DEVELOPMENT OF FIREFLY ALGORITHM BASED METHOD FOR DISTRIBUTED GENERATION PLANNING IN AN UNBALANCED THREE-PHASE DISTRIBUTION NETWORK USING VOLTAGE STABILITY INDEX

BY

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NOVEMBER, 2017

DECLARATION

I GIDEON Rimamfate, hereby declare that the work in this dissertation entitled **"DEVELOPMENT OF FIREFLY ALGORITHM BASED METHOD FOR DISTRIBUTED GENERATION PLANNING IN AN UNBALANCED THREE-PHASE DISTRIBUTION NETWORK USING VOLTAGE STABILITY INDEX"** has been carried out by me under the supervision of Professor B. Jimoh and Dr. Y. Jibril as part of requirement for the award of degree of master of science (M.Sc) in Power system Engineering in the Department of Electrical Engineering. The information derived from literatures has been duly acknowledged in the text and a list of references provided. No part of this dissertation was previously presented for another degree or diploma at this or any other institution.

Gideon Rimamfate	______________________	_________________
	Signature	**Date**

CERTIFICATION

This Dissertation entitled **'DEVELOPMENT OF FIREFLY ALGORITHM BASED METHOD FOR DISTRIBUTED GENERATION PLANNING IN AN UNBALANCED THREE-PHASE DISTRIBUTION NETWORK USING VOLTAGE STABILITY INDEX'** by GIDEON Rimamfate meets the regulations governing the award of the degree of Master of Science (MSc) in Power System Engineering of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

Prof. B. Jimoh ______________________ ________________
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(Dean. School of Postgraduate Studies) (Signature) Date

DEDICATION

This research work is dedicated to my parents and siblings**.**

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ABSTRACT

This research work presents development of Firefly algorithm (FA) and application of voltage stability index (VSI) for optimal planning of Distribution Generation (DG) in an unbalanced three-phase distribution network. The VSI was used to find the DG location while the FA was used for the DG sizing. The developed method was implemented on standard IEEE 37-bus Radial distribution network test system and a local 19-bus Mahuta feeder. The results obtained from the IEEE 37-bus were validated by comparing with a similar work. For the standard IEEE 37-bus unbalanced radial distribution network (URDN), the total power loss obtained are 31.3543 kW and 15.2829 kVAr for active and reactive power respectively without DG in the network. When the developed method is applied, a DG optimal location was found at bus 34 and a DG size of 356 kW and 170 kVAr for active and reactive respectively are obtained. The active and reactive power loss were found to be 19.8329 kW and 10.0014 kVAr respectively. The developed method recorded a loss reduction of 36.75% and 34.56% for both active and reactive power respectively over the base case. Also, the maximum loadability of the network was found to be 18% and 8% of the initial loading with and without DG respectively. For the 19-bus Mahuta feeder, the location for the DG is bus 17 and the DG size of 201.58 kW and 115 kVAr are obtained for active and reactive power respectively. A power loss reduction of 4.48% and 5.62% for active and reactive power were recorded over the base case respectively. The maximum loadability of the network for both the developed method and base case were found to be 119% of the initial loading. When compared with research on similar work, the developed method achieved a loss reduction of 8.14% and 30.42% for active and reactive power respectively over the method applied in the work.

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LIST OF ABBREVIATIONS

ACRONYMS	DEFINITION
S	Distribution System
DN	Distribution Network
DG	Distributed Generation
R	Resistance
X	Reactance
BFS	Backward-Forward Sweep
P	Active power
Q	Reactive power
Z	Impedance
IEEE	Institute of Electrical and Electronics Engineering
KCL	Kirchhoff's Current Law
kW	Kilo Watt
kVAr	Kilo Voltage Ampere Reactive
p.u.	Per Unit
BIBC	Bus Injected to Branch Current
BCBV	Branch Current to Bus Voltage
URDN	Unbalanced Radial Distribution Network
DLF	Distribution Load Flow
FA	Firefly Algorithm
VSI	Voltage Stability Index
MATLAB	Matrix Laboratory

CHAPTER ONE

INTRODUCTION

1.1 Background of Study

The electric power system majorly includes a generating plant, a transmission system and the distribution network (Subramanyam *et al.*, 2015). Modern power systems are evolving from the centralized bulk systems, with generation plants connected to the transmission network, to more decentralized systems, with smaller generating units connected directly to distribution networks close to demand site. The distribution network is mainly a passive network where the flow of both real and reactive power is unidirectional (Satish & Navuri, 2012). However, with significant penetration of distributed generation, the power flow may become reversed, hence the distribution network is no longer a passive system but an active system. In this active system, the power flows and voltages are determined by the topology of the network generation sources as well as the loads (Mahmud *et al.*, 2011). Distributed Generation (DG) also termed as embedded generation, dispersed generation or decentralized generation is defined as a small electric power source that can be connected to a distribution network by a distribution company (DISCO) at any node or by customer at the customer side of the meter (Payasi *et al.*, 2012)**.** DG, unlike conventional generation, aims to generate part of required electrical energy on small scale, closer to the area of consumption, and also to augment the electrical power from the grid within the network. It represents a change in the conceptual framework of electrical energy generation. DG can be an alternative for residential, commercial, and industrial applications (Murthy & Kumar, 2013).

Electrical Distribution Systems (EDS) are expected to experience considerable growth in the near future, with respect to the penetration of DG. This will be mainly due to several factors, ranging from environmental concerns to new technologies such as fuel cells and other alternative energy sources. In spite of the additional complexity in DS planning and operation in the presence of DG, it is of paramount importance that the performance of these systems should be continuously improved to ensure increasing levels of power quality to the customers (Penido *et al.*, 2008). It is well-known that most DS are considerably unbalanced, and in high density load areas such as city centers, the network topology can be highly meshed. Under these circumstances, the three-phase four-conductor configuration with multiple neutral grounding has been largely adopted, due to low installation costs and better sensitivity for fault protection, when compared with the three-phase three-conductor configuration. The presence of neutral conductors and grounding affect not only the system operation but also equipment and human safety (Penido *et al.*, 2008). A distribution system is basically unbalanced because of many factors, such as untransposed feeders, conductor bundles, single-phase loads, unequal three phase loads and single- and double-phase 'radial spurs' on primary feeders (Segura *et al.*, 2011). Furthermore, even when a network is balanced, asymmetrical faults can introduce imbalance. To avoid significant errors arising from inherent system imbalance, a rigorous analysis of the distribution system using detailed component models is required (Segura *et al.*, 2011). Conventional load flow methods like Gauss-Seidel, Newton-Raphson and fast decoupled techniques are inefficient in solving such networks (Prakash & Khatod, 2016). These methods are not very suitable for distribution networks, because of the following characteristics of such systems (Elsaiah *et al.*, 2012):

1. Radial structure with sometimes weakly-meshed topology.
2. High resistance to reactance (R/X) ratio which sometimes causes the Newton-Raphson (NR) and the Fast-Decoupled (FD) methods to diverge.

3. Untransposed or rarely transposed lines where it is often inappropriate to neglect the mutual coupling between phases.
4. Unbalanced loads along with single-phase and double phase laterals.
5. Unbalanced distributed loads.
6. Dispersed generation.

These characteristics, combined with the large number of nodes and branches of distribution networks make the direct use of the aforementioned techniques unsuitable and inefficient for power flow studies of unbalanced distribution systems (Elsaiah *et al.*, 2012).

The loading of a distribution feeder is inherently unbalanced due to a large number of unequal single-phase loads and the nonsymmetrical conductor spacing of three-phase underground and overhead line segments. Due to these factors, conventional power flow programs used for transmission system studies do not show good convergence properties for distribution systems . Single phase representation of three phase system is used for power flow studies on transmission system which is assumed as a balanced network in most cases. But due to the unbalanced loads, radial structure of the network and untransposed conductors makes the distribution system as an unbalanced system. Hence three phase power flow analysis need to be used for distribution systems. The three phase power flow analysis can be carried out in two different reference frames namely phase frame and sequence frame. The phase frame deals directly with unbalanced quantities while the sequence frame deals with three separate phasor systems which, when superposed, give the unbalanced conditions in the circuit (Balamurugan & Srinivasan, 2011).

Different methodologies and approaches have been developed to find the optimal size of DG and identify the optimal location to install the DG (Kansal *et al.*, 2013). (Das, 2015) developed optimal sizing and placement of DG in a radial distribution system using loss sensitivity factor and firefly.

In the work, the loss sensitivity factor is used for optimal DG location and the firerfly algorithm are used for DG sizing. (Bhimarasetti & Kumar, 2014) presented DG planning in unbalanced mesh distribution system with different unbalances, where variational algorithm is used to find the optimal DG capacity and voltage index is used to obtained the optimal DG size. (Chou & Butler-Purry, 2014) showed that loading unbalance degree and DG power output has significant effect on voltage stability. (Reddy & Manohar, 2013) developed optimal placement of DG on unbalanced distribution network. (Al-Sabounchi *et al.*, 2011), (Anwar & Pota, 2012), (Abdelaziz *et al.*, 2015), (Othman & Hegazy, 2015), (Gómez-González *et al.*, 2015), (Dahal & Salehfar, 2016) and a lot of researchers has shown that DG placement on unbalanced system has significant effect on the voltage and the power flowing in the system.

In order to ensure a balance between generation and consumption with a minimum power loss in an unbalanced distribution systems, this research tends to introduce voltage stability index and firefly algorithm method for optimal location and sizing of DG in the network. Also, Backward-Forward Sweep (BFS) based method will be used to achieve a convergence guaranteed of power flow analysis. The BFS method is the most suitable method in solving power flow problem due to its simplicity and better convergence performance compared to Gauss-Siedeland Newton-Raphson based methods under the assumption of radial network structures (Demirok *et al.*, 2012).

1.2 Significance of Research

The significant of this research is the development of Firefly algorithm and voltage stability index for optimal DG planning in an unbalanced three-phase distribution network considering the loading conditions of the phases, thereby minimizing and maximizing the losess and loading of the network respectively. Other researchers had not consider the loading on each phase of the network.

1.3 Statement of Problem

The unbalanced loading between lines causes unsymmetrical current to flow and irregular voltage drop in a network causing branch losses which differ in each phase. Also, the low voltage and high current in the distribution network causes active and reactive power loss. The losses in the branches can be reduced by either external power injection or distribution automation system. As such, many researches have been carried out on optimal placement of DG, from analytical, heuristic and meta-heuristic to hybrid technique. Most of the researchers assumed a balanced network but in practic distribution network is unbalanced in nature due to different loading and asymmetrical component between the phases. This research work tend to address unbalanced and loading conditions in a radial distribution system in the presence of DG placement using firefly algorithm and voltage stability index. Also, in order to ensure a simple and convergence guaranteed power flow, a Backward-forward sweep based method is used in this work.

1.4 Aim and Objectives

The aim of this research is to develop firefly algorithm based method for optimal Distributed Generation planning in unbalanced three phase distribution network using voltage stability index. The objectives of the research are:

1. To perform a three-phase power flow algorithm based on the unbalanced three-phase distribution network.
2. To apply voltage stability index for optimal DG location
3. To develop firefly algorithm for optimal DG sizing.
4. To validate the developed method by comparing with the work of Othman *et al.* (2016) using power loss and voltage profile as the performance metric.

1.5 Methodology

The following methodology are used to carried out this research work:

1. Collection of necessary data (such as conductor length, conductor cross sectional area, conductor current carrying capacity, transformer rating and loads) from Ungwan Boro distribution network Barnawa area 1 office, Kaduna and modelling of the ungwa Boro distribution network.

2. Performance of three-phase power flow based on forward-backward sweep by:

   i. For backward sweep: sum currents or power flows (and possibly updates voltages).

   ii. For forward sweep: calculate voltage drops (and possibly update currents/power flows).

   iii. Repeat steps i and ii above until convergence criteria is met

3. Perform base case power flow analysis on the radial distribution feeder (IEE 37-node feeder and Mahuta 19-node feeder)

4. Modelling and establishment of an appropriate DG model that will suit the loading condition of the given network

5. Application of voltage stability index for optimal DG location by:

   i. Running a three-phase power flow and calculate the voltage stability index (VSI).

   ii. Rank the node based on VSI obtain in (5.i) in descending order.

   iii. Select the node with the highest VSI value as the DG location.

6. Development of a Firefly algorithm (FA) that will be suitable for optimal DG sizing by:

i. Generating the initial fireflies (DG active power, system loadability)

ii. Consider the fitness function as the objective function

iii. Define the firefly algorithm parameters based on (Yang & He, 2013)

iv. Calculating the active power loss and system loadability that correspond to all the initial fireflies based on the three-phase power flow and the VSI obtained in (5) above

v. Select the best DG size that achieve a minimum active power loss and system loadability (the brightest firefly)

vi. Updates the firefly (DG size) and keep the best DG size and system loadability as a new fireflies (system variable)

vii. Continue steps (iv-vi) until the convergence criteria is met

7. Implementation of the developed models on unbalanced three-phase IEEE 37-node feeder and Ungwa Boro radial distribution network

8. Validation of result obtained by comparing with the result of Othman et al. (2016).

1.6 Dissertation Organization

Chapter One presents the general introduction of the research work while chapter two gives a detail explanation and mathematical modelling that govern this research work and review on work related to this dissertation.Chapter three gives the full details on the step taken to achieved this research work and chapter four presents the results and discussion of the work. Finally, conclusion, recommendations of further work and limitation of the work are presented in chapter Five while list of cited work, data and MATLAB codes are given in appendices provided at the end of this dissertation.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter is divided into two sections. The first section shows the review of fundamental concepts that will enable the understanding of the basic aspects of power systems, distribution network, distributed generation, load flow analysis, etc. while the second section presents the review of similar works published in the area of this particular research.

2.2 Review of Fundamental Concepts

The fundamental concepts concerning the developed research work are discussed below in order to give some basic background of the study.

2.2.1 Power System Background

Electric power systems are real-time energy delivery systems. Real time means that power is generated, transported, and supplied the moment you turn on the light switch. Electric power systems are not storage systems like water systems and gas systems. Instead, generators produce the energy as the demand calls for it (Blume, 2008). The system starts with generation, by which electrical energy is produced in the power plant and then transformed in the power station to high-voltage electrical energy that is more suitable for efficient long-distance transportation (Blume, 2008). The power plants transform various sources of energy in the process of producing electrical energy. For example, heat, mechanical, hydraulic, chemical, solar, wind, geothermal, nuclear, and other energy sources are used in the production of electrical energy (Blume, 2008). Finally, substations transform this high voltage electrical energy into lower-voltage energy that is transmitted over distribution power lines that are more suitable for the distribution of electrical energy to its destination, where it is again transformed for residential, commercial, and industrial consumption (Blume, 2008).

2.2.2 Distribution System

Distribution systems are responsible for delivering electrical energy from the distribution substation to the service-entrance equipment located at residential, commercial, and industrial consumer facilities (Blume, 2008).

There are three general classifications of electrical power distribution systems. These are the radial, ring, and network systems (Fardo & Patrick, 2009).

2.2.3 Three-Phase Distribution Network

The three-phase distribution network can be classified as balance and unbalanced network depending on the network parameters.

2.2.3.1 Three-Phase Balanced Distribution Network

This model assumes that the three-phase system can be represented by its equivalent one line system. The model consists of the following elements: distribution lines which is represented by the resistance and reactance in per unit, line shunt capacitance (different to shunt capacitor banks that are considered as loads) is negligible at the distribution voltage levels as found in most practical cases and loads which include shunt capacitors for reactive power compensation, are represented by their active (P_o) and reactive (Q_0) component at 1.0 per unit (pu) (Cespedes, 1990).

2.2.3.2 Three-Phase Unbalanced Distribution Network

This model is based on the following:

i. Any distribution line is formed by one, two-three phases and the neutral conductor. The neutral is considered to be connected directly to ground thus at the same voltage (however neutral conductors may have different current flows according to the amount of phases unbalance).

ii. The three-phase loads are considered to be integrated by three single phase loads connected in a star configuration (Cespedes, 1990).

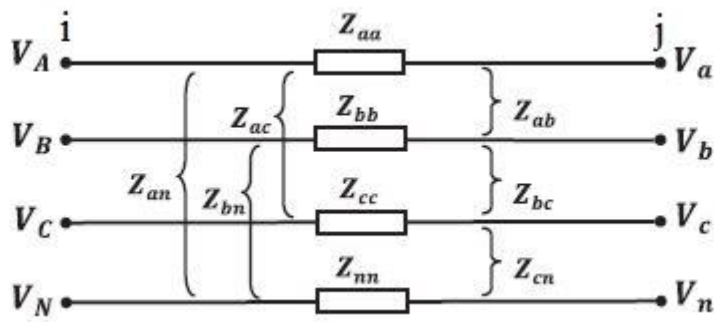

Figure 2.1:A three phase line section model (Khadim *et al.*, 2014)

Figure 2.1 shows a three-phase line section model between bus i and j, the line parameters can be obtained using the method developed by Carson and Lewis. A 4×4 matrix, which takes into account the self and mutual coupling terms, can be expressed as (Khadim *et al.*, 2014):

$$[Z_{abcn}] = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} & Z_{an} \\ Z_{ba} & Z_{bb} & Z_{bc} & Z_{bn} \\ Z_{ca} & Z_{cb} & Z_{cc} & Z_{cn} \\ Z_{na} & Z_{nb} & Z_{nc} & Z_{nn} \end{bmatrix} \tag{2.1}$$

The matrix in equation (2.1) can be represented by 3×3 matrix instead of the 4×4 matrix using Kron's reduction method. The resultant matrix still has the effect of the ground conductor.

$$[Z_{abc}] = \begin{bmatrix} Z_{aa-n} & Z_{ab-n} & Z_{ac-n} \\ Z_{ba-n} & Z_{bb-n} & Z_{bc-n} \\ Z_{ca-n} & Z_{cb-n} & Z_{cc-n} \end{bmatrix} \tag{2.2}$$

Now by applying the KVL to the circuit model of Figure 2.1, the relationships between the bus voltages and branch currents can be simply written as:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} - \begin{bmatrix} Z_{aa-n} & Z_{ab-n} & Z_{ac-n} \\ Z_{ba-n} & Z_{bb-n} & Z_{bc-n} \\ Z_{ca-n} & Z_{cb-n} & Z_{cc-n} \end{bmatrix} \begin{bmatrix} I_{Aa} \\ I_{Ba} \\ I_{Cc} \end{bmatrix} \tag{2.3}$$

It should be noted, however, that single-phase and two-phase line sections are most common in distribution networks. Hence, for the purpose of this research, any phase fails to be presented, the corresponding row and column in equation (2.3) will have zeros entries. For example, for two phase line section with a and b phase, equation (2.3) will be reduced to:

$$[Z_{ab}] = \begin{bmatrix} Z_{aa-n} & Z_{ab-n} \\ Z_{ba-n} & Z_{bb-n} \end{bmatrix} \tag{2.4}$$

Also, for single phase line section, equation (2.3) will be reduced to:

$$V_a = V_A - Z_{aa-n} I_{Aa} \tag{2.5}$$

Where

I_{ABC} is the phase current,

V_{ABC} is the phase voltage on the primary side

I_{abc} is the phase current,

V_{abc} is the phase voltage and

Z_{abcn} is the impedance on the secondary side.

2.2.3.3 Line Series Impedance and Shunt Admittance of a Distribution Network.

The determination of the series impedances and the shunt admittances of any distribution network are crucial steps for distribution network feeder analysis (Musa, 2015). The lines series and shunt admittance are use in modelling a distribution network line parameters.

i. *Series impedance for distribution network*

The series impedance of the distribution line consists of the resistance of the conductors and the self- and mutual inductive reactance resulting of the conductor (Musa, 2015).

The phase impedance of an overhead line can be computed using the Carson's equations based on the general overhead construction configuration given in (Musa, 2015). Equation (2.6) gives the phase impedance matrix for a three-wire delta line determined by the application of Carson's equations (Musa, 2015):

$$Z_{abc} = \begin{bmatrix} z_{aa} & z_{ab} & z_{ac} \\ z_{ba} & z_{bb} & z_{bc} \\ z_{ca} & z_{cb} & z_{cc} \end{bmatrix} \Omega / \text{km} \tag{2.6}$$

The self- and mutual impedances for the phase impedance matrix of Equation (2.6) derived from the computation of inductive reactance at an assumed frequency of 50Hz, and conductor length of 1 km are given by the Equations (2.7) and (2.8) respectively (Musa, 2015).

$$\overline{z_{ii}} = r_i + j0.10111 \cdot In\left(\frac{1}{GMR}\right)\Omega / \text{km} \tag{2.7}$$

$$\bar{z_{ij}} = j0.10111 \cdot In\frac{1}{D_{ij}}\Omega / \text{km} \tag{2.8}$$

where , *r* is the resistance in ohm/mile, and *GMRi* is the Geometric Mean Radius of conductor *i* in foot obtained from a table of standard conductor data. *Dij* is the distance between conductors' positions on the pole. It is also known as the Geometric Mean Distances (GMDs) between phases. The GMDs are used to form the distance matrix specifying the distant relationship between conductor *i* and *j* with each position on the pole in Cartesian coordinates using complex number notation (Musa, 2015). Thus, the self- and mutual impedances are defined respectively by the following Equations (Musa, 2015):

$$z_s = \frac{1}{3} \cdot \left(z_{aa} + z_{bb} + z_{cc}\right)\Omega / \text{km} \tag{2.9}$$

$$z_m = \frac{1}{3} \cdot \left(z_{ab} + z_{bc} + z_{ca}\right)\Omega / \text{km} \tag{2.10}$$

The modified phase impedance matrix is given as in Equation (2.11)

$$Z_{abc} = \begin{bmatrix} z_s & z_m & z_m \\ z_m & z_s & z_m \\ z_m & z_m & z_s \end{bmatrix}\Omega / \text{km} \tag{2.11}$$

2.2.4 Bus Classification

A bus is a point or node in which one or many generators, transmission lines and loads are connected. In a power system study, every bus is associated with four (4) quantities, such as magnitude of voltage (|*V*|), phase angle of voltage (δ), active power (*P*) and reactive power (*Q*)

(Afolabi *et al.,* 2015). Two of these bus quantities are specified and the remaining two are required to be determined through the solution of equation. The buses are classified into three categories, depending on the two known quantities that have been specified (Afolabi *et al.*, 2015)

I. Slack Bus

This is used as a reference bus in order to meet the power balance condition. Slack bus is usually a generating unit that can be adjusted to take up whatever is needed to ensure power balanced. The effective generator at this bus supplies the losses to the network, this is necessary because the magnitude of the losses will not be known until the calculation of the current is complete. Slack bus is usually identified as bus 1. The known variable on this bus is $|V|$ and δ and the unknown is P and Q (Afolabi *et al.*, 2015).

