

Enhancement of Voltage Profile and Minimization of Power Loss through
Optimal Sizing and Placement of Distributed Generation using Genetic
Algorithm (A Case Study: Gelan Distribution Network)



Bilisa Gemechu Kenasa

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

Presented in Partial Fulfilment of the Requirement for the Degree of
Master's in Electrical Power and Control Engineering (Power System
Engineering)

Office of Graduate Studies
Adama Science and Technology University

September 2024
Adama, Ethiopia

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DECLARATION

I hereby declare that this Master Thesis entitled “**Enhancement of Voltage Profile and Minimization of Power Loss through Optimal Sizing and Placement of Distributed Generation using Genetic Algorithm (A Case Study: Gelan Distribution Network)**” is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation

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RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled “**Enhancement of Voltage Profile and Minimization of Power Loss through Optimal Sizing and Placement of Distributed Generation using Genetic Algorithm (A Case Study: Gelan Distribution Network)**” prepared under my guidance by Bilisa Gemechu Kenasa submitted in partial fulfillment of the requirements for the degree of Master’s of Science in Power System Engineering. Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Dr. CS Reddy

Major Advisor

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APPROVAL PAGE

I, the advisors of the thesis entitled “**Enhancement of Voltage Profile and Minimization of Power Loss through Optimal Sizing and Placement of Distributed Generation using Genetic Algorithm (A Case Study: Gelan Distribution Network)**” and developed by Bilisa Gemechu Kenasa, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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Major Advisor

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We, the undersigned, members of the Board of Examiners of the thesis by Bilisa Gemechu Kenasa have read and evaluated the thesis entitled “**Enhancement of Voltage Profile and Minimization of Power Loss through Optimal Sizing and Placement of Distributed Generation using Genetic Algorithm (A Case Study: Gelan Distribution Network)**” and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Power System Engineering.

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Department Head

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Signature

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Office of Postgraduate Studies, Dean

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LIST OF ACRONYMS AND ABBREVIATIONS

ABC	Ant Bee Colony
AC	Alternating Current
ACO	Ant colony optimization
AIA	Artificial Immune Algorithm
BFS	Backward - Forward Sweep
CHP	Combined Heat and Power
CGSA	Chaos-assisted Gravitational Search Algorithm
CSA	Cuckoo Search Algorithm
DC	Direct Current
DFIG	Doubly Fed Induction Generator
DG	Distributed Generation
GA	Genetic Algorithm
ETB	Ethiopian Birr
EEU	Ethiopian Electric Utility
EEP	Ethiopian Electric Power
ENS	Energy Not Supplied
FAIR	Fixed Assets Inventory and Revaluation
GWO	Gray Wolf Optimizer
IEEE	Institute of Electrical and Electronics Engineers.
IPSO	Improved Particle Swarm Optimization
LFA	Load Flow Analysis
MATLAB	Matrix Laboratory
MVAR	Mega Volt Ampere Reactive
MW	Mega Watt
NASA	National Aeronautics and Space Administration
PDS	Power Distribution System
PSO	Particle Swarm Optimization
RDS	Radial Distribution System
SA	Simulated Annealing
SCIG	Squirrel Cage Induction Generator

SI	Swarm Intelligence
VP	Voltage Profile
WOA	Whale Optimization Algorithm

ABSTRACT

Urbanization and the ongoing growth in power consumption necessitate the use of a reliable and high-quality power supply system. As demand rises, the flow of electricity intensifies, resulting in higher currents traversing through distribution lines. Consequently, leading to increased power losses and voltage drops along the distribution network. The study was dedicated to addressing challenges within the Gelan distribution network, specifically targeting voltage profile issues and power losses on the selected feeder. The main objective of the study was to decrease power loss and improve the voltage profile using Genetic Algorithm (GA) through the optimal sizing and placement of a Distributed Generation (DG). To achieve this objective, At Frist load flow analysis was conducted via Backward - Forward Sweep (BFS) within the existing distribution network to analyze the voltage profile and power loss. Then GA was used to optimally size and place the DG by formulating a problem with multiple objective functions with active power loss, reactive power loss, and voltage deviation. The proposed system was then executed using MATLAB 2021a to assess the effect of optimal placement and sizing of the DG on voltage profile and power losses for the selected feeder. The programming results was tested by considering two scenarios (For existing system and Different DG cases), with the second scenario including four different cases (Case I - 1 DG, Case II - 2 DG, Case III - 3 DG, & Case IV - 4 DG). From load flow analysis of existing system, the total active power loss and total reactive power loss was 380.3629 KW and 227.5547 KVAR respectively while the minimum voltage deviation was 0.9301 p.u. From the results derived through the MATLAB programming in Scenario II, the findings across the different cases show that the integration of 3 DG units (Case III) provides the most substantial benefits. In Case III, the total active power loss was decreased to 171.3684 kW after the integration of 3 DG units, a 57.2556% decrease. The total reactive power loss also decreased 102.2332 kVAr, a 74.7501% reduction. The minimum voltage value improved to 0.96259 p.u. Furthermore, a cost analysis was conducted for the proposed system, indicating a payback period of 3.41 years. Consequently, from the attained result, it is likely to say the proposed system was effective to decrease power loss and enhance voltage profile within Gelan distribution network.

Key words: Distributed Generation (DG), Backward - Forward Sweep (BFS) Load Flow, Genetic Algorithm (GA).

CHAPTER ONE

1. INTRODUCTION

1.1 Background of the Study

The distribution network serves as a vital link between the transmission network and end consumers, facilitating the transfer of electricity generated by power plants to individual energy users (Mahdavi et al., 2019). However, with the increasing complexity of modern life, energy consumption has soared, leading to a surge in power losses and voltage drops within distribution systems. Most distribution networks are radial or weakly meshed in structure, designed with a high R/X ratio, which amplifies the significance of line losses and voltage drops, particularly at feeder ends (Gupta & Kumar, 2018).

This escalating demand for electricity contributes directly to power losses within distribution networks. As demand rises, the flow of electricity intensifies, resulting in higher currents traversing through distribution lines. Consequently, these intensified currents encounter resistance within the conductors, leading to increased resistive losses as electrical energy is dissipated as heat. Moreover, the increase in demand often leads to voltage drops along the distribution lines, adversely affecting the performance of electrical devices and appliances. Overloaded equipment, compounded by network congestion and strain on distribution infrastructure (Abdelmotteleb et al., 2017).

Voltage drop in a distribution network poses significant challenges, as it can lead to a cascade of detrimental consequences. These include energy losses, which not only impact the financial viability of the network but also contribute to environmental concerns due to increased energy consumption. Furthermore, voltage drop can cause equipment damage, operational disruptions, and safety hazards, posing risks to both infrastructure and personnel. The need for frequent maintenance to rectify these issues further escalates operational costs and diminishes overall network performance. Moreover, voltage drop diminishes power output, impairing the network's ability to meet demand efficiently (Panda et al., 2023).

These fluctuations have caused voltage to fluctuate beyond acceptable limits at different locations within the network, resulting in energy losses. As a solution, the strategic installation and Distributed Generation (DG) sizing become necessary to improve voltage stability and mitigate power losses. Research indicates that global energy consumption is expected to grow

by 1.6 percent annually until 2025. Therefore, distributed generation, often referred to as substitute energy systems, is poised to assume a more prominent role in the future of power grids (Ntombela et al., 2022a).

Distributed Generation (DG) has emerged as a solution that significantly reduces losses in the distribution network. DG also enhances the distribution network's voltage profile. Although DG units produce electricity in small amounts, their utilization of renewable energy sources makes them more valuable in the context of increasing focus on renewable energy production (Radosavljevic, 2018).

Due to their generally positive influence on electricity grids, DG units are increasingly being incorporated into electrical distribution networks. In the realm of smart grid technology, DG systems function as a fundamental component of intelligent electrical systems. Moreover, these DG systems enhance the reliability of the system by functioning as backup generators for certain customers during power outages (Somefun et al., 2020).

There are two primary groups of distributed generation (DG) technologies: one relies on fossil fuels, and the other harnesses renewable (sustainable) energy sources. Fossil fuel driven DG systems encompass internal combustion engines, combustion turbines, and fuel cells. On the other hand, renewable energy include small-scale hydroelectric, solar, biomass, geothermal, wind turbines, and various DG systems based on these sources. Assessing the technological impacts of DG on electrical systems is essential, and the process of evaluating the technical effects of Distributed Generation (DG) on power grids takes time (Mehigan et al., 2018).

Poor placement and capacity allocation of DGs can lead to various issues, such as fault currents, voltage fluctuations, disruptions in voltage control processes, increased power losses, affects system capital and operating costs, among others. Deciding on the integration of DG units into power systems is a complex task. Installation of DG units at wrong places can results to an increment of system losses, implying in an increment of the costs and, therefore, having an effect contradictory to the desired. Therefore, the careful assessment of the placement and capacity allocation of DG units is essential to reduce losses and enhance the voltage profile. Various optimization techniques are being developed to determine the most efficient DG allocations in electrical distribution networks, aimed at minimizing power losses and improving the voltage profile (Alyu et al., 2023).

Distributed generation (DG) sources that are renewable are abundant in Ethiopia. It is therefore very feasible to choose DG kinds based on renewable resources, particularly solar and wind energy. Even though Ethiopia has a lot of renewable energy overall, PV-based DG was specifically picked for the Gelan area because of its availability. In addition Genetic Algorithm was selected due to its robustness, global search capabilities, adaptability, and flexibility in handling diverse optimization challenges. This study was aimed to use GA to strategically locate and size multiple PV (Photovoltaic) DG units. By doing this, this thesis work was done to improve the Gelan Distribution Network's performance by enhancing the voltage profile and lowering power losses.

1.2 Statement of the Problem

In Ethiopia, the demand for energy is projected to increase significantly due to population growth and socioeconomic development. The Gelan town area has recently experienced a surge in electricity demand, driven by rising living standards, urbanization, and industrial expansion. As a result, the distribution feeders, spanning long distances, suffer from substantial power losses and high voltage drops. The Gelan 3 feeder, in particular, has caused low voltage levels and power losses for customers at its end in Gelan city. This high voltage drop at the load connection point presents challenges for both the Ethiopian Electric Utility (EEU) and its customers. On-Load Tap Changers (OLTCs) have been implemented at Gelan Substation to mitigate these issues, but have not proven entirely effective. Therefore, a strategic approach to reducing power losses and improving voltage profiles is necessary. Integrating distributed generation (DG) into the distribution feeders offers several advantages over OLTCs. However, suboptimal DG placement can increase system losses, leading to higher costs and counterproductive results. Advanced optimization techniques are needed to develop a tailored solution that can simultaneously enhance voltage profile and reduce power losses by determining the optimal placement and size of Photovoltaic(PV) DG units.

This study addresses these challenges by conducting a comparative analysis using performance metrics such as active power loss, reactive power loss, voltage profile, and percentage reduction of active and reactive power among multiple distributed generation (DG) systems to enhance voltage profile and minimize power loss.

1.3 Objectives of the Study

1.3.1 General Objective

The main objective of the study is to enhance the voltage profile and reduce power losses using optimal sizing and placement of Photovoltaic DG in the Gelan distribution network by applying a GA.

1.3.2 Specific Objectives

- Model single line diagram of selected feeder.
- Determine power loss and voltage drop using BFS method within the existing network.
- Investigate optimal sizing and placement of DG to optimize distribution feeder.
- Compare power loss and voltage profile before and after the integration of DG.

1.4 Significance of the Study

By optimally sizing and allocating DG in a radial distribution system, the following advantages can be achieved:

- Addressing critical challenges in the Gelan distribution network
- Quantitative assessment of network performance
- Comparative analysis of multiple DG integration scenarios
- Valuable insights for distribution system planning and operation
- Enhancing voltage profile and minimizing power losses
- Motivating customer and Ethiopian Electric Utility to use renewable energy technologies.

1.5 Scope and Limitations of the Study

The study concentrates on minimizing power losses and enhancing the voltage profile of distribution systems through the application of optimal sizing and placement of DG using GA. This study did not take account of reliability enhancement and the investigation of the impacts of harmonics and protection level on the distribution network.

1.6 Organization of the Study

This thesis is organized into five chapters. Chapter 1 covers the background of the study, statement of the problem, general and specific objectives, scope of the thesis work, and significance of the study. Chapter 2 introduces details of the theoretical background and review of different literatures related to the study. Chapter 3 presents the material and methods which covers design of single line diagram, modeling of load flow analysis, selection of DG

technology, and modeling of Genetic Algorithm. Chapter 4 discusses about simulation result and discussion of the case study of Gelan 3 distribution feeder. The final part presents conclusions, and recommendations. This part summarize the finding of thesis work along with pertinent conclusions and provide additional research in the field as well as potential solutions to the issues encountered during the thesis work.

CHAPTER TWO

2. LITERATURE REVIEWS

2.1 Theoretical Background

Enhancing the voltage profile and reducing power losses pose significant challenges for the electric power utilities in developing country. As electricity demand rises quickly, ensuring a stable power supply becomes challenging due to a poor voltage profile and higher losses, unless suitable measures are implemented. Given the limited financial resources available to utilities for expanding their grid and power sources, it becomes imperative to address power losses. This chapter examines theoretical concepts and related research on distribution systems aimed at reducing power loss and alleviating voltage drops in the distribution network.

2.2 Distribution System of Electric Power

The distribution network of electric power is the system that delivers electricity from the transmission system to consumers for their use. The third phase of the electricity system begins where this network begins. The voltage is deliberately lowered from the transmission level to the typical distribution voltage as energy enters the distribution system. The primary distribution network then uses this medium voltage to transmit it to the distribution transformers. Some loads may be directly connected to large distribution networks or transmission subnetworks, particularly those with medium or industrial power requirements that require highquality power supplies (Salkuti, 2019).

After primary distribution, power flows into the distribution wiring through a substation, eventually arriving at the service location where it is converted to the utilization level, referred to as secondary distribution. This secondary distribution network supplies power to smaller loads, including commercial and residential consumers. The distribution feeders traverse either underground or overhead lines along the roads, transmitting power to consumer loads via the distribution transformers. The role of the distribution substations is not limited to alter the voltage but also faults isolation occurring within either the transmission or distribution systems.

2.2.1 Distribution Network Connection Scheme

Based on their connection scheme distribution network can be classified in to Radial, Ring and interconnected distribution network. In a radial distribution system, power flows in a single direction, making it the simplest and least expensive system to implement. However, if a fault

occurs in the feeder, it can result in supply failure for connected consumers since there is no alternative feeder to supply the distributors. On the other hand, the Ring main distribution system connects distribution transformers in a loop, providing two different paths for power supply. This system is more reliable as each distribution transformer is fed by two feeders, ensuring continuity of supply in case of a fault in any section of the feeder. Additionally, the interconnected distribution system involves a feeder ring energized by two or more generating stations or substations, enhancing reliability and ensuring power supply from alternative paths in case of faults (Mokryani, 2022).

2.2.2 Power Loss and Voltage Drop in Radial Distribution System

Radial distribution systems have only one path between the substation and the customers, so any failure along the feeder can cause an outage (Technology, 2016). Because of this, loop or network systems are more reliable than radial ones. The distribution of loads, level of loading, and type of conductors all affect the voltage drop in radial distribution feeders. Especially for customers who are located distant from the substation, improper sizing or routing of subsequent feeders might result in severe voltage dips. Voltage drop is a secondary problem that can be adjusted for at the substation by voltage regulating equipment, but radial feeders are constructed with current carrying capability as their primary priority (Cui et al., 2019). Significant voltage losses, particularly at the feeder's far end, can happen, though, if the feeder's length, conductor size, and load distribution are not appropriately planned (Deshmukh et al., 2019). Distribution system performance can be strongly impacted by power loss and voltage drop in the following ways:

A) Efficiency and Energy Losses:

- Power loss, caused by the conversion of electrical power to heat due to resistance, decreases the overall efficiency of the distribution system (Sinaga et al., 2021).

B) Voltage Regulation:

- Voltage drop, which is the reduction in voltage across the distribution system impedance, can lead to unacceptable voltage levels at the end-user equipment (Sinaga et al., 2021).
- Excessive voltage drop, often exceeding the acceptable 5% limit, can cause issues with equipment operation and performance (Sinaga et al., 2021).

C) System Reliability:

- The radial nature of distribution systems means that any failures along the feeder can cause outages, reducing the overall reliability of the system (Ymeri et al., 2014).
- Improper design and sizing of successive feeders can exacerbate voltage drop issues, especially for customers located far from the substation.

D) Financial Viability:

- High distribution losses, including commercial losses due to poor billing, revenue collection, and power theft, can significantly impact the financial viability of the distribution system (Technology, 2016).

Addressing power loss and voltage drop issues is crucial for improving the overall efficiency and profitability of the distribution network. Consequently, power loss and voltage drop can greatly affect the efficiency, reliability, and financial feasibility of distribution systems, making it essential to implement suitable mitigation strategies and design considerations.

1.2.3 Distribution Network Performance Improvement Techniques

Distribution networks play a crucial role in the efficient delivery of electrical power to end-users. However, these networks often face challenges related to power losses and voltage profile issues that can impact their overall performance. To address these challenges, researchers have developed various techniques to improve the performance of distribution networks.

A) Network Reconfiguration

Network reconfiguration is a highly effective method for minimizing power losses and enhancing voltage profiles in distribution systems. It involves altering the topology of the distribution network by opening and closing sectionalizing switches (Naresh Manandhar et al., 2023). Network reconfiguration alone can lead to power loss reductions of 5-30%. The crucial aspect is to optimize the network topology by adjusting switches to balance the load and minimize losses. This can be achieved through iterative branch exchange algorithms and clustering techniques (Ntombela et al., 2022b).

Dynamic reconfiguration, which divides the time period into multiple sessions and reconfigures the network for each session to adapt to changing load conditions, can provide further benefits. However, in practice, distribution network switches are not changed frequently to avoid equipment damage, so finding an optimal reconfiguration solution that performs well over the entire operating period is more practical (Gao et al., 2019).

B) Distributed Generation

DG placement and sizing is a key technique for improving the performance of distribution networks. Strategically placing and sizing DG units like solar or wind power can help compensate reactive power, reduce losses, and enhance voltages in distribution systems. However, improper DG placement and sizing can actually increase losses and negatively impact the network, so optimization is crucial. Advanced optimization methods like PSO was commonly used to determine the optimal placement and sizing of DG units. These techniques can consider factors like DG size, location, and type to maximize the benefits. Optimal DG placement and sizing can achieve power loss reductions of 50-80% compared to the base case without DG, making it a highly effective technique for enhancing distribution network performance (Adepoju et al., 2023).

C) Capacitor allocation

Capacitor allocation is a crucial technique for improving the performance of distribution networks. Strategically placing and sizing capacitor banks at optimal locations and sizes helps compensate reactive power and minimize losses. However, improper capacitor placement can actually increase losses, so optimization is crucial. Advanced optimization methods like the Bat Algorithm and Bacterial Foraging Optimization can be used to identify the excellent placements of capacitor that provide the maximum loss reduction and voltage profile improvement. These techniques consider factors like capacitor size, location, and number to optimize the benefits. Optimal capacitor allocation can reduce distribution system power losses by 20-50% depending on the system characteristics and capacitor placement strategy. For example, one study found that after installing capacitors at 3 locations, the total savings was \$50,724 (Lei et al., 2022). Another study showed that before compensation, the power loss was 861.4 kW, which was reduced to 689.1 kW after capacitor installation, a 20% reduction (Yuvaraj et al., 2021).

D) Distribution Transformer Locating and Sizing

Proper placement and sizing of distribution transformers is a key for the performance of power distribution systems. Transformers that are too small or placed in the wrong locations can lead to voltage drops and increased losses, negatively impacting the overall system efficiency.

a) Transformer Sizing

Accurately sizing distribution transformers is essential to ensure they can handle the required load without being overloaded or underutilized. Oversized transformers can lead to higher no-

load losses, while undersized transformers may experience excessive load losses and voltage drops. To determine the optimal transformer size, factors such as the expected load growth, load diversity, and load factor should be considered. Load flow analysis and probabilistic methods can help estimate the future load requirements and guide the selection of appropriate transformer ratings.

b) Transformer Placement

Strategically positioning distribution transformers is also vital for efficiency. They should be situated near load centers to shorten the low-voltage distribution lines and decrease line losses. Placing transformers near the load centers also helps maintain acceptable voltage levels at the customer premises. Factors such as the spatial distribution of loads, terrain, and accessibility should be considered when determining the optimal transformer locations. Clustering techniques and spatial optimization algorithms can be employed to identify the most suitable transformer sites.

c) Voltage Regulation

Proper transformer placement and sizing also contribute to maintaining acceptable voltage regulation throughout the distribution system. Voltage drops along the distribution lines can lead to inefficient operation of electrical equipment and potential violations of voltage limits.

By carefully selecting transformer locations and ratings, the voltage profile can be optimized, ensuring that all nodes in the distribution system operate within the desired voltage range. This helps to reduce losses and increase the overall efficacy of the distribution system.

In conclusion, the careful analysis and strategic placement of distribution transformers is a crucial aspect of improving power distribution efficiency. By optimizing transformer sizing and locations, system losses can be reduced, voltage regulation can be improved, and the overall efficiency of the distribution system can be augmented more.

E) Highly Effective Transformers

Using high-efficiency transformers can considerably diminish transformer losses and advance the overall performance of the power distribution system. Key features that contribute to the high efficiency of these transformers include:

a) Low-Loss Cores

The core of a transformer is responsible for a significant portion of the total losses. By using advanced core materials, such as amorphous or nanocrystalline alloys, the core losses can be

dramatically reduced. As compared to traditional-silicon steel cores, amorphous metal cores, can minimize transformer core losses by more than 60%. The reduction in eddy current and hysteresis losses within the core is mainly due to the disordered atomic structure of these amorphous materials.

b) Optimized Winding Design

The design of the transformer windings also plays a crucial role in minimizing losses. Techniques such as employing low-resistance conductors (e.g., copper), optimizing winding geometry and layout, minimizing the number of turns, and reducing winding skin and proximity effects can significantly lower the copper (I^2R) losses in the transformer.

c) Thermal Management

Effective cooling systems, such as oil cooling or forced-air cooling, help maintain the transformer at an optimal operating temperature. This is important because higher temperatures can increase both core and winding losses. By combining advanced core materials, optimized winding design, and effective thermal management, high-efficiency transformers can achieve substantial decreases in total losses compared to traditional transformer designs. This leads to improvements in the overall efficiency and performance of the power distribution system.

F) Network Re-conducting

Network re-conducting, also known as conductor grading, involves upgrading the distribution lines by replacing smaller conductors with larger ones. This technique can considerably diminish line losses, thereby improving the efficiency of power distribution systems. Here's a detailed explanation of the process and its benefits:

a) reducing Line Losses

The main aim for the efficiency improvement is the reduction in line losses. Electrical power losses in distribution lines are directly proportional to the resistance of the conductors, as described by the formula:

Power Loss = $I^2 * R$ Where: I: Current and R: Resistance in the conductor.

By upgrading to larger conductors, the resistance (R) is decreased, which in turn reduces the power losses along the distribution lines. This is because larger conductors have a lower resistance per unit length compared to smaller conductors.

b) Conductor Sizing

The selection of the appropriate conductor size is crucial for maximizing the efficiency gains. Factors such as the expected load, voltage level, and distance of the distribution line should be considered when determining the optimal conductor size. Larger conductors, such as those with higher cross-sectional areas, have lower resistance and can carry more current without excessive voltage drops. This allows for more efficient power transmission and reduced line losses.

c) Economic Considerations

While upgrading to larger conductors can improve efficiency, it is important to consider the economic aspects as well. The cost of the new conductors, installation, and any necessary infrastructure changes must be weighed against the expected benefits in terms of reduced energy losses and improved system performance. In some cases, a detailed cost-benefit analysis may be necessary to identify the most suitable conductor size and the feasibility of the re-conducting project. It is a highly effective technique for minimizing line losses and enhancing the power distribution systems' efficiency. By upgrading to larger conductors, the resistance of the distribution lines can be decreased, leading to lower power losses and more efficient power transmission. This technique is particularly beneficial when combined with other efficiency-enhancing methods to achieve a comprehensive improvement in system efficiency (Flaih et al., 2017).

2.3 Distributed Generation

The DG units are compact power generation devices located in close proximity to customers. They produce electricity from renewable sources including geothermal, wind, and solar energy. An electrical system is a network of diverse electrical components designed to generate, transmit, distribute, and utilize electricity. Includes generators driven by main engines, grids, substations, transformers, circuit breakers, bus bars and auxiliary equipment. These components work together to transmit electricity from power plants to consumers in the most reliable, economical and efficient manner (Jhansi S, 2019).

