary challenge addressed in this study is minimizing total active and reactive power losses and improving voltage stability without violating the operational constraints of the system. To overcome these challenges, this thesis aims to determine the optimal placement and sizing of a Distribution Static Synchronous Compensator (DSTATCOM) in the Bishoftu Substation II distribution network. Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) techniques were employed to locate and size the DSTATCOM effectively. The research also addresses the existing methodological gap by comparing the performance of these two metaheuristic algorithms on identical network configurations. Load flow analysis was conducted using MATLAB 2022b to simulate different scenarios: the base case, PSO-optimized, and GA-optimized cases. The results revealed significant improvements in system performance due to DSTATCOM integration. Total active power loss was reduced with GA & PSO, achieving approximately 29.3% and 27.4% loss reduction, respectively. Reactive power loss also achieving approximately 23.6% and 24.7% loss reduction (GA&PSO respectively) . Voltage profile analysis showed that the minimum bus voltage improved from 0.981 p.u. in the base case to 0.989 p.u. with GA and 0.9987 p.u. with PSO, indicating enhanced voltage stability. Additionally, branch-level power loss analysis confirmed performance improvements across critical feeders. In general, the strategic integration of DSTATCOM optimized by PSO and GA significantly enhances voltage stability and reduces power losses in the Bishoftu Substation II distribution network. PSO showed slightly superior performance, but both algorithms demonstrated effectiveness, validating metaheuristic-based DSTATCOM planning as a powerful approach for improving the reliability, efficiency, and economic operation of modern distribution systems.

Keywords: *Distribution Static Compensator (DSTATCOM), GA, MATLAB, Optimum location, Optimum size, Power loss, PSO, Voltage Profile, GA-PSO (Genetic Algorithm-particle swarm optimization).*

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The distribution system plays a vital role in the electrical power network, as it is responsible for delivering electricity in a usable form directly to consumers at their point of demand. Therefore, utility providers are required to ensure that the service is reliable, efficient, and economically viable, all while maintaining proper voltage levels and ensuring high power quality.The distribution system can be a radial or loop structure. The distribution system is usually designed in a radial structure due to its simplicity and low cost when compared to a loop structure. It consists of commercial, industrial, and residential loads, as well as it has a high R/X ratio compared to transmission systems. So, the radial distribution system (RDS) has high power loss, high interruption, poor voltage profile, and voltage stability (Mihret D, 2019).

When compared to others, distribution systems experience a high loss of power due to their operation at low voltage. Voltage drop is also a common issue in distribution systems. Distribution feeders may supply or absorb reactive power depending on the load current. At loads below surge impedance, feeders supply net reactive power while at loads above surge impedance loading, they absorb reactive power. Consequently, when feeding heavy loads or employing long-distance distribution feeders, voltage drop issues may emerge (Taye, 2019). The distribution networks acquire higher losses (i.e., around 13%) in the entire power system, and the voltage profile issues of radial distribution systems (RDS) have to be considered urgently (Salkuti, 2021). To minimize the active and reactive line losses and increase the efficiency of the distribution system, it is essential to maintain the voltage at equipment terminals within acceptable limits, so the reactive power flow is limited (Sirjani & Rezaee Jordehi, 2017).

The electric power distribution network is an essential part of the entire power system, tasked with supplying electrical energy to consumers. Therefore, utility companies need to guarantee that the service is dependable, efficient, and economical, while also upholding appropriate voltage levels and power quality.

Distribution generation (DG) refers to small-scale renewable energy resources such as wind, solar photovoltaic (PV), biomass, etc. that are optimally placed to reduce losses in the distribution network. However, the placement of DG does not fulfill reactive power needs, Particle swarm optimization (PSO) is one of the artificial intelligences (AI) algorithms introduced by Kennedy and Eberhart in 1995(Tungadio et al., 2015). Genetic Algorithm (GA) was first introduced by John Holland and further developed by Goldberg, and they suggest that GA uses natural selection to solve an optimization problem (R. K. Singh, 2018). GA can solve complex problems in less time. A power system is a promising field where PSO and GA can be employed to attain optimal performance. This paper illustrates enhancements in voltage profiles and reductions in power losses, utilizing PSO and GA to determine the best locations and sizes for DG and DSTATCOM.

1.2 Description of Case Study Area

Bishoftu substation II is found in the eastern part of Ethiopia, located in the Oromia region East Shoa zone, inside Bishoftu City. Bishoftu substation II is far away from Addis Ababa at a distance of around 60 km. Bishoftu substation II is a substation that receives 132KV from Koka and delivers to Bishoftu city and around through fifteen feeders. In this substation, there are three Power transformers 132/15KV (which are rated at 25 MVA, 31.5 MVA,31.5 MVA), and the total Substation Load is 88 MVA.

1.3 Statement of the Problem

The demand for electrical power has been steadily rising, leading to the overloading of distribution feeders that deliver electricity from substations to consumers. When these long-distance feeders are overloaded, they experience significant power losses and a deterioration in the quality of their voltage profiles. Finding strategies to reduce losses and enhance voltage profiles in the distribution system is therefore essential. The majority of researchers have concentrated on the individual integration of DSTATCOM in the distribution system, as can be seen from the literature review. The authors demonstrated that when these measures are successfully implemented, losses are reduced and the distribution system's voltage characteristics are enhanced. However, installing DSTATCOM in the distribution system offers the possibility of further lowering losses and improving voltage profiles. Bishoftu substation II covers large areas and experiences high power demand, and a low voltage profile, and due to overload, interruption occurs frequently with a significant voltage drop.

Nowadays, as a result of the population growth size and economic development, the electric power consumption is rapidly increasing. However, the existing power fails to satisfy the power demand of customers, posing a major problem. This issue is also present in the

Bishoftu Substation II, which features fifteen outgoing distribution feeders. Despite the potential of these techniques, there is a lack of research focusing on their practical application to Ethiopian distribution networks, particularly in Bishoftu Substation II. A detailed analysis and comparison of PSO and GA methods for optimal DSTATCOM placement, along with cost and payback considerations, is yet to be conducted for this substation. Thus, this research aims to fill this gap by developing and simulating a model of Bishoftu Substation II in MATLAB to evaluate the impact of DSTATCOM integration using optimization methods, using PSO and GA. The study seeks to quantify the improvements in voltage profile, reduction in system losses, and assess the economic feasibility of the proposed solution.

1.4 Objectives

1.4.1 General Objectives

This thesis's main goal is to assess and contrast how well Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) work to minimize power losses and improve the voltage profile of Bishoftu Substation II by strategically placing and sizing DSTATCOM.

1.4.2 Specific Objectives

The specific objectives of this proposal are:

- To assess and quantify the current distribution system's power loss and voltage characteristics.
- To create a DSTATCOM model for Bishoftu substation II.
- Using the PSO and GA, determine the best location and dimensions for DSTATCOM.
- To compare the distribution system power losses and voltage profiles with the base case and examine the impact of DSTATCOM integration.
- To develop conclusions and suggestions based on this study's findings

1.5 Significance of the Study

Finding the most effective method to reduce distribution losses and enhance the voltage profile is greatly aided by this study. With a particular focus on Bishoftu Substation II, this study is essential in tackling the technical and financial issues facing Ethiopia's power distribution system. The goal of the research is to reduce power losses, improve voltage profiles, and increase system stability by integrating a DSTATCOM device as efficiently as possible using Particle Swarm Optimization (PSO) and Genetic Algorithm (GA). The results will provide a workable way to enhance the reliability and quality of power in radial distribution systems, which are widespread throughout Ethiopia.

Furthermore, by offering insight into sophisticated optimization strategies and their efficacy in practical situations, this work has wider relevance. By assessing the financial feasibility of DSTATCOM installation, it also aids in the planning and execution of economic power system upgrades. The findings of this study can support scholarly research in the area of power systems and act as guidelines for utility companies and policymakers.

Main Significances:

- Improves voltage profile and reduces power losses.
- Applies and compares PSO and GA optimization methods.
- Provides economic analysis (cost and payback period).
- Offers practical solutions for Ethiopian distribution systems.
- Supports future research and power quality planning

1.6 Scope of the Study

The goal of this study is to investigate and evaluate how integrating DSTATCOM can improve the voltage profile and reduce power loss in this Bishoftu substation II scenario.

It will also study the current power system power loss and voltage profile problems of Bishoftu substation II, their causes, percentage of improvements that will be gained by integrating DSTATCOM into the present Bishoftu substation II. Also, the cost analysis of DSATCOM installation will be studied. MATLAB simulation tools will be used to simulate the suggested system.

1.7 Limitation of the Study

The thesis will only focus on using MATLAB simulation tools for mathematical modeling and system simulation to improve the voltage profile and reduce power loss by incorporating DSTATCOM into the system. There is no hardware implementation because the cost of acquisition and the availability of components are also challenges for hardware implementation.

1.8 Thesis Outline

There are five chapters in this thesis. Chapter 1 of the research covers a brief background, problem statement, study objectives, significance, scope, and research limitations. The theoretical underpinnings and prior research pertinent to the subjects of distribution network power loss reduction and voltage profile enhancement are presented in Chapter 2. Beginning with a description of the site, data collection, and data analysis, Chapter 3 offers a thorough explanation of the methodology and approaches. The results of the simulation are presented and discussed in Chapter 4. Lastly, the research's findings and suggestions were discussed in Chapter 5.

CHAPTER TWO
LITERATURE REVIEW AND THEORETICAL BACKGROUND

2.1 Introduction

Electrical power is the largest and most complex system, which is a vital element of any modern economy. Electricity can be transported from generating stations to customers through a network of interconnected power lines called an electrical grid. Transmission lines transport electricity from the power generation facilities to the distribution substations, and distribution lines transport electricity from the substations to the end users. Inside the substation, high-voltage power is converted to medium and low-voltage levels using step-down transformers and is supplied to customers via different distribution feeders (Mihret Desta, 2019).

2.2 Electric Power Distribution System

The electric power distribution system represents the final stage in delivering electricity from generation sources to users. It is essential for ensuring that the electrical energy produced at power plants is delivered to users safely, reliably, and efficiently. The distribution system begins at the substation, where transmission voltage is reduced to an appropriate level (usually between 11 kV and 33 kV), and ends at the customer's service entrance. It comprises various components, including feeders, distributors, service mains, transformers, protection devices, and switching equipment.

The 45 kV, 33 kV, or 15 kV electrical power distribution network in Ethiopia is categorized as medium voltage. Typically, 33kV and 15kV overhead cables are used to provide power to as many as 80 step-down distribution transformers on each of the 33kV and 15kV circuits. Before reaching the consumer, the voltage is stepped down to 380 volts for three-phase systems or 220 volts for single-phase systems (Mihret Desta, 2019). These include voltage instability, high technical losses, and poor voltage regulation, which necessitate the integration of compensation devices like DSTATCOMs to enhance performance and reliability. A distribution transformer reduces the primary distribution voltage to a lower secondary voltage, typically 380/220 volts, suitable for ed-user applications. There are three common methods of electric power distribution systems, classified based on the configuration of the feeder lines and how loads are connected:

2.2.1 Radial Distribution System

The most straightforward and widely applied approach is the radial system, especially in rural and semi-urban regions. Each distribution feeder in this setup comes from a single substation and only provides power to consumers in one direction. Each branch serves a particular area, giving it a structure similar to a tree. The radial system's primary benefits are its affordability and simplicity of use (Alyu et al., 2023). Its main disadvantage is that all downstream customers lose power in the event of a feeder failure, and the voltage significantly drops with increasing distance from the substation.

2.2.2 Ring Main Distribution System

In a ring main system, the distribution feeders form a closed loop or ring, with each load point connected to two sources. This configuration enhances system reliability because power can flow from either direction. If a fault arises on one side of the ring, the load can still be provided from the opposite side. This system is more reliable and flexible than the radial configuration, but is also more expensive and complex to operate. It is commonly used in urban areas and for industrial loads requiring high reliability.

2.2.3 Networked (Interconnected) Distribution System

The networked distribution system is used in densely populated urban areas where reliability and flexibility are critical. In this system, multiple sources are interconnected, and each load point can receive power through several paths. The system allows for better voltage regulation, lower losses, and improved fault tolerance. However, it is complex in design, expensive to implement, and requires advanced protection and control systems. It is mainly used in central business districts, hospitals, and large industrial zones.

2.3 Power Loss and Voltage Profile

Power loss in an electrical distribution system primarily occurs due to resistance in conductors and equipment, resulting in I^2R losses (where I is the current and R represents the resistance of the line). These losses are categorized as technical losses, which encompass resistive losses in transmission lines, transformers, and other system components. In radial distribution networks, current magnitude increases toward the source, leading to higher losses in the upstream sections of the feeder. These losses not only reduce the efficiency of power delivery but also increase the operational costs for utilities. Power losses in distribution systems are affected by a number of variables, including conductor sizes, transformers, distribution line length, and load level. Active and reactive power loss are the two forms of power loss that electrical systems encounter. Reactive components cause reactive power loss, whereas line resistance causes actual power loss.

Because real power loss reduces the effectiveness of energy delivery to customers, utilities usually concentrate more on it. But there is also a considerable loss of reactive power.
The voltage profile in a power distribution system refers to the variation of voltage magnitude along the distribution line. It is crucial because electrical equipment needs to operate near its rated voltage for optimal performance. Factors such as load demand, line impedance, etc., can influence the voltage profile. If the voltage deviates significantly from the rated value, it can lead to inefficient operation or even damage to the equipment. Therefore, maintaining an appropriate voltage profile is an important aspect of power system management.

2.4 Techniques of Power Loss Reduction and Voltage Profile Improvement Techniques

Reducing power loss and enhancing the voltage profile are the primary goals of distribution system operation and planning, particularly in radial networks where line resistance and load fluctuation cause significant technical losses and voltage drops. To address these issues, a number of strategies have been created and implemented with the goal of enhancing system dependability, efficiency, and power quality (Amin et al., 2019):- This section discusses a few of the many strategies for reducing voltage deviation and power loss in distribution feeders.

Network reconfiguration: Changing switch locations to modify the circuit topology with the goal of lowering operating costs while respecting system limitations is known as network reconfiguration. It is an effective method for minimizing losses in distribution systems by modifying power flow through the creation of new paths or by selectively opening and closing switches along the feeder. This approach restructures the network into a tree-like formation, allowing for the redistribution of loads from heavily burdened feeders to those with lighter loads. By optimizing the resistance path from the source to the load point, it also makes it possible to reroute power through routes with lower resistance, reducing overall system losses. These load transfers improve voltage profiles along the distribution lines and minimize overall system losses, in addition to balancing the load across feeders and lowering power losses. However, the effectiveness of feeder reconfiguration largely depends on the level of automation and the proximity of the feeders. When feeders are automated and located relatively close to one another, reconfiguration can be efficient and practical. In contrast, for non-automated systems with feeders spread over large distances, the cost and complexity involved may outweigh the potential benefits, making the approach less economically viable.(Mehammed, 2017.he key benefits of reconfiguration are as follows (Abayneh &

Fekadu Shewarega, 2022).

- Restoring service during feeder faults
- Performing corrective and preventive network maintenance
- Alleviating network overload and enhancing bus voltage levels
- Minimizing power losses

Conductor Grading: In order to lower electrical resistance, conductor grading entails replacing current feeder conductors with more effective and optimally designed ones. This can be accomplished by adding more conductors to run in parallel with the existing ones, which lowers the overall resistance, or by replacing smaller cables with larger cross-sectional conductors that show lower resistance. While this approach can significantly reduce power losses, it is generally not cost-effective and is typically only implemented when absolutely necessary, as the expense of new conductors and their installation often outweighs the value of the energy savings achieved.

Shunt and Series Capacitor Compensation: Shunt capacitive compensation is widely used in electrical power systems to minimize active and reactive power losses and sustain constant voltage levels in situations with high reactive loads. Shunt capacitive compensation devices are widely used to minimize losses and voltage drops in transmission and distribution networks. Power electronics developments have enabled shunt active compensators, including Static Var Compensators (SVC) and Static Compensators (Statcom). The main functions of these devices are to maintain voltage profiles at desired levels and compensate reactive power within the system. By connecting capacitors in series with transmission and distribution lines, series compensation improves maximum power transfer capability, lowers effective reactive power losses, and lowers the transfer reactance between connected buses. Large, high-voltage transmission lines are the primary application for series capacitors. They contribute to improving the system's reactive power balance and voltage stability even though they are not frequently used expressly for voltage regulation. A series capacitor's reactive power rises in direct proportion to the power flowing through the line.

Shunt capacitors are generally more cost-effective to install and maintain compared to FACTS controllers. When placed near the load or at points of need, shunt capacitors help enhance voltage stability. However, they provide limited voltage control and cannot maintain a stable operating point once compensation exceeds a certain level. Furthermore, a shunt capacitor's reactive power is proportional to the square of the terminal voltage; as a result, when the terminal voltage falls, the reactive power support falls as well, potentially exacerbating the voltage condition.

Distributed Generation (DG): Distributed Generation (DG) is a recent development in power systems aimed at meeting growing electricity demand. The DG concept encompasses a variety of technologies and applications. The production of electricity from smaller facilities than conventional grid-connected power plants is known as distributed generation, or DG. Almost anywhere in the power system, these facilities can be connected. The IEEE compares the size of DG units to that of traditional generating plants. The International Council on Large Electric Systems (CIGRE), which Chambers references in his analysis of the economic aspects of distributed generation (DG), defines DG as "relatively small generating units of 30 MW or less, located at or near customer sites, designed to fulfill specific customer needs, improve the economic functioning of the distribution grid, or both."

Various distributed generation technologies are integrated into power systems. While some have been utilized for many years, others are relatively new developments. Despite their differences, all DG technologies share common goals: enhancing efficiency and reducing costs associated with installation, operation, and maintenance. In general, DG technologies fall into two groups: nonrenewable technologies (such as fuel cells, combustion turbines, and micro-turbines) and renewable technologies (such as wind turbines and photovoltaic systems). The optimal size and location for connecting to the power system or customer loads are significantly influenced by the DG technology selection. An extensive discussion of the best DG technologies relevant to this study is given in this section.

Air is the source of oxygen, whereas hydrogen is usually derived from fossil fuels like natural gas. High-current, low-voltage DC power is produced by this electrochemical process. A DC/AC converter and filtering system convert the power into AC so that the fuel cell output can be connected to the electrical grid. Fuel cells generate electricity with 40% to 60% efficiency, produce very few harmful pollutants, and run quietly enough for residential use. These advantages, along with their scalability and modular design, emphasize the benefits of fuel cells. However, the main challenge preventing their broader commercialization is the high upfront investment cost. Despite this, fuel cells offer several significant advantages.

Higher Efficiency: Because fuel cells directly transform the chemical energy of the fuel into electrical energy, they are more efficient. This method gets around the drawbacks of conventional combustion-based power generation systems, which are caused by the Carnot thermodynamic cycle.

Low Chemical, Acoustic, and Thermal Emissions: Because of their higher efficiency and lower fuel oxidation temperatures, fuel cells generate significantly less carbon dioxide and nitrogen oxides per unit of electricity. With the exception of auxiliary parts like pumps, blowers, and transformers, they also produce very little noise and vibration because they don't have any moving parts.

Modularity: Each fuel cell generates less than one volt of electrical potential. To generate higher voltages, fuel cells are stacked and connected in series. Each of the cells that comprise these stacks has an anode, a cathode, an electrolyte, and a bipolar separator plate. The number of cells used in a stack depends on the performance of each cell and the desired power output. A stack may be a few hundred watts, several hundred kilowatts, or even several megawatts in size.

Fuel Flexibility: Fuel cells are versatile because they can operate on a variety of fuels, including natural gas, coal gas, propane, landfill gas, anaerobic digester gas, and military logistic fuels. Hydrogen continues to be the most popular fuel, particularly for low-temperature fuel cells that require pure gases to operate effectively.

