Addis Ababa University

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

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

A Thesis Submitted to Addis Ababa Institute of Technology, School of Graduate Studies, Addis Ababa University

In partial fulfillment of the requirement for the Degree of Master of Science in Electrical Power Engineering

By: Biniyam Abayneh

Advisor: Dr. Ing. Fekadu Shewarega

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DECLARATION

I guarantee that this thesis is my original work, that the work detailed in it has never been submitted for a degree at this or any other university, and that all sources and materials utilized in the thesis have been properly acknowledged.

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This thesis has been submitted for examination with my approval as a university advisor.

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Finally, I praise and glorify the name of GOD, the Almighty, the Creator who creates all these nice people and these pleasant opportunities.

ABSTRACT

This research presents the way of improving the performance of the distribution network by improving the voltage profile and reduces the power loss by integrating D-STATCOM to Kotebe K3 distribution feeder. Kotebe distribution substation is one of the distribution substations found in Addis Ababa, Ethiopia feeding areas around Kotebe, Wesen, CMC, Figa and Gurdshola. Among those feeders, Kotebe K3 has been selected as test system due to its longest rout length, large loads and high permanent power interruption rate. The selected feeder has been modeled in MATLAB computational tool and load flow analysis has been simulated using Newton-Raphson method. It has been observed that the Newton-Raphson load flow simulation of Kotebe K3 gives a power loss of 1.7351 MW and 0.7080 MVAR respectively and 41 buses below the expected voltage range.

This research uses a hybrid of Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) for optimal placement and sizing of D-STATCOM for power loss reduction and improvement of voltage profile. The GA-PSO optimization technique considers both real and reactive power losses. The combined sensitivity factor uses both real and reactive sensitivity factors to identifying the candidate buses for D-STATCOM allocation. The combined sensitivity factor identifies bus 22,23,24,25 and 26 as the most five sensitive buses, which are used for placement of D-STATCOM. The GA-PSO optimized result shows that bus 22 is the most effective bus for placing D-STATCOM in terms of reducing the power loss at relatively small size and keeps the bus voltage under the acceptable range. The simulation result of the integrated D-STATCOM on bus 22 reduces the real power loss from 1.7351 MW to 1.0948 MW, which is by 36.90%, and the reactive power loss from 0.7080 MVAR to 0.4453 MVAR, which is by 37.11%, while maintaining all bus voltages in the range between 0.95 and 1.05pu. Furthermore, a comparison analysis shows that GA-PSO method gives the greatest reduction in both real and reactive power loss compared to GA and PSO methodologies.

Key words: D-STATCOM, GA, PSO, Power loss reduction, Voltage profile improvement

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LIST OF ACRONYMS

AC	Alternating Current
CSF	Combined Sensitivity Factors
DG	Distributed Generator
D-STATCOM	Distribution Static Synchronous Compensator
EEU	Ethiopian Electric Utility
ETB	Ethiopian Birr
FACTS	Flexible Alternating Current Transmission Systems
GA	Genetic Algorithm
N-R	Newton-Raphson
PLRI	Real Power Loss Reduction Index
PV	Photovoltaic
PSO	Particle Swarm Optimization
SVC	Static Var compensator
SSSC	Static synchronous series compensator
TCPST	Thyristor-controlled phase shifting transformer
QLRI	Reactive Power Loss Reduction Index
VPII	Voltage Profile Improvement Index
VSC	Voltage source converter
UPFC	Unified power flow controller
USD	United States Dollar

CHAPTER ONE

INTRODUCTION

1.1 Background

The distribution system is the most important part of an electrical power network. It is a part of the power system that distributes power in ready-to-use form to various customers at their point of consumption. As a result, utilities must provide reliable, efficient, and cost-effective service while maintaining required service voltages and power quality.

In Ethiopia electric power distribution system is labeled as medium voltage for 45kV, 33kV and 15kV. Mostly 33kV and 15kV overhead conductors are used for feeding up to 80 distribution step down transformers on each of 33kV and 15kV feeder then voltage reaches to the customer reduced as to 380 volts three-phase or 220 volts single-phase [1].

Power losses occur at each stage of the power distribution process. When compared with other, distribution loss is very high, since it operates at low voltage. The other problem of the distribution networks is voltage drop problem. Distribution feeders absorb or supply reactive power depending on the load current. Feeders provide net reactive power at loads below surge impedance loading and absorb reactive power at loads above surge impedance loading. As a result, voltage drop issues may emerge when employing long-distance distribution feeders or feeding heavy loads [2].

The equipment in the distribution system is designed to function at a specific voltage level. For distribution power systems to operate efficiently and reliably, voltage and reactive power regulation must achieve the following goals. To reduce the distribution system's active and reactive line losses to a bare minimum and to maximize the system's utilization level, the voltage at the terminals of all equipment in the system should be within acceptable limits, so the reactive power flow is limited [3].

Kotebe substation is located at the Eastern part of Addis Ababa and delivers electric power at 15kV level to different areas in the vicinity of the substation. In addition, 132kV outgoing feeders also available routing to Kality and Addis East substations. The low voltage radial feeders of Kotebe substation are characterized by overloading of the line, high power interruption rate and under voltage at the customer premises.

Distribution lines are driven near to or even beyond their transfer capacity as a result of rising electric power demand, resulting in overloaded lines and congestion. Several technologies, such as Flexible AC Transmission Systems (FACTS) devices, can be used to alleviate electricity congestion. [4]. STATCOM is a type of shunt FACTS device used in high voltage transmission network. It's called D-STATCOM when it's utilized in a low-voltage distribution network. In the near future, it will be one of the most widely utilized methods for improving voltage profiles in distribution networks. The effect of voltage profile augmentation would be greatly influenced by the placement and size of D-STATCOM [5].

1.2 Statement of Problem

Demand for electrical power is increasing from time to time due to living standard changes in Addis Ababa. As a result, the distribution feeders which transfer power from substation to the customers are overloaded beyond their power carrying capacity. Overloaded distribution feeders that travel long distances have large power losses and degradation of voltage profile too. In this regard, finding loss reduction and voltage profile improvement mechanisms for the distribution networks is a critical issue. It is therefore important to consider the current technologies such as D-STATCOM as a way to overcome the problem. Optimal allocation of D-STATCOM can improve the distribution systems voltage profile and reduce power loss too. Kotebe substation feeders cover large areas and there are a lot of power interruptions with a considerable voltage drop amount. The GA-PSO optimization technique is used to find the optimal size and location of D-STATCOM.

This thesis considers the problem of power loss reduction and voltage profile improvement of Kotebe distribution system by optimal placement of D-STATCOM using a hybrid of GA-PSO method.

1.3 Objectives of the Thesis

General Objective

The general objective of this thesis is to carryout studies on power loss reduction and voltage profile improvement on Kotebe distribution feeder through optimal allocation of D-STATCOM using a hybrid of Genetic algorithm and Particle swarm optimization method.

Specific Objectives

The specific objectives of this thesis are:

- ❖ To collect necessary data and analyze Kotebe substation outgoing feeders. Which are monthly peak load data, monthly power interruption data, routes of the feeders and line data used on the feeder
- ❖ To perform load flow analysis of Kotebe distribution system for determination of power loss and voltage drop using Newton-Raphson method
- ❖ To formulate a combined sensitivity factor (CSF) so as to find the weakest and sensitive buses along the feeder
- ❖ To formulate a multi-objective function taking into consideration real power loss reduction index (PLRI), reactive power loss reduction index (QLRI) and voltage profile improvement index (VPII).
- ❖ To formulate and use a hybrid GA-PSO approach for optimal allocation of D-STATCOM in the distribution system.
- ❖ To analyze the effect of D-STATCOM integration on the distribution system power losses and voltage profiles in comparison with the base case.
- ❖ To draw conclusions and recommendations based on the finding of this research.

1.4 Methodology

Before visiting the substation, I started by reviewing books, published literature from international electrical engineering journals such as the Institute of Electrical and Electronics Engineers (IEEE) found and reviewed with important relevant subjects related to voltage profile improvement, power loss reduction and different technologies introduced so far to mitigate the problem. Historical and current important data of the existing network have been collected from Ethiopian electric power and Ethiopian electric utility. Interview with engineers of the substation and distribution network have been considered. The following relevant information’s have been gathered for the successful completion of this study. These were monthly peak load data of the feeders, line data, bus data, routes of the feeder, interruption data, the current electricity tariff of the country and the last but not the list discussed with the substation engineers about the electrical and technical characteristics of the substation and the feeders they observed so far.

The block diagram describing the methodology followed in this thesis given in Figure 1.1.

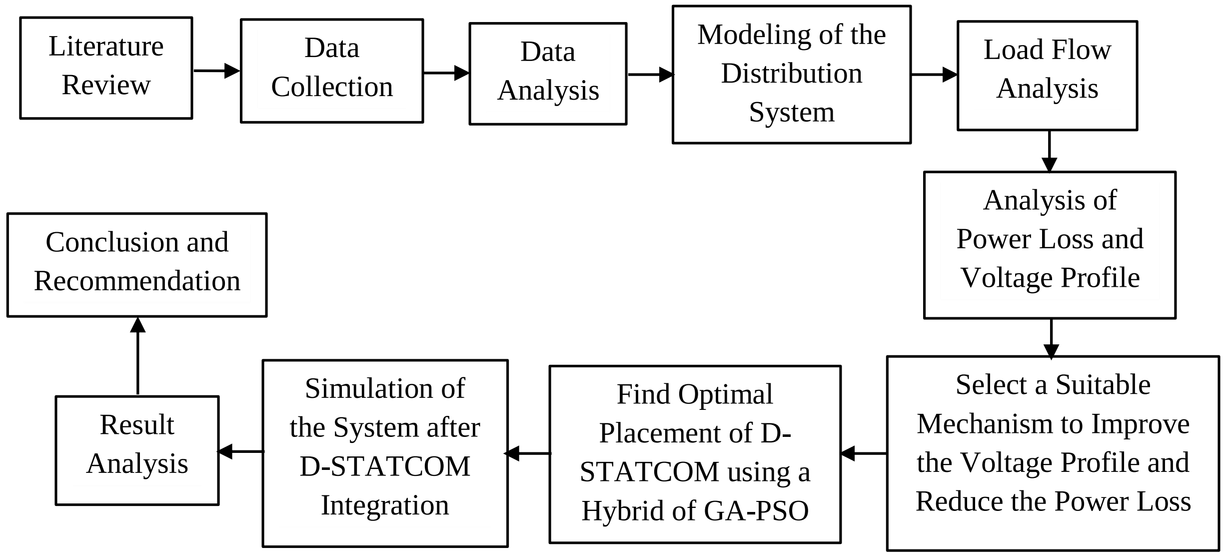


Figure 1.1: Block diagram of the research methodology

Using the collected data, the base case network model was developed with the help of MATLAB software. Newton-Raphson method is selected for performing load flow analysis of the distribution system. Newton-Raphson is selected due to its fast convergence, less computational time and superior performance than Gauss-Seidel method. After the selection of the suitable method, a power flow analysis was carried out to determine the initial power loss and voltage profile of the distribution network. Base on the result obtained on the load flow and the behavior of the distribution system a feasible and efficient technology has been selected from the available technologies for improving the ability of the power distribution system.

Two artificial intelligence optimization methodologies, namely GA and PSO algorithms, are integrated in this thesis to provide a more superior algorithm for this goal. The goal of the hybrid approach is to keep the positive aspects of both techniques while avoiding the negative aspects. Some GA operators, that is, crossover and mutation are incorporated in the PSO algorithm so as to help in coming up with more superior particles as well as discarding the inferior ones.

Both real and reactive power flow and power loss sensitivity factors are used in identifying the candidate buses for D-STATCOM allocation. This aids in reducing the search space for the algorithm thus reducing the iteration time. Moreover, the multi-objective function contains both real and reactive power loss reduction index and voltage profile improvement index has been incorporated with the hybrid GA-PSO to find the best location and the size of D-STATCOM. Finally, the base case is compared with that the compensated system and economic analysis has performed for the selected mechanism.

1.5 Scope of the Thesis

The thesis is limited to the optimal allocation of D-STATCOM in a distribution network. The impact of D-STATCOM on the distribution network is investigated. The thesis is limited to investigating only the impact on power losses and voltage profile improvement.

1.6 Organizations of the Thesis

The organization of the thesis has been made in such a way that the reader finds an introduction, literature review of different methods for improving voltage deviation and power loss reduction, results of the simulations, conclusion and future work. The layout of the thesis is as follows:

Chapter one gives an introduction background, statement of the problem, objectives of the study, scope, methodology followed in the thesis work and finally it provides the thesis outline.

Chapter two gives the detail of theoretical background and review of different literatures related to voltage profile improvement and power loss minimization in the distribution network and optimization techniques used to solve voltage drop and power loss reduction in the distribution network.

Chapter three describes data collection process, the type of data collected for Kotebe distribution feeder and modeling of the distribution network.

Chapter four covers mainly the implementation of GA-PSO formulation to help in solving the problem stated. Here the combined sensitivity factors are described and formulated. The multi-objective function and the operational constraints are also formulated in this chapter.

Chapter five presents simulation studies using MATLAB software and analysis of the results.

Chapter six includes the conclusions, recommendations and suggestions for future work to further investigate the research work carried out in this thesis.

CHAPTER TWO

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

This chapter reviews the related theoretical background and literature reviews of the study. Section 2.2 presents about electric power distribution system and section 2.3 presents about power loss and voltage drop in the power distribution system. Techniques for power loss reduction and voltage profile improvement are discussed in section 2.4. Section 2.5 reviews about distribution static synchronous compensators. Section 2.6 presents about modelling of D-STATCOM. Section 2.7 discussed about a comparison analysis between D-STATCOM and a conventional device. Literature review is presented in section 2.8.

2.2 Electric Power Distribution System

Electric power distribution is the final stage of electric power delivery; it transports energy from the transmission system to individual users, industry, and other power-dependent infrastructure. The medium voltage electricity is delivered to distribution transformers near the customer's location by primary distribution lines. The primary distribution system connects the distribution substation and distribution transformers in the electric distribution system. Secondary feeders or distribution feeders are the circuits that make up the system. Power is provided to both primary and secondary circuits by a standard power distribution feeder.

An electrical grid is a network of interconnected power lines that transport electricity from generating stations to consumers. It is made up of producing stations that generate electricity, high-voltage transmission lines that transport electricity from far sources to demand centers, and distribution lines that link end customers. Within the substation, high voltage power lines run through step down transformers, resulting in a useable voltage that is divided and delivered in various directions through low voltage power feeders [1]. A distribution transformer steps the primary distribution power down to a low-voltage secondary circuit, usually 380/220 volts.

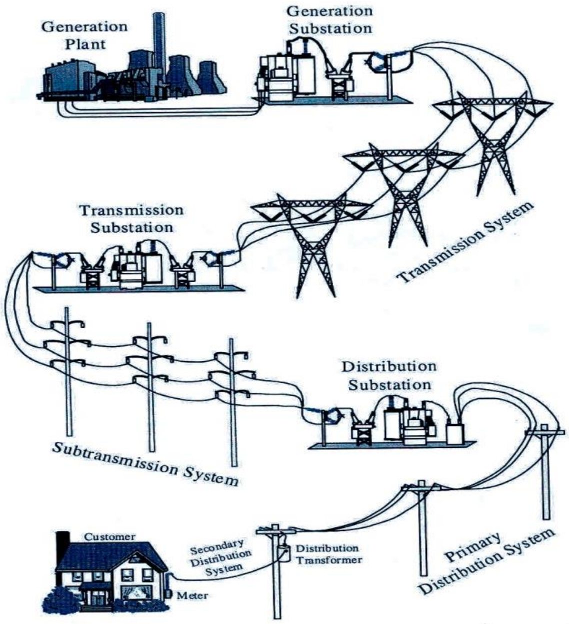


Figure 2.1: Electric power distribution system

Distribution network losses are conventionally divided into two parts [5]:

- Technical losses
- Non-technical losses

Technical Losses: Technical losses in power systems are caused by energy dissipation in electrical system components such lines, transformers, interconnections, monitoring systems, and other equipment that transfer energy to and from customers. Technical losses are sometimes known as 'Physical losses,' since they refer to energy that is converted to heat and noise during the distribution of electricity and therefore physically lost. Customers pay for this energy waste, and it contributes to carbon emissions. The physical qualities of the electrical equipment used in distribution networks directly cause technical losses. They depend on the design of the power grid, the voltage and transformation levels and the length of the power lines [5].

Technical losses can be further divided into variable losses and fixed losses [2][5]

Variable Losses: All conductors, whether they are coils in transformers, aluminum or copper wires in overhead lines or cables and even in switchgear, fuses, or metering equipment, have an internal electrical resistance which causes them to heat when transporting electric current.

Because energy losses from heat dissipation to the environment are proportional to the current flowing through conductors in electrical networks, these losses are called 'variable losses'. These losses are also usually referred as 'ohmic losses', 'copper losses' or 'resistive losses'. Transmission networks see reduced losses as a result of variable losses altering as power flows grow and decrease, since at higher voltages, a lower current is required to transport the same amount of electric power. Distribution networks, on the contrary, suffer from larger losses (at lower voltages). Additional factors that affect the value of currents flowing through conductors, such as network imbalance, power factor, and power quality, can have an impact on variable losses. Variable losses, which change in proportion to the resistance, are also affected by the length and cross section of the conductor.

Fixed Losses: As a result of being linked to the network and powered, some electrical energy is wasted by network components and equipment like transformers and wires. Even if no power is delivered to customers, the system has losses just because it is electrically energized. Fixed losses do not change with current; they depend on the applied voltage. However, as the applied voltage is relatively stable while the network equipment is energized, they are essentially fixed. Therefore, fixed losses are a function of the network itself and depend mainly on the number of energized components.

Non-Technical Losses: In addition to technical losses, not all of the energy delivered through the distribution network and consumed by end users can be measured or otherwise properly accounted-for. These additional losses also present themselves as 'lost energy'. The majority of non-technical losses are due to misidentified, misallocated, and incorrect energy flows. They are, in essence, the quantity of energy given but not accounted for. It's critical to distinguish non-technical losses from two scenarios: energy accounted for but not invoiced, and energy billed but not paid. The thing using the energy is known in both circumstances. Non-technical losses, on the other hand, have an unknown end user or an unknown amount of energy utilized [5].

Non-technical losses include [2][5]:

Theft and Fraud: Illegally obtaining power from the network may be accomplished in a number of ways. The majority of non-technical losses in power systems are thought to be due to theft and fraud. Any unauthorized abstraction of power for consumption elsewhere than at premises where any metering points or metering systems have been registered by a supplier is classified as theft. It can happen when an unauthorized network connection is formed or when an unlawful reconnection is made. The unauthorized abstraction of power inside the boundaries of a customer's property is referred to as fraud. All metered customers purchase electricity from a supplier and are associated to a registered meter point. Fraud happens as a result of an ill-intentioned and illegal manipulation of the meter, by tampering or bypassing the meter.

Measurement errors: Errors in measurement Is the disparity between the quantity of energy provided through the meter and the amount that the meter records. Measurement errors may occur due to: uncertainty of measurement equipment, errors in manual or automatic meter reading, defective measurement equipment and incorrect installation or configuration of measurement equipment.

2.3 Power Loss and Voltage Drop

Voltage drop and power loss Electrical power losses in distribution systems are affected by a variety of factors, including the amount of power lost through transmission and distribution lines, transformers, capacitors, and insulators, among others. There are two types of power losses: actual power loss and reactive power loss. Real power loss is caused by line resistance, whereas reactive power loss is caused by reactive elements. Real power loss usually attracts the utilities' attention since it decreases the efficiency of transporting energy to customers. Reactive power loss, on the other hand, is unquestionably significant. This is because the system's reactive power flow must be maintained at a specific level in order to maintain a proper voltage level. As a result, reactive power allows actual power to be sent to customers via transmission and distribution lines [6].

The distribution network is the terminal stage of power system and ended by consumers. Consumers and utilities are both affected by faults in the distribution network. One of these issues is voltage loss, which must be decreased in order to keep voltages at load sites within acceptable ranges. When employing lateral radial feeders over long distances or feeding heavy loads, the voltage drop problem might occur. As a result, the solution to this challenge becomes critical, requiring that the voltage at various nodes of the system be managed. The term "voltage control" really refers to the regulation of reactive power. As a result of controlling reactive power and regulating node voltages, power loss is reduced, which is a major problem for utilities. The distribution systems are equipped with a variety of voltage regulating devices, including as network restructure, DG implementation, tap change transformers, voltage regulators, shunt/series capacitors, FACTS device integration, and so on, to improve voltage and regulate reactive power [6].

2.4 Techniques for Power Loss Reduction and Voltage Profile Improvement

There are different techniques to reduce power loss and voltage deviation of a distribution feeder. Some of these techniques have been discussed here is this section

Network reconfiguration: The process of manipulating switches to modify the circuit topology in order to lower operating costs while meeting specified limits is known as network reconfiguration. Network reconfiguration, in which the power flow is altered by the development of new links, is one of the available strategies for minimizing loss in distribution systems with a feeder to form tree structure or by opening or closing the appropriate switches on the feeder. Feeder reconfiguration allows loads to be transferred from severely loaded feeders to lighter-laden feeders, and from higher-resistance routs to lower-resistance routs to achieve the lowest loss, where the resistance route is the entire resistance from the source to the load point. Such transfers are successful not only in terms of changing the amount of loads on the switched feeder and lowering losses, but also in terms of improving the voltage profile on the feeders and lowering total system power losses. Feeder reconfiguration, on the other hand, is successful if the distribution feeders are automated and not too far apart. For an unautomated and fare apart feeders, feeder reconfiguration may not be cost effective [2]. he key benefits of reconfiguration are as follows [7]:

- Service recovery during feeder faults
- Network maintenance for both corrective and preventive maintenance
- Network overload relief and bus voltage improvement
- Loss minimization

Conductor Grading: Conductor grading is the technique of replacing the existing conductor on the feeder by a highly efficient and perfectly designed conductor to minimize the resistance. This can be achieved by replacing the small size cables with a larger cross-sectional area with less resistive value, or by installing auxiliary conductors to work in parallel with the existing ones. So that the equivalent resistance is reduced. Although these methods could give a large loss reduction, it is not cost effective, and it is not used unless there is a special need, as the cost of conductors and their installation are usually in excess of the cost of the energy saved [2].

Shunt and Series Capacitor Compensation: Shunt capacitive compensation is commonly used in electrical power systems to decrease active and reactive power losses and to obtain recognized voltage levels during severe reactive loading circumstances. Shunt capacitive compensation devices are often used to reduce losses and voltage dips in transmission and distribution systems. The development of shunt active compensators, such as Static Var Compensator (SVC) and Static Compensator (Statcom) devices, has been aided by advancements in the power electronics filed. One of the major key applications of such devices is to compensate for system reactive power and keep system voltage profiles at desirable levels [8].

The transmission and distribution lines are linked in series with capacitors in series compensation. This lowers the transfer reactance between buses linked to the line, increases the maximum power that can be conveyed, and lowers effective reactive power losses. It is mostly used in a very big high voltage line. Although series capacitors are not often used for voltage control, they do help to improve the voltage and reactive power balance of the system. The reactive power produced by a series capacitor rises in proportion to the transmission line's transmitted power [8].

Shunt capacitors are less costy to install and maintain in comparison with FACTS controllers. Shunt capacitors installed in the load region or at the point where they are required will improve voltage stability. Shunt capacitors, on the other hand, have poor voltage control and cannot achieve a steady working point beyond a certain amount of compensation. Furthermore, the shunt capacitor's reactive power is related to the square of the terminal voltage; when the terminal voltage is low, Var support lowers, worsening the situation. [9].