2.3.1 Classification of Distributed Generation

Distributed Generation is categorized based on their size, operating principles and the DG-unit interaction with the grid, the source of power generation (either reactive or active, or both), etc.

A) Size based Classification of DG

The classification of DG systems according to their size involves categorizing them based on their placement in active power generation and consumptions. DG units are generally classified into four types depending on their deployment within the distribution system. This classification system helps in understanding the different roles and applications of DG units within the power distribution network (Irfan et al., 2018). DG Classifications based on their Size was depicted in table 2.1.

Table 2. 1: DG Classifications based on their Size (Barkhouse et al., 2015)

Type	Size
DG (Micro)	1 Watt $\leq$ 5 kW
DG (Small)	5 kW $\leq$ 5 MW
DG (Medium)	5 MW $\leq$ 50 MW
DG (Large)	50 MW $\leq$ 300 MW

B) Classification based on the source of power generation (either reactive or active, or both)

The classification of DG based on the source of power generation typically involves categorizing them into different categories according to their capacity to generate active (real) power, reactive power, or both. So based on these criteria, DG can be classified as: -

- **Type 1 DG:** It generates only active power and it does not offer any support for reactive power. It typically includes non-synchronous sources PV panels or wind turbines that rely on power electronics converters to synchronize with the grid.
- **Type 2 DG:** Type 2 DG systems generate active power and can also provide limited reactive power support. These systems usually involve synchronous generators like diesel generators or gas turbines that can regulate active power output and offer some reactive power.
- **Type 3 DG:** It generates active power along with a significant reactive power support. They have a tendency for regulating active power output and supplying reactive power to meet the grid's requirements. Type 3 DG often includes synchronous generators equipped with voltage regulators and power factor control capabilities.
- **Type 4 DG:** Type 4 DG systems primarily generate reactive power and can also produce limited active power. These systems are designed to supply reactive power support to

the grid and are commonly used to address power quality issues like voltage fluctuations and regulation problems.

C) Classification based on the principles of operation and the interface between the grid & DG-unit

In this aspect, DG can again be classified in to two parts. First, it can be divided into two primary categories: rotating machine DG and inverter-based DG. Inverters can be utilized in DG systems normally, but only after the generation process that is, after the voltage is converted from DC to AC and only after the nominal voltage and frequency have been adjusted. Consequently, the voltage needs to be first converted to DC and then back to AC with the nominal specifications using inverter. The few types of current DG technologies: fuel cells, solar cells, wind turbines, and micro turbines (Irfan et al., 2018). Figure 2.1 show classification of DG based on principles of operation & interface with the Grid.

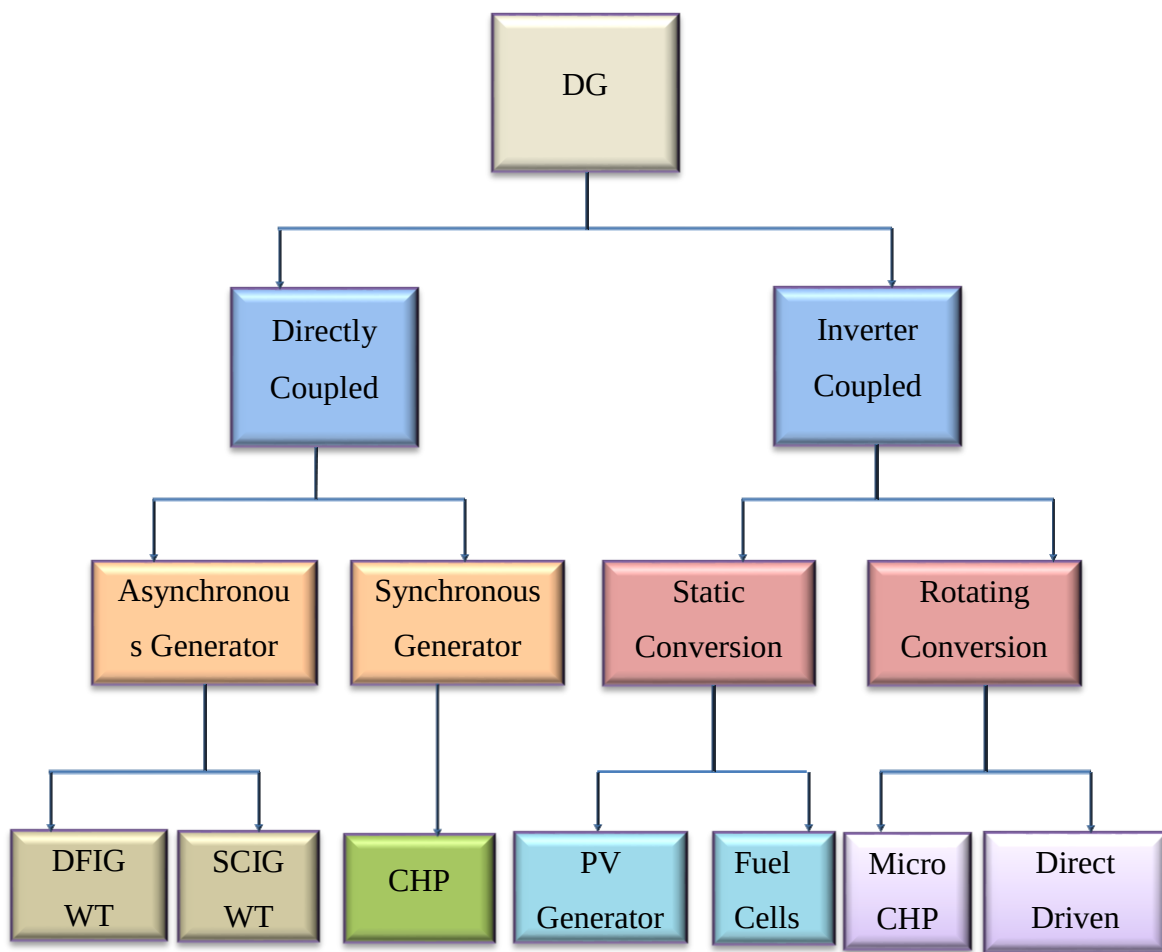


Figure 2. 1: Grid-Connected Distributed Generation Units Based on Coupling and Conversion Methods (Kaddah et al., 2015)

a) Photovoltaic (PV) System

The primary purpose of this system is to transform solar light into electrical energy. When photons are exposed to the sun in the proper way to receive as much light as possible, the self-contained energy they contain is converted into electrical power by the photovoltaic system, which is mostly made of semi-conductive material. These systems are largely environmentally friendly because they are simple to operate, require little maintenance, and simply need to be exposed to sunlight. However, they do require a large amount of area, and their initial cost is rather high. Figure 2.2 demonstrate Schematic Diagram of Solar Panel.

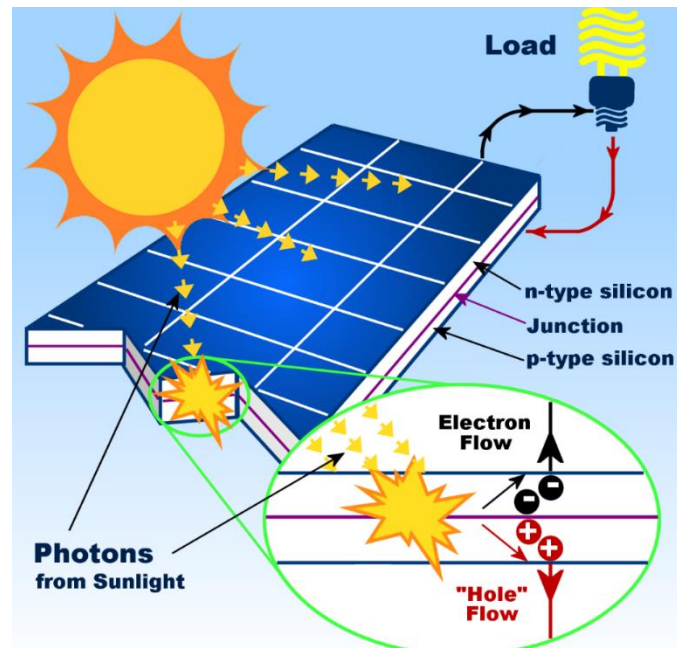


Figure 2. 2: Schematic Diagram of Solar Panel (Raj, 2023)

2.4 Distribution Network Load Flow Analysis

The flow of load, known as power flow analysis, is a fundamental tool for power engineers, allowing them to examine and optimize the operation of an electric power system. It consists of the solution of a set of equations giving the steady-state voltages, currents, and power flows in the system. It is directed towards the power system operating within its specified limits and generally towards the evaluation of the power transfer from the utilities. So, the load flow analysis offers essential information relative to the power system's operational conditions. The basic parameters derived from the load flow calculation include:

- Magnitudes and angles of the load bus voltages: The load bus is one on which, within the power system, electrical power is consumed. The magnitudes and angles of the

voltages of these buses are obtained from load flow analysis, from which a better understanding is made of the voltage profile at the buses, to determine if the system is voltage unstable or not.

- Reactive powers and voltage phase angles at generator buses: Generator buses are the buses where electrical power is being produced. Load flow analysis provides the reactive power outputs and voltage phase angles at such buses, as these are necessary for maintaining voltage stability and thus the operation of generators on a coordinated basis.
- Real and reactive power flows on the distribution system: The analysis of real and reactive power flow in the distribution system will give a calculated appreciation of the real and reactive power flow at different buses of the distribution system. Such information becomes a necessity for the proper identification of probable overload conditions, voltage drops, and power losses. It helps in the determination of the right configuration of the system to decrease the losses and improve efficiency.
- Power at the reference bus: The load flow analysis has a reference bus which the voltage and power is referenced from. The power at the reference bus is given and is normally used as a reference power in the evaluation of the power flows and voltage profiles all over the system (Mishra & Brar, 2022).

2.4.1 Backward - Forward Sweeps Load Flow Analysis

Load flow analysis, which is also referred to as power flow analysis, is a crucial and fundamental technique employed in electrical engineering to examine and calculate the stable operating conditions of an electric power system. It entails solving a series of mathematical equations to determine various electrical parameters, including voltage magnitudes and angles, current magnitudes and angles, as well as active and reactive power flows within a network of interconnected electrical elements such as generators, transformers, transmission lines, and loads. It refers to the computational method or numerical algorithms used to calculate the steady-state operating characteristics of a power system network based on line data and bus data (Chary et al., 2020).

Forward and backward sweeps are also commonly used in the context of load flow analysis, a critical component of power system analysis in electrical engineering. Load flow analysis, also known as power flow analysis, is used to determine the steady-state operating conditions of an electrical power system, including voltage magnitudes and phase angles at different buses in the

network (Ouali & Cherkaoui, 2020). In load flow analysis, the forward and backward sweeps are part of the iterative numerical methods used to solve the power flow equations. The goal is to find the voltages and power flows in a network of interconnected power system components, such as generators, transformers, transmission lines, and loads. How forward and backward sweeps are applied in this context:

A) Backward Sweep:

The input currents or power flows on each side are updated based on the residual voltages by summing the power flows. This update is consistent with the boundary condition of zero current or power flow at the end of the side cable. This process starts from the branches connected to the end node and continues to the branches connected to the source node. The updated actual power flows in each branch are calculated during back propagation up to, taking into account the node voltages from the previous iteration. This means that the voltage values are remain constant during backward propagation and the updated energy flows in each branch are transmitted backwards along the supply via the reverse path.

B) Forward Sweep:

When scanning forward, the tail voltages are updated based on the input currents or power flows on both sides, which are determined through voltage drop calculations. This update depends on the specified source voltage boundary condition. This phase is mainly concerned with calculating voltage drops with possible updates to currents and power flows. The node voltages are then updated in a forward scan, starting from the branches of the first layer and progressing to those of the last layer. It is clear that the voltage at the power plant was adjusted to the actual value, as expected. During forward propagation, the active power in each branch remains unchanged at the value determined during backward propagation.

The forward and backward sweeps are typically part of an iterative load flow analysis process. The process is repeated until the calculated voltages and power flows converge to a stable solution that satisfies the power flow equations and network constraints (Ouali & Cherkaoui, 2020).

2.5 Genetic Algorithm Optimization Technique

Optimization is the process of examining for better values of an objective function. Essentially, it involves regulating the inputs or features of a device, either through mathematical calculations or through experiments, with the aim of finding the minimum or maximum output. In this context, the inputs are represented by variables, and the objective function, cost function, or fitness function represents the process or function itself. The resulting output is indicated by the cost or fitness level. The cost or fitness level represent output results (SINGH, 2015).

Optimization strategies in this context include classical approaches based on established principles, intelligent methods utilizing clever approaches for accurate solutions, metaheuristic search techniques popular for providing high-quality solutions, miscellaneous strategies encompassing diverse approaches, and future intelligent strategies representing promising directions for solving complex problems. There are different metaheuristic algorithm. The fundamental concept behind the evolutionary algorithm that is one of metaheuristic algorithm involves selecting the best performing individuals from the population to serve as parents, encouraging them to reproduce and expand the generation. During this reproduction process, genetic material from both parents combines through crossover, and occasionally, an unintended change known as mutation occurs. Subsequently, the next generations are tasked with reproducing their own offspring, and this iterative process continues. The inspiration for the evolutionary algorithm is drawn from this interplay of crossover and mutation, where crossover is utilized to generate new solutions by combining genetic information from the population, and mutation introduces novel information or maintains diversity within the population. This helps prevent premature convergence and results in a more versatile solution (Jebali et al., 2017).

GA is one of a most widely utilized optimization technique, which utilizes a search-based method that draws its principles from biological evolution, genetics, and natural selection. It is widely employed to find optimal to complex problems within the search space, which would otherwise demand a considerable amount of time to solve. Figure 2.3 shows the flow chart of GA optimization technique.

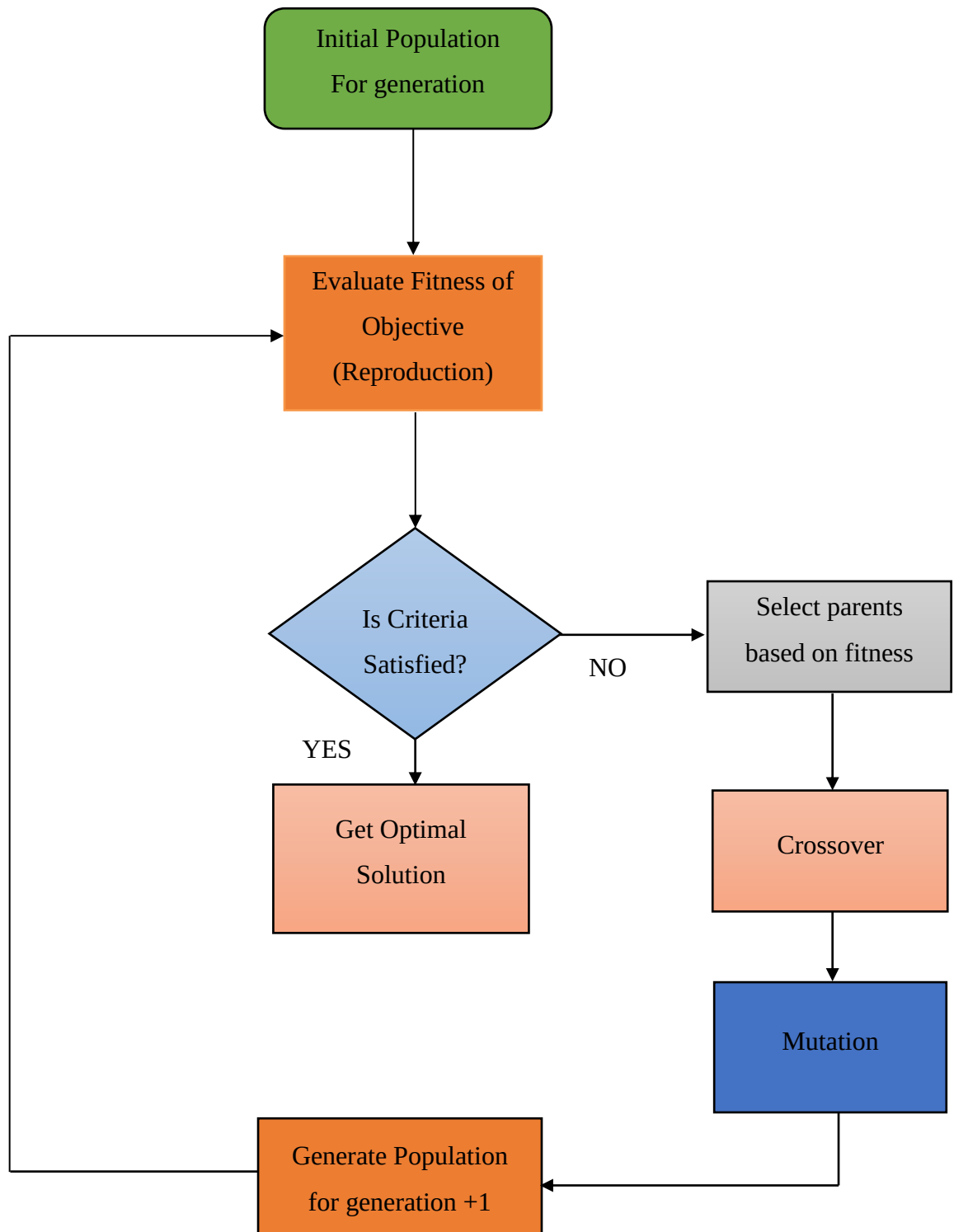


Figure 2. 3: Flow Chart of GA Optimization (Chandrasekar, 2023)

- a) **Population (or Generation):** This refers to a collection of all conceivable solutions or candidate solutions that are used to initiate the search process. GA undergoes multiple iterations across various generations until it identifies an optimized solution.
- b) **Chromosome:** A chromosome represents an individual candidate solution within the population.
- c) **Gene:** A gene is a singular component of the decision variable, encompassing both the value (allele) and the position (locus) within a specific chromosome. The following figure demonstrate population, chromosomes and genes. Figure 2.4 demonstrates Population, Chromosomes and Genes

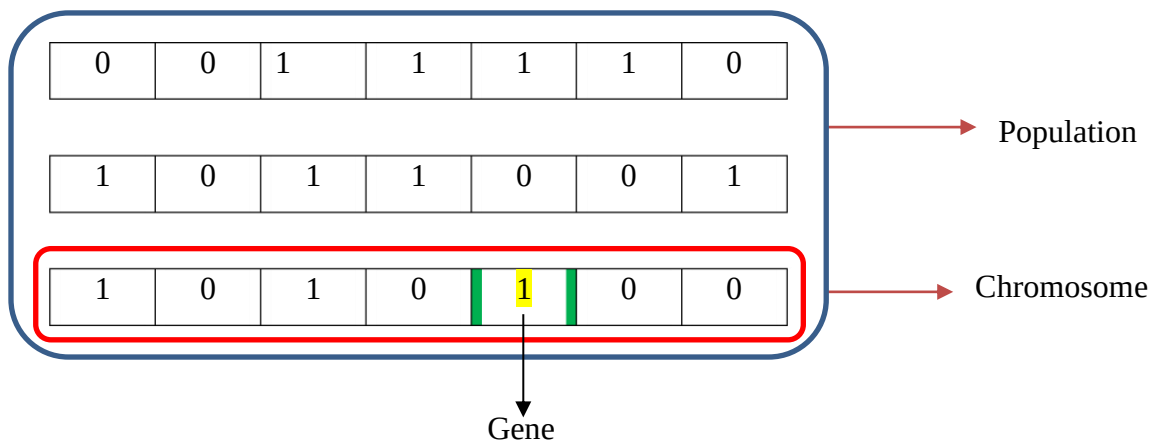


Figure 2. 4: Population, Chromosomes and Genes (Biswas, 2022)

The initial generation is established through random initiation, known as Random Initialization. Typically, the algorithm commences with a population that is randomly generated. The population's size is contingent upon the characteristics of the problem and is directly related to the number of decision variables. This population size remains constant across all subsequent generations. Another alternative for initializing the population involves using a predefined heuristic specifically tailored to the problem, termed Heuristic Initialization. However, this approach is generally discouraged because it can lead to a population consisting of similar solutions with minimal diversity (Khair et al., 2018).

2.5.1 Advantages of Genetic Algorithm

As GA is a powerful optimization technique, it offers several advantages over other optimization methods, particularly in dealing with complex problems. Here are the key benefits of using genetic algorithms:

No Gradient Information Required: GA do not rely on gradient information, making them suitable for optimizing non-differentiable, discontinuous, or multi-modal functions. This is particularly advantageous in complex problem spaces where other methods may struggle due to local minima issues.

Robustness and Versatility: Genetic algorithms can handle a wide variety of problem types and are applicable in numerous fields, including engineering design, machine learning, and bioinformatics. Their flexibility allows them to be adapted for different optimization scenarios, from circuit design to feature selection in machine learning

Parallel Processing Capabilities: The inherent parallelism of genetic algorithms allows them to evaluate multiple solutions simultaneously. This feature can significantly reduce computation time and enhance the efficiency of the optimization process, especially in large-scale problems.

Proven Success in Diverse Applications: GA has been successfully applied in numerous areas, including:

- ❖ Machine Learning: For feature selection and model optimization.
- ❖ Engineering: In circuit design and structural optimization.
- ❖ Environmental Science: To optimize resource consumption and improve sustainability efforts

Continuous Improvement over Generations

GA is designed to produce solutions that improve over successive generations. This iterative process ensures that the solutions converge towards optimal or near-optimal outcomes, enhancing the overall effectiveness of the algorithm.

Generally, due to their versatility, robustness, and ability to handle complex problem spaces without requiring derivative information, genetic algorithms are considered as a powerful optimization tool. Their applications span various fields, making them a valuable asset in both scientific research and practical implementations.

2.6 Review of Related Works

Voltage profiles and power loss have become increasingly prominent issues, driven by the integration of advanced, high-performance devices in automated distribution systems. The strategic placement of DG in these systems is a complex challenge, prompting extensive research in the field of power quality. The following literature reviews offer succinct summaries

of research findings and valuable insights regarding power quality, DG sizing, and optimal placement within distribution networks. Table 2.2 shows review of related works.

Table 2: 1 Review of Related Works

Author(s)	Contribution	Gap
Assefa (2019)	Focuses on reducing power losses and improving voltage profiles through optimal allocation and sizing of DG units using analytical methods and PSO.	Did not mention equality/inequality constraints, lacked a defined objective function, and did not consider comparative analysis of multiple DG units.
Setegn (2022)	Investigates benefits of DG integration using loss sensitivity factor for optimal location and GA for sizing, finding significant power loss reduction.	Used Newton-Raphson load flow analysis inappropriate for distribution networks and no economic analysis performed.
Ajewole et al. (2022)	Proposes GA for optimizing sizing and placement of DG units to enhance system performance and reduce power losses.	Focused only on single DG, did not considered real distribution network data, did not included economic analysis.
Venkatraman et al. (2016)	Presents a strategy to minimize power losses by including DG losses in optimization, achieving lower total system power losses.	Focused on conventional methods without considering broader implications of DG integration beyond line losses.
Holi et al. (2022)	Optimizes placement and size of DG using Forward and Backward sweep method combined with PSO to improve network efficiency.	Tested on standard IEEE 33-bus system; focused on single DG unit; lacks cost analysis.
Vita (2017)	Develops a decision-making algorithm for optimizing DG sizing and allocation to reduce power losses and improve voltage profiles.	Did not use real distribution data, single objective function consideration.

CHAPTER THREE

3. SYSTEM DESCRIPTIONS AND METHODOLOGY

3.1 Introduction

This chapter covers the materials and techniques used, the necessary data to be gathered, and the mathematical modeling for performance evaluation of the current distribution system. There includes discussion of load flow analyses using forward and backward sweeps to examine the distribution system's performance. This chapter also covers the modeling of DG and its integration into the BFS load flow. The formulation of constraints and the objective function of optimization problems are examined. Finally, the use of GA to solve the pre-formulated optimization problem that is, the strategical placement and dimensions of the DG is discussed.

3.2 Materials

Several software tools are essential to the study in this thesis in various ways. Writing algorithms is done with MATLAB/2021a, a computer program and programming language. It makes it possible to create and apply intricate mathematical modellings and data analysis. The thesis material is edited using Microsoft Office 2021, which enables the formatting and organization of study findings. Microsoft Visio is a diagramming application that are used to produce visual representations (single line diagram) of the feeder. The last tool for precisely drafting and formatting mathematical formulas and equations is the Math Type 7.0 equation editor, ensuring precision and consistency in representing mathematical concepts within this study.