The flexibility of a fuel cell is greatly influenced by its operating temperature range; generally speaking, higher operating temperatures allow the use of less pure gases. All current fuel cell technologies are still in the early stages of research and face a number of challenges that limit their applicability in comparison to other technologies, despite the many promising benefits that fuel cells offer.

- Fuel cells are still too expensive (in €/Wh) to be a viable alternative to fossil fuel-based systems for stationary electricity generation.
- It is still unclear how long many fuel cell technologies last and how quickly they degrade, particularly high-temperature models that are perfect for producing electricity.
- A major fuel for many fuel cell systems, hydrogen is costly, and there is currently a lack of a widespread infrastructure for its production and distribution.

Wind Power: Wind turbines are the technology that converts the kinetic energy of wind into electrical energy. Recently, advancements have focused on increasing the power output of these turbines. Locations with high wind speeds, such as coastal areas and high-altitude sites, are ideal for maximizing energy extraction from wind turbines. Over recent years, wind turbines have become more commonly integrated into distribution networks due to their renewable nature and zero pollution characteristics. Compared to conventional power generation techniques, wind energy generation is fuel-free and has lower operating and maintenance costs. However, the main disadvantage of wind power technology is that its output is unpredictable and variable. Power generation varies with the wind speed throughout the day. Power quality problems like voltage fluctuations (both rises and dips), higher power losses, and decreased voltage stability within the power system are caused by this intermittency.

Photovoltaic system: Global energy demand is growing faster than energy production due to rising industrialization, population growth, and improved living standards. When placed close to end users, distributed generation (DG) can enhance overall power quality and stabilize the electrical grid. DG encompasses small-scale technologies, frequently using small generators or renewable energy sources that generate electricity near consumption sites. A photovoltaic (PV) system is made up of solid-state semiconductor devices that produce electricity when exposed to sunlight. Multiple solar cells connected in series and parallel make up a photovoltaic module, commonly referred to as a solar panel. The core part of a photovoltaic system is the solar cell. PV modules are connected in series to increase the output voltage and arranged in parallel to maximize the output current. Due to their low maintenance requirements and long-term advantages, solar PV power systems have been promoted in many countries. One of the biggest implementation challenges for PV power systems is managing the nonlinear behavior of PV arrays. Temperature and irradiance levels are two examples of variables that affect PV module performance. Shade from surrounding structures, trees, or passing clouds causes variations in irradiance, which alters how much sunlight the PV array receives.

2.5 Flexible AC Transmission Systems (FACTS) Devices

In AC power transmission systems, FACTS devices are static controllers and power-electronic devices. By controlling voltage, current, and power flow, they increase controllability and power transmission capacity (Hingorani et al., 2000). FACTS devices are designed with cutting-edge power electronics technology and possess the capability to execute control actions at a high speed. The primary function of FACTS is to control power flow and regulate voltage levels in the transmission lines where they are connected. FACTS devices can be classified into two based on the power electronics devices they use; Thyristor valve/convertor-based FACTS devices like TCSR, TCSC, and SVC and voltage source convertor-based FACTS devices such as STATCOM, SSSC, and UPFC.

In general, FACTS devices can be classified as below (Hingorani et al., 2000).

- Shunt-connected controllers like SVC, STATCOM, etc.
- Series-connected controllers like SSSC, TCSR, etc.
- A combination of series-connected and shunt-connected controllers like UPFC and TCPST.

2.6 .1 Shunt-Connected Controllers

The current is injected into the line using shunt-connected controllers. The shunt controller can provide reactive power without interfering with the flow of active power by making sure that the injected current is in quadrature (90 degrees out of phase) with the line voltage. Actual power is used when the injected current is not in quadrature phase. Two instances of shunt-connected controllers are SVC and STATCOM.

Static Var Compensator (SVC):

A shunt-connected SVC is a device that can be fine-tuned to either inject or absorb reactive power into the electrical grid. This adjustment capability allows for the regulation of specific parameters within the power system, such as maintaining desired voltage levels at specific points (buses) in the network (Hingorani et al., 2000). SVC is constructed using thyristors that do not possess a gate turn-off feature. It is made up of separate parts for leading and managing lagging. Varis: a thyristor-switched capacitor for supplying reactive power and a thyristor-controlled reactor for absorbing it. The simplicity, minimal losses, reduced harmonics generation, and cost-effectiveness of SVC have led to its extensive utilization in comparison to other shunt FACTS devices (Abayneh & Fekadu Shewarega, 2022).

Static Synchronous Compensator (STATCOM)

STATCOM functions as a shunt connected SVC, enabling independent control of its capacitive or inductive output current regardless of the AC system voltage (Hingorani et al., 2000). Either a voltage-sourced or a current-sourced converter can be used to implement STATCOM, a crucial FACTS controller. Voltage-sourced converters seem to be the best option when considering cost (Hingorani et al., 2000). By converting DC input voltage to AC output voltage, it modifies the active and reactive power of the system. When it comes to reactive power compensation and voltage regulation, STATCOM performs better than SVC. STATCOM enhances power system stability, mitigates power oscillations in transmission systems, and ensures adequate reactive power compensation. It achieves this by regulating voltage levels within transmission and distribution networks. When a STATCOM incorporates an energy storage system at its DC terminal, it can exchange real power with the system (Abayneh & Fekadu Shewarega, 2022).

The key distinction between an SVC and a STATCOM lies in their operational methods. A STATCOM employs a converter to generate reactive power and operates like a shunt-connected synchronous voltage source. On the other hand, an SVC utilizes Thyristor- switched capacitors and, Thyristor-controlled reactors, operating as a shunt-connected controlled reactive admittance.

Series Connected Controllers

All series controllers in operation introduce voltage along the line, including situations in which a variable impedance interacts with the current flowing through it to produce a series voltage along the line (Hingorani et al., 2000). The series controller only exchanges reactive power when the line current and the voltage are in phase quadrature; otherwise, it will handle real power.

i) Static Synchronous Series Compensator (SSSC)

One of the most important FACTS controllers is SSSC. Because its alternating current (AC) voltage output is connected in series with the transmission line, it functions similarly to a STATCOM but differently. Both voltage-sourced and current-sourced converters are available for use in SSSCs. The SSSC is composed of a DC bus (storage unit), converter, and coupling transformer (Abayneh & Fekadu Shewarega, 2022). According to Hingorani et al. (2000), the voltage injected in series is usually much lower than the transmission line voltage. When the injected voltage is in quadrature with the line current, reactive power is transmitted; when the injected voltage is in phase with the line current, active power is exchanged. Therefore, the STATCOM has the capability to exchange both real and reactive power within a transmission line when it is equipped with energy storage (Abayneh & Fekadu Shewarega, 2022).

ii) **Thyristor-Controlled Series Capacitor (TCSC)**

It’s a compensator with capacitive reactance comprising a series capacitor bank, and shunted thyristor-controlled reactor to offer a smoothly adjustable series capacitive reactance (Hingorani et al., 2000). The TCSC utilizes thyristors that do not have a gate turn-off feature. It serves as an option to the SSSC mentioned earlier and, similar to the SSSC, it holds significant importance as a FACTS controller. A series capacitor connects to a variable reactor, such as a Thyristor-Controlled Reactor (TCR). The reactor becomes non-conductive and the series capacitor displays its typical impedance when the TCR firing angle reaches 180 degrees. On the other hand, the reactor switches to full conduction and the total impedance becomes inductive when the TCR firing angle reaches 90 degrees. Because the reactor impedance is purposefully set lower than the series capacitor impedance, this shift takes place. The TCSC contributes to fault current limitation by operating at a 90-degree firing angle. To increase its efficiency, TCSC can be a single large unit or several capacitors of different or equal sizes.

Combination of Series and Shunt-connected Controllers

This scenario could involve a mix of distinct shunt and series controllers, operated in a synchronized fashion, or a Unified Power Flow Controller integrating both series and shunt elements (Hingorani et al., 2000). Shunt and series controllers are typically used in conjunction to add voltage in series with the line through the series portion of the controller and add current to the system through the shunt component. However, when shunt and series controllers are integrated, real power can be transferred between the shunt and series controllers through the power link (Hingorani et al., 2000).

Unified Power Flow Controller (UPFC)

UPFC is set up comprising STATCOM and SSSC, coupled through a shared DC link, which enables bidirectional real power exchange between the output terminals of the SSSC and the STATCOM. This configuration is to deliver simultaneous actual and reactive power, series compensation without necessitating an external electrical power source (Hingorani et al., 2000). The UPFC is capable of simultaneously adjusting all three aspects of line power flow; voltage, line impedance, and phase angle (Abayneh & Fekadu Shewarega, 2022). The SSSC unit acquires its active power from the line through the associated STATCOM shunt unit, which also serves as a voltage regulator by managing its reactive power.

This comprehensive controller manages both actual and reactive power distribution across the line, while also maintaining control over line voltage. Incorporating extra storage like a superconducting magnet linked to the DC link through an electronic interface would offer a way to boost the effectiveness of the UPFC even further (Hingorani et al., 2000).

Thyristor-Controlled Phase Shifting Transformer (TCPST)

A phase-shifting transformer that provides a rapidly adjustable phase angle and is managed by thyristor switches. Phase shifting is usually accomplished by connecting a phase in series with a perpendicular voltage vector. Transformers connected in parallel are used to create this vector from the remaining two phases (Hingorani et al., 2000). The adjustable perpendicular series voltage is achieved through various power electronics setups. A circuit design capable of managing voltage reversals can induce phase shifts in either direction.Overall, the effectiveness of FACTS devices across various uses is summarized in Table 2.1(Hingorani et al., 2000; Abayneh & Fekadu Shewarega, 2022).

Table 2. 1 Summary of FACTS device applications

FACTS Devices					
Connection type	Series		Shunt		Combined
Device	TCSC	SSSC	SVC	STATCOM	UPFC
Problem					
Dynamic voltage control	***	**	**	**	***
Steady-state phase balancing	*	*	**	**	***
Steady-state voltage control	***	**	**	***	***
Steady-state power flow control	**	**	***	***	***
Transient stability	**	*	***	**	**

***, Strong influence; **, Medium influence; *, Low influence

2.6.1 Distribution Static Synchronous Compensator (DSTATCOM)

A shunt-connected FACTS device called a STATCOM (Static Synchronous Compensator) aids in regulating the electricity flow in high-voltage transmission networks. When used in a low-voltage distribution network, it is known as DSTATCOM. Based on a voltage source converter (VSC), DSTATCOM is a three-phase shunt-connected FACTS device that improves the distribution system's voltage profile and compensates reactive power. At the point of common connection (PCC), the DSTATCOM has the ability to inject or absorb both actual and reactive power. However, it is practically unfeasible for DSTATCOM to inject active power continuously for an extended duration due to the limitations imposed by energy storage. Therefore, most of the time in steady state operation there is only reactive power exchange between DSTATCOM and the system. A schematic diagram of a DSTATCOM connected to a bus k is shown in Figure 2.4. The typical type of DSTATCOM designed for steady-state operation consists of a transformer with leakage reactance, a DC capacitor, a voltage source converter (VSC), and a GTO/IGBT in its configuration (Iqbal et al., 2018).

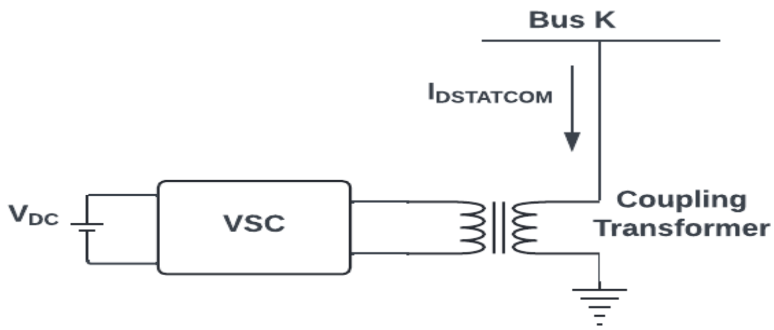

Figure 2. 1; DSTATCOM connected to a certain bus k

Since The source of DSTATCOM is DC Capacitor bank and it's function is By varying the amplitude of its output voltage, which is synchronized with the system voltage (Vs), the DSTATCOM regulates the exchange of reactive power. When the DSTATCOM output voltage (Vsc) exceeds Vs, it acts as a capacitor (capacitive mode) to inject reactive power into the system. Conversely, when Vs is higher than Vsc, the DSTATCOM absorbs reactive power, acting as an inductor (inductive mode). When Vsc equals Vs, no reactive power exchange occurs, resulting in a zero net reactive power flow (no-load mode) (Hingorani et al., 2000).

2.6.1.1 Mathematical Modelling of DSTATCOM

The DSTATCOM mathematical modeling is presented in this section. Distribution networks are typically designed radially, with power coming from only one side. The mathematical modeling of DSTATCOM in a steady state can be illustrated using a basic distribution network with two buses, as depicted below.

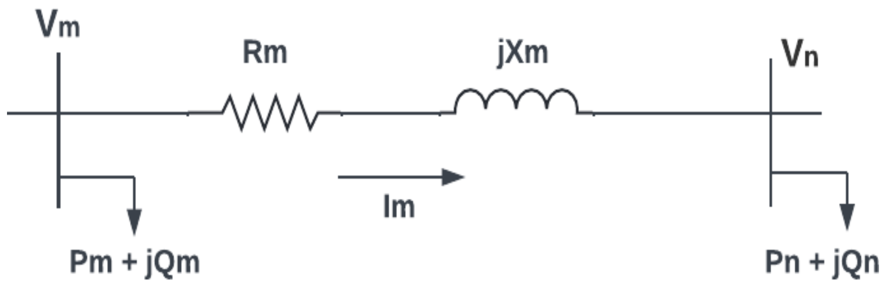

Figure 2. 2 Two-bus radial distribution network

Where R_m denotes the line resistance and X_m denotes the line reactance between the bus m and n, $P_m + jQ_m$ and $P_n + jQ_n$ denote the local loads connected at the bus m and n, respectively. Likewise, V_m and V_n, denote the voltages at the bus m and n, respectively.

The voltage equation for a two-bus system can be expressed as

$$V_n = V_m \angle \theta_m - (R_m + jX_m)_m \angle \delta \qquad (2.1)$$

The DSTATCOM is installed at two bus radial distribution networks for steady-state modeling, as depicted in Figure 2.6.

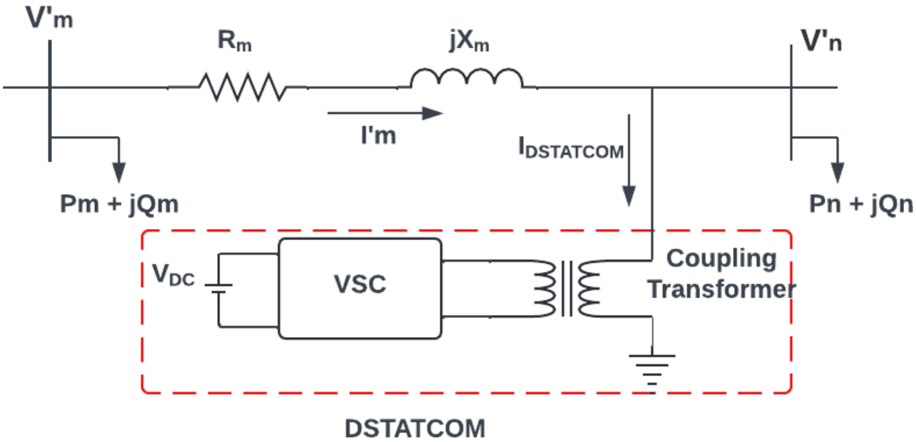

Figure 2. 3 Two-bus radial distribution network with DSTATCOM

After the installation of DSTATCOM, the voltages at the bus where it's connected and at the neighboring bus will change. The new voltage values at the candidate bus will be denoted as V'_n and at the previous neighboring buses as V'_m. These changes in voltage are accompanied by changes in the current, denoted as I'_m. The new current is a combination of I_m and $I_{DSTATCOM}$, where $I_{DSTATCOM}$ represents the current injected by DSTATCOM.

$$V'_n \angle \theta_n = V'_m \angle \theta'_m - (R_m + jX_m)(I_m \angle \delta + I_{DS} \angle (\frac{\pi}{2} + \theta'_n)) \text{ .... } (2.2)$$

Here θ'_n, θ'_m and δ are the phase angles of V'_n, V'_m and I_m respectively.

$V'_n = b$

$h_1 = Real(V'_m \angle \theta'_m) - Real(Z_m I_m \angle \delta)$

$h_2 = Imag(V'_m \angle \theta'_m) - Imag(Z_m I_m \angle \delta)$

$h_3 = -X_m$

$h_4 = -R_m$

$I_{DS} = x_1$

$\theta'_n = x_2$

When the real and imaginary portions of the preceding equations are separated, we obtain

$$V'_n\cos\theta'_n = Real(V'_m \angle \theta'_m) - Real(Z_m I_m \angle\delta) - R_m I_{DS} \cos\left(\frac{\pi}{2} + \theta'_n\right) + X_{m\_DS} I \sin\left(\frac{\pi}{2} + \theta'_n\right) \ldots\ldots (2.3)$$

$$V'_n\sin\theta'_n = Imag(V'_m \angle \theta'_m) - Imag(Z_m I_m \angle\delta) - X_m I_{DS} \cos\left(\frac{\pi}{2} + \theta'_n\right) + R_{m\_DS} I \sin\left(\frac{\pi}{2} + \theta'_n\right) \ldots (2.4)$$

So equations (2.3) and (2.4) changes to

$$bcosx_2 = h_1 - h_4x_1sinx_2 - h_3\, x_1cosx_2 \ldots\ldots (2.5)$$

$$bsinx_2 = h_2 - h_3x_1sinx_2 - h_4\, x_1cosx_2 \ldots\ldots (2.6)$$

So from equation (2.5) and 2.6

$$x_1 = \frac{bcosx_2 - h_1}{-h_4sinx_2 - h_3\,cosx_2} \ldots\ldots (2.7)$$

$$x_1 = \frac{bsinx_2 - h_2}{-h_3sinx_2 - h_4\,cosx_2} \ldots\ldots (2.8)$$

By equating both equations (2.7) and (2.8), we get

$$bh_4 + (h_1h_3 - h_2\,h_4)sinx_2 + (-h_1h_4 - h_2\,h_3)cosx_2 = 0 \ldots\ldots (2.9)$$

Let

$sinx_2 = t$

$(h_1h_3 - h_2\,h_4) = k_1$

$(h_1h_4 + h_2\,h_3) = k_2$

So equation (2.9) changes to

$$bh_4 + k_1t - k_2\sqrt{1 - t^2} = 0 \ldots\ldots (2.10)$$

On squaring both sides and manipulating, we get

$$(k_1^2 + k_2^2)t^2 + 2bh_4\,k_1t + b^2h_4^2 - k_2^2 = 0 \ldots\ldots (2.11)$$

Thus

$$t = \frac{-B \pm \sqrt{D}}{2A}$$

$D = B^2 - 4AC$

where

$A = k_1^2 + k_2^2$

$B = 2bh_4\,k_1$

$C = b^2h_4^2 - k_2^2$

On putting values of k_1 and k_2 we get,

$$A = (h_1h_3 - h_2h_4)^2 + (h_1h_4 + h_2h_3)^2 \quad \text{.......... (2.12)}$$

$$B = 2(h_1h_3 - h_2h_4) + (V'_n)(h_4) \quad \text{.......... (2.13)}$$

$$C = (V'_nR_m)^2 - (h_1h_4 + h_2h_3)^2 \quad \text{.......... (2.14)}$$

Now there are two roots of t. For determining the correct value of root, the boundary considerations are examined $V'_n = V_n \Rightarrow I_{DS} = 0$ and $\theta'_n = \theta_n$

$$\theta'_n = sin^{-1}\left(\frac{-B \pm \sqrt{D}}{2A}\right) \quad \text{.......... (2.15)}$$

D-STATCOM current angle and magnitude is:

$$\angle I_{DS} = \frac{\pi}{2} + k_2 = \frac{\pi}{2} + sin^{-1}t \quad \text{.......... (2.16)}$$

$$|I_{DS}| = k = \frac{V^F_n cos\theta_n - h_1}{-h_4 sin\theta^F_n - h_3 cos\theta^F_n} \quad \text{.......... (2.17)}$$

Finally, the reactive power injected is:

$$jQ_{DS} = (V'_n \angle \theta'_n).(I_{DS} \angle (\frac{\pi}{2} + \theta'_n))^* \quad \text{.......... (2.18)}$$

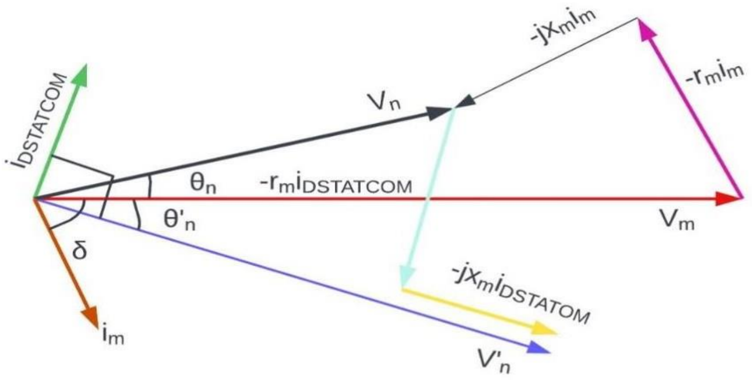

Figure 2. 4 The voltage and current phasor diagram of the system after taking DSTATCOM into account

2.6.1.2 Reason for Choosing DSTATCOM

A significant challenge within distribution networks is the ability to meet the full power demand of loads while keeping the voltage levels within acceptable limits. Addressing this issue necessitates the integration of advanced technologies aimed at voltage regulation and power loss reduction. These technologies include automated voltage regulators (AVRs), capacitor banks, shunt and series reactors, and FACTS devices like Static Synchronous Series Compensator (SSSC), Distribution STATCOM (DSTATCOM), Unified Power Quality Conditioner (UPQC), and Static VAR Compensators (SVC). DSTATCOM is unique among these in that it can continuously and quickly supply or absorb reactive power.