Distributed Generation (DG): Distributed Generation (DG) is one of the latest trends in power systems used to support the increased demand. DG concepts involve many technology and application. According to the definition of DG, it is the generation of electricity by facilities that are smaller than grid connected generating plants and allow interconnection at nearly any point in a power system. IEEE likened the size of the DG to that of a typical generating plant. Chambers looks into the economic aspect of his concept, which is offered by the International Council on Large Electric Systems (CIGRE). "The relatively modest generating units of 30 MW or fewer that are sited at or near customer sites to address specific customer demands, to maintain the economic functioning of the distribution grid, or both," he describes distributed generation as [10].

Different distributed generation technologies are involved in power systems. Some of these technologies have been in use for a long time while others are newly emerging. However, the features that all DG technologies have in common are to improve efficiency and cut down costs related to installation, running and maintenance. DG technologies are broadly categorized into two types: renewable technologies (for example, photovoltaic and wind turbine) and nonrenewable technologies (for example Micro-turbines, Combustion turbines and fuel cells). DG technologies have an important impact on the choice of the appropriate size and place, to be connected to a power system or customer loads [10][11]. Here the details of the most feasible, for this specific study, DG technologies were discussed

Fuel cells: Fuel cells are relatively new and considered an emerging DG technology. Their application as distributed generation ranges from a few kW to 3 MW capacity. They are electrochemical devices that convert chemical energy from a fuel directly into electrical energy by combining oxygen, as an oxidant, and hydrogen, as a fuel, without combustion [10]. The hydrogen is usually procured from a fossil fuel “natural gas” while air is used as a source of oxygen. The result of this electrochemical process is high-current/low-voltage DC power. To connect the fuel cell to the grid, a DC/AC converter and filter system current are used to convert the output to AC power. Fuel cells efficiencies ranges from 40 to 60% in production of electricity, with negligible harmful emissions, and operate so quietly that they can be used in residential environment. These are the merits of fuel cells, besides their scalability and modularity. The main disadvantage of the commercialization of fuel cells is the huge investment cost [10][11]. The use of fuel cells brings the following advantages [12]

- ***Higher Efficiency:*** The higher efficiency of fuel cells is a consequence of the direct (chemical) production of electric energy from the fuel used. As a result, the Carnot thermic cycle restrictions, which hamper all combustion-based electric generating systems, have no effect on the approach.
- ***Low Chemical, Acoustic, and Thermal Emissions:*** Due to better efficiencies and lower fuel oxidation temperatures, fuel cells produce less carbon dioxide and nitrogen oxides per kilowatt of electricity generated. Another feature is that noise and vibration are minimal

because fuel cells have no moving parts (except for ancillary pumps, blowers, and transformers).

- ***Modularity:*** A single fuel cell will have an electrical potential of less than one volt. Fuel cells are layered on top of each other and linked in series to create larger voltages. cascading fuel cell units, each with an anode, cathode, electrolyte, and bipolar separator plate, make up cell stacks. The number of cells in a stack depends on the desired power output and individual cell performance. The stacks have sizes which range from a few hundreds of W to several hundred of kW (up to some MW).
- ***Fuel Flexibility:*** Natural gas, propane, landfill gas, anaerobic digester gas, military logistic fuels, and coal gas have all been used to demonstrate fuel adaptability in a number of different systems. Hydrogen is the most commonly used fuel (especially for low temperature fuel cell technologies that require pure gasses to operate); Natural gas, propane, landfill gas, anaerobic digester gas, military logistic fuels, and coal gas have all exhibited fuel adaptability in various systems. This flexibility depends for the most on the operative temperature range of the type of fuel cells used (in principle, the higher the temperature the less pure the gas that the fuel cell can use).

Even though they can offer a number of significant benefits, all fuel cell technologies are still in the early stages of research and are plagued by a number of issues that make their usage less convenient than that of other technologies presently in use [12].

- Fuel cell pricing (€/Wh) for stationary electric generation are still too high, rendering them unsuitable for replacing fossil-fuel-based systems.
- Many fuel cell technologies' life cycles and deterioration times (particularly high temperature technologies, which are optimal for electric power production) are yet unknown.
- Hydrogen, which is one of the primary fuels for fuel cell technologies, is costly, and there is currently no network for its manufacture and distribution.

Wind Power: The technology used for converting the kinetic energy of wind to electricity is a wind turbine. Recently, a new development observed in this field has been to increase the output of power generation. Peak wind speed zones, such as high altitude and sea-side places, are desirable for extracting maximum energy from these wind turbines. Wind turbines have been increasingly integrated into distribution networks in recent years because to their inexhaustible and nonpolluting features. Power generation from wind turbines is fuel free and requires less operational and maintenance cost compared to power generation through conventional means. The biggest disadvantage of this technology is the unpredictability of its output. The wind speed varies during the day. The wind speed varies during the day. This causes changes in its power output, which degrades power quality by increasing voltage profile rise and dips, power losses, and decreasing the voltage stability of the power system [12].

Photovoltaic system: Because of increased industrialization, population growth, and higher living conditions, global energy demand is expanding faster than energy generation. Distributed generation (DG) near end users can help to maintain the electrical grid's stability and improve the quality of the power system. The DG is made up of a small-scale technology that uses renewable energy or generators to create electricity close to the end users. A photovoltaic (PV) system is a collection of solid-state semiconductor devices that generate energy when exposed to light. A solar cell is the component that makes up a solar panel. A photovoltaic module is made up of several solar cells connected in series and parallel. PV modules are linked in series to achieve maximum output voltage, and in parallel to achieve maximum output current. Many nations have marketed solar PV power systems because of its advantages, such as long-term benefits and little maintenance. Dealing with the nonlinear properties of PV arrays is a key difficulty when deploying PV power production systems. PV characteristics are affected by the amount of irradiance and the temperature. Due to passing clouds, neighboring buildings, or trees, the PV array receives varying amounts of irradiance [13].

Implementing photovoltaic system distribution generation PVDG has a number of advantages, including higher dependability and lower losses. Aside from that, integrating PVDG into the distribution system might enhance the voltage profile, allowing the system to handle higher loads. Other benefits include reduced transmission and/or distribution stress. Finally, DG technologies such as combined heat and power and micro-turbines pollute the environment less and are more efficient. While renewable energy-based DG, such as PVDG, produces no emissions and does not contaminate the environment, There are certain disadvantages to the technique. PVDG penetration levels beyond a certain threshold may result in reverse power flow at the feeder and substation transformer levels. A distribution system's unidirectional protection mechanism might be harmed. As a result, some transformers' voltages and loading limitations may be affected. Furthermore, because to the integrated uncertainty sources, high DG penetration levels may induce voltage variations. The volatility of the solar source will induce over or under voltage in PVDG. Another disadvantage is that DG penetration is great, which might lead to increased harmonic propagation. It has the potential to increase losses and reduce the equipment's lifespan. As a result, an appropriate protection mechanism is required. Another flaw is the narrow efficiency range of PV panels, which ranges from 12 to 20% [14].

Micro-Turbine: The compressor, combustor, turbine generator, and recuperator are the core components of the micro-turbine, which operate on the same principles as regular gas turbines. The air is taken into the compressor, where it is compressed and pushed into the recuperator's chilly side. Exhaust heat is used to warm the air before it enters the combustion chamber. The warm air is then mixed with the fuel in the combustion chamber, which then bums it. The turbine, which drives the compressor and generator, expands the mixture. After that, the combusted air is evacuated through the recuperator and vented through the exhaust exit [15]. To generate alternative power, most micro-turbines use high-speed permanent magnet generators. The heat generated by the burning of fuel in turbines is used to improve energy efficiency. The micro-electrical turbine's efficiency ranges from 25% to 33%, with a power range of 25 kW to 1000 kW [16].

The output voltage from micro-turbines cannot be directly linked to the power grid or utility; instead, it must be converted to DC and then back to AC to achieve the utility's nominal voltage and frequency. The main advantage of micro-turbines is the clean operation with low emissions produced and good efficiency [16]. Micro-turbines, unlike standard backup generators, are designed to run for long periods of time with no maintenance. They may meet a customer's base-load needs as well as provide standby, peak shaving, and cogeneration power. Furthermore, the current generation of micro-turbines meet the following requirements [17]:

- High efficiency, fuel-to-electricity conversion can reach 25%-33%. However, if the waste recovery is used, combined heat and electric power could achieve energy efficiency levels greater than 80%.
- NOx emissions for natural gas machines in actual working ranges are less than 7 parts per million, demonstrating environmental superiority.

- They use well-known technology, are simple to start, have strong load tracking capabilities, and require little maintenance due to their basic design [11].
- Natural gas, diesel, ethanol, landfill gas, and other bio-mass generated liquids and gases are among the alternative/optional fuels that can be used.
- The micro-flexibility turbine's to be regulated effectively is increased by a modern power electronic interface between the micro-turbine and the load or grid [10]

Due to their short construction lead time and compact size, distributed generating sources provide high flexibility and response to changes in the economic environment. Furthermore, distributed generating technologies can assist providers in filling up the gaps in the liberalized market and providing clients with the power services they demand. DG can provide several different benefits to the distribution system; some are listed below [18].

- Increases power supply reliability and reduces transmission and distribution systems losses.
- Can improve voltage profile; enhance power quality and supports voltage stability, so that the system can withstand higher loading situations.
- DG has least installation time and payback period. Many countries are subsidizing the development of renewable energy projects through a portfolio obligation and green power certificates. This incentives investment in small generation plants.
- Some DG technologies, such as combined heat and power (CHP) and micro-turbines, produce little pollution and have high overall efficiency.
- Reduces environmental impacts and greenhouse-gas emissions. This is because lots of DG units are renewable or low emission generators based sources.

On the distribution side, DG connected to the grid will undoubtedly have an influence on power system stability. When a high number of DGs are linked to the grid, it has a significant impact on distribution system design, control, operation, and protection, as well as system reliability and security. This necessitates making necessary adjustments to standard distribution network planning methodologies [32]. Some of the challenges are listed below [11] [19]:

- Power converters are needed to connect DG with the grid we need, which are capable of injecting harmonics into the system.
- If coordination with the utility supply is not effectively performed, the connection of DG may result in over-voltage, fluctuation, and imbalance of the system voltage.

- Depending on the network layout, penetration level, and kind of DG technology, DG power injection may increase power losses in the distribution system.
- When a DG is connected to the network, the short circuit values are altered. As a result, relay settings should be changed, and the relay should be reset to its previous configuration if the DG is detached.

Flexible AC transmission systems (FACTS) Devices: For the past two decades, FACTS devices have been implemented in the power systems to enhance their capacity, stability, security and good power quality. Since FACTS devices are designed based on advanced power electronics technology, they are capable of providing control action at high speed. Several types of FACTS devices have been developed for application in power systems. The function of these devices is primarily to control the power flow through the transmission lines and regulate the voltage level where they are installed [33]. FACTS devices can generally be classified as below [20][21][22]

- Shunt connected controllers such as static Var compensator (SVC) and static synchronous compensator (STATCOM)
- Series connected controllers such as static synchronous series compensator (SSSC), series capacitive reactance compensator (SCRC), Thyristor-switched series capacitor (TCSC), and Thyristor-controlled series reactor (TCSR)
- A combination of shunt and series connected controllers such as unified power flow controller (UPFC), Thyristor-controlled phase shifting transformer (TCPST).

The Flexible AC Transmission System (FACTS) is a concept that includes using high-power electronic controllers in AC transmission networks to adjust power flows and voltages quickly and reliably. FACTS controllers have a substantial influence on power system oscillation damping and dynamic reactive power compensation.

Based on power electronic devices employed, FACTS devices are classified in to two groups; Thyristor valve/convertor based FACTS devices such as Static VAR Compensator (SVC) and Thyristor Controlled Series Compensator (TCSC) and voltage source convertor employed FACTS such as Static Synchronous Series Compensator (SSSC), Static Synchronous Compensator (STATCOM) and Unified Power Flow Controller (UPFC) [20][21]

Static Var Compensators (SVC): SVC is considered as the first generation of shunt connected FACTS devices that have been implemented in power systems to provide fast-acting reactive power and voltage support to the power grid. By incorporating inductive and capacitive branches, SVC is able to regulate the voltage at a chosen bus by supplying or absorbing reactive power. The advantages of simplicity, low losses, low harmonics production and low cost have made SVC to be used extensively compared to other shunt FACTS devices [22].

It's a variable impedance device that uses back-to-back Thyristor valves to regulate current via a reactor. The Thyristor was crucial in completing the SVC and allowing control of its reactive power flow. By changing the firing angle, it may be utilized as a switch or as a constantly controlled valve. It's worth noting that the SVC current will have some harmonic content, which should be considered throughout the design phase. The advantages of simplicity, low losses, low harmonics production and low cost have made SVC to be used extensively compared to other shunt FACTS devices [20][22].

Thyristor Controlled Series Compensator (TCSC): It is based on the Thyristor-based FACTS technology, which allows for line impedance management using a Thyristor-controlled capacitor connected in series with the transmission or distribution line. It is used to boost the transmission line's capabilities by adding a series capacitor that lowers the net series impedance, enabling more power to be sent. Capacitor bank, bypass inductor, and two bidirectional Thyristors are the three primary components of the TCSC device [21].

Static Synchronous Series Compensator (SSSC): Is a solid-state voltage source converter that produces the required voltage magnitude regardless of line current. A converter, DC bus (storage unit), and coupling transformer make up the SSSC. The dc bus uses the inverter to synthesize an AC voltage waveform that is inserted in series with transmission line through the transformer with an appropriate phase angle and line current. When the injected voltage is in phase with the line current, real power is transmitted; when the injected voltage is in quadrature with the line current, reactive power is transferred. Therefore, it has the ability to exchange both the real and reactive power in a transmission line [23].

Static Synchronous Compensator (STATCOM): It is based on an electronic device called a voltage source converter (VSC) that includes a Gate turn off Thyristor and a DC capacitor, as well as a step down transformer connected to a transmission line. By converting DC input voltage into AC output voltages, it adjusts the active and reactive power of the system. The STATCOM is used for voltage control mechanism and reactive power compensation, and it has superior properties than the SVC. By managing the voltage in transmission and distribution systems, STATCOM increases the voltage stability of a power system, dampens power oscillation in transmission systems, and offers the appropriate reactive power compensation of a power syste [21][24]. The fundamental difference between an SVC and a STATCOM is that a STATCOM uses a converter-based Var generation and functions as a shunt connected synchronous voltage source, whereas an SVC uses Thyristor controlled reactors and Thyristor switched capacitors and functions as a shunt connected controlled reactive admittance. As long as the current injected by the controller stays in phase quadrature with the bus voltage, the shunt controller injects or absorbs reactive power into or from the bus. Any other phase relationship will necessitate the management of actual power. If STATCOM is fitted with an energy storage element at its DC terminal, it may interchange actual power from the system [20].

Unified Power Flow Controller (UPFC): Is a device that can regulate all three characteristics of line power flow at the same time (line impedance, voltage and phase angle). It's a member of the FACTS family, and it's used to optimize transmission power flow. The UPFC is made up of a static synchronous compensator (STATCOM) and a static synchronous compensator (STATCOM) (SSSC). Both converters are powered by a single DC connection that includes a DC storage capacitor. Between the two-AC branches, actual power can easily flow in any direction. At the AC output terminals, each converter can create or absorb reactive power individually. The controller sends gating signals to the converter valves, which give the proper series voltages while also pulling the necessary shunt currents. The inverter requires a dc source with regenerative capability to produce the requisite series injected voltage. The shunt inverter might be used to facilitate the DC bus voltage [23].

In general, the performance of FACTS devices for different applications is summarized in table 2.1 [21][25][26].

Table 2.1: Applications of FACTS Devices

FACTS Devices					
Connection Type	**Shunt**		**Series**		**Combined**
Device	**SVC**	**STATCOM**	**TCSC**	**SSSC**	**UPFC**
Problem					
Voltage control steady state	**	***	***	**	***
Voltage control dynamic	**	**	***	**	***
Phase balancing steady state	**	**	*	*	***
Transient stability	***	**	**	*	**
Power flow steady state	***	***	**	**	***

∗, Low influence; ∗∗, Medium influence; ∗∗∗, Strong influence.

2.5 Distribution Static Synchronous Compensator (D-STATCOM)

STATCOM is a voltage-source converter-based device that compensates the active and reactive demands of the system by converting a DC input voltage to an AC output voltage. STATCOM has superior features than SVC in that when the system voltage drops low enough to push the STATCOM output to its ceiling, the voltage magnitude has no effect on the maximum reactive power output. When the voltage is below the limit, it shows constant current characteristics. STATCOM's used at the distribution level are known as D-STATCOMs (Distribution STATCOM) [27].

The D-STATCOM is a three-phase shunt connected Voltage Source Converter (VSC) designed for use in the distribution network to compensate for the bus voltage so as to provide better power factor and reactive power. At the point of common coupling, the device can inject or absorb both active and reactive current (PCC). D- STATCOM's to inject active power over a lengthy period of time is essentially impossible due to the energy storage restriction. D-STATCOM cannot inject active power over a lengthy period of time due to the energy storage restriction. D-STATCOM cannot inject active power over a lengthy period of time due to the energy storage restriction. Thus, the operation is mostly in steady-state with reactive power being the power exchange between D-STATCOM and the system. A popular D-STATCOM model for steady-state operation includes a coupling transformer with a leaky reactance, a GTO/IGBT, a voltage source converter (VSC), and a DC capacitor [28]. Figure 2.2 shows a schematic diagram of D-STATCOM incorporated to a bus k [27].

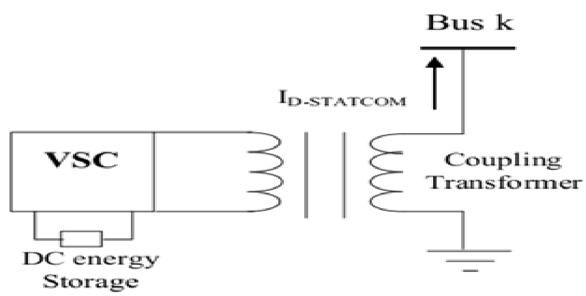


Figure 2.2: D-STATCOM connected to a certain bus k

D-STATCOM is similar to a synchronous machine in that it provides trailing current when under excited and leading current when overexcited. The D-STATCOM voltage is injected in phase with the line voltage, and there is no energy exchange with the network in this instance; instead, only reactive power is injected (or absorbed) by the D-STATCOM. The reactive power exchange with the network is achieved by varying the amplitude of the output voltages. The output voltage of the V_{sc} is controlled in phase with the system voltage V_S. If V_{SC} is greater than V_S then D-STATCOM will act as a capacitor and generates reactive power (Capacitive mode). On the other hand, if V_S is greater V_{SC} then the DSTATCOM will act as an inductor and consume reactive power (Inductive mode). If V_{SC} is equal to V_S then D-STATCOM does not generate or absorbs reactive power and the reactive power is zero (No-load mode) [27][28].

A three-phase inverter using SCRs, MOSFETs, or IGBTs, a DC capacitor that provides the inverter with DC voltage, D-STATCOM is made up of a link reactor that links the inverter output to the AC supply side and filter components that remove high-frequency components created by the PWM inverter. The inverter generates a three-phase voltage from the DC Side capacitor. The AC supply is synced with this. The link inductor links system voltage to the AC supply side [28].

2.6 Modeling of D-STATCOM

This section represents the mathematical modeling of D-STATCOM. The majority of distribution systems are radial in nature, with electrical power provided from a single side. The steady state mathematical modeling of D-STACOM is explained as follows, a simple two bus radial distribution system is shown below in Figure 2.3[28][29].

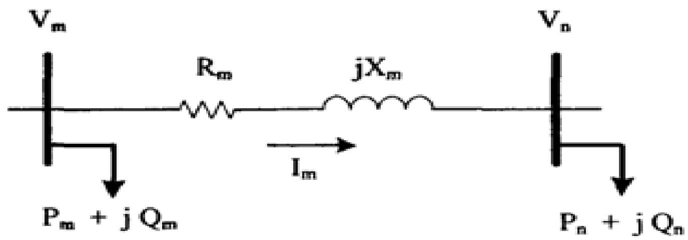


Figure 2.3: Two bus radial distribution system [28]

The voltage equation for the two bus system is given as follows

$$V_n = V_m \angle \theta_m - (R_m + jX_m) I_m \angle \delta \text{ .... (2.1)}$$

For steady state modeling of D-STATCOM is installed at two bus radial distribution systems as shown in Figure 2.4.

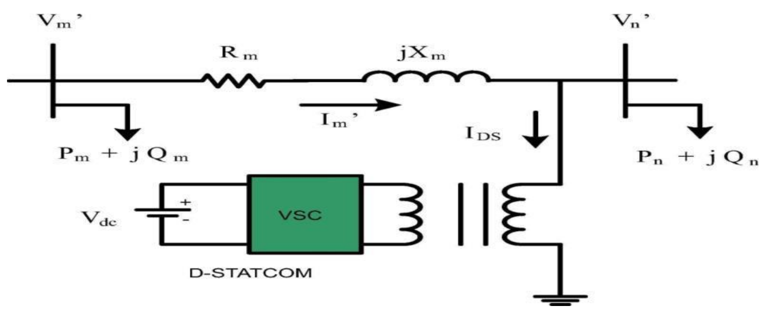


Figure 2.4: Two bus radial distribution system with D-STATCOM [28]

By installing D-STATCOM, the voltage values at the bus where it is installed and at the neighboring bus changes. The new voltages are V_n' at the candidate bus and V_m' at previous neighboring buses changes. The current changes to I_m' which the summation is of I_m and I_{DS}. Here I_{DS} is the current injected by D-STATCOM and is in quadrature with voltage. As a result, the new voltage after installing D-STATCOM is expressed as

$$V_n' \angle \theta_n = V_m' \angle \theta_m' - (R_m + jX_m)(I_m \angle \delta + I_{DS} \angle (\frac{\pi}{2} + \theta_n')) \text{ .... (2.2)}$$

Here θ_n', θ_m' and δ are the phase angles of V_n', V_m' and I_m respectively.