3.3 Methods

The method used in this thesis work include literature review of related papers, gathering and analyzing the data required for the study, performing load flow analysis of existing distribution network(the selected feeder), modeling and formulation of optimization problem, performing computer simulation, drawing discussion, and conclusion based on the result obtained and providing recommendation for future enhancement. Figure 3.1 show the thesis methodology block diagram.

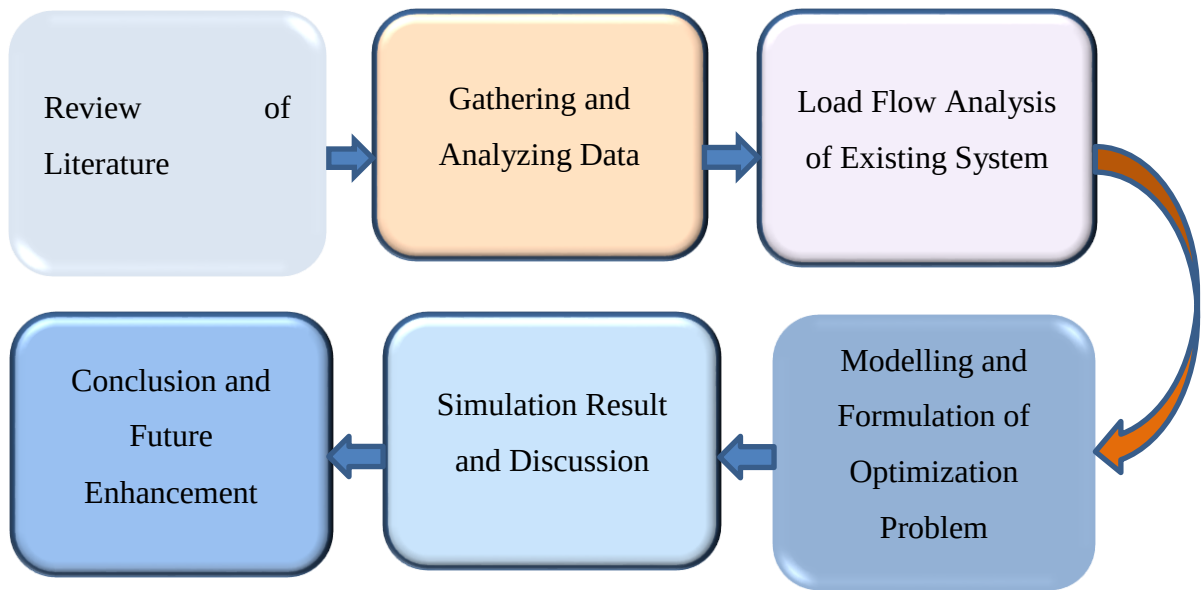


Figure 3. 2: The Thesis Methodology Block Diagram

Detail explanation of the above block diagram is given on table 3.1

Table 3. 1: The Thesis Methodology Block Diagram Explanation

Methods	Descriptions
1. Review of Literature	Relevant literature pertaining to this thesis has been thoroughly examined, encompassing published materials such as books, articles, lectures, journals, and unpublished papers. These sources primarily focus on the distribution network performance, DG, method for optimal allocation and sizing, and metaheuristic optimization algorithms deployed by another researched to improve distribution network performance.
2. Gathering and Analyzing Data	For the purposes of this thesis work, the data was collected at the Gelan Substation, Ethiopian Electric Utility Fair Project office and NASA. Some additional data was collected by interviewing relevant personnel at the substation and using available secondary data.
3. Load Flow Analysis of Existing System	The RDS faces challenges such as a high R/X ratio and convergence issues encountered in Gauss-Seidel and Newton-Raphson methods. However, to address these

	issues, a LFA using backward-forward sweep was done on the selected feeder to evaluate the existing feeder performance.
4. Modelling and Formulation of Optimization Problem	The system formulates the function in relation to the problem through the following methods: ➤ Objective function ➤ Operational constraints ➤ Backward Forward sweep analysis The selected feeder (Gelan 3) from Gelan Substation was modelled with the integration of DG for system analysis.
5. Simulation Result and Discussion	MATLAB 2021a Software was used for carrying out load flow analysis of the load and for placing and sizing of DG optimally in the chosen feeder (Gelan 3). The base case and DG integration were the two scenarios that were run through computer simulation. Ultimately, the evaluation of the feeder performance involved comparing the base case with DG integration.
6. Conclusion and Future Enhancement	Following the completion of the computer simulation, conclusion was made using the data gathered. Additionally, a recommendation was offered for the upcoming researcher.

3.4 Description of Case Study Area

The study is conducted in Gelan Distribution Network, situated in Gelan, an industrial zone in the Oromia region. Gelan is strategically located 25 km southeast from Addis Ababa, making it attractive to both local and international investors due to its proximity to the capital and comfortable environment. The town is located in the Shagar City, Oromia. The town has a Longitude and Latitude of 8° 52' 0" N 37° 46' 59" E with an elevation of 2,394 meters above sea level. Gelan Substation supply electric power to the Gelan city and the nearby areas and it receives power via 400KV power lines from Holota Substation, Sebeta Substation and Wolaita Sodo Substation. The substation is ring connection scheme and it receive 400KV from those substations. 400KV voltage is step down to 230KV by 500MVA autotransformer and 230KV is

step down to 132KV by 125MVA autotransformer. 132KV is stepdown to 33KV and 15KV. In General, 4000KV voltages are stepped down in to 230/132/33/15KV by using auto transformers in Gelan Substation. Gelan Substation consist of nine 15KV outgoing feeders namely Gelan-1, Gelan-2, Gelan-3, Gelan-5, Gelan-6, Gelan-7, Gelan-8, and Gelan-9. At the substation, there is OLTC to regulate power flow, the impact of voltage profile, or power loss in the distribution systems, which cannot respond quickly to changes in load demand, providing a more flexible solution for maintaining voltage levels. The Gelan substation's outgoing feeders are all radial in structure. Additionally, there was no separate feeder for commercial, industrial, and residential clients. The geographical location of the study area is shown in figure 3.2

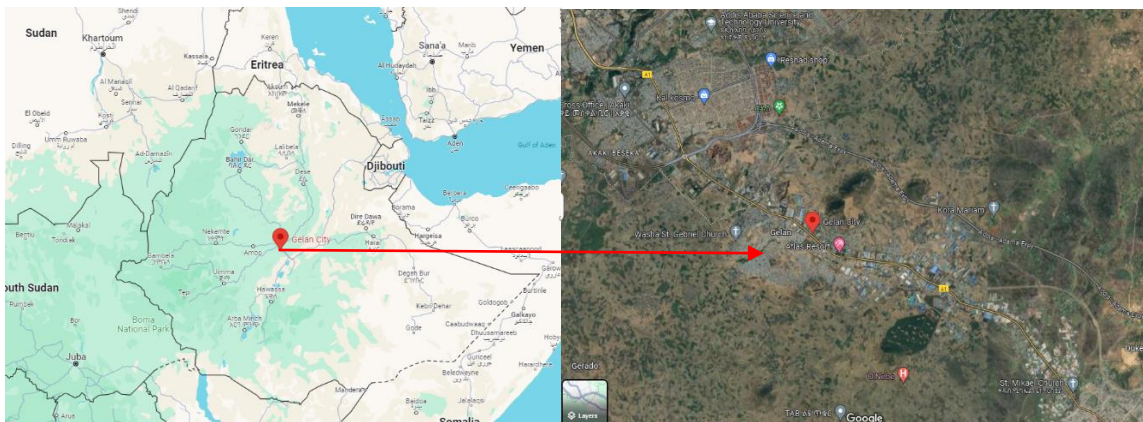


Figure 3. 3: Geographical Location of Case Study Area

3.5 Data Collection and Analysis

3.5.1 Data Collection

Before the data was asked, the letter was written from the Department of Electrical Power and Control Engineering, Adama Science and Technology University, to Ethiopian Electric Utility (FAIR project office) and Ethiopian Electric Power (Central Region 2). Then, using this permission letter, the data was collected to conduct the study. The data related to distribution networks was obtained from Ethiopian Electric Utility (EEU) and Ethiopian Electric Power (EEP), while the data related to metrology was acquired from NASA. The data collection was done through physical observation at the Gelan Substation, previously recorded data of the feeders, feeder roots, and interviewing of the personnel at the substation. The distribution transformer size and rating, distribution line configuration, conductor type, and branch length of the chosen feeder are among the details required for this study that were obtained from the Ethiopian Electric Utility, FAIR project office.

3.5.2 Single line Diagram of the Selected Feeder

This thesis study only addresses the 15 KV voltage level primary distribution system of the Gelan distribution system. Among 15KV outgoing feeders from Gelan Substation, Gelan-3 has longest distance, peak load, higher interruption, and supply electricity to the largest commercial area in Gelan city, which is characterized by a combination of commercial, residential, and industrial loads. Gelan-3 feeder has 108 bus system and 107 branches and it is constructed from the all-aluminum conductor (AAC-50mm²) and (AAC-95 mm²) with a total length of 30.64Km. From the specification the resistance and reactance of AAC-50mm² is 0.68Ω/km and 0.362Ω/km while the resistance and reactance of AAC-95mm² is 0.58Ω/km and 0.341Ω/km respectively. The distribution line is trapezoidal in shape and has three phases and three wires with a wooden pole. Figure 3 3 demonstrate single line diagram of Gelan 3 feeder.

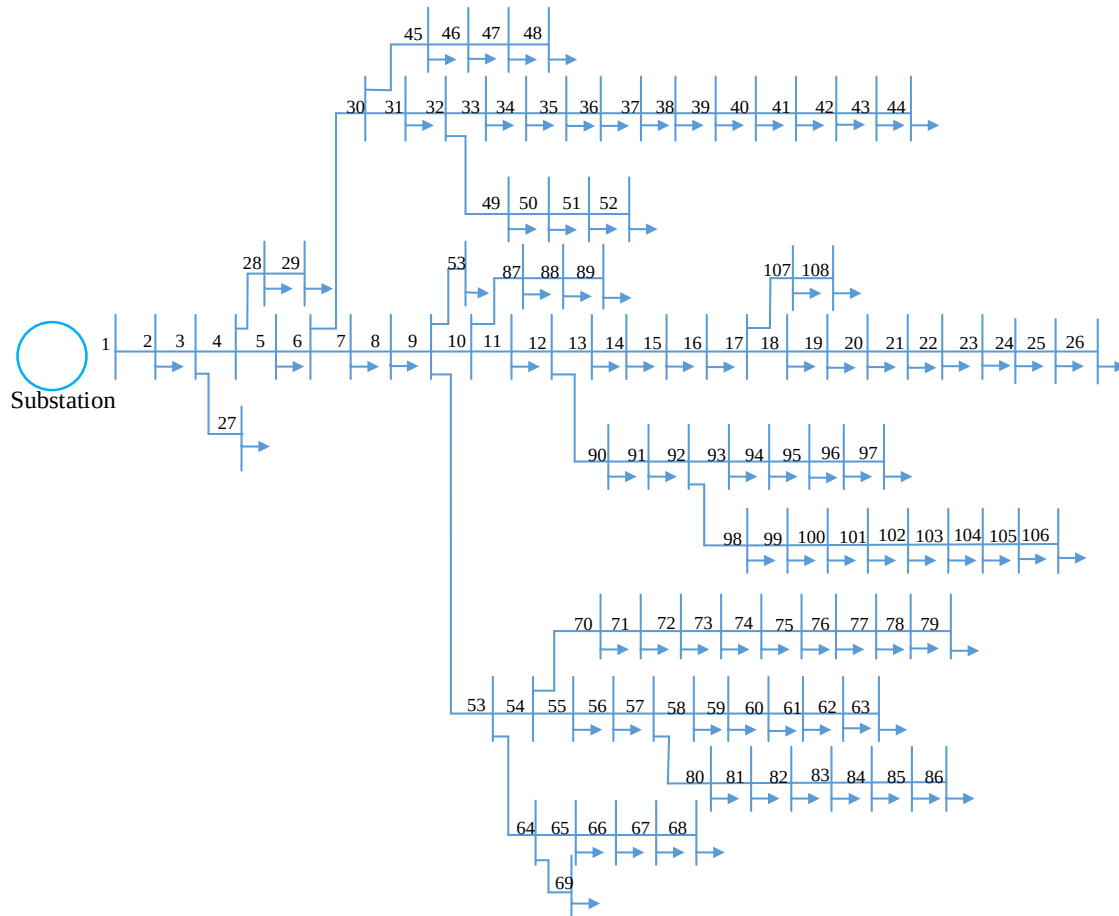


Figure 3. 4: Single Line Diagram of Gelan 3 Feeder

3.5.3 Per Unit Calculation

In the context of load flow analysis and per unit calculations in power systems, the following equations relate the actual values of resistance (R), reactance (X), active power (P), and reactive power (Q) to their per unit (pu) values:

MVA Base (S_{base}): MVA base represents the base apparent power for per unit calculations and is typically chosen based on the rating of a reference component in the system, such as a generator or transformer.

KV Base (KV_{base}): KV base represents the base voltage for per unit calculations and is typically chosen based on the rated voltage of the system.

Z Base (Z_{base}): Z base represents the base impedance for per unit calculations and is derived from the chosen MVA base and kV base.

$$Z_{base} = \frac{KV_{base}^2}{MVA_{base}} \quad (3.1)$$

R_{pu} (Per Unit Resistance):

Per unit resistance (R_{pu}) is the ratio of the actual resistance (R) to the base impedance (Z_{base}).

$$R_{pu} = \frac{R_{actual}}{Z_{base}} \quad (3.2)$$

X_{pu} (Per Unit Reactance):

Per unit reactance (x_{pu}) is the ratio of the actual reactance (X) to the base impedance (Z_{base}).

$$X_{pu} = \frac{X_{actual}}{Z_{base}} \quad (3.3)$$

P_{pu} (Per Unit Active Power):

Per unit active power (P_{pu}) is the ratio of the actual active power (P) to the MVA base (S_{base}).

$$P_{pu} = \frac{P_{actual}}{1000 * MVA_{base}} \quad (3.4)$$

Q_{pu} (Per Unit Reactive Power):

Per unit reactive power (Q_{pu}) is the ratio of the actual reactive power (Q) to the MVA base (S_{base})

$$Q_{pu} = \frac{Q_{actual}}{1000 * MVA_{base}} \quad (3.5)$$

In summary, MVA_{base} , KV_{base} , and Z_{base} are used to establish the reference values for per unit calculations, while R_{pu} , X_{pu} , P_{pu} , and Q_{pu} represent the normalized per unit values of resistance, reactance, active power, and reactive power, respectively, with respect to these base values.

3.6 Distributed Generation Technology Selection

A particular DG technology selection for a given location relies on the following factors including the presence of resources, cost of technology, and adaptability to the local environment. Various regions possess distinct sets of resources, encompassing both renewable and non-renewable options. For example, the availability of solar energy fluctuates across different locations. Hence, these should be taken into an account. Moreover, DG technologies exhibit divergent effects on the environment, encompassing both advantageous and disadvantageous impacts on the surrounding ecosystem.

As outlined in the second chapter, various technologies and resources are available for DG. Within this array of options, the selection of a specific DG technology for a specific area is contingent upon the availability of resources, compatibility with the local environment, and the cost associated with the technology. Among the range of DG technologies presented, solar energy has been selected for this study due to the above-mentioned factors on the case study area.

3.7 Load flow Analysis using Backward - Forward Sweep for Radial Feeder

Even though there are various types of LFA, this study used the BFS load flow analysis since it has a low X/R ratio and suits and efficient in distribution networks. Load flow in the FBS uses both load data and line data for distribution network analysis. This load flow analysis is used for calculating power loss and voltage drop. Because the distribution system is short in length, the influence of line charging capacitance is neglected in this study. For each node, the active and reactive power are set to $0.9 * kVA$ and $0.435 * kVA$ of the transformer's rating, respectively. Figure 3.4 show the diagram of Forward/Backward-Sweep Method.

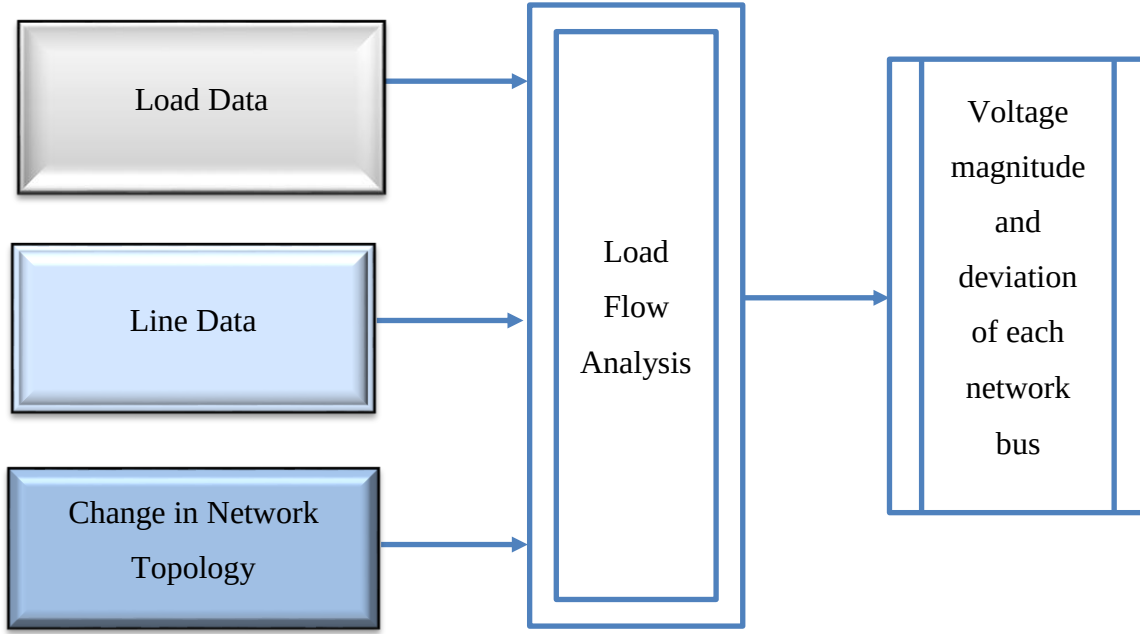


Figure 3. 4: Diagram of Backward/ Forward Sweep Method (Ouali & Cherkaoui, 2020)

Considering distribution line connecting buses i and j , with a series resistance R_{ij} and series reactance X_{ij} . At the j^{th} bus, there are active and reactive loads denoted as P_{Lj} and Q_{Lj} respectively. Assuming that the network is balanced radial distribution network and capacitance line charging effect is negligible, which can be depicted by single line diagram. Figure 3.5 depicts the Equivalent branch of an electrical distribution network.

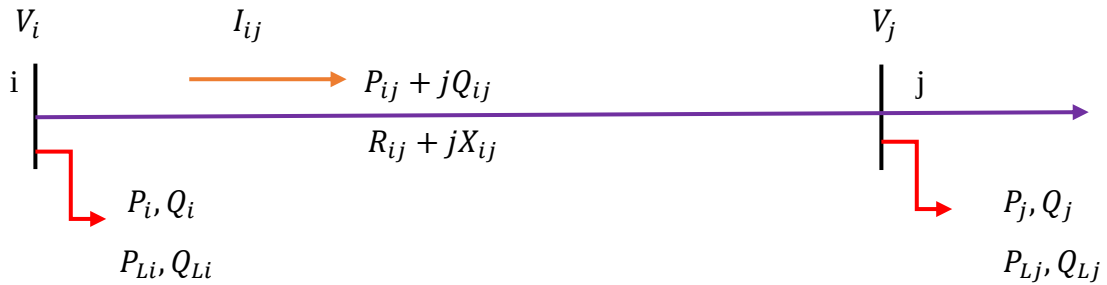


Figure 3. 5: Equivalent branch of an Electrical Distribution Network (Riaño et al., 2021)

The formula for calculating P_i and Q_i flowing through branch 'm' from node 'i' to node 'j' can be derived as follows:

$$P_i = P_j + P_{Lj} + \frac{V_i^2 - V_j^2}{r} \quad (3.6)$$

$$Q_i = Q_j + Q_{Lj} + \frac{V_i^2 - V_j^2}{x} \quad (3.7)$$

Where P_i is effective active power and Q_i is effective reactive power.

P_{Lj} and Q_{Lj} represent the loads connected at node 'j', and P_j and Q_j are the effective real and reactive power flows at node 'j'. The voltage magnitude at node 'i' is denoted by V_i , and at node 'j' by V_j . The impedance of branch 'm' is represented by $Z_m = r_m + jx_m$.

Perhaps the voltage at node i denoted by $V_i \angle \delta_i$ and the voltage at node j denoted by $V_j \angle \delta_j$. Then the current flowing through branch 'm' between node 'i' and j is given by:

$$I_m = \frac{(V_i \angle \delta_i - V_j \angle \delta_j)}{Z_m} \quad (3.8)$$

And it is clear that the current through branch 'm' can be given by

$$I_m = \frac{(P_i - j Q_i)}{V_i \angle - \delta_i} \quad (3.9)$$

By equating these equations

$$\begin{aligned} \frac{(V_i \angle \delta_i - V_j \angle \delta_j)}{Z_m} &= \frac{(P_i - j Q_i)}{V_i \angle - \delta_i} \\ (r_m + jx_m) * (P_i - j Q_i) &= (V_i \angle \delta_i - V_j \angle \delta_j) * V_i \angle - \delta_i \\ r_m P_i + jx_m P_i - jQ_i r_m + x_m Q_i &= V_i^2 = V_i V_j \angle (\delta_j - \delta_i) \\ V_i^2 - P_i r_m + Q_i x_m - V_i V_j \cos(\delta_j - \delta_m) &+ j(P_i x_m + Q_i r_m) + j V_i V_j \sin(\delta_j - \delta_i) = 0 \end{aligned}$$

After equating imaginary and real parts on both side,

$$\begin{aligned} V_i^2 - P_i r_m + Q_i x_m - V_i V_j \cos(\delta_j - \delta_m) &= 0 \\ j(P_i x_m + Q_i r_m) + j V_i V_j \sin(\delta_j - \delta_i) &= 0 \end{aligned}$$

Squaring and adding both equation results

$$(V_i V_j)^2 - [V_i^2 - (P_i r_m + Q_i x_m)]^2 - (Q_i r_m - P_i x_m)^2 = 0$$

And from trigonometric formula, $\cos(\delta_k)^2 + \sin(\delta_k)^2 = 1$. Where $\delta_k = \delta_j - \delta_m$

$$(V_i V_j)^2 - V_i^4 + 2V_i^2(P_i r_m + Q_i x_m) - [P_i^2 + Q_i^2] * [r_m^2 + x_m^2] = 0$$

Solving for V_j

$$V_j^2 = \frac{V_i^4 - 2V_i^2(P_i r_m + Q_i x_m) + [P_i^2 + Q_i^2] * [r_m^2 + x_m^2]}{V_i^2}$$

$$V_j^2 = V_i^2 - 2(P_i r_m + Q_i x_m) + [r_m^2 + x_m^2] \frac{[P_i^2 + Q_i^2]}{V_i^2}$$

$$\delta_j = (\delta_i) + \tan^{-1} \frac{[Q_i x_m - P_i r_m]}{[V_i^2 - (r_m + Q_i x_m)]}$$

$$P_{loss}(m) = r_m \frac{[Q_i^2 + P_i^2]}{V_i^2} \quad (3.10)$$

$$Q_{loss}(m) = x_m \frac{[Q_i^2 + P_i^2]}{V_i^2} \quad (3.11)$$

where $Q_{loss}(m)$ are the reactive power loss through the branch 'm' and $P_{loss}(m)$ is the active power loss through the branch 'm'. For the radial distribution system, the total active power loss of branch 'm' $PL_{total}(m)$ and the total reactive power loss of branch 'm' is calculated as follows.

$$PL_{total}(m) = \sum_{m=1}^f r_m \frac{[Q_i^2 + P_i^2]}{V_i^2} \quad (3.12)$$

$$QL_{total}(m) = \sum_{m=1}^f x_m \frac{[Q_i^2 + P_i^2]}{V_i^2} \quad (3.13)$$

Where f is number of branch

3.7.1 BIBC Matrix Formation

The backward sweep method also termed as the BIBC (Branch Incidence and Branch Current) matrix is basically a technique that assists in forming part of the power system analysis, especially to do with load flow studies and fault analyses. It is mostly used to calculate the branch currents and the voltages for each part of the network in RDS. This method is based on the advance over the branches of the network with the loads in the direction of the source node, normally considered to be the substation. This approach allows for the determination of branch currents and voltages without the need for iterative calculations. It is a formal mathematical form of representation of the relation between the branch currents and voltages in a RDS. It is a very sparse matrix, taking into account the network connectivity and electrical characteristics of the branches. Simple 6 bus RDS is shown on Figure 3.6.