When connected to a specific load, DSTATCOM can supply adequate leading or lagging reactive current, ensuring that the total system demand complies with utility standards. Additionally, it can correct voltage imbalances and mitigate harmonic distortions. The strategic placement of DSTATCOM not only increases the load-handling capability of the system but also reduces power losses, enhances system stability, supports reactive power compensation, and improves overall power quality.

2.7 Comparison between D-STATCOM and Conventional Devices

D-STATCOM is a shunt-connected Voltage Source Converter (VSC) utilized in distribution networks to regulate bus voltage, enhance power factor, and control reactive power. It provides fast and continuous compensation for both capacitive and inductive conditions. When connected to a specific load, a D-STATCOM can inject leading or lagging compensating current as needed, ensuring that the total power demand meets utility connection standards. At the same time, it can mitigate voltage imbalances and harmonic distortions. As power system demands rise, D-STATCOM is anticipated to be an essential part of radial distribution systems. Strategically placing D-STATCOM units enhances load capacity, decreases power losses, improves system stability, compensates for reactive power, and elevates power quality through voltage regulation, voltage balancing, and flicker mitigation.
In summary, the primary functions of a D-STATCOM include:

- Regulating voltage and compensating reactive power
- Enhancing the load capacity of distribution lines
- Reducing power losses
- Minimizing harmonic currents
- Correcting the power factor
- Reducing voltage flicker effects

A major challenge in distribution systems is meeting the total power demand while maintaining voltage levels within acceptable limits. Addressing this challenge effectively requires advanced technologies aimed at minimizing power losses in the distribution network. Capacitor banks, shunt and series reactors, automated voltage regulators (AVRs), and the newly created Flexible AC Transmission Distribution System (DFACTS) devices, like the Distribution Static Compensator (D-STATCOM), Unified Power Flow Controller (UPFC), and Static Synchronous Series Compensator (SSSC), are a few examples of these technologies. D-STATCOM offers several benefits compared to traditional reactive power compensation devices, such as reduced power losses, minimal harmonic distortion, superior control capabilities, lower cost, and compact size. Furthermore, unlike shunt or series capacitors, D-STATCOM does not experience operational problems like resonance or transient harmonics. Traditional series voltage regulators, due to their incremental operation, are unable to generate reactive power and respond slowly. Likewise, when paired with inductive elements, shunt capacitors are limited in their ability to provide continuously variable reactive power and display inherent oscillatory behavior. A D-STATCOM can provide compensating current when it is connected to a particular load in order to guarantee that the overall power demand satisfies utility connection requirements. Additionally, it can remove harmonic distortions and rectify imbalances in the power at the utility bus. Through voltage regulation, voltage balancing, and flicker mitigation, D-STATCOM is anticipated to become increasingly important in increasing load capacity, boosting system stability, compensating reactive power, lowering power losses, and improving power quality as power system loads increase.

2.8 Literature Review

A wide range of strategies have been put forth by numerous researchers to lessen power losses and voltage drops in radial distribution systems (RDS). Below is a summary of some of the noteworthy approaches and optimization strategies:

Devabalaji and Ravi (2016) suggest a new optimization technique that entails figuring out the best places and dimensions for Distribution Static Compensators (DSTATCOM) and Distributed Generators (DG). Their approach sought to enhance the voltage profile while reducing power losses and operating expenses. The Bacterial Foraging Optimization Algorithm (BFOA) was used to size these devices, and the Location Sensitivity Factor (LSF) was used to determine the best locations.

In (Amin et al., 2019) the author, proposed an analytical technique for optimally sizing and placing DG and DSTATCOM in RDS, targeting total power loss minimization and voltage profile improvement. They utilized the Power Stability Index (PSI) for location determination and sensitivity analysis for sizing. The method’s performance was verified using IEEE 34-bus and 69-bus systems, with comparisons drawn against alternative techniques.

In order to ascertain the ideal positioning and dimensions of DGs within an RDS, this paper (Aditya Prasad Padhy, 2020) created a computationally effective analytical method. The technique aimed to improve the voltage profile and lower active power losses. The buses with the highest loads were chosen for DG placement based on the Voltage Stability Index (VSI). The DG size was calculated using the Continuous Increment of Step Size (CISS) technique.

For the best co-integration of PV-based DG and DSTATCOM into IEEE 33-bus and 69-bus distribution systems, Lasmari et al. (2020) used different iterations of the Particle Swarm Optimization (PSO) algorithm. A single objective function served as the foundation for the optimization, which sought to maximize the Active Power Loss Limitation (APLL) in order to achieve an effective Energy Management Strategy (EMS).

A different strategy was used by Bilgundi (2020), who provided an analytical framework to identify the best location and capacity for DG and DSTATCOM in order to reduce active power loss and improve voltage regulation. Sitting and sizing were done using the PSI method, and the analysis was done using the Backward/Forward Sweep (BFS) load flow method. The algorithm was implemented and tested on the IEEE 33-bus system using MATLAB.

In (Salkuti, 2021), introduced a multi-technique approach involving VSI for locating DSTATCOMs and LSF for DG placement, while the Bat Algorithm (BA) was applied for optimal sizing. This hybrid methodology aimed to minimize losses and improve voltage profiles. The IEEE 34-bus and 85-bus systems were used for validation.

In (Alwazni & Al-kubragyi, 2021) developed a Multi-Objective Particle Swarm Optimization (MOPSO) approach to determine both location and sizing of DG and DSTATCOM. Using VSI to pre-identify installation points, MOPSO optimized the capacity of these devices to improve voltage profile and stability while reducing overall losses under various load models.

A Fuzzy Logic Firefly Bat Algorithm (FLFBA) was proposed by Reddy et al. (2022) to determine the best places for DG and Flexible AC Transmission Systems (FACTS) devices in distribution networks. Enhancing the minimum VSI was given priority in this approach, which also took active and reactive power loss reductions into account. The method was evaluated on the IEEE 33-bus system and contrasted with other algorithms, such as PSO, FA, and BA.

In (Mustapha et al., 2023) evaluated an Artificial Bee Colony (ABC)-based method for optimal DG and DSTATCOM placement, taking into account varying load factors. The study compared performance outcomes when the devices were placed together versus separately. Results indicated that separate placement reduced power losses more effectively, while co-located placement slightly improved voltage profiles.

In (Maurya & Sharma, 2024) utilized the Arithmetic Optimization Algorithm (AOA) to determine optimal positions and sizes for DGs and DSTATCOM in RDS. The goal was to reduce power losses and voltage deviations, enhance VSI, and save energy annually. DGs were tasked with active power compensation, and DSTATCOMs with reactive power. AOA demonstrated superior performance over BFOA, Grasshopper, and Immune algorithms through simulation results.

In (Ferminus Raj & Gnana Saravanan, 2024) proposed a hybrid method combining LSF and the Discrete Mayfly Optimization (DMO) technique. Initially, LSF identified potential installation points for DG and DSTATCOM, followed by DMO for final location and size optimization. The approach was simulated in MATLAB Simulink and benchmarked against DA, SGO, and SAA using IEEE standard systems, showing improved dynamic stability and operational performance.

(Isha et al., 2025) introduced the Elitist Harris Hawks Optimization (EHHO) algorithm to address multi-objective optimization in RDS. The method aimed to improve voltage stability, reduce power losses, and enhance voltage profiles through optimal DG and DSTATCOM placement and sizing. Load flow was analyzed using the Newton-Raphson method, and simulation was conducted on the IEEE 30-bus system using MATLAB. The EHHO algorithm outperformed several other optimization techniques such as FLSA, IWHO, TLBO, and BONMIN under varying load conditions.

Table 2. 2 Related work

S/N.	Title of Journals	Year of publi.	Gaps
1	Devabalaji & Ravi	2016	Did not consider dynamic loading conditions; focused only on LSF and BFOA for sizing without multi-objective trade-offs.
2	Amin et al.	2019	Focused on analytical methods but did not evaluate real-time adaptability or non-linear load behavior.
3	Aditya Prasad Padhy	2020	Relies on analytical approach; lacks consideration of DSTATCOM alongside DG for combined performance analysis.
4	Lasmari et al.	2020	Uses only PSO variants and considers a single objective; lacks broader comparison with multi-objective or hybrid methods.
5	Bilgundi	2020	Did not consider dynamic scenarios or real-time system variation; application limited to IEEE-33 system.
6	Salkuti	2021	Optimization handled separately for DG and DSTATCOM; limited by algorithm scalability for large systems.
7	Alwazni & Al-kubragyi	2021	Lacked flexibility to adapt to real-time voltage stability threats; did not include economic or load sensitivity analyses.

8	Reddy et al.	2022	Mainly targeted VSI enhancement; limited exploration of simultaneous power loss and cost optimization.
9	Mustapha et al.	2023	Did not fully analyze voltage stability under varying load conditions; focused on same vs separate placements only.
10	Maurya & Sharma	2024	Used AOA but lacked comparison with real-time control or adaptability to load changes over time.
11	Isha et al.	2025	Focused on EHHO algorithm; lacks exploration of other load models and economic cost impact.

The focus on reducing power losses and enhancing voltage profiles through the ideal positioning and sizing of DSTATCOM using a variety of optimization techniques is generally highlighted in the literature reviewed in this section. Analytical techniques were used in many earlier studies to determine the best places for DSTATCOM units. While some used the Newton-Raphson method for load flow analysis, others used single-objective functions for both placement and sizing. The absence of investment cost analysis for DSTATCOM implementations, however, is a common limitation shared by the majority of studies.

By using metaheuristic optimization algorithms to determine the best location and dimensions for DSTATCOM, this study seeks to fill in these research gaps. Furthermore, in order to efficiently lower power losses and improve voltage profiles, this work investigates the coordinated integration of DSTATCOM into the distribution network.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter describes the materials and methodology used in this study, which aims to determine the best location and size for Distribution Static Compensator (D-STATCOM) and Distributed Generation (DG) in radial distribution systems (RDS) in order to improve voltage profiles and reduce power losses. DG and D-STATCOM integration has become a viable and efficient solution in response to the growing demand for improved power quality and operational efficiency in distribution networks.

To achieve the objectives of this research, an appropriate test system is selected and modeled. The performance of the system is analyzed using a direct load flow method. Furthermore, a multi-objective optimization approach is employed to determine the optimal locations and sizes of DG and DSTATCOM units. This study utilizes a metaheuristic optimization technique due to its ability to efficiently handle complex, nonlinear, and multi-dimensional problems with multiple constraints.

The methods used in this study include problem formulation, development of an objective function, implementation of system constraints, and simulation procedures using MATLAB software. The investment cost analysis of both DG and DSTATCOM is also incorporated into the objective function to ensure economic feasibility. This chapter provides a detailed explanation of the chosen methodology and tools that contribute to the achievement of reliable and efficient system performance.

3.1 Description of Case Study Area

Bishoftu substation II is found in the east part of Ethiopia, located in the Oromia region east Shoa zone inside of Bishoftu City. Bishoftu substation II is far away from Addis Ababa at a distance of around 60 km. Bishoftu substation II is a substation that receives 132KV from Koka and delivers to Bishoftu city and arounds through fifteen feeders. In this substation, there are three Power transformers 132/15KV (which are rated at 25 MVA, 31.5 MVA, and 31.5 MVA) and the total Substation Load is 88 MVA.

3.2 Data Collection

The data essential for this research has been gathered primarily from Bishoftu Substation II, the Load Dispatch Center, Ethiopian Electric Power (EEP), Ethiopian Electric Utility (EEU), Ethiopian National Metrology Institute, and NASA. The data collected includes historical records of feeder peak loading, voltage levels, solar radiation, and other critical technical parameters relevant to the performance and analysis of the distribution system.

Bishoftu Substation II is situated in the eastern part of Ethiopia, within the Oromia region, East Shoa Zone, inside Bishoftu City. The substation is approximately 60 kilometers from Addis Ababa. It receives 132 kV transmission from Koka and distributes electric power to Bishoftu city and its surrounding areas through fifteen 15 kV feeders.

The substation houses three power transformers rated at 132/15 kV with capacities of 25 MVA, 31.5 MVA, and 31.5 MVA, respectively. The total load capacity of the substation is 88 MVA, which supports a broad and growing urban and semi-urban demand.

The directions of the Bishoftu Substation II power distribution feeders have been explained below:

Table 3. 1: Directions and Coverages of the Bishoftu Substation II power distribution feeders

Incoming TRAFO	Feeder Name	Bus Bar Voltage (KV)	Destination/Coverage Area
TRAFO 3	K1	15KV	Sanitel Steel Factory
TRAFO 3	K2	15KV	Sanitel Steel Factory
TRAFO 3	K4	15KV	For Substation by itself
TRAFO 3	K6	15KV	Sanitel Steel Factory
TRAFO 3	K7	15KV	Adulala Town
TRAFO 2	K8	15KV	Bishoftu Town
TRAFO 2	K9	15KV	Bishoftu Town
TRAFO 2	K12	15KV	Abyssinia Steel Factory
TRAFO 2	K13	15KV	Abyssinia Steel Factory
TRAFO 1	K14	15KV	Out of Service
TRAFO 1	K16	15KV	Bishoftu Town
TRAFO 1	L1	15KV	Bishoftu Town

TRAFO 1	L2	15KV	Bishoftu Automotive & Defence hospital

Among the fifteen feeders (currently two feeders not active), a specific feeder (or feeders K-8) is selected for case analysis based on criteria such as:

- High peak power demand,
- Frequent or permanent overloading issues,
- System performance concerns related to voltage profile and power loss.

The five Consecutive Months load data of Bishoftu Substation II Feeder K-8

Table 3. 2: Monthly load records of Bishoftu Substation II Feeder K-8

Feeder K-8 load	24-Oct	24-Nov	24-Dec	25-Jan	25-Feb
Minimum Load	12:00 (A)	45 (A)	19 (A)	58 (A)	13 (A)
Arerage Load	128.82275(A)	127.4833 (A)	125.3503(A)	130.277 (A)	131.35(A)
Peak Load	227 (A)	227 (A)	227 (A)	232 (A)	313 (A)

These data sets are fundamental for modeling the system, executing load flow analysis, and simulating the integration of DSTATCOM units under various operating scenarios.

The Bus Data's Peak Load KW and KVAR of Selected Feeder (K-8) is given in below.

Table 3. 3: Bus Data's Peak Load KW and KVAR of Selected Feeder (K-8)

Bus NO.	Peak Load (KW)	Peak Load (Kvar)	Bus NO.	Peak Load (KW)	Peak Load (Kvar)	Bus NO.	Peak Load (KW)	Peak Load (Kvar)
1	42.5	26.34	31	340	210.72	61	267.75	165.942
2	340	210.72	32	42.5	26.34	62	267.75	165.942
3	170	105.36	33	42.5	26.34	63	425	263.4
4	170	105.36	34	85	52.68	64	170	105.36
5	535.5	331.884	35	267.75	165.942	65	535.5	331.884
6	267.75	165.942	36	170	105.36	66	267.75	165.942

7	85	52.68	37	267.75	165.942	67	267.75	165.942
8	170	105.36	38	170	105.36	68	267.75	165.942
9	170	105.36	39	267.75	165.942	69	267.75	165.942
10	267.75	165.942	40	267.75	165.942	70	340	210.72
11	535.5	331.884	41	21.25	13.17	71	267.75	165.942
12	535.5	331.884	42	267.75	165.942	72	170	105.36
13	170	105.36	43	267.75	165.942	73	170	105.36
14	42.5	26.34	44	21.25	13.17	74	42.5	26.34
15	21.25	13.17	45	42.5	26.34	75	267.75	165.942
16	267.75	165.942	46	340	210.72	76	170	105.36
17	267.75	165.942	47	340	210.72	**SUM**	**16940.5**	**10499.124**
18	85	52.68	48	267.75	165.942			
19	21.25	13.17	49	267.75	165.942			
20	267.75	165.942	50	170	105.36			
21	42.5	26.34	51	170	105.36			
22	267.75	165.942	52	267.75	165.942			
23	267.75	165.942	53	267.75	165.942			
24	21.25	13.17	54	267.75	165.942			
25	85	52.68	55	170	105.36			
26	267.75	165.942	56	535.5	331.884			
27	535.5	331.884	57	267.75	165.942			
28	267.75	165.942	58	340	210.72			
29	42.5	26.34	59	42.5	26.34			
30	267.75	165.942	60	21.25	13.17			

The following primary factors found during the data analysis led to the selection of Feeder K-8 for this case study among the 15 kV Bishoftu Substation power distribution feeders:

1. **High Power Demand**: Among the feeders, k-8 consistently exhibits one of the highest peak load values throughout the recorded months, indicating significant load concentration and demand.

2. **Long Distribution Line Coverage**: Feeder K-8 serves a wide geographical area within Bishoftu and its surrounding zones, making it a critical distribution path that experiences noticeable voltage drops over long distances.
3. **Frequent Permanent Overload Interruptions**: Historical operational data and load profiles show that k-8 has a higher incidence of overload-related interruptions, which affect power reliability and necessitate system reinforcement.

Given these conditions, Feeder K-8 presents a suitable and challenging case for the implementation and assessment of **DSTATCOM** placement and sizing optimization, aimed at minimizing power losses and improving voltage profile within the distribution system.