II. Generator (PV) Bus

This is a voltage control bus. The bus is connected to a generator unit in which output power generated by this bus can be controlled by adjusting the prime mover and the voltage can be controlled by adjusting the excitation. Variables of the generator, often, limits are given to the values of the reactive power depending upon the characteristics of individual machine. The known variable in this bus is P and $|V|$ and the unknown is Q and δ (Afolabi *et al.*, 2015).

III. Load (PQ) Bus

This is a non-generator bus which can be obtained from historical data records, measurement or forecast. The real and reactive power supply to a power system are defined to be positive, while the power consumed in a power system are defined to be negative. The consumer power is met at this bus. The known variable for this bus is P and Q and the unknown variable is $|V|$ and δ. (Afolabi *et al.*, 2015). Table 2.1 shows the types of bus with their variables.

Table 2.1: Bus classification (Afolabi et al., 2015)

No	**Type of Bus**	**Variable**			
		P	Q	$\|V\|$	δ
1	Slack Bus	Unknown	Unknown	Known	Known
2	Generator Bus	Known	Unknown	Known	Unknown
3	Load Bus	Known	Known	unknown	Unknown

2.2.5 Distribution Generation

Traditionally, electric power is produced at central station power plants and delivered to consumers using transmission and distribution networks. Today, there is a trend toward the use of distributed generation (DG) units, for economic, technical and environmental reasons, in addition to the traditional large generators connected to the transmission system (Mirzaei *et al.,* 2014).

2.2.5.1 Distributed Generation Definitions

As known, distributed generation signify the electric power generation within distributed network to meet the rapid energy demand of consumers. However, There is many terms and definitions used for DG explanations and that's create a various perspectives (Guerriche & Bouktir, 2015):

i. The Electric Power Research Institute (EPRI) defines distributed generation as generation from 'a few kilo-watts up to 50 MW'.

ii. International Energy Agency (IEA) defines distributed generation as generating plant serving a customer on-sit or providing support to a distribution network, connected to the grid at distributed level voltages.

iii. The International Conference on large High Voltage Electric Systems (CIGRE) defines DG as ‘smaller than 50-100 MW’.

Although there are variations in definitions, however, the concept is almost same. DG can be treated as small scale power generation to mitigate the consumer energy demand (Guerriche & Bouktir, 2015).

2.2.5.2 Classification of DG Technologies

There are various types of DGs. The main categorization of DG is according to the nature of fuel used and they are broadly classified as renewable energy DGs and non-renewable energy DGs (Sivasangari & Kamaraj, 2015):

i. The renewable energy DGs include photovoltaic, fuel cells, wind, biomass and hydro plants of small size

ii. The non-renewable energy DGs include micro turbine, gas turbines and diesel plants technologies.

DG technologies have a significant impact on the selection of the appropriate size and placement to which the DG unit is to be connected to a grid or customer loads (Singh, 2014). Figure 2.2 below show the type of DGs technologies with their corresponding examples.

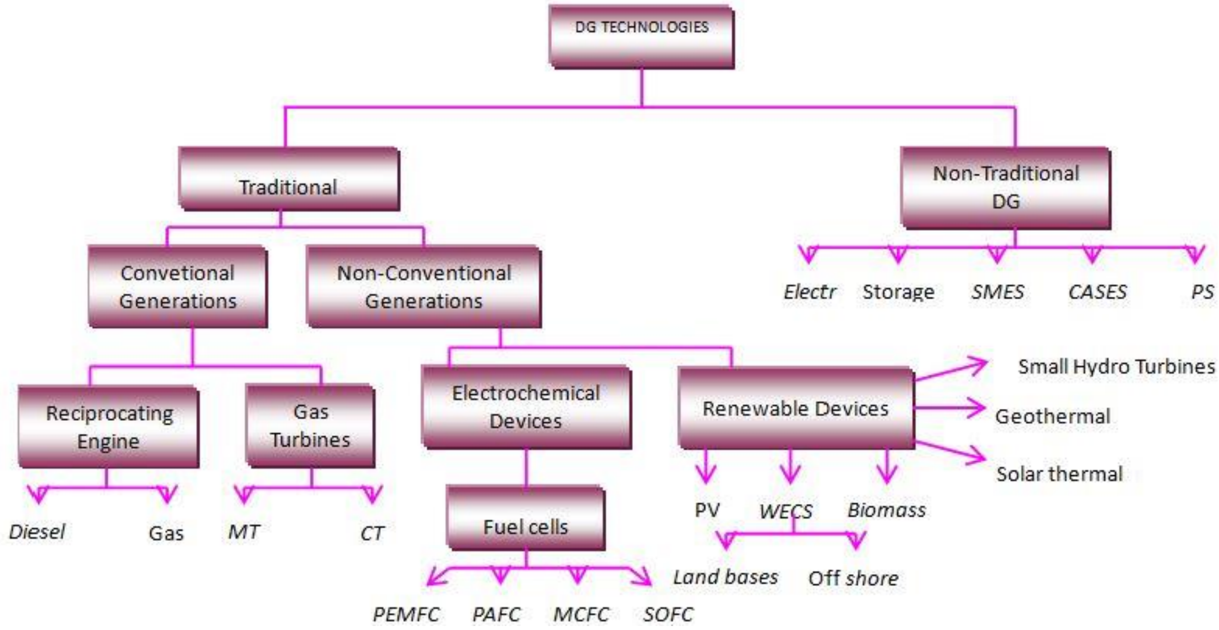

Figure 2.2: Distributed Generation Technologies (Haruna, 2015)

The DGs are further classified based on their model in the radial distribution network. The DGs can be represented as a Constant Real Power model, Constant Power factor model, Variable Reactive Power model, Constant Reactive Power model and constant voltage model (Sivasangari & Kamaraj, 2015).

Table 2.2 shows the types of DG model with their corresponding examples

Table 2.2: Types of DG and their modeling (Sivasangari & Kamaraj, 2015)

Type of DG	Model of DG	Real power of DG P_{DG}	Reactive power of DG Q_{DG}	Example
Type I	Constant Real Power	P_{DGi}	0	Solar photovoltaic cells
Type II	Constant Power Factor	$P_{DGi} = S_{DGi} \cos\phi$	$Q_{DGi} = S_{DGi} \sin\phi$	Gas turbine
Type III	Variable Reactive Power	P_{DGi}	$Q_{DGi} = -(0.5 + 0.04(P_{DGi})^2)$	Induction generators
Type IV	Constant Reactive Power	0	Q_{DGi}	Synchronous compensators

In general, DG can be classified into four types (Das 2016):

I. **Type 1:** DG capable of injecting constant active power P

II. **Type 2:** DG capable of injecting only reactive power Q

III. **Type 3:** DG capable of injecting both active power P and reactive power Q

IV. **Type 4:** DG capable of injecting constant power P but consumes reactive Q.

2.2.5.3 Distributed Generation Modeling

The DG can be Modeled as shown below depending on the type of DG.

For a given i^th bus, the injected active and reactive power P_i and Q_i, the types of the DGs can be mathematically represented as follows (Hung *et al.*, 2010):

$$P_i = P_{DG_i} - P_{D_i} \tag{2.12}$$

$$Q_i = Q_{DG_i} - Q_{D_i} = \alpha_i P_{DG_i} - Q_{D_i} \tag{2.13}$$

where P_{D_i} and Q_{D_i} are the active and reactive power demand of the i^{th} load bus and P_{DG_i} and Q_{DG_i} are the active and reactive power generation of the DG unit connected to the i^{th} bus and α_i is given by equation (2.14) below

$$\alpha_i = (sign)\tan\left(\cos^{-1}\left(PF_{DG}\right)\right) \tag{2.14}$$

where PF_{DG} is the DG power factor.

The reactive power output of the DG can be expressed as:

$$Q_{DG_i} = \alpha P_{DG_i} \tag{2.15}$$

If,

Sign = +1: implies that the DG is injecting reactive power

Sign = -1: implies that the DG is consuming reactive power.

Therefore,

For type I DG, the PF_{DG} = 1 and α_i = 0,

for type II DG, the PF_{DG} = 0 and α_i = ∞, for type III DG, the PF_{DG} lies between 0 and 1, sign = +1 and 'α_i' is constant and

for type IV DG, the PF_{DG} lies between 0 and 1, sign = -1 and 'α_i'is a constant

2.2.6 Power Flow (Load Flow)

Power flow (load flow) analysis is the determination of current, voltage, active power and reactive power (volt amperes) at various points in a power system operating under normal steady state or static conditions (Kansal *et al.*, 2013). Load flow studies are made to plan the best operation and control of the existing system are well as to plan the future expansion to keep pace with the load growth.

There are three conventional method of power flow analysis, namely (Kansal *et al.*, 2013):

I. Gauss-Seidel method

II. Newton Raphson method

III. Fast decoupled method

Usually, a power system is assumed to be balanced and the power flow analysis is carried out for the single-phase system. In single-phase power flow analysis, the power flow problem is solved for any one of the three-phases by assuming that all the three-phase voltages are equal in magnitude and displaced by 120 degrees (Mahmoud & Abdel-Akher, 2010). In many cases, the radial distribution systems include untransposed lines which are unbalanced because of single phase, two phase and three phase loads. Thus, load flow analysis of balanced radial distribution systems will be inefficient to solve the unbalanced cases and the distribution systems need to be analyzed on a three phase basis instead of single phase basis. Due to the high R/X ratios and unbalanced operation in distribution systems, the Gauss-Seidel, Newton-Raphson and ordinary Fast Decoupled Load Flow method may provide inaccurate results and may not converged. Therefore, conventional load flow methods cannot be directly applied to distribution systems (Subrahmanyam & Radhakrishna, 2009).

2.2.6.1 Backward-Forward Sweep (BFS) Method for Power Flow Analysis

The BFS technique is a straightforward implementation of Kirchhoff's current and voltage laws on a feeder. Here, branch currents and bus voltages are updating by traversing between the root (source or slack) bus and end buses in iterative way as shown in figure 2.3. Thus, giving the BFS method a more simplicity and better convergence performance compared to Gauss-like and Newton Raphson based method under the assumption of radial network (Demirok *et al.*, 2012).

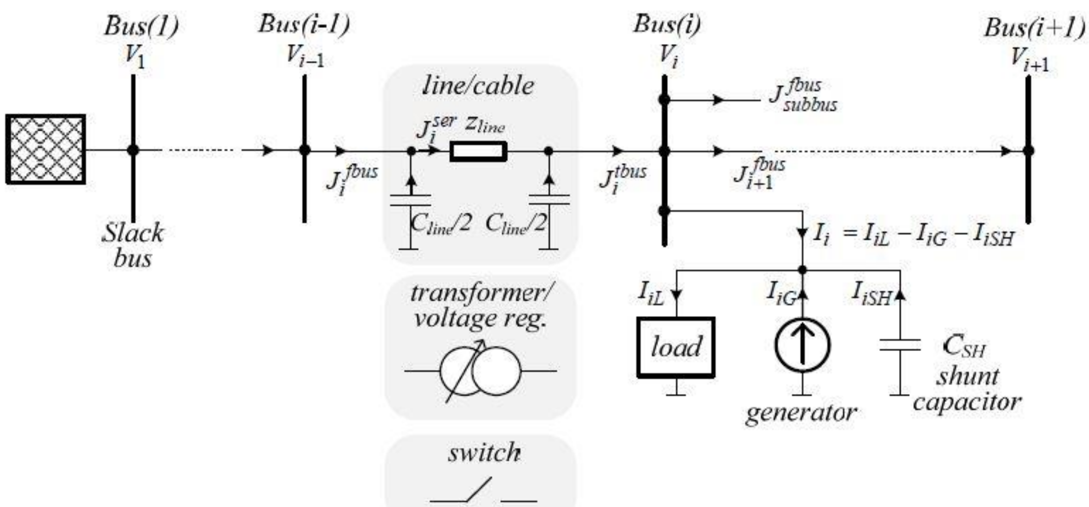

Figure 2.3: Two-bus and single-line representation of distribution networks for the solution of BFS algorithm (Demirok *et al.*, 2012).

A sensitivity matrix, used to calculate the incremental relation between the voltage magnitude and current injections, is derived and used for voltage-specified generator bus (Subrahmanyam, 2009). Two developed matrices, the bus-injection to branch-current matrix (BIBC) and the branch-current to bus-voltage (BCBV) matrix, and matrix multiplications are utilised to obtain power flow solution. The BIBC and BCBV matrices are developed based on the topological structure of

distribution feeders. The BCBV matrix represents the relation between branch currents and bus voltages. The corresponding variations at bus voltages, caused
by the variations at branch currents, can be calculated directly by the BCBV matrix (Balamurugan & Srinivasan, 2011).

The relation between current injections and branch currents can be expressed as (Teng, 2008):

$$[B]=[BIBC][I] \tag{2.16}$$

where $[B]$ and $[I]$ are the vectors of branch currents and bus current injections, respectively.

The constant $BIBC$ matrix is an upper triangular matrix and has non-zero entries of $+1$ only.

The relation between branch currents and bus voltages can be written as

$$[V_0]-[V]=[BCBV][B] \tag{2.17}$$

where $[V]$ and $[V_O]$ are the vectors of bus voltages and no-load bus voltages, respectively.

Equation (2.17) can also be rewritten as

$$[\Delta V]=[BCBV][B] \tag{2.18}$$

The constant BCBV matrix has non-zero entries consisted by line impedance values.

If the line section between bus i and bus j is a three-phase line section, the corresponding branch current B_1 will be a 3×1 vector, the $+1$ in the BIBC matrix becomes a 3×3 identity matrix and the Z_{ij} in the $BCBV$ matrix is a 3×3 impedance matrix as shown in (2.2). Note that the effects of the neutral or ground wire are included in (2.2).

Combining (2.16) and (2.18), the relation between bus current injections and bus voltages can be expressed as

$$[\Delta V]=[BCBV][BIBC][I]=[DLF][I] \tag{2.20}$$

And the solution for distribution load flow can be obtained by calculating (2.21) iteratively (Taher & Karimi, 2014):

$$I_i^k = I_i^r\left(V_i^k\right) + jI_i^i\left(V_i^k\right) = \left(\frac{P_i + jQ_i}{V_i^k}\right)^* \quad (2.21a)$$

$$\lfloor \Delta V^{k+1} \rfloor = [DLF]\lfloor I^k \rfloor \quad (2.21b)$$

$$\lfloor V^{k+1} \rfloor = \lfloor V^0 \rfloor + \lfloor \Delta V^{k+1} \rfloor \quad (2.21c)$$

where

V^k and I^k are the bus voltage and equivalent current injection of bus i^{th} at the k^{th} iteration, respectively. I_i^r and I_i^i are the real and imaginary parts of the equivalent current injection of bus i at the kth iteration, respectively ΔV Is the vector of bus voltage differences compared to substation voltage, DLF is the distribution load flow, $P_i + jQ_i$ is the injected complex power of i^{th} bus which is calculated as follows:

$$P_i + jQ_i = \left(P_{iD} - P_{iG}\right) + j\left(Q_{iD} - Q_{iG}\right) \quad (2.22)$$

where

$P_{iD} + jQ_{iD}$ and $P_{iG} + jQ_{iG}$ are the total demand and the total power generation at the i^{th} bus respectively (Taher & Karimi, 2014).

Therefore, for three-phase unbalanced network, the forward sweep equation is given by (Maya & Jasmin, 2015):

$$[VLN_{ABC}]_i = [A]*[VLN_{abc}]_j - [B]*[I_{abc}]_j \quad (2.23)$$

The backward sweep equation given by (Maya & Jasmin, 2015):

$$[I_{ABC}]_i = [C]*[VLN_{abc}]_j + [D]*[I_{abc}]_j \quad (2.24)$$

where $\left[VLN_{ABC}\right]_i$ and $\left[VLN_{abc}\right]_j$ denotes the vector matrix of the three-phase voltage at the sending (i) and receiving (j) end respectively and $\left[I_{ABC}\right]_i$ and $\left[I_{abc}\right]_j$ denotes the vector matrix of the three-phase current at the sending (i) and receiving (j) end respectively. The matrices A, B, C, D are the generalized matrices.

Where

$$[A] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.25}$$

$$[B] = [Z] = \begin{bmatrix} z_{aa} & z_{ab} & z_{ac} \\ z_{ba} & z_{bb} & z_{bc} \\ z_{ca} & z_{cb} & z_{cc} \end{bmatrix} \tag{2.26}$$

$$[C] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{2.27}$$

$$[D] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.28}$$

The iterative routine starts by initializing the node currents in (2.23) as equal to zero. Thus the no load voltages of all the buses can be computed. This voltage is used to determine the currents at the end nodes and current summation used to sum it up to the source node. The resulting current from the backward sweep is used to calculate the voltage in the forward sweep until the end of the radial branches. The voltage from the forward sweep are used to calculate the currents in the backward sweep of the next iteration. The convergence criteria is achieved when the difference in the calculated source voltage in the forward sweep and the specified source voltage is within the tolerance limits (Maya & Jasmin, 2015).

2.2.7 Load Models

The loads on a distribution system are typicallly specified by the complex power consumed and the specified load will be the maximum diversified demand. This demand can be specified as kVA and power factor, kW and power factor, or kW and kVAr (Kersting, 2012). Three-phase loads can be connected in wye or delta while single-phase loads can be connected line-to ground or line-to-line. All loads can be modeled as constant kW and kVAr (PQ), constant impedance (Z) or constant current (I) (Kersting, 2001). The loads are generally available in the three phase unbalanced distribution systems as spot and distributed loads (Subrahmanyam, 2009).

In the case of three phase loads connected in star or single phase loads connected line to neutral, the load current injections at the j^{th} bus can be given by (Subrahmanyam, 2009):

$$\begin{bmatrix} Il_j^a \\ Il_j^b \\ Il_j^c \end{bmatrix} = \begin{bmatrix} \left(\frac{SL_j^a}{V_j^a}\right)^* * \left|V_j^a\right|^n \\ \left(\frac{SL_j^b}{V_j^b}\right)^* * \left|V_q^b\right|^n \\ \left(\frac{SL_j^c}{V_j^c}\right)^* * \left|V_j^c\right|^n \end{bmatrix} = \begin{bmatrix} \left(\frac{PL_j^a + jQL_j^a}{V_j^a}\right)^* * \left|V_j^a\right|^n \\ \left(\frac{PL_j^b + jQL_j^b}{V_j^b}\right)^* * \left|V_j^b\right|^n \\ \left(\frac{PL_j^c + jQL_j^c}{V_j^c}\right)^* * \left|V_j^c\right|^n \end{bmatrix} \tag{2.29}$$

The current injections at the j^{th} bus for three phase loads connected in delta or single phase loadsconnected line to line can be expressed by (Subrahmanyam, 2009):

$$\begin{bmatrix} Il_j^{a} \\ Il_j^{b} \\ Il_j^{c} \end{bmatrix} = \begin{bmatrix} \left(\frac{SL_j^{ab}}{V_j^{ab}}\right)^* * \left|V_j^{ab}\right|^n - \left(\frac{SL_j^{ca}}{V_j^{ca}}\right)^* * \left|V_j^{ca}\right|^n \\ \left(\frac{SL_j^{bc}}{V_j^{bc}}\right)^* * \left|V_j^{bc}\right|^n - \left(\frac{SL_j^{ab}}{V_j^{ab}}\right)^* * \left|V_j^{ab}\right|^n \\ \left(\frac{SL_j^{ca}}{V_j^{ca}}\right)^* * \left|V_j^{ca}\right| - \left(\frac{SL_j^{bc}}{V_j^{bc}}\right)^* * \left|V_j^{bc}\right|^n \end{bmatrix}$$

$$= \begin{bmatrix} \left(\frac{PL_j^{ab} + jQL_j^{ab}}{V_j^{ab}}\right)^* * \left|V_j^{ab}\right|^n - \left(\frac{PL_j^{ca} + jQL_j^{ca}}{V_j^{ca}}\right)^* * \left|V_j^{ca}\right|^n \\ \left(\frac{PL_j^{bc} + jQL_j^{bc}}{V_j^{bc}}\right)^* * \left|V_j^{bc}\right|^n - \left(\frac{PL_j^{ab} + jQL_j^{ab}}{V_j^{ab}}\right)^* * \left|V_j^{ab}\right|^n \\ \left(\frac{PL_j^{ca} + jQL_j^{ca}}{V_j^{ca}}\right)^* * \left|V_j^{ca}\right|^n - \left(\frac{PL_j^{bc} + jQL_j^{bc}}{V_j^{bc}}\right)^* * \left|V_j^{bc}\right|^n \end{bmatrix} \quad (2.30)$$

where PL is the load active power, QL is the load reactive power, SL is the apparent power, Il is the load current, V is the voltage and j is the receiving end or load bus.

Equations. (2.29) and (2.30) represents a generalized model for star and delta load models. Where the n is defined as follows:

$n = 0$ constant power

$n = 1$ constant current

$n = 2$ constant impedance

`2.2.8 Objective Function

In carrying out this research work, two objective were achieved, which are power loss minimization and loadability maximization. However, the maximum loadability was done in order to know the load carrying capacity of the network, most especially the 19-bus Mahuta feeder.

I. To minimize the power loss of the system, the current loss formulae based on Sultana *et al.* (2016), is adopted in this work, which is given as follows:

$$P_{L\phi} = \min \sum_{i=1}^{nb} \left| I_{bi\phi} \right|^2 R_{bi\phi} \tag{2.31}$$

Subject to the following constraints (Abdelaziz *et al.*, 2015):

i. Voltage limits: voltage at each bus should be within a permissible range usually:

$$0.95\,p.u \leq V \leq 1.05\,p.u \tag{2.32}$$

ii. Lines thermal limit (line Ampacity): it represents the maximum current that the line can withstand at certain DG penetration, exceeding this value leads to melting of the line:

$$I_{flow} \leq I_{thermal} \tag{2.33}$$

iii. Substation limit: this constraint represents the maximum apparent power that the substation can provide:

$$S_{substation,flow} \leq S_{substation,\max} \tag{2.34}$$

iv. Power balance: the sum of input power should be equal to the sum of output active power in addition to the active power loss. The input power may include the DG active power and the active power supplied by the utility. The active output power is the sum of loads active power:

$$P_{substation} + \sum P_{DG} = \sum P_{demand} + P_{loss} \tag{2.35}$$

where, $P_{L\phi}$ is the total power losses of the three-phase distribution system, nb is the total number of branches, $I_{bi\phi}$ is the current magnitude of i^{th} branch of the three-phase distribution system, $R_{bi\phi}$ is the branch resistances of the three-phase distribution system and ϕ is the phase frame (a , b and c).