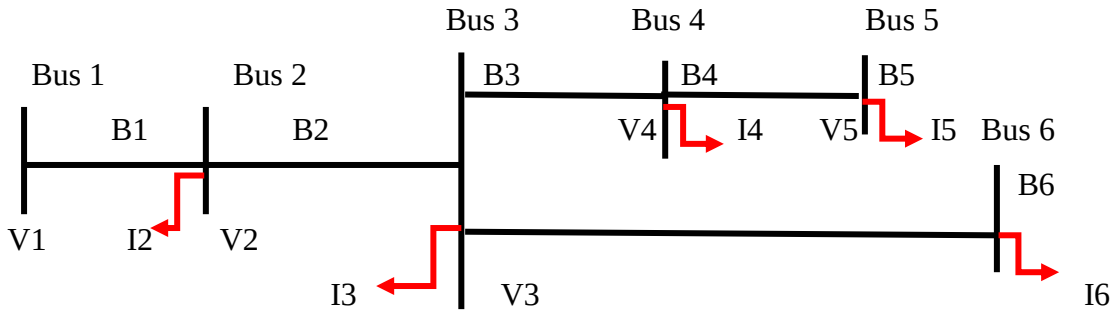


Figure 3. 5: Simple 6 bus RDS

The first step for the backward sweep method is the initialization of the branch currents and voltages at the load nodes. Starting at the load nodes, the branch currents are calculated by application of Kirchhoff's current law (KCL) on the branches of each node. Currents entering a node, in this case, are equal to the sum of currents leaving a node through its branches. For a bus i , the complex load $S_i = P_l(i) + jQ(i)$. From the specified complex power at each node, the equivalent current injection can be derived as;

$$I_l(i) = \frac{P_l(i) + jQ(i)}{V(i)} \quad (3.14)$$

Where $I_l(i)$ is the equivalent current injection at bus i , $V(i)$ is the voltage at bus, $P_l(i)$ is the active and $Q(i)$ is reactive power at bus i . When all the branch currents are established, the branch voltages can be calculated using Ohm's law ($V = I * Z$), where V is voltage, I is current, and Z is the impedance of the branch. Next, branch currents and branch voltages of the BIBC are both put in a matrix where each row signifies a branch, and each column signifies a node in the network. After the computation of branch currents and voltages for the load nodes, the process goes backward up to the source node by taking up the iterative process of calculating current and voltage for every upstream branch until the substation is reached

A) BIBC Matrix Formation

The above represents 6 buses and 5 branches. Applying Kirchhoff's Current Law (KCL) to the above the network, the following an algorithm is developed to compute the nodes feed by a particular branch. It is evidently that,

$$\begin{aligned} B_1 &= I_2 + I_3 + I_4 + I_5 + I_6 \\ B_2 &= I_3 + I_4 + I_5 + I_6 \\ B_3 &= I_4 + I_5 \\ B_4 &= I_5 \\ B_5 &= I_6 \end{aligned} \quad (3.15)$$

Furthermore, the Bus Injection to Branch-Current (BIBC) matrix can be obtained as,

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} \quad (3.16)$$

The above equation can be expressed as

$$B = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} \quad (3.17)$$

In addition, the total current flowing through the bus can be given by

$$I = \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} \quad (3.18)$$

$$\text{BIBC} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.19)$$

Therefore,

$$B = \text{BIBC} * I \quad (3.20)$$

B) BCBV Matrix Formation

It is a data structure to be used in the backward-forward sweep algorithm, one of the most widely used numerical methods to solve the load flow equations in the analysis of power systems. In general, the BCBV matrix represents the branch parameters (resistance, reactance, and admittance), the nodal voltages, and other relative data for each branch that forms the network of the power system. In this manner, the BCBV matrix is successively updated during the backward-forward sweep algorithm in order to carry out the computation of the voltage magnitudes and angles at every bus until convergence is achieved.

By applying Kirchhoff's Voltage Law (KVL) to the above figure, the relationship between branch current and bus voltage can be obtained as;

$$\begin{aligned} V_2 &= V_1 - Z_{12} * B_1 \\ V_3 &= V_2 - Z_{23} * B_2 \\ V_4 &= V_3 - Z_{34} * B_3 \\ V_5 &= V_4 - Z_{45} * B_4 \\ V_6 &= V_3 - Z_{36} * B_5 \end{aligned} \quad (3.21)$$

So the voltage at each bus can be obtained as the function of substation voltage (V_1) as follows;

$$V_2 = V_1 - Z_{12} * B_1$$

$$\begin{aligned}
V_3 &= V_1 - Z_{12} * B_1 - Z_{23} * B_2 \\
V_4 &= V_1 - Z_{12} * B_1 - Z_{23} * B_2 - Z_{34} * B_3 \\
V_5 &= V_1 - Z_{12} * B_1 - Z_{23} * B_2 - Z_{34} * B_3 - Z_{45} * B_4 \\
V_6 &= V_1 - Z_{12} * B_1 - Z_{23} * B_2 - Z_{36} * B_5
\end{aligned} \tag{3.22}$$

Where V_i is the bus voltage of bus i, and Z_{ij} the line impedance between bus i and bus j.

So the bus voltage can be updated as

$$\begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} - \begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{36} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} \tag{3.23}$$

The above expression can be expressed as

$$[\Delta V] = [BCBV][BIBC][I] \tag{3.24}$$

Where

$$\begin{aligned}
[\Delta V] &= \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} - \begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} \\
[BIBC] &= \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \\
[BCBV] &= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ 0 & Z_{23} & 0 & 0 & 0 \\ 0 & 0 & Z_{34} & 0 & 0 \\ 0 & 0 & 0 & Z_{45} & 0 \\ 0 & 0 & 0 & 0 & Z_{36} \end{bmatrix} \tag{3.25}
\end{aligned}$$

$$[BCBV] = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{36} \end{bmatrix} \tag{3.26}$$

The above equation can be rewritten as, Assuming that the bus voltage at $(n + 1)^{th}$ iteration,

$$V_1 - [V^{n+1}] = [BCBV][B]$$

$$[\Delta V] = [DLF][I] \tag{3.27}$$

Where $[DLF] = [BCBV][BIBC]$

3.7.2 Overall Procedure for Backward - Forward Sweep Load flow Analysis

1. Information about the power system such as physical parameters, loads, network topology, characteristics of the generator, load data, and physical parameters like resistance (R) and reactance (X) of the branches is taken.
2. Compute the [BCBV] and [BIBC] matrices. The [BCBV] matrix is the product of the susceptance of the branch (B) and the magnitude of the voltage of the bus (V). The [BIBC] matrix is the product of the susceptance of the branch (B) and the magnitude of the current in the branch (I). Compute these matrices as per the configuration of the system.
3. Assume voltage at each bus $i+j0$. Initially, every bus voltage has to be assumed a complex number having purely real part (i.e., imaginary part is zero). This assumption provides us the initial starting point of load flow calculations.
4. Compute $I_i^n = [\frac{P_i^n + jQ_i^n}{V_i^n}]^*$ where the nodes and iteration numbers are denoted by 'i' and 'n' respectively. In the next step, the complex current injections (I_i^n) at each bus due to the complex power injections (P and Q) and the voltage magnitude at each bus (V) are computed. The superscript 'n' denotes the iteration number, and the asterisk (*) represents the complex conjugate.
5. Compute $[\Delta V] = [BCBV] [BIBC][I]$. Here, the voltage correction ($[\Delta V]$) is going to be computed by the multiplication of the [BCBV] matrix, the [BIBC] matrix, and the complex current injections [I]. Compute the real and reactive power on branches.
 $P_{loss_m}(n) = B_m^2 R_m$ and $Q_{loss_m}(n) = B_m^2 X_m$ where B_m is m^{th} branch current.
6. Check if error = $[\Delta V(n) - \Delta V(n-1)]$ is less than convergence criterion. If not go back to number 4 and repeat the whole procedure. Check for the voltage difference between voltage correction at the current iteration ($\Delta V(n)$) and voltage correction at the previous iteration ($\Delta V(n-1)$). If the error is less than a preset convergence criterion, then the analysis is said to be converged. Otherwise, the procedure continues from step 4.
7. Total system losses computation and printing of the node voltages. Once the load flow analysis converges, then the total system losses can be computed as the sum of the branch losses. In addition, the final node voltages resulting from the load flow analysis can be printed.

3.7.3 Flowchart of Backward - Forward Sweep Load Flow Analysis

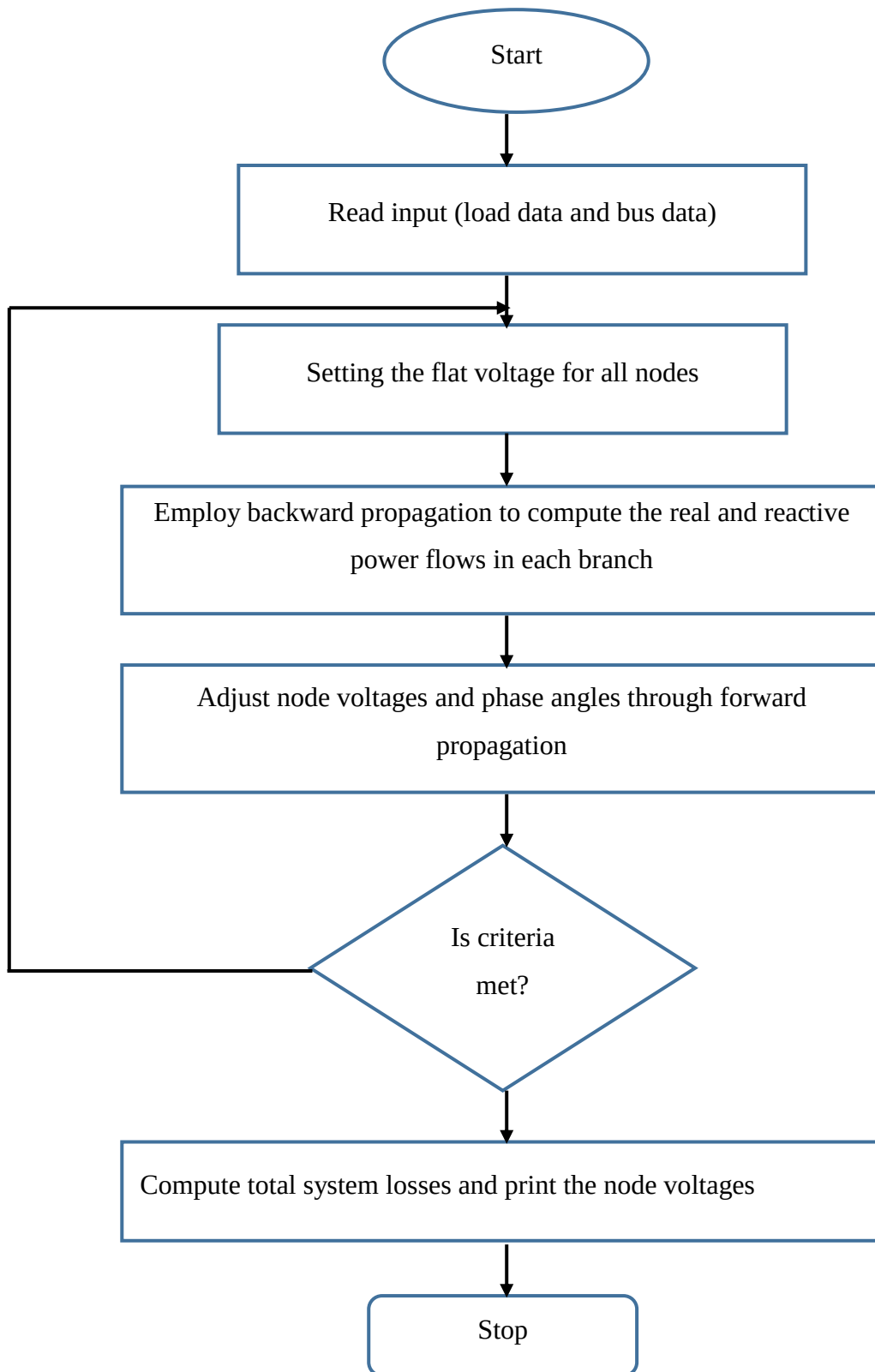


Figure 3. 6: Flowchart of Backward - Forward Sweep Load Flow Analysis

3.8 Modelling of Distributed Generation

DG is treated as either a constant active power and voltage (PV) or constant active and reactive power (PQ) model in distribution system power flow analysis. The PQ model is especially helpful when the DG unit has to supply or absorb reactive power to control the voltage in the network while maintaining a certain active power output. The DG units must balance the load requirements, power loss, and voltage drop in distribution systems with a high penetration of renewable energy sources (Rehman et al., 2024). The study characterized the DG unit as a negative load, or as a PQ model that injects or consumes reactive power into the system while keeping the output of active power constant.

$$P_{load'i'} = P_{Load'i'}^* + P_{DG'i'} \quad (3.28)$$

$$Q_{load'i'} = Q_{Load'i'}^* + Q_{DG'i'} \quad (3.29)$$

Where $P_{load'i'}$ the existing feeder load power at i^{th} node, $Q_{DG'i'}$ and $P_{DG'i'}$ is the reactive and active power of Distribution Generator at i^{th} node, and $P_{Load'i'}^*$ the active power after implementation of DG devices. Inverter PV based DG is used in this study, $Q_{DG'i'}$ is zero.

The total reactive power to preserve the voltage at a definite value when modeled as PQ can be stated by using:

$$Q_a = Q_n + Q_m \quad (3.30)$$

Where the generated reactive power is denoted by Q_n , reference reactive power is denoted by Q_a and reactive power of the load is represented by Q_m .

3.9 Load Flow Analysis after Integration of DG

Since inverter-based Photovoltaic technology is assumed to be capable of providing active power and either delivering or absorbing reactive power. The relationship between the active and reactive power (P_{DG^i} and Q_{DG^i}) of the PV system at the integrated bus i can be expressed in the following manner:

$$Q_{DG^i} = \alpha_i P_{DG^i} \quad (3.31)$$

Where α_i is $\pm \tan(\cos^{-1}(DG_{pf}))$ where as DG_{pf} is the DG (PV in this case) operating power factor at bus i . It can be noted that the value of α_i is negative when absorbing reactive power and positive when delivering reactive power. Due to injection of reactive and active power of DG at bus i during DG integration, the value of active and reactive power flow from the source

are decreased, whereas the others sections are unaffected. For this reason, the equation for reactive and active power loss given by equations (3.12) and (3.13) can be rewritten as follows.

$$P_{DG(loss)} = \sum_{m=1}^f x_m \frac{[Q_i]^2}{|V_i|^2} + \sum_{i=1}^f x_m \frac{[Q_i - Q_{DG^i}]^2}{|V_i|^2} + \sum_{i=1}^f r_m \frac{[P_i]^2}{|V_i|^2} + \sum_{i=1}^f r_m \frac{[P_i - P_{DG^i}]^2}{|V_i|^2}$$

Extending $\sum_{i=1}^f r_m \frac{[P_i - P_{DG^i}]^2}{|V_i|^2}$ results $\sum_{i=1}^f r_m \frac{P_i^2 - 2P_i * P_{DG^i} - P_{DG^i}^2}{|V_i|^2}$

Extending $\sum_{i=1}^f x_m \frac{[Q_i - Q_{DG^i}]^2}{|V_i|^2}$ results $\sum_{i=1}^f x_m \frac{Q_i^2 - 2Q_i * Q_{DG^i} - Q_{DG^i}^2}{|V_i|^2}$

$$\text{Since } Q_{DG^i} = \alpha_i P_{DG^i}$$

$$\sum_{i=1}^f x_m \frac{[Q_i - Q_{DG^i}]^2}{|V_i|^2} = \sum_{i=1}^f x_m \frac{[Q_i - \alpha_i P_{DG^i}]^2}{|V_i|^2}$$

$$P_{DG(loss)} = \sum_{m=1}^f x_m \frac{[Q_i]^2}{|V_i|^2} + \sum_{i=1}^f x_m \frac{Q_i^2 - 2Q_i * \alpha_i P_{DG^i} - \alpha_i^2 P_{DG^i}^2}{|V_i|^2} + \sum_{i=1}^f r_m \frac{[P_i]^2}{|V_i|^2} + \sum_{i=1}^f r_m \frac{P_i^2 - 2P_i * P_{DG^i} - P_{DG^i}^2}{|V_i|^2}$$

$$Pl_{DG} = \sum_{i=1}^f r_m \frac{P_{DG^i}^2 - 2P_i * P_{DG^i}}{|V_i|^2} + \sum_{i=1}^f r_m \frac{\alpha_i^2 P_{DG^i}^2 - 2Q_i * \alpha_i P_{DG^i}}{|V_i|^2} + \sum_{m=1}^f r_m \frac{[Q_i^2 + P_i^2]}{V_i^2}$$

$$Ql_{DG} = \sum_{i=1}^f x_m \frac{P_{DG^i}^2 - 2P_i * P_{DG^i}}{|V_i|^2} + \sum_{i=1}^f r_m \frac{\alpha_i^2 P_{DG^i}^2 - 2Q_i * \alpha_i P_{DG^i}}{|V_i|^2} + \sum_{m=1}^f x_m \frac{[Q_i^2 + P_i^2]}{V_i^2}$$

The PV system in this study only produces active power due to its unity power factor, resulting α_i equal to zero. This means the DG only generates active power and no reactive power. In this case, the equations simplify to:

$$Pl_{DG} = \sum_{i=1}^f r_m \frac{P_{DG^i}^2 - 2P_i * P_{DG^i}}{|V_i|^2} + \sum_{m=1}^f r_m \frac{[Q_i^2 + P_i^2]}{V_i^2} \quad (3.32)$$

$$Ql_{DG} = \sum_{i=1}^f x_m \frac{P_{DG^i}^2 - 2P_i * P_{DG^i}}{|V_i|^2} + \sum_{m=1}^f x_m \frac{[Q_i^2 + P_i^2]}{V_i^2} \quad (3.33)$$

3.10 Problem Formulation for Optimal Allocation and Sizing of DG

A) Objective Function

In a multi-criteria optimization modeling of RDS with DG implementation, an objective function remains one of the important quantities. The three major objective functions under this study are as follows:

a) Minimization of Active Power Loss

Active power losses occur due to the resistance in the conductors, transformers, and other components of the distribution system. These losses can lead to heating, accelerated aging of insulated lines, reduced insulation, and increased risk of line leakage. Minimizing these losses improves the energy efficiency of electrical equipment and processes, thereby enhancing the overall system efficiency and reducing the cost of electricity distribution. The objective function for active power loss minimization can be given as:

$$\text{Min } P_l = \sum_{i=1}^N I_{Bi}^2 * R_i \quad (3.34)$$

Where P_l is the total active power, N is total number node on Distribution Network, I_{Bi} is the load current flowing through node i and R_i is the resistance of the branch associated with node i.

b) Minimization of Reactive Power Loss

Reactive power losses are due to the reactance in the conductors, transformers, and other components of the distribution system. These losses contribute to heating, accelerated aging of insulated lines, reduced insulation, and increased risk of line leakage. Reducing reactive power losses improves the energy efficiency of electrical equipment and processes, thus enhancing the overall system efficiency and lowering the cost of electricity distribution. The objective function for reactive power loss minimization can be given as:

$$\text{Min } Q_l = \sum_{i=1}^N I_{Bi}^2 * X_i \quad (3.35)$$

Where Q_l is the total active power, N is total number node on distribution network, I_{Bi} is the load current flowing through node i and X_i is the resistance of the branch associated with node i.

$$\text{Percentage of active Power Reduction} = \frac{(P_E - P_{DG})}{P_E} \quad (3.36)$$

$$\text{Percentage of reactive Power Reduction} = \frac{(Q_E - Q_{DG})}{Q_E} \quad (3.37)$$

Where P_E is baseline active power, P_{DG} is active power after DG integration, Q_E is baseline reactive power, and Q_{DG} is reactive power after DG integration.

c) Minimization of Voltage Drop

The voltage stability of the system deteriorate gradually as load increases, results system in risky. So the voltage deviation should be one of the factor to evaluate power quality and operational efficiency of the system. The objective function for voltage deviation can be expressed as:

$$\text{Min } V_d = \sum_{k=0}^N (1 - V_k)^2 \quad (3.38)$$

Where V_k is voltage real value of k^{th} node of distribution network when Distribution network is integrated. It is assumed that rated value of the voltage is 1 p.u.

So the Multiple Objective Function (MOF) is given by,

$$\text{MOF} = \text{Min}(k_1 * P_l + k_2 * Q_l + k_3 * V_d) \quad (3.39)$$

Where k_1 , k_2 , and k_3 the appropriate weighting factor selection values, and their sum are equals unity.

B) Constraints

The integration of DG on distribution network has a great impact on power flow, quality of power, branch current and voltage distribution. So to design model of the system both equality and inequality constraints.

a) Equality Constraints

The following equation depicts power flow equation constraints

$$P_{DG_i} - P_{Li} = V_i \sum_{m=i}^N V_m (G_{im} \cos \theta_{im} + B_{im} \sin \theta_{im}) \quad (3.40)$$

$$Q_{DG_i} - Q_{Li} = V_i \sum_{m=i}^N V_m (G_{im} \sin \theta_{im} + B_{im} \cos \theta_{im}) \quad (3.41)$$

Where P_{DG_i} is active power of DGs injected at i^{th} node, Q_{DG_i} is reactive power of DGs injected at i^{th} node, P_{Li} is i^{th} node load active power output, Q_{Li} is i^{th} node load reactive power output, V_m is the amplitude of voltage of all k^{th} nodes connected to i^{th} nodes, G_{im} is Conductance of

branch, B_{im} is susceptance of the branch, θ_{im} is voltage angle difference between i^{th} node and m^{th} node, N is number of branch existed with the i^{th} node.

b) Inequality constraints

The inequality constraints in the DG modeling are such conditions or restrictions to be fulfilled within the optimization model. Similarly, nothing but the upper and lower limits on variables or parameters that constitute the DG system so as to assure that the solution lies within feasible boundaries. In this regard, some of the general categories of inequality constraints from the DG modeling perspective include:

Node Voltage Limitations

These are the limits within which the voltage levels at different sections within the distribution system are contained. They maintain the quality and steadiness of voltage within permissible ranges. It is defined to ensure the all node voltages within the network are kept within some specified upper and lower limits.

$$V_i^{max} \geq V_i \geq V_i^{min} \quad (3.42)$$

Where V_i^{min} is the lower limit voltage amplitude of i^{th} node, V_i^{max} is the upper limit voltage amplitude of i^{th} node, and V_i is Amplitude of voltage of i^{th} node.

Branch Current Limitations

Branch current is the magnitude of the electric current that passes through a certain identified branch in an electric circuit, which has to be kept within the suggested bounds or limits. These limits are established either by the maximum permissible current rating to the branch considering the impedance or by considering other electrical parameters. The aforesaid is too significant in order to secure the overall operation of an electrical system with integrity and safety, elimination of overload conditions, and preservation of respective component longevity.

$$I_{ij}^{max} \geq I_{ij} \quad (3.43)$$

Where I_{ij}^{max} is the maximum current allowed by the branch (i, j) and I_{ij} is the current flowing through the branch (i, j).

Limitation on Penetration Level of DG

The penetration level of DG is a measure of the proportion of total load that is supplied by DG units. The limitation on the penetration level of DG is essential to ensure the stability and reliability of the distribution network. The maximum allowable penetration level is dependent on several factors, including the voltage control, the DG location and size, and the maximum

loading of the distribution network. Static stability of a distribution system is only improved when the DG penetration level is below 50% (Ajewole et al., 2022).

$$\sum \frac{P_{DG}^{i+1}}{P_L} \leq \eta \quad (3.44)$$

Where as P_{DG}^{i+1} is the sum of the DG active power at i+1 bus, η is threshold value, and the total active power of the load.

DG Penetration Location.

The location of DG penetration play a vital role in distribution system. It should be not located on slack bus.

$$N_B \geq DG_L > S_B \quad (3.45)$$

Where N_B is number of bus, DG_L is DG penetration location, and S_B is Swing bus

3.11 Optimal Sizing and Placement of DG Using Genetic Algorithm

GA is a search-based optimization technique that draws its principles from biological evolution, genetics, and natural selection. It is widely employed to find optimal or near optimal solutions to complex problems within the search space, which would otherwise demand a considerable amount of time to solve. The three operators commonly used in a simple GA are:

Selection: Which members of the existing population will be selected as parents for the following generation is decided by the selection operator. Each candidate is usually chosen based on their level of fitness, with the likelihood of selection being higher for those with better fitness scores. There are several selection techniques that can be applied, including rank-based, roulette wheel, and tournament selection.