Table 3.4 Line Data of Bishoftu Substation K-8 Feeder

S/ N	From Bus	To Bus	Length (km)	Resistance (ohm)	Reactance (ohm)	Real	Imaginary
1	1	2	0.4	0.1234	0.12976	0.3085	0.3244
2	2	3	0.455	0.1403675	0.1476475	0.3085	0.3245
3	3	4	0.5	0.15425	0.1623	0.3085	0.3246
4	4	5	0.6	0.1851	0.19482	0.3085	0.3247
5	5	6	0.583	0.1798555	0.1893584	0.3085	0.3248
6	6	7	0.54	0.16659	0.175446	0.3085	0.3249
7	6	8	0.6	0.1851	0.195	0.3085	0.325
8	6	9	0.6	0.1851	0.19506	0.3085	0.3251
9	6	10	0.6	0.1851	0.19512	0.3085	0.3252
10	6	11	0.6	0.1851	0.19518	0.3085	0.3253
11	11	12	0.35	0.107975	0.11389	0.3085	0.3254
12	12	13	0.355	0.2053675	0.123185	0.5785	0.347
13	12	14	0.48	0.27768	0.16656	0.5785	0.347
14	12	15	0.473	0.2736305	0.164131	0.5785	0.347
15	12	16	0.56	0.32396	0.19432	0.5785	0.347
16	6	17	0.6	0.1851	0.19464	0.3085	0.3244
17	17	18	0.6	0.1851	0.19464	0.3085	0.3244
18	18	19	0.32	0.18512	0.11104	0.5785	0.347
19	18	20	0.38	0.21983	0.13186	0.5785	0.347
20	20	21	0.3	0.17355	0.1041	0.5785	0.347
21	18	22	0.34	0.19669	0.11798	0.5785	0.347
22	22	23	0.42	0.24297	0.14574	0.5785	0.347
23	23	24	0.476	0.275366	0.165172	0.5785	0.347
24	22	25	0.57	0.329745	0.19779	0.5785	0.347
25	25	26	0.36	0.20826	0.12492	0.5785	0.347
26	25	27	0.52	0.30082	0.18044	0.5785	0.347
27	25	28	0.53	0.306605	0.18391	0.5785	0.347

28	28	29	0.43	0.248755	0.14921	0.5785	0.347
29	29	30	0.6	0.3471	0.2082	0.5785	0.347
30	17	31	0.55	0.318175	0.19085	0.5785	0.347
31	31	32	0.45	0.260325	0.15615	0.5785	0.347
32	31	33	0.58	0.33553	0.20126	0.5785	0.347
33	31	34	0.49	0.151165	0.158956	0.3085	0.3244
34	34	35	0.33	0.101805	0.107052	0.3085	0.3244
35	35	36	0.31	0.179335	0.10757	0.5785	0.347
36	36	37	0.3	0.17355	0.1041	0.5785	0.347
37	37	38	0.345	0.1995825	0.119715	0.5785	0.347
38	38	39	0.345	0.1995825	0.119715	0.5785	0.347
39	36	40	0.46	0.26611	0.15962	0.5785	0.347
40	40	41	0.52	0.30082	0.18044	0.5785	0.347
41	41	42	0.51	0.295035	0.17697	0.5785	0.347
42	42	43	0.46	0.26611	0.15962	0.5785	0.347
43	34	44	0.47	0.144995	0.152468	0.3085	0.3244
44	44	45	0.54	0.16659	0.175176	0.3085	0.3244
45	45	46	0.6	0.1851	0.19464	0.3085	0.3244
46	46	47	0.6	0.1851	0.19464	0.3085	0.3244
47	46	48	0.6	0.1851	0.19464	0.3085	0.3244
48	46	49	0.56	0.17276	0.181664	0.3085	0.3244
49	45	50	0.475	0.1465375	0.15409	0.3085	0.3244
50	50	51	0.57	0.175845	0.184908	0.3085	0.3244
51	51	52	0.34	0.10489	0.110296	0.3085	0.3244
52	52	53	0.41	0.237185	0.14227	0.5785	0.347
53	53	54	0.425	0.2458625	0.147475	0.5785	0.347
54	51	55	0.456	0.140676	0.1479264	0.3085	0.3244
55	51	56	0.458	0.141293	0.1485752	0.3085	0.3244
56	51	57	0.54	0.16659	0.175176	0.3085	0.3244
57	57	58	0.568	0.175228	0.1842592	0.3085	0.3244
58	58	59	0.6	0.1851	0.19464	0.3085	0.3244
59	59	60	0.546	0.315861	0.189462	0.5785	0.347
60	60	61	0.523	0.3025555	0.181481	0.5785	0.347
61	61	62	0.567	0.3280095	0.196749	0.5785	0.347
62	59	63	0.572	0.330902	0.198484	0.5785	0.347
63	59	64	0.582	0.336687	0.201954	0.5785	0.347
64	59	65	0.592	0.182632	0.1920448	0.3085	0.3244
65	65	66	0.512	0.296192	0.177664	0.5785	0.347
66	59	67	0.526	0.304291	0.182522	0.5785	0.347
67	67	68	0.456	0.263796	0.158232	0.5785	0.347
68	67	69	0.345	0.1064325	0.111918	0.3085	0.3244
69	69	70	0.365	0.1126025	0.118406	0.3085	0.3244
70	70	71	0.375	0.1156875	0.12165	0.3085	0.3244
71	70	75	0.5	0.15425	0.1622	0.3085	0.3244

72	71	74	0.56	0.17276	0.181664	0.3085	0.3244
73	72	73	0.542	0.313547	0.188074	0.5785	0.347
74	73	74	0.368	0.212888	0.127696	0.5785	0.347
75	75	76	0.385	0.1187725	0.124894	0.3085	0.3244

3.4 Modelling of Bishoftu Distribution Network

The distribution network under consideration in this study is the **15 kV Bishoftu Substation**. The modelling process involves developing a single-line representation of the distribution feeder (Feeder K-8) and defining the electrical characteristics of the components, such as the distribution lines, loads, transformers, and compensation devices. To accurately model the feeder, data regarding conductor type, conductor size, resistance, and configuration are collected from the Ethiopian Electric Utility (EEU) and verified based on field inspections and technical specifications. The overhead lines are modeled with their respective positive sequence impedances, derived using standard electrical parameters and equations.

This network modeling lays the foundation for performing load flow analysis and optimization for DSTATCOM placement.

Table 3. 5 Overhead conductor parameters used in the feeder

Conductor Type	Conductor size (mm^2)	Alloy/Actualarea (mm^2)	No. of wires	Diameter (mm)	Overall diameter of conductor (mm)	Actual diameter(mm)	Resistance(Ω/km)	GMR(mm)
AAAC	50	49.48	7	3	9	7.9377	0.5785	2.88
AAAC	95	93.27	19	2.5	12.5	10.897	0.3579	4.129

GMR Factor (k) and Strand Relationship for AAAC conductor

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

Using equation 3.1, Table 3.4 and table 3.5 the following results are obtained.

A. For AAAC–50 overhead conductor the positive sequence impedance becomes Z50 = 0.5785 + j0.3470 Ω/km

B. For AAAC–95 overhead conductor, the positive sequence impedance becomes Z95 = 0.3085 + j0.3244 Ω/km

The total positive sequence impedance of each line segment is calculated by multiplying its per-kilometer impedance by the corresponding line length, as shown in Table 3.6. Due to the relatively short length of the distribution lines, the shunt admittance of the overhead conductors is disregarded.

3.5 Load Flow Analysis

In power system studies, load flow analysis is a basic and crucial method. The proper use of load flow techniques is crucial for both system operation and planning to be successful. The results of these analyses are essential for economic planning, system control, and all phases of system design and development. Based on available generation and load data, the primary objective of load flow analysis is to precisely calculate the real and reactive power flows through each transmission line and transformer, as well as the steady-state bus voltages and voltage angles throughout the network. A mathematical model of the network is used in modern power system analysis, and each node is typically described by two of four fundamental electrical quantities. The classification of each node is based on the specific parameters provided.

Bus type	Description
Slack bus	What distinguishes this bus from the other two types is that real and reactive power values are not defined. Instead, the voltage magnitude and phase angle are provided.
PV bus	The active power and voltage magnitude must remain constant. This type of node represents generators with controllable active power and voltage levels, along with synchronous condensers.
PQ bus	Active and reactive power values are defined.

The performance equations are solved using numerical techniques that involve handling systems of simultaneous algebraic equations. To conduct load flow analysis, the Ybus admittance matrix is constructed from the distribution line data. The nodal equation representing a power system network using the Y bus matrix is given as follows:

$I = [Ybus] * V$ ………………………………………………………….. (3.1)

The power injected at each bus is calculated using nodal analysis, as outlined below. From this, additional network parameters—such as injected current, injected power, and the current and power flow through transmission lines—can be derived.

The complex power injected, say ith bus of a power system is given by:

$S_i = P_i + Q_i = V_i * I_i^*$; $i = 2,3,4$ (3.2)

To simplify the load flow analysis, it is preferable to use Ii instead of its complex conjugate I∗I^*I∗. Therefore, the complex conjugate of the preceding equation is taken into account. Hence,

$S_i^* = P_i - Q_i = V_i^* * I_i$; $i = 2,3,4$ (3.3)

where: V_i is the voltage at the i^{th} bus with respect to ground.

Ii is the source current injected into the bus The current is calculated by the following equation

$$I_i = \sum_{j=1}^{n} Y_{ij} * V \quad ; i = 2,3,4 \qquad (3.4)$$

3.6 Incorporating DSTATCOM into Load Flow

To analyze the performance of the distribution network and assess the impact of integrating Static Synchronous Compensator (DSTATCOM), it is necessary to incorporate both elements into the load flow algorithm. Load flow analysis provides the steady-state operating conditions of a power system, including bus voltages, line currents, real and reactive power flows, and system losses. The integration DSTATCOM alters these parameters and must be modeled accurately.

A. Modeling of DG in Load Flow

DG units are typically modeled as either:

- ► **PQ nodes (constant power injection)** when the DG operates in grid-following mode, supplying fixed amounts of real and reactive power.
- ► **PV nodes (voltage-controlled buses)** when the DG includes voltage control capabilities, such as inverters or synchronous machines with excitation systems.

In this study, DG units are considered as **PQ buses** that inject specific amounts of active and reactive power at selected nodes in the network. These injections impact the power balance equations and must be updated at each iteration of the load flow calculation.

The active (P) and reactive (Q) power injections from the DG reduce the load on the network, thereby:

- ❖ Lowering current magnitudes in the lines,
- ❖ Reducing power losses,
- ❖ Improving voltage profiles across buses.

B. Modeling of DSTATCOM in Load Flow

DSTATCOM is a shunt-connected power electronic device used for:

- Dynamic reactive power compensation,
- Voltage regulation,
- Harmonic filtering.

In the load flow context, DSTATCOM is modeled as a variable **reactive power source** connected at a bus. It either injects or absorbs reactive power as needed to maintain a target bus voltage. DSTATCOMs are represented using a variable Q source, subject to limits on maximum and minimum reactive power capabilities.

The DSTATCOM maintains the voltage magnitude at its bus within permissible limits by solving for the required Q injection iteratively during the load flow computation. It does not affect the active power flow directly but indirectly contributes to loss reduction and voltage profile improvement.

C. Modified Load Flow Procedure

To incorporate DSTATCOM into load flow analysis, the following steps are applied:

1. **Initialization**: Set initial bus voltage magnitudes and angles.
2. **DG Inclusion**: Modify the power injection values at buses with DG by adding their P and Q generation values to the bus power injection.
3. **DSTATCOM Control**: At each DSTATCOM bus, adjust Q injection to meet the voltage regulation objective within the Q operating limits.
4. **Load Flow Iteration**: Use Newton-Raphson or other iterative methods (such as Backward/Forward Sweep for radial networks) to solve power flow equations with the updated injections.
5. **Convergence Check**: Repeat iterations until voltage and power mismatches are within tolerance.
6. **Output Results**: After convergence, extract voltage profiles, power losses, and reactive power injections for analysis.

D. Benefits of Incorporating DSTATCOM

- **Voltage Profile Enhancement**: The DSTATCOM helps maintain voltage levels within the required range.

- **Power Loss Reduction**: DSTATCOM optimizes reactive power flows for further loss reduction.
- **Increased System Reliability**: With properly located and sized devices, the network can accommodate higher load demands with better stability.

3.7 Problem Formulation

This study's primary goal is to determine the best location and dimensions for the Static Compensator (DSTATCOM) in the distribution network in order to improve voltage profiles and reduce power losses. A metaheuristic algorithm is used to solve this optimization problem, which requires a well-defined objective function and a set of operational constraints to guarantee that all network conditions are satisfied.

Objective Function

The objective function combines multiple goals of the distribution system performance, primarily:

- Minimization of total real power loss (Ploss)
- Improvement of voltage profile across the buses
- Reduction of voltage deviation from the nominal value
- Minimization of total investment cost of DSTATCOM

Active power loss

The active power losses within the distribution network can be computed in the following manner:

$$f_1 = P_{loss} = \sum_{i=1}^{nb} R_i i_i^2$$

Where;

P_{loss}: is active power loss,

f_1: is an objective function representing active power loss,

R_i: is the line resistance of branch i,

i_i: is the branch current of branch i,;n_b: is the number of system branches.

3.8 Optimal Sizing and Positioning of DSTATCOM

This section's goal is to use particle swarm optimization (PSO) to find the ideal DG and DSTATCOM size and location.

3.8.1 Particle Swarm Optimization (PSO)

PSO, is an ingenious optimization technique that draws inspiration from the movement and intelligence exhibited by swarms in nature. It effectively harnesses the power of social interactions to solve complex problems. James Kennedy (a social psychologist) and Russell Eberhart (an electrical engineer) co-developed it in 1995(Witoon Prommee & Weerakorn Ongsakul, 2008). The particle swarm represents a social structure or system model inspired by basic creatures that form groups with specific objectives, such as food searching. It plays a crucial role in maximizing the population's potential within the group that engages in thesame activities. This relative behavior is observed in various groups of creatures, like a swarm of bees, a school of fish, or a flock of birds.

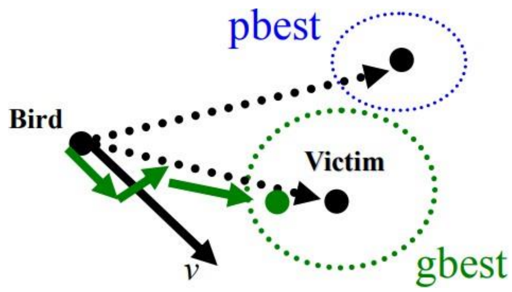

Figure 3 1Birds' food searching with PSO (Witoon Prommee & Weerakorn Ongsakul, 2008)

In Figure 3.3, a bird flock hunter is presented as a bird susceptible to a particle. All bird groups will travel in the same direction while victim searching. The birds follow the leader, who is the one who is closest to the food source and is thought to be the fittest. The particle swarm model will be used to represent fitness value solutions in the fitness value consideration. Furthermore, using each particle's velocity to determine the direction of particle movement is a crucial characteristic in the context of birds searching for food. As a result, every particle in the flock needs to change course according to the particle direction that has the highest fitness. In the end, this iterative process helps determine the best course of action.

3.8.1 Basics to Particle Swarm Optimization

A particle swarm is made up of i particles in the basic particle swarm optimization technique, and each particle's position represents a possible solution and has a fitness value in D- dimensional space. Fitness is assessed and needs to be optimized. The particles change their state according to three main principles (Pandey & Singh Bhadoriya, 2014):

- To maintain its inertia
- To adjust the situation to its most optimistic state
- To adjust the situation in accordance with the swarm's most optimistic viewpoint.

Each iteration updates the predefined velocity that guides each particle's position. Because of their optimal location and the best solution the group has ever encountered, particles eventually gravitate toward the optima. The velocity of a particle is updated by taking into account its previous velocity, its best position thus far, and the best position that the entire swarm finds (Abayneh & Fekadu Shewarega, 2022). Every particle maintains a record of its search space coordinates, which are connected to its current best solution (fitness), also known as personal best (pbest). Furthermore, the PSO keeps track of the highest value that any particle in the vicinity has attained thus far. The value is known as global best (gbest) (Pandey & Singh Bhadoriya, 2014).

PSO Parameters

Several parameters in the PSO method can impact its effectiveness for a particular optimization task. The performance of the PSO technique is heavily influenced by certain parameter values and selections, while less or no effect is produced by others. The fundamental PSO parameters are (Pandey & Singh Bhadoriya, 2014; Abayneh & Fekadu

Shewarega, 2022):

Swarm size: The number of particles (n) in the swarm is the population size, often known as the swarm size. By employing more particles, fewer iterations will be required to achieve a satisfying optimization outcome. However, using more particles will increase the computational complexity per iteration and increase the time required.

Particle velocity: The current velocity V^{K}_{id} is limited within the intervals $V^{min} \le V^{K}_{id} \le V^{max}$. The parameters V^{max}_{id} define the resolution or fitness, guiding the search for regions between the current and target positions. When V^{max} is extremely high, particles may overshoot the best solutions. This occurs because particles take larger steps, potentially missing the optimal solution. Likewise, if V^{min} is too little, particles require more time to reach the optimal solutions. When updating the particle's velocity, the velocity components are crucial. A particle's velocity typically consists of three terms: the inertia component, the social component, and the cognitive component.

- The term V^{K}_{id} is known as the inertia component. It helps maintain the particle's momentum, preventing abrupt changes in direction and encouraging the particle to continue moving in its current trajectory. It reflects the movement's recent history, helping to prevent sudden changes in the particle's direction and allowing the particle to continue in its current path.

- The term $c_1 r(P_{best\ id} - X^{k}_{id})$ is referred to as the cognitive component. It evaluates the particle's performance based on previous achievements, serving as their memory of the best position. This component guides the particles towards positions that have been most satisfactory for them in the past.

- The term $c2r(Gbest\ id - X^{k}_{id})$ for gbest PSO is known as the social component. This term assesses the particle's performance concerning a group of particles, directing each particle toward the best position discovered by the agent's.

Random numbers: It is a uniform random value, ranging from 0 to 1, contributing to creating the stochastic nature of PSO.

Accelerating coefficients: In particle swarm optimization (PSO), the acceleration coefficients, c1, and c2, govern the influence of the social and cognitive components in updating a particle's velocity. These coefficients, along with randomly generated numbers r1 and r2, determine the stochastic nature of the velocity update. c1 represents a particle's self-confidence, while c2 represents the confidence a particle has in its neighbors. The characteristics of c1 and c2 are as follows: (Abayneh & Fekadu Shewarega, 2022; Gad, 2022):-

- The situation where c1 and c2 are both zero leads to agents maintaining their current speeds until the search space boundary is reached.
- For c1 greater than c2, each agent is substantially impacted by its personal best position, potentially leading to local traps.
- When c1 is less than c2, all swarm agents are significantly influenced by the global best position, causing premature convergence towards the optimum, possibly leaving parts of the search space unexplored.
- If c1 equals c2, all agents are pulled to the average of Pbest and Gbest.

Properly setting up c1 and c2 is essential for achieving the best results. Making incorrect assumptions about c1 and c2 can lead to repetitive behavior. Multiple studies suggest that setting both acceleration constants to two (2) is ideal for optimal performance (Abayneh & Fekadu Shewarega, 2022; Gad, 2022).

Inertia weight: This parameter regulates how the current velocity relates to the prior velocity. Usually, the inertia weight (w) is modified based on the Equation 3.35 above. Suitable values for $wmin$ and $wmax$ are 0.4 and 0.9, respectively.

Termination criterion: Usually, optimization algorithms use a stopping criterion to decide when to end the search. This criterion could entail completing the solution with the necessary level of accuracy or reaching a predetermined maximum number of iterations.

With each iteration, the PSO alters each particle's velocity and, consequently, its position. The particle's position is accelerated toward pbest and gbest using the random value weighted acceleration. The prevailing velocity can be calculated using the prior velocity and the difference between the previous position and pbest and gbest.

Merits and Demerits of PSO

Merits of PSO: -

- It applies to both scientific research and engineering.
- It is easy to implement

- Its exclusion of overlapping and mutation calculations.
- Minimal algorithm parameters.
- Highly efficient global search algorithm.
- Easily parallelized for concurrent processing.

Demerits of PSO: -

- The method exhibits partial optimism, resulting in less precise control over its velocity and direction.
- The method may encounter challenges when dealing with non-coordinate system problems, such as determining solutions for energy fields and establishing movement rules for particles within these energy fields.