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

$$V_n' cos\theta_n' = Real(V_m' \angle \theta_m') - Real(Z_m I_m \angle \delta) - R_m I_{DS} \cos\left(\frac{\pi}{2} + \theta_n'\right) + X_m I_{DS} \sin\left(\frac{\pi}{2} + \theta_n'\right) \ldots.. (2.3)$$

$$V_n' sin\theta_n' = Imag(V_m' \angle \theta_m') - Imag(Z_m I_m \angle \delta) - X_m I_{DS} \cos\left(\frac{\pi}{2} + \theta_n'\right) + R_m I_{DS} \sin\left(\frac{\pi}{2} + \theta_n'\right) .. (2.4)$$

Now by taking some assumptions

$V_n' = b$

$h_1 = Real(V_m' \angle \theta_m') - Real(Z_m I_m \angle \delta)$

$h_2 = Imag(V_m' \angle \theta_m') - Imag(Z_m I_m \angle \delta)$

$h_3 = -X_m$

$h_4 = -R_m$

$I_{DS} = x_1$

$\theta_n' = x_2$

So equations (2.3) and (2.4) changes to

$$bcosx_2 = h_1 - h_4 x_1 sinx_2 - h_3 x_1 cosx_2 \ldots\ldots (2.5)$$

$$bsinx_2 = h_2 - h_3 x_1 sinx_2 - h_4 x_1 cosx_2 \ldots\ldots (2.6)$$

So from equation (2.5) and 2.6

$$x_1 = \frac{bcosx_2 - h_1}{-h_4 sinx_2 - h_3 cosx_2} \ldots\ldots (2.7)$$

$$x_1 = \frac{bsinx_2 - h_2}{-h_3 sinx_2 - h_4 cosx_2} \ldots\ldots (2.8)$$

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

$$bh_4 + (h_1 h_3 - h_2 h_4) sinx_2 + (-h_1 h_4 - h_2 h_3) cosx_2 = 0 \ldots\ldots (2.9)$$

Let

$sinx_2 = t$

$(h_1 h_3 - h_2 h_4) = k_1$

$(h_1 h_4 + h_2 h_3) = k_2$

So equation (2.9) changes to

$$bh_4 + k_1 t - k_2\sqrt{1-t^2} = 0 \quad \text{…………………………………………….. (2.10)}$$

On squaring both sides and manipulating, we get

$$(k_1^2 + k_2^2)t^2 + 2bh_4 k_1 t + b^2 h_4^2 - k_2^2 = 0 \quad \text{……………………………… (2.11)}$$

Thus

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

$$D = B^2 - 4AC$$

where

A = $k_1^2 + k_2^2$

B = $2bh_4 k_1$

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

On putting values of k_1 and k_2 we get,

$$A = (h_1 h_3 - h_2 h_4)^2 + (h_1 h_4 + h_2 h_3)^2 \quad \text{……………………………. (2.12)}$$

$$B = 2(h_1 h_3 - h_2 h_4) + (V_n')(h_4) \quad \text{………….....……………………… (2.13)}$$

$$C = (V_n' R_m)^2 - (h_1 h_4 + h_2 h_3)^2 \quad \text{……………………………………… (2.14)}$$

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

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

D-STATCOM current angle and magnitude is:

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

$$|I_{DS}| = k_1 = \frac{V_n' cos\theta_n - h_1}{-h_4 sin\theta_n' - h_3 cos\theta_n'} \quad \text{……………………………………………….….. (2.17)}$$

Finally, the reactive power injected is:

$$jQ_{DS} = (V_n' \angle \theta_n').(I_{DS} \angle (\frac{\pi}{2} + \theta_n')) * \quad \text{…………………………………….... (2.18)}$$

where * denotes the complex conjugate

2.7 Comparison Between D-STATCOM and Conventional Devices

D-STATCOM is a shunt-connected Voltage Source Converter (VSC) used in distribution networks to adjust for bus voltage and increase power factor and reactive power control. D-STATCOM offers the capacity to compensate capacitive and inductive modes quickly and continuously. When D-STATCOM is linked to a specific load, it may inject enough leading or lagging compensatory current to ensure that the overall demand fulfills the requirements for utility connection. Simultaneously, it may remove any imbalance or harmonic distortion from the voltage. Due to the rising power system demand, D-STATCOM is expected to play a key role in radial distribution systems. D-optimal STATCOM's allocation increases load capability, power loss reduction, stability improvement, reactive power compensation, and power quality enhancements such voltage control, voltage balancing, and flicker suppression [30][31].

In summary the basic functions of D-STATCOM are:

- Voltage regulation and reactive power compensation
- Maximize the loading capability of the distribution line
- Power loss minimization
- Minimize the harmonic currents
- Correction of the power factor
- Mitigation of voltage flickers

One of the key system restrictions in the distribution system is meeting the power demand of the whole load while keeping voltage magnitude within an acceptable range. To fully fix this issue, very sophisticated technologies for power loss reduction in the distribution network are required. Capacitor banks, shunt and series reactors, automated voltage regulators (AVRs), and the newly created Flexible AC Transmission Distribution network (DFACTS) devices such as Distribution Static Compensator (D-STATCOM), Unified Power Flow Conditioner (UPQC), and Static Synchronous Series Compensator are examples of such devices (SSSC). D-STATCOM provides a number of advantages over conventional reactive power compensation devices, including low power losses, low harmonic output, excellent regulatory capabilities, cheap cost, and small size. In addition, unlike shunt or series capacitors, the D-STATCOM has no operating issues like as resonance or transient harmonics. Because of their step-by-step actions, traditional series voltage regulators cannot create reactive power and have a delayed reaction. When employed in the same circuit as inductive components, shunt capacitors have the drawback of being unable to provide continuously varying reactive power and their natural oscillating nature. When a D-STATCOM is connected to a specific load, it may inject compensating current to ensure that the overall demand matches the utility connection requirements. Alternatively, it may remove any imbalance and harmonic distortion from the utility bus power. D-STATCOM will play a larger role in power system load ability capacity, stability improvement , reactive power compensation, power loss reduction, and power quality enhancements such as flicker suppression, voltage regulation, and voltage balancing as a result of the rising power system load [28][30][31][32]

2.8 Literature Review

Different researchers have proposed several ways for solving the problem of voltage drop and power loss in distribution systems.

RezaIndra Satrioa and Subiyanto: The modeling technique utilized to reorganize electrical network topology, minimize drop voltage, reduce power losses, and build a new distribution transformer to improve power system distribution reliability is presented in this study. The goal of the restructured electrical network was to explore and analyze the electric demands of a distribution transformer. For each customer, real voltage and real current measurements were completed twice, once in the morning and once at night or at peak load. ETAP Power Station Software was used for design and simulation. As a result of the findings, restructuring the electrical network and adding a new distribution transformer can be used to minimize drop voltage and power losses [33] In this method, the loss and voltage drop are reduced to some extent but the cost of the added transformers and tie switches is not considered. The payback period may be very large due to the cost of transformers.

T.Manglani and Y.S.Shishodia: The author studied the improvement of voltage profile of radial distribution system by capacitor placement using plant growth simulation algorithm. Loss sensitivity factor is used to identify the candidate buses then plant growth simulation algorithm is used to select the size of the capacitors. The author tested his solution on IEEE 9 bus system and got a considerable voltage profile improvement. The author assumed a constant load model but in reality, the distribution load is variable. Switchable type capacitors are not also considered. If the compensating capacitor is not switchable type, the voltage rise problem may be occurred during off peak periods [34].

Minnan Wang and Jin Zhong: Two optimization methods were proposed to find the appropriate placements of DGs and capacitor banks in distribution systems in order to maintain improved voltage profiles. The optimum DG placement problem was first presented as a modified optimal power flow problem with a novel mathematical description of voltage profile optimization. After that, the problem of capacitor ideal location was modeled and solved. The IEEE 41 bus distribution system, which is a radial system, was used to evaluate both concepts. From their research they concluded that the strategic placement of DG units would have a strong influence on the voltage profile improvement of the distribution system and capacitor banks could be assigned optimally to procure a better voltage profile [35]

Fahad Iqbal and Mohd Tauseef Khan: Propose a system for improving bus voltages and reducing losses in the active distribution network. A DG in the form of tiny renewable energy resources such as solar PV, wind, and biomass is strategically positioned to reduce network losses. Because the installation of DG does not meet the network's reactive power demands, some buses are experiencing undervoltage. DSTATCOM's optimal placement eliminates the problem of undervoltageThe DLF technique is used on the MATLAB platform for load flow calculations, and the LSF is combined with voltage deviation in the goal function for optimal DG positioning [37].

K.R. Devabalaji and K. Ravi: Propose a novel approach for determining the optimal allocatiom and sizing of DG and DSTATCOM, and formulate an objective function for minimizing power loss, operational costs, and voltage profile enhancement of the system under equal and equal constraints. To determine where the DG and DSTATCOM should be positioned, the loss sensitivity factor (LSF) is employed. The Bacterial Foraging Optimization Algorithm (BFOA) is used to determine the size of the DG and DSTATCOM [38].

Hussain and Subbaramiah: Proposed a practical analytical approach for determining the best position for D-STATCOM in the radial distribution system in order to reduce power loss and enhance voltage profile. For load flow analysis, a backward-forward sweep approach was used in this study. By assuming a voltage magnitude of 1p.u. at the candidate node, the D-STATCOM was modeled and its size estimated. The ideal position of D-STATCOM was determined using an objective function that included total system losses and system voltage profile. A conventional IEEE 33-bus radial distribution system was used to test this concept [39].

Yuvaraj and K.R.Devabalaji: Investigated an optimal placement and sizing of D-STATCOM using harmony search algorithm. Power loss minimization is a single objective function that is considered as an optimization function. The proposed work was tested in the IEEE 33-bus system. It uses a direct approach of BIBC matrix for load flow analysis. The proposed work compares the annual total loss of RDS before and after installation with D-STATCOM. [40].

Sunil S.Gurav and H.T.Jadhav: In this study, a new load compensation approach for DSTATCOM with non-stiff sources is suggested, which takes into account both linear and non-linear loads. In the presence of feeder impedance, load flows from the distribution system, causing voltage and current distortion at the PCC. This is referred to as a non-stiff source. D-STATCOM is also utilized in distribution systems to compensate for reactive power and imbalance produced by varied loads. This approach employs a series and shunt filter, which has the advantage of reducing inverter losses. The voltage source inverter (VSI) switching instruction is created utilizing the hysteresis band current control approach. Simulating the suggested approach is done with Matlab Simulink [30].

T. N. Shukla, S.P. Singh and K. B Naik: In radial distribution networks, GA was used to find the best location for DG with the least amount of system losses. The problem is stated as an optimization problem with the goal of minimizing real power loss while keeping equality and inequality constraints in mind, and the solution is found using GA. The best position is determined by the sensitivity of active power loss to actual power injection through DG. They showed that the advantage grows as the number of places within a given area grows, until it becomes uneconomical. Only active power losses were included in this method [41].

Kumarasamy and Raghavan: Using particle swarm optimization, proposed a cost-effective strategy for appropriate placement and size of many STATCOM. System parameters such as voltage profile, system loss, reactive power compensation, and system voltage stability are all included in the objective function. In contrast to traditional optimization issues, the real-time cost or penalty value determines the size of the weighting for the sub-objective function. The IEEE 30 bus system was used as a test system, and power flow analysis was performed using Newton-Rapson load flow. The weight of the goal functions varies, hence the placement of numerous STATCOM in the network varies [44].

Gupta and Kumar: With the goal of lowering loss, improving voltage profile, and total energy savings, an analytical technique for identifying the best position and size of D-STATCOM for radial power distribution networks was presented. The ideal position of D-STATCOM was determined using two separate sensitivity methods: the power loss index (PLI) and the voltage stability index (VSI). The vibrational approach was used to determine the ideal size of DSTATCOM. On a conventional IEEE 33-bus test system, this method was used [45].

Joseph Sanam: Proposed the optimal allocation of D-STATCOM and DG in a power distribution network using the exhaustive search algorithm. The problem formulated for allocation of DG and D-STATCOM is integrated into the Forward- Backward sweep load flow algorithm to study the impact of allocation devices. The performance of the proposed approach is tested on IEEE 33- bus distribution system. Some range of active and reactive power simultaneously injected at each node of distribution by corresponding the size and location of DG and D-STATCOM respectively [46].

The reviewed works of literature state different methods for an optimal allocation problem. Thus studies have certain limitations like single objective function, values of the weighting factors for multi-objective functions were simply taken based on theoretical assumptions, fails to consider both real and reactive power loss and other associated constraints have not been considered while solving the location and sizing problems. This research fills the gap of previous works in the area of optimal placement and sizing of D-STATCOM like multi-objective optimization function, consider both real and reactive power loss reductions, economic impact of D-STATCOM integration and system constraints for GA-PSO simulation. Moreover, the integration of D-STATCOM in a distribution network for power loss minimization and voltage profile improvement has been studied.

CHAPTER THREE

MODELING AND ANALYSIS OF KOTEBE DISTRIBUTION SYSTEM

3.1 Introduction

In Ethiopia most of 15kV outgoing distribution feeders are connected in radial fashion. Mostly those feeders are used to feeding up to 80 distribution transformers [7]. The distribution transformers are used to step down the voltage on the feeders to utilization voltage of 380 volts three-phase or 220 volts single-phase supply required by end users. Kotebe substation is located in Addis Ababa, Yeka sub-city administration under Ethiopian electric power east district management and which deliver electric power to areas around Kotebe. Section 3.2 presents about data collection and section 3.3 discussed about modelling of Kotebe distribution system. Load flow analysis is discussed in section 3.4. Section 3.5 reviewed about power flow sensitivity factors. Power loss sensitivity factors are presented in section 3.6.

3.2 Data Collection

The necessary data for this thesis work has been collected from Kotebe distribution substation, load dispatch center, Ethiopian Electric Utility (EEU) and Ethiopian Electric Power (EEP) Engineering office. The data have been gathered from past recorded feeders loading (peak load) data of the substation, year's interruption data, the type and impedance of the conductor and other important data's are collected.

Kotebe substation has two 230 kV incoming feeders, both from Legetafo substation and six 132 kV outgoing feeders route to Addis East, Kality and Ayat GIS substations. There are two auto transformers a capacity of 125MVA which steps down the incoming voltage to 132kV. Furthermore, there are two, two winding power transformers of capacity 50MVA which operate in parallel to feed about eight 15kV outgoing lines and three of them are not energized yet. There are another two power transformers capacity of 31.5 MVA and 16 MVA, which supplies six 15 kV and one 33 kV feeders, from which two of them are idle. The directions and the single line diagram of the power distribution feeders have been explained below.

Table 3.1: Feeder name, capacity, route and length of Kotebe substation feeders

Feeder name	Bus bar volatge (kV)	Length (km)	Destination
COT - 04	15 KV	12	Civil Service
COT - 05	15 KV	7	Figa
COT - 06	15 KV	14	CMC
COT - 07	15 KV	7	Dehnenet
COT - 08	15 KV	5	Teaching college
K1	15 KV	9	Kidanmeheret
K2	15 KV	11	Gurdshola
K3	15 KV	17	Wesen
K5	15 KV	1.6	Water supply
COT - 33	33 KV	25	Sendafa

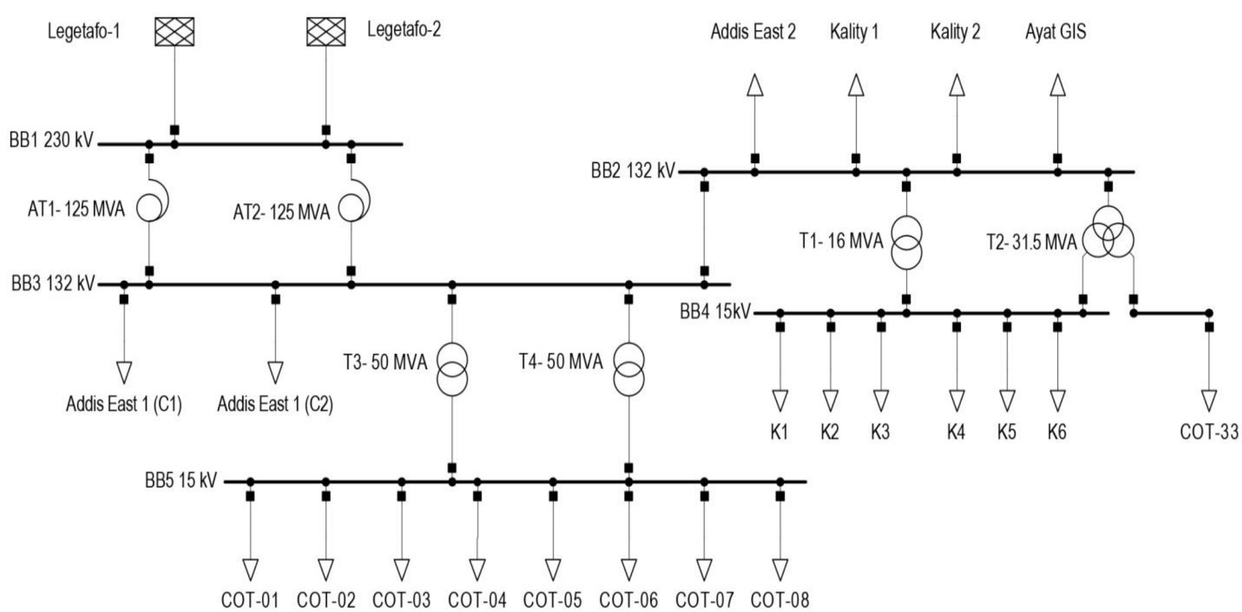


Figure 3.1: Single Line Diagram of Kotebe Distribution Substation

The monthly peak load data of the substation and the fault registered along the live feeders also tabulated on the table below Table 3.2 and Table 3.3 respectively. It consists of three months peak load data of each feeder and three years fault statistics.

Table 3.2: Details of Kotebe Distribution Feeders

Feeder	Total power permanent interruption (frequency/Year)			Power Interruption due to Overload Frequency(Interruption /Year)		
	2018	2019	2020	2018	2019	2020
COT -04	-	384	148	-	14	23
COT -05	218	150	120	49	12	10
COT -06	170	348	227	55	21	34
COT -07	137	357	321	29	11	15
COT -08	126	455	290	18	10	27
COT -33	169	735	457	11	28	67
K1	71	107	111	6	13	13
K2	41	277	210	8	7	16
K3	239	387	380	85	18	31
K5	66	189	124	9	3	4

Table 3.3: July, August and September 2021 Peak Load Data of Kotebe Feeders

Feeder Name	Peak Load					
	July		August		September	
	Power (MW)	Current (A)	Power (MW)	Current (A)	Power (MW)	Current (A)
COT-01	9.4	400	9.6	412	9.5	406
COT-04	12.6	540	9.1	388	9.6	412
COT-05	11.4	488	12	515	10.6	455
COT-06	6.7	287	8.3	353	7.2	307

COT-07	6.6	284	7.5	320	8.1	346
COT-08	9.3	396	8.1	345	8.3	354
COT-09	9.7	417	10	427	10.1	434
K1	7.2	310	6.4	275	6.1	261
K2	6	256	6.8	292	6.5	278
K3	8.6	368	7.5	320	9.8	420
K5	3.6	156	2.8	120	2.6	110

From the 15 kV Kotebe substation power distribution feeders K3 feeder is selected for this case study because of the following reason observed during data analysis.

1. High power demand
2. Distribution lines cover large distance
3. High permanent overload power interruption rate

3.3 Modelling of Kotebe Distribution Network

In this section modeling and simulation has been performed on Kotebe ‘K3’ power distribution feeder. In order to successfully accomplish the modeling and the simulation work on the feeder the line data, bus data and the load data has been used and MATLAB simulation tool is the software selected for this specific study. The MATLAB simulation tool is used for performing power flow analysis of the network with D-STATCOM and at base case too. Hence, different MATLAB code files have been developed, one to model the existing network alone and the second is to model the network containing D-STATCOM

The impedance of the conductor used in the power distribution system depends upon the material, dimensions, and configuration of the wires and length with the spacing between them. The conductors that are used in Kotebe distribution feeders are stranded conductors and 50 Hz frequency also applied for calculating the inductive reactance. The impedances are then calculated by the following equations [46][47].

$$Z_a = R_a + j0.06283 \ln\left(\frac{D}{GMR_a}\right) \Omega \,/\, km \quad \text{......} (3.1)$$

$$D = \sqrt[3]{D_{ab} B_{bc} C_{ac}} \quad \text{......} (3.2)$$

$$GMR = k * r \quad \text{......} (3.3)$$

where:

Z_a = Impedance of conductor in Ω/ *km*

R_a = Resistance of conductor in Ω/ *km*

D_{ab}, D_{bc}, D_{ac}, = Distance between conductors a and b, b and c, a and c in meter

GMR_a = Geometric mean radius of conductor a

k = GMR factor

r = Actual conductor radius

The overhead conductor's parameters which are given in Table 3.4 are collected from the standard overhead conductor data sheet and the GMR's are calculated using Equation 3.3

Table 3.4: Overhead conductor parameters used in the feeder

Conductor Type	Conductor size (mm^2)	Alloy/Actual area (mm^2)	No. of wires	Diameter (mm)	Overall diameter of conductor (mm)	Actual diameter (mm)	Resistance (Ω/km)
AAAC	25	24.26	7	2.1	6.3	5.56	1.3703
AAAC	35	34.36	7	2.5	7.5	6.864	0.9669
AAAC	50	49.48	7	3	9	7.9377	0.6714
AAAC	95	93.27	19	2.5	12.5	10.897	0.3579
AAAC	120	116.99	19	2.8	14	12.32	0.2854
AAAC	150	147.11	37	2.25	15.8	13.904	0.2274

Table 3.5: GMR Factor (k) and Strand Relationship for AAAC conductor

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

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

A. For AAAC – 25 overhead conductor the positive sequence impedance becomes

$$Z_{25} = 1.181 + j0.3736\ \Omega/km$$

B. For AAAC – 35 overhead conductor the positive sequence impedance becomes

$$Z_{35} = 0.9669 + j0.3561\ \Omega/km$$

C. For AAAC – 50 overhead conductor the positive sequence impedance becomes

$$Z_{50} = 0.5785 + j0.3470\ \Omega/km$$

D. For AAAC – 95 overhead conductor the positive sequence impedance becomes

$$Z_{95} = 0.3085 + j0.3244\ \Omega/km$$

E. For AAAC – 120 overhead conductor the positive sequence impedance becomes

$$Z_{120} = 0.2854 + j0.3166\ \Omega/km$$

F. For AAAC – 150 overhead conductor the positive sequence impedance becomes

$$Z_{150} = 0.2274 + j0.3158\ \Omega/km$$

The line segments total positive sequence impedances are obtained by multiplying the impedance per kilometer by its length as tabulated in Table 3.6. Since the distribution lines are relatively short, the shunt admittance of overhead lines is neglected.

Kotebe 'K3' Radial Power Distribution Feeder Impedance Calculation

Kotebe 'K3' feeder is radially configured power distribution line covering areas around Wesen. It consists of 79 buses and from which bus number one, bus one, is considered as slack bus. The remaining 63 buses employ a step-down distribution transformer to connect to loads, while the other

16 are common coupling nodes. The single line diagram of the K3 feeder is shown in below figure 3.2.