The current $I_{bi\phi}$ is calculated using equation (2.36)

$$I_{bi\phi} = \left(\frac{{P_{bi\phi}}^2 - {Q_{bi\phi}}^2}{V_i^2} \right) \tag{2.36}$$

where, $P_{bi\phi}$, $Q_{bi\phi}$ are the active and reactive power of i^{th} branch of the three-phase distribution system respectively. V_i is the voltage magnitude of i^{th} bus.

II. To maximize the system loadability (transmitted power) on the network without any bus voltage violation or branch loading, the load factor (λ) of the network is increased in an iterative optimization process as follows (Ghahremani & Kamwa, 2013):

At initial condition, λ is equal to 1 ($\lambda_{\circ} = 1$) .

For the load buses (PQ bus) the active and reactive demands (P_D and Q_D) are increased as follows (Ghahremani & Kamwa, 2013):

$$P_{Di} = \lambda_i P_{D0i} \tag{2.33}$$

$$Q_{Di} = \lambda_i Q_{D0i} \tag{2.34}$$

$$\lambda_i = \lambda_\circ + (i + 0.01) \qquad i = 1, 2, \ldots\ldots\ldots.. \tag{2.35}$$

For each iteration, based on equation (2.33) and (2.34), the load factor is increased by 1% and the optimization constraints, which are bus voltage violation and branch loading, are verified. When it is no longer possible to satisfy the constraints, it is concluded that the maximum loadability has been reached (Ghahremani & Kamwa, 2013)

Therefore, the maximized power system loadability (λ) can be formulated as

$$F = Max(\lambda) \tag{2.36}$$

Subject to the following constrainst (Basiri-Kejani & Gholipour, 2016):

$$S_l \le S_{l\max} \quad \text{for all lines} \tag{2.37}$$

$$1 - |V| \le 0.05 \quad \text{for all buses} \tag{2.38}$$

where, S_l and $S_{l\max}$ are the apparent power on the line and maximum bound on the apparent power of the line respectively.

2.2.9 Methods for Optimal DG Placement and Sizing

The major techniques and methods used for sizing and siting of DG can be categorized as follows (Prakash & Khatod, 2016):

I. Analytical Techniques

The analytical techniques represent the system by a mathematical model and compute its direct numerical solution. The results obtained by these techniques are very accurate and offer less computation time. Such techniques are suitable for small and simplistic system where the numbers of state variables involved are small in number. Examples are Eigen-value based analysis (EVA), index method analysis (IMA), sensitivity based method (SBM), point estimation method, etc.

II. Classical Optimization Techniques

These optimization techniques are applied to maximize or minimize the developed formulation according to requirement under given conditions and within the limits of constraints. Subsequently, apply suitable optimization technique which would provide the optimized value of the objective functions. Examples are Linear Programming (LP), mixed non-linear programming (MINLP), Dynamic Programming (DP), Sequential Quadratic Programming (SQP), Ordinal Optimization (OO), Optimal Power Flow (OPF), and Continuous Power Flow (CPF).

III. Artificial Intelligent(Meta-heuristic) Techniques

These techniques are capable enough to get efficient, accurate and optimal solutions in smart way called intelligent methods. The methods are most auspicious for solving optimization problems in diversified areas. Some example of the meta-heuristic algorithm are genetic algorithm(GA), particle swarm optimization (PSO), Firefly algorithm (FA), bat algorithm (BA), Cuckoo search (CS), non-dominated sorting GA-II (NSGA-II), body immune optimization (BIA), ant colony optimization (ACO), artificial bee colony (ABC) and Invasive weed optimization (IWO) algorithm.

IV. Hybrid based techniques

Integration of a meta-heuristic with other optimization approaches which may also be called hybrid metaheuristic optimization technique. Methods are capable to provide more efficient performance and reliable results with higher flexibility. This is because hybrid meta-heuristics combine their advantages with the complementary strengths. The integration of meta-heuristic techniques not only accelerates the capability of exploitation and convergence but provide better results also. It provides best performance with reduced number of iterations.

In order to exploit the advantage of analytical technique in reducing search space and the advantage of artificial intelligent in finding optimal solution, this research tends to combine voltage stability index method and meta-heuristic firefly algorithm to provide a better solution for optimal planning of DG in unbalanced three-phase distribution network.

2.2.10 Sensitivty Based Method

Sensitivity based method is based on the principle of linearization of original nonlinear equation around the initial operating point, which helps to reduce the number of solution space. (Acharya *et al.*, 2006). The sensitivity based method for DG planning are loss sensitivity that is power loss sensitivity (PLS) or loss sensitivity factor (LSF) and index based sensitivity. Some of the index based sensitivity are voltage stability index (VSI), power stability index (PSI), optimal locator index (OLI), voltage ranking index (VRI), power loss index (PLI), etc (Sultana *et al.*, 2016).

2.2.11 Voltage Stability Index

Voltage stability is the ability of a power system to maintain the voltage in an acceptable level, so that if the system nominal load increases, the active power delivered to the load increases, as well, and the both active power and voltage are controllable (Nojavan *et al.*, 2015). Consider a simple radial distribution system (RDS) with source at one end and load at the other end with two nodes is shown in Figure 2.4.

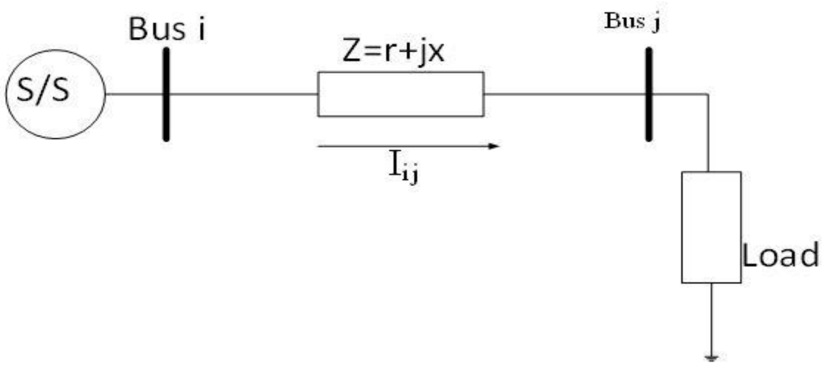

Figure 2.4: Equivalent Circuit Model of Radial Distribution Network(Murty & Kumar, 2015)

The voltage stability index can be derived as followed:

The current flowing between branch i and j can be calculated by equation (2.39) (Murty & Kumar, 2015);

$$I_{ij} = \left[\frac{P_j + jQ_j}{V_j\angle\delta}\right]^* \tag{2.39}$$

The receiving end bus voltage can be written as

$$V_j\angle\delta = V_i\angle 0 - (R + jX)I_{ij} \tag{2.40}$$

Substituting equation (2.39) into (2.40)

$$V_j\angle\delta = V_i\angle 0 - (R + jX)\left[\frac{P_j + jQ_j}{V_j\angle\delta}\right]^* \tag{2.41}$$

$$V_j\angle\delta = V_i\angle 0 - (R - jX)\left[\frac{P_j - jQ_j}{V_j\angle -\delta}\right] \tag{2.42}$$

$$V_j^{\,2} = V_iV_j\angle -\delta - (R + jX)\left[P_j - jQ_j\right] \tag{2.43}$$

$$V_j^2 = V_i V_j \cos\delta - jV_i V_j \sin\delta - (R + jX)(P_j - jQ_j) \tag{2.44}$$

$$V_j^2 + \left[P_j R + Q_j X + j(P_j X - Q_j R) \right] = V_i V_j \cos\delta - jV_i V_j \sin\delta \tag{2.45}$$

Separate real and imaginary parts in equation (2.45)

$$V_j^2 + (P_i R + Q_j X) = V_i V_j \cos\delta \tag{2.46}$$

$$P_j X - Q_j R = -V_i V_j \sin\delta \tag{2.47}$$

Let $\delta \simeq 0$

$$V_j^2 + P_j R + Q_j X = V_i V_j \tag{2.48}$$

$$P_j X - Q_j R = 0 \tag{2.49}$$

$$R = \frac{P_j R}{Q_j} \tag{2.50}$$

Substitute equation (2.50) in (2.48)

$$V_j^2 + P_j \frac{P_j X}{Q_j} + Q_j X = V_i V_j \tag{2.51}$$

$$V_j^2 - V_j V_i + \left(\frac{P_j^2}{Q_j} + Q_j \right) X = 0 \tag{2.52}$$

From the quadratic equation principle, $ax^2 + bx + c$ where a, b, and c are constants, that is

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{2.53}$$

Transforming equation (2.52) into equation (2.53) where $a = 1$, $b = V_i$ and $c = \left(\frac{P_j^2}{Q_j} + Q_j \right) X$

For stable bus voltages, $b^2 - 4ac \geq 0$.

Therefore,

$$V_i^2 - 4\left(\frac{P_j^2}{Q_j} + Q_j \right) X \geq 0 \tag{2.54}$$

$$1 \geq \frac{4X}{V_i^2} \left(\frac{P_j^2}{Q_j} + Q_j \right) \tag{2.55}$$

Hence, the voltage stability index (VSI) given by

$$VSI = \frac{4X}{V_i^2} \left(\frac{P_j^2}{Q_j} + Q_j \right) \leq 1 \tag{2.56}$$

The VSI is a kind of sensitivity index in which the weaknesses of the buses are rank in either ascending or descending order.

For stability of particular node the value of VSI must be VSI<1. The range of VSI values is 0<VSI<1. If the value of VSI approaches or greater than unity, then that node is highly unstable (Hussain & Visali, 2012). Under normal operating conditions, VSI value should be less than unity. If the value of VSI is closer to zero, then the system will be more stable. If the value of VSI is high, then the system is vulnerable to stability. The bus with high VSI value is more sensitivity and it is selected for optimal DG placement (Murty & Kumar, 2015).

2.2.12 Firefly Algorithm

Firefly Algorithm (FA) is first developed by Xin-She Yang in late 2007 and 2008 at Cambridge University, which is based on the flashing patterns and behaviour of fireflies. In essence, FA uses the following three idealized rules(Yang, 2010b):

I. Fireflies are unisex so that one firefly will be attracted to other fireflies regardless of their sex.

II. The attractiveness is proportional to the brightness, and they both decrease as their distance increases. Thus for any two flashing fireflies, the less bright one will move towards the brighter one. If there is no brighter one than a particular firefly, it will move randomly.

III. The brightness of a firefly is determined by the landscape of the objective function.

Similarly to other metaheuristics optimization methods, firefly algorithm generates random initial population of feasible candidate solutions. All fireflies of the population are handled in the solution search space with the aim that knowledge is collectively shared among fireflies to guide the search to the best location in the search space. Each individual of the population is called a firefly (Brajevic *et al.*, 2012).

Its main advantage is the fact that it uses mainly real random numbers, and it is based on the global communication among the swarming particles i.e., the fireflies, and as a result, it emerges as an effective for multi-objective optimization (Farook & Raju, 2013). The pseudo-code for implementing the algorithm is depicted below as presented by (Yang, 2010a)

Objective function $f(X)$ $X = (x_i, ..., x_d)^T$

Generate initial population of fireflies X_i $(i = 1, 2, ...n)$

Light intensity I_i *at* X_i *is* determined *by* $f(X_i)$

Define light absorption coefficient γ

While $(t < MaxGeneration)$

for 1 *: n all n fireflies*

for *j* = 1 *: n all n fireflies*

if $(I_j > I_i)$, *Move firefly* ***i*** *towards j in d* – dim*ension ;* ***end if***

Attractiveness varies *with distance r via* $\exp[-\gamma r]$

Evaluate new solutions and update light intensity

***end for** j*

end for i

Rank the fireflies and find the current best

end while

Postprocess results and visualization

end

The flashing light can be formulated in such a way that it is associated with the objective function to be optimized, which makes it possible to formulate new optimization algorithms. (Yang, 2010b)

2.2.12.1 The attractiveness of the firefly

For simplicity, it is assumed that the attractiveness of a firefly is determined by its brightness which in turn is associated with the encoded objective function. In the simplest case for maximum optimization problems, the brightness I of a firefly at a particular location X can be chosen as $I(X) \propto f(X)$. However, the attractiveness β is relative, it should be seen in the eyes of the beholder or judged by the other fireflies. Thus, it will vary with the distance r_{ij} between firefly $\boldsymbol{i}$ and firefly j . In addition, light intensity decreases with the distance from its source, and light is also absorbed in the media, so we should allow the attractiveness to vary with the degree of absorption. In the simplest form, the light intensity $I_{(r)}$ varies according to the inverse square law (Yang, 2010b)

$$I_{(r)} = \frac{I_s}{r^2} \tag{2.57}$$

where;

I_s is the intensity at the source, and

r is the distance between two fireflies

For a given medium with a fixed light absorption coefficient , the light intensity I varies with the distance r . That is:

$$I = I_o e^{-\gamma r} \tag{2.58}$$

where I_o is the original light intensity.

In order to avoid the singularity at r = 0 in the equation (2.62) the combined effect of both the inverse square law and absorption can be approximated using the following Gaussian form (Yang, 2010b)

$$I(r) = I_o e^{-\gamma r^2} \tag{2.59}$$

As a firefly's attractiveness is proportional to the light intensity seen by adjacent fireflies, we can now define the attractiveness β of a firefly by

$$\beta = \beta_o e^{-\gamma r^2} \tag{2.60}$$

where β_o is the attractiveness at $r = 0$ As it is often faster to calculate $\frac{1}{(1+r^2)}$ than an exponential function, the above function, if necessary, can conveniently be replaced by

$$\beta = \frac{\beta_o}{1+\gamma r^2} \tag{2.61}$$

Equation (2.64) defines a characteristic distance $\Gamma = \frac{1}{\sqrt{\gamma}}$ over which the attractiveness changes significantly from β to $\beta_o e^{-1}$

In the implementation, the actual form of attractiveness function $\beta(r)$ can be any monotonically decreasing functions such as the following generalized form:

$$\beta(r) = \beta_o e^{-\gamma r^m}, (m \geq 1) \tag{2.62}$$

For a fixed, the characteristic length becomes:

$$\Gamma = \gamma^{\frac{1}{m}} \to 1, \text{As } m \to \infty \tag{2.63}$$

Conversely, for a given length scale Γ in an optimization problem, the parameter can be used as a typical initial value. That is:

$$\gamma = \frac{1}{\Gamma^m} \tag{2.64}$$

2.2.12.2 Distance and movement

The distance between any two fireflies ‘ i ’and ‘ j ’at ‘ X_i ’ and ‘ X_j ’, respectively, is the Cartesian distance:

$$r_{ij} = \| X_i - X_j \| = \sqrt{\sum_{k=1}^{d} \left(x_{i,k} - x_{j,k} \right)^2} \tag{2.65}$$

where:

$x_{i,k}$ is the k^{th} component of the spatial coordinate X_i of i^{th} firefly.

In 2-D case,

$$r_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \tag{2.66}$$

The movement of a firefly ‘ $\boldsymbol{i}$ ’ is attracted to another more attractive (brighter) firefly ‘ j ’ is determined by

$$X_i^* = X_i + \beta_o e^{-\gamma r^2_{ij}} \left(X_j - X_i \right) + \alpha \in_i \tag{2.67}$$

where:

$\beta_o e^{-\gamma r^2_{ij}} \left(X_j - X_i \right)$ is due to attractiveness,

$\alpha \in_i$ is a randomization with α being the randomization parameter and $\in_i$ Is a vector of random numbers drawn from a Gaussian or uniform distribution.

The parameter now characterizes the variation of the attractiveness, and its value is crucially important in determining the speed of the convergence and how the FA algorithm behaves.

2.2.13 Radial Distribution Test System

The radial distribution test feeders adopted for this work are 19-bus Mahuta feeder and IEEE 37-bus unbalanced test system.

2.2.13.1 IEEE 37-bus radial distribution system

This feeder is an actual feeder in California, with a 4.8 kV operating voltage. It is characterized by delta configuration, all line segments are underground, substation voltage regulation is two single-phase open-delta regulators, spot loads, and very unbalanced (Kersting, 2001). The feeder is edited by removing the connected regulators and capacitors to clearly evaluate the impact of DG on power loss and voltage profile, closing the normally closed switches and opening the normally open switches. In addition, the feeders are renumbered for simplicity (Othman *et al.*, 2016).

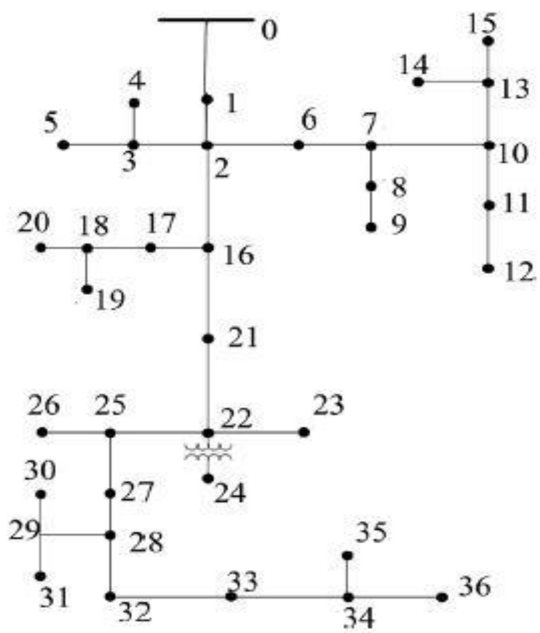

Figure 2.5: Single Line Diagram of IEEE 37-Bus Unbalanced Radial Distribution Network.(Othman *et al.*, 2016).

2.2.13.2 Mahuta 19-bus feeder radial distribution network

The Mahuta 19-bus feeder is a practical Nigeria distribution feeder which is fed from ungwa Boro 33/11kV injection substation, connected to a grid through Mando transmission substation Kaduna state. The injection substation has $2\times15MVA$ power transformer with one incoming feeder and three outgoing feeder. One of the outgoing feeder is connected to a transformer $TX1$ and the other two outgoing feeder are connected to transformer $TX2$ has shown in figure 2.6.

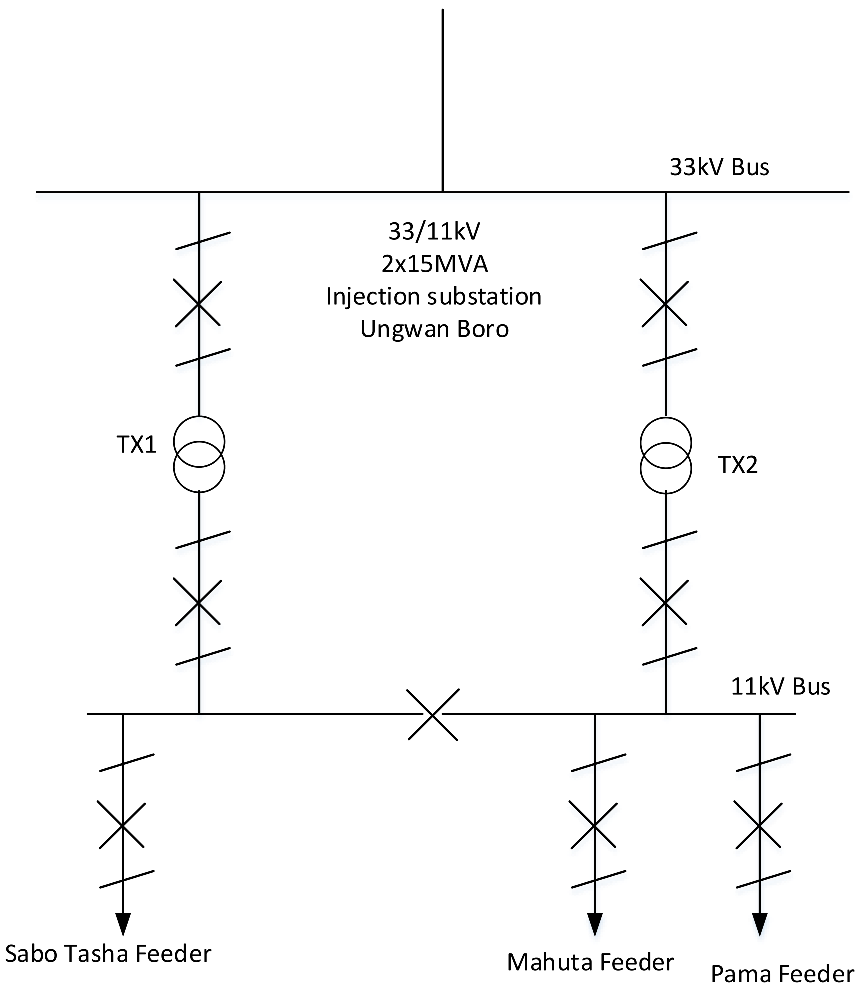

Figure 2.6: Single line diagram of 33/11kV injection susbstation Ungwan Boro.

Among the three outgoing , the feeder considered in this work is the Mahuta feeder which consists of 19-bus, 11kV radial distribution system. The network single line diagram is shown in figure 2.7.

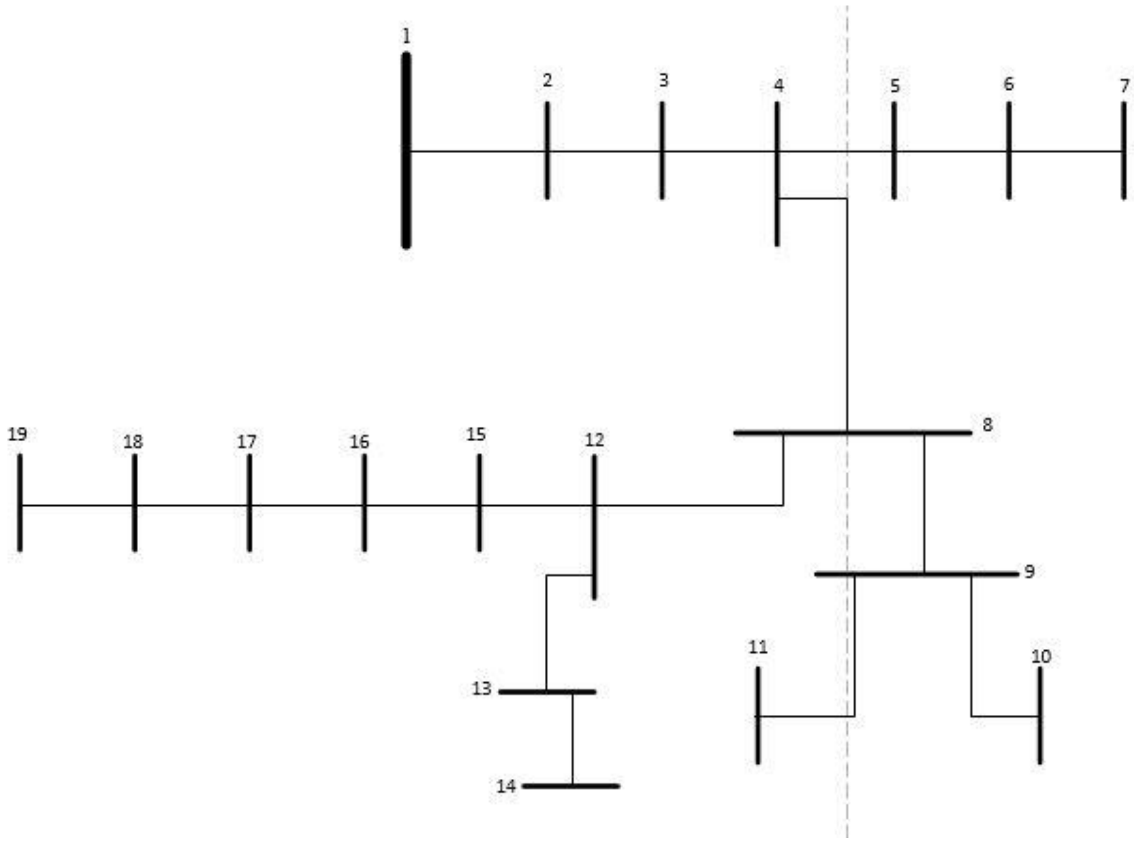

Figure 2.7: Single Line Diagram of Mahuta 19-Bus feeder

2.3 Review of Similar Works

The placement of DG in DN has attract a lot of research and different techniques had been employed for the optimal location and sizing of the DG. Most of the researchers assumed a balance network but the DN is not balance in nature due to certain characteristers exhibited by the network. However, other researchers considered the unbalanced nature of DN and some of the work done on this field are review below.