Crossover: In order to produce offspring for the following generation, the crossover operator combines the genetic material of two chosen parents. It imitates the way DNA recombination occurs naturally. Crossover is the process of producing new individuals by exchanging or combining specific locations or portions of the parents' genetic material, which is typically represented as chromosomes or strings of values. Depending on the issue domain, several crossover sites and genetic material combinations may be used.

Mutation: The genetic material of specific individuals undergoes random modifications or alterations due to the mutation operator. It delays the population's early convergence to less-than-ideal solutions and contributes to the preservation of genetic diversity. A mutation usually entails a random alteration of a chromosome, such as flipping or altering bits, values, or

components. The likelihood of a mutation happening is determined by its mutation rate, which is often kept low to prevent undue disturbance of the genetic composition of the population.

An essential factor in determining an individual's or solution's quality within the population is the fitness function. Each person is given a fitness score, which is a numerical number determined by how successfully they answer the given task, by the fitness function. An individual's solution gets better the higher their fitness score.

3.11.1 Genetic Algorithm Implementation Procedure for Optimal DG Placement and Sizing

The primary aim of optimization is to determine the appropriate size and location of a set of DG to be integrated into the distribution system. This optimization process, employing GA, aims to establish an economical and reliable network with enhanced technical characteristics. These include reduced power losses, improved node voltage profiles, and better ratios of branch current/thermal limits, all while maximizing the DG power injection to alleviate excessive demands on the distribution network for active and reactive power. The GA operates through iterations, commencing with an initial population generated randomly. Encoding strategies for the initial population vary according to the specific optimization problem at hand. Fitness values and objective functions are calculated for each chromosome in the population. Based on the evaluated fitness, a subset of chromosomes is selected for the mating pool using selection operators. These operators ensure that the chromosomes in the mating pool possess superior average fitness compared to the initial population, while maintaining the same population size. Crossover and mutation operators are then applied to the selected chromosomes, generating new offspring. This iterative process continues, often yielding improved solutions as the iterations progress, ultimately leading to the attainment of an optimal solution.

The detail discussion of Basic GA for DG placement is described as follows:

A) Coding Scheme

It defines how the genetic information of an individual is encoded into a data structure that can be manipulated by the genetic operations like crossover and mutation. The two basic coding scheme in GA are binary and real number coding scheme. For this study binary coding scheme is selected due to its Discrete Decision, reduced search space and computational efficiency. The radial distribution system in this study has only one potential node while the other are load loads.

DG can be incorporated to the other node except potential node. So the placement of DG can be randomly selected from load nodes using binary encoding of chromosome.

B) Initialization

Initialization refers to the process of creating an initial population of candidate solutions (individuals) to kick-start the evolutionary optimization process. The initial population is randomly generated which contain the optimization variable (location, Sizing, number of DG). The population size, generation size, crossover probability, and mutation probability are critical parameters in GA that directly influence their efficiency and performance.

Encoding of Chromosome for DG Allocation:

1. Number of DG
2. Corresponding DG rating
3. Number of node to which DG is to be connected

Table 3.2: Encoding of Chromosome for DG Allocation

N_{DG}	k_1	k_1	k_3		k_4	K_1	K_2	K_3		K_4
Number of DG	← DG Ratings →					← DG size →				

C) Fitness Function

The generated population of required size of the corresponding load flow solution is to evaluate the objective function for every chromosome. The process of determining the load flow solution, evaluating the objective function and fitness function is iteratively performed for every individual in the population. In this study, the objective function comprises multiple objectives, namely active power loss minimization, reactive power loss minimization, and voltage profile improvement. The fitness function is calculated after calculation of objective function.

$$f(k)_i = \frac{1}{k(x_p, x_v, x_q)} \quad (3.46)$$

Where i is population size.

D) Reproduction

The reproduction process is to allow the genetic information, stored in the good fitness for survive the next generation of the artificial strings, whereas the population's string has assigned a value and its aptitude in the object function. This value has the probability of being chosen as the parent in the reproduction process of a new generation. For this study, Roulette Wheel selection has been chosen due to its ability to incorporate fitness proportionate selection,

exploration, exploitation, simplicity, efficiency, and diversity maintenance principles. It involves constructing a roulette wheel based on the relative fitness of each individual, represented as a pie chart. The size of each individual's section on the roulette wheel corresponds to its relative fitness. The sum of all relative fitness values is calculated, and a random number within the range of 0 to the sum is generated. The population is then traversed, and the relative fitness values are accumulated until the sum exceeds the randomly generated number. At that point, the corresponding individual is selected. Since individuals with higher fitness values occupy larger sections on the pie chart, they have a higher probability of being chosen. For this study consider one offspring and the following procedures are carried out for Roulette Wheel selection procedure:

$$\gamma_i = \frac{f(k)_i}{\sum f(k)_i} \quad (3.47)$$

where i is population size.

Step 1: Calculate the total fitness of the population by summing the fitness value of the chromosome.

Step 2: Produce a random value (k) within the range from zero up to the sum of all fitness values

Step 3: Choose a chromosome such that the sum of its fitness along with the fitness of the preceding chromosome(s) is equal to or exceeds the randomly generated number (k).

E) Crossover

Crossover is a genetic operator used to vary the programming of a chromosome or chromosomes from one generation to the next. Two strings are picked from the mating pool at random to crossover in order to produce superior offspring. Once the parents have been chosen, crossover operations can be performed utilizing different methods. In this thesis two uniform cross over has been used due to its reduced risk of building biases, preservation of diversity, flexibility and adaptability. The crossover probability, also referred to as the crossover rate, is a decision variable used to determine whether or not to perform the crossover operation. It is a value between 0 and 1, indicating the likelihood of crossover occurring during the reproduction phase of a genetic algorithm. The following procedures are executed to conduct the crossover.

Step 1: Create a mating pool of parental chromosomes using random selection, with the pool size matching the population size.

Step 2: Choose a pair of parents from the mating pool and generate a random number between 0 and 1.

Step 3: Define a crossover probability ' Ω_c '.

Step 4: If the randomly generated number exceeds the crossover probability ' Ω_c ', no crossover takes place, and the offspring will inherit only one parent's chromosome. The offspring can be selected by best fitness parents among the parent pair.

Step 5: If the randomly generated number is lower than the crossover probability ' Ω_c ', then crossover occurs, resulting in the creation of a single offspring.

F) Mutation

It involves randomly selecting one or more positions within the chromosome and making changes to the genetic values at those positions. The specific changes can vary based on the problem domain and representation used. For binary representations, mutation may flip bits from 0 to 1 or vice versa. In real-valued representations, mutation can involve adding a small random value to the existing value. In present work, it is nothing but change of chromosome variable or optimization of variables (DG size, location and number). Hence, GA can improve their solutions through mutation. Mutation, which happens during evolution, is governed by a user-defined mutation probability. It is crucial to keep this probability low because if it is set too high, the search process can degrade into a basic random search. Typically, the mutation probability (' Ω_m ') should be set below 5%. The mutation process involves the following steps:

Step 1: Generate a random number between 0 and 1.

Step 2: Define the mutation probability

Step 3: If the randomly generated number is lower than the mutation probability (' Ω_m '), then mutation is applied to the offspring generated after the crossover operation.

G) Elitism

Elitism is used in genetic algorithms to preserve some of the best solutions in each generation, allowing them to carry over to the next generation. This helps in maintaining the quality of solutions and prevents the algorithm from converging too quickly to a suboptimal solution. Elitism ensures that the best solutions found so far are not lost and provides a mechanism for exploration and exploitation of the search space. It helps in improving the convergence speed and the diversity of solutions in the population. Elitism has been observed to be effective in various optimization problems, including inventory control in distribution systems and service

placement in fog computing environments. It allows for a better exploration of the Pareto frontier and improves the overall performance of the genetic algorithm.

3.11.2 Genetic Algorithm Control Parameter Selection

GA is commonly used to solve optimization and search problems by mimicking the process of natural evolution. Even though the control parameters include population size, crossover rate, mutation rate, selection criteria, and termination conditions, Population size, crossover rate and mutation are the common control parameters.

Population size: refers to the number of individuals (or candidate solutions) present in each generation of the genetic algorithm. A larger population size generally leads to a more diverse and extensive search space exploration. This can increase the chances of finding better solutions but also requires more computational resources. Conversely, a smaller population size reduces the exploration ability but may converge faster. The optimal population size depends on the problem's complexity and the available computational resources.

Crossover Rate (Ω_c): determines the probability of performing crossover, which is a genetic operator that combines genetic information from two parent individuals to create offspring individuals. A higher crossover rate promotes exploration but can also lead to premature convergence if it is too high, causing the algorithm to lose diversity and get trapped in suboptimal regions. Conversely, a lower crossover rate reduces exploration and slows down convergence.

Mutation Rate (Ω_m): indicates the likelihood of introducing haphazard alterations or mutations to a person's genetic code. It makes it possible for the algorithm to investigate previously unexplored regions of the search space that crossover may not be able to access. A higher mutation rate makes the algorithm more capable of exploring new areas, but if it is set too high, it may interfere with the convergence of good solutions. A decreased mutation rate, on the other hand, discourages exploration and may cause premature convergence.

$$\Omega_m = 1 - \frac{L_G}{G_n} \quad (3.48)$$

$$\Omega_c = \frac{L_G}{G_n} \quad (3.49)$$

$$M = \Omega_m * P \quad (3.50)$$

$$C = \Omega_c * P \quad (3.51)$$

Where L_G is generation level, G_n is maximum generation, Ω_m is mutation probability, M is individual to be mutated from generation level, C is individual are to be used for the crossover process at generation level and Ω_c is crossover probability. In this thesis study the number of population assumed is 100.

3.11.3 Steps for DG Placement and Sizing Using Genetic Algorithm

In the previous sections the layout of minimizing losses and calculating allocations, for DGs has been discussed. Here are the steps outlined to address the DGs allocation issue;

- 1: Begin by reviewing the line data and bus data of distribution networks, including branch impedance, real and reactive power values of each load node. Also specify the parameters for DGs.
- 2: Conduct a load flow analysis of distribution networks to record all node voltages, branch current magnitudes and total power loss.
- 3: Initialize GEN as 0.
- 4: Create a population randomly with chromosomes representing values DG number, DG positions and DG active power values.
- 5: Decode the population to update load data and bus data in network matrices based on their positions.
- 6: Perform a load flow analysis of distribution networks with updated system data. Calculate power loss, for each population.
- 7: Assess the objective function and fitness value for each chromosome.
- 8: Prioritize the individuals and ensure the survival of the community.
- 9: Increase the generation count, by one.
- 10: Create the mating pool from the initial population using the Roulette Wheel Selection procedure.
- 11: Apply crossover to each pair of chromosomes in the mating pool, generating one offspring from each pair.
- 12: Introduce mutations to the offspring resulting from the crossover operation.
- 13: Decode the set of offspring and determine the location and size of DGs for each chromosome.
- 14: Perform load flow analysis for each offspring to determine the objective function and assign a fitness value to each offspring.

15: Apply elitism by selecting the best chromosome from both the current population and the offspring. Replace the initial population with the selected best individuals and use them for the next generation.

16: Return to step 9 and continue the process until a solution convergence is achieved.

17: STOP the algorithm as the desired outcome has been reached.

3.11.4 Flowchart for Optimal Sizing and Placement of DG Using Genetic Algorithm

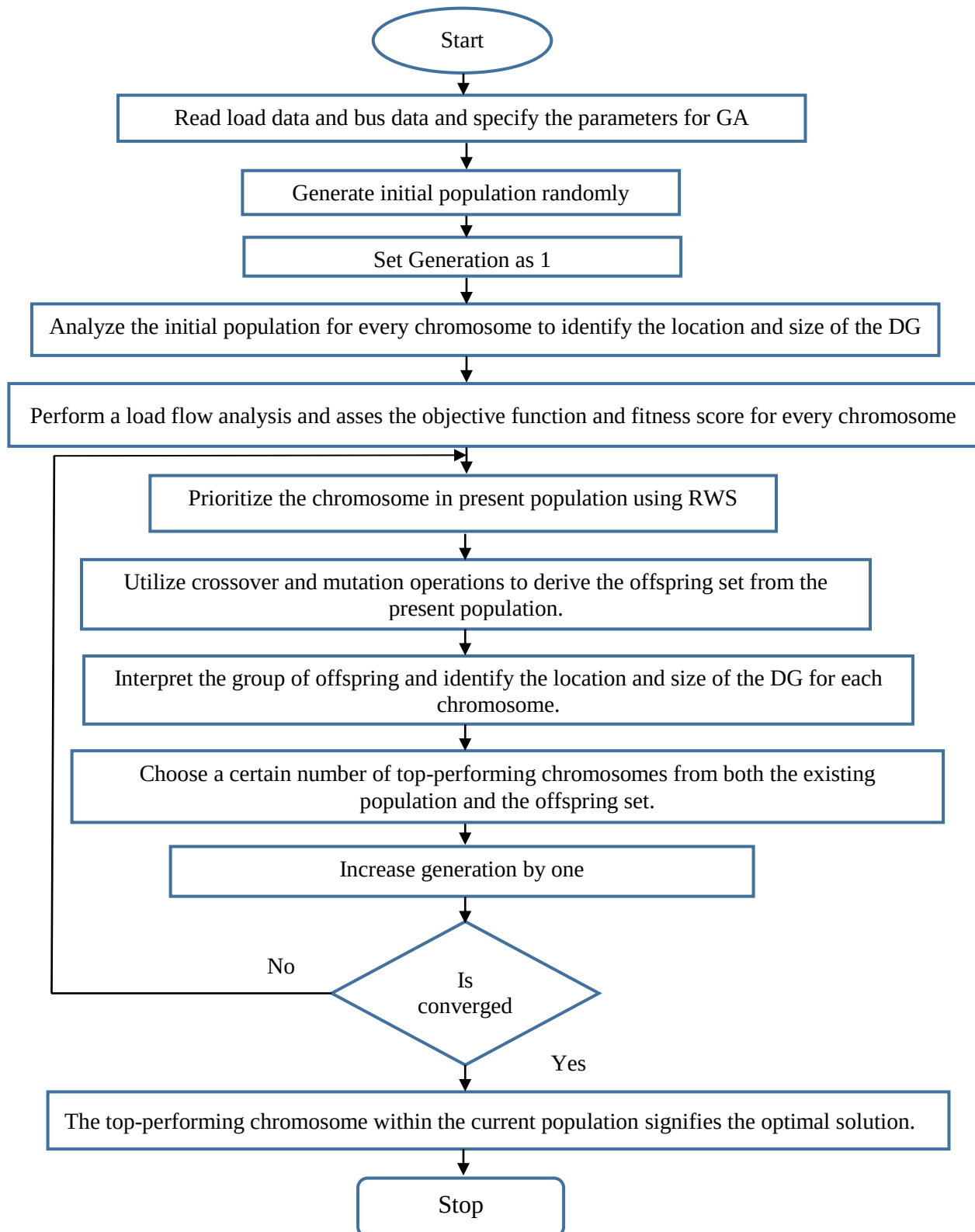


Figure 3. 7: Flowchart for Optimal Sizing and Placement of DG Using Genetic Algorithm

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

4.1 Introduction

Chapter Four provides the simulation results and discussions regarding the optimal sizing and placement of DG using a GA. The algorithm aforementioned and modeled in the previous chapter was programmed and implemented on Matlab 2021a. The proposed algorithm code based on the implementation steps is given in Appendix E. The results are categorized into different scenarios for more illustration. Different comparisons have been made to show the reliability of the proposed algorithm in voltage profile improvement, active power loss and reactive power loss minimization by placing and sizing DG optimally.

3.2 Simulation Result of Gelan 3 Distribution Network

Load flow analysis has been conducted depending on the collected line and load data using BFS techniques. The results of this analysis include the voltage profile and total active and reactive power loss for the Gelan 3 feeder before and after DG integration. By integrating the GA, the optimal size and location for the DG were determined. The simulation result for the proposed algorithm was done by considering two different scenarios for more illustration:

- a) Scenario I: Distribution Network without DG (Base – Case)
- b) Scenario I: Distribution Network with incorporation of DG

4.2.1 Distribution Network without DG (Base - Case): Scenario I

The feeder's active power and reactive power are 12.605 MW and 6.092 MVar respectively. It is important to mention here that the input parameters are transfigured to per unit with the base power of 100MVA and base voltage of 15KV. The base case LFA has been performed by taking line and bus data as input, and the results-voltage profile, total reactive power loss, and total active power loss have been obtained. Figure 4.1, 4.2, and 4.3 shows voltage profile of Gelan 3 feeder, active and reactive power loss for base case respectively.

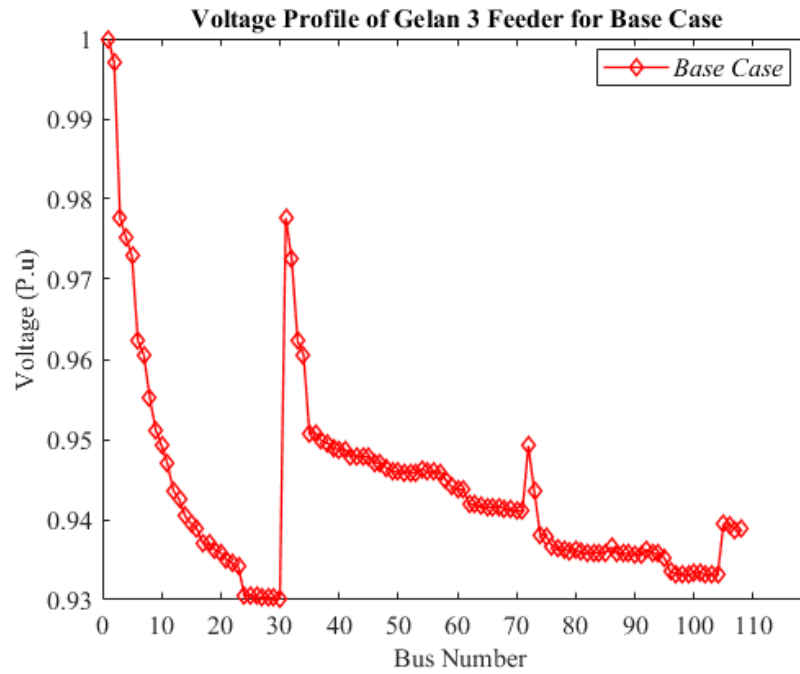


Figure 4. 1: Voltage Profile Gelan 3 Feeder of Base Case

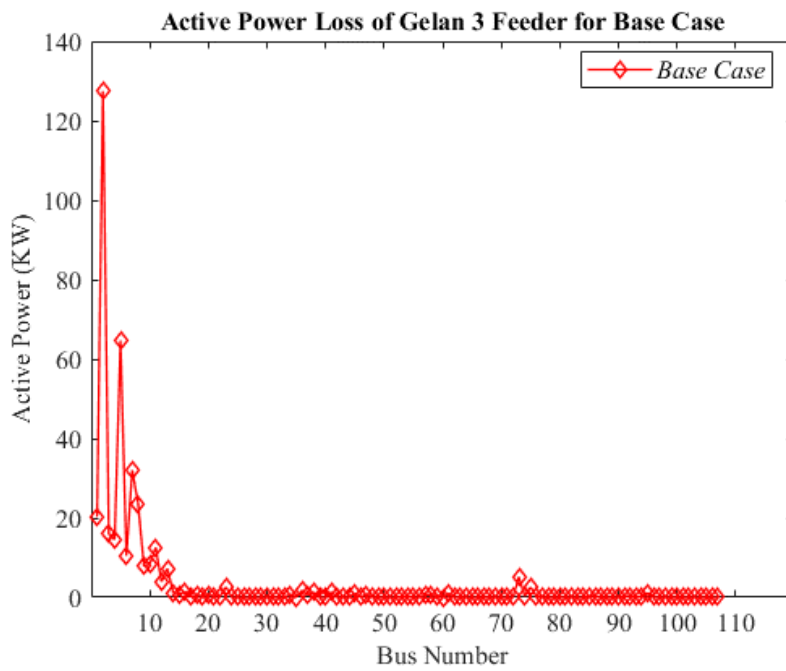


Figure 4. 2: Active Power loss Gelan 3 Feeder of Base Case

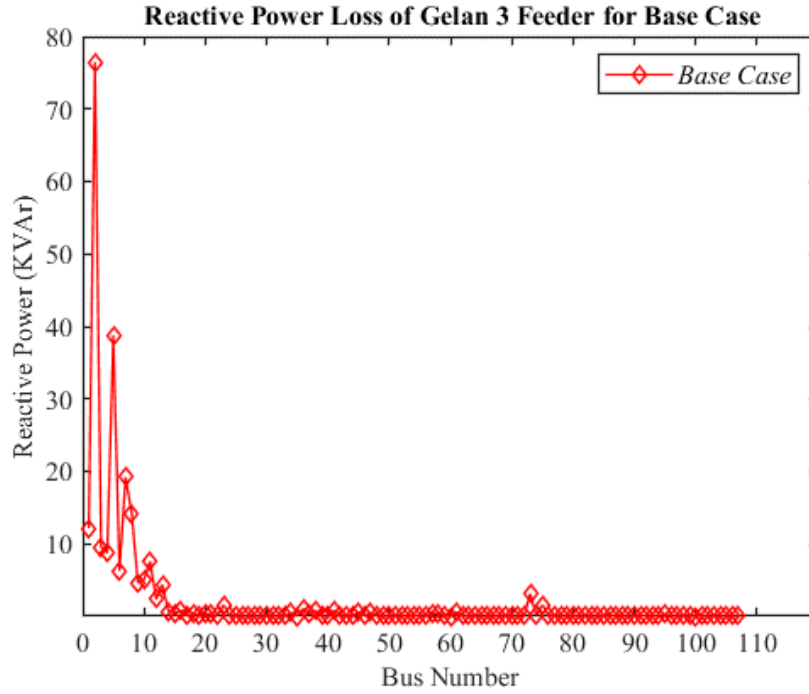


Figure 4. 3: Reactive Power loss Gelan 3 Feeder of Base Case

The summary of the above figures was presented in Table 4.1.

Table 4. 1: The Summary of Scenario I

S. No	Description	Value
1	Total reactive loss(KVAr)	227.5577
2	Total active loss(KW)	380.3629
3	Minimum voltage appear at bus number	30
4	Value of Minimum voltage(p.u)	0.9301

From the simulation results, the total active and reactive power loss of the branch of the feeder was 380.3629KW and 227.5577KVAr. Furthermore, the minimum voltage of the feeder was 0.9301 p.u., and 82.4% of buses were below the 0.95 p.u. As a company, EEU losing this much power is not economical.

4.2.2 Incorporation of DG into the Distribution Network: Scenario II

In this scenario, the analysis focuses on the impact of integrating DG systems into the Gelan 3 distribution feeder. The study considers four different cases, each with a varying number of DG units integrated into the network.

A. Case I - 1 DG

In this case, the analysis focuses on the impact of integrating a single DG system into the Gelan 3 distribution feeder. Figure 4.4, 4.5, 4.6 and 4.7 indicates voltage profile, active power, reactive power, and 1 DG convergence curve respectively.