The conductors that are used for feeder K3 are All Aluminum alloy conductor type with a size of AAAC – 25, AAAC – 35, AAAC – 50, AAAC – 95, AAAC – 120 and AAAC – 150 with the total length of 17 km. These feeders are used to distribute medium voltage power of 15 kV from Kotebe Substation to the distribution transformers. The line, bus and load data of this feeder has found on the table below

Table 3.6: Line and load data of K3 Kotebe feeder

From Bus	To Bus	Length (km)	R (ohm)	X (ohm)	Load P (MW)	Load Q (MVAr)
1	2	0.0316	0.0005	0.0012	0	0
2	3	0.0814	0.3005	0.1812	0.304	0.096
3	4	0.4270	0.0251	0.0294	0.076	0.024
4	5	0.5639	0.366	0.1864	0.108	0.072
5	6	0.0643	0.3811	0.1941	0.152	0.048
6	7	0.1774	0.0922	0.047	0.152	0.048
7	8	0.2425	0.6093	0.2451	0.239	0.156
8	9	0.1607	0.819	0.2707	0.152	0.046
9	10	0.7952	0.1872	0.0619	0.019	0.006
10	11	0.2465	0.7114	0.2351	0.038	0.012
11	12	0.5902	1.03	0.34	0.038	0.012
12	13	0.0874	1.044	0.058	0.154	0.045
13	14	0.0660	1.058	0.3496	0.241	0.074
14	15	0.0875	0.1966	0.065	0.241	0.074
15	16	0.2193	0.3744	0.1238	0.608	0.292
16	17	0.0300	0.1947	0.8416	0.076	0.024
17	18	0.5147	1.3276	0.8083	0.06	0.035
18	19	0.2650	0.2106	0.069	0	0
19	20	0.1908	0.3416	0.1129	0.244	0.173

20	21	0.0549	1.014	0.0046	0.239	0.176
21	22	0.0530	0.1591	0.0529	0.075	0.023
22	23	0.0303	0.3463	0.1145	0	0
23	24	0.0562	0.7488	0.2475	0.28	0.101
24	25	0.0591	0.3089	0.1021	0.27	0.081
25	26	0.3562	0.1732	0.0572	0.038	0.01
2	27	0.2760	0.0044	0.0108	0.036	0.014
27	28	0.0633	0.064	0.1565	0	0
28	29	0.0528	0.3978	0.1315	0.151	0.045
29	30	0.3013	0.0702	0.0232	0.149	0.051
30	31	0.0466	0.351	0.116	0	0
31	32	0.3417	0.839	0.2816	0	0
32	33	0.1294	1.708	0.5646	0.039	0.01
33	34	0.0234	1.474	0.4873	0.233	0.07
2	35	0.0834	0.0044	0.0108	0.13	0.189
35	36	0.1231	0.064	0.1565	0.19	0.156
36	37	0.2195	0.1053	0.123	0.024	0.074
37	38	0.0972	0.0304	0.0355	0	0
38	39	0.4598	0.0018	0.0021	0.024	0.017
39	40	0.0636	0.7283	0.8509	0.024	0.017
40	41	0.0728	0.31	0.3623	0.018	0.008
41	42	0.1956	0.041	0.0478	0	0
42	43	0.1819	0.0092	0.0116	0.021	0.005
43	44	0.3917	0.1089	0.1373	0.038	0.015
44	45	0.0242	0.0009	0.0012	0.016	0.009
3	46	0.6700	0.0034	0.0084	0	0
46	47	0.2583	0.0851	0.2083	0.0392	0.0263
47	48	0.1113	0.2898	0.7091	0.0392	0.0263
48	49	0.2238	0.0822	0.2011	0	0
6	50	0.6006	0.0928	0.0473	0.0795	0.0564

50	51	0.2746	0.3319	0.1114	0.0384	0.012
7	52	0.0928	0.174	0.0886	0.0384	0.0127
52	53	0.3045	0.203	0.1034	0.0405	0.0283
53	54	0.1140	0.2842	0.1447	0.253	0.094
54	55	0.1164	0.2813	0.1433	0.244	0.078
55	56	0.6156	1.59	0.5337	0.031	0.014
56	57	0.3169	0.7837	0.263	0.142	0.039
57	58	0.1662	0.3042	0.1006	0	0
58	59	0.1016	0.3861	0.1172	0	0
59	60	0.4178	0.5075	0.2585	0	0
60	61	0.1987	0.0974	0.0496	0.1	0.072
61	62	0.1021	0.145	0.0738	0	0
62	63	0.4336	0.7105	0.3619	0.044	0.018
63	64	0.0402	1.041	0.5302	0.032	0.023
9	65	0.0194	0.2012	0.0611	0	0
65	66	0.3973	0.0047	0.0014	0.027	0.062
10	67	0.0276	0.7394	0.2444	0.059	0.042
67	68	0.9581	0.0047	0.0016	0.018	0.013
68	69	0.0219	0.0622	0.0174	0.018	0.013
69	70	0.0312	0.0422	0.0274	0.144	0.092
70	71	0.2153	0.0422	0.0274	0.071	0.028
71	72	0.2864	0.0764	0.0458	0	0
72	73	0.4506	0.1157	0.0519	0.028	0.021
73	74	0.0412	0.0645	0.1947	0.132	0.077
74	75	0.3973	0.0997	0.0551	0.028	0.02
75	76	0.0906	0.188	0.0961	0.075	0.023
76	77	0.0635	0.0314	0.0181	0.076	0.024
77	78	0.1064	0.0949	0.1209	0.199	0.115
78	79	0.1152	0.0319	0.0186	0.019	0.006

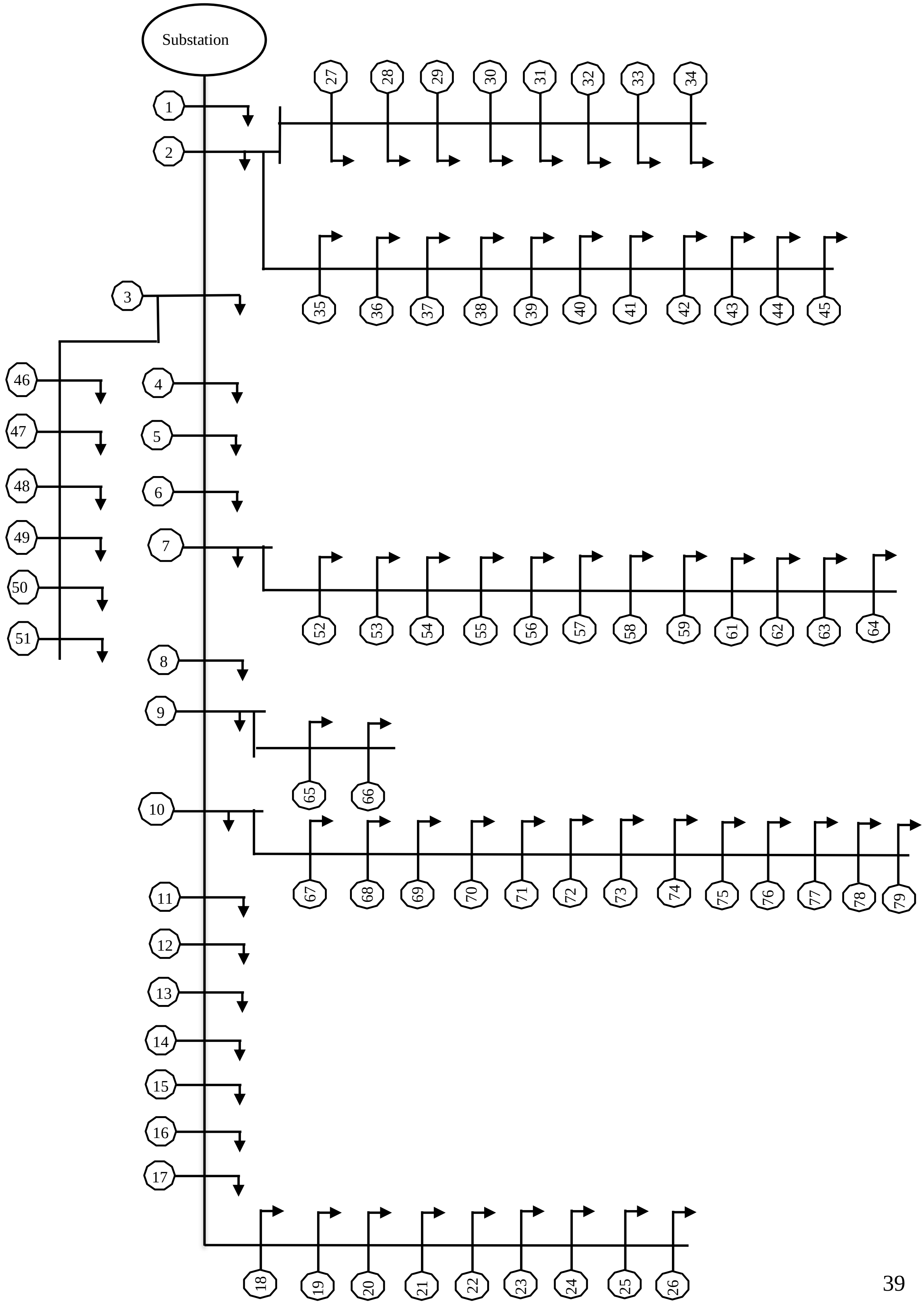


Figure 3.2: Kotebe K3 distribution feeder single line diagram

3.4 Load Flow Analysis

Load flow analysis is a very important and fundamental tool in power system analysis. The operation and planning of power systems depend upon the effective use of load flow techniques. Their findings and analyses are crucial throughout the control and economic planning stages of any system, as well as during the growth and design phases. Based on given generation and load, the goal of any load flow analysis is to estimate accurate steady-state voltages and voltage angles for all buses in the network, as well as actual and reactive power flows into each line and transformer. Modern power system analysis is based on a mathematical model of a power system [48][49] Typically, two of these four values are used to represent network nodes. Depending on the quantities specified, nodes can be classified as [2].

Table 3.7: Bus type

Bus type	Description
Slack bus	The fact that actual and reactive powers are not stated distinguishes this bus from the other two kinds. Rather, the magnitude and phase angle of the voltage are stated.
PV bus	The active power and voltage magnitude must be constant. Generators with controllable active power and voltage magnitude, as well as synchronous condensers, are represented by this sort of node.
PQ bus	Active and reactive powers are specified.

The solution of the performance equations is based on numerical analysis including the solution of algebraic simultaneous equations. To manipulate load flow analysis, Y_{bus} admittance is created using the distribution line data. The nodal equation for a Ybus-based power system network is as follows [3]:

$$I = [Y_{bus}] * V \quad \text{...} \quad (3.4)$$

Bus power injection at each bus is determined by applying nodal analysis as given below from which other network equations such as, injected current, injected power, current and power flows through a line, are derived.

The complex power injected, say i^{th} bus of a power system is given by:

$$S_i = P_i + Q_i = V_i * I_i^*; \; i = 2,3,4 \ldots\ldots\ldots (3.5)$$

So as to handle the load flow problem more conveniently the use of I_i rather than I_i^* is encouraged. As a result, the complex conjugate of the above equation is considered. Hence,

$$S_i^* = P_i - Q_i = V_i^* * I_i \quad ; \; i = 2,3,4 \ldots\ldots\ldots (3.6)$$

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

I_i is the source current injected into the bus

The current is calculated by the following equation

$$I_i = \sum_{j=1}^{n} Y_{ij} * V_j \; ; \, i = 2,3,4 \ldots\ldots\ldots (3.7)$$

where, ij is branch number and

n is total number of branches in the distribution system.

Thus, substituting this equation into the complex conjugate equation of power injection we have:

$$P_i - Q_i = V_i^* * \left(\sum_{j=1}^{n} Y_{ij} * V_j \right) \qquad ; i = 2,3.4 \ldots\ldots\ldots (3.8)$$

Considering two buses ‘i’ and ‘j’, the following sets of power flow equations are derived

Real and Reactive power injections to a bus ‘i’:

$$P_i = \sum_{j=1}^{nbus} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) \qquad ; i = 2,3,4 \ldots\ldots\ldots (3.9)$$

$$Q_i = -\sum_{j=1}^{nbus} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j) \qquad ; i = 2,3,4 \ldots\ldots\ldots (3.10)$$

Current flow through the line connecting buses i and j become

$$I_{ij} = (V_i - V_j)\, y_{ij} \qquad ; i = 2,3,4 \ldots\ldots\ldots (3.11)$$

Line power flow (power fed to line) from bus ‘i’ and ‘j’:

$$S_{ij} = V_i * I_{ij}^* \ldots\ldots\ldots (3.12)$$

$$P_{ij} = |V_i||I_{ij}|\cos\theta_{ij} \ldots\ldots\ldots (3.13)$$

$$Q_{ij} = |V_i||I_{ij}|\sin\theta_{ij} \ldots\ldots\ldots (3.14)$$

$$S_{ji} = V_j * I_{ij}^* \quad \ldots\ldots (3.15)$$

$$P_{ji} = |V_j||I_{ij}|\cos\theta_{ij} \quad \ldots\ldots (3.16)$$

$$Q_{ji} = |V_j||I_{ij}|\sin\theta_{ij} \quad \ldots\ldots (3.17)$$

To solve the load flow problem for Kotebe power distribution feeder K3, Newton-Raphson load flow method is implemented in MATLAB computational tool. The formulation of N-R load flow method presented on Appendix A.

3.5 Power Flow Sensitivity Factors

System power flow sensitivity is the change in power flow in a transmission or distribution line connected between two buses say bus *i* and bus *j* due to unit change in the power injected at a bus in the system. From equations (4.2), (4.6) and (4.7) the complex, real and reactive power injected by the source is introduced.

Change in Real and Reactive Power Flow Analysis

The real and reactive power flow in a line *k* connecting two buses, bus *i* and bus *j* can be expressed as

$$P_{ij} = V_i V_j Y_{ij} \cos\left(\theta_{ij} - \delta_i + \delta_j\right) - V_i^2 Y_{ij} \cos\theta_{ij} \quad \ldots\ldots (3.18)$$

$$Q_{ij} = -V_i V_j Y_{ij} \sin\left(\theta_{ij} - \delta_i + \delta_j\right) + V_i^2 Y_{ij} \sin\theta_{ij} \quad \ldots\ldots (3.19)$$

where;

V_i and V_j are the voltage magnitudes at buses *i* and *j*

δ_i and δ_i are the voltage angles at buses *i* and *j*

Y_{ij} is magnitude of the *ij*th element of the Y_{Bus} matrix

θ_{ij} is the angle of the *ij*th element of the Y_{Bus} matrix

Mathematically, the real and reactive power flow sensitivity can be written as:

$$\begin{bmatrix} \frac{\Delta P_{ij}}{\Delta P_n} \\ \frac{\Delta P_{ij}}{\Delta Q_n} \end{bmatrix} \quad and \quad \begin{bmatrix} \frac{\Delta Q_{ij}}{\Delta P_n} \\ \frac{\Delta Q_{ij}}{\Delta Q_n} \end{bmatrix} \text{ ; i and j = 1,2,3} \quad \ldots\ldots (3.20)$$

Using Taylor series approximation while ignoring second and higher order terms the change in real and reactive line flow can be expressed as:

$$\Delta P_{ij} = \frac{\partial P_{ij}}{\partial \delta_i}\Delta\delta_i + \frac{\partial P_{ij}}{\partial \delta_j}\Delta\delta_j + \frac{\partial P_{ij}}{\partial V_i}\Delta V_i + \frac{\partial P_{ij}}{\partial V_j}\Delta V_j \quad \text{;i and j = 1,2,3………….… (3.21)}$$

$$\Delta Q_{ij} = \frac{\partial Q_{ij}}{\partial \delta_i}\Delta\delta_i + \frac{\partial Q_{ij}}{\partial \delta_j}\Delta\delta_j + \frac{\partial Q_{ij}}{\partial V_i}\Delta V_i + \frac{\partial Q_{ij}}{\partial V_j}\Delta V_j \quad \text{;i and j = 1,2,3…………… (3.22)}$$

where;

ΔP_{ij} and ΔQ_{ij} are the change in real and reactive power flow in the distribution system

$\frac{\partial P_{ij}}{\partial \delta_i}$ and $\frac{\partial Q_{ij}}{\partial \delta_i}$ are the partial derivatives of real and reactive power with respect to δ

$\frac{\partial P_{ij}}{\partial V_i}$ and $\frac{\partial Q_{ij}}{\partial V_i}$ are the partial derivatives of real and reactive power with respect to V

$\Delta\delta_{i(j)}$ and $\Delta V_{i(j)}$ are the change in the voltage angle and voltage magnitude

ΔP_n and ΔQ_n the injected power on the selected bus n

Formulating the Power Flow Sensitivity Factors

The real power flow sensitivity factors represent the change in the real power flow over a transmission or distribution line connected between bus-*i* and bus-*j* due to the change in active or reactive power injected at any other bus-n while the reactive power flow sensitivity factors represent the change in the reactive power flow over a transmission or distribution line connected between bus-*i* and bus-*j* due to the change in reactive or real power injected at any other bus-n. The equations for the changes in the line flows can be arranged in matrix form and expressed as;

$$\begin{bmatrix}\Delta P_{ij}\\ \Delta Q_{ij}\end{bmatrix} = \begin{bmatrix}\frac{\partial P_{ij}}{\partial \delta_{i(j)}} & \frac{\partial P_{ij}}{\partial V_{i(j)}}\\ \frac{\partial Q_{ij}}{\partial \delta_{i(j)}} & \frac{\partial Q_{ij}}{\partial V_{i(j)}}\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta V\end{bmatrix} \quad \text{;i and j = 1,2,3…………………….. (3.23)}$$

The variables $\Delta\delta$ and ΔV can be obtained from load flow solution using Newton Raphson technique as follows;

$$\begin{bmatrix}\Delta P_{ij}\\ \Delta Q_{ij}\end{bmatrix} = [J]\begin{bmatrix}\Delta\delta\\ \Delta V\end{bmatrix} = \begin{bmatrix}J1 & J2\\ J3 & J4\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta V\end{bmatrix} \quad \text{;i and j = 1,2,3………….... (3.24)}$$

where;

ΔP_{ij} and ΔQ_{ij} are the change in real and reactive power flow in the distribution system

$\Delta\delta$ and ΔV are the change in the voltage angle and voltage magnitude

J is the Jacobian matrix, which is determined using numerical equations

$$\begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix} = [J]^{-1}\begin{bmatrix}\Delta P_{ij} \\ \Delta Q_{ij}\end{bmatrix} \text{ ;i and j = 1,2,3} \quad \ldots\ldots\ldots\ldots (3.25)$$

Now substituting the obtained equation for Δδ and ΔV in the equation for the change in line flows we have:

$$\begin{bmatrix}\Delta P_{ij} \\ \Delta Q_{ij}\end{bmatrix} = \begin{bmatrix}\frac{\partial P_{ij}}{\partial \delta_{i(j)}} & \frac{\partial P_{ij}}{\partial V_{i(j)}} \\ \frac{\partial Q_{ij}}{\partial \delta_{i(j)}} & \frac{\partial Q_{ij}}{\partial V_{i(j)}}\end{bmatrix}[J]^{-1}\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} \text{ ;i and j = 1,2,3} \quad \ldots\ldots (3.26)$$

The above equation gives the change in both real and reactive power flow and thus using this equation the real and reactive power flow sensitivity factors will be determined. The real and the reactive power flow sensitivity factors are represented as follows

$$\begin{bmatrix}\frac{\partial P_{ij}}{\partial P_n} \\ \frac{\partial P_{ij}}{\partial Q_n}\end{bmatrix} = \begin{bmatrix}F_{P-P} \\ F_{P-Q}\end{bmatrix} = [J]^{-1}\begin{bmatrix}\frac{\partial P_{ij}}{\partial \delta_{i(j)}} \\ \frac{\partial P_{ij}}{\partial V_{i(j)}}\end{bmatrix} \quad \ldots\ldots\ldots\ldots (3.27)$$

$$\begin{bmatrix}\frac{\partial Q_{ij}}{\partial P_n} \\ \frac{\partial Q_{ij}}{\partial Q_n}\end{bmatrix} = \begin{bmatrix}F_{Q-P} \\ F_{Q-Q}\end{bmatrix} = [J]^{-1}\begin{bmatrix}\frac{\partial P_{ij}}{\partial \delta_{i(j)}} \\ \frac{\partial P_{ij}}{\partial V_{i(j)}}\end{bmatrix} \quad \ldots\ldots\ldots\ldots (3.28)$$

where:

F_{P-P} : is the real power flow sensitivity related to the real power injection

F_{P-Q} : is the real power flow sensitivity related to the reactive power injection.

F_{Q-P} : is the reactive power flow sensitivity related to the real power injection

F_{Q-Q} : is the reactive power flow sensitivity related to the reactive power injection.

J^T: is the transpose of the Jacobian matrix

3.6 Power Loss Sensitivity Factors

The real power loss sensitivity factors represent the change in the real power loss over a transmission or distribution line connected between bus-*i* and bus-*j* due to the change in active power or reactive power injected at any other bus-n while the reactive power loss sensitivity factors represent the change in the reactive power loss over a transmission or distribution line connected between bus-*i* and bus-j due to the change in reactive power or real power injected at any other bus-n.

From the circuit diagram shown below both real and reactive power loss sensitivity factors can be calculated.

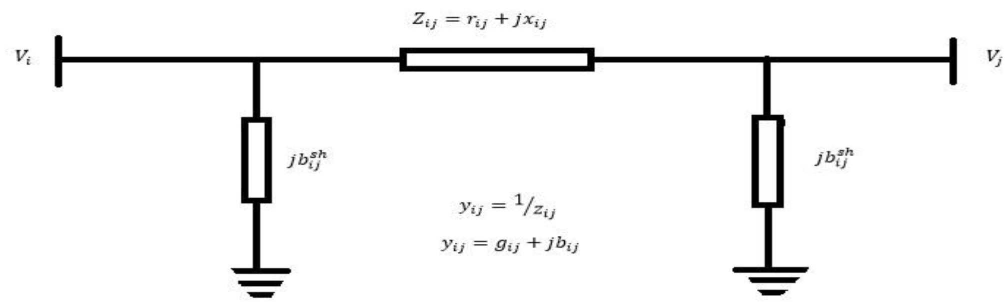


Figure 3.3: Circuit diagram of a line lumped (pie) model [3]

Change in Real and Reactive Power Loss Analysis

The active power loss of the line lumped model shown in the line-*(pie)* circuit is given by;

$$P_{L(ij)} = g_{ij}\left(V_i^2 + V_j^2 - 2V_iV_jcos\delta_{ij}\right) \quad (3.29)$$

Thus the total active and reactive power loss in the circuit can be expressed as;

$$P_{L(total)} = \sum_{l=1}^{nL}\left[g_{ij}\left(V_i^2 + V_j^2 - 2V_iV_jcos\delta_{ij}\right)\right] \quad (3.30)$$

$$Q_{L(total)} = \sum_{l=1}^{nL}\left[-b_{ij}(V_i^2 + V_j^2) - b_{ij}\left(V_i^2 + V_j^2 - 2V_iV_jcos\delta_{ij}\right)\right] \quad (3.31)$$

where;

nL : is the number of lines of the network

g_{ij} : is the conductance of the line *i-j*

b_{ij} : is the shunt susceptance of the line *i-j*

V_i : is the nodal voltage of bus *i*

V_j : is the nodal voltage of bus *j*

δ_{ij} *:* is the phase angle difference between the busses *i* and *j*

Mathematically, the real and the reactive power loss sensitivity can be written as:

$$\begin{bmatrix} \frac{\Delta P_{L(ij)}}{\Delta P_n} \\ \frac{\Delta P_{L(ij)}}{\Delta Q_n} \end{bmatrix} \text{ and } \begin{bmatrix} \frac{\Delta Q_{L(ij)}}{\Delta P_n} \\ \frac{\Delta Q_{L(ij)}}{\Delta Q_n} \end{bmatrix} \quad \ldots\ldots (3.32)$$

Using Taylor series approximation while ignoring second and higher order terms the change in real power loss can be expressed as:

$$\Delta P_{L(ij)} = \frac{\partial P_{L(ij)}}{\partial \delta_i}\Delta\delta_i + \frac{\partial P_{L(ij)}}{\partial \delta_j}\Delta\delta_j + \frac{\partial P_{L(ij)}}{\partial V_i}\Delta V_i + \frac{\partial P_{L(ij)}}{\partial V_j}\Delta V_j \quad \ldots\ldots (3.33)$$

$$\Delta Q_{L(ij)} = \frac{\partial Q_{L(ij)}}{\partial \delta_i}\Delta\delta_i + \frac{\partial Q_{L(ij)}}{\partial \delta_j}\Delta\delta_j + \frac{\partial Q_{L(ij)}}{\partial V_i}\Delta V_i + \frac{\partial Q_{L(ij)}}{\partial V_j}\Delta V_j \quad \ldots\ldots (3.34)$$

Formulating the Power Loss Sensitivity Factors

The equations for the changes in the line flows can be arranged in matrix form and expressed as;

$$\begin{bmatrix} \Delta P_{L(ij)} \\ \Delta Q_{L(ij)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_{L(ij)}}{\partial \delta_{i(j)}} & \frac{\partial P_{L(ij)}}{\partial V_{i(j)}} \\ \frac{\partial Q_{L(ij)}}{\partial \delta_{i(j)}} & \frac{\partial Q_{L(ij)}}{\partial V_{i(j)}} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \quad \ldots\ldots (3.35)$$

where;

$\Delta P_{L(ij)}$ and $\Delta Q_{L(ij)}$ are the change in real and reactive power loss in the distribution system

$\frac{\partial P_{L(ij)}}{\partial \delta_{i(j)}}$ and $\frac{\partial Q_{L(ij)}}{\partial \delta_{i(j)}}$ are the partial derivatives of real and reactive loss with respect to δ

$\frac{\partial P_{L(ij)}}{\partial V_{i(j)}}$ and $\frac{\partial Q_{L(ij)}}{\partial V_{i(j)}}$ are the partial derivatives of real and reactive loss with respect to V

$\Delta\delta$ and ΔV are the change in the voltage angle and voltage magnitude

Now substituting the obtained equation for $\Delta\delta$ and ΔV in the equation for the change in line flows we have:

$$\begin{bmatrix} \Delta P_{L(ij)} \\ \Delta Q_{L(ij)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_{L(ij)}}{\partial \delta_{i(j)}} & \frac{\partial P_{L(ij)}}{\partial V_{i(j)}} \\ \frac{\partial Q_{L(ij)}}{\partial \delta_{i(j)}} & \frac{\partial Q_{L(ij)}}{\partial V_{i(j)}} \end{bmatrix} [J]^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad \ldots\ldots (3.36)$$

Now, the real and the reactive power flow sensitivity factors are represented as follows

$$\begin{bmatrix} \frac{\partial P_{L(ij)}}{\partial P_n} \\ \frac{\partial P_{L(ij)}}{\partial Q_n} \end{bmatrix} = \begin{bmatrix} S_{P-P} \\ S_{P-Q} \end{bmatrix} = [J^T]^{-1} \begin{bmatrix} \frac{\partial P_{L(ij)}}{\partial \delta_{i(j)}} \\ \frac{\partial P_{L(ij)}}{\partial V_{i(j)}} \end{bmatrix} \quad \text{.......} (3.37)$$

$$\begin{bmatrix} \frac{\partial Q_{L(ij)}}{\partial P_n} \\ \frac{\partial Q_{L(ij)}}{\partial Q_n} \end{bmatrix} = \begin{bmatrix} S_{Q-P} \\ S_{Q-Q} \end{bmatrix} = [J^T]^{-1} \begin{bmatrix} \frac{\partial P_{L(ij)}}{\partial \delta_{i(j)}} \\ \frac{\partial P_{L(ij)}}{\partial V_{i(j)}} \end{bmatrix} \quad \text{.......} (3.38)$$

where:

S_{P-P} : is the real power loss sensitivity related to the real power injection.