Subrahmanyam and Radhakrishna (2009) proposed a variational algorithm with voltage index analysis for optimal location and sizing of DG in three-phase unbalanced radial distribution network (URDN) for power loss minimization and the voltage profile improvement of the system. In the work, the location of the DG was determined by using voltage index analysis and the size of DG were computed by variational technique algorithm and the developed method was tested on 25-bus and IEEE 37- bus URDN. Voltage sensitive nodes were first identified by penetrating DG with 20% of the total feeder loading, at each node and the node with least voltage index after placing DG was picked as the best location for the DG placement. While the Variational Algorithm was used to find the optimal size of the DG formulated as a constrained optimization problem adapted from a reactive power compensation sizing algorithm. The developed method was observed to solved DG placement and sizing in unbalanced radial distribution systems but the location of the DG was basically based on trial and error which may not give an optimal solution.

Ramana *et al.* (2010) presented a voltage index analysis and variational technique algorithm for Distributed generator placement and sizing in unbalanced radial distribution system. In the work, the voltage sensitive nodes were first identified by penetrating DG with 20% of the total feeder load at each node, and the node with least the voltage index after placing DG was picked as the best location for the DG placement, while the variational algorithm was used to find the optimal

DG size. The work minimized system losses while satisfying the voltage and power limits constraint and the work was implemented on 25-bus and IEEE 37-bus unbalanced radial distribution system. The solution may give a necessary but not sufficient optimal solution as more iteration was required because of the assumption made under DG penetration, which could lead to improper placement of the DG.

Al-Sabounchi *et al.* (2011) developed a feasible optimization interval (FOI) algorithm for optimal sizing and location of a single PVDG unit on a 3-phase unbalanced radial distribution feeder. The objective function was to maximized the line energy (ΔEL) and avoid the reversed power flow. The line was checked through the backward/forward power flow algorithm and the power flow was drived by the load demand along the feeder and the production of the PVDG unit. The developed method was iterated at every node along the feeder in the upstream direction starting from the far end node. By the end of the iteration process, the node and associated size at which the PVDG unit results in maximum ΔPL_{FOI} was selected as the optimal solution. The developed method required so many iteration process to find the optimal solution which is time consuming and also, the location and size of the DG depend on the power flow determined by the DG which may guaranteed a optimal solution.

Anwar and Pota (2012) presented unbalanced three-phase optimal power flow (TOPF) using particle swarm optimization (PSO) for optimum generation capacity of multiple Distributed generation (DG) units. In the work, PSO was used for optimum generation capacity of the DG and the unbalanced three-phase distribution load flow (DLF) are performed using an open source tool called openDSS. The analysis were carried out on IEEE 123-node distribution test feeder for three different DG technologies and the results obtained were compared with Brute-Force search algorithm. It was observed that among the three DG technologies considered, the type-3 DG units has less power loss reduction. The developed method shows a significant power loss reduction (79.4% for type-1 DG unit, 80.1% for type-2 DG unit and 46.3% for type-3 DG unit) and the developed algorithm performed more better than the exhaustive search algorithm. In the work, separate platform are required for power flow and power loss calculation which is tedious.

Reddy and Manohar (2013) proposed a Genetic Algorithm (GA) for optimal placement and sizing of distributed generation in an unbalanced distribution network. The objective function of the worked was maximization of net benefit of distribution systems such as power losses, voltage levels and reliability. The work was validated using IEEE 13 nodes and 37 nodes test feeder. The result obtained showed improvement in voltage profile and decreased in power loss after inclusion of DG into the system. The technique used lack accuracy when high-quality solution is required which may not give an optimal solution

Teja and Kumar (2014) presented Optimal DG Placement in Unbalanced Mesh Distribution System for Loss Reduction and Voltage Profile Improvement. In the work, the optimal location of DG was identified by calculating Voltage index at each node by penetrating DG size of 20% of the total feeder load at each node. Then the node with least voltage sensitive index was selected as the best location for the DG placement while the variational technique was used to find the DG size. The developed method was tested on 25-bus unbalanced mesh distribution system with diferent loading conditions (low, normal and high conditions) and also two different power factor were considered (Unity and 0.9 lagging power factor). The results obtained shows that, the percentage reduction in real and reactive power loss was more with 0.9 lagging power factor (LPF) than the unity power factor (UPF) while the voltage profile was better in case of DG with 0.9 LPF than UPF. The technique required more iteration and approximation, which may not give an optimal solution.

Othman *et al.* (2015) developed a supervised Big Bang-Big Crush method for optimal placement and sizing of Distributed generators (DG) in unbalanced distribution systems. In the developed method, the DG was modelled as voltage controlled (PV) node with the flexibility to be converted to constant power (PQ) node in case of reactive power limit violation and the developed algorithm was implemented on IEEE 33-bus and IEEE 37- node feeder. The voltage regulation in the IEEE 37-node feeder was removed in order to evaluate the effects of the DG in the system voltage profile and backward-forward sweep technique were used in performing the power flow analysis. The result obtained was compared with the work of other authors using the IEEE 33-bus feeder. The developed method showed a significant reduction in power loss (69.67%) as compared to when uisng GA (44.83%) and ABC (48.19%). Also the daily energy loss was evaluated showing a 62.83% reduction in dialy energy loss for IEEE-37 node without the application of the developed method and 68.35% daily energy loss reduction when the supervised BB-BC method was apply as compared to the base case where no DG is connected. The work did not considered uncertainty of loading conditions in the network which can affect the utilization of the DG in the network

Othman and Hegazy (2015) developed a novel heuristic algorithm to determined the best sizing and location of distributed generators in unbalanced distribution network for power loss reduction. The developed algorithm start with ranking the system nodes according to their sensitivity to power losses reduction, and then, the planned power loss was achieved by determination of the magnitude of DG injection required. The developed algorithm was tested on the IEEE 37-node feeder. Two cases scenerio are considered, the first case was to rank the DG locations according to their sensitivity to power loss reduction and 10% of system loss reduction were assumed. The second case considered optimal location and power for different specified power loss. The real state of the network can not be ascertaind because of the assumptions made in the power losses which can affect the DG penetration level.

Xue *et al.* (2015) presented Affine Arithmetic algorithm for ubalanced three-phase distribution system power flow with distributed generation (DG) to study the impact of DG on distribution system as well as the three-phase voltage unbalanced factor. In the work, the Affine Arithmetic algorithm were used to modify a three-phase BFS power flow model of distribution system on the basis of uncertainty of the DG (such as wind power, PV and electric vehicle) and the asymmetry of load and power line and the developed method was tested on IEEE 33-bus system. The results obtained show that the farther the bus from the balanced bus, the more asymmetry the three-phase voltage of each bus and also, the three-phase bus voltage unbalanced factor of some of the buses increased. However, in the work, the DG are not optimally placed but rather assumed which could lead to reversal power flow and more losess as a result of wrong size and location of the DG.

Gómez-González *et al.* (2015) presented a Binary Shuffled frog leaping algorithm (BSFLA) with a probabilistic technique for optimal allocation and sizing of Biomass distributed generation in unbalanced radial systems. The objective function is to determined the performanced of the DG on distribution system and the model are tested on IEEE-13 node unbalanced distribution system. In the work, the three-phase power flow are determined by the combination of probabilitic power flow and Monte Carlo technique and the BSFLA are used for the DG location and sizing. The optimal power and site of the DG are placed where the system losses were minimal. The results obtained showed a good reduction of the power losses and the unbalance factor. The limitation of the work is that, it can only be applicable to a small network and which when subjected to a larger network may not converge

Dahal and Salehfar (2016) proposed a particle swarm optimization (PSO) based method to determined the optimal allocation of Distributed generators (DG) on a multi-phased unbalanced distribution network. The objective function was to reduce power loss and increase the voltage of three phase unbalanced distribution network. In the work, an open source software called openDSS were used to solved the unbalanced three-phase optimal power flow (TOPF). The developed method are tested on IEEE-123 node distribution feeder and the result were compared with repeated load flow (RLF) method. From the resuls obtained, when three type of DG (type 1,2,3) were considered type 2 showed a maximum power loss reduction in the distribution system and the overall power loss reduction in the system is 18.6kW while the voltage profile were improved from 0.93pu to 0.96pu. However, the work only adopt the method presented by Anwar and Pota (2012) without any significant improvement.

(Othman *et al.* (2016)) developed a supervised firely algorithm for finding the optimal location and capacity of dispatchable DGs connected to balanced/unblanced distribution feeders for power/energy loss minization without violating the system constraints. In the developed algorithm, the traditional firefly is modified by introducing an adaptive tuning parameters and updating equations and the DG was modelled as that of Othman et al., (2015). The results show that the supervised FA method was superior in evaluating the optimal DG location and power due to it robustness, efficiency and high speed of convergence. The results obtained were also compared with that of traditional firefly algorithm, and with other published work (GA and ABC). However, the placement of the DG on the network without considering the loading on the phases will lead to more losses or reversal current from any of the phase since the load are not distributed equally on the phases.

Based on the literature review so far, its evident that the unbalanced nature of the distribution network have significant effect on the power losses and the voltage profile of the distribution network. As such, so many researchers employed the use of DG to reduce the power losses and improve the voltage of the distribution network using the different technique. However, some of the method emloyed by this researchers lack accuracy on account of large network, require so many iteration to find the optimal solution, while other are base on assumption. In order to ensure a balance between the power demand and power generation, this research employed the used of firefly algorithm and voltage stability index for optimal DG planning in an unblanced three-phase distribution network.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter gives the detailed procedures (materials and methods) used in achieving the research work, and are discussed below.

3.2 Materials

The materials employed for the actualization of this research are as follows:

3.2.1 Personal computer

All simulations analysis are carried out using HP-14r002ne with the following specification:

I. Processor: Intel(R) Core(TM) i5-4210u CPU @ 1.7GHz 2.40GHz

II. Installed Memory (RAM): 8.00GB

III. System type: 64-bit Operating system, x64-based processor

IV. Operating System: Windows 8.1 single language.

3.2.2 MATLAB 2013a software

All the simulations, analysis and evaluation are carried out in MATLAB 2013a environment and details of the program developed are provided in appendix C.

3.2.3 Distribution network parameters

In order to evaluate the developed method, two radial distribution network feeders were adopted in this work. These are standard IEEE-37 node test feeder and a 19-node Mahuta distribution feeder located in Kaduna metropolitan city distribution network. However, due to limited line data for the three-phase line of the 19-bus Mahuta feeder, the impedance of all the three-phase are assumed to be the same.

3.3 Methodology

The methodology used in carrying out the research work are listed in chapter one sub-section (1.5) and are discussed below:

3.3.1 Development of three-phase power flow based on backward and forward sweep technique

In developing the three-phase power flow based on the BFS technique for the unbalanced distribution network, the following three steps are involved:

I. Nodal Current Injection

For the nodal current calculation, an initial phase voltage at each bus are assign to each phase and are usually taken as the nominal voltage which is $1\angle 0^{\circ}$ p.u. The current at each node is calculated using equation (2.21a)

II. Backward Sweep:

The Backward sweep update the current values towards the source node. The process normally start from the far end and then move towards the source end. The current in each branch is calculated using Kirchoff's current law given by equation (2.24)

III. Forward Sweep:

The forward sweep calculate the voltage at each node, starting from the source node to the last or receiving end node. The equation used in updating the voltage is given by equation (2.23).

3.3.2 Power flow analysis

The power flow analysis was carried using the pseudocode below and the matlab code is given in appendix C4.

i. Read the network parameters
ii. Formation of line and bus matrix, and assign a base voltage ($1\angle 0^{\circ}$ p.u) and deviation error limit ($\in$ = 0.0001)
iii. Calculate the three-phase bus current injection and three-phase branch currents using equation (2.24) and (2.21a)
iv. Set iteration count k = 1
v. Calculate the current injections for each branch using equation (2.24)
vi. For Backward Sweep: calculate the branch current starting from the far end node
vii. For Forward Sweep: calculate and update the bus voltages starting from the source node to the end node using equation (2.23)
viii. Calculate and check for voltage mismatch using equation (2.21c)
ix. If $\Delta V_{max} \leq \in$ go to step x, else, set $k = k+1$ and go to step v
x. Print the voltage magnitude, phase angle and total power losses
xi. Stop.

3.3.4 Voltage Stability Index (VSI) application

The value of the parameters obtained from the power flow analysis such as active power, reactive power and voltage with the reactance of the line are used in evaluating the VSI of the network. The VSI was developed in Matlab with the following script:

```
% %VSI(b)= (4*X(a-b)/V_a^2)*(P_b^2/Q_b+Q_b)
%
%    S_VSI=zeros(n,1);
% for i=2:n
%    if P(i)==0
%       p(i)=NLB;
%       Q(i)=NLB;
%    end
%    a=(4*X(i-1));
%    b=(Vi(i-1)^2);
%    c=(P(i)^2/Q(i)+Q(i));
%    VSI=(a/b)*(c);
%
%    S_VSI(i)=VSI;
% end
%    VSI=S_VSI;
```

Once the VSI of the network was obtained from the above Matlab script, the VSI was ranked in decending order using the Matlab script below:

```
%    [VSI_R index]=sort(VSI,1,'descend');
%     VSI_RANK=[VSI_R index VSI_NO];
```

The location of the DG will be obtain using the following Matlab script:

```
         % for j=1:length(VSI)
%    if (VSI(j))==max(VSI(:,1))
%       Max_VSI=VSI(j);
%       opt_loc=j;
%    end
% end
% Max_VSI;
% opt_loca(iw)=opt_loc;
```

The Matlab code for the developed VSI are shown in appendix C2

3.3.3 Model of the Distributed Generation Planning

The DGs are capable of supplying active, reactive power or both dpending on the type of DG used. In most cases, the DG are modelled as PQ or PV bus depending on the purpose to which it is made to served. Modeling the DG as PV bus provide a means for reactive power control which is a function of a voltage and this help in evaluating the maximum loading of the network. Also, modeling DG as PQ bus provide a means for reducing the active power losses of the network and it also help in controlling the reactive power flow of the line by serving as a negative load.

The DGs model are discussed in subsection (2.2.5.3) and the model used in this research work is the type III DG with the following characteristics: $0<PF_{DG}<1$, Sign = +1 and α_i is constant.

3.3.4 Development of the firefly algorithm for optimal DG sizing

After obtaining the location of the DG using the VSI, the FA was then used in finding the optimal DG size that is suitable for the location with a minimum power loss and the steps involved in developing the FA for optimal DG size are as follows:

I. Generate an initial Firefly N_i base on the location obtained by the VSI and define the FA parameters.
II. Consider the fitness function (brightness) as the objective function.
III. Calculate the objective function from equation (2.31) and (2.36) that correspond to all the initial fireflies obtained in (i) above.
IV. Select the best DG size that achieved a minimum power loss and maximum system loadability, and keep the best DG size and system loadability as a new fireflies (system variables).
V. If the convergence criteria is met, go to step (vi) else, repeat step (iii and iv) for iteration counter $i = i + 1$.
VI. Display the results with the brightest firefly.

The paremeters used are given in Table 3.1.

Table 3.1: Firefly Parameter definition, notation and value

Parameter	Notation	Value
Brightness	Objective function	
Alpha (α)	Randomization parameter	0.25
Beta (β)	Attractiveness	0.20
Gamma (γ)	Absorption coefficient	1
Number of generation (i)	Iterations	50
Number of fireflies (N)	Populations	10

These parameters are selected based on (Yang & He, 2013), and are applied by (Kundur, 2013), so as to achieve a fast convergence and reliable solution.

3.3.5 Developed method for DG planning

The developed method involved the combination of the VSI and Firefly algorithm for the location and szing of the DG respectively. The steps involved in carried out the developed method are as follows:

I. Input the network parameter (line and bus data) and Firefly parameter (α, β, γ, i and N)

II. Run the base case three-phase power flow and calculate the bus voltage, branch current and power losses of the network.

III. Calculate the VSI for each bus of the network using equation 2.56

IV. Make the list of the VSI in descending order and select the bus with the highest value of VSI as the DG location.

V. Generate a random Firefly i as the DG size based on the location obtained by from step IV above.

VI. Compute the objective function from equation 2.31 and 2.36 and display the result.

The flow chart for the developed method is shown in figure 3.1

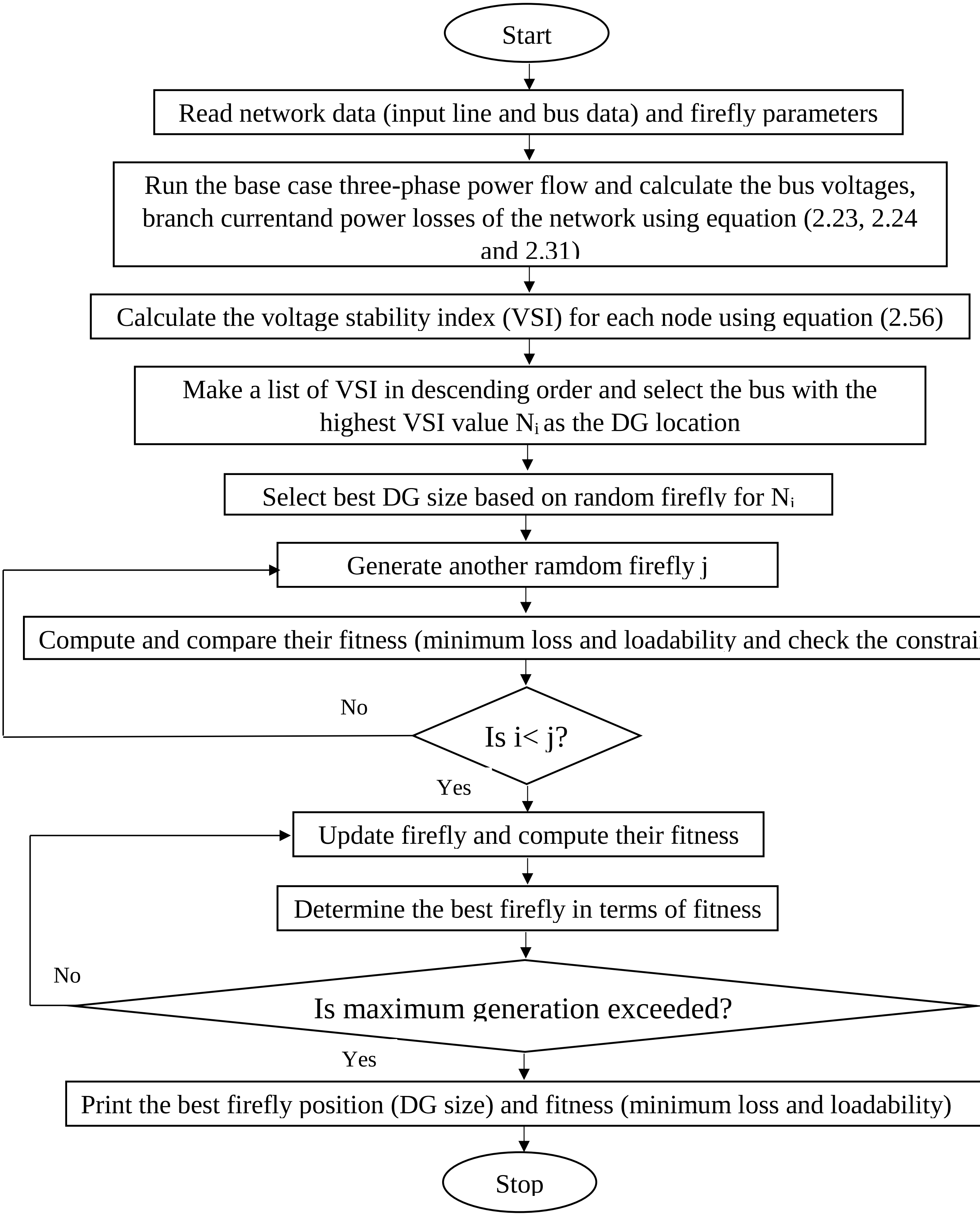

Figure 3.1: Flowchart of the developed method

3.3.6 The Network Maximum Loadability

The maximum loadability of the network is carry out using equation (2.36) as discussed in subsection (2.2.8). This is done by increasing the load with 1% of the present state load untill the constrainsts given by equation 2.37 and 2.38 are violated. The point at which the constraint can no longer hold is taking as the maximum loading factor of the network. At that point, it is assumed that the maximum loadability of the network has been reached.

3.3.6 Test Systems

Two test systems were used in implementing the developed method. The standard IEEE 37-node feeder and Mahuta 19-node feeder. The systems details and single line digram are discuss in sub-section (2.2.13) of chapter two (2) and their respective network parameters are given in appendice A and B.

3.3.7 Performance Evaluation

The evaluation analysis carried out in this work involved two case, the case without DG (Base case) and the case with DG. In each case, power flow analysis is performed to know the steady state of the network parameters such as voltage magnitude, phase angle and the power losses on each phase of the network. The base case and the optimised method is compared to show the improvement. Also,the optimised method is validated by comparing with the work of Othman et al., (2016). To calculate the percentage improvement, the equation (3.1) below is used

$$\text{Percentage improvement (\%)} = \frac{Y_i - Y_f}{Y_i} \tag{3.1}$$

Where Y_i is the initial value and Y_f is the final value.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the results obtained and the discussion of the results. The results included the base case (network without DG) and the case with DG and also the maximum loadability of the network are evaluated. The implementation of the work are done on IEEE 37-bus and 19-bus Mahuta feeder. The comparison between the developed method with the work of Othman *et al.*, (2016) are also presented in this chapter**.**

4.2 The IEEE 37-Bus Unbalanced Radial Distribution Test System

The IEEE 37-Bus test system details are discussed in subsection (2.2.13.1) and the single line diagram is shown in figure 2.5. The line and bus data are given in appendix A Table A1 and A2. The detailed of the test on the IEEE 37-bus is discussed in subsection (3.3.7) and the results are discussed in subsection 4.2.1 and 4.2.2.