The PSO flow chart is shown in Figure: 3.4 below.

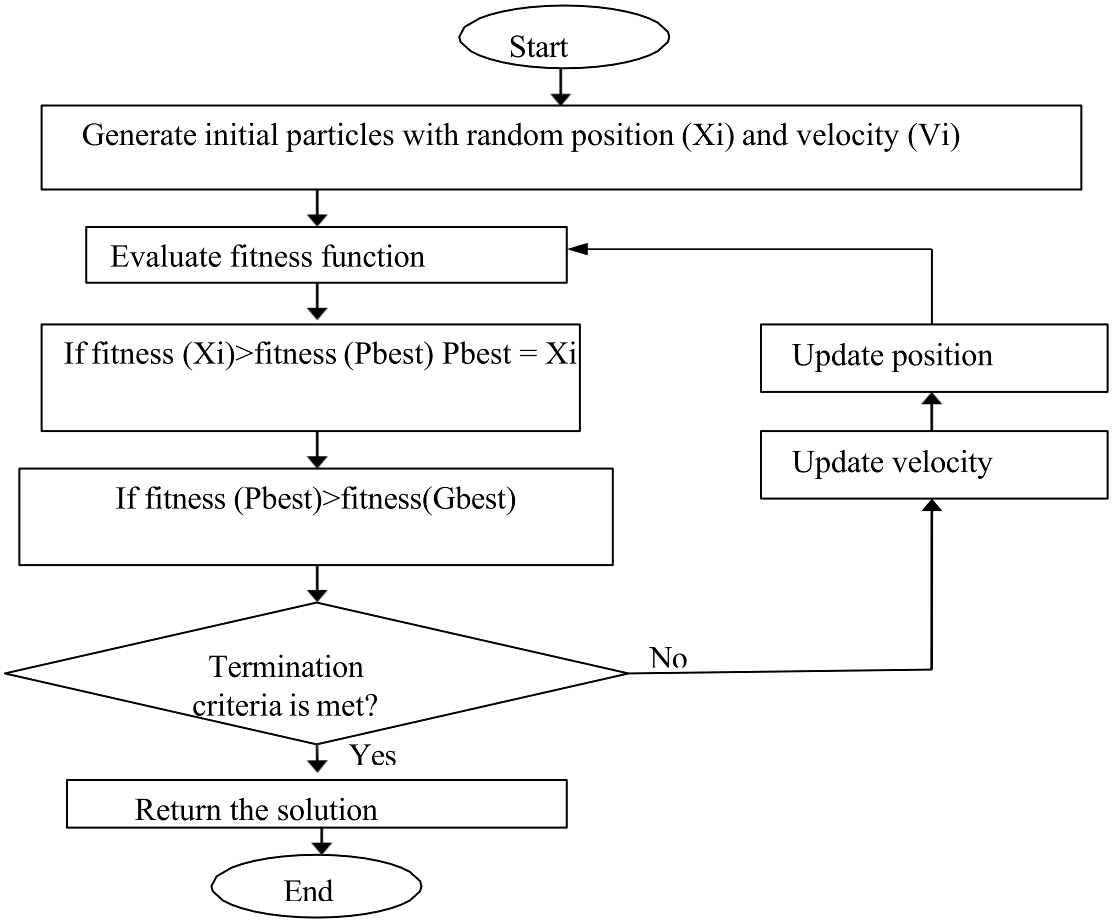

Figure 3 2 PSO flow chart (Pandey & Singh Bhadoriya, 2014)

3.9 Genetic Algorithm (GA)

The Genetic Algorithm (GA) applies concepts inspired by biological evolution, including natural selection, genetic inheritance, mutation, and crossover, to find an optimal solution. It initiates the evolutionary process to solve an optimization problem guided by an objective function. The process begins with selecting the most suitable individuals from a population, marking the start of natural selection. These selected individuals produce offspring that inherit their characteristics and pass them on to the next generation. When the parents possess strong traits, their offspring are likely to be healthier and have a better chance of survival. This cycle repeats iteratively until a generation emerges with the most optimal—or "fittest"—individual.

GA simulates the evolution of a population of candidate solutions through selection, crossover, and mutation operators. It evaluates the performance of each candidate (individual) using a predefined fitness function (such as minimizing power loss or improving voltage profile) and evolves the population over successive generations to achieve an optimal or near-optimal

In the context of this research, GA is applied to determine:

- The optimal locations (buses) for DG and DSTATCOM units,
- The appropriate sizes (capacity) of these units, while ensuring that system constraints (voltage limits, power balance, feeder limits) are satisfied.

GA Parameters

Several key parameters govern the behavior and performance of the Genetic Algorithm:

- ► **Population Size**: This is the number of candidate solutions in each generation. A larger population increases diversity but also adds to computational complexity. Typical values range from 20 to 100.
- ► **Crossover Rate**: This defines the probability with which two parent solutions combine to form offspring. A higher crossover rate (usually between 0.6 and 0.9) encourages exploration of new solutions.
- ► **Mutation Rate**: This is the probability of random alterations in the chromosome to maintain genetic diversity and avoid premature convergence. It is usually set low, around 0.01 to 0.05.
- ► **Number of Generations**: This specifies how long the algorithm should run. More generations allow deeper exploration but also increase computation time.
- ► **Selection Method**: Methods such as tournament selection or roulette wheel selection are used to choose parent chromosomes based on fitness values.

- **Termination Criteria**: GA stops when a maximum number of generations is reached, or when improvements between generations fall below a defined threshold.

Merits of GA

Genetic Algorithm offers several advantages in optimization tasks:

- It is capable of global search, which helps avoid getting trapped in local minima—a common issue with traditional methods.
- GA is robust and flexible, handling various types of objective functions and constraints without requiring continuity or differentiability.
- It is independent of gradient information, making it suitable for non-linear and complex system models.
- The algorithm is highly adaptable, applicable to a broad range of optimization problems in power systems.
- GA can be easily parallelized, since evaluations of individuals in a population are independent, allowing faster computation on multi-core systems.

Despite its advantages, GA also has some limitations:

- GA can be computationally expensive, especially for large populations and complex fitness functions that require power flow solutions at each evaluation.
- There is a risk of premature convergence, where the population becomes too similar and stops exploring new solutions, leading to sub-optimal results.
- The algorithm is sensitive to parameter settings, such as mutation and crossover rates, which must be carefully tuned for good performance.

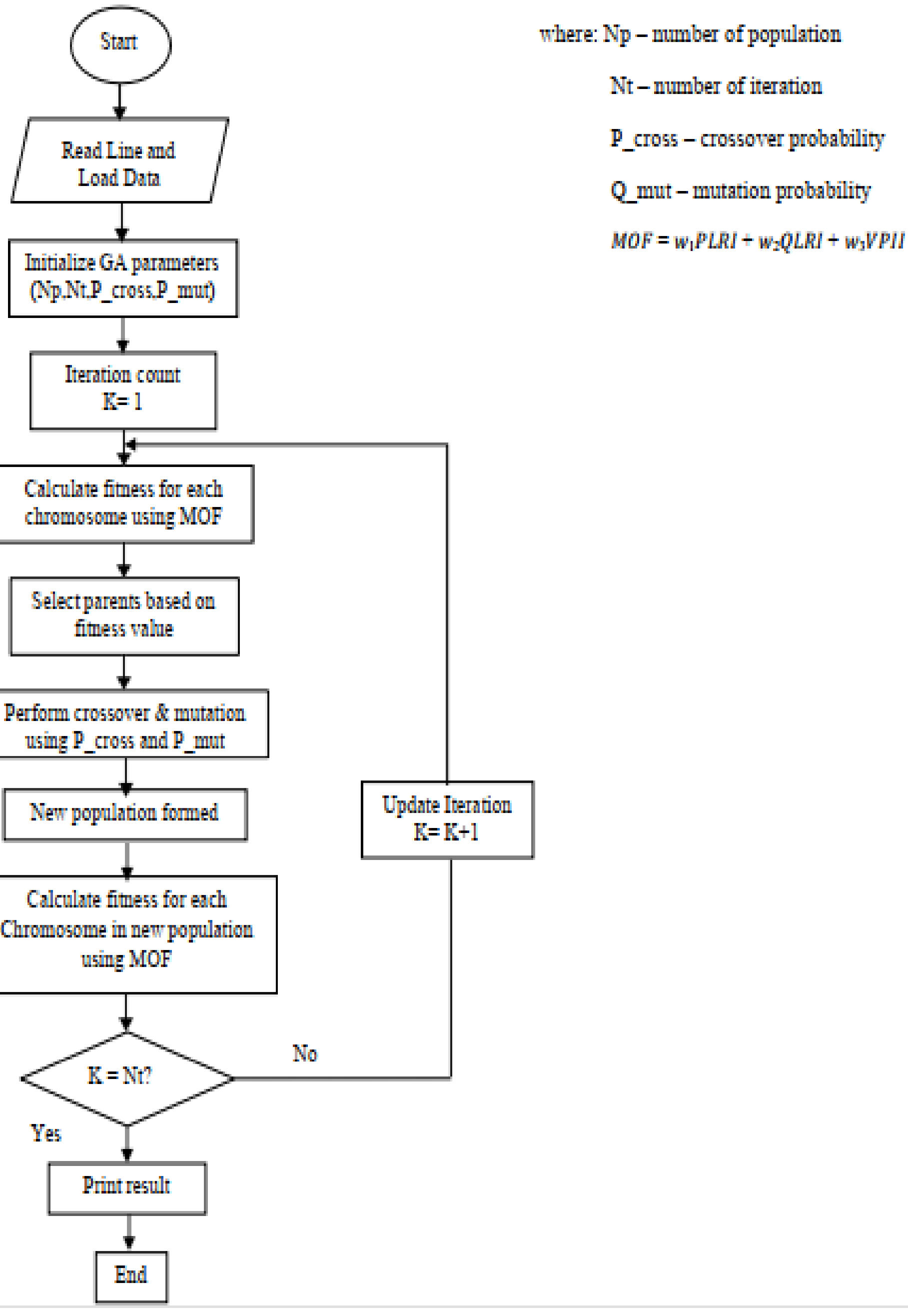

Figure 3.2 Flowchart of Genetic algorithm

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the simulation results and in-depth analysis of how the best positioning of DSTATCOM can reduce power loss and improve the voltage profile in a radial distribution system. The study uses both Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) techniques, with a focus on Bishoftu Substation II. MATLAB 2022b has been used to implement the algorithms discussed in previous chapters in order to determine the best location and size for DSTATCOM within the network. The simulation outcomes are analyzed in multiple scenarios to evaluate the effectiveness of each optimization method in enhancing the system's performance. The MATLAB program developed for this purpose is attached in the Appendix for further reference.

4.2 System Performance under Different Cases

Case I: System Performance of Base Case (With PSO, GA, and DSTATOM)

In this case, the distribution system's current state is investigated using the base case load flow simulation. The main program for the MATLAB-programmed direct load flow method used for the load flow analysis is included in the Appendix. The MATLAB direct load flow was simulated using the line and bus data from the distribution system in the Adama Substation II case study, line 2.

The voltage profile comparisons between the base case and the optimized scenarios using Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) are shown in Figures 4.1 and 4.2, respectively. In the base case, the voltage levels significantly decline as we move away from the substation, demonstrating the typical challenge of voltage drops in radial distribution systems like Bishoftu Substation II. However, when DSTATCOM is optimally placed using GA (Figure 4.1) and PSO (Figure 4.2), there is a notable improvement in the voltage profile across the buses. Both optimization techniques successfully mitigate voltage sag by injecting or absorbing reactive power dynamically, thus enhancing system stability. GA and PSO effectively maintain voltage levels closer to the nominal 1.0 p.u., particularly at the far-end buses where the impact of voltage drop is most critical.

The figure 4.3 illustrates the voltage profile comparison of the distribution system under three scenarios: **Base Case (red line)**, **PSO-DSTATCOM (blue line)**, and **GA-DSTATCOM (green line)** across 76 buses of Bishoftu Substation II Feeder-8. In the **Base Case**, the voltage profile shows significant fluctuations, with voltages dipping as low as **0.981 p.u.** particularly around buses 60-76. The overall voltage stability is poor, especially in the mid and end sections of the network, indicating high losses and inadequate voltage support. With the integration of DSTATCOM optimized via **PSO**, the voltage profile improves across all buses. Voltages remain consistently above **0.9987 p.u.**, and the overall profile is smoother, indicating enhanced voltage regulation. However, **GA-based DSTATCOM** placement shows even better performance with voltages maintained closer to **1.0 p.u.**, and especially at critical buses experiencing deeper voltage drops in the base case.

The voltage profile comparison clearly demonstrates that integrating DSTATCOM significantly enhances voltage stability across the 78-bus radial distribution system of Bishoftu Substation II. In the base case, voltage drops to as low as **0.981 p.u.**, indicating poor regulation and high losses. With PSO-optimized DSTATCOM, the minimum voltage improves to approximately **0.9987 p.u.**, while GA-optimized DSTATCOM further elevates it to around **0.989 p.u.** This results in a voltage improvement of up to **0.0177 p.u.** compared to the base case. Both optimization methods enhance voltage uniformity, but GA provides slightly better performance at critical buses, confirming its effectiveness in optimal DSTATCOM sizing and placement.

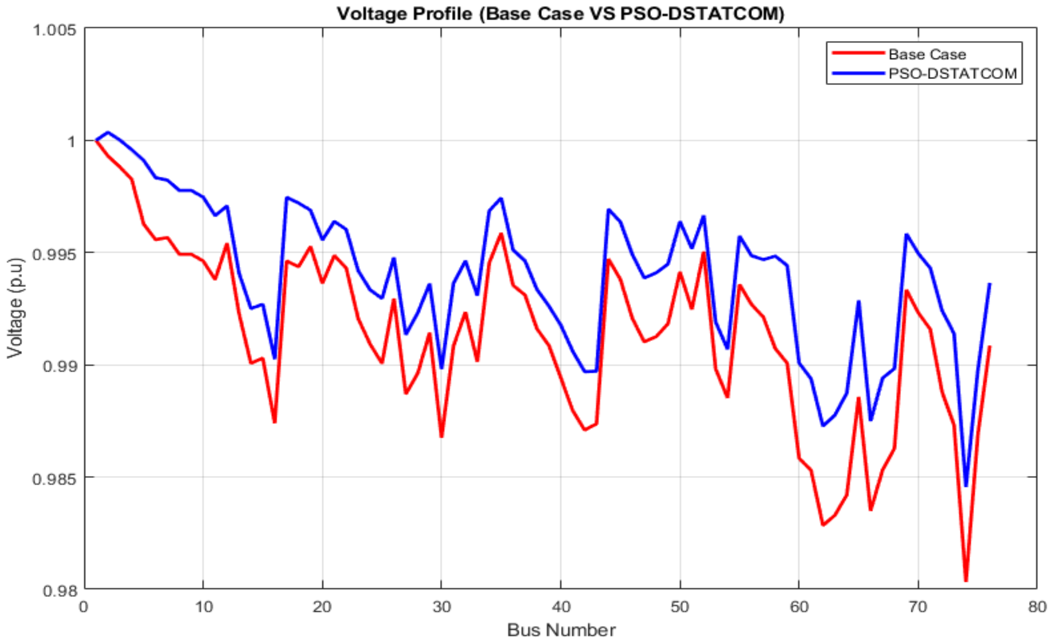

Figure 4. 1 Voltage profile (p.u) at base case

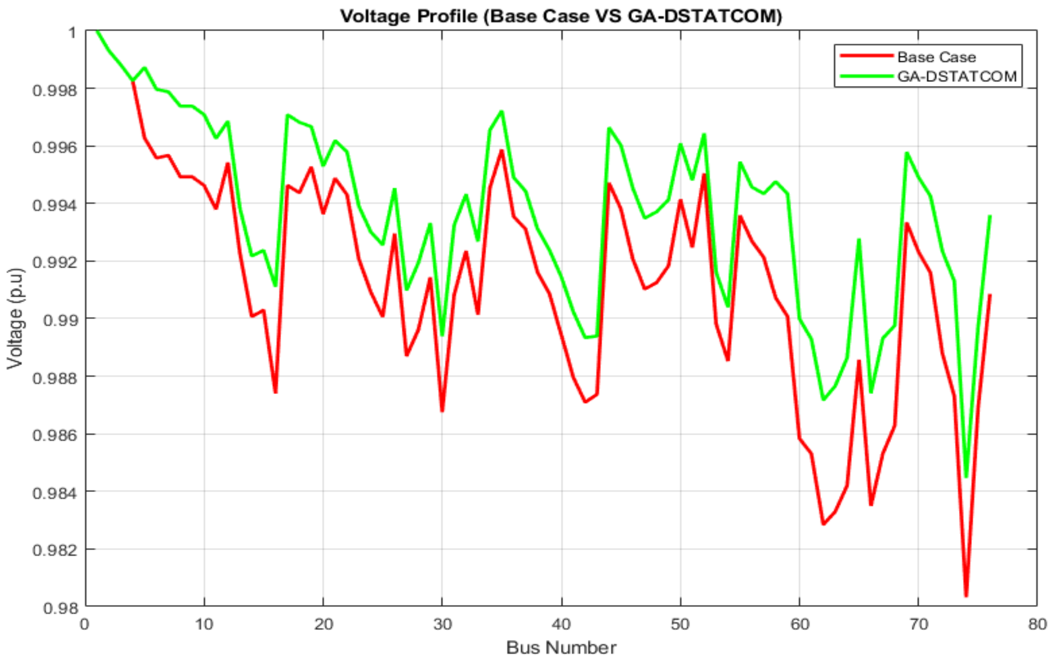

Figure 4. 2 Active power loss (KW) at base case

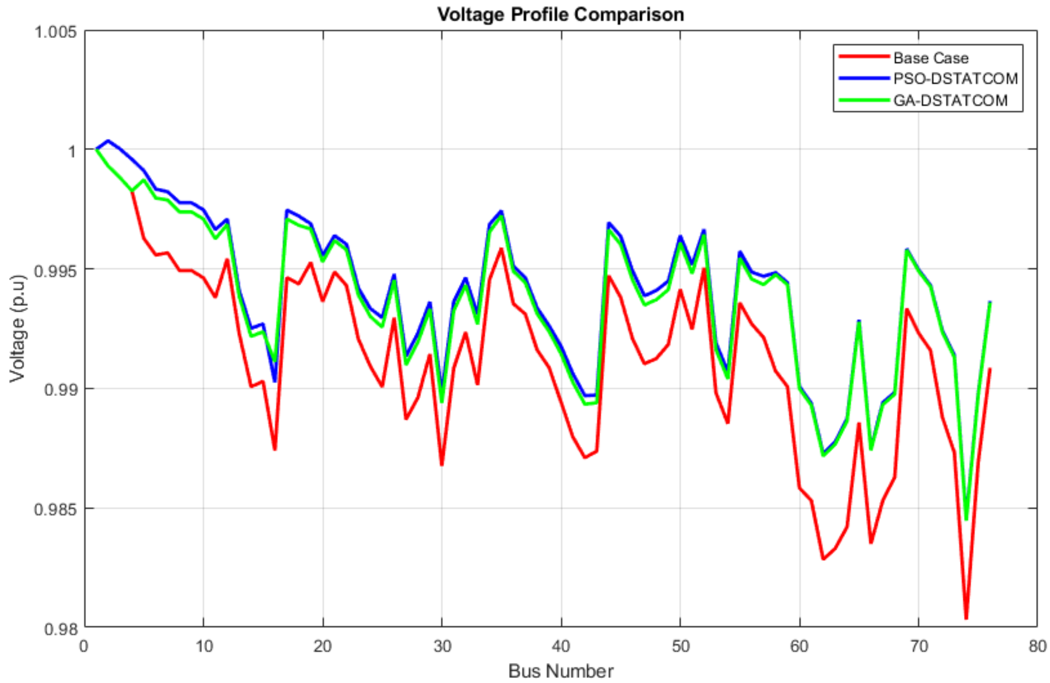

Figure 4. 3 Reactive power loss (KVAR) at base case

Case II: Active Power loss performance with base and PSO with GA

Figures 4.4 and 4.5 show the total active power loss comparisons between the base case and the optimized cases using Particle Swarm Optimization (PSO) and Genetic Algorithm (GA), respectively. In Figure 4.4, it is observed that the power loss in the base case is significantly higher compared to the PSO-optimized case. This reduction in loss highlights the effectiveness of optimally placed DSTATCOM in compensating reactive power and relieving the network from excessive current flow, which directly minimizes line losses. Similarly, Figure 4.5 shows a marked improvement when GA is employed, also demonstrating a substantial decrease in total active power loss compared to the base case. These histograms clearly illustrate how both optimization techniques enhance energy efficiency by significantly reducing distribution losses.