S_{P-Q} : is the real loss sensitivity related to the reactive power injection.

S_{Q-P} : is the reactive power loss sensitivity related to the real power injection

S_{Q-Q} : is the reactive power loss sensitivity related to the reactive power injection.

J^T: is the transpose of the Jacobian matrix

Finally, both system power flow sensitivity factors and system power loss sensitivity factors have been formulated to be used in getting the combined sensitivity factors. The combined sensitivity factors will be used to get the candidate busses for D-STATCOM allocation. The combined sensitivity factor (CSF) is computed as follows.

$$CSF_i = (F_{P-Pi} \ x \ F_{Q-Pi}) + (F_{P-Qi} \ x \ F_{Q-Qi}) + (S_{P-Pi} \ x \ S_{Q-Pi}) + (S_{P-Qi} \ x \ S_{Q-Qi}) \text{....} (3.39)$$

CHAPTER FOUR

OPTIMAL PLACEMENT OF D-STATCOM USING A HYBRID OF GA AND PSO METHOD

4.1 Introduction

In this thesis optimal location and size of D-STATCOM is determined using a hybrid of GA-PSO. An optimization problem with multiple objectives is known as multi-objective optimization and in this research the objective of reduction in power loss and improvement in voltage profile of the system are the two main aims. Section 4.2 presents about multi-objective function optimization for placement of D-STATCOM and section 4.3 discussed about Genetic algorithm. Particle swarm optimization is discussed on section 4.4 and section 4.5 presents about hybridization of GA-PSO.

4.2 Multi-Objective Function Optimization for Placement of D-STATCOM

The multi-objective index for the performance calculation of distribution systems for D-STATCOM size and location planning with load models considers the below mentioned indices by giving a weight to each index.

The generalized objective function becomes;

$$\text{Minimize } (x) = \{f1(x), f2(x), \ldots \ldots \ldots .., fk\ (x)\} \quad (4.1)$$

where,

K – is the number of objective functions

$f1(x)$, $f2(x)$........$fk(x)$ are variables in the objective function

Multi-Objective Function (MOF) required to achieve the performance calculation of the power distributed systems for D-STATCOM size and location is given by;

$$MOF = w_1PLRI + w_2QLRI + w_3VPII \quad (4.2)$$

where,

w_1, w_2 and w_3 are the respective weights assigned to each factor.

$PLRI$ and $QLRI$ are the real and reactive power loss reduction index

$VPII$ is the voltage profile improvement index

The total sum of the weight assigned to all parameters of MOF should be equal to one;

$$w_1 + w_2 + w_3 = 1 \quad \text{.......} \quad (4.3)$$

These weights are used to assign a commensurate priority to each impact index for D-STATCOM penetration with load models, and they vary depending on the analysis. The weights are varying based on the engineer's considerations. The index whose impact outperforms the others in terms of importance and benefits is given a larger weight and vice versa.

Real and Reactive Power Loss Reduction Index

A common strategy for sizing and placement of D-STACOM is to minimize system power loss of the power system. Real Power Loss Reduction Factor Index per node is defined as the ratio of percentage reduction in real power loss from base case when a D-STACOM is installed at selected bus. Real Power Loss Reduction Index (PLRI) is expressed as:

$$F_1 = PLRI = \frac{P_{L(base)} - P_{L(DSTATi)}}{P_{L(base)}} \quad \text{.......} \quad (4.4)$$

where,

$P_{L(base)}$ is the active power loss before D-STATCOM installation

$P_{L(DSTATi)}$ is the real power loss in study system after installation of D-STATCOM

In order to determine the effect of D-STATCOM in reactive power losses, Reactive Power Loss Reduction Factor Index is incorporated in the objective function. This refers to the ratio of percentage reduction in reactive power loss from base case when a D-STATCOM is installed at bus i. Reactive Power Loss Reduction Index (QLRI) is expressed as;

$$F_2 = QLRI = \frac{Q_{L(base)} - Q_{L(DSTATAi)}}{Q_{L(base)}} \quad \text{.......} \quad (4.5)$$

where,

$Q_{L(base)}$ is the active power loss before D-STATCOM installation

$Q_{L(DSTATi)}$ is the real power loss in study system after installation of D-STATCOM

Voltage Profile Improvement Index

In a power system the voltage at each bus should be within the acceptable range and the line flows within the limits. These limits are important so that integration of D-STATCOM into the system does not increase the cost for voltage control or replacement of existing lines. The Voltage Profile Improvement Index penalizes size-location pairs that produce bigger voltage deviations from the base voltage. The Voltage Profile Improvement Index (VPII) is defined as;

$$F_3 = VPII = \frac{1}{\lambda + max_{i=2}^{n}(|1 - V_{DSTATi}|)} \quad \ldots\ldots (4.6)$$

where;

V_{DSTATi} is the voltage value after D-STATCOM installation

λ is a scalar value

4.2.1 Operational Constraints Formulation

The above-mentioned multi-objective function is reduced under multiple operational restrictions in order to meet the distribution network's electrical requirements.

System Constraint: For each bus, the following load regulations should be satisfied;

$$P_{Gi} - P_{Di} - P_i = 0 \quad \ldots\ldots (4.7)$$

$$Q_{Gi} - Q_{Di} - Q_i = 0 \quad \ldots\ldots (4.8)$$

where;

P_{Gi} and Q_{Gi} – Real and Reactive power generated at bus i

P_{Di} and Q_{Di} – Real and Reactive power demand at bus i

P_i and Q_i – Real and Reactive power flow at bus i

Power Generation Limit: This includes the upper and lower real and reactive power generation limit of generators and other reactive sources at bus-i.

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max}, \ i = 1,2,3,\ldots \quad \ldots\ldots (4.9)$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max}, \ i = 1,2,3,\ldots \quad \ldots\ldots (4.10)$$

where;

P_{Gi}^{min} *and* P_{Gi}^{max} are the minimum and maximum real power generation limits

Q_{Gi}^{min} and Q_{Gi}^{max} are the minimum and maximum reactive power generation limits

Voltage Limit: This includes the upper and lower voltage magnitude limit, $\boldsymbol{V_i^{min}}$and $\boldsymbol{V_i^{max}}$ at bus i. The bus voltage limit is determined by keeping the magnitude of the bus voltage within acceptable operational limits during the optimization process;

$$V_i^{min} \leq V_i \leq V_i^{max} \text{ , } i = 1,2,3,\ldots \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(4.11)}$$

where;

V_i^{min} and V_i^{max}: are the minimum and maximum voltage limits.

The system voltage is constrained with $0.95pu \leq V_i \leq 1.05pu$

4.2.2 Optimization Techniques

In the recent past, much effort has been contributed for solving the optimal placement problem of different FACTS technologies, utilizing different algorithms and considering different objectives. The D-STATCOM placement problem could be formulated as an optimization problem. Various algorithms are used to solve the problem. The methods used to solve this problem can be divided into three categories [46][48][49];

1. Analytical Methods
2. Computational Methods
3. Artificial Intelligence Methods

Analytical Methods: Although the analytical methods suffer from many drawbacks, they are still used in optimizing the location and size of FACTSs in distribution systems. This is because they are easy to work with and their logical analysis can easily be followed.

Computational Methods: Another class of techniques used for optimizing the location and size of FACTSs in a power system is the computational methods. Although these methods are fast compared to the other classes of techniques, their drawback is that they are complex and reproduction of their results may be difficult or sometimes impossible.

Artificial Intelligence Methods: Genetic Algorithms (GAs), for example, are adaptive heuristic search algorithms based on natural selection and genetics as evolutionary theories. Artificial intelligence refers to the intelligent use of a random search to solve optimization issues. Particle swarm optimization is also based on evolutionary calculations and is inspired by natural swarms with communications. As a result, analytical and computational optimization approaches are being phased out in favor of the most promising artificial intelligence methods, such as PSO, GA, and ABC, in order to achieve more accuracy in the optimization process [2][46][49].

As we discussed above there are different optimization techniques which can be used in optimizing the location and size of FACTSs in a distribution power system so as to ensure reduced system power losses and improved voltage profile. With this keep in mind, we need to come up with the most effective optimization techniques so that reliable results are obtained.

In this research Genetic algorithm, GA, is selected as one of the optimization techniques. This is because GA as a technique which has the ability to search a vast area and come up with reliable results [21][46][48]. On the other hand particle swarm optimization, PSO, is chosen as the other optimization technique for its flexibility to absorb other parameters for improvement [2][48]. Thus as a result GA was selected to be used in the initial stages for exploration purposes and then a PSO improved by incorporating crossover and mutation parameters was selected to be used later for exploitation purposes. Given the merits of the two optimization strategies, it was determined that hybridization would produce great outcomes.

4.2.3 Weight Value Choices for the Mult-Objective Function

Multi-Objective Function (MOF) required to achieve the performance calculation of the power distributed systems for D-STATCOM size and location under the Chromosome/Particle fitness identification is given in equation (4.2) and the respective weights assigned to each factor is given equation (4.3)

As mentioned earlier, the allocation of the various weights in a given multi-objective function vary according to the engineer's concern. In this research work, more emphasizes is given to real power loss reduction since this results to a considerable decrease in total cost of operation. Though, this is not to mean that the other two factors are not important. Thus taking this into consideration a study of the effect of the weights on the fitness was done so as to determine the best weights combination to adopt in coming up with the multi-objective function. Different researchers and this study too took the values of the weights positive and restricted as; $0.5 \leq w1 \leq 0.8$ and $0.1 \leq w2 \,\&\, w3 \leq 0.4$ [46][48][49].

Table 4.1: Effects of weights on power loss reduction and voltage profile improvement indices

$w1$	$w2$	$w3$	Best Fitness
0.8	0.1	0.1	0.7576
0.7	0.2	0.1	0.7566
0.7	0.1	0.2	0.6834
0.6	0.3	0.1	0.7556
0.6	0.2	0.2	0.6824
0.6	0.1	0.3	0.6091
0.5	0.4	0.1	0.7546
0.5	0.3	0.2	0.6814
0.5	0.2	0.3	0.6081
0.5	**0.1**	**0.4**	**0.5349**

From the results presented in the above Table 4.1 the combination of weights chosen is the one which gave the minimum best fitness. Thus the weights chosen were w_1 = 0.5 for real power loss reduction w_2 = 0.1 for reactive power reduction and w_3 = 0.4 for voltage profile improvement. The MOF becomes:

$$MOF = 0.5PLRI + 0.1QLRI + 0.4VPII \quad (4.12)$$

4.3 Genetic Algorithm

Genetic Algorithm uses biologically inspired techniques which involve natural selection, genetic inheritance, mutation and crossover in determining an optimal solution. The Genetic Algorithm starts the natural selection and evolution process, with the goal of solving an optimization problem with an objective function. The selection of the fittest individuals from a population begins the natural selection process. They generate kids who inherit the parents' qualities and are passed on to the next generation If parents are physically healthy, their children will be fitter and have a greater chance of surviving. This procedure continues to iterate until a generation with the fittest person is discovered [2][48].

GA operates with a population made up of a number of solutions, with the population size equal to the number of solutions. Individual solutions are referred to as such. Each solution has its own chromosome. The chromosome is a set of characteristics that characterizes a person. A group of genes is found on each chromosome. Each person has a fitness worth as well. A fitness function is used to choose the greatest persons. The fitness value, which represents the solution's quality, is the output of the fitness function. The higher the fitness value, the better the quality of the solution [2].

GA Parameter Selection and Optimization Process: These are five basic GA operators which are Population, Fitness function, Selection, Crossover and mutation [2][21][50].

***Initial Population*:** The procedure starts with a group of people known as a Population. Each person is a potential solution to the issue you're attempting to solve. Genes are a set of factors (variables) that describe a person. A Chromosome is made up of a string of genes (solution). GA works on a population of N chromosomes at the same time. These numbered vectors' starting population is generated at random. Each of these vectors represents one possible solution to the challenge of finding a match. One of the most critical elements that influences the performance of genetic algorithms is the population size. The population size determines the number of individuals in a population. Larger population sizes enhance the amount of variance in the original population yet necessitate additional fitness assessments. The ideal population size is determined to be application dependent as well as related to individual size (number of chromosomes within). A good population of individuals contains a diverse selection of potential building blocks resulting in better exploration. When a population loses its variety, it is considered to have "premature convergence," which means that little research is done.

Fitness Function: Determines a person's fitness level (the potential of an individual to battle with other individuals). It assigns a fitness score to each individual. The likelihood of an individual being chosen for reproduction is determined by their fitness value.

***Selection*:** This operator creates a temporary population, the mating pool, by selecting good chromosomes based on their fitness values. Based on their fitness scores, two pairs of people (parents) are chosen. Individuals who are physically fit have a better probability of being chosen for reproduction. Many other systems may be used to do this, but the most frequent is Roulette Wheel Selection. The fitness of each of the solution choices is rigged into the roulette wheel.

Crossover: A genetic operator known as crossover is used in genetic algorithms to modify the programming of a chromosome or chromosomes from one generation to the next. It's similar to reproduction and biological crossover, which are the foundations of genetic algorithms. Crossover is the process of combining multiple parent solutions to create a child solution. There are several methods for chromosomal selection. The major search tool is the crossover operator. It crosses over the mated couples with probability crossover, Pcross, and develops candidate offspring by marrying chromosomes in the mating pool in pairs. Many researchers suggest crossover rate to be between 0.6 and 1.0 [48][49][50][51].

Mutation: Mutation is the process of passing on a diversity transformation gene from one generation of genetic algorithm chromosomes to the next. Mutation is employed to give new information about the population (uncover new chromosomes) and also prevents the population of becoming saturated with similar chromosomes, simply said to avoid premature convergence. It's comparable to biological mutation. A mutation alters the values of one or more genes in a chromosome from their initial condition. The consequence of a mutation might be very different from the prior result. As a result, GA can use mutation to find a better solution. After crossover, some of the genes in the candidate offspring are inverted with the probability P*mut*. Typically, the probability of mutation P*mut* is assumed to be between 0.01 and 0.1[48][49][50].

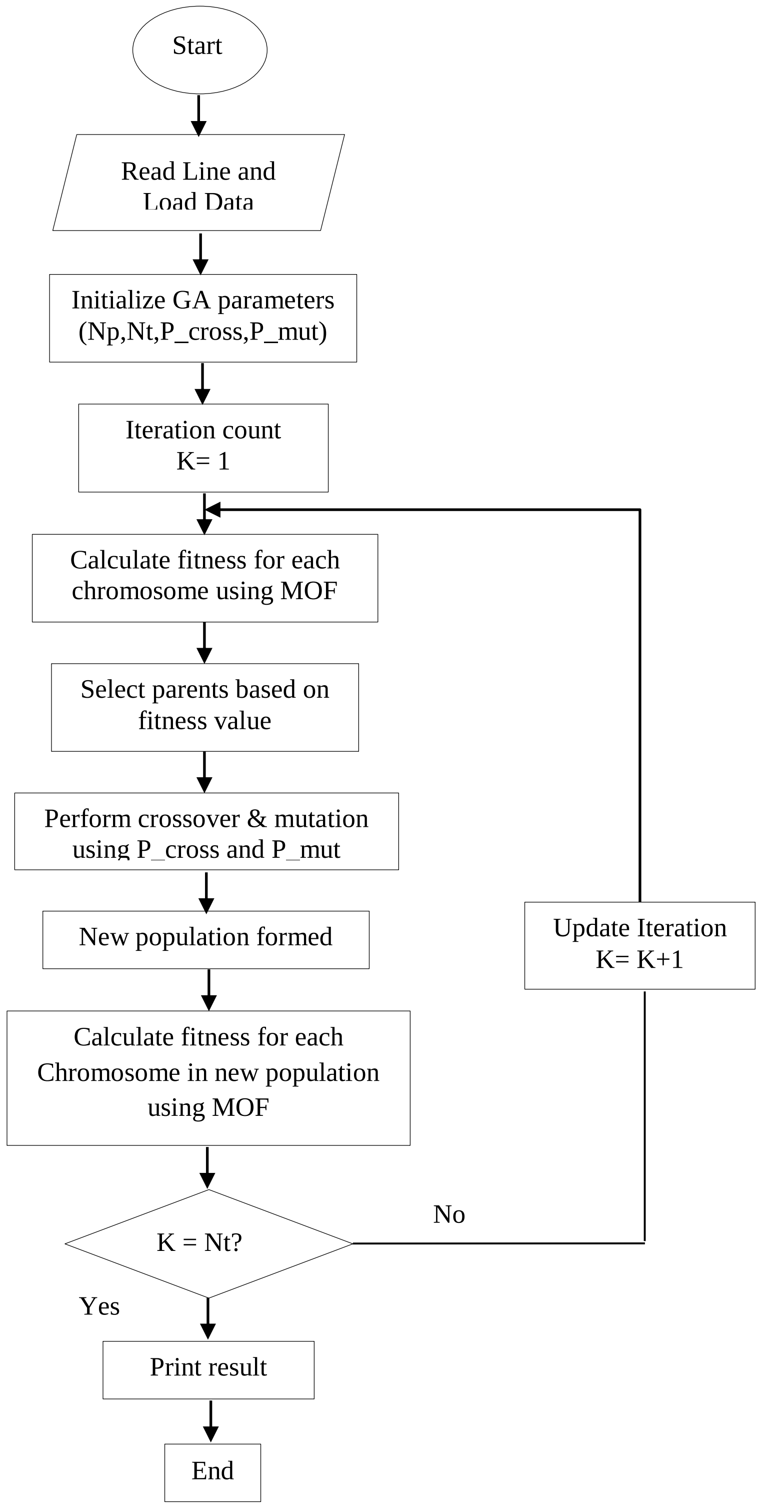
Elitism: If the best number in the newly created population is lower than the best number in the old population, the worst chromosome in the newly generated population is replaced by the best chromosome in the previous population. This is done to ensure that the algorithm will converge. Elitism is the term for this approach of reserving the elite parent.

New population**:** The particle selection, mutation and crossover are repeatedly performed on the population until a new generation is obtained which is then taken as the new population. Moreover, an elitist strategy can be applied so as to ensure only survival of the best individuals get to be replaced with new ones. The Advantage of GA includes the following:

- The solutions are resistant to being trapped into a local optima and
- It can scan a vast solution set quickly
- Bad proposals are discarded and hence do not negatively affect the end solution

The disadvantages are the following:

- High computational time



where: Np – number of population

Nt – number of iteration

P_cross – crossover probability

Q_mut – mutation probability

$$MOF = w_1PLRI + w_2QLRI + w_3VPII$$

Figure 4.1: Flowchart of Genetic algorithm

4.4 Particle Swarm Optimization

The optimization technique is used to find the best solution for any given circumstances. PSO is a robust stochastic optimization method based on swarm intelligence and mobility. PSO is a swarm intelligence and mobility-based resilient stochastic optimization approach. PSO is a population-based meta-heuristic optimization approach created in 1995 by James Kennedy and Russell Eberhart and motivated by flocking birds or schooling fish [59]. PSO is initialized with a random number of solutions called particles which are left free on a 'search space'. Each particle is a possible solution of the problem and has a fitness value. The fitness is evaluated and is to be optimized. A velocity is defined which directs each particle's position and gets updated in each iteration. Particles eventually shift toward the optima as a result of their best location and the finest solution that group has ever encountered. The velocity of a particle is updated based on three factors: the particle's previous velocity, the best position the particle has ever been in, and the best position the entire swarm has ever been in [47][48].

Each particle keeps track of its search space coordinates, which are linked to the particle's best solution (fitness) thus far. Personal best, or *pbest*, is the name given to this number. Another best value that the PSO keeps track of is the best value acquired so far by any particle in that particle's vicinity. *gbest* is the name given to this value. The main idea behind PSO is to use a random weighted acceleration to accelerate each particle toward its *pbest* and *gbest* positions at each time step [48][49]. With each iteration, the PSO alters the velocity and hence the location of each particle. The acceleration is weighted by a random term to create random values, which aids acceleration towards *pbest* and *gbest*. Using the prior velocity and the distance between *pbest* and *gbest*, the prevailing velocity can be computed. [47]. The positions of all the particles are modified according to the personal flying experience called *pbest* (personal best) as well as the flying experience of the other particles in the group called *gbest* (Global best).