4.2.1 Case I: Network without DG (Base Case)

For the base case, power flow analysis are carried out without DG on the network. The power flow analyses are performed using a three-phase power flow based on (BFS) technique discussed in sub-section (2.2.6.1) in a MatLab R2013a environment where the steady state of the network are determined. The step involved in carried out the power flow is given in sub-section (3.3.1.1). The result of the analysis (voltage magnitude and phase angle) of the three-phase are presented in appendix A, Table A3.

From the result obtained, it is observed that, each phase voltage magnitude and phase angle differ with the exception of bus 1 which is the slack bus. At the slack bus, the value of the voltage magnitude is taken to be 1p.u with a displacement of 120º between the phases. Phase A has a minimum voltage magnitude of 0.9543 p.u at bus 33, phase B has a minimum voltage magnitude of 0.9734 p.u at bus 24 and phase C has a minimum voltage magnitude of 0.9541 located at bus 36. Phase C has the highest voltage drop due to heavy load on it as compared to phase A and B. Also, the phase angle between the phases are not equally displaced due to the unbalanced loading between the phases as shown in appendix A, table A3. Maximum voltage magnitude of 0.9884, 0.9908 and 0.9827 p.u for phase A, B and C respectively are observed with the exception of the slack bus which is shown in Table 4.1 and are all located at bus 2 due to its closeness to the grid supply. The active and reactive power loses for phase A, B and C are found to be 12.2816 kW, 7.7743 kW and 11.3297 kW and 5.8341 kVAr, 3.6227 kVAr and 5.8261 kVAr respectively. The losses are calculated using equation (2.31). It was observed that phase B has the lowest power loss because of the low load connected to it as compared to phase A and C. The average voltage magnitude for phase A, B and C obtained are 0.9694, 0.9788 and 0.9616 p.u. The total active and reactive power loss for the base case are found to be 31.3543 kW and 15.2829 kVAr respectively.

4.2.2 Network with DG

After running the three-phase power flow, the value of the voltage and the power obtained from the base case are used to obtain the DG location using the VSI from equation (2.56) and the procedure used in obtaining the location is given in sub-section (3.3.2). Figure 4.1 shows the VSI graph for the IEEE 37-bus URDN.

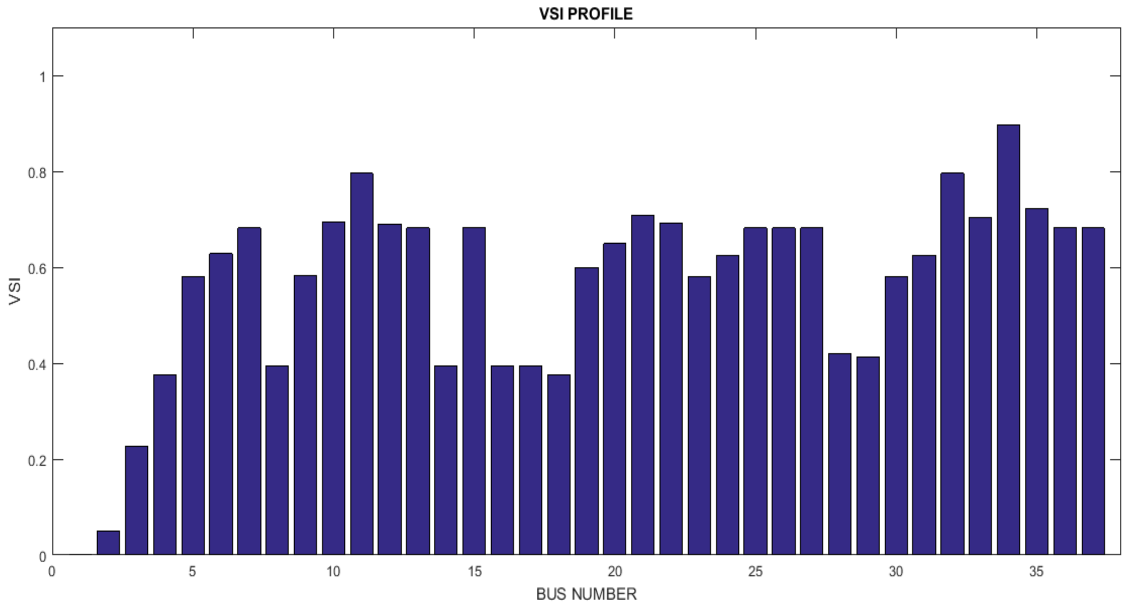

Figure 4.1: Voltage stability index (VSI) for IEEE 37-bus URDN

From the figure 4.1, it is observed that bus 34 has the highest value of VSI. Therefore, it is selected as the optimal DG location. The firefly algorithm is then used in finding the DG size that give the minimum power loss based on the location obtained by the VSI and the procedure used in finding the DG size are given in sub-section (3.3.4). From the simulation results obtained in MatLab, the optimal DG size of 356 kW and 170 kVAr for active and reactive power are obtained respectively. After the DG placement, power flow analysis are carried out using the procedure given in sub-section (3.3.1.1) and the real power losses are calculated using equation (2.31). From the results obtained, the line losses on each phase of the network are different, with phase A, B, and C having an active power loss of 7.3717 kW, 3.5443 kW and 8.9169 kW and reactive power losses of 3.5601 kVAr, 1.7464 kVAr and 4.6949 kVAr respectively. The total power loss for the entire network is found to be 19.8329 kW and 10.0014 kVAr for both active and reactive power respectively. The value of the voltage magnitude and phase angle for the three-phase line are given in appendix A, table A4 and the numerical values obtained are based on the power flow performed when DG is incorporated into the network.

From the result obtained, a minimum voltage magnitude 0.9764, 0.9865 and 0.9762 p.u are observed at bus 33, 24 and 36 for phase A, B and C respectively. Phase C has the lowest voltage magnitude due to the heavy load connected to it. The average voltage magnitude for phase A, B and C obtained are 0.9861, 0.9902 and 0.9808 p.u respectively for the entire network.

4.2.3 Network Voltage Profile with and without DG

The base case and the developed method voltage magnitude are plotted against their respective buses from the numerical values given in appendix A, table A3 and A4. The figure 4.2, 4.3 and 4.4 shows the voltage magnitude for the base case and the optimized case for phase A, B and C

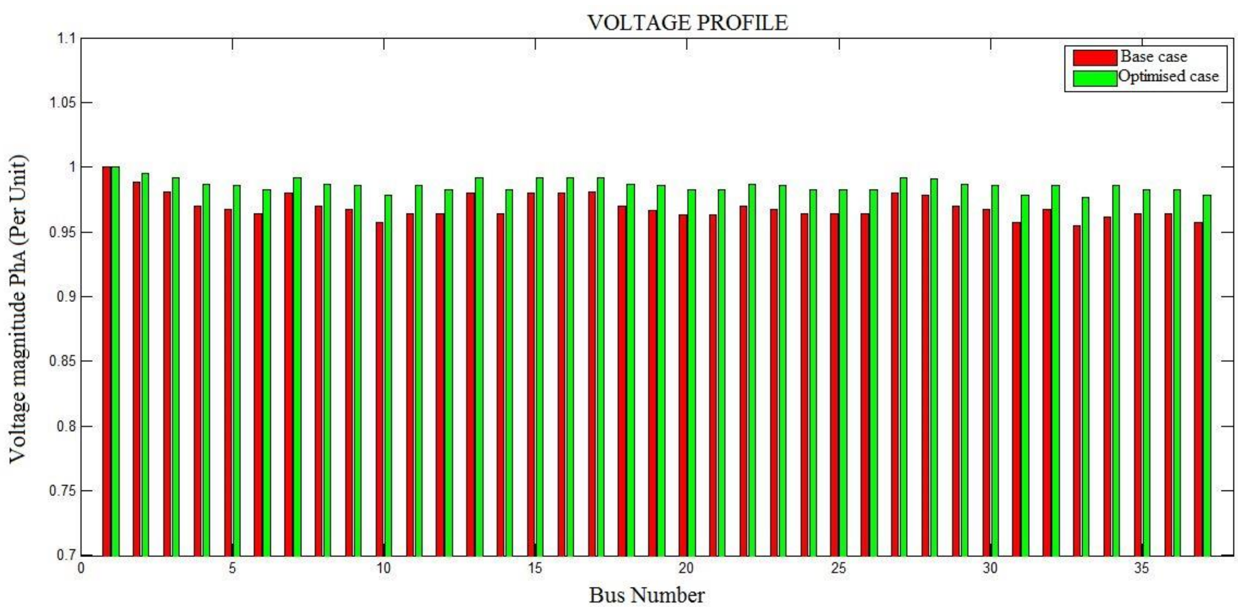

Figure 4.2: Voltage Profile for the Developed Method and the Base Case for IEEE 37-Bus URDN phase A

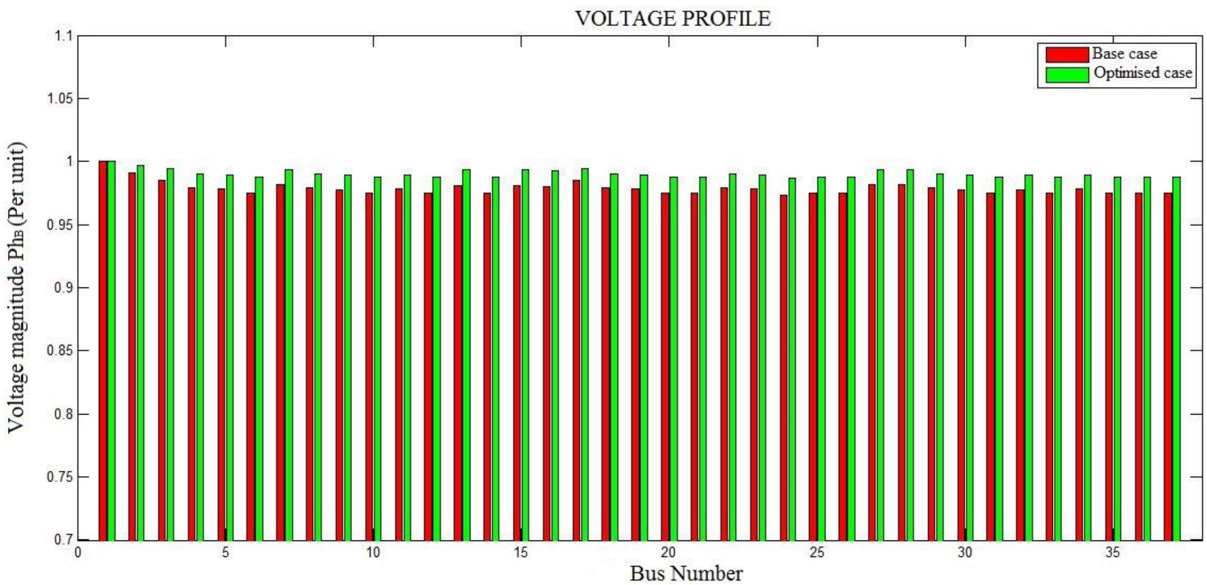

Figure 4.3: Voltage Profile for the Developed Method and the Base Case for IEEE 37-Bus URDN phase B

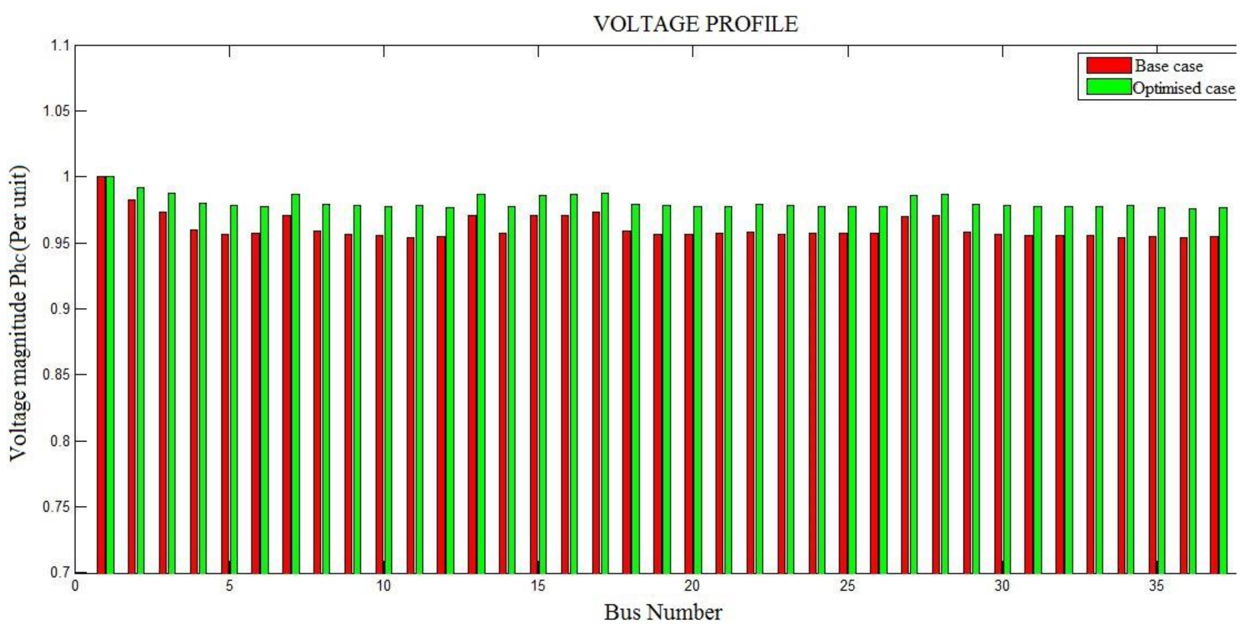

Figure 4.4: Voltage Profile for the Developed Method and the Base Case for IEEE 37-Bus URDN phase C

From figure 4.2, 4.3 and 4.4, a voltage profile improvement are observed from a minimum voltage of 0.9543, 0.9734 and 0.9541 p.u to 0.9764, 0.9865 and 0.9762 p.u for phase A, B and C respectively. This shows a 2.32%, 1.35% and 2.32% minimum voltage profile improvement for phase A, B and C respectively.

4.2.4 IEEE 37-Bus Loadability

The maximum amount of load which the network can carry without violating the system constraints is determined as discussed in sub-section (3.3.6). Figures 4.5 and 4.6 shows the plot of voltage magnitude against the loading factor for the base case and the developed method for the IEEE 37-Bus network respectively.

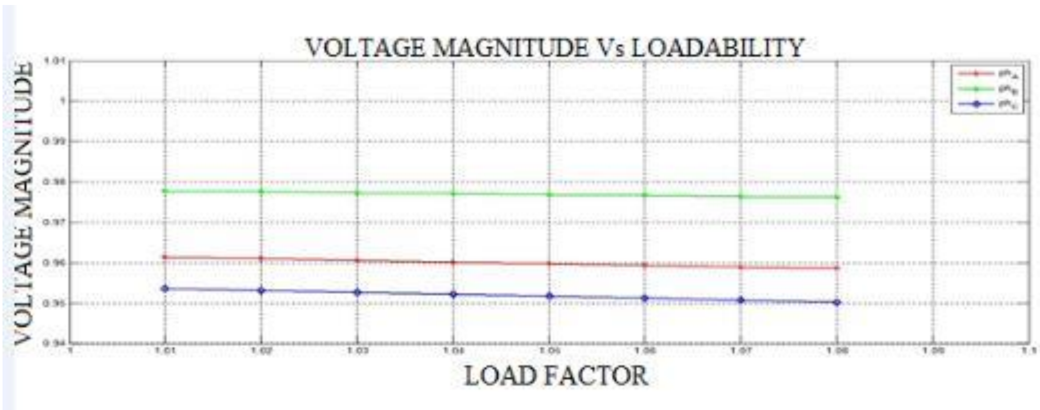

Figure 4.5: IEEE 37-Bus URDN Maximum Loadability for Base Case

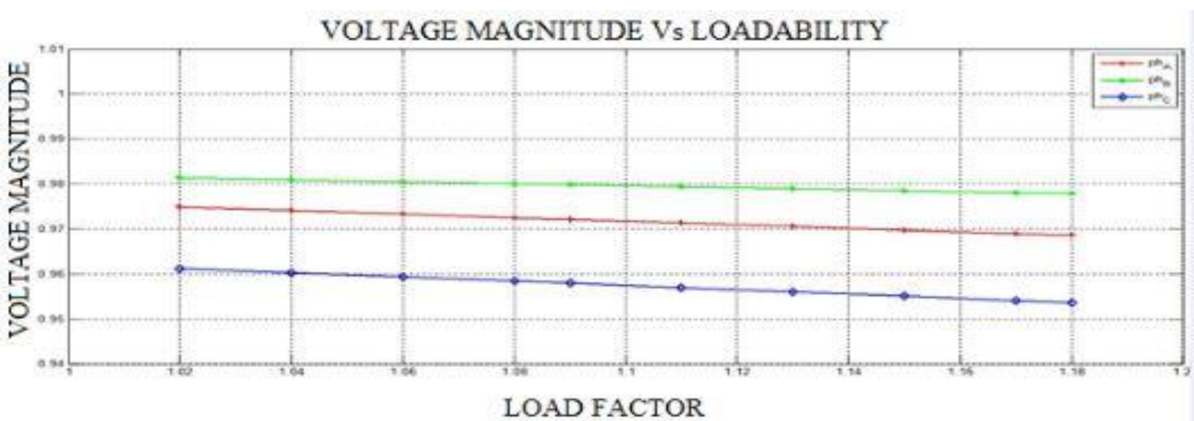

Figure 4.6: IEEE 37-Bus URDN Maximum Loadability with DG

From figure 4.5 and 4.6, it can be seen that the maximum loadability of the network for both base case and the developed method are 1.08 (8%) and 1.18 (18%) respectively over the initial loading of the network. Phase A has better loading factor as compared to Phase B and C, with Phase C having the least loadability. This implies that, the addition of equal amount of load to all the phases will cause phase C to violate the network constraints given by equation (2.37) and (2.38), which may result to network collapse. The maximum loadability improvement of the network is found to be 9.26%. Table 4.3 shows the summary of the results obtained for the IEEE 37-bus URDN.

Table 4.3: Summary of Test Result for IEEE 37-Bus Unbalance Radial Distribution Network

Description	Case I (without DG)			Case II (with DG)		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
DG location					34	
DG size (P&Q)					356kW and 170 kVAr	
Minimum voltage(p.u)	0.9543	0.9734	0.9541	0.9764	0.9865	0.9762
Voltage profile improvement				1.72%	1.16%	2%
Active Power loss (kW)	12.2816,	7.7743,	11.3297,	7.3717,	3.5443,	8.9169,
% active power reduction	-	-	-	39.98%	54.41%	21.29%
Reactive power loss	5.8341	3.6227	5.8261	3.5601	1.7464	4.6949
% reactive power loss reduction	-	-	-	38.98%	51.79%	19.42%
Loading factor		1.08 (8%)			1.18 (18%)	
% loading factor improvement			9.26%			

4.3 19-Bus Mahuta Radial Distribution Network Feeder

The 19-Bus Mahuta feeder is discussed in subsection (2.2.13.2) and the line and bus parameters are given in appendix B. Two case scenario are considered in carrying out the test on this feeder which are discussed below.

4.3.1 Case I: Network without DG (Base Case)

For the base case, the three-phase power flow is performed on the feeder based on the steps given in sub-section (3.3.1.1) to obtain the steady state voltage magnitude and phase angle of the network without the DG. The numerical value obtained when the power flow is performed in Matlab environment are shown in Table B3, appendix B.

From the results obtained, it is observed that the voltage magnitude and phase angle in all the buses differ in each phase due to the different loading in the network with a minimum voltage of 0.9962 p.u, 0.9963 p.u and 0.9967 p.u and a maximum voltage of 0.9993 p.u, 0.9993 p.u and 0.9994 p.u for Phase A, B and C respectively. But with the exception of the slack bus, which value is based on the initial operating point giving in sub-section (3.3.1.1). The minimum voltage magnitude of all the phases are found at the far end of the network due to the line voltage drop because of the distance and impedance of the line. The network real power loses are calculated using equation (2.31). The active and reactive power loss for phase A, B and C are found to be 0.5392 kW, 0.4986 kW and 0.4108 kW and 0.3852 kVAr, 0.3419 kVAr and 0.2841 kVAr respectively. The total active and reactive power loss of the network are 1.4486 kW and 1.0112 kVAr respectively. The average voltage magnitude of the base case for phase A, B and C of the entire network are found to be 0.9968, 0.9969 and 0.9973 p.u respectively.

4.3.2 Case II: Network with DG

After running the three-phase power flow, the value of the voltage and power obtained from the base case power flow are used to obtain the DG location using the VSI from equation (2.56). Figure 4.7 shows the VSI graph for the 19-bus feeder.