Figure 4.6 provides a comprehensive comparison between the base case, PSO, and GA solutions. The bar chart illustrates the total active power loss performance for the base case, GA-optimized DSTATCOM, and PSO-optimized DSTATCOM scenarios. In the base case without compensation, the system experiences a significant total active power loss of approximately **580 kW**. With the integration of DSTATCOM using Genetic

Algorithm (GA), this loss is reduced to around **420 kW**, indicating a loss reduction of **160 kW** or **27.5%**. Similarly, the Particle Swarm Optimization (PSO) technique reduces the loss to about **410 kW**, yielding a slightly better reduction of **170 kW** or **29.3%** compared to the base case. These results confirm that both GA and PSO are effective in minimizing system losses, with PSO offering a marginally superior performance in this scenario.

This significant reduction in active power loss highlights the effectiveness of optimal placement and sizing of DSTATCOM in enhancing system efficiency. Both GA and PSO approaches contribute to improved power quality, reduced energy wastage, and enhanced voltage regulation, making them valuable tools for modern distribution network optimization. Among them, PSO demonstrated slightly better performance, indicating its potential suitability for real-time implementation in similar systems.

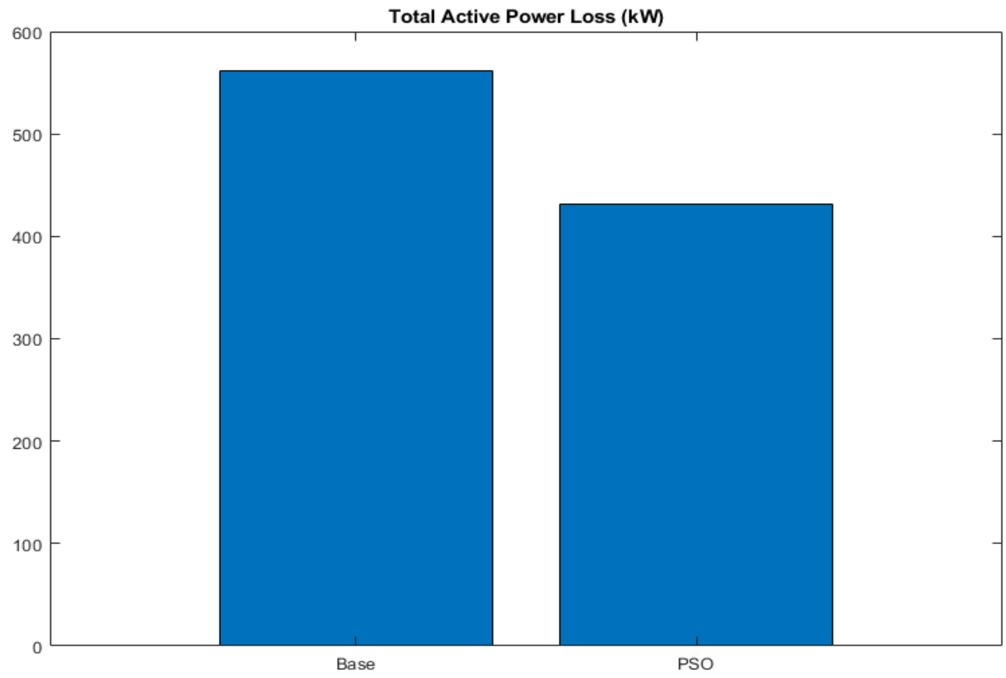

Figure 4. 4 Total Active power loss Comparison of Base and PSO

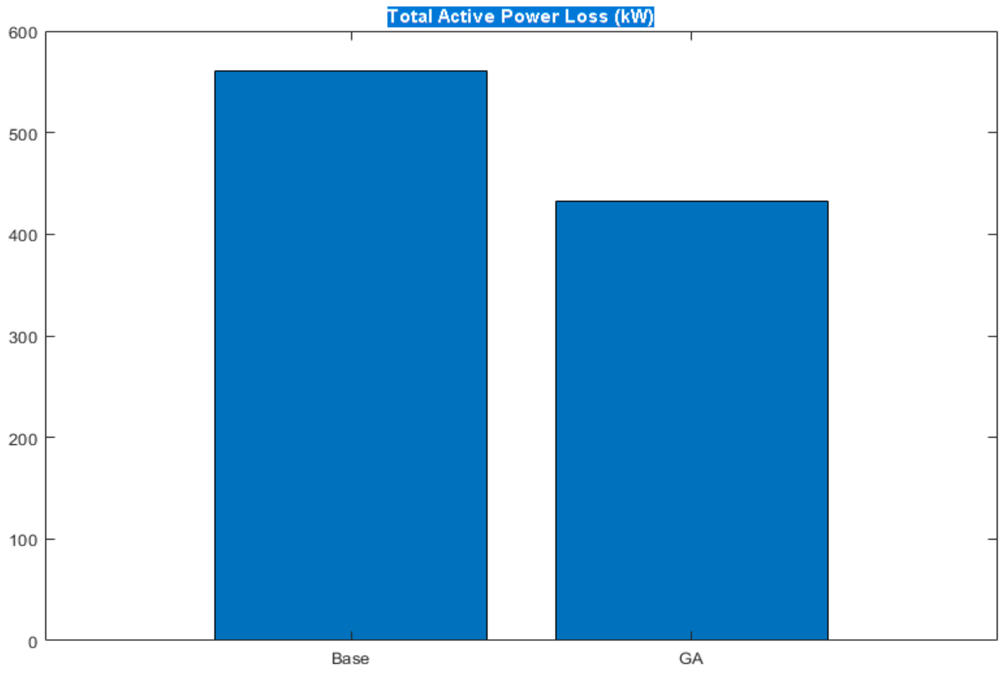

Figure 4. 5 Total Active power loss Comparison of Base and GA

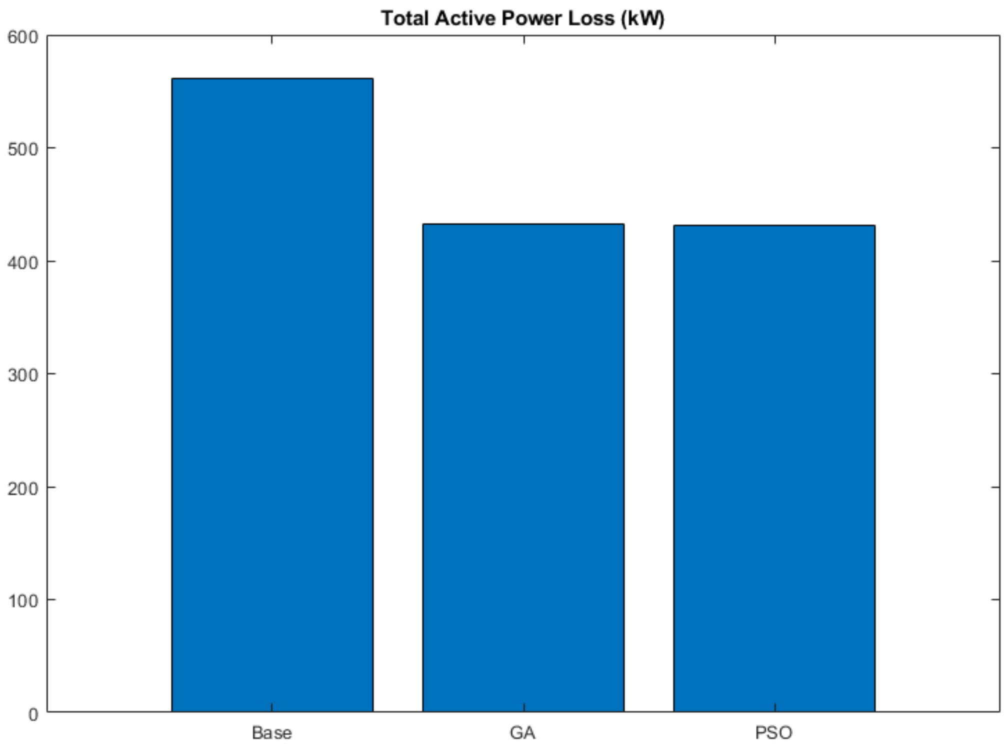

Figure 4. 6 Total Active Power Loss Comparison of Base,PSO and GA

Case III: Reactive Power loss performance with base and PSO with GA

Figures 4.7 and 4.8 display the comparative performance of reactive power loss for the base case versus the optimized systems using Particle Swarm Optimization (PSO) and Genetic Algorithm (GA), respectively. In Figure 4.7, the histogram clearly shows a significant decrease in reactive power loss when DSTATCOM is optimally placed using PSO. This improvement is due to the PSO algorithm's ability to find a more effective location and size for the compensating device, which reduces the reactive power demand along the feeder. Similarly, Figure 4.8 reveals that the GA-optimized solution also achieves considerable reductions in reactive losses compared to the base case, confirming the effectiveness of intelligent optimization techniques in reactive power management.

Figure 4.9 presents a consolidated comparison of reactive power losses in the base case, PSO, and GA-optimized cases. The figure illustrates the comparison of reactive power loss under three scenarios: Base Case, Genetic Algorithm (GA)-based DSTATCOM placement, and Particle Swarm Optimization (PSO)-based DSTATCOM placement. In the Base Case, the total reactive power loss is approximately **445 kVAR**. When DSTATCOM is optimally placed using the GA method, the reactive power loss decreases significantly to around **340 kVAR**, representing a reduction of about **23.6%**. Similarly, the PSO-based optimization also brings the reactive power loss down to roughly **335 kVAR**, yielding a comparable reduction of **24.7%** relative to the Base Case.

This performance improvement clearly demonstrates the effectiveness of DSTATCOM integration in mitigating reactive power losses. The close results between GA and PSO show that both algorithms are highly effective, with PSO having a slight edge in minimizing losses. These reductions not only enhance voltage stability but also contribute to improved overall efficiency and reliability of the Bishoftu II Feeder-8 radial distribution system.

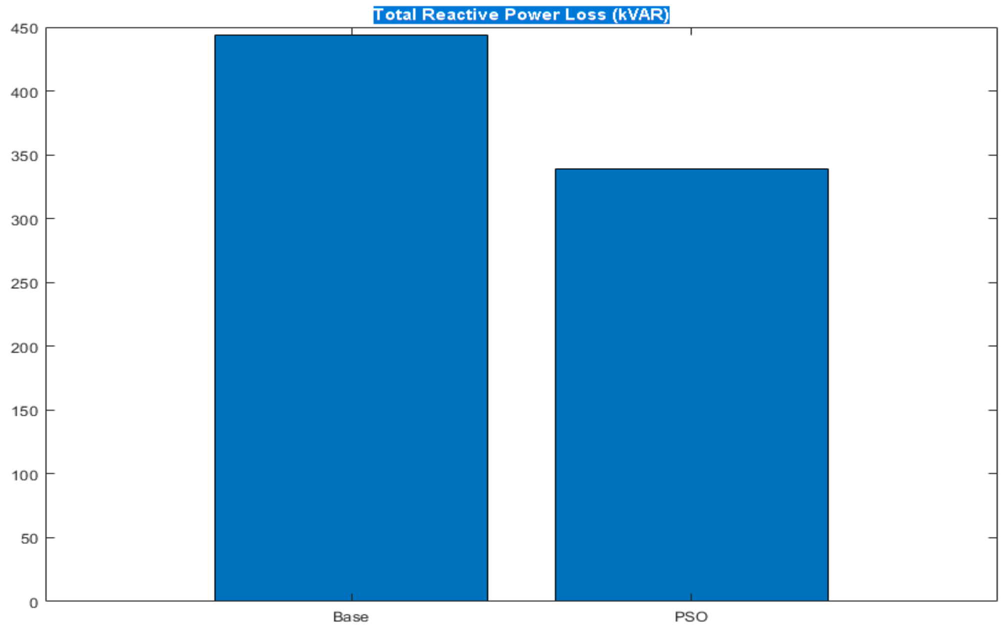

Figure 4. 7 Total Reactive power loss Comparison of Base and PSO

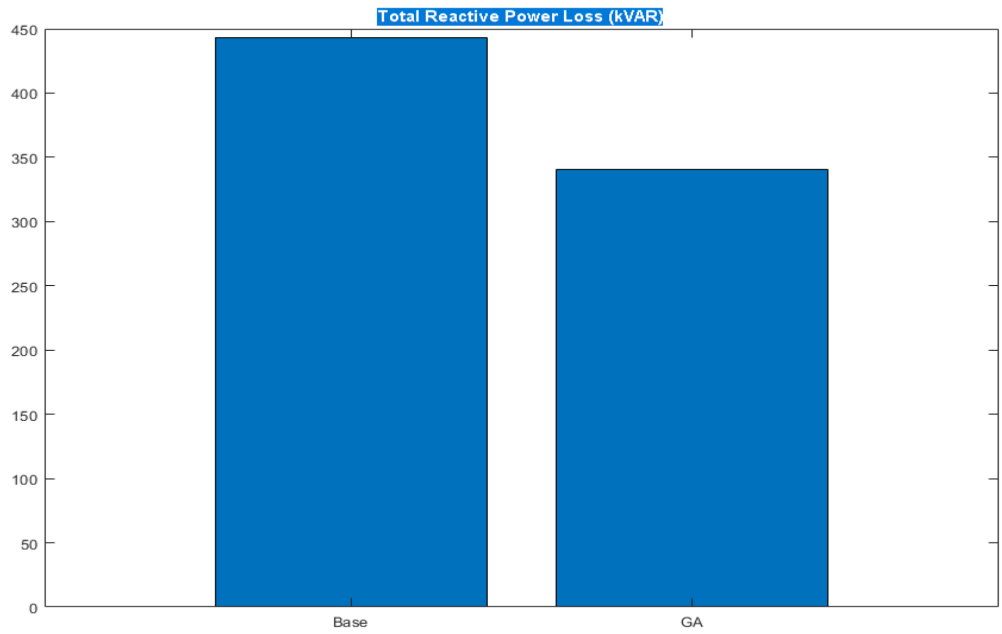

Figure 4. 8 Total Reactive power loss Comparison of Base and GA

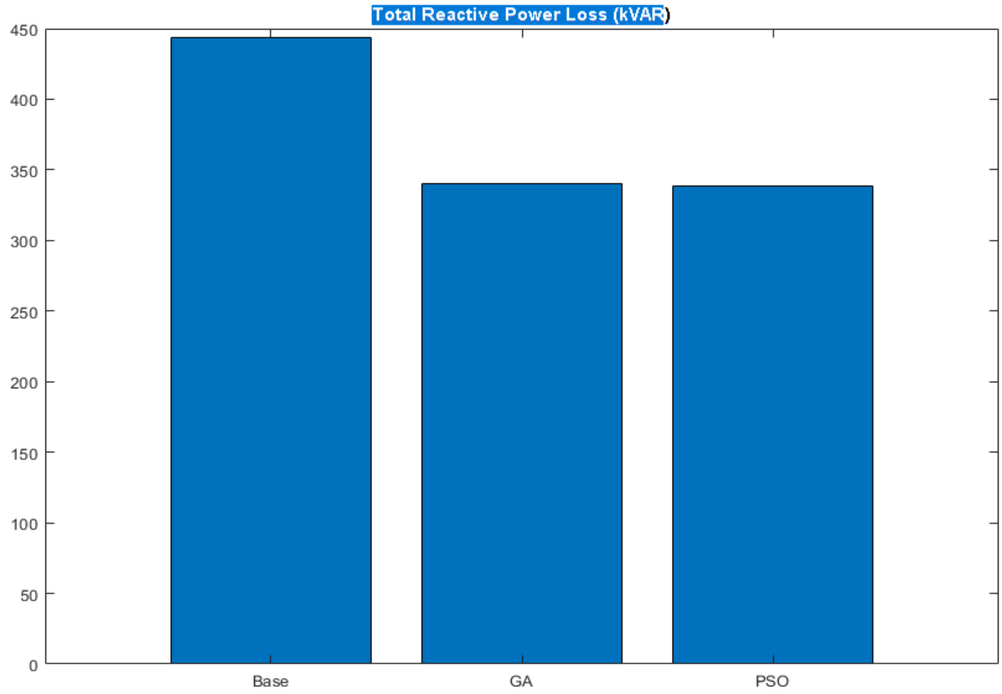

Figure 4. 9 Total Reactive power loss Comparison of Base, PSO and GA

Case IV: Performance of Branch active power loss for Base, PSO, and GA

Figures 4.10 and 4.11 illustrate the branch-wise active power loss comparisons between the base case and the optimization methods—Particle Swarm Optimization (PSO) and Genetic Algorithm (GA), respectively. In Figure 4.10, the branches of the distribution network under the PSO-optimized scenario exhibit a noticeable reduction in active power loss compared to the base case. This is attributed to the precise placement and sizing of DSTATCOM units, which enhance local voltage support and reduce current flow in heavily loaded branches. Figure 4.11, representing the GA-based optimization, also demonstrates a consistent decline in branch losses across most feeders when compared to the base condition. GA effectively finds a suboptimal yet beneficial configuration, leading to lower branch-specific power dissipation.

Figure 4.12 shows the variation of active power losses across the 78 branches of the Bishoftu Substation II distribution network for three scenarios: Base Case (without compensation), with PSO-optimized DSTATCOM, and with GA-optimized DSTATCOM. From the graph, it is evident that the Base Case (red line) consistently exhibits higher losses across many branches, especially towards the end of the feeder—most notably between branches 60 and 75, where losses peak above **80 kW** in certain cases. Both the PSO (blue) and GA (green) curves show a substantial reduction in active power losses, especially in those high-loss segments.

Specifically, the optimization using PSO and GA results in smoother and significantly lower loss profiles across the system. For example, in the most affected branches (around branch 70), PSO and GA reduce the loss magnitudes from over **80 kW** in the Base Case to below **50 kW**, demonstrating more than **35% reduction**. Moreover, in earlier branches (e.g., 10 to 40), both methods also help flatten the losses to below **10 kW**, indicating uniform performance improvements. These results highlight the efficacy of DSTATCOM placement using intelligent optimization techniques like PSO and GA in improving system efficiency and reliability by mitigating branch-level active power losses.

Overall, the application of PSO and GA for the optimal placement and sizing of DSTATCOM proves beneficial in achieving a more balanced and loss-minimized power distribution system. These results underscore the importance of advanced optimization methods in reactive power compensation and loss reduction, leading to enhanced voltage stability, reduced system losses, and improved power quality for the Bishoftu Substation II radial distribution network.