These particles are assigned with random velocities. Mathematically the modification process may be expressed as follows:

$$V_{id}^{k+1} = wV_{id}^{k} + c_1 r\left(P_{best_{id}} - S_{id}^{k}\right) + c_2 r\left(G_{best_{id}} - S_{id}^{k}\right) \quad \text{........................ (4.13)}$$

$$S_{id}^{k+1} = S_{id}^{k} + V_{id}^{k+1} \;\; ; \text{ i = 1,2,…,n \& d = 1,2,…,m} \quad \text{................................ (4.14)}$$

where;

V_{id}^{k+1} - Modified velocity of particle 'i'

V_{id}^{k} - Current velocity of particle 'i'

w - Inertia weight

c_1 ,c_2 - Acceleration coefficients

$P_{best_{id}}$ - The particles best position value

$G_{best_{id}}$ - The groups best position value

S_{id}^{k+1} - The modified searching point of a particle

S_{id}^{k} - Current searching point of a particle

r - Random number generated in the range [0 1] , which is added in the model to introduce stochastic nature.

n - Number of particles in the swarm

k - Number of iteration

The following weight function is used:

$$w_k = w_{max} - \frac{(w_{max} - w_{min})}{k_{max}} . k \quad \text{(4.15)}$$

where;

w_{min} and w_{max} are the minimum and maximum weights respectively

PSO Parameter Selection and Optimization Process

For any given optimization problem, some of the parameters in the PSO algorithm may affect its efficiency. Some of these parameters' values and choices have a significant impact on the PSO technique's performance, while others have little or no impact. The basic parameters of PSO are [47][48][49]:

Swarm *Size:* Swarm size is defined as the number of agents 'n' in the swarm. A huge swarm generates more particles and most of the search space is to be covered per iteration. A number of iterations may be reduced in order to achieve the best optimization value using a large number of agents. But the computational complexity per iteration will be increased by using more amounts of agents and also it is more time-consuming.

***Particle Velocity*:** The current velocity V_i^k is constrained in the limits $V_{id}^{min} \leq V_{id}^k \leq V_{id}^{max}$. The parameters V_{id}^{max} establishes the resolution, or fitness, indicating which regions between the current and target positions should be searched. If V_{id}^{max} is very high, particles might fly past good solutions. This is because the particles move in larger steps and the solution reached may not optimal. Similarly if V^{max} is too small, particles take longer time to reach desired solutions. They may even not explore sufficiently hence being captured in local minimum solutions. While updating the agent's velocity, the velocity components play a vital role. There are three terms in an agent's velocity. They are the inertia component, the cognitive component, and social component.

- The term V_{id}^k is called inertia component. It provides information about the movement's recent history. This component prevents abrupt changes in the agent's orientation and gives the agent a propensity to proceed in the same direction.
- The term $c_1 r_1 \left(P_{best_{id}} - S_{id}^k\right)$ is called a cognitive component. It is used to measure the performance of the agents with respect to their past performances. It acts as an individual memory of the best position for an agent. The effect of this component is to make the agents to positions which satisfied them the most in the past
- The term $c_2 r_2 \left(G_{best_{id}} - S_{id}^k\right)$ for *gbest* PSO is called social component. It is used to measure the performance of the agents with respect to a group of agents. It makes each agent move towards the best position found by the agent's neighborhood.

***Random Numbers*:** The uniform random values are in the range [0, 1]. They assist in achieving PSO's stochastic nature.

***Accelerating Coefficients*:** The stochastic influence of the social and cognitive components of the agent's velocity depends upon acceleration coefficients $c1$ and $c2$, together with the randomly generated numbers $r1$ and $r2$, respectively. The confidence that an agent has in itself is represented by $c1$ and the confidence that an agent has in its neighbors is represented by $c2$. The properties of $c1$ and c2 [47][48]:

- When $c1$= $c2$=0 until search spaces boundary is met, all the agents will continue to move with their current speed.
- When $c1 > c2$ each agent is greatly influenced by its personal best position, and hence they get locally trapped
- When $c1 < c2$ then all agents in the swarm are greatly influenced by the global best position which makes all agents run prematurely to the optimal (search space will be left not properly explored.).
- When $c1 = c2$ all agents will get attracted towards an average of *Pbest,* and *Gbest.*

Initialization of $c1$ and $c2$ plays a great role in obtaining the optimum values. The wrong assumption of $c1$ and $c2$ results in cyclic behavior. From many types of research, the values of two acceleration constants should be $c1$ and $c2 = 2$ [47][48][49][53].

***Inertia Weight*:** The inertia weight determines how much of the preceding time step's velocity should be kept. However, the greatest results were obtained by adopting an inertia weight that drops from 0.9 to 0.4 throughout the first simulation course. This parameter enables the PSO to search a vast region at the start of the simulation when the inertia weight is high, and then refine the search later when the inertia weight is lower. Another benefit of adopting a decreasing inertia weight is that it dampens the oscillations of the particles near gbest. In addition, damping the oscillations of the particles around *gbest* is another advantage gained by using a decreasing inertia weight. These oscillations are recorded when a large constant inertial weight is used. As a result, suppressing such oscillations aids the swarm's particles in converging to the global best solution. According to, the value of inertia weight (w) is expected to drop linearly from 0.9 to 0.4 during the experiment [47][48][54]. In general, the inertia weight (w) is adjusted according to equation (4.3) above. Appropriate values for w_{min} and w_{max} are 0.4 and 0.9 respectively.

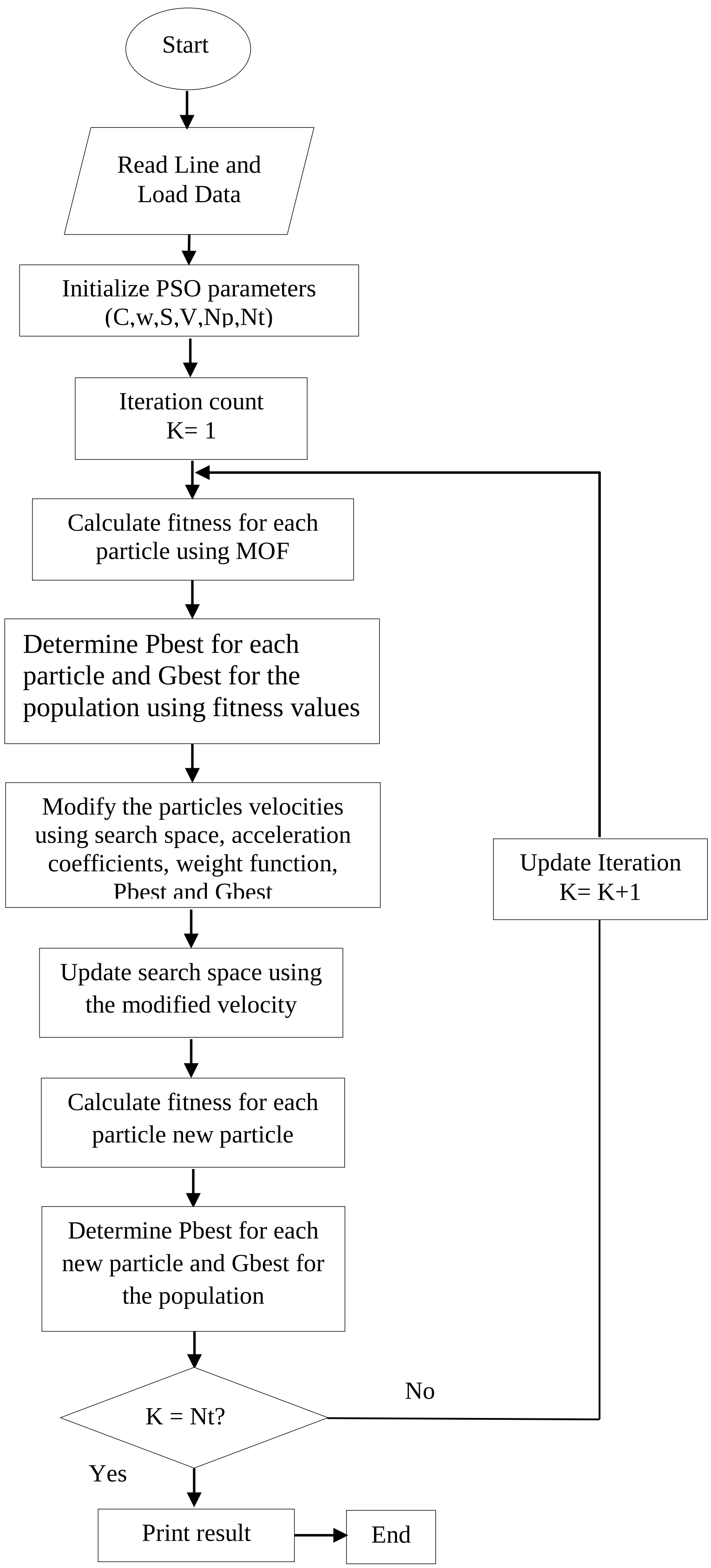
Termination criterion: After the initial phase, several iterations of update and evaluation steps are performed until a stopping condition is met. Generally, the stopping condition is the attainment of a predefined maximum numbers of iterations or the attainment of certain accuracy in the solution.

PSO has the following advantages which include [47][48][54];

1. PSO is based on the swarm intelligence. It can be applied into both scientific research and engineering use.
2. PSO has an advantage of a fast convergence rate in comparison to most optimization techniques including Genetic Algorithm.
3. PSO have no overlapping and mutation calculation. The particle's speed might be used to do the search, for example in comparison to GA.
4. PSO has a stronger memory capability than GA since each particle remembers its own prior best value as well as the neighborhood best.
5. PSO is more effective at maintaining swarm diversity than GA because the bad solutions are discarded and only the good ones are saved, resulting in a population that evolves around a subset of the best individuals because all particles use information from the most successful particle to improve themselves.

The major disadvantages of PSO are;

1. The approach is prone to partial optimism, which leads it to be less precise in regulating its speed and direction.
2. The method may not work out properly the problems of non-coordinate system, such as the solution to the energy field and the moving rules of the particles in the energy field.



where: S- Search space of a particle

V- Velocity of a particle

C – Acceleration coefficient

w – Weight function

Np – number of particles

Nt – number of iteration

$$MOF = w_1 PLRI + w_2 QLRI + w_3 VPII$$

Figure 4.2 Flowchart of PSO

4.5 Hybridization of GA-PSO Algorithm

The development of the PSO-GA technique was motivated by the need to combine the benefits of genetic algorithms with particle swarm optimization. Incorporating genetic operators into the basic PSO improves the balance between exploration and exploitation capabilities even more. Both models, however, offer advantages and disadvantages. In GA, if an individual is not chosen, the information they possess is lost, but PSOs have memory. PSOs, on the other hand, may squander money on impoverished people if they don't have a selection operator. As a result, the primary concept behind PSO-GA is to combine PSO's social thinking capacity with GA's local search capabilities. Because GA and PSO are both population-based algorithms, the hybrid PSO-GA technique is likewise population-based and hence finds the global answer. The method began with the initialization phase, in which the swarm's particles and related velocities were produced at random throughout the search space [55].

This research work proposes the use of a hybrid of Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) for optimal allocation of D-STATCOM. The D-STATCOM is considered to be located in the distribution system with the aim of reducing power system losses and improving voltage profile in the distribution network.

The candidate buses for D-STATCOM position were determined using system power flow and power loss sensitivity parameters. This reduces the search space for the algorithm, allowing it to converge more quickly. The results of these sensitivity factors are then passed to GA which gives possible D-STATCOM sizes for each location. This is accomplished by randomly initializing the sizes for each place and then optimizing them using a multi-objective function. In general, GA explores and finds potential ideas, which are then forwarded to PSO for fine tweaking.

The GA output which is handed to PSO comprise of some sets of solutions each having a D-STATCOM location and the associated size too. The GA optimized findings are then used by PSO as its starting particle set. This aids in the attainment of quicker convergence. PSO fine tunes solutions from Genetic Algorithm so as to come up with an optimal solution.

In this research work crossover and mutation has been applied to both GA and PSO sections in the hybridized algorithm. These operators help in avoiding pre-mature convergence/partial optimism and thus improving the performance of algorithms. In Michalewicz, 1994 and Gen & Cheng, 1997 arithmetic crossover is defined as the combination of two parent chromosomes X_{p1} and X_{p2} to give two children chromosomes X_{c1} and X_{c2} to as follows [48]:

$$X_{c1} = \lambda X_{p1} + (1-\lambda)X_{p2} \quad \text{.......} \quad (4.16)$$

$$X_{c2} = \lambda X_{p2} + (1-\lambda)X_{p1} \quad \text{.......} \quad (4.17)$$

$\lambda \in (0,1)$ is generated randomly between 0 and 1 and used to compute the children as shown

For a given child;

$$X_{cl}^{k} = X_{l1}^{k},,,X_{lj}^{k},,,X_{lm}^{k} \quad \text{.......} \quad (4.18)$$

If the element X_{lj}^{k} is selected for mutation, the resulting offspring is given by;

$$X_{cl}^{k} = X_{l1}^{k},,,X_{lj}^{k*},,,X_{lm}^{k}$$

$$X_{lj}^{k*} = X_{lj}^{k} + \Delta X_{lj}^{k} \quad \text{.......} \quad (4.19)$$

ΔX_{lj}^{k} is randomly selected from the two possible choices

$$\Delta X_{lj}^{k} = r\left(X_{l1}^{max} - X_{l1}^{k}\right)\left(1 - \frac{k}{k_{max}}\right) \quad \text{.......} \quad (4.20)$$

Or $\Delta X_{lj}^{k} = r\left(X_{l1}^{min} - X_{l1}^{k}\right)\left(1 - \frac{k}{k_{max}}\right)$ r is a random number In between 0 and 1

Steps for the Hybrid GA-PSO Algorithm

The proposed GA-PSO based approach for optimal allocation of D-STATCOM units in the distribution systems is as detailed in the following implementation steps;

1. Get system data by reading the power system parameters.
2. Employ Newton-Raphson method for load flow studies Compute CSF for each bus and arrange buses in order of sensitivity.

   $$CSF_i = \left(F_{P-Pi} \; x \; F_{Q-Pi}\right) + \left(F_{P-Qi} \; x \; F_{Q-Qi}\right) + \left(S_{P-Pi} \; x \; S_{Q-Pi}\right) + \left(S_{P-Qi} \; x \; S_{Q-Qi}\right)$$
3. Buses with high sensitivities are chosen as candidate buses.
4. Input both GA and PSO parameters.
5. Set candidate bus count $i = 1$
6. While $i \leq 1$
   a. Initialize N chromosomes with random values to represent possible D-STATCOM sizes.

      $P_{DSi}^{min} \leq P_{DSi} \leq P_{DSi}^{max}$ and $Q_{DSi}^{min} \leq Q_{DSi} \leq Q_{DSi}^{max}$, i = 1,2,3,….

b. Set iteration count (for GA) $k = 1$

c. While $k \leq 1$

   I. Evaluate each chromosomes fitness using the multi-objective

   II. Using roulette wheel selection method select two chromosomes (X_{p1} and X_{p2})

   III. Perform crossover and mutation based on the probabilities (P_{cross} and P_{mut})

   IV. Create a new population by repeating steps (II) and (III) while accepting the newly formed children until the new population is complete.

   V. Replace old population with new population

   VI. Update the iterations counter $k = k + 1$

d. Stop and pass current chromosomes (partially optimized) to PSO.

e. Use GA optimized chromosomes as initial PSO particles.

f. Calculate the fitness value for each particle using the multi-objective function. The result of each particle becomes its p_{best}. The particle value with the best fitness among all the p_{best} is denoted as g_{best}

g. Set iteration count PSO $iter = 1$

h. While $iter \leq iter_{max}$

   I. Modify the velocity of each particle element as shown
   $V_{id}^{k+1} = wV_{id}^{k} + c_1 r_1 \left(P_{best_{id}} - S_{id}^{k}\right) + c_2 r_2 \left(G_{best_{id}} - S_{id}^{k}\right)$

   II. Then generate the new position for each particle element
   $S_{id}^{iter+1} = S_{id}^{iter} + V_{id}^{iter+1}$.

   III. Using Roulette wheel selection method select two chromosomes (S_{p1} and S_{p2})

   IV. Perform crossover and mutation based on the probabilities (P_{cross} and P_{mut})

   V. Establish a new population by repeating steps (III) and (IV) while accepting the newly formed children until the new population complete.

   VI. Update the iteration counter, $iter = iter + 1$

i. Stop. The particle that result the best, g_{best} is the optimal solution

j. With the latest g_{best} in the network calculate system power loss and bus voltages

k. Update the candidate bus $i = i + 1$

7. Compare the fitness of candidate buses g_{best} and get the most minimized one(s).
8. The result gives the optimal locations and their respective optimal D-STATCOM size

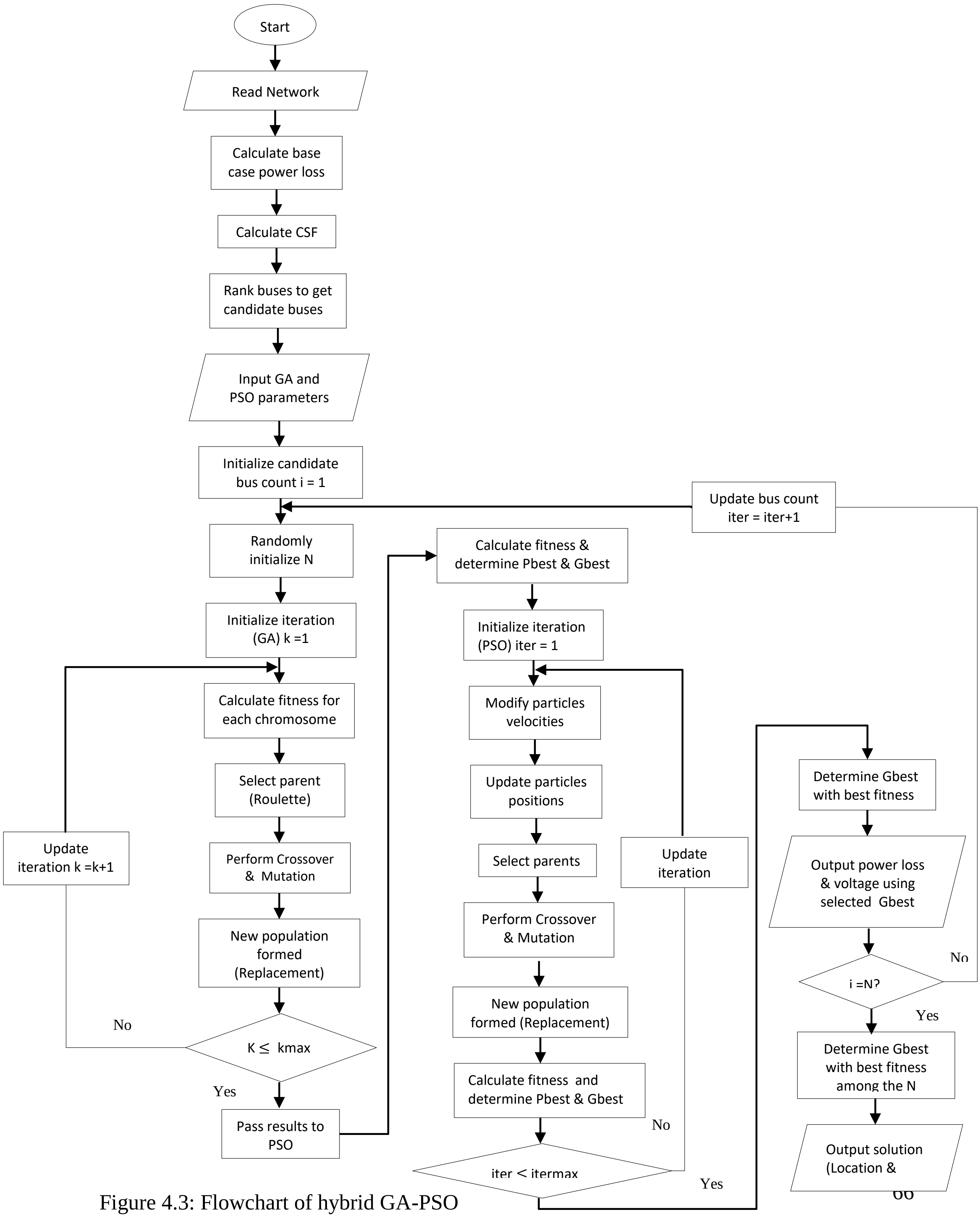


Figure 4.3: Flowchart of hybrid GA-PSO

CHAPTER FIVE

SIMULATION STUDIES AND ANALYSIS OF RESULTS

In this chapter the results obtained using GA-PSO hybrid method have been presented. The hybrid algorithm discussed in the previous chapter is implemented and programmed in MATLAB 2013 software. The main codes programmed according to the implementation steps of the proposed algorithm are given in Appendix section. The result of this research work are obtained and analyzed as follows:

A. The base case voltage profile and line losses at the buses in the power distribution system have been found, first without integrating any D-STATCOM device.
B. The voltage profile and line losses at the buses in the distribution system have been found, after integrating D-STATCOM in the distribution system.
C. The result obtained using D-STATCOM and the base case was analyzed. Comparison has made on the voltage profile of the buses, the power loss of the system and come up the possible recommendation to enhance the performance operation of Kotebe substation feeder.

5.1 Base Case Load Flow Analysis

The base case load flow simulation is performed to analyze the current status of the power system network. The load flow analysis has been performed using the Newton-Raphson algorithm coded in MATLAB, the source code of which is provided in Appendix B. Using the line and peak load bus data of the distribution network under study (Kotebe K3), the MATLAB Newton-Raphson load flow has been simulated.

The selected power distribution feeder for this study is a radial system with a total real power loss of 1.7351 MW and a total reactive power loss of 0.7080 MVAR. To reduce the power loss and improve the voltage profile, hybrid GA-PSO based optimization technique has been used. The voltage profile of the existing power distribution system for feeder K3 at the base case is shown in figure 5.1 below.

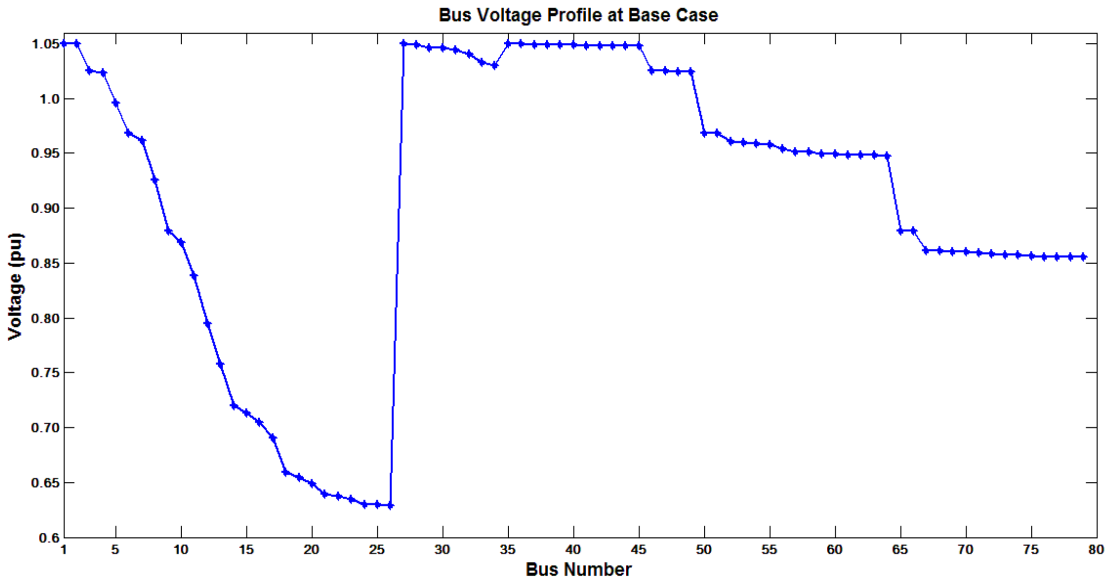


Figure 5.1: Base case voltage profile of Kotebe K3 feeder

5.2 CSF and GA-PSO Result

For each bus combined sensitivity factor (CSF) are analyzed and the buses with high CSF are taken as a candidate bus for placement. Hence, those weak buses are considered for optimal placement of D-STATCOM after GA-PSO optimization. The candidate bus selection algorithm and GA-PSO code is shown in Appendix C and D. The CSF for each bus is shown on Table 5.1 and Figure 5.2.