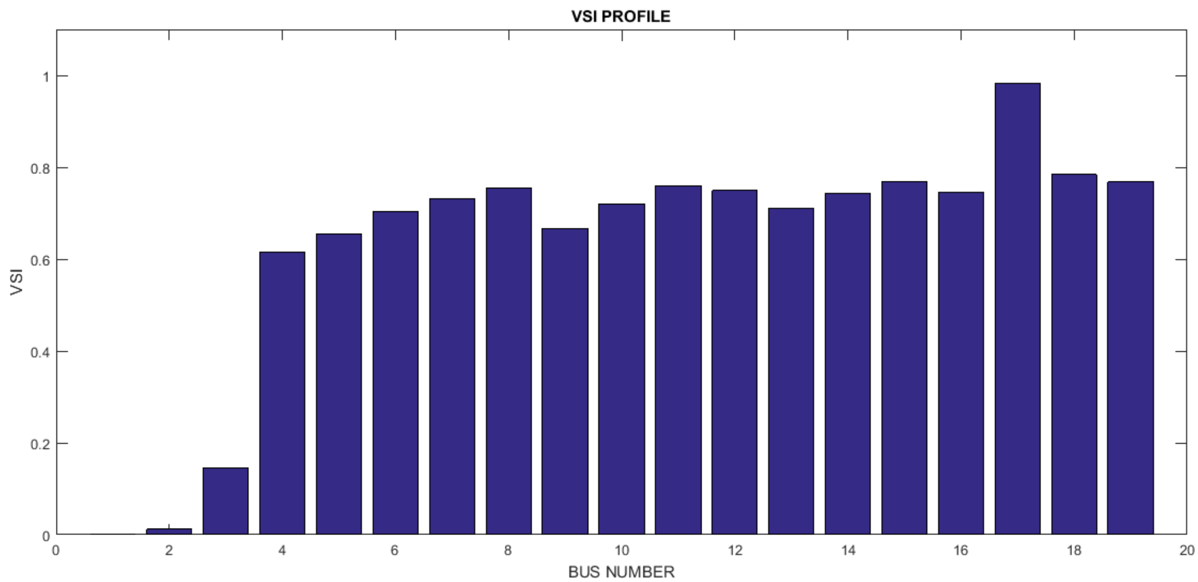

Figure 4.7: Voltage stability index (VSI) for 19-Bus Mahuta Distribution Network Feeder

From figure 4.7, it can be seen that the bus with the highest value of VSI is bus 17 and is therefore, taken as the optimal location of the DG. The firefly algorithm is then used in finding the DG size that give the minimum power loss based on the location obtained by the VSI, the procedure used in finding the DG size is given in sub-section (3.3.4). From the simulation results obtained using Matlab environment, the size of the DG active and reactive power obtained are 201.58 kW and 115 kVAr respectively. After the DG placement, power flow analysis is carried out using the procedure given in sub-section (3.3.1.1) and the power losses are calculated using equation (2.31). Table B4 in appendix B shows the voltage magnitude and phase angle of the buses obtained when DG are incorporated into the network.

From the result obtained, a minimum voltage magnitude for phase A, B and C are found to be 0.9987p.u, 0.9988p.u and 0.9989p.u as compared to the base case which are 0.9962p.u, 0.9963p.u and 0.9967p.u respectively as shown in table B4, appendix B. Like the base case scenario, the minimum voltage magnitude are found at the far end of the network (at bus 19) due to almost balanced nature of the feeder and the assumption made. Also, a power loss for phase A as 0.5167 kW and 0.3664 kVAr, phase B as 0.4659 kW and 0.3145 kVAr and 0.3997 kW and 0.2749 kVAr for phase C are obtained, which give a total network losses of 1.4123 kW and 0.9558 kVAr for both active and reactive power respectively. The average voltage magnitude of the network when DG are installed are found to be 0.9990, 0.9990, and 0.9991 p.u for phase A, B and C respectively.

4.3.3 19-Bus Mahuta Feeder Network Voltage Profile

Based on the numerical values presented in Table 4.4 and 4.5, the voltage magnitude for both the base case and the optimized case are plotted against their respective buses which is shown in figure 4.5a, 4.5b and 4.5c for phase A, B and C respectively.

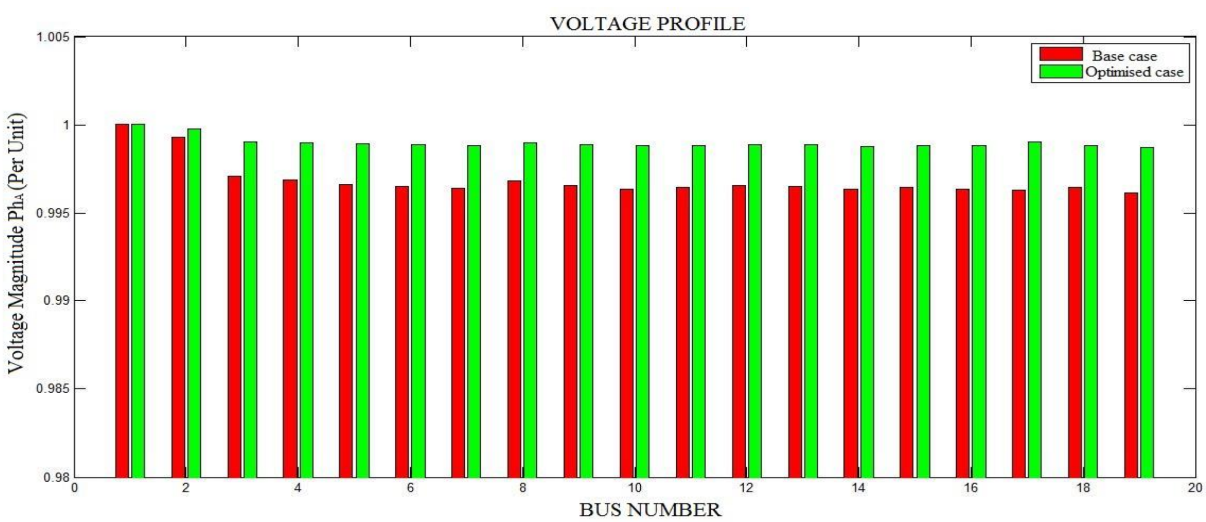

Figure 4.8: Voltage Profile for the Base Case the Developed Method for 19-Bus Mahuta Distribution Network Feeder phase A

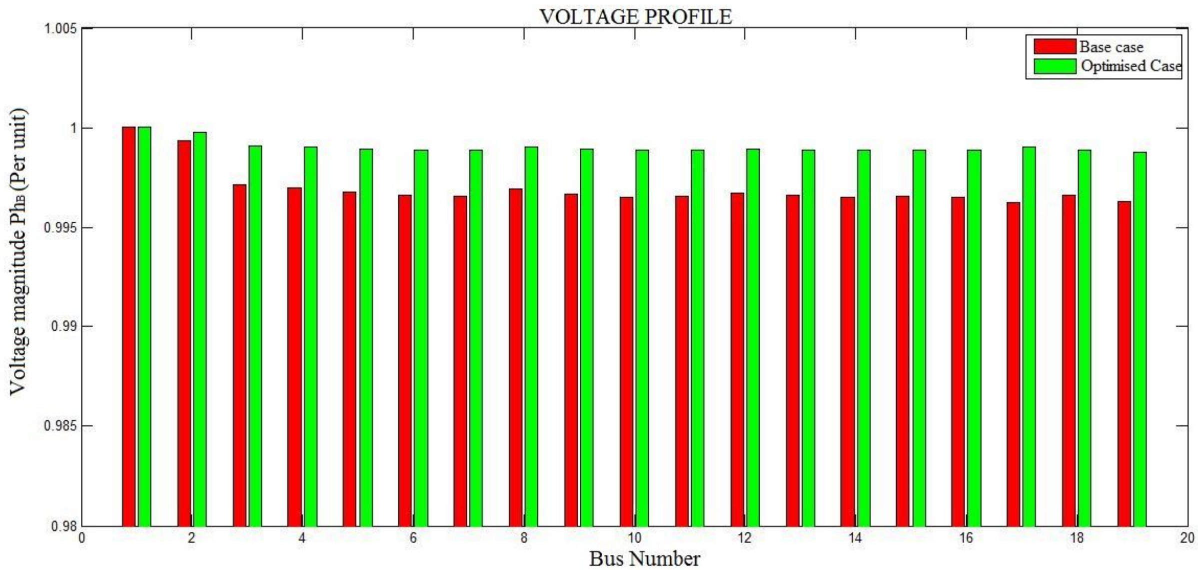

Figure 4.9: Voltage Profile for the Base Case and the Developed Method for 19-Bus Mahuta Distribution Network Feeder phase B

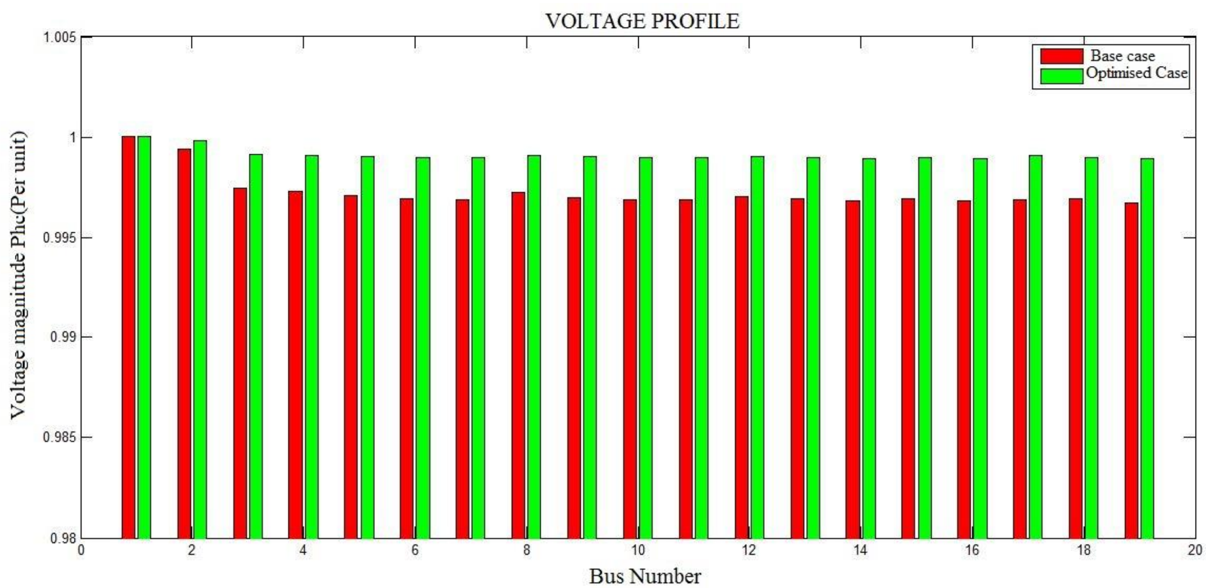

Figure 4.10: Voltage Profile for the Base Case and the Developed Method for 19-Bus Mahuta Distribution Network Feeder phase C

From figure 4.8, 4.9 and 4.10, a voltage profile improvement from a minimum voltage 0.9962, 0.9962 and 0.9967 p.u of the base case to a minimum voltage of 0.9987, 0.9988 and 0.9989 p.u for the optimised case was observed. This shows that placement of DG in the network has effect on the voltage profile.

4.3.4 19-Bus Mahuta Feeder Loadability

The maximum loadability of the Mahuta feeder are evaluated to know the amount of load which when added to the network may result to the network steady state violation. Figure 4.11 and 4.12 shows the plot of voltage magnitude against the loading factor for both the base case and the developed method respectively for the 19-Bus Mahuta Distribution network Feeder.

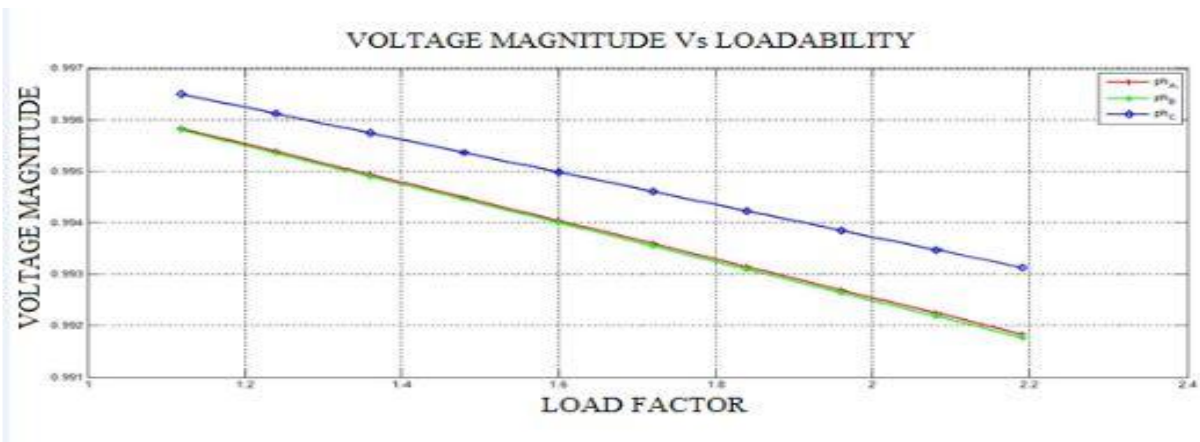

Figure 4.11: 19-Bus Mahuta Distribution Network Feeder Maximum Loadability without DG (Base Case)

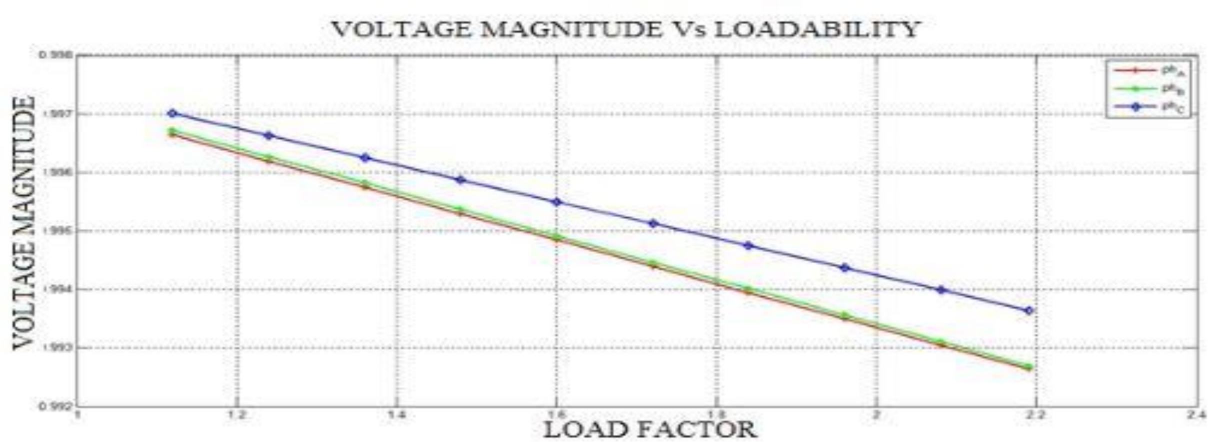

Figure 4.12: 19-Bus Mahuta Distribution Network Feeder Maximum Loadability with DG

From figure 4.11 and 4.12, it is observed that the maximum loadability for the 19-bus Mahuta feeder for both the base case and the developed method is the same, which is 2.19 (119%). This imply that, the network will only violate the network constraints given by equation (2.37) and (2.38) only when the load is increase twice the existing load on the network with an additional 19% of the load. The indifferent between the developed method and the base case is due to current carrying capacity of the line. When the load is increase beyond this loading factor, it result to voltage collapse (melting of the line) of the network. The summary of the test result obtained for the 19-Bus Mahuta DN Feeder is shown in Table 4.6.

Table 4.6: Summary of Test Result for 19-Bus Mahuta Distribution Network Feeder

Description	Case I (without DG)			Case II (with DG)		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
DG location					17	
DG size (P&Q)					210.58 kW and 115 kVAr	
Minimum voltage(p.u)	0.9962	0.9963	0.9967	0.9987	0.9988	0.9989
Active Power loss (kW)	0.5392	0.4986	0.4108	0.5167	0.4659	0.3997
% active power loss reduction	-	-	-	4.17%	6.56%	2.70%
Reactive power loss kVAr	0.3882	0.3419	0.2841	0.3664	0.3145	0.2749
% reactive power loss reduction	-	-	-	5.62%	8.01%	3.24%
Loading factor		2.19 (119%)			2.19 (119%)	

4.4 Validation of the Optimized Method

The results of the optimized method (developed method) are compared with the work of Othman *et al.* (2016). The performance metric used for the comparison are power loss and voltage profile and the comparison is done on standard IEEE 37-Bus URDN.

In the optimized method, the optimal DG location obtained is bus 34 and the DG size are 356 kW and 170 kVAr for active and reactive respectively. The active and reactive power loss of the network are found to be 19.8329 kW and 10.0014 kVAr as compared to the base case of 31.3543 kW and 15.2829 kVAr respectively. This shows a percentage loss reduction of 36.75% and 34.56% for active and reactive power respectively.

For Othman *et al* (2016), the optimal location at which the DG is placed is bus 22 of the network and the size of the DG are 1502.25 kW and 730.1 kVAr for active and reactive power respectively. The power loss obtained by the Othman et al., (2016) are 21.5911 kW and 14.3730 kVAr for active and reactive power as compared to the base of 31.3543 kW and 15.2829kVAr respectively. This showed a percentage loss reduction of 31.14% and 5.95% for both active and reactive power respectively.

However, the comparison between the optimized method and Othman *et al* (2016) method, the optimized method showed a percentage loss reduction of 8.14% and 30.42% for active and reactive power respectively over the work of Othman *et al* (2016).

Figure 4.6 shows the voltage profile of the base case, optimized method (optimized method) and Othman *et al* (2016).

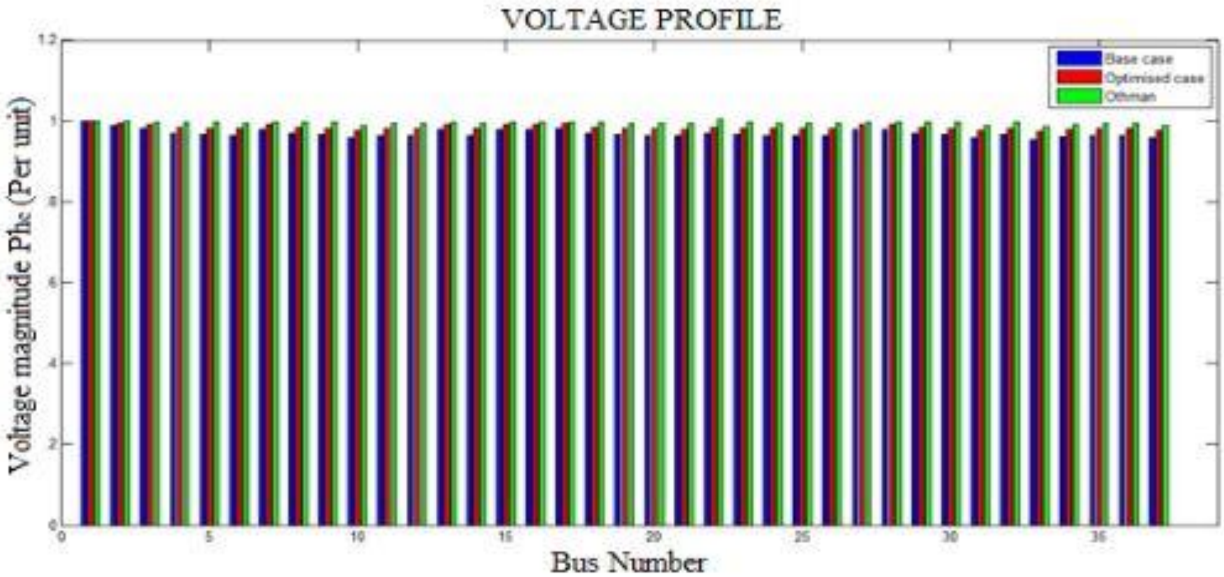

Figure 4.7: Voltage profile for the Base Case, Optimized Method and Othman *et al* (2016).

As it can be seen from figure 4.7, the blue line represents the base case, the red line represents the optimised case, while the green line represents the Othman *et al.*, (2016). The Othman *et al.*, (2016) method has a better voltage profile as compared to the optimised method and the base case. This is due to the large size of DG placed in the network which causes the significant different on the voltage profile of the netwok. The percentage average voltage profile for Othman *et al* (2016) and the optimised method over the base case are 2.6862% and 1.5615% respectively. However, in terms of power loss reduction, the optimised method had a better loss reduction than that of the Othman *et al*(2016) when compared with the base case. The optimised method gave a percentage loss reduction of 36.75% and 34.56% for active and reactive power while the Othman *et al*(2016) gave a percentage loss reduction of 31.14% and 5.95% for active and reactive power respectively over the base case. Table 4.7 shows the summary of the comparison between Othman et al (2016) results and the optimised results

Table 4.7: Summary of Results from Othman et al (2016) and Optimized Method

Descriptions	Othman *et al*(2016)	Optimized method
Optimal DG location	22	34
Optimal DG active power	1502.25 kW	356 kW
Optimal DG reactive power	730.1 kVAr	170 kVAr
Active power loss	21.5911 kW	19.8328 kW
Reactive power loss	14.3730 kVAr	10.014 kVAr
% loss reduction of active and reactive power	-	8.14% & 30.42%

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Summary

Development of firefly based algorithm with voltage stability index has been presented to reduce the losses and increase the loadability of an unbalanced three-phase network. In the work, problem associated with three-phase network was stated, fundamental concept and literature on similar work were reviewed. Material and methods used in achieving the research work were presented and also results obtained were discussed. Conclusion drawn were presented, limitation and recommendation for further work were also presented.

5.2 Conclusion

This research work presents a development of Firefly algorithm based method for optimal planning of DG in an Unbalanced three-phase distribution network using voltage stability index. The VSI is used to determine the DG location while the FA is used for the DG sizing. A three-phase power flow is carrying out to determine the initial steady state operating condition of the network. Two test system are used in implementing the work, the standard IEEE 37-bus URDN and a local 19-bus Mahuta feeder. The developed method is validated using a paper presented by Othman *et al.*, (2016) and is done on the standard IEEE 37-bus test system.

For the standard IEEE 37-bus URDN, the total power loss obtained is 31.3543 kW and 15.2829 kVAr for active and reactive power respectively without DG in the network. When the developed method is applied, a DG optimal location is found at bus 34 and a DG size of 356 kW and 170 kVAr for active and reactive are obtained respectively. The active and reactive power loss obtained when DG was placed in the network are 19.8329 kW and 10.0014 kVAr respectively,. The developed method recorded a loss reduction of 36.75% and 34.56% for both active and reactive power respectively over the base case. Also, the maximum loadability of the network are determined. It is discovered that the network can only carry additional 8% of the initial loading without DG and 18% of the load when DG was incorporated without violating the network constrainst (such as line and voltage limit).

For the 19-bus Mahuta feeder, the location found for the DG is bus 17 and the DG size of 201.58 kW and 115 kVAr are obtained for active and reactive power respectively. A power loss reduction of 4.48% and 5.62% for active and reactive power are recorded over the base case respectively. The maximum loadability of the network are found to be 2.19 (119%) over the initial loading of the network for both the developed method and the base case.

For the validation with the work of Othman *et al.,* (2016), DG size of 356 kW and 170 kVAr for active and reactive power is obtained as against the 1502.25 kW and 730 kVAr obtained by Othman *et al*., (2016) respectively. A loss reduction of 8.14% and 30.42% for active and reactive power are recorded when compared to the work of Othman *et al*., (2016). However, Othman *et al.,*had a better voltage profile when compared to the optimised method due to the large size of DG used but the optimized method voltage profile is still within the voltage limit. From the results obtained, it is evident that the developed method has a better performance in term of power loss reduction over the work of Othman *et al*., (2016).