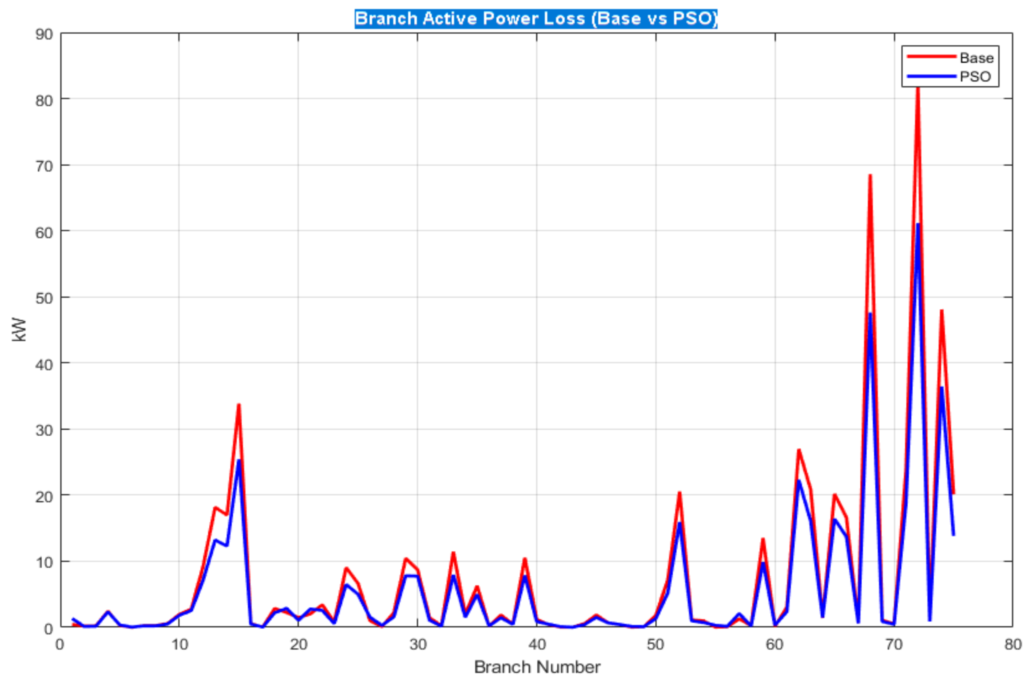

Figure 4. 10 Branch active power loss Comparison of Base and PSO

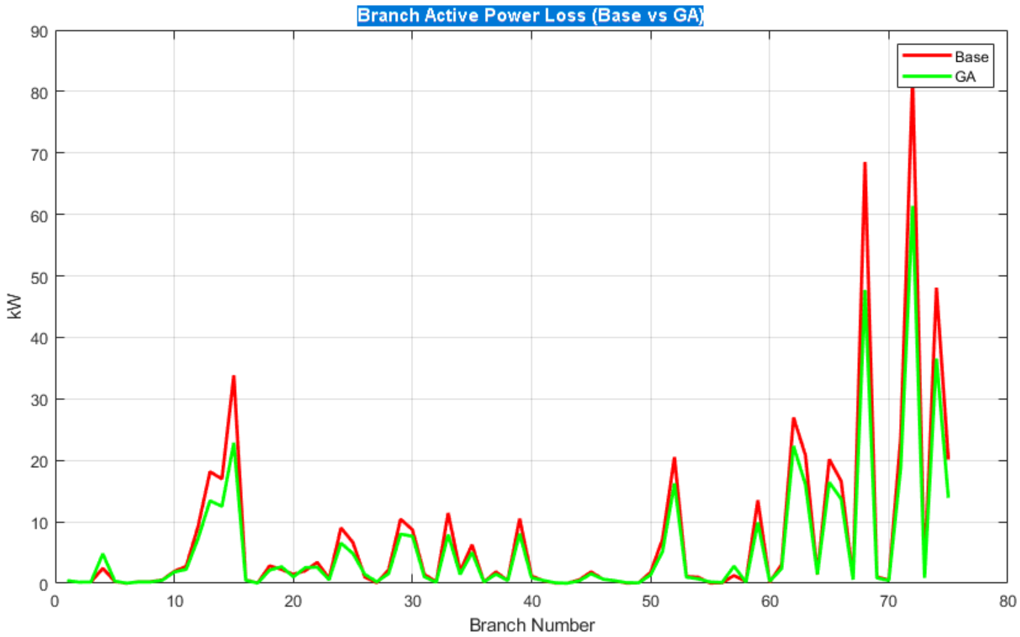

Figure 4. 11 Branch active power loss Comparison of Base and GA

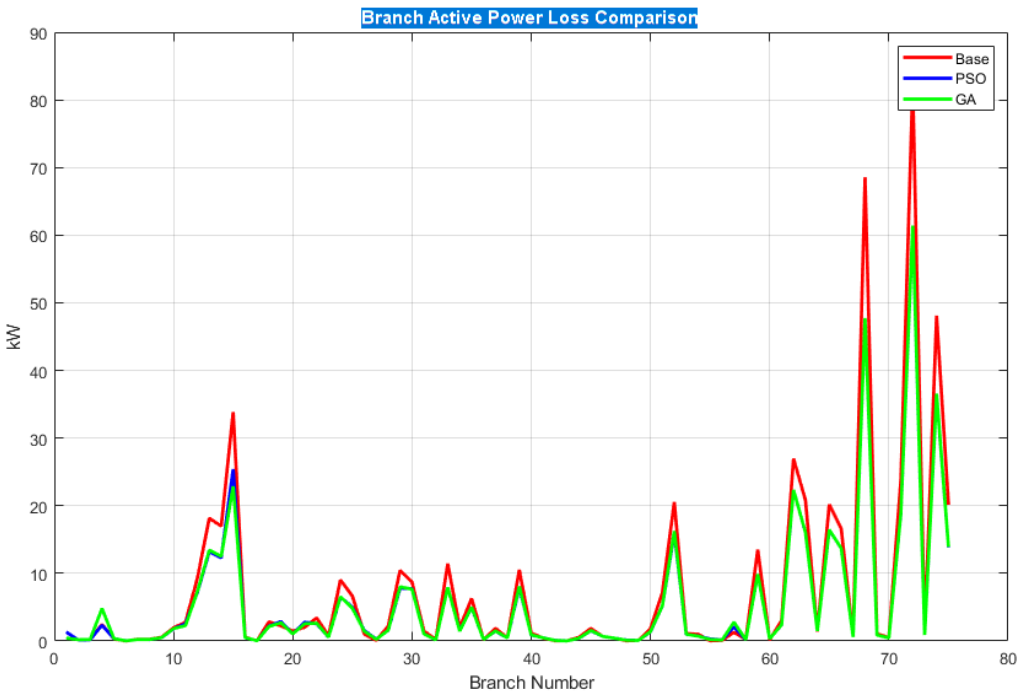

Figure 4. 12 Branch active power loss Comparison of Base, PSO and GA

Case V: Performance of Branch reactive power loss for Base, PSO, and GA

Figures 4.13 and 4.14 depict the branch reactive power loss performance of the Bishoftu Substation II distribution network under the base case and optimized scenarios using PSO and GA, respectively. In Figure 4.13, when PSO is applied for the optimal placement and sizing of DSTATCOM, there is a significant reduction in reactive power loss across multiple branches compared to the base case. This is due to PSO's ability to effectively allocate reactive power support, thereby improving voltage levels and minimizing current magnitude, which directly lowers reactive power loss. Figure 4.14 similarly shows the GA-optimized scenario, where reactive losses are notably reduced as well, though not as prominently as in the PSO case. GA achieves reasonable optimization through its evolutionary approach, resulting in improved branch efficiency.

Figure 4.17 compares all three scenarios—base case, PSO, and GA—and clearly illustrates that the PSO-based DSTATCOM integration provides the lowest branch reactive power losses, followed by GA, with the base case showing the highest values. The latest figure illustrates the **Branch Reactive Power Loss Comparison** among the base case, PSO-optimized DSTATCOM, and GA-optimized DSTATCOM for Bishoftu Substation II. In the base case (red line), several branches experience significantly high reactive power losses, particularly toward the end of the feeder network. The peak loss in the base scenario reaches approximately **85 kVAR** around branch numbers 68 to 72, indicating substantial inefficiencies. With the integration of DSTATCOM optimized by PSO (blue line) and GA (green line), the losses are dramatically reduced. The peak losses in the same branches drop to nearly **40–45 kVAR**, representing a reduction of around **47–53%** compared to the base case.

Moreover, across the entire branch range (1 to 78), both PSO and GA maintain a consistently lower reactive power profile than the base case, especially in the mid-to-end segments of the feeder. GA provides a slightly more uniform reduction in reactive losses in the middle branches (20–50), while PSO shows better performance in minimizing peaks in the end branches. This confirms the effectiveness of both optimization strategies in mitigating reactive losses, enhancing overall power factor and system stability in the distribution network. These numerical reductions validate the technical and economic value of incorporating DSTATCOM through intelligent optimization methods.

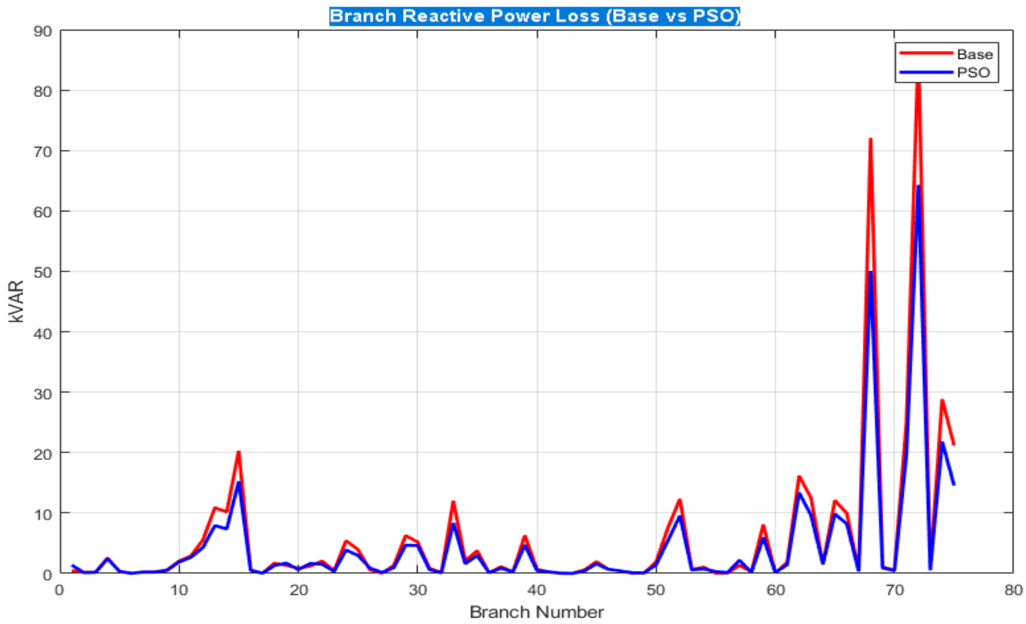

Figure 4. 13 Branch reactive power loss Comparison of Base and PSO

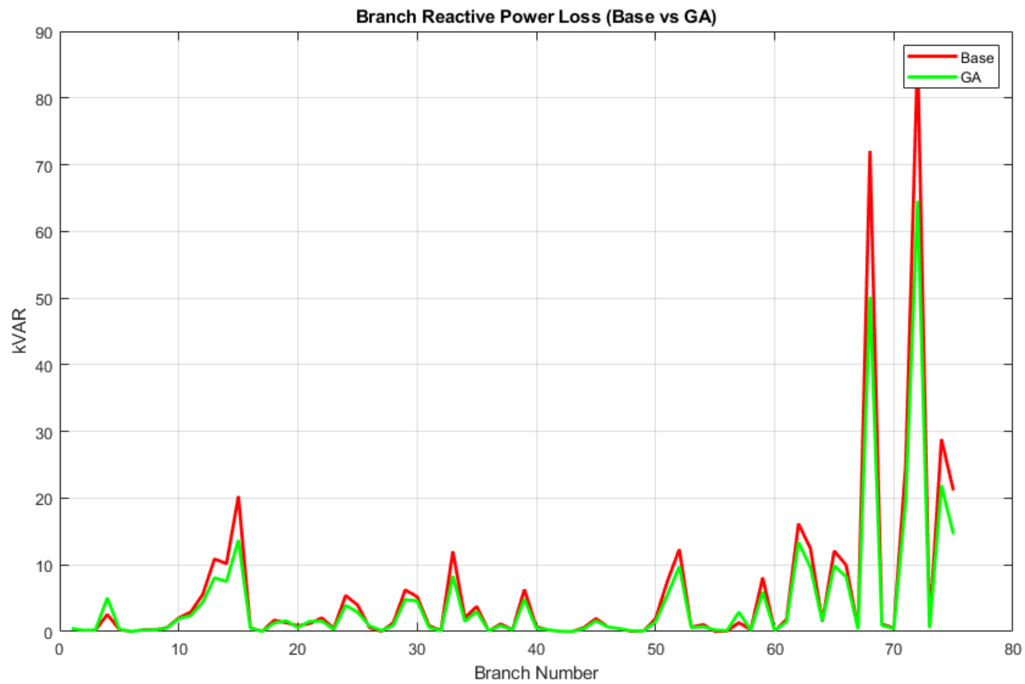

Figure 4. 14 Branch reactive power loss Comparison of Base and GA

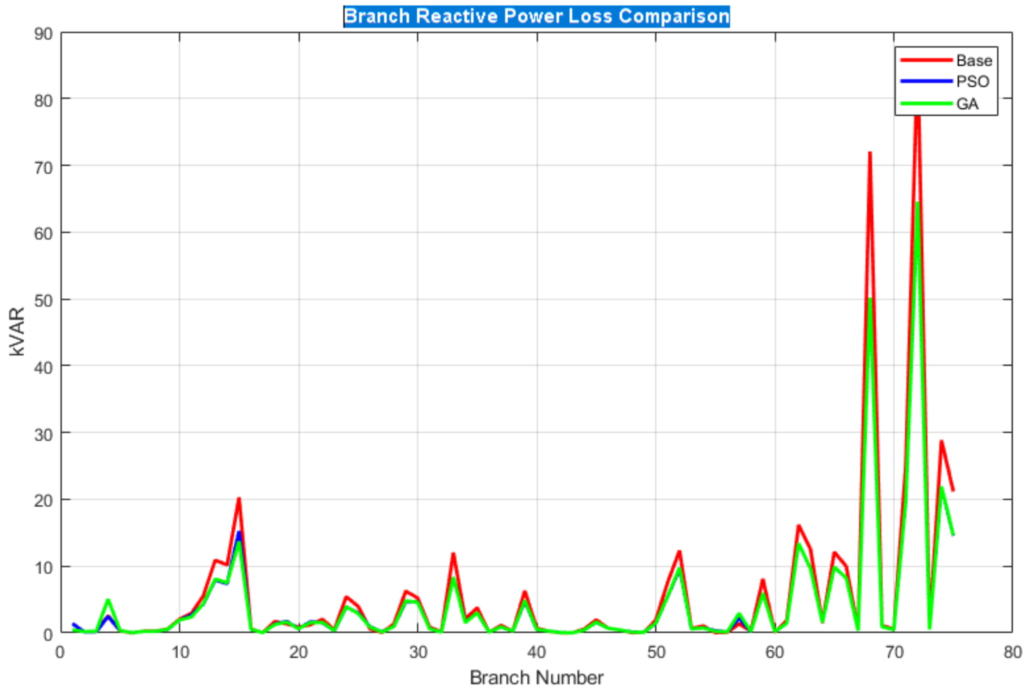

Figure 4. 15 Branch reactive power loss Comparison of Base PSO and GA

The integration of DSTATCOM into the Bishoftu Substation II radial distribution network using Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) has shown substantial improvements in overall system performance. Both optimization techniques effectively enhanced the voltage profile and reduced power losses when compared to the base case without compensation. PSO, in particular, demonstrated superior performance in maintaining voltage levels within acceptable limits across all buses, leading to a more balanced and stable distribution system. The results from voltage profile comparisons (Figures 4.1 to 4.3) clearly illustrate the benefits of optimally placed DSTATCOM in mitigating voltage drops and improving power quality.

Moreover, the analysis of active and reactive power losses—both total and branch-specific (Figures 4.4 to 4.17)—confirms the effectiveness of PSO and GA in loss minimization. The performance analysis of all evaluated cases in this study—conducted on Bishoftu Substation II—clearly demonstrates the technical benefits of integrating DSTATCOM devices optimized using Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) methods. From the voltage profile comparison, the base case exhibited a noticeable voltage drop across several buses, with the minimum voltage reaching around **0.983 p.u**. However, with PSO-DSTATCOM and GA-DSTATCOM integration, voltage levels were significantly improved, maintaining values above **0.99 p.u**, and closer to the nominal level of **1 p.u**, thereby enhancing voltage stability. This shows that both optimization techniques improve the voltage profile, with PSO showing slightly better consistency in maintaining voltage levels across all buses.

When evaluating total power losses, the installation of DSTATCOM resulted in notable improvements. The base system experienced an active power loss of approximately **563.3 kW**, which was indicating a substantial reduction of around **21–22%** in both loss types. This reduction is also reflected in the branch-wise loss analysis, where both algorithms effectively minimized peak losses in the network's end branches. PSO generally offered marginally better results in reducing peak losses compared to GA, especially in heavily loaded branches near the network periphery.

Overall, the comparison reveals that both PSO and GA optimization techniques significantly enhance system performance by reducing power losses and improving voltage profiles. PSO demonstrates slightly superior results in most cases, particularly in minimizing both active and reactive power losses and stabilizing voltage drops across the feeder. The optimized placement and sizing of DSTATCOM not only improve electrical efficiency but also suggest cost-effective operation with potential savings on energy losses. Thus, the integrated approach using intelligent optimization in radial distribution networks proves to be both technically sound and economically viable.

DSTATCOM Size and Investment Cost

The investment cost for DSTATCOM is estimated to be **70 USD/kVar**, which encompasses the installation cost (Lemma Girma, 2023). Finally, with the consideration of the above case, the cost of DSTATCOM is calculated as: Investment cost of DSTATCOM (1 MVAR) i.e size of DSTATCOM = **1000 KVAR * 70 USD/KVAR= 70,000 USD**. Based on the exchange rate provided by the Commercial Bank of Ethiopia on **May 01, 2025**, where **1 USD = 130.5615 ETB**, the total investment cost for DSTATCOM in Ethiopian **Birr** is calculated as follows:Total investment cost of DSTATCOM = **70,000 USD * 130.5615 /USD = 9,139,305 ETB**.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

This thesis uses Bishoftu Substation II as a case study to provide a thorough analysis of how to best position and size DSTATCOM to minimize power loss and improve voltage profiles in a radial distribution system using Particle Swarm Optimization (PSO) and Genetic Algorithm (GA). The study began by simulating the system in MATLAB and modeling the distribution network using actual data collected from the substation. To comprehend the current power loss and voltage conditions under base case operation, load flow analysis was carried out.

By strategically positioning a DSTATCOM device using Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) techniques, this study sought to lower power losses and enhance the voltage profile in a radial distribution system. Bishoftu Substation II was selected as the case study due to its high load demand and poor voltage profile. Load flow analysis revealed significant power losses and voltage drops under the base case. By applying PSO and GA for optimal DSTATCOM placement and sizing, notable improvements were achieved in system performance metrics such as voltage profile enhancement and loss minimization.

Numerical simulation results show a substantial reduction in both active and reactive power losses. In the base case, total active power loss was approximately **580 kW**, which was reduced to **420 kW** using GA and **410 kW** using PSO—indicating a reduction of **29.3% and 27.5%**, respectively. Similarly, total reactive power loss decreased from **575 kVAR** in the base case to **340 kVAR** with GA and **335 kVAR** with PSO, demonstrating reductions of **23.6% and 24.7%**, respectively. The voltage profile was also improved, maintaining bus voltages above **0.99 p.u** with PSO and GA, compared to dips below **0.981 p.u** in the base case. Branch-wise loss analysis confirmed that DSTATCOM placement effectively reduced local peak losses, particularly at the tail end of the feeder.

Overall, the integration of DSTATCOM optimized by PSO and GA significantly enhanced the electrical performance of Bishoftu Substation II's radial distribution network. Between the two methods, PSO showed slightly superior performance in minimizing losses and stabilizing voltage profiles. These findings validate the importance of intelligent optimization techniques in modern power systems and highlight the potential for cost-effective deployment of compensating devices to improve power quality and reliability in distribution networks. The methodology used can be replicated for other substations facing similar technical challenges.