Table 5.1: Combined sensitivity factor of the buses

Bus No.	CSF	Bus No.	CSF	Bus No.	CSF	Bus No.	CSF
1	0.0000	21	0.9543	41	0.1831	61	0.1044
2	0.0000	22	0.9605	42	0.1936	62	0.1046
3	0.0090	23	0.9735	43	0.1960	63	0.1049
4	0.0106	24	0.9889	44	0.2238	64	0.1052
5	0.0344	25	0.9908	45	0.2239	65	0.3294
6	0.0733	26	0.9913	46	0.0090	66	0.3296
7	0.0847	27	0.0000	47	0.0091	67	0.4320
8	0.1684	28	0.0000	48	0.0092	68	0.4324

9	0.3205	29	0.0000	49	0.0093	69	0.4359
10	0.3534	30	0.0000	50	0.0734	70	0.4382
11	0.4108	31	0.0000	51	0.0735	71	0.4401
12	0.5011	32	0.0000	52	0.0858	72	0.4433
13	0.6031	33	0.0000	53	0.0870	73	0.4475
14	0.7098	34	0.0000	54	0.0885	74	0.4512
15	0.7294	35	0.0000	55	0.0899	75	0.4542
16	0.7591	36	0.0030	56	0.0965	76	0.4593
17	0.7704	37	0.0103	57	0.0998	77	0.4599
18	0.8698	38	0.0132	58	0.1011	78	0.4612
19	0.8863	39	0.0134	59	0.1025	79	0.4614
20	0.9079	40	0.1120	60	0.1042		

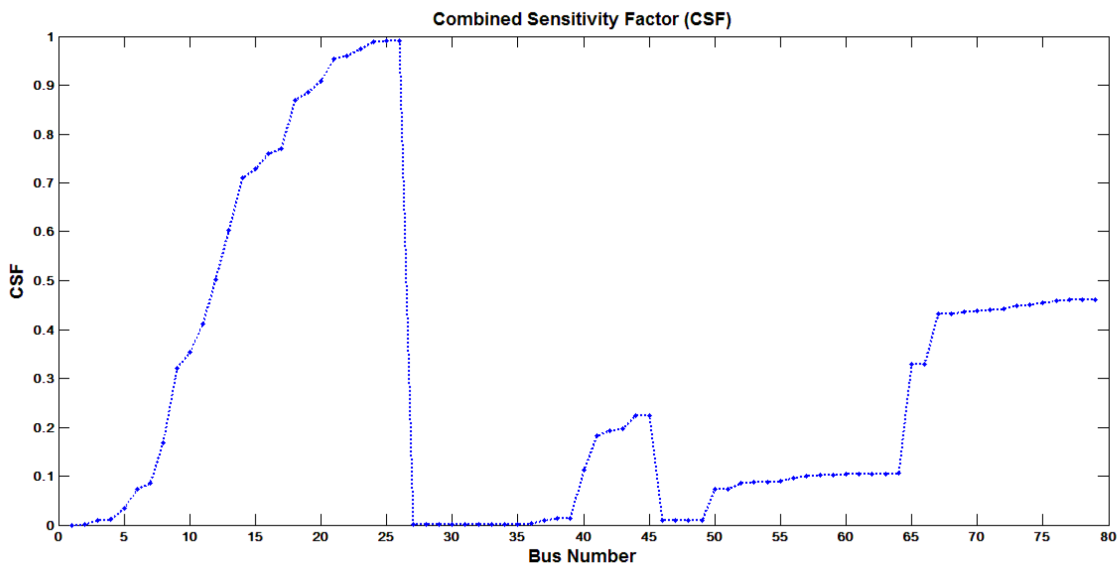


Figure 5.2: Combined sensitivity factor for Kotebe K3 feeder

From Table 5.1 and figure 5.2 it is observed that the top five critical buses in the Kotebe K3 feeder are 26,25,24,23 and 22 respectively and therefor considered for D-STATCOM integration.

Table 5.2: Results for CSF, Fitness and optimal D-STATCOM sizes for candidate buses

Candidate Bus	CSF	Fitness	D-STATCOM Size (MVAR)
22	0.9605	0.8188	1.2472
23	0.9735	0.8215	1.1481
24	0.9889	0.8296	1.0835
25	0.9908	0.8333	1.0218
26	0.9913	0.8352	1.0334

5.3 Power Loss and Bus Voltage Profile After D-STATCOM Integration

The selected five optimal locations for the integration of D-STATCOM and their optimal sizes are tabulated on table above. The GA-PSO optimization program generates the size of the D-STATCOM with their respective fitness value as tabulated on Table 5.2. The five selected optimal locations and their respective optimal D-STATCOM sizes were as follows in order of effectiveness;

1. Bus number 22 with a D-STATCOM size of 1.2472 MVAR
2. Bus number 23 with a D-STATCOM size of 1.1481MVAR
3. Bus number 24 with a D-STATCOM size of 1.0835MVAR
4. Bus number 25 with a D-STATCOM size of 1.0218 MVAR
5. Bus number 26 with a D-STATCOM size of 1.0334 MVAR

Table 5.3: Power loss comparison before and after D-STATCOM integration

Bus No.	D-STATCOM Size	Power Loss at Base Case		Power Loss after D-STATCOM		% Power Loss Reduction	
	MVAR	MW	MVAR	MW	MVAR	% MW	% MVAR
22	1.2472	1.7351	0.7080	1.0948	0.4453	36.90	37.11
23	1.1481	1.7351	0.7080	1.1236	0.4634	34.24	34.54
24	1.0835	1.7351	0.7080	1.1337	0.4601	34.62	35.01
25	1.0218	1.7351	0.7080	1.1718	0.4757	32.46	32.81
26	1.0334	1.7351	0.7080	1.1836	0.4818	31.78	31.94

From the above result GA-PSO method gave great percentage reduction in both real and reactive power losses. From the listed highly sensitive five buses with different D-STATCOM size up to 37% reduction in both real and reactive power is obtained. Bus number 22 gives high percentage in both real and reactive power loss reduction and which is the most effective bus for D-STATCOM placement.

When DSTATCOM is placed at bus 22, the total real and reactive power losses are reduced to 1.0948 MW and 0.4453 MVAR respectively. Moreover, the voltage profiles of all 79 buses were kept under the acceptable range. Initially in the base case 41 of the buses voltage were not in the acceptable range of deviation and bus number 26's voltage was at the lowest end and which was 0.6293pu. This voltage value improves to 0.9701pu when DSTATCOM is places in the distribution feeder. The voltage profile of the buses after and before D-STATCOM integration at bus number 22 were shown in figure 5.3.

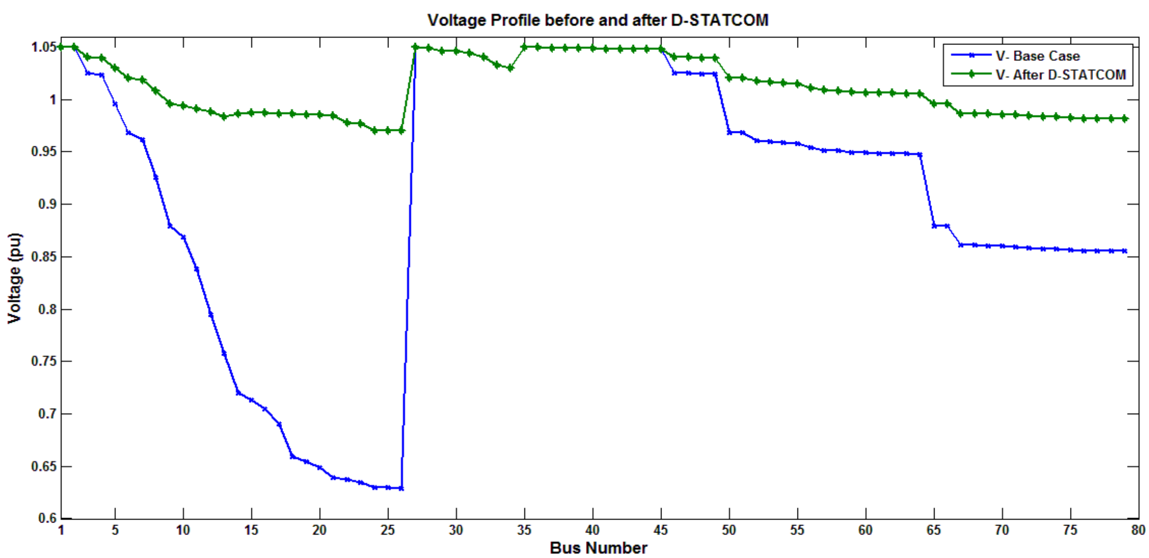


Figure 5.3: Voltage profile of Kotebe K3 feeder before and after D-STATCOM integration at bus 22

5.4 Comparative Analysis of GA-PSO, PSO and GA

Simulation has performed for the case of D-STATCOM on the selected feeder using the three methodologies known as Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Hybrid of GA and PSO (GA-PSO). A comparison analysis has performed on Table 5.4 on the weakest bus found so far, bus 22. From Table 5.4 it is observed that the GA-PSO method gives the greatest reduction in both real and reactive power loss compared with other two methodologies.

Table 5.4: A comparison of Results obtained using different methodologies

Methodology	Base Case Power Loss		D-STATCOM Size	Power Loses		%Power Loss Reduction	
	MW	MVAR	MVAR	MW	MVAR	MW	MVAR
GA-PSO	1.7351	0.7080	1.2472	1.0948	0.4453	36.90	37.11
GA	1.7351	0.7080	1.4456	1.1925	0.4826	31.32	31.83
PSO	1.7351	0.7080	1.3832	1.1451	0.4637	34.01	34.50

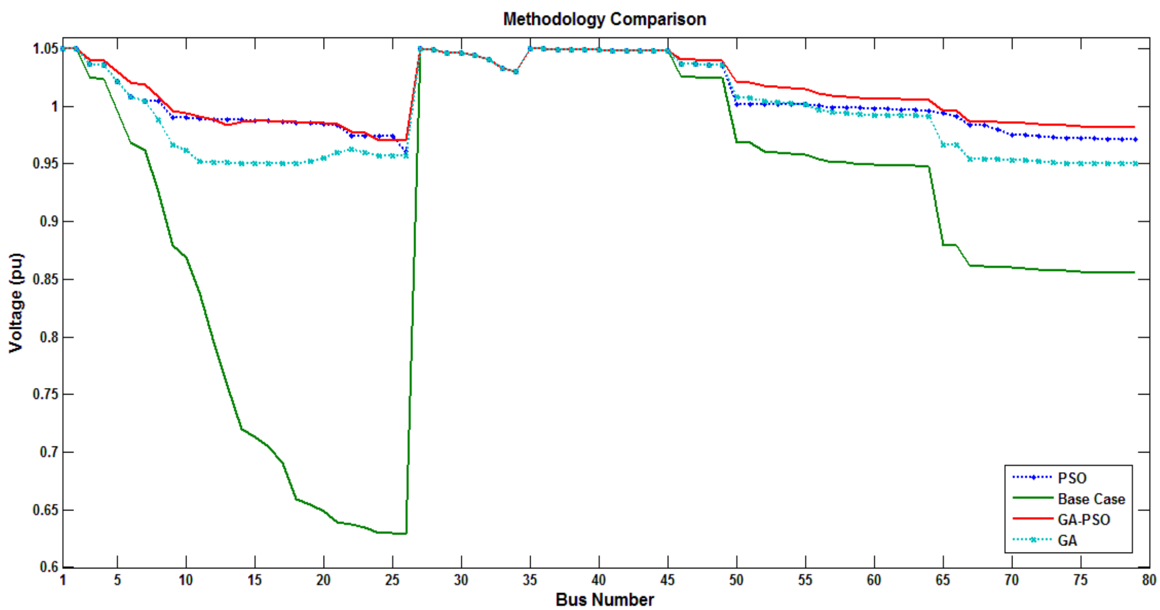


Figure 5.4: Voltage profile under base case and after placement of D-STATCOM using GA, PSO and GA-PSO methods at bus 22.

The above result on table 5.4 clearly shows that the GA-PSO method gives the greatest reduction in both real and reactive power loss compared to all the other methodologies. The percentage real power loss reduction from this method was 36.90% compared to 34.01% for PSO and 31.32% for GA. The reactive power losses is reduced by a percentage of 37.11% for GA-PSO and which is 31.83% GA, 34.50% PSO. It is also important to note that the sizes of D-STATCOM obtained compare well to the sizes from the other methods. Therefore the GA-PSO method is seen to be superior to the other three methods in terms of optimizing the location and size of D-STATCOM with the objective of reducing system power losses.

The bus voltage profile of Kotebe K3 feeder after the penetration of D-STATCOM for the three methodologies is shown in figure 5.4. All bus voltages were kept under the acceptable voltage range, which is in between 0.95pu and 1.05pu.

5.5 Cost Analysis

Once the sizing and location of D-STATCOM has determined, the cost it needs for the successful implementation of this devices is the next subject. The cost analysis had started by finding the total annual energy lost at peak load

- **Annual energy loss at base case**

Total annual energy loss of Kotebe K3 feeder = Peak power loss (MW)*8760h
= 1.7351 MW * 8760 h
= 15.19 GWh

The financial loss evaluation is based on the ETB/kWh energy rates for Ethiopian Electric Utility, under the new power tariff. The cost of energy is rated at 1.193 ETB/kWh or 1193 ETB/MWh, by taking Ethiopian Electric Utility tariff order for Industrial Medium voltage 15 kV/Tariff 4/[56]. Using 1193 ETB/MWh, the total amount of annual financial loss due to the power loss is estimated as follows:

- **Annual financial loss at base case**

Annual financial loss (ETB) = Total annual energy loss*1193 ETB/MWh
= 18.12 million ETB/year

- **Annual energy loss reduction after D-STATCOM integration**

Total annual energy loss reduction of Kotebe K3 feeder = Power loss reduction (MW)*8760h
= (1.7351 - 1.0948 MW) * 8760 h
= 5.61 GWh

- **Annual financial loss reduction after D-STATCOM integration**

Annual financial loss reduction (ETB) = Total annual energy loss reduction*1193 ETBMWh

= 6.69 million ETB/year

D-STATCOM integration to Kotebe K3 feeder reduces the annual financial loss from 18.12 Million ETB to 11.43 Million ETB, which is 36.92% reduction in annual energy cost. The Cost of D-STATCOM per KVAR is 244 USD including installation cost [57][58]. Based on the exchange rate of Commercial bank of Ethiopia on January 10, 2022, 1 USD = 49.47 ETB. The payback in a year is calculated as follows [15]:

- **Payback period analysis**

Payback period = Net investment/ Net profit

= (Cost in USD*Size D-STATCOM*Exchange Rate)/Net Profit

= (244 USD/KVAR*1.2472 MVAR*49.47 ETB/USD)/(6.69 mil.ETB/year)

= 15.05/6.69

Payback period = 2.25 year

The economic analysis show that the payback period for the initial investment cost is 2.25 years.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

In conclusion, this research work showed the formulation and implementation of a hybridized GA-PSO algorithm to help in reducing Kotebe distribution network power losses and improving voltage profile by optimal location and sizing of D-STATCOM. The combined sensitivity factors is formulated and used effectively in reducing the search space for the algorithm. The buses 22,23,24,25 and 26 are the most sensitive buses and have been selected for D-STATCOM allocation. Bus 22 is the most effective bus for placing D-STATCOM in terms of power loss reduction and voltage profile improvement.

The base case MATLAB simulation results indicate that the Kotebe feeder 'K3' encountered a total real power loss of 1.7351 MW and 0.7080 MVAR reactive power losses respectively. Moreover, 41 of the buses were not under the acceptable voltage range. After D-STATCOM integration at bus 22, 36.9% real power loss reduction and 37.11% reactive power loss reduction is obtained and all bus voltages are kept under the acceptable range. The GA-PSO method also improved the lowest bus voltage from a value of 0.6293pu to 0.9701pu. Furthermore, simulation has also performed to investigate the effectiveness of the hybrid GA-PSO method. The comparison result obtained indicated that GA-PAO mechanism gives a better result than both GA and PSO in terms of power loss reduction and size of D-STATCOM.

Finally, the cost analysis has been done to determine the economic feasibility of the solution. The economic analysis shows that 15.05 million ETB investment cost is needed to install 1.2472 MVAR D-STATCOM size. The payback period analysis shows that 2.25 years are needed to return the investment. Hence, it is profitable to install D-STATCOM and enhance the performance of the Kotebe power distribution system.

6.2 Recommendation

Based on the findings of this research, it is recommended to use D-STATCOM in order to improving the voltage profile and reduce the power loss on Kotebe substation.

It is further recommended to use D-STATCOM at the most sensitive and weak bus to significantly improve the voltage profile and reduce the power loss of the network.

6.3 Suggestion for Future Work

This study is focused only on the steady state power system condition. Therefore, further research can be done on capability of D-STATCOM on power loss minimization and voltage profile improvement during transient condition of a power system. In addition, the following works are suggested to further extend the research

- The Multi-objective function can be improved by taking into consideration other power system parameters like stability issues.
- The possibility of hybridizing two or more D-FACTS devices can also be considered, and deal with its effect on the improvement of the performance system
- Further analysis can be performed by considering network reconfiguration, simultaneous placement of DG and D-SATCOM.
- After programming the code in Matlab 2013, long iteration time ,30 minutes, is noted and thus more work can be done in trying to reduce this time.

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APPENDICES

Appendix A: Newton-Raphson Load Flow Method.

The Newton-Raphson technique is an iterative approach that uses Taylor's series expansion to approximate a collection of non-linear simultaneous equations to a set of linear equations, with terms limited to first order approximation. Load flow analysis using Newton-Raphson (NR) method is more efficient and practical for large power systems. The main advantages of this method are that the number of iterations required to obtain a solution is independent of the size of the problem and computationally it is very fast. Here the load flow problem is formulated in polar form. The load flow may be solved in two ways using the Newton Raphson approach. For the variables, the first technique employs rectangular coordinates, whereas the second method uses polar coordinates. The polar coordinate form is the most often utilized of these two techniques [5].

Consider a set of n non-linear algebraic equations

$$f_i(x_1, x_2, \dots, x_n) = 0 \text{ ; I = 1,2,..,n} \quad \dots\dots \quad \text{A-1}$$

Assume initial values of unknowns as x_1^0, x_2^0,…, x_n^0. Let Δx_1^0, Δx_2^0,…, Δx_n^0 be the corrections, which on being summed to the initial guess, give the actual solutions. Therefore,

$$f_i(x_1^0 + \Delta x_1^0,\ x_2^0 + \Delta x_2^0, x_n^0 + \Delta x_n^0) = 0 \text{ ; I = 1,2,..,n} \quad \dots\dots \quad \text{A-2}$$

Expanding these equations in Tayler series around the initial guess, we have

$$f_i(x_1^0, x_2^0, \dots, x_n^0) + \left[\left(\frac{\partial f_i}{\partial x_1}\right)^0 \Delta x_1^0 + \left(\frac{\partial f_i}{\partial x_2}\right)^0 \Delta x_2^0 + \cdots \left(\frac{\partial f_i}{\partial x_n}\right)^0 \Delta x_n^0\right] + Hight\ order\ term = 0 \quad \dots\text{A-3}$$

where$\left(\frac{\partial f_i}{\partial x_1}\right)^0$, $\left(\frac{\partial f_i}{\partial x_2}\right)^0$,…, $\left(\frac{\partial f_i}{\partial x_n}\right)^0$are the derivatives of f_i with respect to $x_1, x_2, \dots, x_n$ evaluated at x_1^0, x_2^0,…, x_n^0.

Neglecting higher order terms, we can write Equation (A-3) in matrix form

$$\begin{bmatrix} f_1^0 \\ f_2^0 \\ \vdots \\ f_n^0 \end{bmatrix} + \begin{bmatrix} \left(\frac{\partial f_1}{\partial x_1}\right)^0 & \left(\frac{\partial f_1}{\partial x_2}\right)^0 & \cdots & \left(\frac{\partial f_1}{\partial x_n}\right)^0 \\ \left(\frac{\partial f_2}{\partial x_1}\right)^0 & \left(\frac{\partial f_2}{\partial x_2}\right)^0 & \cdots & \left(\frac{\partial f_2}{\partial x_n}\right)^0 \\ \left(\frac{\partial f_n}{\partial x_1}\right)^0 & \left(\frac{\partial f_n}{\partial x_2}\right)^0 & \cdots & \left(\frac{\partial f_n}{\partial x_n}\right)^0 \end{bmatrix} \begin{bmatrix} \Delta x_1^0 \\ \Delta x_2^0 \\ \vdots \\ \Delta x_n^0 \end{bmatrix} \cong \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \dots\dots\dots\dots\dots\dots\dots\dots\dots A.4$$

Or in vector form

$$f^0 + J^0 \Delta x^0 \cong 0 \quad \text{.......A-5}$$

J^0 is called as the Jacobian matrix

Equation (A-5) can be written as

$$f^0 \cong [-J^0 \Delta x^0] \quad \text{.......A-6}$$

Approximate values of corrections Δx^0 can be obtained from equations (A-6). Updated values of x are then

$$x^1 = x^0 + \Delta x^0$$

Or, in general, for the (r +1)th iteration

$$x^{r+1} = x^r + \Delta x^r \quad \text{.......A-7}$$

Iterations are continued till Eq. A-1 is satisfied to any desired accuracy, i.e.

$$\left| f_i(x^{(r)}) \right| < \epsilon \ (specified\ value); \text{ I = 1,2,…,n} \quad \text{.......A-8}$$