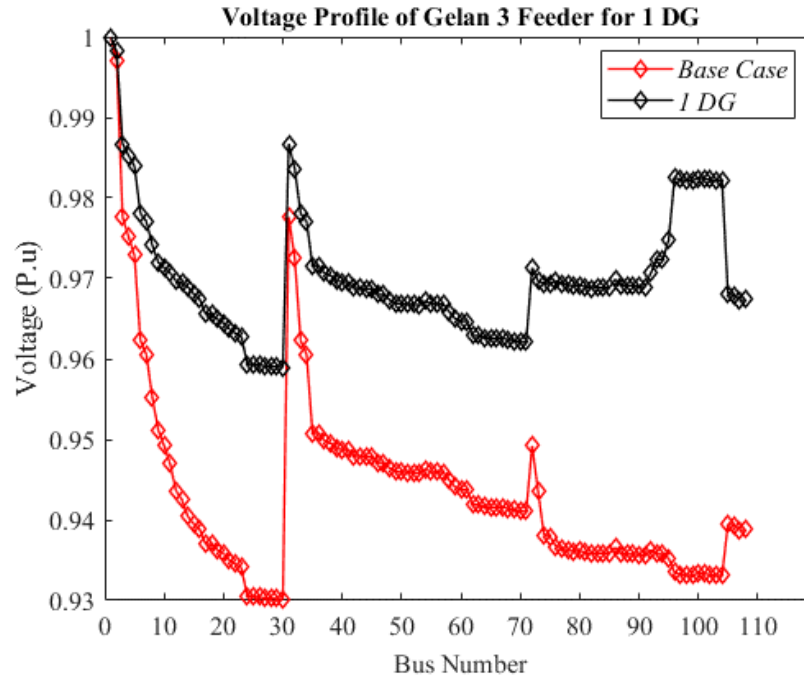


Figure 4. 4: Voltage Profile of Gela 3 feeder for 1 DG

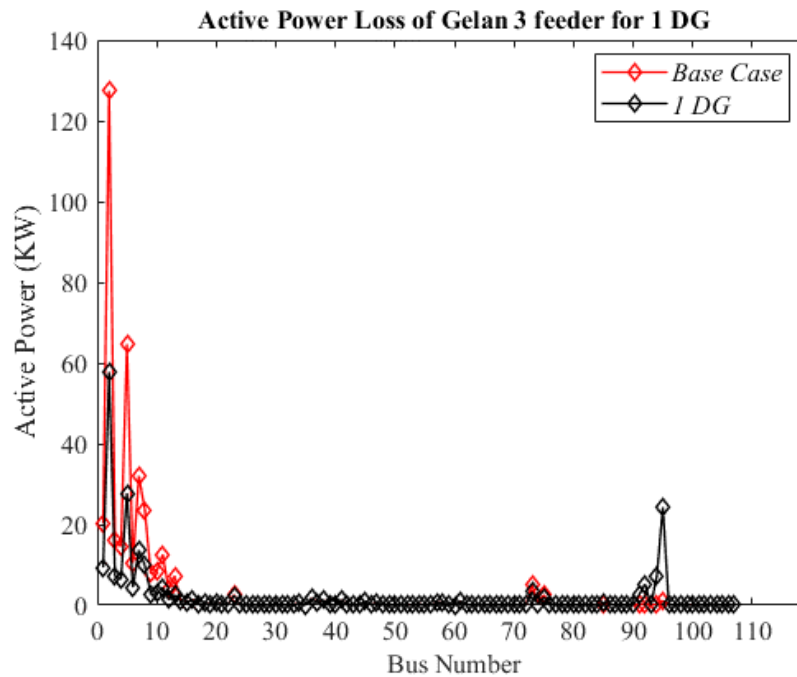


Figure 4. 5: Active Power Loss of Gela 3 feeder for 1 DG

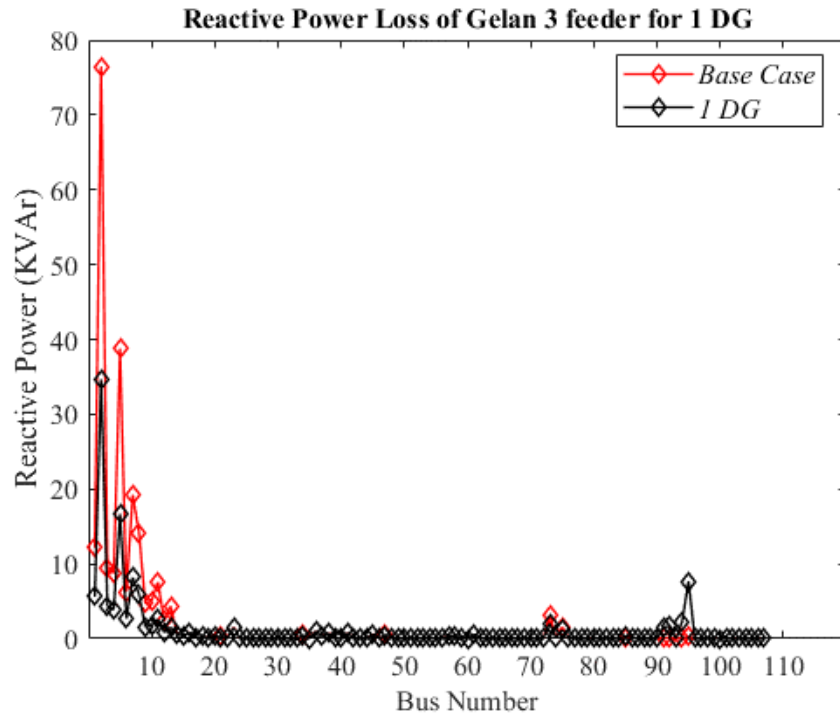


Figure 4. 6: Reactive Power Loss of Gelan 3 feeder for 1 DG

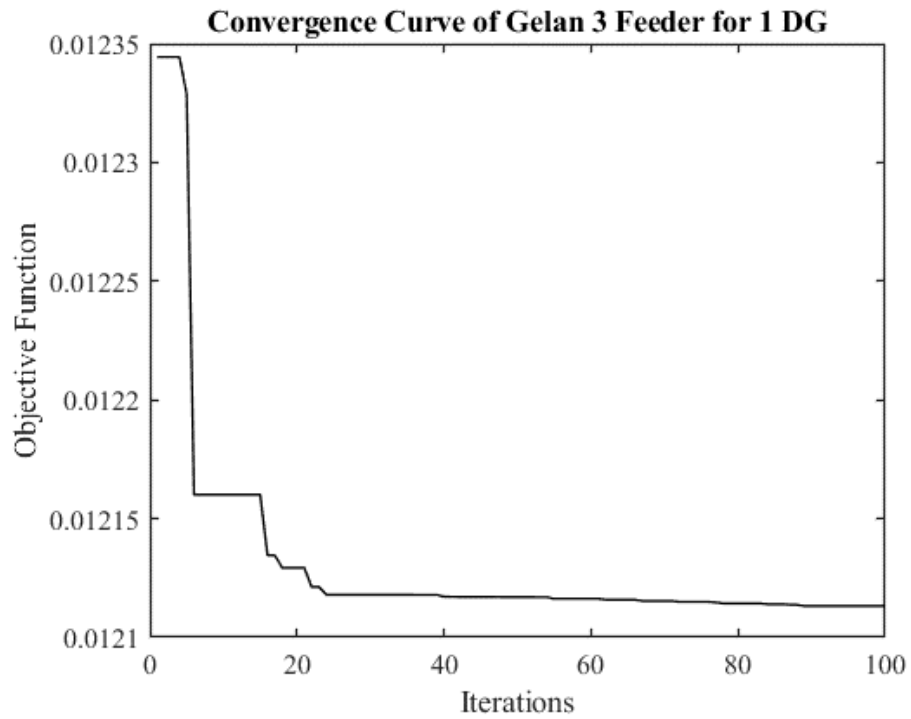


Figure 4. 7: Convergence Curve of Gela 3 feeder for 1 DG

Table 4. 2 demonstrate case I summary result.

Table 4. 2: Case I Summary Result

S.No	Description	Value
1	Active power loss before DG integration(KW)	380.3629
2	Reactive power loss before DG integration(KVAr)	227.5547
3	Active power loss after DG integration(KW)	215.685
4	Reactive power loss after DG integration(KVAr)	118.8729
5	Optimal location of DG(bus number)	96
6	Optimal size of DG(MW)	3.375
7	Value of Minimum voltage(p.u)	0.95893
8	Maximum voltage deviation (%)	4.1067
9	Active power reduction (%)	46.2017
10	Reactive power reduction (%)	70.6404

The integration of a 3375 kW single DG system at the optimal location of bus 96 has bring about in significant improvements for the Gelan 3 distribution feeder. The total active loss before DG integration was 380.3629 kW, which decreased by 46.2017% to 215.685 kW after integration. Similarly, the total reactive loss before DG integration was 227.5547 kVAr, which decreased by 70.6404% to 118.8729 kVAr after integration. The strategic placement and sizing of the DG system have been crucial in achieving, active and reactive power loss reduction. Following DG integration, the minimum voltage was 0.95893 p.u., with a maximum voltage deviation of 4.1067%, indicating improved voltage profile within acceptable limits.

Overall, the integration of the 1 DG system has led to a more efficient and reliable power system for the Gelan 3 distribution feeder, with significant improvements in voltage profile and reductions in active and reactive power losses.

B. Case II - 2 DG

In this second case, the analysis focuses on the impact of integrating two DG systems into the Gelan 3 distribution feeder. Figure 4.8, 4.9, 4.10 and 4.11 demonstrates voltage profile, active power, reactive power, and 2 DG convergence curve respectively.

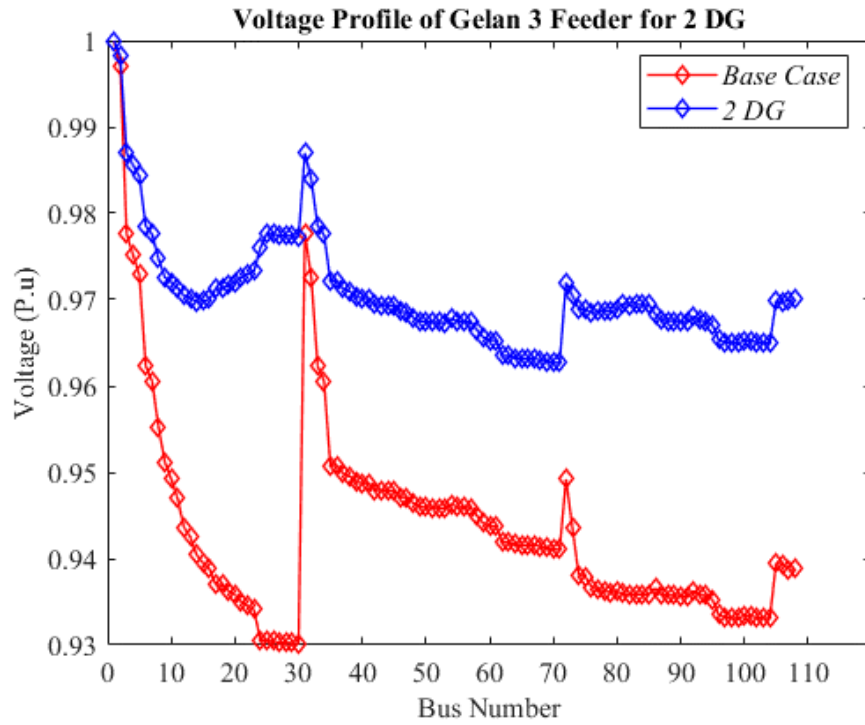


Figure 4. 8: Voltage Profile of Gelan 3 Feeder for 2 DG

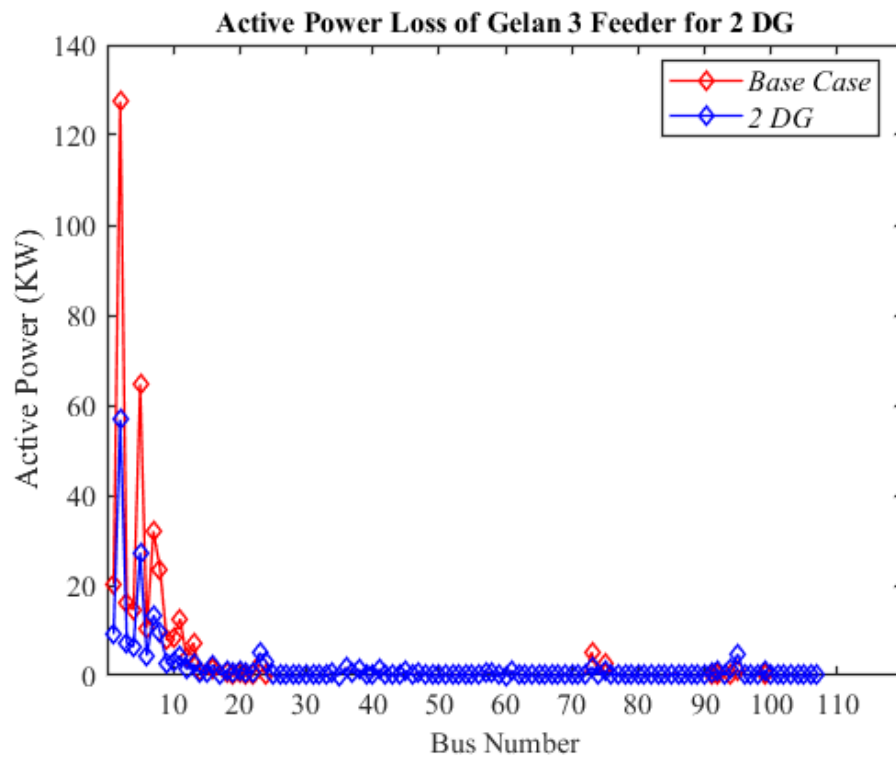


Figure 4. 9: Active Power Loss of Gelan 3 Feeder for 2 DG

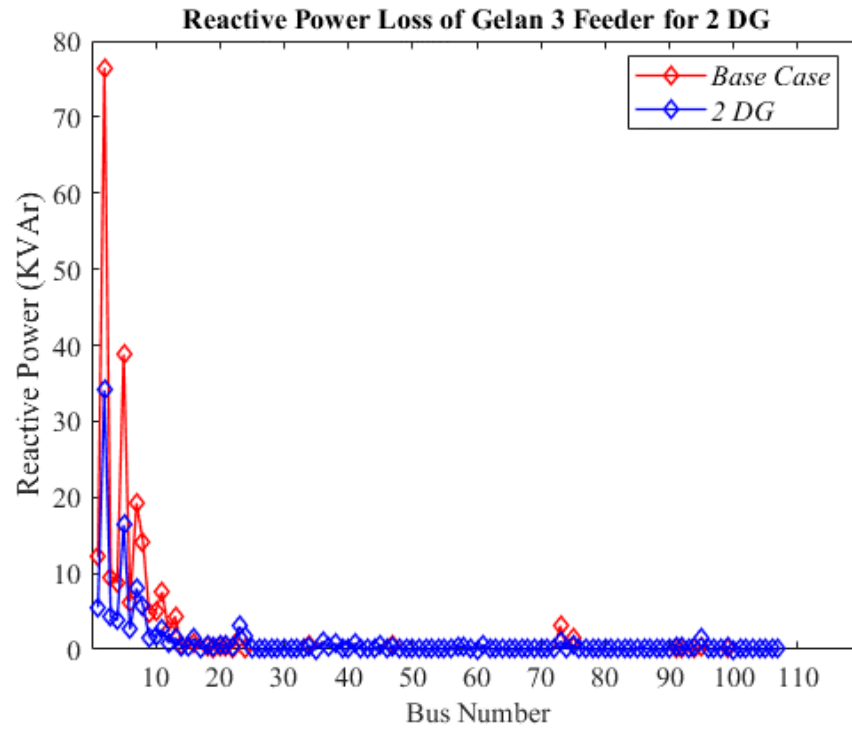


Figure 4. 10: Reactive Power Loss of Gelan 3 Feeder for 2 DG

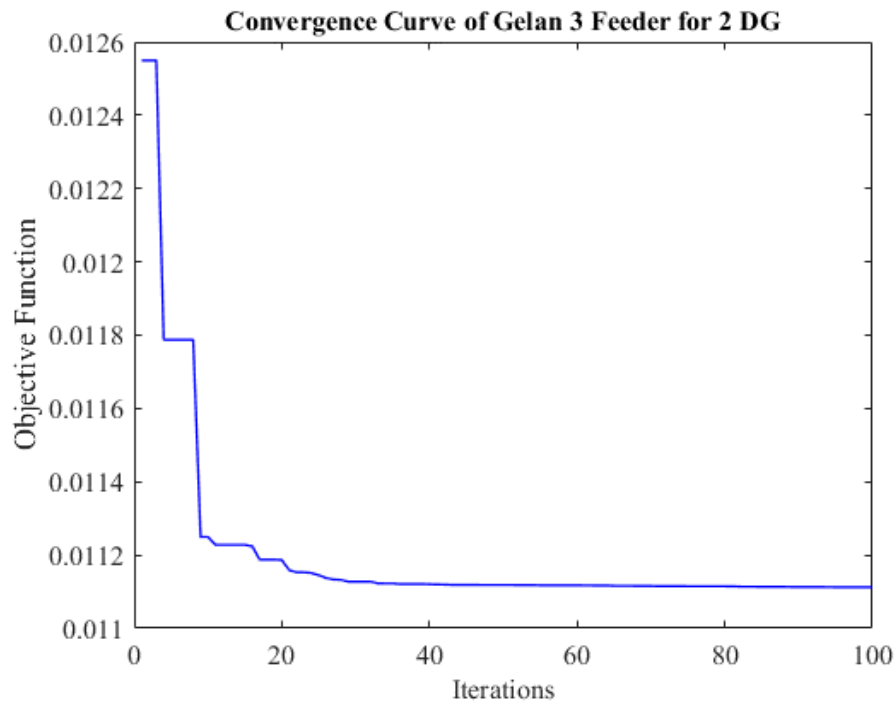


Figure 4. 11: Convergence Curve of Gelan 3 Feeder for 2 DG

Table 4. 3 depict summary of result for case II

Table 4. 3: Summary of Result for Case II

S.No	Description	Value
1	Active power loss before DG integration(KW)	380.3629
2	Reactive power loss before DG integration(KVAr)	227.5547
3	Active power loss after DG integration(KW)	183.6586
4	Reactive power loss after DG integration(KVAr)	109.5971
5	Optimal location of DG(bus number)	25, 80
6	Optimal size of DG(MW)	1.687@25, 1.688@80
7	Value of Minimum voltage(p.u)	0.96168
8	Maximum voltage deviation (%)	3.8318
9	Active power reduction (%)	54.1901
10	Reactive power reduction (%)	72.9313

The incorporation of the two DG, as presented in Case II, resulted in significant improvements in the system's performance. The total active power loss before DG integration was 380.3629 kW, which was reduced to 183.6586 kW after the 2 DG integration, representing a 54.1901% decrease. Similarly, the reactive power loss was reduced from 227.5547 kVAr to 109.5971 kVAr, with 72.9313% reduction. The optimal placement of the two DG was determined to be at buses 25 and 80, with sizes of 1.687 MW and 1.688 MW, respectively. This strategic placement and appropriate sizing of the DG played significant merits in achieving the observed performance improvements.

Furthermore, the two DG unit's integration led to enhancements in voltage profile of distribution network. The minimum voltage value improved from 0.9301 p.u. to 0.96168 p.u., and the maximum voltage deviation decreased to 3.8318%. These results demonstrate the beneficial impact of incorporating multiple DG systems on the overall voltage stability and quality.

In summary, Case II resulted in substantial reductions in both active and reactive power losses, significant improvements in the voltage profile. These findings highlight the advantages of utilizing multiple DG systems in distribution network planning and optimization, as opposed to relying on a single DG unit.

C. Case III - 3 DG

The third case examines the impact of incorporating 3 DG systems into the Gelan 3 distribution feeder. Figure 4.12, 4.13, 4.14 and 4.15 indicates voltage profile, active power, reactive power, and 3 DG convergence curve respectively.

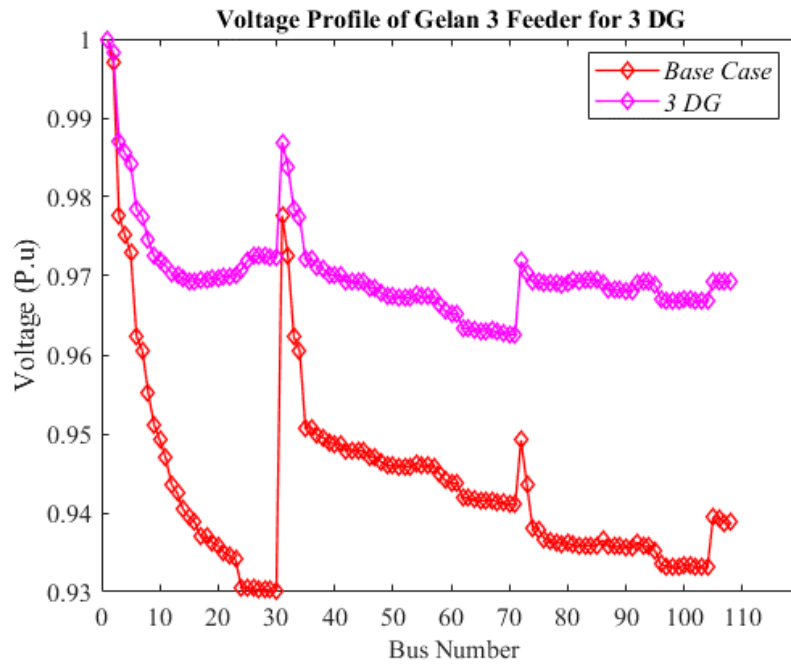


Figure 4. 12: Voltage Profile of Gelan 3 Feeder for 3 DG

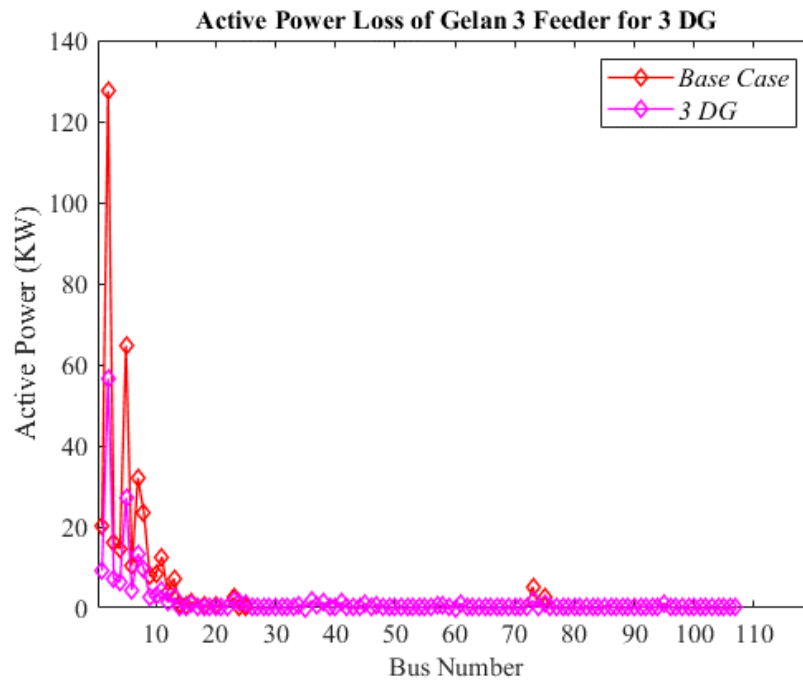


Figure 4. 13: Active Power loss of Gelan 3 Feeder for 3 DG

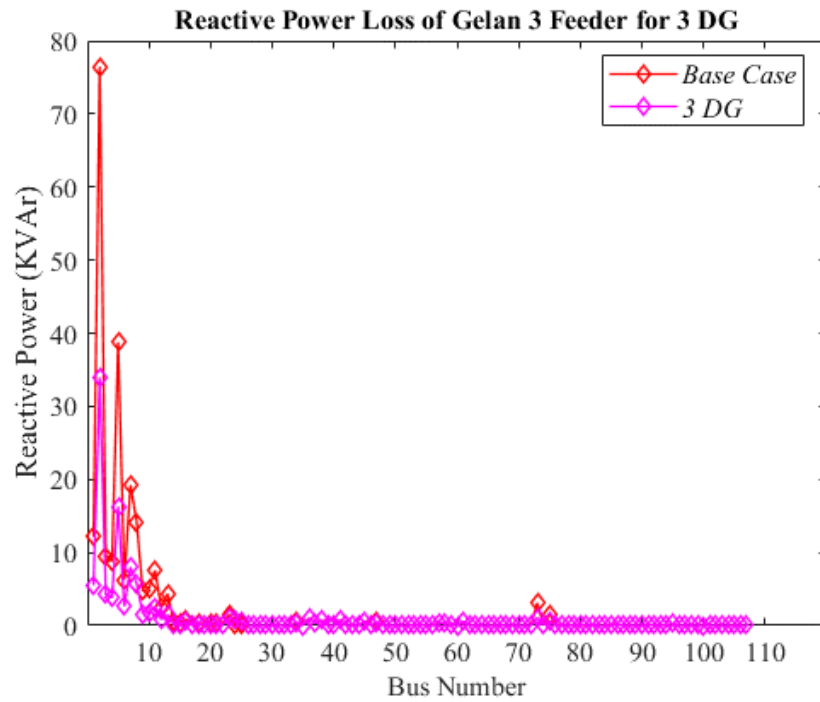


Figure 4. 14: Reactive Power loss of Gelan 3 Feeder for 3 DG

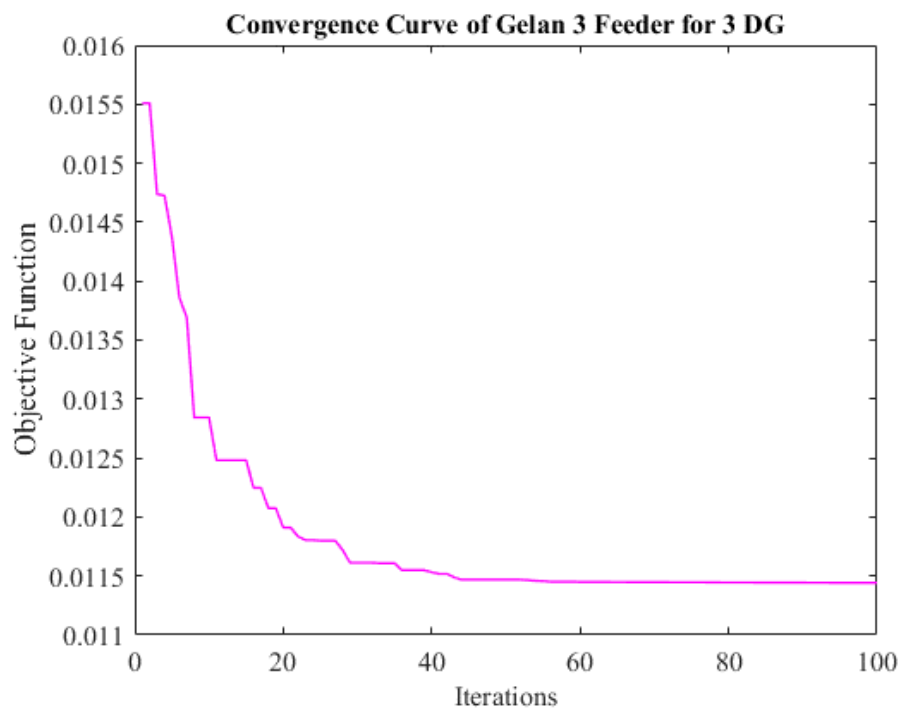


Figure 4. 15: Convergence Curve of Gelan 3 Feeder for 3 DG

Table 4. 4: Case III Result Summary

S.No	Description	Value
1	Active power loss before DG integration(KW)	380.3629
2	Reactive power loss before DG integration(KVAr)	227.5547
3	Active power loss after DG integration(KW)	183.6586
4	Reactive power loss after DG integration(KVAr)	102.2332
5	Optimal location of DG(bus number)	26, 83, 93
6	Optimal size of DG(MW)	1.125@26,1.125@83,1.125@93
7	Value of Minimum voltage(p.u)	0.96259
8	Maximum voltage deviation (%)	3.7415
9	Active power reduction (%)	57.2556
10	Reactive power reduction (%)	74.7501

Case III presents the results of integrating three DG units into the distribution network which shows better performance. The total active power loss before DG integration was 380.3629 kW and after the integration of three DG units, reduced to 171.3684 kW, a 57.2556% decrease. The total reactive power loss also decreased substantially, from 227.5547 kVAr to 102.2332 kVAr, a 74.7501% reduction. The optimal placement for the three DG were determined to be buses 26, 83, and 93, with each unit having a size of 1.125 MW. The strategic placement of the DG units at these specific locations, along with the appropriate sizing, contributed to the significant performance improvements observed in Case III. The integration of three DG units also led to notable enhancements of voltage profile in distribution network. The minimum voltage value enhanced from 0.9301 p.u. (before DG integration) to 0.96259 p.u., and the maximum voltage deviation decreased to 3.7415%.