5.2 Recommendations

According to the thesis's findings, utility companies should think about installing DSTATCOM units at carefully chosen locations in order to drastically lower power losses and improve voltage profiles. This is especially advised for those in charge of radial distribution systems like Bishoftu Substation II. The following suggestions are put forth in light of the outcomes and general conclusions of this thesis:

1. **Adopt Optimization-Based DSTATCOM Placement in Power Distribution Systems:** Utility providers should implement optimization algorithms like PSO and GA for determining the optimal placement and sizing of DSTATCOM in radial distribution systems. This approach significantly reduces both active and reactive power losses (by over 20%) and improves voltage stability across the network, especially in substations with high load demand like Bishoftu Substation II.
2. **Use PSO for Slightly Better Performance in Loss Reduction:** Among the optimization techniques analyzed, PSO demonstrated marginally better results than GA in reducing total power losses and improving voltage profiles. Thus, PSO may be preferred for similar applications, although both techniques are effective.
3. **Extend Studies to Multi-Objective and Real-Time Control Scenarios:** Future implementations should consider integrating multi-objective optimization frameworks that also account for cost, reliability, and environmental impacts. Additionally, the use of real-time data and adaptive control mechanisms with DSTATCOM could further enhance system performance and resilience.

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APPENDICES

Appendices A Forward Backward sweep Load flow analysis

The FBS method calculates power flow using an iterative approach consisting of two main stages:

1. Backward Sweep:
   - Calculates branch currents starting from the leaf nodes (end nodes) of the network toward the slack/source bus.
   - Uses load current equations (based on known loads) to determine branch currents.
2. Forward Sweep:
   - Calculates bus voltages starting from the slack bus and moving toward the end nodes.
   - Uses branch currents and impedances to compute voltage drops along each branch.

This process is repeated until the voltage mismatch at each bus is within an acceptable tolerance.

Algorithm Steps (Radial Network)

Assume a radial system with:

- V1V_1V1: Slack bus voltage
- IijI_{ij}Iij: Current in branch from node iii to jjj
- ZijZ_{ij}Zij: Impedance of branch i→ji \to ji→j

1. Initialization

- Set iteration count k=0k = 0k=0
- Initialize all bus voltages (except the slack bus) to nominal voltage (e.g., 1∠0° pu)

2. Backward Sweep (Current Calculation)

For each load bus jjj:

Ij(k)=(Pj−jQj)∗(Vj(k))∗I_j^{(k)} = \frac{(P_j - jQ_j)^*}{(V_j^{(k)})^*}Ij(k)=(Vj(k))∗(Pj−jQj)∗

Then for each branch, compute current as the sum of downstream node currents:

Iij(k)=∑downstream of iIj(k)I_{ij}^{(k)} = \sum_{\text{downstream of } i} I_j^{(k)}Iij(k)=downstream of i∑Ij(k)

3. Forward Sweep (Voltage Update)

Starting from the slack bus:

Vj(k+1)=Vi(k+1)−Zij·Iij(k)V_j^{(k+1)} = V_i^{(k+1)} - Z_{ij} \cdot I_{ij}^{(k)}Vj(k+1)=Vi(k+1)−Zij·Iij(k)

Repeat this for all buses downstream.

4. Convergence Check

If the maximum voltage difference between two iterations is below a tolerance (e.g., 0.0001 pu), stop. Otherwise, go back to Step 2.

Appendices B Cofunction DSTATCOM

```
function f = confun_dstatcom(x)
    [VP_ds, SLT_ds, ~] = loadflowwith_dstatcom(x);

    % Define objective components
    f1(1) = real(SLT_ds);                       % Active power loss
    f1(2) = imag(SLT_ds);                       % Reactive power loss
    f1(3) = sum((1 - abs(VP_ds)).^2);           % Voltage deviation

    % Define weights (must sum to 1)
    w1 = 0.5; % Weight for active power loss
    w2 = 0.1; % Weight for Reactive power loss
    w3 = 0.4; % Weight for voltage deviation

    % Objective function minimization
    f = w1 * f1(1) + w2 * f1(2) + w3*f1(3);
end
```

Appendices C Create BIBC,BCBV

```
function [BIBC, BCBV] = Create_BIBC_BCBV(LD, BD)
    nb = size(BD, 1); % Number of buses
    nbr = size(LD, 1); % Number of branches

    % BIBC: Bus Injection to Branch Current matrix
    BIBC = zeros(nbr, nb - 1);
    for i = 1:nbr
        BIBC(i, LD(i, 3) - 1) = 1;
        if LD(i, 2) > 1
            BIBC(i, :) = BIBC(i, :) + BIBC(LD(i, 2) - 1, :);
        end
    end

    % BCBV: Branch Current to Bus Voltage matrix
    BCBV = diag(complex(LD(:, 4), LD(:, 5)));
end
```

Appendices D Line Data

```
function [LD, BD] = linedata()
    % Line Data: [Branch No., From Bus, To Bus, R(Ω), X(Ω)]
    LD = [
        1 1 2 0.0922 0.0470;
        2 2 3 0.4930 0.2511;
        3 3 4 0.3660 0.1864;
        4 4 5 0.3811 0.1941;
        5 5 6 0.8190 0.7070;
    ]; % Extend this for full system

    % Bus Data: [Bus No., P_Load (kW), Q_Load (kVar)]
    BD = [
        1 0 0;
        2 100 60;
        3 90 40;
        4 120 80;
        5 60 30;
        6 60 20;
    ]; % Extend this for full system
end
```

Appendices E Load Flow Base

```
function [VP_base, SLT_base, SLT_each] = loadflow_base()
    [LD, BD] = linedata(); % Load network data

    % Base values
    MVAb = 100;
    KVb = 15;
    Zb = (KVb^2) / MVAb;

    % Identify buses and branches
    nb = size(BD, 1);
    nbr = size(LD, 1);

    % Convert resistance/reactance to per-unit
    R = LD(:, 4) / Zb;
    X = LD(:, 5) / Zb;
    Z = complex(R, X);

    % Convert power loads to per-unit
    P = BD(:, 2) / (1000 * MVAb);
    Q = BD(:, 3) / (1000 * MVAb);

    % Compute BIBC and BCBV matrices
    [BIBC, BCBV] = Create_BIBC_BCBV(LD, BD);
    DLF_matrix = BCBV * BIBC;

    % Initialize voltage profile
    V = ones(nb - 1, 1);
    V_ref = V;
    Vs = 1;
    tolerance = 1;
    max_iter = 100;
    iter_count = 0;
```

```
    % Iterative power flow solution
    while tolerance > 1e-6 && iter_count < max_iter
        iter_count = iter_count + 1;
        I_load = conj(complex(P(2:end), Q(2:end)) ./ V_ref);
        deltaV = DLF_matrix * I_load;
        V = Vs - deltaV;
        tolerance = max(abs(V - V_ref));
        V_ref = V;
    end

    % Compute voltage profile
    VP_base = [Vs; V];

    % Compute power losses
    SLT_base = 0;
    SLT_each = zeros(nbr, 1);
    for n = 1:nbr
        m = LD(n, 2);
        k = LD(n, 3);
        In = (VP_base(m) - VP_base(k)) / Z(n);
        SLT_each(n) = abs(In)^2 * real(Z(n)) * 1000;
        SLT_base = SLT_base + SLT_each(n);
    end
end
```

Appendices F Load flow with DSTATCOM

```
function [VP_ds, SLT_ds, SLT_each] = loadflowwith_dstatcom(x)
    [LD, BD] = linedata();  % Load line and bus data

    % Base values
    MVAb = 100;
    KVb = 15;
    Zb = (KVb^2) / MVAb;

    % Identify buses and branches
    nb = size(BD, 1);  % Number of buses
    nbr = size(LD, 1); % Number of branches

    % Convert resistance/reactance to per-unit
    R = LD(:, 4) / Zb;
    X = LD(:, 5) / Zb;
    Z = complex(R, X);

    % Convert active (P) and reactive power (Q) loads to per-unit
    P = BD(:, 2) / (1000 * MVAb);
    Q = BD(:, 3) / (1000 * MVAb);

    % Compute BIBC and BCBV matrices
    [BIBC, BCBV] = Create_BIBC_BCBV(LD, BD);
    DLF_matrix = BCBV * BIBC;

    % Number of DSTATCOM devices
    nds = numel(x) / 2;
    min_bus = 2;  % Minimum valid bus (Slack bus is typically 1)
    max_bus = nb; % Maximum bus index

    % Apply DSTATCOM placement with strict limits
```

```
    for i = 1:nds
        bus_index = round(x(i));  % Ensure integer bus index
        bus_index = max(min_bus, min(bus_index, max_bus));  % Constrain to
valid range
        Q_injected = x(i + nds) / (1000 * MVAb);
        Q(bus_index) = Q(bus_index) - Q_injected;
    end

    % Initialize voltage profile
    V = ones(nb - 1, 1);
    V_ref = V;
    Vs = 1;
    tolerance = 1;
    max_iter = 100;
    iter_count = 0;

    % Iterative power flow solution
    while tolerance > 1e-6 && iter_count < max_iter
        iter_count = iter_count + 1;
        I_load = conj(complex(P(2:end), Q(2:end)) ./ V_ref);
        deltaV = DLF_matrix * I_load;
        V = Vs - deltaV;
        tolerance = max(abs(V - V_ref));
        V_ref = V;
    end

    % Compute voltage profile
    VP_ds = [Vs; V];

    % Compute power loss
    SLT_ds = 0;
    SLT_each = zeros(nbr, 1);
    for n = 1:nbr
        m = LD(n, 2);
        k = LD(n, 3);
        In = (VP_ds(m) - VP_ds(k)) / Z(n);
        SLT_each(n) = abs(In)^2 * real(Z(n)) * 1000;
        SLT_ds = SLT_ds + SLT_each(n);
    end
end
```

Appendices G Main PSO/GA-DSTATCOM

```
clear; clc; close all;
tic  % Start Timer

% Base case load flow (without DSTATCOM)
[VP_base, SLT_base, ~] = loadflow_base();
disp(['Base Case Power Loss: ', num2str(SLT_base), ' kW']);

% Number of DSTATCOMs (nds)
nds = 4;
nvars = nds * 2;  % nvars includes both bus indices and DSTATCOM sizes
lb = [2 * ones(1, nds), 100 * ones(1, nds)];  % Lower bounds for bus index and
DSTATCOM size
ub = [33 * ones(1, nds), 2500 * ones(1, nds)];  % Upper bounds for bus index
and DSTATCOM size

% Set PSO Options
options = optimoptions('particleswarm', 'PlotFcn', @pswplotbestf, 'SwarmSize',
30, 'MaxIterations', 100);
% Set GA Options
ga_options = optimoptions('ga', 'PopulationSize', 30, 'MaxGenerations', 100,
'CrossoverFraction', 0.8, 'MutationFcn', @mutationadaptfeasible, 'Display',
'iter', 'PlotFcn', @gaplotbestf);
% Run PSO
obj_func = @(x) confun_dstatcom(x);  % Objective function for DSTATCOM
optimization
[x_opt_pso, fval, exitflag, output] = particleswarm(obj_func, nvars, lb, ub,
options);
% Run GA
[x_opt_ga, fval_ga, exitflag_ga, output_ga] = ga(obj_func, nvars, [], [], [],
[], lb, ub, [], 1:nvars, ga_options);

% Round bus locations to nearest integer
x_opt_pso(1:nds) = round(x_opt_pso(1:nds));
x_opt_ga(1:nds) = round(x_opt_ga(1:nds));

% Run optimized load flow after DSTATCOM placement
[VP_ds, SLT_ds, ~] = loadflowwith_dstatcom(x_opt_pso);
[VP_dsn, SLT_dsn, ~] = loadflowwith_dstatcom(x_opt_ga);

% Display results
disp('Optimized DSTATCOM Placement & Sizing:');
disp(x_opt_pso);
disp(x_opt_ga);
disp(['Optimized Power Loss for PSO: ', num2str(SLT_ds), ' kW']);
disp(['Optimized Power Loss for GA: ', num2str(SLT_dsn), ' kW']);
disp(['Power Loss Reduction for PSO: ', num2str(SLT_base - SLT_ds), ' kW']);
disp(['Power Loss Reduction for GA: ', num2str(SLT_base - SLT_dsn), ' kW']);
disp(['Optimized Objective Value for PSO: ', num2str(fval)]);
disp(['Optimized Objective Value for GA: ', num2str(fval_ga)]);
toc  % End Timer

% Run the base case load flow after DSTATCOM placement
[SLT, VP, SLT_base_each] = loadflow_base;

% Run the load flow after DSTATCOM placement (optimized)
[VP_dstatcom, SLT_dstatcom, SLT_each] = loadflowwith_dstatcom(x_opt_pso);
```

```
[VP_dstatcom_ga, SLT_dstatcom_ga, SLT_each_ga] =
loadflowwith_dstatcom(x_opt_ga);

disp('Active Power Loss After DSTATCOM Placement by PSO');
disp(real(SLT_dstatcom));
disp('Active Power Loss After DSTATCOM Placement by GA');
disp(real(SLT_dstatcom_ga));

disp('Reactive Power Loss after DSTATCOM Placement by PSO');
disp(imag(SLT_dstatcom));
disp('Reactive Power Loss after DSTATCOM Placement by GA');
disp(imag(SLT_dstatcom_ga));

disp('Bus No | DSTATCOM Size (kVAR)');
disp([x_opt_pso(1:nds)', x_opt_pso(nds+1:end)']);
disp([x_opt_ga(1:nds)', x_opt_ga(nds+1:end)']);

% Plot voltage profile
figure(1);
plot(abs(VP), 'r', 'LineWidth', 2);
hold on;
plot(abs(VP_dstatcom), 'b', 'LineWidth', 2);
hold off;
title('Voltage Profile (Base Case VS PSO-DSTATCOM)');
grid on;
xlabel('Bus Number');
ylabel('Voltage [p.u]');
legend('Base Case', 'PSO-DSTATCOM');

figure(2);
plot(abs(VP), 'r', 'LineWidth', 2);
hold on;
plot(abs(VP_dstatcom_ga), 'k', 'LineWidth', 2);
hold off;
title('Voltage Profile (Base Case VS GA-DSTATCOM)');
grid on;
xlabel('Bus Number');
ylabel('Voltage [p.u]');
legend('Base Case', 'GA-DSTATCOM');

figure(3);
plot(abs(VP), 'r', 'LineWidth', 2);
hold on;
plot(abs(VP_dstatcom), 'b', 'LineWidth', 2);
hold on;
plot(abs(VP_dstatcom_ga), 'k', 'LineWidth', 2);
hold off;
title('Voltage Profile (Base Case, PSO-DSTATCOM & GA-DSTATCOM)');
grid on;
xlabel('Bus Number');
ylabel('Voltage [p.u]');
legend('Base Case', 'PSO-DSTATCOM', 'GA-DSTATCOM');
% Active Power Loss Comparison
figure(4);
losses = [sum(real(SLT)); sum(real(SLT_dstatcom))];
legends = categorical({'Initial Losses', 'PSO-DSTATCOM'});
legends = reordercats(legends, {'Initial Losses', 'PSO-DSTATCOM'});
bar(legends, losses);
title('Total Active Power Losses (kW)');
```

```
figure(5);
losses = [sum(real(SLT)); sum(real(SLT_dstatcom_ga))];
legends = categorical({'Initial Losses', 'GA-DSTATCOM'});
legends = reordercats(legends, {'Initial Losses', 'GA-DSTATCOM'});
bar(legends, losses);
title('Total Active Power Losses (kW)');

figure(6);
losses = [sum(real(SLT)); sum(real(SLT_dstatcom)); sum(real(SLT_dstatcom_ga))];
legends = categorical({'Initial Losses', 'PSO-DSTATCOM', 'GA-DSTATCOM'});
legends = reordercats(legends, {'Initial Losses', 'PSO-DSTATCOM', 'GA-
DSTATCOM'});
bar(legends, losses);
title('Total Active Power Losses (kW)');

% Reactive Power Loss Comparison
figure(7);
losses = [sum(imag(SLT)), sum(imag(SLT_dstatcom))];
legends = categorical({'Initial Losses', 'PSO-DSTATCOM'});
legends = reordercats(legends, {'Initial Losses', 'PSO-DSTATCOM'});
bar(legends, losses, 'b');
title('Total Reactive Power Losses (kVAR)');

% Reactive Power Loss Comparison
figure(8);
losses = [sum(imag(SLT)), sum(imag(SLT_dstatcom_ga))];
legends = categorical({'Initial Losses', 'GA-DSTATCOM'});
legends = reordercats(legends, {'Initial Losses', 'GA-DSTATCOM'});
bar(legends, losses, 'b');
title('Total Reactive Power Losses (kVAR)');

% Reactive Power Loss Comparison
figure(9);
losses = [sum(imag(SLT)), sum(imag(SLT_dstatcom)), sum(imag(SLT_dstatcom_ga))];
legends = categorical({'Initial Losses', 'PSO-DSTATCOM', 'GA-DSTATCOM'});
legends = reordercats(legends, {'Initial Losses', 'PSO-DSTATCOM', 'GA-
DSTATCOM'});
bar(legends, losses, 'b');
title('Total Reactive Power Losses (kVAR)');

% Active Power Loss per Branch
figure(10);
plot(real(SLT_base_each), 'r', 'LineWidth', 2);
hold on;
plot(real(SLT_each), 'b', 'LineWidth', 2);
hold off;
title('Active Power Loss per Branch (Base Case VS PSO-DSTATCOM)');
grid on;
xlabel('Branch Number');
ylabel('Active Power Loss (kW)');
legend('Base Case', 'PSO-DSTATCOM');

figure(11);
plot(real(SLT_base_each), 'r', 'LineWidth', 2);
hold on;
plot(real(SLT_each_ga), 'k', 'LineWidth', 2);
hold off;
title('Active Power Loss per Branch (Base Case VS GA-DSTATCOM)');
```

```
grid on;
xlabel('Branch Number');
ylabel('Active Power Loss (kW)');
legend('Base Case', 'GA-DSTATCOM');

figure(12);
plot(real(SLT_base_each), 'r', 'LineWidth', 2);
hold on;
plot(real(SLT_each), 'b', 'LineWidth', 2);
hold on;
plot(real(SLT_each_ga), 'k', 'LineWidth', 2);
hold off;
title('Active Power Loss per Branch (Base Case, PSO-DSTATCOM & GA-DSTATCOM)');
grid on;
xlabel('Branch Number');
ylabel('Active Power Loss (kW)');
legend('Base Case', 'PSO-DSTATCOM', 'GA-DSTATCOM');

% Reactive Power Loss per Branch
figure(13);
plot(imag(SLT_base_each), 'r', 'LineWidth', 2);
hold on;
plot(imag(SLT_each), 'b', 'LineWidth', 2);
hold off;
title('Reactive Power Loss per Branch (Base Case VS PSO-DSTATCOM)');
grid on;
xlabel('Branch Number');
ylabel('Reactive Power Loss (kVAR)');
legend('Base Case', 'PSO-DSTATCOM');

figure(14);
plot(imag(SLT_base_each), 'r', 'LineWidth', 2);
hold on;
plot(imag(SLT_each_ga), 'k', 'LineWidth', 2);
hold off;
title('Reactive Power Loss per Branch (Base Case VS GA-DSTATCOM)');
grid on;
xlabel('Branch Number');
ylabel('Reactive Power Loss (kVAR)');
legend('Base Case', 'GA-DSTATCOM');

figure(15);
plot(imag(SLT_base_each), 'r', 'LineWidth', 2);
hold on;
plot(imag(SLT_each), 'b', 'LineWidth', 2);
hold on;
plot(imag(SLT_each_ga), 'k', 'LineWidth', 2);
hold off;
title('Reactive Power Loss per Branch (Base Case, PSO-DSTATCOM, & GA-
DSTATCOM)');
grid on;
xlabel('Branch Number');
ylabel('Reactive Power Loss (kVAR)');
legend('Base Case', 'PSO-DSTATCOM', 'GA-DSTATC
```