Appendix B: The Newton-Raphson Load Flow MATLAB Program

```
clc

clear all

num = 79;                      % IEEE-14, IEEE-30, IEEE-57, Kotebe-79..
Y = ybusppg(num);              % Calling ybusppg.m
busd = busdatas(num);          % Calling busdata79.m to get busdatas..
BMva = 100;                    % Base MVA
bus = busd(:,1);               % Bus Number
type = busd(:,2);              % Type of Bus 1-Slack, 2-PV, 3-PQ..
V = busd(:,3);                 % Specified Voltage..
del = zeros(length(V),1);      % Voltage Angle..
Pg = busd(:,5)/BMva;           % PGi..
Qg = busd(:,6)/BMva;           % QGi..
Pl = busd(:,7)/BMva;           % PLi..
Ql = busd(:,8)/BMva;           % QLi..
Qmin = busd(:,9)/BMva;         % Minimum Reactive Power Limit..
Qmax = busd(:,10)/BMva;        % Maximum Reactive Power Limit..
nbus = max(bus);               % To get no. of buses..
P = Pg - Pl;                   % Pi = PGi - PLi..
Q = Qg - Ql;                   % Qi = QGi - QLi..
Psp = P;                       % P Specified
Qsp = Q;                       % Q Specified
G = real(Y);                   % Conductance..
B = imag(Y);                   % Susceptance..

pv = find(type == 2 | type == 1);      % Index of PV Buses..
pq = find(type == 3);                  % Index of PQ Buses..
npv = length(pv);                      % Number of PV buses..
npq = length(pq);                      % Number of PQ buses..

Tol = 1;
Iter = 1;                    % iteration starting
while (Tol > 1e-5)           % Iteration starting..
    P = zeros(nbus,1);
    Q = zeros(nbus,1);
    % Calculate P and Q
    for i = 1:nbus
        for k = 1:nbus
            P(i) = P(i) + V(i)* V(k)*(G(i,k)*cos(del(i)-del(k)) +
B(i,k)*sin(del(i)-del(k)));
            Q(i) = Q(i) + V(i)* V(k)*(G(i,k)*sin(del(i)-del(k)) -
B(i,k)*cos(del(i)-del(k)));
        end
    end
```

```
    % Checking Q-limit violations..
    if Iter <= 10 && Iter > 2    % Only checked up to 10th iterations..
        for n = 2:nbus
            if type(n) == 2
                QG = Q(n)+Ql(n);
                if QG < Qmin(n)
                    V(n) = V(n) + 0.01;
                elseif QG > Qmax(n)
                    V(n) = V(n) - 0.01;
                end
            end
         end
    end

    % Calculate change from specified value
    dPa = Psp-P;
    dQa = Qsp-Q;
    k = 1;
    dQ = zeros(npq,1);
    for i = 1:nbus
        if type(i) == 3
            dQ(k,1) = dQa(i);
            k = k+1;
        end
    end
    dP = dPa(2:nbus);
    M = [dP; dQ];       % Mismatch Vector

    % Jacobian
    % J1 - Derivative of Real Power Injections with Angles..
    J1 = zeros(nbus-1,nbus-1);
    for i = 1:(nbus-1)
        m = i+1;
        for k = 1:(nbus-1)
            n = k+1;
            if n == m
                for n = 1:nbus
                    J1(i,k) = J1(i,k) + V(m)* V(n)*(-G(m,n)*sin(del(m)-
del(n)) + B(m,n)*cos(del(m)-del(n)));
                end
                J1(i,k) = J1(i,k) - V(m)^2*B(m,m);
            else
                J1(i,k) = V(m)* V(n)*(G(m,n)*sin(del(m)-del(n)) -
B(m,n)*cos(del(m)-del(n)));
            end
        end
    end

    % J2 - Derivative of Real Power Injections with V..
```

```
    J2 = zeros(nbus-1,npq);
    for i = 1:(nbus-1)
        m = i+1;
        for k = 1:npq
            n = pq(k);
            if n == m
                for n = 1:nbus
                    J2(i,k) = J2(i,k) + V(n)*(G(m,n)*cos(del(m)-del(n)) +
B(m,n)*sin(del(m)-del(n)));
                end
                J2(i,k) = J2(i,k) + V(m)*G(m,m);
            else
                J2(i,k) = V(m)*(G(m,n)*cos(del(m)-del(n)) +
B(m,n)*sin(del(m)-del(n)));
            end
        end
    end

    % J3 - Derivative of Reactive Power Injections with Angles..
    J3 = zeros(npq,nbus-1);
    for i = 1:npq
        m = pq(i);
        for k = 1:(nbus-1)
            n = k+1;
            if n == m
                for n = 1:nbus
                    J3(i,k) = J3(i,k) + V(m)* V(n)*(G(m,n)*cos(del(m)-del(n))
+ B(m,n)*sin(del(m)-del(n)));
                end
                J3(i,k) = J3(i,k) - V(m)^2*G(m,m);
            else
                J3(i,k) = V(m)* V(n)*(-G(m,n)*cos(del(m)-del(n)) -
B(m,n)*sin(del(m)-del(n)));
            end
        end
    end

    % J4 - Derivative of Reactive Power Injections with V..
    J4 = zeros(npq,npq);
    for i = 1:npq
        m = pq(i);
        for k = 1:npq
            n = pq(k);
            if n == m
                for n = 1:nbus
                    J4(i,k) = J4(i,k) + V(n)*(G(m,n)*sin(del(m)-del(n)) -
B(m,n)*cos(del(m)-del(n)));
                end
                J4(i,k) = J4(i,k) - V(m)*B(m,m);
            else
                J4(i,k) = V(m)*(G(m,n)*sin(del(m)-del(n)) -
B(m,n)*cos(del(m)-del(n)));
            end
        end
    end
```

```
    J = [J1 J2; J3 J4];          % Jacobian Matrix

    X = J\M;                     % INV(J) x M, Correction Vector..
    dTh = X(1:nbus-1);           % Change in Voltage Angle..
    dV = X(nbus:end);            % Change in Voltage Magnitude..

    % Update State Vectors (Voltage Angle & Magnitude)
    del(2:nbus) = dTh + del(2:nbus);
    k = 1;
    for i = 2:nbus
        if type(i) == 3
            V(i) = dV(k) + V(i);
            k = k+1;
        end
    end
    Iter = Iter + 1;
    Tol = max(abs(M));
end
Del = 180/pi*del;   % Convert radians to degrees

% Call LoadFlow
[fb, tb, Pij, Qij] = loadflow(num,V,del,BMva);
```

Appendix C: MATLAB Program for Combined Sensitivity Analysis

```
% This code calculates combined sensitivity factors

function F = CSFsenstivity(nb, num, V, del, BMVa)
nbus =79;                    % IEEE-14, IEEE-30, IEEE-57, Kotebe-79..
num = nbus;
nb = nbus;
for count=1:nbus+1
    Ubusdt = busdatas(nbus);
    if count~=nbus+1
         diff = Ubusdt(count,8)-Ubusdt(count,6);
        if diff>0
            Ubusdt(count,6) =+ diff;
        end
    end
busd = Ubusdt;
linedt = linedatas(num);
fb = linedt(:,1);
tb = linedt(:,2);
nl = length(fb);
Y = ybusppg(num);            % Calling ybusppg.m to get Y-Bus Matrix..
BMva = 100;                  % Base MVA..
bus = busd(:,1);             % Bus Number..
type = busd(:,2);            % Type of Bus 1-Slack, 2-PV, 3-PQ..
V = busd(:,3);               % Specified Voltage..
del = busd(:,4);             % Voltage Angle..
Pg = busd(:,5)/BMva;         % PGi..
Qg = busd(:,6)/BMva;         % QGi. .
Pl = busd(:,7)/BMva;         % PLi..
```

```
Ql = busd(:,8)/BMva;          % QLi..
Qmin = busd(:,9)/BMva;        % Minimum Reactive Power Limit..
Qmax = busd(:,10)/BMva;       % Maximum Reactive Power Limit..
P = Pg - Pl;                  % Pi = PGi - PLi..
Q = Qg - Ql;                  % Qi = QGi - QLi..
Psp = P;                      % P Specified..
Qsp = Q;                      % Q Specified..
g = real(Y);                  % Conductance matrix..
b = imag(Y);                  % Susceptance matrix..
pv = find(type == 2 | type == 1);   % PV Buses..
pq = find(type == 3);               % PQ Buses..
npv = length(pv);                   % No. of PV buses..
npq = length(pq);                   % No. of PQ buses..
Tol = 1;
Iter = 1;
     while (Tol > 1e-5)             % Iteration starting..

        P = zeros(nbus,1);
        Q = zeros(nbus,1);
        % Calculate P and Q
        for i = 1:nbus
            for k = 1:nbus
                P(i) = P(i) + V(i)* V(k)*(g(i,k)*cos(del(i)-del(k)) +
b(i,k)*sin(del(i)-del(k)));
                Q(i) = Q(i) + V(i)* V(k)*(g(i,k)*sin(del(i)-del(k)) -
b(i,k)*cos(del(i)-del(k)));
            end
        end

        % Checking Q-limit violations..
        if Iter <= 10 && Iter > 2    % Only checked up to 10th iterations..
            for n = 2:nbus
                if type(n) == 2
                    QG = Q(n)+Ql(n);
                    if QG < Qmin(n)
                        V(n) = V(n) + 0.01;
                    elseif QG > Qmax(n)
                        V(n) = V(n) - 0.01;
                    end
                end
             end
        end

        % Calculate change from specified value
        dPa = Psp-P;
        dQa = Qsp-Q;
        k = 1;
        dQ = zeros(npq,1);
        for i = 1:nbus
            if type(i) == 3
                dQ(k,1) = dQa(i);
                k = k+1;
            end
        end
```

```
        dP = dPa(2:nbus);
        M = [dP; dQ];       % Mismatch Vector

        % Jacobian
        % J1 - Derivative of Real Power Injections with Angles..
        J1 = zeros(nbus-1,nbus-1);
        for i = 1:(nbus-1)
            m = i+1;
            for k = 1:(nbus-1)
                n = k+1;
                if n == m
                    for n = 1:nbus
                        J1(i,k) = J1(i,k) + V(m)* V(n)*(-g(m,n)*sin(del(m)-
del(n)) + b(m,n)*cos(del(m)-del(n)));
                    end
                    J1(i,k) = J1(i,k) - V(m)^2*b(m,m);
                else
                    J1(i,k) = V(m)* V(n)*(g(m,n)*sin(del(m)-del(n)) -
b(m,n)*cos(del(m)-del(n)));
                end
            end
        end

        % J2 - Derivative of Real Power Injections with V..
        J2 = zeros(nbus-1,npq);
        for i = 1:(nbus-1)
            m = i+1;
            for k = 1:npq
                n = pq(k);
                if n == m
                    for n = 1:nbus
                        J2(i,k) = J2(i,k) + V(n)*(g(m,n)*cos(del(m)-del(n)) +
b(m,n)*sin(del(m)-del(n)));
                    end
                    J2(i,k) = J2(i,k) + V(m)*g(m,m);
                else
                    J2(i,k) = V(m)*(g(m,n)*cos(del(m)-del(n)) +
b(m,n)*sin(del(m)-del(n)));
                end
            end
        end

        % J3 - Derivative of Reactive Power Injections with Angles..
        J3 = zeros(npq,nbus-1);
        for i = 1:npq
            m = pq(i);
            for k = 1:(nbus-1)
                n = k+1;
                if n == m
                    for n = 1:nbus
                        J3(i,k) = J3(i,k) + V(m)* V(n)*(g(m,n)*cos(del(m)-
del(n)) + b(m,n)*sin(del(m)-del(n)));
                    end
                    J3(i,k) = J3(i,k) - V(m)^2*g(m,m);
```

```
                else
                    J3(i,k) = V(m)* V(n)*(-g(m,n)*cos(del(m)-del(n)) -
b(m,n)*sin(del(m)-del(n)));
                end
            end

        end
        % J4 - Derivative of Reactive Power Injections with V..
        J4 = zeros(npq,npq);
        for i = 1:npq
            m = pq(i);
            for k = 1:npq
                n = pq(k);
                if n == m
                    for n = 1:nbus
                        J4(i,k) = J4(i,k) + V(n)*(g(m,n)*sin(del(m)-del(n)) -
b(m,n)*cos(del(m)-del(n)));
                    end
                    J4(i,k) = J4(i,k) - V(m)*b(m,m);
                else
                    J4(i,k) = V(m)*(g(m,n)*sin(del(m)-del(n)) -
b(m,n)*cos(del(m)-del(n)));
                end
            end
        end

        J = [J1 J2; J3 J4];     % Jacobian Matrix..

        X = J\M;                % Correction Vector
        dTh = X(1:nbus-1);      % Change in Voltage Angle..
        dV = X(nbus:end);       % Change in Voltage Magnitude..

        % Updating State Vectors..
        del(2:nbus) = dTh + del(2:nbus);     % Voltage Angle..
        k = 1;
        for i = 1:nbus
            if type(i) == 3
                V(i) = dV(k) + V(i);         % Voltage Magnitude..
                k = k+1;
            end
        end

        Iter = Iter + 1;
        Tol = max(abs(M));                   % Tolerance..

    end

end

% Line power loss
for m = 1:nl
    i = fb(m); j = tb(m);
    % Real Line Losses
```

```
    PL(m) = -(g(i,j)*((V(i))^2 + (V(j))^2 - 2*V(i)*V(j)*cos(del(i)-del(j))));
   % Reactive Line Losses
    QL(m) = b(i,j)*((V(i))^2 + (V(j))^2 - 2*V(i)*V(j)*cos(del(i)-del(j)));
end

PLoss = sum(PL)*BMva
QLoss = sum(QL)*BMva

% Real power Loss Derivatives
DPLdel = zeros(nb-1,1);
DQLdel = zeros(nb-1,1);
for m = 1:nl
    i = fb(m); j = tb(m);
    for n = 1:nb-1
       if i ==n
          DPLdel(n) = DPLdel(n) + (-2 * g(i,j) * V(i) * V(j)*sin(del(i)-
del(j)));
          DQLdel(n) = DQLdel(n) + (2 * b(i,j) * V(i) * V(j)*sin(del(i)-
del(j)));
       end
    end
end
DPLV = zeros(npq,1);
DQLV = zeros(npq,1);
for m = 1:nl
    i = fb(m); j = tb(m);
    for n = 1:npq
    if i == pq(n)
       DPLV(n) = DPLV(n) + (-2 * g(i,j) * (V(i) - V(j)*cos(del(i)-del(j))));
       DQLV(n) = DQLV(n) + (2 * (b(i,j) * (V(i) - V(j)*cos(del(i)-del(j)))));
    end
    end
end
% Line power flows
for m = 1:nl
    i = fb(m); j = tb(m);
  % Real Line flows
     P(i,j) = g(i,j) * V(i)*(V(j)*cos(del(i) - del(j))-V(i)) -
b(i,j)*V(i)*V(j)*sin(del(i)-del(j));
% Reactive Line loss
     Q(i,j) = - V(i)*V(j)*(b(i,j)*cos(del(i) - del(j))- g(i,j)*sin(del(i)-
del(j))) + (V(i))^2*(b(i,j));
end

% Power Flow Derivatives
DPdel = zeros(nb-1,1);
DQdel = zeros(nb-1,1);
for m = 1:nl
    i = fb(m); j = tb(m);
    for n = 1:nb-1
    if i == n
       DPdel(n) = DPdel(n) + (V(i)*V(j)*(g(i,j)*sin(del(i)-del(j)) +
b(i,j)*cos(del(i)-del(j))));
```

```
        DQdel(n) = DQdel(n) + (-V(i)*V(j)*(g(i,j)*cos(del(i)-del(j)) -
b(i,j)*sin(del(i)-del(j))));
    end
    end
end
DPV = zeros(npq,1);
DQV = zeros(npq,1);
 for m = 1:nl
     i = fb(m); j = tb(m);
     for n = 1:npq
     if i == pq(n)
         DPV(n) = DPV(n) + (V(i)*(g(i,j)*cos(del(i)-del(j))
b(i,j)*sin(del(i)-del(j))) - 2*V(i)*g(i,j));
         DQV(n) = DQV(n) + (-V(j)*(b(i,j)*cos(del(i)-del(j)) +
g(i,j)*sin(del(i)-del(j))) + 2*V(i)*(b(i,j)));
     end
     end
 end
Jinv = inv(J);
Jtran= transpose(J);
Jtraninv = inv(Jtran);
M1 = [DPLdel;DPLV];
M2 = [DQLdel;DQLV];
M3 = [DPdel;DPV];
M4 = [DQdel;DQV];
S_P = Jtraninv *M1;
S_Q = Jtraninv *M2;
F_P = Jtraninv *M3;
F_Q = Jtraninv *M4;
for k = 1:nb-1
    Sp_p(k) = S_P(k);
    Sq_p(k) = S_Q(k);
    Fp_p(k) = F_P(k);
    Fq_p(k) = F_Q(k);
end
for k = 1:npq
    Sp_q(k) = S_P((nb-1)+k);
    Sq_q(k) = S_Q((nb-1)+k);
    Fp_q(k) = F_P((nb-1)+k);
    Fq_q(k) = F_Q((nb-1)+k);
end
CSF = zeros(nb-1,1);
for m = 2:nb
    for n = 1:npq
     if m == pq(n)
CSF(m) = ((Sp_p(m-1)*Sq_p(m-1)) + (Sp_q(n)*Sq_q(n)) + (Fp_p(m-1)*Fq_p(m-1)) +
(Fp_q(n)*Fq_q(n)));
     end
    end
   for n = 2:npv
   if m ==pv(n)
     CSF(m) = (Sp_p(m-1)*Sq_p(m-1)) + (Fp_p(m-1)*Fq_p(m-1));
   end

   end
```

```
end
 CSF()
[sortedCSF, I] = sort(CSF,'descend');
candidateBuses = I(1:10)
```

Appendix D: The Main GA-PSO MATLAB Program

```
% This function performs GA-PSO optimization

%GAPSO(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V)

Np = 20;                            % Number of chromosome/ particle
Nd = 2;                             % Dimension/Gene in the chromosome
Nt = 10;                            % Number of iteration
num =79;
PDSTAT_min = 0;
% Real power injected, Minimum
PDSTAT_max = 0;
% Real power injected, Maximum
QDSTAT_min = 0;
% Reactive power injected/absorbed, Minimum
QDSTAT_max = 3;
% Reactive power injected/absorbed, Maximum
busd = busdatas(num);
V = busd(:,3);
CandidateBus = [22];
for z = 1;
Bus = CandidateBus(z)
xMin = [PDSTAT_min,QDSTAT_min];      % Search space boundary
xMax = [PDSTAT_max,QDSTAT_max];      % Search space boundary
vMin = 0.95;                         % Voltage deviation limit
vMax = 1.05;                         % Voltage deviation limit
w_max = 0.9;
% Inertia weight, Control the balance between global best local best
w_min = 0.4;
% Inertia weight, Control the balance between global best local best
C1 = 2.00;
% weighting Coefficients for accelerating the particle to reach to the target
C2 = 2.00;

    % initializing the population
        Vel = zeros(Np,Nd);
        R = zeros(Np, Nd);
          for p = 1:Np
             for i = 1:Nd %
                 R(p,i) = xMin(1,i) + (xMax(1,i) - xMin(1,i)) *rand;
% Initialize N chromosomes with random values to represent possible D-STATCOM
             end
          end
p = 0;
k = 0;
```

```
M = Fitness(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V);
R;
for p = 1:Np
    pBestValue(p) = M(p);
%Best fitness for each chromosome, Personal
    for i = Nd
        pBestPosition(p,i) = R(p,i);
% Best D-STATCOM Size, Personal best of the chromosome
    end
end
      gBestValue = min (M);
% Best fitness in all chromosomes, fitness values
      index = find(M==min(M));
      gBestPosition = R(index,:);
% Best DSTATCOM size among all DG sizes, Global best (Optimum size)

      gBestPosition;
      pBestValue;
      pBestPosition(p,i) = R(p,i);

for k = 1:Nt % for each iteration
     R = UpdatedR(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V);
% Update position
     Pnew = [];
     for u = 1:Np/2
         X = CrossMut(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p,
V);
         Pnew = [Pnew;X];               %New population is created
     end
     Pnew;
     R = Pnew;
% Replace old population with new population

             for p = 1:Np
             for i = 1:Nd
              % Correct any errors     % Elitism
          if R(p,i) > xMax (1,i)
             R(p,i) = xMax (1,i);
          elseif R(p,i) < xMin (1,i)
                 R(p,i) = xMin (1,i);
          end
             end
            end

M = Fitness(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V);
% Evaluate the fitness for the new population
R;
        for p = 1:Np
        % Check if it is a personal best
        % If it is, record the value and the position
            if M(p) < pBestValue(p)
% If the new chromosomes fitness less than its own personal best
               pBestValue(p) = M(p);
               for i = 1:Nd
```

```
                  pBestPosition(p,i) = R(p,i);
              end
           end

      % Check if it is a global best
      % If it is, record the value and the position

           if M(p) < gBestValue
              gBestValue = M(p);
              for i = 1:Nd
               gBestPosition(i) = R(p,i);
              end
           end
        end
        bestFitnessHistory(k) = gBestValue;

       % Calculate Velocity
       w = w_max - ((w_max-w_min)/Nt)*k;
% Weight function for updating the velocities the particle
       for p = 1:Np
          for i = 1:Nd
             Vel(p,i) = w*Vel(p,i) + rand*C1*(pBestPosition(p,i)-R(p,i)) +
rand*C2*(gBestPosition(i) - R(p,i));  % Updating the velocity..
            if Vel(p,i) > vMax
               Vel(p,i) = vMax;
            elseif Vel(p,i) < vMin
                   Vel(p,i) = vMin;
            end
          end
       end
       Vel;
       gBestPosition = gBestPosition(1,:);
       gBestValue;
       k = k+1;
end

      pBestPosition;
      gBestPosition;
      pBestValue;
      gBestValue;
    z=z+1;
    [SL V] = NewtonRaphson(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel,
Bus, p, V);
    PL = SL(1,1)
    QL = SL(1,2)

end
```

Appendix E: The Sub-Program to Determine the Fitness

```
function M = Fitness(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, V)
% Initialize Fitnes Values
M = zeros(Np,1);
PLbase = 1.7351;        % Base case Real power loss
QLbase = 0.7080;        % Base case Reactive power loss
R;
for p = 1:Np
[SL V] = NewtonRaphson(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p,
V);
PL = SL(1,1);
QL = SL(1,2);

   for n=2:79
     VPII(n) = (1 - V(n));          % Voltage profile improvement index
   end

VPI(p) = 1/(11 + max(abs(VPII)));  % Voltage profile improvement index
PLRI(p) = ((PLbase -PL)./PLbase);  % Real Power Loss Reduction Factor Index
QLRI(p) = ((QLbase -QL)./QLbase);  % Reactive Power Loss Reduction Factor
Index

% Define weights for MOF. These weights must sum to unity
w1 = 0.5;                          % Weights value for MOF
w2 = 0.1;                          % Weights value for MOF
w3 = 0.4;                          % Weights value for MOF

M(p) = (w1*PLRI(p)) + (w2*QLRI(p)) + (w3*VPI(p));  % Multi-Objective function

end
M;
End
```

Appendix F: The Sub-Program to Implements Crossover and Mutation

```
% this function implements crossover and mutation

function X = CrossMut(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p,
V)
for j = 1:Nd/2
% Call Roulette wheel selection method select two chromosomes ( Xp1 and Xp2)
Rp = Selection(Np, Nd, Nt, xMin, xMax, vMin, vMax, R, k, Vel, Bus, p, V);
% Parent chromosome 1 selected based on their fitness to produce child
chromosome Xc1 and Xc2 in combination with Xp2
Xp1 = Rp(1,:);
% Parent chromosome 2 selected based on their fitness to produce child
chromosome Xc1 and Xc2 in combination with Xp2
Xp2 = Rp(2,:);
PDSTAT_max = 2;
```

```
QDSTAT_max = 3;
Xcmax = [PDSTAT_max QDSTAT_max];
P_cross = 0.85;                      % Crossover probabaity
P_mut = 0.01;                        % Mutation probabaity

    z = rand(1);
% Randomly generated number between 0 & 1to compute crossover computation
  if z<P_cross
     u = rand(1);
% Crossover computation to produce offspring Xc1
    Xc1 = (u*Xp1) + ((1-u)*Xp2);
% Crossover computation to produce offspring Xc2
    Xc2 = (u*Xp2) + ((1-u)*Xp1);
  else
    Xc1 = Xp1;
    Xc2 = Xp2;
  end
  Xc1;
  Xc2;
  if z < P_mut
% randomly generated number between 0 & 1 to compute mutation computation
     r = rand(1);
% Mutation computation to mutate the genes in the candidate offspring
     DXc1 = r*(Xcmax-Xc1)*(1-k./Nt);
     DXc2 = r*(Xcmax-Xc2)*(1-k./Nt);
     X1 = Xc1 + DXc1;
     X2 = Xc2 + DXc2;
  else
     X1 = Xc1;
     X2 = Xc2;
  end
X = [X1;X2];
End
```

Appendix G: Conference paper manuscript