5.3 Significant Contribution

The significant contributions of this research work are as follows:

1. Development of firefly algorithm based method for Distributed generation planning in an unbalanced three-phase distribution network.
2. The optimized method achieved a loss reduction of 36.75% and 34.56% for active and reactive power respectively over the based case and loadability improvement of 9.26% for the 37-Bus unbalanced distribution network.
3. The developed method achieved a percentage loss reduction of 4.48% and 5.52% for active and reactive power over the base case for the 19-Bus Mahuta feeder.

5.4 Limitations

The aim of this research work is successfully achieved, but some of the limitations of this research work are highlighted as follows:

1. Only steady state analysis of the network are considered.
2. Insufficient data for the Ungwan Boro distribution network.

5.5 Recommendations

This dissertation work can be further extended to the following areas of research:

1. A load balancing control technique can be developed to control (monitor) the overloading of a particular phase.
2. Distribution network transformer can be model and incorporated into the unbalanced three-phase network when modelling the system.

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APPENDIX A

IEEE 37-Bus URDN Paramaters and power flow results

Table A1: Line data of IEEE 37-node feeder (Kersting, 2001)

S/N	Sending End	Receiving End	Length (km)	Phase code
1	0	1	0.564	321
2	1	2	0.293	322
3	2	3	0.122	325
4	3	4	0.073	325
5	3	5	0.098	325
6	2	6	0.11	323
7	6	7	0.158	323
8	7	8	0.024	325
9	8	9	0.158	325
10	7	10	0.243	323
11	10	11	0.183	323
12	11	12	0.085	325
13	10	13	0.293	325
14	13	14	0.037	325
15	13	15	0.232	325
16	2	16	0.402	322
17	16	17	0.073	325
18	17	18	0.085	325
19	18	19	0.061	325
20	18	20	0.085	325
21	16	21	0.183	323
22	21	22	0.061	323
23	22	23	0.183	323
24	22	24	0.00031	10

S/N	Sending End	Receiving End	Length (km)	Phase code
25	22	25	0.098	323
26	25	26	0.098	325
27	25	27	0.098	323
28	27	28	0.171	323
29	28	29	0.158	325
30	29	30	0.391	325
31	29	31	0.061	325
32	28	32	0.195	323
33	32	33	0.122	323
34	33	34	0.122	323
35	34	35	0.061	325
36	34	36	0.122	323

Table A2: Bus data of IEEE 37-node feeder (Kersting, 2001)

		Phase A		Phase B		Phase C	
Bus Code	Load model	kW	kVar	kW	kVar	kW	kVar
1	D-PQ	140.47	69.74	140.47	69.74	350.75	174.15
4	D-PQ	0	0	0	0	84.11	41.76
5	D-Z	8.41	4.18	84.11	41.76	0	0
6	D-PQ	0	0	0	0	84.11	41.76
8	D-I	16.82	8.35	21.03	10.44	0	0
9	D-Z	84.11	41.76	0	0	0	0
10	D-PQ	0	0	0	0	84.11	41.76
12	D-PQ	0	0	42.06	20.88	0	0
14	D-I	0	0	140.47	69.74	21.03	10.44
15	D-Z	0	0	42.06	20.88	0	0
17	D-PQ	0	0	0	0	42.06	20.88
18	D-PQ	42.06	20.88	0	0	0	0
19	D-PQ	42.06	20.88	42.06	20.88	42.06	20.88
20	D-I	42.06	20.88	0	0	0	0
21	D-Z	0	0	0	0	84.11	41.76
23	D-Z	0	0	84.11	41.76	0	0
26	D-PQ	0	0	0	0	42.06	20.88
27	D-I	84.11	41.76	0	0	0	0
28	D-PQ	0	0	0	0	42.06	20.88
30	D-PQ	0	0	42.06	20.88	0	0
31	D-PQ	0	0	0	0	84.11	41.76
32	D-Z	140.47	69.74	0	0	0	0
33	D-PQ	126.7	62.64	0	0	0	0
35	D-PQ	0	0	0	0	84.11	41.76
36	D-I	0	0	0	0	42.06	20.88
Total		726.74	360.81	638.43	316.96	1086.74	539.55

Phase impedance matrices of IEEE 37-node feeder (Kersting, 2001)

Configuration 321

Z (R +jX) in ohms per kilo-meter

0.1818	0.1226	0.0418	-0.0229	0.0209	-0.0259
		0.1644	0.1181	0.0418	-0.0229
				0.1818	0.1226

Configuration 322

Z (R +jX) in ohms per kilo-meter

0.2952	0.1847	0.1012	-0.0203	0.0767	-0.0377
		0.2789	0.1664	0.1012	-0.0203
				0.2952	0.1847

Configuration 323

Z (R +jX) in ohms per kilo-meter

0.8038	0.4171	0.3027	0.1312	0.2849	0.0945
		0.8092	0.3931	0.3027	0.1312
				0.8038	0.4171

Configuration 324

Z (R +jX) in ohms per kilo-meter

1.3019	0.4821	0.3234	0.1701	0.3061	0.1319
		1.3091	0.4597	0.3234	0.1701
				1.3019	0.4821

Table A3: Base Case Power flow for IEEE 37-Bus Unbalanced Radial Distribution Network

Bus No.	Phase A		Phase B		Phase C	
	Voltage Mag.(p.u)	Phase angle(deg.)	Voltage mag.(p.u)	Phase angle(deg.)	Voltage mag.(p.u)	Phase angle(deg.)
1	1.0000	0.000	1.0000	-120.0000	1.0000	120.0000
2	0.9884	-0.0889	0.9908	-120.0863	0.9827	119.8677
3	0.9807	-0.1342	0.9847	-120.1137	0.9729	119.8106
4	0.9696	-0.0661	0.9788	-120.0713	0.9599	119.8921
5	0.9672	-0.0509	0.9780	-120.0654	0.9566	119.9134
6	0.9640	-0.0309	0.9752	-120.0448	0.9569	119.9111
7	0.9796	-0.1353	0.9819	-120.1123	0.9710	119.8086
8	0.9696	-0.0661	0.9788	-120.0713	0.9591	119.8913
9	0.9671	-0.0504	0.9777	-120.0635	0.9562	119.9157
10	0.9576	0.0098	0.9752	-120.0448	0.9557	119.9188
11	0.9636	-0.0551	0.9780	-120.0654	0.9541	119.9108
12	0.9640	-0.0309	0.9752	-120.0448	0.9551	119.9092
13	0.9796	-0.1353	0.9813	-120.1077	0.9710	119.8086
14	0.9640	-0.0309	0.9752	-120.0448	0.9569	119.9111
15	0.9796	-0.1353	0.9810	-120.1057	0.9709	119.8095
16	0.9796	-0.1353	0.9802	-120.0999	0.9710	119.8086
17	0.9807	-0.1342	0.9847	-120.1137	0.9729	119.8106
18	0.9696	-0.0661	0.9788	-120.0713	0.9593	119.8957
19	0.9666	-0.0468	0.9780	-120.0654	0.9566	119.9134

Bus No.	Phase A		Phase B		Phase C	
	Voltage Mag.(p.u)	Phase angle(deg.)	Voltage mag.(p.u)	Phase angle(deg.)	Voltage mag.(p.u)	Phase angle(deg.)
20	0.9636	-0.0280	0.9747	-120.0415	0.9564	119.9141
21	0.9634	-0.0268	0.9752	-120.0448	0.9569	119.9111
22	0.9696	-0.0661	0.9788	-120.0713	0.9581	119.8902
23	0.9672	-0.0509	0.9780	-120.0654	0.9566	119.9134
24	0.9640	-0.0309	0.9734	-120.0439	0.9569	119.9111
25	0.9640	-0.0309	0.9752	-120.0448	0.9569	119.9111
26	0.9640	-0.0309	0.9752	-120.0448	0.9569	119.9111
27	0.9796	-0.1353	0.9819	-120.1123	0.9703	119.8132
28	0.9787	-0.1363	0.9819	-120.1123	0.9710	119.8086
29	0.9696	-0.0661	0.9788	-120.0713	0.9583	119.8904
30	0.9671	-0.0504	0.9777	-120.0635	0.9562	119.9157
31	0.9576	0.0098	0.9752	-120.0448	0.9557	119.9188
32	0.9671	-0.0504	0.9773	-120.0602	0.9553	119.9217
33	0.9543	0.0063	0.9752	-120.0448	0.9557	119.9188
34	0.9618	-0.0572	0.9780	-120.0654	0.9541	119.9108
35	0.9640	-0.0309	0.9752	-120.0448	0.9551	119.9092
36	0.9640	-0.0309	0.9752	-120.0448	0.9541	119.9151
37	0.9576	0.0098	0.9752	-120.0448	0.9551	119.9182

Table A4: IEEE 37-Bus Unbalanced Radial Distribution Network power flow with DG.

Bus NO.	Phase A		Phase B		Phase C	
	Voltage Mag.(p.u)	Phase angle(deg.)	Voltage Mag.(p.u)	Phase angle(deg.)	Voltage Mag.(p.u)	Phase angle(deg.)
1	1.0000	0.0000	1.0000	-120.0000	1.0000	120.0000
2	0.9952	-0.4685	0.9966	-120.3624	0.9920	119.2159
3	0.9921	-0.7613	0.9942	-120.5696	0.9875	118.7980
4	0.9865	-1.1034	0.9901	-120.8117	0.9799	118.3341
5	0.9860	-1.1366	0.9895	-120.8452	0.9784	118.2401
6	0.9827	-1.3361	0.9876	-120.9622	0.9779	118.2091
7	0.9914	-0.8107	0.9936	-120.6170	0.9863	118.7107
8	0.9865	-1.1034	0.9901	-120.8117	0.9795	118.2977
9	0.9859	-1.1396	0.9894	-120.8563	0.9782	118.2248
10	0.9783	-1.6039	0.9876	-120.9622	0.9771	118.1585
11	0.9861	-1.1385	0.9895	-120.8452	0.9785	118.2384
12	0.9827	-1.3361	0.9876	-120.9622	0.9768	118.1244
13	0.9914	-0.8107	0.9932	-120.6429	0.9863	118.7107
14	0.9827	-1.3361	0.9876	-120.9622	0.9779	118.2091
15	0.9914	-0.8107	0.9936	-120.6167	0.9863	118.7048
16	0.9914	-0.8107	0.9924	-120.6877	0.9863	118.7107
17	0.9921	-0.7613	0.9942	-120.5696	0.9875	118.7980
18	0.9865	-1.1034	0.9901	-120.8117	0.9795	118.3109
19	0.9856	-1.1633	0.9895	-120.8452	0.9784	118.2401

Bus NO.	Phase A		Phase B		Phase C	
	Voltage Mag.(p.u)	Phase angle(deg.)	Voltage Mag.(p.u)	Phase angle(deg.)	Voltage Mag.(p.u)	Phase angle(deg.)
20	0.9824	-1.3554	0.9873	-120.9810	0.9776	118.1896
21	0.9822	-1.3630	0.9876	-120.9622	0.9779	118.2091
22	0.9865	-1.1034	0.9901	-120.8117	0.9789	118.2498
23	0.9860	-1.1366	0.9895	-120.8452	0.9784	118.2401
24	0.9827	-1.3361	0.9865	-120.0431	0.9779	118.2091
25	0.9827	-1.3361	0.9876	-120.9622	0.9779	118.2091
26	0.9827	-1.3361	0.9876	-120.9622	0.9779	118.2091
27	0.9914	-0.8107	0.9936	-120.6170	0.9858	118.6799
28	0.9909	-0.8548	0.9936	-120.6170	0.9863	118.7107
29	0.9865	-1.1034	0.9901	-120.8117	0.9790	118.2583
30	0.9859	-1.1396	0.9894	-120.8563	0.9782	118.2248
31	0.9783	-1.6039	0.9876	-120.9622	0.9771	118.1585
32	0.9859	-1.1396	0.9890	-120.8750	0.9775	118.1858
33	0.9764	-1.7545	0.9876	-120.9622	0.9771	118.1585
34	0.9861	-1.1394	0.9895	-120.8452	0.9785	118.2384
35	0.9827	-1.3361	0.9876	-120.9622	0.9768	118.1244
36	0.9827	-1.3361	0.9876	-120.9622	0.9762	118.0853
37	0.9783	-1.6039	0.9876	-120.9622	0.9767	118.1303

Appendix B

19-Bus Mahuta Feeder Distribution Network Parameters

Table B1: 19-node Mahuta feeder line data

Line number	Substation	Sending end	Receiving end	Length (km)	Cross section area (mm^2)
1	Injection substation				
2	Boro II	1	2	1.71	150
3	Nasarawa	2	3	6.23	150
4	Boro III	2	4	0.497	150
5	Boro V	4	5	0.973	150
6	Janruwa	5	6	0.94	150
7	Kaladu	6	7	1.196	100
8	Boro IV	4	8	1.085	150
9	Mozen	8	9	1.564	150
10	Kamazou GRA	9	10	2.116	150
11	Abyelo	9	11	1.748	100
12	Baba Limi	8	12	2.07	150
13	Before our lady of Fatima	12	13	2.397	100
14	Our ladies of Fatima	13	14	2.484	150
15	Our lady School	12	15	2.576	100
16	Auditor	15	16	2.97	100
17	Tsaunin Kura II	16	17	3.49	150
18	Tsaunin Kura I	17	18	3.87	150
19	Wilson colledge	18	19	4.905	100

Table B2: 19-node Mahuta feeder Bus data

Line section number	Name of Distribution substation	Transformer Rating (kVA)	Active Power P (kW)			Reactive Power Q (kVAr)		
			Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
1	Injection substation							
2	Boro II	500	125.12	137.39	107.04	72.24	79.32	61.8
3	Nasarawa	100	0	0	0	0	0	0
4	Boro III	500	89.17	102.88	77.73	51.48	59.4	44.88
5	Boro V	500	126.37	108.08	141.54	72.96	62.4	81.72
6	Janruwa	500	85.01	80.85	65.68	49.08	46.68	37.92
7	Kaladu	300	22.66	23.9	19.75	13.08	13.8	11.4
8	Boro IV	500	132.19	125.75	108.08	76.32	72.6	62.4
9	Mozen	500	61.73	73.37	74.41	35.64	42.36	42.96
10	Kamazou GRA	500	64.22	64.85	59.24	37.08	37.44	34.2
11	Abyelo	300	57.99	66.72	62.15	33.48	38.52	35.88
12	Baba Limi	300	83.14	55.91	75.24	48	32.28	43.44
13	Before our lady of Fatima	100	0	0	0	0	0	0
14	Our ladies of Fatima	500	93.95	63.81	72.33	54.24	36.84	41.76
15	Our lady School	300	31.8	36.37	30.14	18.36	21	17.4
16	Auditor	300	30.76	34.5	29.51	17.76	19.92	17.04
17	Tsaunin Kura II	500	67.13	82.72	46.14	38.76	47.76	26.64
18	Tsaunin Kura I	500	71.71	68.8	49.88	41.4	39.72	28.8
19	Wilson college	500	101.84	92.08	62.77	58.8	53.16	36.24
	TOTAL		1244.79	1217.98	1081.63	718.68	703.2	674.34

Table B3: Base Case Power Flow for the 19-Bus Mahuta Distribution Network Feeder

Bus No.	Phase A		Phase B		Phase C	
	Voltage Mag.(p.u)	Phase angle(deg.)	Voltage Mag.(p.u)	Phase angle(deg.)	Voltage Mag.(p.u)	Phase angle(deg.)
1	1.0000	0.0000	1.0000	-120.0000	1.0000	120.00
2	0.9993	-0.0068	0.9993	-120.0066	0.9994	119.9941
3	0.9971	-0.0291	0.9972	-120.0282	0.9974	119.9747
4	0.9969	-0.0313	0.9970	-120.0303	0.9973	119.9728
5	0.9966	-0.0339	0.9967	-120.0327	0.9971	119.9705
6	0.9965	-0.0354	0.9966	-120.0341	0.9969	119.9693
7	0.9964	-0.0364	0.996	-120.0349	0.9969	119.9684
8	0.9968	-0.0320	0.9969	-120.0310	0.9972	119.9722
9	0.9966	-0.0346	0.9967	-120.0334	0.9970	119.9698
10	0.9964	-0.0365	0.9965	-120.0352	0.9969	119.9684
11	0.9964	-0.0359	0.9965	-120.0347	0.9969	119.9686
12	0.9966	-0.0344	0.9967	-120.0331	0.9970	119.9700
13	0.9965	-0.0354	0.9966	-120.0341	0.9969	119.9692
14	0.9963	-0.0371	0.9965	-120.0354	0.9968	119.9679
15	0.9964	-0.0358	0.9966	-120.0346	0.9969	119.9688
16	0.9964	-0.0369	0.9965	-120.0355	0.9968	119.9679
17	0.9963	-0.0175	0.9964	-120.0131	0.9969	119.9822
18	0.9965	-0.0354	0.9966	-120.0343	0.9969	119.9692
19	0.9962	-0.0393	0.9963	-120.0377	0.9967	119.9667

Table B4: Power Flow Results for 19-Bus Mahuta Distribution Network Feeder with DG

Bus	Phase A		Phase B		Phase C	
No.	Voltage Mag.(p.u)	Phase angle(deg.)	Voltage Mag.(p.u)	Phase angle(deg.)	Voltage Mag.(p.u)	Phase angle(deg.)
1	1.0000	0.0000	1.0000	-120.0000	1.0000	120.0000
2	0.9998	-0.0353	0.9998	-120.0341	0.9998	119.9688
3	0.9990	-0.1502	0.9991	-120.1433	0.9991	119.8670
4	0.9990	-0.1590	0.9990	-120.1517	0.9991	119.8592
5	0.9989	-0.1732	0.9990	-120.1649	0.9990	119.8465
6	0.9988	-0.1813	0.9989	-120.1726	0.9990	119.8398
7	0.9988	-0.1861	0.9989	-120.1765	0.9990	119.8358
8	0.9990	-0.1614	0.9990	-120.1541	0.9991	119.8571
9	0.9989	-0.1769	0.9990	-120.1688	0.9990	119.8430
10	0.9988	-0.1875	0.9989	-120.1784	0.9990	119.8353
11	0.9988	-0.1841	0.9989	-120.1757	0.9990	119.8368
12	0.9989	-0.1763	0.9989	-120.1669	0.9990	119.8437
13	0.9988	-0.1813	0.9989	-120.1726	0.9990	119.8398
14	0.9988	-0.1902	0.9988	-120.1793	0.9989	119.8327
15	0.9988	-0.1836	0.9989	-120.1751	0.9990	119.8377
16	0.9988	-0.1886	0.9989	-120.1793	0.9989	119.8335
17	0.9990	-0.1607	0.9990	-120.1531	0.9991	119.8564
18	0.9988	-0.1818	0.9989	-120.1735	0.9990	119.8396
19	0.9987	-0.2011	0.9988	-120.1907	0.9989	119.8269