In summary, Case III demonstrates that the integration of three DG at the strategical locations and sizes resulted in reductions of active and reactive power losses, the most significant improvements in the voltage profile compared to the previous cases. These findings highlight the benefits of incorporating multiple DG systems in distribution network.

D. Case IV- 4 DG

The forth case examines the impact of incorporating four DG systems into the Gelan 3 distribution feeder. Figure 4.16, 4.17, 4.18 and 4.19 demonstrate voltage profile, active power, reactive power, and 3 DG convergence curve respectively.

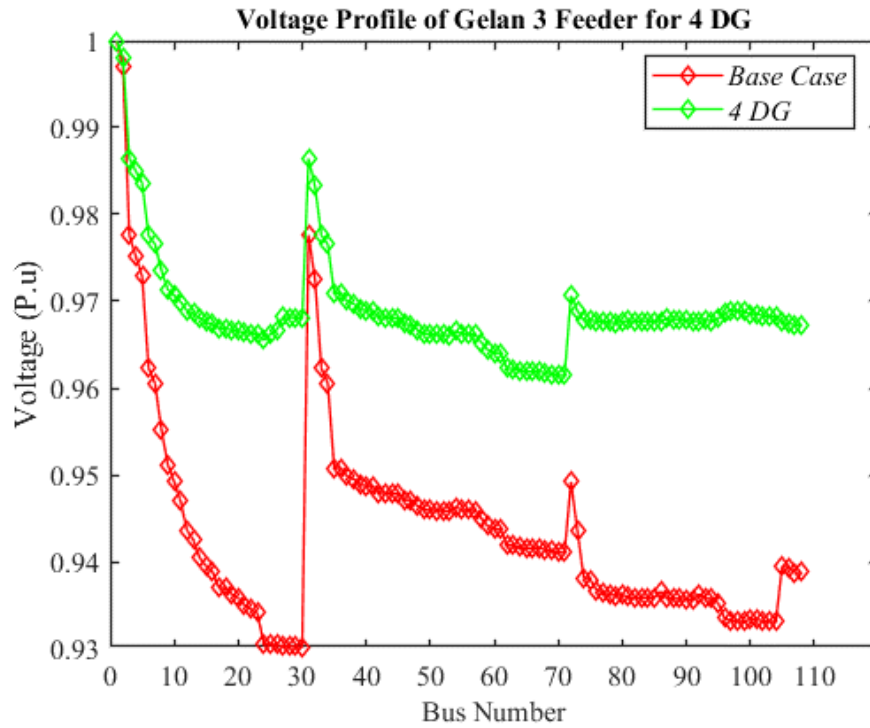


Figure 4. 16: Voltage Profile of Gelan 3 feeder for 4 DG

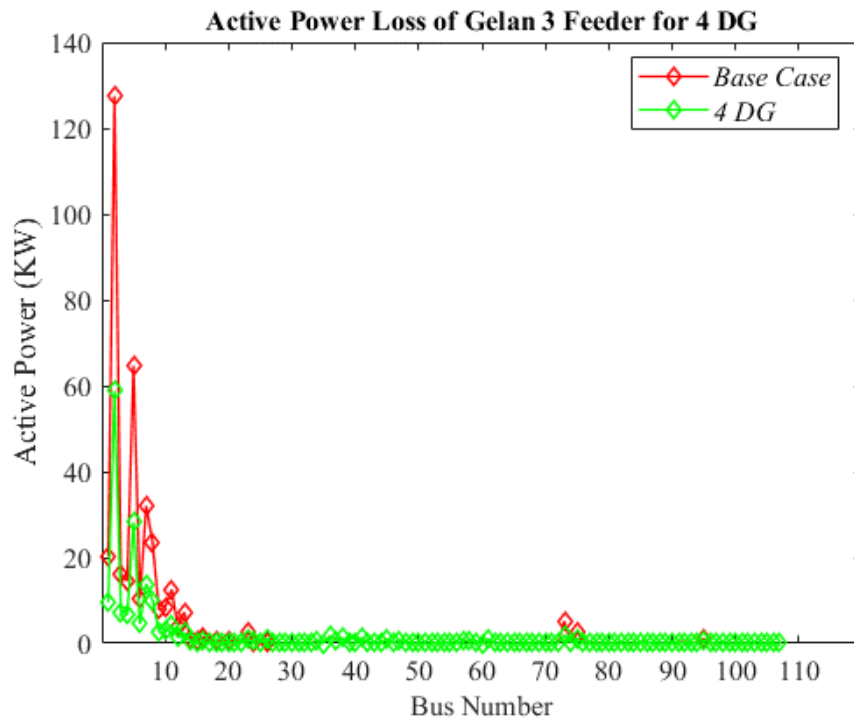


Figure 4. 17: Active Power Loss of Gelan 3 feeder for 4 DG

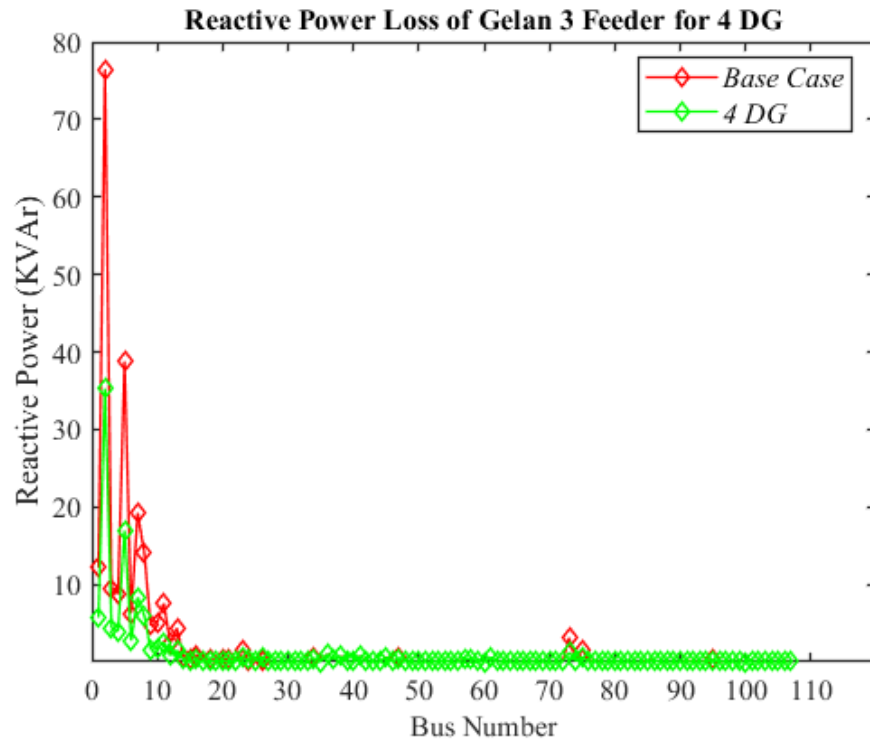


Figure 4. 18: Reactive Power Loss of Gelan 3 feeder for 4 DG

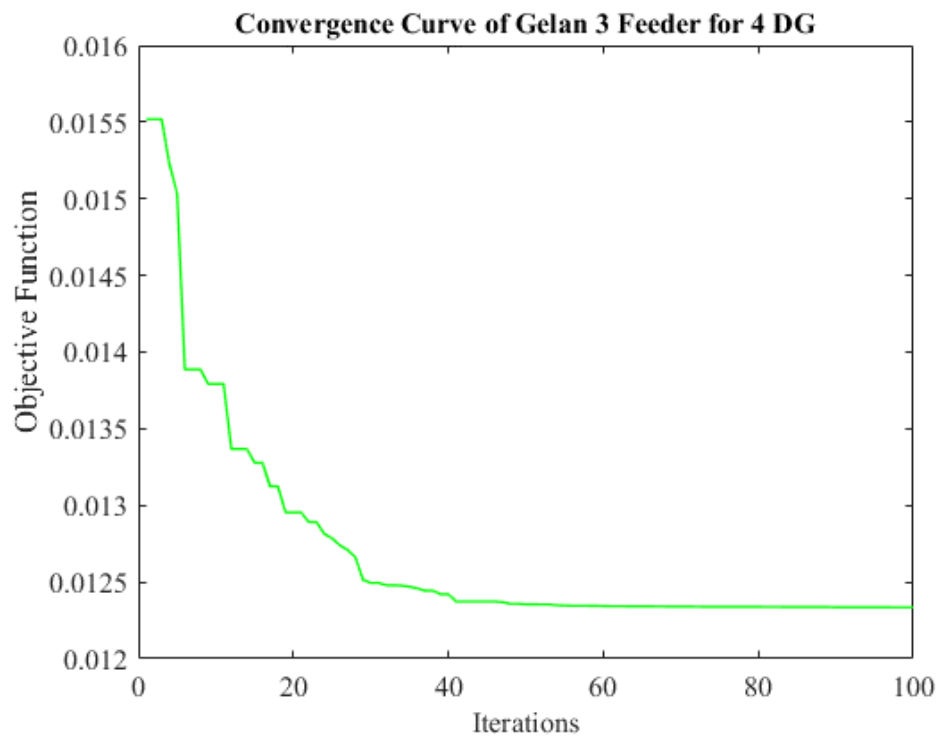


Figure 4. 19: Convergence Curve of Gelan 3 Feeder for 4 DG.

Table 4. 5: Case IV Result Summary

S.No	Description	Value
1	Active power loss before DG integration(KW)	380.3629
2	Reactive power loss before DG integration(KVAr)	227.5547
3	Active power loss after DG integration(KW)	174.0187
4	Reactive power loss after DG integration(KVAr)	103.9655
5	Optimal location of DG(bus number)	21, 81, 87, 97
6	Optimal size of DG(MW)	0.844@21, 0.844@81, 0.843@87, 0.843@97
7	Value of Minimum voltage(p.u)	0.96144
8	Maximum voltage deviation (%)	3.8558
9	Active power reduction (%)	56.9545
10	Reactive power reduction (%)	74.3222

Case IV presents the results of integrating four DG units into the distribution network. The findings demonstrate significant improvements in system performance, though not as substantial as those observed in previous cases do.

The active power loss before DG integration was 380.3629 kW and following the integration of four DG units, reduced to 174.0187 kW, a 56.9545% decrease. The total reactive power loss decreased from 227.5547 kVAr to 103.9655 kVAr, a 74.3222% reduction. The optimal locations for the four DG units were determined to be buses 21, 81, 87, and 97, with each unit having a size of approximately 0.844 MW, 0.844 MW, 0.843 MW, and 0.843 MW, respectively. Regarding the voltage profile, the four DG integration led to an improvement in the minimum voltage value from 0.9301 p.u. (before DG integration) to 0.96144 p.u. The maximum voltage deviation also decreased to 3.8558%.

To summarize, Case IV illustrates how the integration of four distributed generation units at ideal locations and sizes led to notable decreases in both active and reactive power losses and enhancements in the voltage profile. However, the performance improvements were not as substantial as those observed in previous cases, suggesting that the optimal number of DG units for this distribution network may be not four. Therefore, increment in number of DG can diminish power loss and enhance voltage profile, but only up to a certain DG value.

E. Comparison for Different DG Penetration Levels.

After presenting the results for the four individual cases (Case I - 1 DG, Case II - 2 DG, Case III - 3 DG, and Case IV - 4 DG), a comprehensive comparative analysis was conducted to evaluate the performance and effectiveness of the different DG integration scenarios. This analysis provided insights into the optimal number of DG systems and their impact on the Gelan 3 distribution feeder. The comparative analysis was focused on the key performance metrics such as active power loss, reactive power loss, voltage profile, percentage of active power loss reduction, and percentage of reactive power loss reduction.

To provide a clear and concise visualization of the comparative results, the key performance metrics were presented in a single table, allowing for a side-by-side comparison of the different DG integration cases. This format enabled a thorough evaluation of the tradeoffs and benefits associated with each DG integration scenario, helping to identify the optimal solution for the Gelan 3 distribution feeder. Figure 4.20, 4.21, and 4.22 demonstrates voltage profile of all cases, active and reactive power loss for all cases, and percentage of active and reactive power loss reduction respectively.

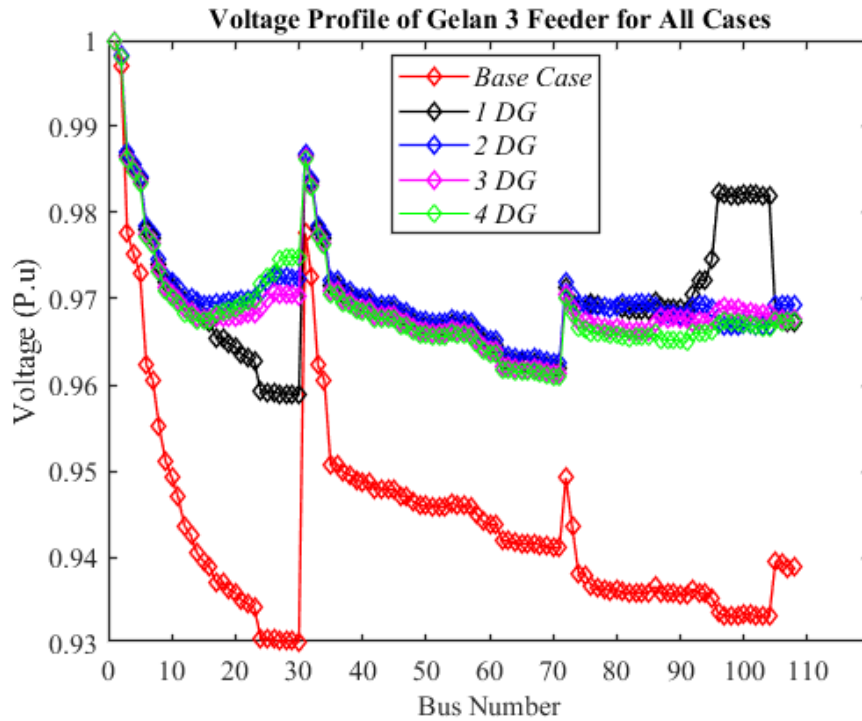


Figure 4. 20: Voltage Profile of Gelan 3 Feeder for All Cases

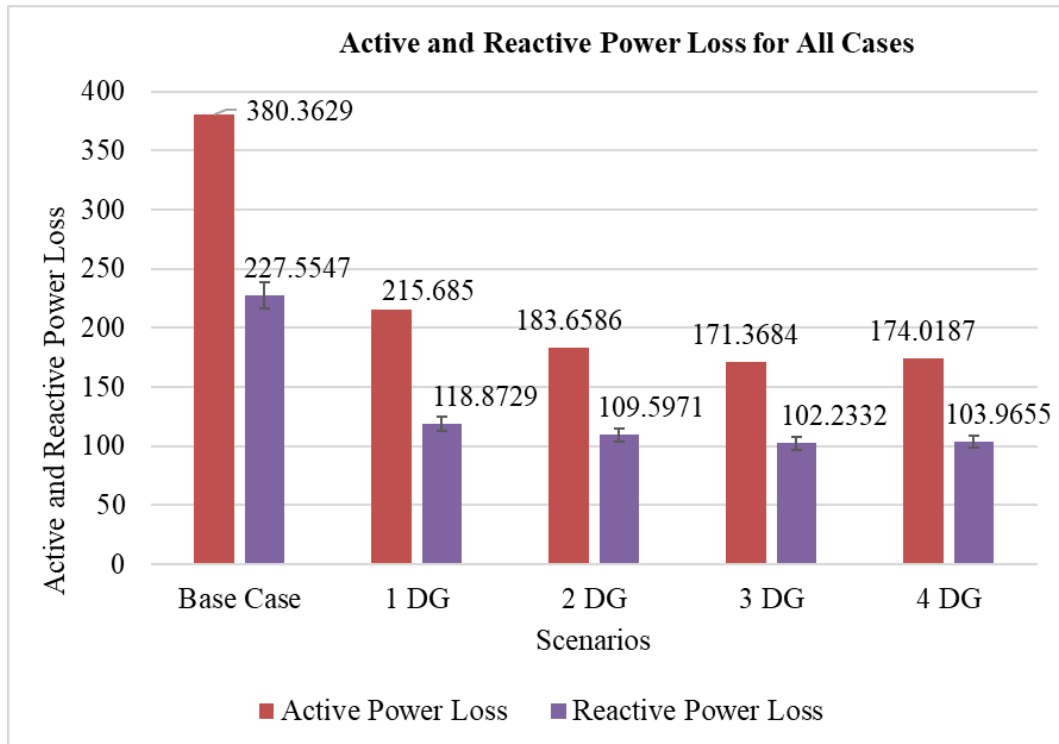


Figure 4. 21: Active and Reactive Power for All Cases

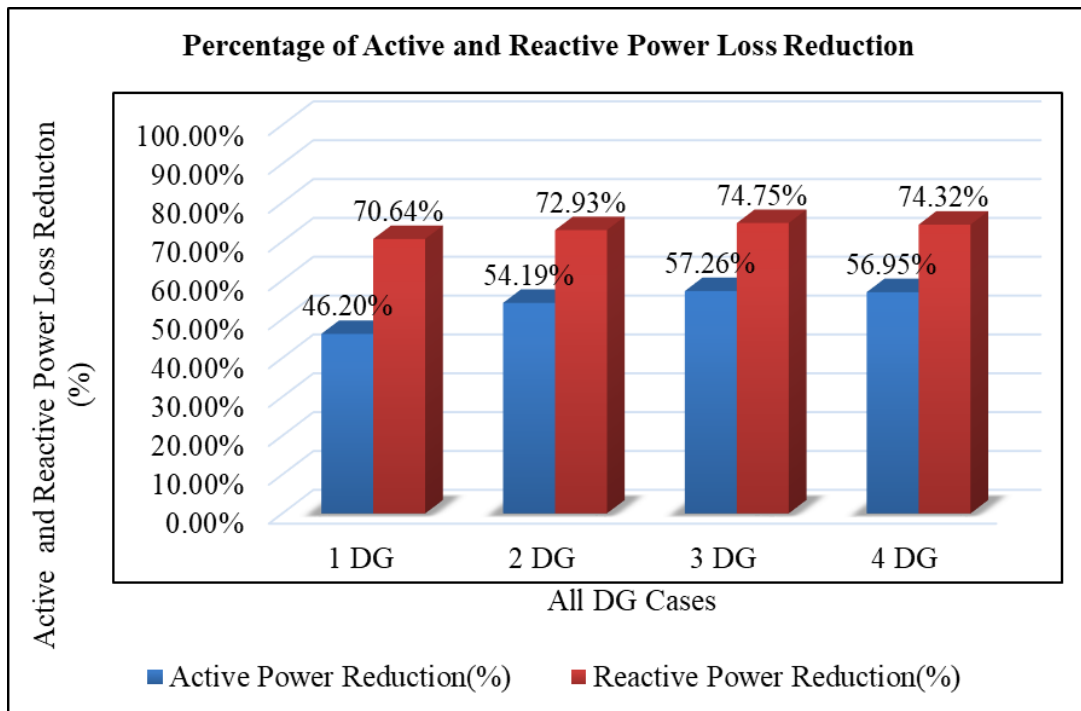


Figure 4. 22: Percentage of Active and Reactive Power Reduction

Table 4. 6: The Summary for all Scenarios

S. No	Description	Scenarios			
		Case I	Case II	Case III	Case IV
1	Total active loss before DG integration(KW)	380.3629	380.3629	380.3629	380.3629
2	Total reactive loss before DG integration(KVAr)	227.5547	227.5547	227.5547	227.5547
3	Total active loss after DG integration(KW)	215.685	183.6586	171.3684	174.0187
4	Total reactive loss after DG integration(kvar)	118.8729	109.5971	102.2332	103.9655
5	Optimal location of DG(bus number)	96	25, 80	26, 83, 93	21, 81, 87, 97
6	Optimal size of DG(MW)	3.375	1.687, 1.688	1.125, 1.125, 1.125	0.843, 0.844, 0.844, 0.843
7	Value of Minimum voltage(p.u)	0.95893	0.96168	0.96259	0.96144
8	Maximum voltage deviation (%)	4.1067	3.8318	3.7415	3.8558
9	Active power reduction (%)	46.2017	54.1901	57.2556	56.9545
10	Reactive power reduction (%)	70.6404	72.9313	74.7501	74.3222

The comparative analysis from Table 4.6 clearly demonstrates the benefits of incorporating DG units into the distribution network and the table provided presents the results of four different DG integration cases (Case I - 1 DG, Case II - 2 DG, Case III - 3 DG, and Case IV - 4 DG) in a distribution network. The comparative analysis reveals several key findings.

Firstly, the integration of DG systems leads to a significant reduction in both active and reactive power losses. The total active power loss before DG integration was 380.3629 kW across all cases, but after DG integration, this value decreased substantially. Case III - 3 DG showed the lowest active power loss of 171.3684 kW, indicating that increasing the number of DG units

from 1 to 3 results in the greatest reduction in active power losses. A similar trend was observed for reactive power losses, with Case III - 3 DG achieving the lowest value of 102.2332 KVar. Regarding the optimal placement and sizing of the DG units, the flexibility of incorporating multiple DG systems allowed for better optimization. Case III - 3 DG has the most optimal placement of the DG units (at buses 26, 83, and 93) and smaller individual sizes (0.843 MW, 0.844 MW, 0.844 MW), suggesting that this configuration was the most effective in terms of system performance.

The voltage profile also showed significant improvements as the number of DG units increased. The minimum voltage value improved from 0.95893 p.u. in Case I - 1 DG to 0.96259 p.u. in Case III - 3 DG, and the maximum voltage deviation decreased from 4.1067% in Case I - 1 DG to 3.7415% in Case III - 3 DG. These results indicate that the integration of three DG units provided the most substantial enhancement in the voltage profile.

Furthermore, the power reduction percentages were highest in Case III - 3 DG, with an active power reduction of 57.2556% and a reactive power reduction of 74.7501%. These values further confirm that the integration of three DG units offers the greatest improvements in terms of active and reactive power reduction.

In conclusion, the comparative analysis demonstrates that Case III - 3 DG is the optimal solution, as it achieves the best system performance. The integration of three DG units leads to the most significant reductions in active and reactive power losses, the greatest enhancement in voltage profile, and the highest overall system efficiency.

4.3 Economic Evaluation

After proposed solution to problems economic feasibility is one basic steps. The cost effectiveness of DG integration in Gelan - 3 feeder is determined by saving cost, which is the difference of cost of energy losses in birr before and after integration of DG. The cost analysis of this thesis work includes the cost of DG, cost of energy due to interruption, cost of energy loss, Cost of supplied Energy by DG, and total cost saving with a payback period for the best scenario.

Cost of Energy Loss

The cost of energy loss in the feeder can be calculated by:

$$C_{EL} = P_{tot} * E_C * t \quad (4.1)$$

Where C_{EL} is feeder cost of energy loss, P_{tot} the total feeder active power loss, and E_C is energy cost rate (Birr/KWh), and t is the time in hour. From the updated Ethiopian Electric Utility Tariff, 1 KWhr for general tariff is 2.1240Birr.

$$C_{EL} = 380.3629kw * 2.124birr/kwhr * 8760hr$$

Where the total feeder active power loss before DG incorporation is 380.3629kw, and t is 8760hr.

$$C_{EL} = 7,077,123.41 \text{ birr}$$

By using the same equation on (4.1), the cost of energy loss after 3 DG integration can be calculated as follows:

$$C_{EL} = 171.3684kw * 2.124birr/kwhr * 8760hr$$

$$C_{EL} = 3,188,521.58 \text{ birr}$$

Cost of supplied Energy by DG

The cost of energy supplied by the DG is given as

$$DG_A = DG_p * E_C * t \quad (4.2)$$

Where DG_A is the cost of energy is supplied by DG, and DG_p is generated power by DG

$$DG_A = 3375kw * \frac{2.124birr}{kwhr} * 8760 \text{ hr}$$

$$DG_A = 62,796,060 \text{ birr}$$

Technological advancements in solar PV modules, leading to improved efficiency and lower manufacturing costs. Economies of scale as solar PV deployment has rapidly grown, allowing for cost reductions in the balance of system (BoS) components. The average installed cost of residential solar PV systems in the U.S. has decreased from around \$3.05/W in the second half of 2018 to \$2.98/W in 2019. Additionally, NREL has estimated the engineering-based benchmark (technically feasible) price to be \$2.70/W, which has been consistently below the reported installed cost by \$0.73/W to \$0.98/W since 2013 (Webb et al., 2020). The total installation cost of solar PV systems has been decreasing over time due to technological advancements, economies of scale, and manufacturing improvements (Ramasamy et al., 2021).

$$IC_{DG} = DG_p * C_{pV} \quad (4.3)$$

Where IC_{DG} is the investment cost of PV-DG, DG_p is generated power by DG, and C_{pV} is cost of PV in dollar per watt. Based on benchmark data of the USA for 2021, the average installed cost for PV fixed-tilt utility-scale system is 1.08\$/W.

$$IC_{DG} = 3375kw * 1.08\$/W$$

$$IC_{DG} = 3,645,00 \text{ USD}$$

1 USD was 58.49 ETB in accordance with the exchange rate of the Commercial Bank of Ethiopia (CBE) on June 2, 2024.

$$\text{So } IC_{DG} = 3,645,00 * 58.49 \text{ birr} = 213,196,050 \text{ birr}$$

Even though the operation and maintenance cost vary depending on the size of the system, its location, the type of technology used, and the specific maintenance requirements. On average, O&M costs for solar PV systems can range from 1% to 2% of the total installed cost of the system.

$$\text{Operation and maintenance cost} = 0.02 * 213,196,050 \text{ birr} = 4,263,921.00 \text{ birr}$$

Finally, payback period is calculated as follows:

$$PB_P = \frac{N_I}{N_{AR}} \quad (4.3)$$

Where N_I is DG investment cost and N_{AR} is net annual return of DG.

$$PB_P = \frac{213,196,050 \text{ birr}}{3,888,602 \text{ birr} + 62,796,060 \text{ birr} - 4,263,921.00 \text{ birr}}$$

$$PB_P = 3.41 \text{ years}$$

The economic evaluation of integrating three DG units into the Gelan-3 feeder shows substantial cost savings. The total cost of energy losses before DG integration was 7,077,123.41 birr, which was reduced to 3,188,521.58 birr after the integration of the three DG units, resulting in an annual cost saving of 3,888,602 birr. The cost of energy supplied by the three DG units was 62,796,060 birr, which was offset by the significant reduction in energy losses. The investment cost of 213,196,050 birr has a payback period of only 3.41 years, demonstrating the economic viability and benefits of integrating three DG units, including reduced losses, improved reliability, and increased energy independence for the utility.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this thesis work, the enhancing voltage profile and minimizing power loss in the radial distribution system for the Gelan 3 distribution network have been accomplished by using an optimal placement and sizing of DG. BFS load flow analysis was performed both before and after DG integration to determine the voltage deviation, active and reactive power loss. GA was deployed to decide the optimal location, size, and number of DG. The multiple objective function, comprising active power loss, reactive power loss, and voltage profile optimization, was formulated for the optimal allocation and sizing of DG using the GA. The MATLAB programming results were tested by considering two scenarios, with the second scenario including four different cases (Case I - 1 DG, Case II - 2 DG, Case III - 3 DG, and Case IV - 4 DG). From the results under Scenario II, the key findings across the different cases shown that the integration of DG units enhance voltage profile and minimize voltage drop.

The comprehensive analysis and evaluation conducted in this thesis work have provided valuable insights into the optimal integration of DG units within the Gelan 3 distribution feeder. The systematic comparison has demonstrated the significant benefits that can be achieved through the strategic deployment of multiple DG systems. The key findings across the different cases show that the integration of three DG units (Case III) provides the most substantial benefits. Case III - 3 DG has the most optimal placement of the DG units (at buses 26, 83, and 93) and smaller individual sizes (0.843 MW, 0.844 MW, 0.844 MW). The total active power loss was reduced to 171.3684 kW after the integration of three DG units, a 57.2556% decrease. The total reactive power loss also was decreased to 102.2332 kVAr, a 74.7501% reduction. The minimum voltage value was 0.96259 p.u., with maximum voltage deviation of 3.8558%.

Furthermore, the economic evaluation revealed that the integration of three DG units has a relatively short payback period of 3.41 years, demonstrating the cost-effectiveness of this solution and the potential for long-term financial benefits.

In conclusion, the findings of this work clearly indicate that the integration of three DG units is the optimal solution for the Gelan 3 distribution feeder, providing the most significant enhancements in voltage profile, power loss minimization, and long-term financial viability.

5.2 Recommendations

This thesis work offers substantial advantages for both customers and EEU. The reduction in power loss and enhancement of the voltage profile will lead to increased profitability for EEU, while customers will benefit from a more stable voltage level. This improvement is likely to enhance customer satisfaction. Therefore, I strongly recommend that EEU implement this initiative within the Gelan distribution network.

5.3 Suggestions for Future Work

Because of the complexity and range of themes, it is impossible for any scientific endeavor to address all concerns at once; instead, researchers must give priority to some elements over others. This prioritizing frequently results in the identification of crucial issues that, although significant, cannot be thoroughly investigated within the confines of a single study. Some future study areas are listed below.

- ❖ This study considered a balanced load model, but future work could explore unbalanced load models.
- ❖ Future research should take into account the effects of DG integration, such as harmonics, stability issues, and short-circuit level, as well as reliability analysis, and consider these factors in objective function.
- ❖ Researchers could explore hybrid approaches, combining DG with FACTS devices and using hybrid optimization techniques, while also considering cost-effectiveness.
- ❖ Additionally, future research should consider a time-varying load model to better reflect real-world conditions.

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APPENDICES

Appendix A: Daily Irradiation, Clearness Index and Temperature of Gelan City

Table Appendix A: Daily Irradiation, Clearness Index and Temperature of Gelan City

Parameters	Year	Months											
Clearness Index		Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
	2018	0.67	0.64	0.62	0.57	0.58	0.48	0.46	0.45	0.59	0.64	0.62	0.7
	2019	0.75	0.67	0.65	0.57	0.59	0.5	0.43	0.44	0.45	0.63	0.61	0.66
	2020	0.7	0.66	0.61	0.59	0.57	0.54	0.38	0.39	0.5	0.65	0.7	0.72
	2021	0.7	0.64	0.67	0.57	0.58	0.55	0.36	0.48	0.48	0.63	0.66	0.71
	2022	0.66	0.66	0.65	0.59	0.63	0.52	0.39	0.42	0.48	0.6	0.68	0.65
Daily Radiation (Kwh/m ² /day)	2018	6.12	6.25	6.42	5.97	5.98	4.88	4.65	4.6	5.98	6.27	5.7	6.2
	2019	6.77	6.5	6.68	6.01	6.13	5.09	4.35	4.5	4.68	6.25	5.62	5.83
	2020	6.28	6.36	6.27	6.24	5.89	5.41	3.88	4	5.09	6.33	6.45	6.33
	2021	6.33	6.21	6.94	5.96	5.95	5.56	3.66	4.94	4.95	6.26	6.09	6.3
	2022	5.93	6.5	6.64	6.17	6.52	5.22	3.98	4.33	4.98	5.94	6.26	5.73
Temp (°C)	2018	28.3	30.72	31.36	31.55	31.48	24.35	22.93	22.73	23.93	23.99	24.52	27.23
	2019	30.64	31.76	32.19	28.4	31.57	27.58	23.51	22.52	22.88	23.92	23.94	24.83
	2020	28.05	32.17	32.41	32.85	30.15	24.95	22.31	22.14	22.84	23.44	23.58	25.43
	2021	26.84	28.78	32.36	31.94	27.58	27.64	22.33	23.07	23.48	23.43	24.02	25.8
	2022	26.78	29.88	31.87	32.9	31.76	29.69	23.03	22.72	22.98	23.58	23.57	24.6

Appendix B: Line Data of Gelan 3 Feeder

Table Appendix B: Line Data of Gelan 3 Feeder

Bus No	To Bus	From Bus	R (Ohm)	X(Ohm)	Bus No	To Bus	From Bus	R(Ohm)	X (Ohm)
1	1	2	0.07463	0.04477	55	55	56	0.0619	0.03713
2	2	3	0.4923	0.29531	56	56	57	0.02314	0.01388
3	3	4	0.06248	0.03748	57	57	58	0.01736	0.01041
4	4	5	0.05901	0.0354	58	58	59	0.19958	0.11972
5	5	6	0.29099	0.17455	59	59	60	0.19958	0.11972
6	6	7	0.04744	0.02846	60	60	61	0.10587	0.0635
7	7	8	0.1481	0.08884	61	61	62	0.00636	0.00382
8	8	9	0.1157	0.0694	62	62	63	0.56057	0.33626
9	9	10	0.08388	0.05032	63	53	64	0.01736	0.01041
10	10	11	0.0995	0.05969	64	64	65	0.08793	0.05275
11	11	12	0.15041	0.09023	65	65	66	0.19495	0.11695
12	12	13	0.05149	0.03088	66	66	67	0.03182	0.01909
13	13	14	0.10124	0.06073	67	67	68	0.01388	0.00833
14	14	15	0.12438	0.07461	68	64	69	0.09545	0.05726
15	15	16	0.11859	0.07114	69	54	70	0.07868	0.04719
16	16	17	0.38875	0.2332	70	70	71	0.20826	0.12493
17	17	18	0.00694	0.00416	71	71	72	0.14578	0.08745
18	18	19	0.14463	0.08676	72	72	73	0.01446	0.00868
19	19	20	0.09545	0.05726	73	73	74	0.00868	0.00521
20	20	21	0.17529	0.10515	74	74	75	0.17355	0.10411
21	21	22	0.12264	0.07357	75	75	76	0.01099	0.00659
22	22	23	0.09256	0.05552	76	76	77	0.09835	0.05899
23	23	24	0.79833	0.47889	77	77	78	0.06074	0.03644
24	24	25	0.22562	0.13534	78	78	79	0.03066	0.01839
25	25	26	0.15272	0.09161	79	57	80	0.05207	0.03123

26	3	27	0.49346	0.29601	80	80	81	0.02488	0.01492
27	4	28	0.09777	0.05865	81	81	82	0.10239	0.06142
28	28	29	0.24702	0.14818	82	82	83	0.25859	0.15512
29	6	30	0.69941	0.41955	83	83	84	0.04281	0.02568
30	30	31	0.01446	0.00868	84	84	85	0.03008	0.01805
31	31	32	0.18859	0.11313	85	85	86	0.02603	0.01562
32	32	33	0.05322	0.03193	86	14	87	0.02314	0.01388
33	33	34	0.05322	0.03193	87	87	88	0.24471	0.14679
34	34	35	0.03587	0.02152	88	88	89	0.0538	0.03227
35	35	36	0.01388	0.00833	89	12	90	0.0214	0.01284
36	36	37	0.08215	0.04928	90	90	91	0.10297	0.06177
37	37	38	0.02603	0.01562	91	91	92	0.20248	0.12146
38	38	39	0.06364	0.03817	92	92	93	0.07	0.04199
39	39	40	0.09025	0.05414	93	93	94	0.1429	0.04521
40	40	41	0.05033	0.03019	94	94	95	0.09448	0.02989
41	41	42	0.10066	0.06038	95	95	96	0.18896	0.05979
42	42	43	0.13595	0.08155	96	96	97	0.62003	0.19618
43	43	44	0.00983	0.0059	97	93	98	0.15353	0.04858
44	30	45	0.01678	0.01006	98	98	99	0.09448	0.02989
45	45	46	0.0862	0.05171	99	99	100	0.13936	0.04409
46	46	47	0.01273	0.00763	100	100	101	0.09448	0.02989
47	47	48	0.08909	0.05344	101	101	102	0.01417	0.00448
48	32	49	0.2314	0.13881	102	102	103	0.1925	0.06091
49	49	50	0.07578	0.04546	103	103	104	0.14054	0.04447
50	50	51	0.09661	0.05795	104	104	105	1.21525	0.38451
51	51	52	0.01562	0.00937	105	105	106	0.00463	0.00278
52	9	53	0.15099	0.09057	106	16	107	0.11859	0.07114
53	53	54	0.03066	0.01839	107	16	108	0.14231	0.08537
54	54	55	0.07463	0.04477					

Appendix C: Bus Data of Gelan 3 Feeder

Table Appendix C: Bus Data of Gelan 3 Feeder

Node No	Active Power(KW)	Reactive Power (KVA)	Node No	Active Power(KW)	Reactive Power (KVA)
1	0	0	55	180	87.17
2	283.5	137.3	56	90	43.5
3	0	0	57	0	0
4	0	0	58	283.5	137.5
5	283.5	137.3	59	22.5	10.9
6	0	0	60	180	87.17
7	180	87.17	61	90	43.5
8	360	174.35	62	22.5	10.9
9	0	0	63	180	87.17
10	0	0	64	0	0
11	90	43.5	65	360	174.35
12	0	0	66	180	87.17
13	360	174.35	67	22.5	10.9
14	45	21.8	68	180	87.17
15	283.5	137.3	69	180	87.17
16	283.5	137.3	70	90	43.5
17	0	0	71	45	21.8
18	180	87.17	72	22.5	10.9
19	90	43.5	73	180	87.17
20	450	217.9	74	45	21.8
21	45	21.8	75	22.5	10.9
22	283.5	137.3	76	45	21.8
23	283.5	137.3	77	90	43.5
24	567	274.6	78	22.5	10.9
25	567	274.6	79	22.5	10.9
26	45	21.8	80	22.5	10.9
27	22.5	10.9	81	180	87.17
28	180	87.17	82	22.5	10.9
29	90	43.5	83	90	43.5
30	0	0	84	22.5	10.9
31	283.5	137.5	85	180	87.17
32	22.5	10.9	86	90	43.5
33	45	21.8	87	45	21.8

34	90	43.5	88	90	43.5
35	45	21.8	89	0	0
36	0	0	90	90	43.5
37	90	43.5	91	90	43.5
38	180	87.17	92	45	21.8
39	180	87.17	93	22.5	10.9
40	90	43.5	94	45	21.8
41	283.5	137.5	95	22.5	10.9
42	180	87.17	96	45	21.8
43	45	21.8	97	90	43.5
44	45	21.8	98	283.5	137.5
45	180	87.17	99	22.5	10.9
46	45	21.8	100	0	0
47	90	43.5	101	283.5	137.5
48	180	87.17	102	283.5	137.5
49	90	43.5	103	22.5	10.9
50	180	87.17	104	45	21.8
51	90	43.5	105	45	21.8
52	90	43.5	106	283.5	137.5
53	0	0	107	45	21.8
54	0	0	108	45	21.8

Appendix D: Ethiopian Electric Utility Energy Tariff

Table Appendix D: Ethiopian Electric Utility Energy Tariff amendment study according to consumer's class(EEU, 2019)s

Tariff amendment		As of Dec. 18 onward	As of Dec. 19 onward	As of Dec. 20 onward	As of Dec. 21 onward
Tariff Category	kwh/month	Birr/kwh	Birr/kwh	Birr/kwh	Birr/kwh
1.Residential tariff block					
1.1 1st block	Up to 50kwh	0.2730	0.2730	0.2730	0.2730
1.2 2nd block	Up to100kwh	0.4591	0.5617	0.6644	0.7670
1.3 3rd block	Up to 200kwh	0.7807	1.0622	1.3436	1.6250
1.4 4th block	Upto300kwh	0.9125	1.2750	1.6375	2.0000
1.5 5th block	Upto400 kwh	0.9750	1.3833	1.7917	2.2000
1.6 6th block	Upto500kwh	1.0423	1.4965	1.9508	2.4050
1.7 7th block	Above500kwh	1.1410	1.5877	2.0343	2.4810
2. General Tariff					
2.1 Flat Rate		1.0352	1.3982	1.7611	2.1240
3. Low Voltage Industry Tariff					
3.1 Flat Rate		0.8161	1.0544	1.2927	1.5310
3.2 Demand Charge rate		50.00	100.00	150.00	200.00
4. Medium Voltage Industry Tariff. 15kv & 33kv					
4.1 Flat Rate		0.6047	0.8008	0.9969	1.1930
4.2 Demand Charge rate		36.885	73.770	110.655	147.540
5. High Voltage Industry Tariff. Above 66kv					
5.1 Flat Rate		0.5174	0.6540	0.7911	0.9280
5.2 Demand Charge rate		21.9100	43.8200	65.7300	87.6400
6. Street Light Tariff					
6.1 Flat Rate		1.0352	1.3982	1.7611	2.1240
7. Bulk Supply Tariff					

Appendix E: Thesis Work Sample Matlab Program

Appendix E 1: Matlab Code for Backward and Forward Sweep Method

```
% Read data from Excel file
linedata = xlsread('Feederdata.xlsx', 'linedata');
busdata = xlsread('Feederdata.xlsx', 'busdata');

% Set base values
baseKV = 15;
baseMVA = 100;
PBASE = baseMVA * 1000;
ZBASE = (baseKV^2) / baseMVA;

% Convert data to per unit
busdata(:, 2:3) = busdata(:, 2:3) / PBASE;
linedata(:, 4:5) = linedata(:, 4:5) / ZBASE;
perunit_imped = complex(linedata(:, 4), linedata(:, 5));

% Generate BIBC matrix
[bibc_matrix] = bibc_gen(linedata, busdata);

% Remove source rows and columns from BIBC matrix
bibc_matrix(source_num, :) = [];
bibc_matrix(:, source_num) = [];
final_bibc_matrix = bibc_matrix';

% Calculate DLF matrix
final_bcbv_matrix = final_bibc_matrix' * diag(perunit_imped);
final_dlf_matrix = final_bcbv_matrix * final_bibc_matrix;

% Calculate load matrix
complex_load_d = complex(busdata(:, 2), busdata(:, 3));
complex_load_g = zeros(size(busdata, 1), 1);
final_load_matrix = (complex_load_d - complex_load_g);
final_load_matrix(length(source_num)) = [];

% Initialize voltage and set iteration parameters
initial_volt_value = ones(size(busdata, 1) - length(source_num), 1);
voltage_drop_value = initial_volt_value;
```

```

max_iter = 100;
% Perform backward sweep iterations
for ind_lop = 1:max_iter
    % Calculate injected current
    inject_current_data = conj(final_load_matrix ./ voltage_drop_value);
    % Calculate branch currents and voltage drops
    IB = final_bibc_matrix * inject_current_data;
    old_volt = voltage_drop_value;
    volt_drop_each = final_dlf_matrix * inject_current_data;
    voltage_drop_value = initial_volt_value - volt_drop_each;
    % Check convergence
    error_volt_tolr = max(abs(old_volt - voltage_drop_value));
    if error_volt_tolr <= 0.2e-3
        break;
    end
end
% Calculate final voltage data and voltage drops
final_volt_data = [ones(length(source_num), 1); voltage_drop_value];
locvoltm = find(final_volt_data > 1);
final_volt_data(locvoltm) = 1;
for ind = 1:length(from_node)
    volt_diff_value(ind,:) = final_volt_data(from_node(ind)) - final_volt_data(to_node(ind));
end
volt_diff_value1 = abs(volt_diff_value);

```

Appendix E 2: Matlab Code for Genetic Algorithm

```
% Selection Probabilities
c = [pop.Cost];
avgc = mean(c);
if avgc ~= 0
    c = c/avgc;
end
probs = exp(-beta*c);
% Initialize Offsprings Population
popc = repmat(empty_individual, nC/2, 2);
% Crossover
for k = 1:nC/2
    % Select Parents
    p1 = pop(RouletteWheelSelection(probs));
    p2 = pop(RouletteWheelSelection(probs));
    % Perform Crossover
    [popc(k, 1).Position, popc(k, 2).Position] = ...
        UniformCrossover(p1.Position, p2.Position, gamma);
end
% Convert popc to Single-Column Matrix
popc = popc(:);
% Mutation
for l = 1:nC
    % Perform Mutation
    popc(l).Position = Mutate(popc(l).Position, mu, sigma);
    % Check for Variable Bounds
    popc(l).Position = max(popc(l).Position, VarMin);
    popc(l).Position = min(popc(l).Position, VarMax);
    % Evaluation
    % popc(l).Cost = CostFunction(popc(l).Position);
    popc(l).Cost=Loadflow_DG(popc(l).Position,Num_DG,Type_DG);
```

```
% Compare Solution to Best Solution Ever Found
if popc(l).Cost < bestsol.Cost
    bestsol = popc(l);
```

Appendix F: Gelan 15 KV Feeders Peak Load and Interruption Data

Table Appendix E: Gelan 15 KV Feeders Peak Load and Interruption Data

Name of 15 15KV Feeder	Gelan 15 KV 2015 Interruption and Peak Load Data										Total Interruption		Peak load
	Permanent Fault				Temporary Fault				OP(Planned)				
	DPEF		DPSC		DTEF		DTSC						
	F	D [Hr.]	F	D [Hr.]	F	D [Hr.]	F	D [Hr.]	F	D [Hr.]	F	D(Hr)	MW
Gelan – 1	6	60.25	8	28.5	11	0.4	7	2	11	17	43	108.15	3.29
Gelan – 2	2	32.75	3	24.44	4	0.2	2	1	9	19	20	77.29	4.67
Gelan – 3	11	62.13	14	31.23	13	0.8	6	3	13	23.67	57	120.83	7.48
Gelan – 4	3	12.5	5	11.32	7	0.7	6	0.27	8	16.8	29	30.59	6.37
Gelan – 5	5	23.17	6	16.45	6	0.57	3	1.35	11	12.3	31	53.84	4.53
Gelan – 6	7	47.89	12	36.5	9	1.6	0	0.15	5	5.6	33	91.74	3.68
Gelan – 7	5	26.5	9	23.6	8	1.2	7	0.5	14	17	43	68.8	7.13
Gelan – 8	12	25.3	10	29.74	10	1.23	5	0.95	12	14	49	71.22	4.24
Gelan - 9	1	2	0	1	4	0.35	0	2	7	8	15	13.35	3.14

Note: DPEF = Distribution Permanent Earth Fault

DPSC = Distribution Permanent Short Circuit

DTEF = Distribution Temporary Earth Fault