Appendix C1

m-file: Matlab Code for the Developed Method

```
function  [DG_Location, Loss_with_DG]=FFA(~)
clear all;
clc;
format short;
warning('off');

% V_base=12.66e3;
S_base=10e6;
%loca=VSI_bus_loca
len_loca=length(loca);
ll=len_loca;
n=37;
    llline_imp_3ph=line_imp_3ph;
        line_a=(llline_imp_3ph(:,1:(n-1)));
        line_b=llline_imp_3ph(:,n:(2*n-2));
        line_c=llline_imp_3ph(:,(2*n-1):((n-1)*3));

    load=load_power_3ph;
    load_power=1e3*load;
    S_Demand=load_power/S_base;
    S_Demand=((transpose(S_Demand)));

        load_a=S_Demand(1,:);
        load_b=S_Demand(2,:);
        load_c=S_Demand(3,:);

%%%%%%%%%%%%%%%   Base CAse Power Flow   %%%%%%%%%%%%%%%%%
[P_LOSS_a,Vi_a, Q_LOSS_a ]=JAHFLOW1(line_a, load_a);
[P_LOSS_b,Vi_b, Q_LOSS_b ]=JAHFLOW1(line_b, load_b);
[P_LOSS_c,Vi_c, Q_LOSS_c ]=JAHFLOW1(line_c, load_c);

    P_LOSS_a=P_LOSS_a*1e4
    Q_LOSS_a=Q_LOSS_a*1e4
    Vi_ma=abs(Vi_a)
    Vi_aa=(angle(Vi_a)*180/pi)

    P_LOSS_b=P_LOSS_b*1e4
    Q_LOSS_b=Q_LOSS_b*1e4
    Vi_mb=abs(Vi_b)
    Vi_ab=(angle(Vi_b)*180/pi)-120

    P_LOSS_c=P_LOSS_c*1e4
    Q_LOSS_c=Q_LOSS_c*1e4
    Vi_mc=abs(Vi_c)
    Vi_ac=(angle(Vi_c)*180/pi)+120

%%%%%%%%%%%%%%  loadability base case  %%%%%%%%%%%%%%
line_abc=llline_imp_3ph;
load_abc=S_Demand;
```

```
max_load_factor_BC=loadability(line_abc,load_abc,0,1,0,1,0,1)

%%%%%%%%%%%%%%   firefly parameters    %%%%%%%%%%%%%%%
nb=n;
maxGen=20;
alpha=0.25;
Beta0=0.20;
gamma=1;
delta=0.97;
N=nb;

%%%%%%%%%%%%%    Parameters initialisation   %%%%%%%%%
FIREFLY=0;
if FIREFLY==0
    popa=rand (N,1);
%     popb=rand (N,1);
%         popb=popb*1i;
%     pop=popa+popb;
    pop=popa;%*1i;

else
    pop=FIREFLY;
end
popi=(1e5*pop)/1e6;

        PP_LOSS_MEM=zeros(N,ll);
        QQ_LOSS_MEM=zeros(N,ll);
        VVi_MEM=ones(nb*ll,N);
        SS_DG_x_MEM=zeros(N,ll);

 for df=1:ll
     ol=loca(df);                    % 3ph DG loca from VSI

     if df==1                        % 3ph line para
        line=line_a;
    elseif df==2
        line=line_b;
    elseif df==3
        line=line_c;
     end

     if df==1                        % 3ph load para
        new_load_power=load_a;
    elseif df==2
        new_load_power=load_b;
    elseif df==3
        new_load_power=load_c;
    end

    P_LOSS_MEM=zeros(N,1);
    Q_LOSS_MEM=zeros(N,1);
    Vi_MEM=zeros(nb,N);
    S_DG_x_MEM=zeros(N,1);

 for ii=1:maxGen
```

```
    for bus=1:N
        S_DG=zeros(size(S_Demand(1,:)));
        S_DG(ol)=popi(bus);

        S_D=(S_Demand(df,:))-S_DG;
        size(S_D);%69x1

        new_load_power=(conj(S_D));
        %new_load_power=transpose(new_load_power);
        size(new_load_power); % 1X69
        [P_LOSS,Vi, Q_LOSS ]=JAHFLOW1(line, new_load_power);

        S_DG_x=S_DG(ol);
        S_S_DG=zeros(N,1);
        S_S_DG(bus)=S_DG_x;
        S_S_DG=S_DG_x_MEM+S_S_DG;
        S_DG_x_MEM=S_S_DG;

        S_P_LOSS=zeros(N,1);
        S_P_LOSS(bus)=P_LOSS;
        S_P_LOSS=P_LOSS_MEM+S_P_LOSS;
        P_LOSS_MEM=S_P_LOSS;

        S_Q_LOSS=zeros(N,1);
        S_Q_LOSS(bus)=Q_LOSS;
        S_Q_LOSS=Q_LOSS_MEM+S_Q_LOSS;
        Q_LOSS_MEM=S_Q_LOSS;

        vvv=ones(nb,1);
        vvv(2:end)=Vi;
        S_Vi=zeros(nb,N);
        S_Vi(:,bus)=vvv;
        S_Vi=Vi_MEM+S_Vi;
        Vi_MEM=S_Vi;

    end
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%    Results of popi iterative
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    S_DG_x_MEM;
    Ii=P_LOSS_MEM;
    abs(Vi_MEM);
  %%
   % Ranking the fireflies by their light intensity
        [Lightn,Index]=sort(Ii);
        popi=popi(Index);
        popj=popi;
        Lighto=Lightn;

       % Updating fireflies
            for i=1:N,
                   % The attractiveness parameter beta=exp(-gamma*r)
               for j=1:N,
                  r=sqrt(sum((popi(i)-popj(j)).^2));
                  % Update moves
```

```
                    if (abs(real (Lightn(i))))>(abs(real (Lighto(j)))) %
Brighter and more attractive
                       beta=Beta0*exp(-gamma*r.^2);
                       popi(i)=popi(i).*(1-beta)+popj(j).*beta
+((alpha.*(rand-0.5)));%*1i);
%                      popj(i)=popj(i).*(1-beta)+popj(j).*beta+alpha.*(rand-
0.5);
                  end
               end % end for j

            end % end for i

        % Reduce randomness as iterations proceed
           alpha=newalpha(alpha,delta);
        % New popi after move per iteration
           popi;

        P_LOSS_MEM=zeros(N,1);
        Q_LOSS_MEM=zeros(N,1);
        Vi_MEM=zeros(nb,N);
        S_DG_x_MEM=zeros(N,1);

        for bus=1:N
            S_DG=zeros(size(S_Demand(1,:)));
            S_DG(ol)=popi(bus);

            S_D=(S_Demand(df,:))-S_DG;
            size(S_D);%69x1

            new_load_power=(conj(S_D));
            %new_load_power=transpose(new_load_power);
            size(new_load_power); % 1X69
            [P_LOSS,Vi,Q_LOSS_a ]=JAHFLOW1(line, new_load_power);

            S_DG_x=S_DG(ol);
            S_S_DG=zeros(N,1);
            S_S_DG(bus)=S_DG_x;
            S_S_DG=S_DG_x_MEM+S_S_DG;
            S_DG_x_MEM=S_S_DG;

            S_P_LOSS=zeros(N,1);
            S_P_LOSS(bus)=P_LOSS;
            S_P_LOSS=P_LOSS_MEM+S_P_LOSS;
            P_LOSS_MEM=S_P_LOSS;

            S_Q_LOSS=zeros(N,1);
            S_Q_LOSS(bus)=Q_LOSS;
            S_Q_LOSS=Q_LOSS_MEM+S_Q_LOSS;
            Q_LOSS_MEM=S_Q_LOSS;

            vvv=ones(nb,1);
            vvv(2:end)=Vi;
            S_Vi=zeros(nb,N);
            S_Vi(:,bus)=vvv;
            S_Vi=Vi_MEM+S_Vi;
```

```
            Vi_MEM=S_Vi;

                end

 end
    S_DG_x_MEM;
    P_LOSS_MEM;
    Q_LOSS_MEM;
    Vv=(Vi_MEM);

    SS_DG_x_MEM(:,df)=S_DG_x_MEM;
    PP_LOSS_MEM(:,df)=P_LOSS_MEM;
    QQ_LOSS_MEM(:,df)=Q_LOSS_MEM;

    if df==1
        VVi_MEM(1:n,:)=Vv;
    elseif df==2
        VVi_MEM((n+1):(2*n),:)=Vv;
    elseif df==3
        VVi_MEM((2*n+1):(n*3),:)=Vv;
    end
    VVi_MEM;

 end

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%    Results of popi fitness
after move   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    popi=SS_DG_x_MEM;
    DG_S=popi;
    PLOSS=PP_LOSS_MEM;
    QLOSS=QQ_LOSS_MEM;
    VVi_MEM;

    sz_loss=size(PLOSS);

    %%%%%%%%%%%%   opt loca   %%%%%%%%%%%%%
    Min_P_Loss=zeros(1,ll);
    min_PLloc=zeros(1,ll);
    best_Vi=ones(nb,ll);

    for bn=1:ll
        for j=1:sz_loss(1)
            if real(PLOSS(j,bn))==min(real(PLOSS(:,bn)))
                Min_P_Loss(bn)=PLOSS(j,bn);
                Min_Q_Loss(bn)=QLOSS(j,bn);
                min_PLloc(bn)=j;

                        if bn==1
                            Vv=VVi_MEM(1:n,:);
                            elseif bn==2
                                Vv=VVi_MEM((n+1):(2*n),:);
                            elseif bn==3
                                Vv=VVi_MEM((2*n+1):(n*3),:);
                        end
```

```
                        S_Vvm=zeros(1,N);
                        for kl=1:sz_loss(1)
                            S_Vvm(kl)=min(Vv(:,kl));
                        end
                            [mx_SVvm, idx]=max(S_Vvm);

                        if bn==1
                            best_VVi=VVi_MEM(1:n,:);
                            elseif bn==2
                                best_VVi=VVi_MEM((n+1):(2*n),:);
                            elseif bn==3
                                best_VVi=VVi_MEM((2*n+1):(n*3),:);
                        end
                 best_Vi(:,bn)=best_VVi(:,idx);
            end
        end
    end
    Min_P_Loss;
    Min_Q_Loss;
    minn_PLloc=min_PLloc;
    best_Vi;

%%%%%%%%%%%%%  Phase A  %%%%%%%%%%%%%%
figure
DG_Size=DG_S(:,1);
    min_PLloc=minn_PLloc(1);
OPT_DG_Size_a=DG_Size(min_PLloc)
DG_Location_a=loca(1)
PLoss_with_DG_a=Min_P_Loss(1)*1e4
QLoss_with_DG_a=Min_Q_Loss(1)*1e4
Va_DG=best_Vi(:,1);
    Vma_DG=abs(Va_DG)
        Vaa_DG=(angle(Va_DG)*180/pi)
Q=1:length (PLOSS(:,1));
plot(Q,real (PLOSS(:,1)));
title('THE POWER LOSS TREND Vs FF GENERATORS');
xlabel ('GENERATION');
ylabel ('TOTAL REAL POWER LOSS');

%%%%%%%%%%%%%  Phase B  %%%%%%%%%%%%%%
figure
DG_Size=DG_S(:,2);
    min_PLloc=minn_PLloc(2);
OPT_DG_Size_b=DG_Size(min_PLloc)
DG_Location_b=loca(2)
PLoss_with_DG_b=Min_P_Loss(2)*1e4
QLoss_with_DG_b=Min_Q_Loss(2)*1e4
Vb_DG=best_Vi(:,2);
    Vmb_DG=abs(Vb_DG)
        Vab_DG=(angle(Vb_DG)*180/pi)-120
Q=1:length (PLOSS(:,2));
plot(Q,real (PLOSS(:,2)));
title('THE POWER LOSS TREND Vs FF GENERATORS');
xlabel ('GENERATION');
ylabel ('TOTAL REAL POWER LOSS');
```

```
%%%%%%%%%%%%%  Phase C  %%%%%%%%%%%%%%
figure
DG_Size=DG_S(:,3);
    min_PLloc=minn_PLloc(3);
OPT_DG_Size_c=DG_Size(min_PLloc)
DG_Location_c=loca(3)
PLoss_with_DG_c=Min_P_Loss(3)*1e4
QLoss_with_DG_c=Min_Q_Loss(3)*1e4
Vc_DG=best_Vi(:,3);
    Vmc_DG=abs(Vc_DG)
        Vac_DG=(angle(Vc_DG)*180/pi)+120
Q=1:length (PLOSS(:,3));
plot(Q,real (PLOSS(:,3)));
title('THE POWER LOSS TREND Vs FF GENERATORS');
xlabel ('GENERATION');
ylabel ('TOTAL REAL POWER LOSS');

%%%%%%%%%%%%%%  loadability DG case  %%%%%%%%%%%%%%
line_abc=llline_imp_3ph;
load_abc=S_Demand;
DG_a=OPT_DG_Size_a;
    DGL_a=DG_Location_a;
DG_b=OPT_DG_Size_b;
    DGL_b=DG_Location_b;
DG_c=OPT_DG_Size_c;
    DGL_c=DG_Location_c;
max_load_factor_DG=loadability(line_abc,load_abc,DG_a,DGL_a, DG_b,DGL_b,DG_c,
DGL_c)
end

%Reduce the randomness during iterations
            function [alpha]=newalpha(alpha,delta)
            alpha=alpha*delta;
            end
```

Appendix C2

m-file: Matlab Code for the Optimal DG Location

```
function  [opt_loca]=VSI_bus_loca(~)
% clear all;
% clc;

% n=37;
% NLB=0.00001;  % magnitude for no load bus to use for VSI
% lload_power_3ph=load_power_3ph;
% sz_ldpow=size(lload_power_3ph);
% no_ph=sz_ldpow(2);
%
%%%%%%%%%%%%%%%%%%%%% VSM %%%%%%%%%%%%%%%%%%%%%%%%
lload_power_3ph=load_power_3ph;
sz_ldpow=size(lload_power_3ph);
no_ph=sz_ldpow(2);

opt_loca=zeros(no_ph,1);
VSM_3PH=zeros(n,no_ph);
for iw=1:no_ph
%%%%%%%%%%%%%%%  Parameter for VSM  %%%%%%%%%%%%%%%%%%%%%%
T_Load=lload_power_3ph(:,iw);
load_power=1e3*T_Load;
V_base=4.8e3;
% V_base=11e3;
S_base=10e6;
S_Demand=load_power/S_base;
S_Demand=transpose(S_Demand);
size(S_Demand); % 37x1

lline_imp_3ph=line_imp_3ph;
if iw==1
    line=lline_imp_3ph(:,1:(n-1));
elseif iw==2
    line=lline_imp_3ph(:,n:(2*n-2));
elseif iw==3
    line=lline_imp_3ph(:,(2*n-1):((n-1)*3));
end

sz_line=size(line);
len_line_col=sz_line(2);
llc=len_line_col;

% lline=zeros(1,llc);
% for ie=1:llc
%     lline(ie)=sum(line(:,ie));
% end
% X=imag(lline);
%%%%%%%%%%%% base case result %%%%%%%%%%%%%
[BIBC, Ii, Vi, load_power]=JAHFLOW2(line, S_Demand);
%%%%%%%  P&Q transfer through each branch   %%%%%%%%%%%%%
```

```
Ii;
size(Ii);
size(load_power);
load_power=transpose(load_power);
Branch_current=BIBC*Ii;
s_BR_CU=size(Branch_current);
%Apparent_power_transfer=Vi.*Branch_current;
Apparent_power_transfer=Vi.*Ii;
%%%%%%%%%%%%%%%    Full V with slack bus   %%%%%%%%%%%%%
Vi;
Vii=ones(length(Vi)+1,1);
Vii(2:end)=Vi;
Vi=Vii;

% Apparent_power_transfer=BIBC*load_power
real_APT=real(Apparent_power_transfer);
imag_APT=imag(Apparent_power_transfer);
rA=real_APT;
iA=imag_APT;
NLB=1e-6;

%%%%%%%%%%%%%%%    linedata     %%%%%%%%%%%%%%%%%%%%%%%%%
R=real(linedata(:,iw));
X=imag(linedata(:,iw));

%%%%%%%%%%%%%%%    VSM          %%%%%%%%%%%%%%%%%%%%%%%%%
VSM=ones(length(Vi), 1);
for i=2:length(R)+1
    a=(Vi(i-1)^4);
    b=4*(rA(i-1)*X(i-1)+iA(i-1)*R(i-1))^2;
    c=4*(((Vi(i-1))^2)*(rA(i-1)*R(i-1)+iA(i-1)*X(i-1)));
    VSM(i)=a-b-c;
end
VSM;

    %%%%%%%%%%%%    VSM with BUS NO   %%%%%%%%%%%%%%%
    S_bus_mem=zeros(size(VSM));
    for r=1:length(VSM)
        bus=r;
        S_bus=zeros(size(VSM));
        S_bus(r)=bus;
        S_bus=S_bus_mem+S_bus;
        S_bus_mem=S_bus;
    end
    VSM_NO=S_bus_mem;
    VSM_with_VSM_NO=[VSM VSM_NO];

    %%%%%%%%%%%%    VSM RANK    %%%%%%%%%%%%%%%%%%
    [VSM_R, index]=sort(VSM,1,'descend');
     VSM_RANK=[VSM_R index VSM_NO];
    %%%%%%%%%%%%    OPTIMAL LOCATION   %%%%%%%%%%%%%%%%%
for j=1:length(VSM)
    if (VSM(j))==min(VSM(:,1))
        Min_VSM=VSM(j);
        opt_loc_VSM=j;
    end
```

```
end
Min_VSM;
opt_loc_VSM;
opt_loca(iw)=opt_loc_VSM;

VSM_3PH(:,iw)=VSM;
end

Q=1:length(VSM);
% plot(Q,VSM_3PH(:,1),'r+-', Q,VSM_3PH(:,2),'g*-', Q,VSM_3PH(:,3),'bd-'),grid
ON;
plot(Q,VSM_3PH(:,1),'g+-','LineWidth',2 ),grid ON;
%legend('ph_A','ph_B','ph_C');
%legend('3PHASE');
%bar_VSM=bar(Q, VSM);
title('VSI PROFILE');
axis([0 n+3 0.95 1.01]);
xlabel('BUS NUMBER');
ylabel('VSI');
opt_loca;
end
```

Appendix C3

m-file: Matlab Code for Determination of Maximum Loadability

```
%%%%%%%%%%%%%   Loadability  %%%%%%%%%%%%%%%%%%
function [opt_load_factor]= loadability(line_abc,load_abc,DG_a,DGL_a,
DG_b,DGL_b,DG_c, DGL_c)
% function to calcaulate the loadability of the network using varying load
% factor
warning('off');
n=19;
V_lim=0.9500;
S_base=10e6;
I_lim=0.0313;

dg_a=DG_a;
dgl_a=DGL_a;
dg_b=DG_b;
dgl_b=DGL_b;
dg_c=DG_c;
dgl_c=DGL_c;

line_abc=line_abc;
load_abc=load_abc;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

info=sprintf('Results from base case');
    %disp(info);

    line=line_abc;
        line_a=line(:,1:(n-1));
        line_b=line(:,n:(2*n-2));
        line_c=line(:,(2*n-1):((n-1)*3));


    load=load_abc;
    load=load;
        load_a=load(1,:);
        load_b=load(2,:);
        load_c=load(3,:);

    [P_LOSS_a,Vi_a, Q_LOSS_a, Ii_a ]=JAHFLOW1(line_a, load_a);
    [P_LOSS_b,Vi_b, Q_LOSS_b, Ii_b ]=JAHFLOW1(line_b, load_b);
    [P_LOSS_c,Vi_c, Q_LOSS_c, Ii_c ]=JAHFLOW1(line_c, load_c);

%%%%%%%%%%%%%%    load factor  para    %%%%%%%%%%%%%%%%
lfs=0.01;              % load factor stepsize
lf=1;                  % load factor initial value
iter=0;
max_iter=(S_base/1e5)/lfs;

lline=line_abc;
lload=load_abc;
```

```
S_load_factor=zeros(max_iter,1);
Via=ones(n,max_iter);
Vib=ones(n,max_iter);
Vic=ones(n,max_iter);


for iiter=1:max_iter
    if ((min(Vi_a))>V_lim) && ((min(Vi_b))>V_lim) && ((min(Vi_c))>V_lim)
        if ((max(Ii_a))<I_lim) && ((max(Ii_b))<I_lim) && ((max(Ii_c))<I_lim)

        %iter=iter+1;
        lf=lf+lfs;

        line_abc=lline;
        line=line_abc;
            line_a=line(:,1:(n-1));
            line_b=line(:,n:(2*n-2));
            line_c=line(:,(2*n-1):((n-1)*3));

%         dg_a=DG_a;
%         dgl_a=DGL_a;
%         dg_b=DG_b;
%         dgl_b=DGL_b;
%         dg_c=DG_c;
%         dgl_c=DGL_c;

        S_DG_a=zeros(1,n);
            S_DG_a(dgl_a)=dg_a;
        S_DG_b=zeros(1,n);
            S_DG_b(dgl_b)=dg_b;
        S_DG_c=zeros(1,n);
            S_DG_c(dgl_c)=dg_c;

        load_abc=lload;
        load=load_abc;
        load=load*lf;
            load_a=load(1,:)-S_DG_a;
            load_b=load(2,:)-S_DG_b;
            load_c=load(3,:)-S_DG_c;

        info=sprintf('Results from load factor of %d',lf);
        disp(info);
        [P_LOSS_a,Vi_a, Q_LOSS_a, Ii_a ]=JAHFLOW1(line_a, load_a);
        [P_LOSS_b,Vi_b, Q_LOSS_b, Ii_b ]=JAHFLOW1(line_b, load_b);
        [P_LOSS_c,Vi_c, Q_LOSS_c, Ii_c ]=JAHFLOW1(line_c, load_c);

        S_load_factor(iiter)=lf;
        Via(2:end,iiter)=Vi_a;
        Vib(2:end,iiter)=Vi_b;
        Vic(2:end,iiter)=Vi_c;
    end
   end

end
```

```
    Via;
    Vib;
    Vic;

    S_load_factor;
    size(S_load_factor);
    nlf=find(S_load_factor>0);
    m_nlf=max(nlf);

    SS_load_factor=zeros(m_nlf,1);
    SVia=zeros(n,m_nlf);
    SVib=zeros(n,m_nlf);
    SVic=zeros(n,m_nlf);
    for uu=1:m_nlf
        SS_load_factor(uu,1)=S_load_factor(uu,1);
        SVia(:,uu)=Via(:,uu);
        SVib(:,uu)=Vib(:,uu);
        SVic(:,uu)=Vic(:,uu);
    end
    SS_load_factor;
    sss=size(SS_load_factor);
    S_load_factor=SS_load_factor(1:end-1);
    Via=SVia(:,1:end-1);
    Vib=SVib(:,1:end-1);
    Vic=SVic(:,1:end-1);

        %%%  for max loadability plot  %%%
        slf=S_load_factor;
        va=Via;
        vb=Vib;
        vc=Vic;
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    [opt_LF, idx]=max(S_load_factor);
    opt_load_factor=opt_LF;
    opt_load_factor=(opt_load_factor-1)*100;

%     DG_a=0.0222;
      DGL_a=dgl_a;
%     DG_b=0.0222;
      DGL_b=dgl_a;
%     DG_c=0.0222;
      DGL_c=dgl_a;

      lldf=length(S_load_factor);
      r=zeros(lldf,1);
      for iy=1:lldf
          r(iy)=iy;
      end
      r;
      q=[r, S_load_factor];
    Q=zeros(10,1);
    vVia=zeros(1,10);
    vVib=zeros(1,10);
    vVic=zeros(1,10);
    for i=1:10
```

```
        mxp=i/10;
        qr=max(r)*mxp;
        qr=ceil(qr);
        Q(i)=S_load_factor(qr);
        vVia(1,i)=Via(DGL_a,qr);
        vVib(1,i)=Vib(DGL_b,qr);
        vVic(1,i)=Vic(DGL_c,qr);
    end
    Q;
    Via=vVia;
    Vib=vVib;
    Vic=vVic;

    figure;
    lq=length(Q);
    plot(Q,Via,'r+-', Q,Vib,'g*-', Q,Vic,'bd-','LineWidth',2 ),grid ON;
    legend('ph_A','ph_B','ph_C');
    %bar_VSM=bar(Q, VSM);
    title('VOLTAGE MAGNITUDE vs LOADABILITY');
    %axis([1 opt_LF+(0.01*opt_LF) 0.94 1.015]);
    xlabel('LOAD FACTOR');
    ylabel('VOLTAGE MAGNITUDE');

End
```

Appendix C4

m-file: Matlab Code for the Power Flow

```
function [P_LOSS, Vi, Q_LOSS,Ii] = JAHFLOW1(line, load_power)
% UNTITLED Summary of this function goes here
% Detailed explanation goes here
% clc
% clear all
format short;
sample_number=1;
% w=2*pi*50;

for jj=1:sample_number

% V_base=4.8e3;
V_base=11e3;
S_base=10e6;
Z_base=V_base^2/S_base;
line=line/Z_base;

% Size_line=size(line);
Size_load_power=size(load_power);
[line_number,xxx]=size(find(line~= 0));
[xxx,load_power_number]=size(find(load_power~= 0));

    %%%%%%%%  for BIBC   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

BIBC=zeros(line_number,Size_load_power(1,2)-1);

for i=1:line_number
    for j=1:Size_load_power(1,2)-1
        if line(i,j)~= 0
            B=j;
            if i==1 && j==1
                BIBC(i,j)=1;
            else
                BIBC(:,j)=BIBC(:,i-1);
                BIBC(B,j)=1;
            end
        end
    end
end


for i=2:Size_load_power(1,2)

    if load_power(1,i)== 0
        BIBC(:,i-1)=0;
    end
end
BIBC;
%size(BIBC);
```

```matlab
%%%%%%%%      for BCBV      %%%%%%%%%%%%%%%%%%%%%%%%

BCBV=zeros(line_number,Size_load_power(1,2)-1);


for i=1:line_number
    for j=1:Size_load_power(1,2)-1
        if line(i,j)~= 0
            B=j;
            if i==1 && j==1
                BCBV(i,j)=line(i,j);
            else
                BCBV(j,:)=BCBV(i-1,:);
                BCBV(j,j)=line(i,j);
            end
        end
    end
end
 % %%%%%%%%%%%%   main  load flow        %%%%%%%%%%%%%%%

size(BIBC);
size(BCBV);
DLF=BCBV*BIBC;
 V1=ones(Size_load_power(1,2)-1,1);
 V_bus=ones(Size_load_power(1,2)-1,1);
 I=zeros(Size_load_power(1,2)-1,1);
 Iaa=zeros(Size_load_power(1,2)-1,1);
 i=1;
 telorance=1;

 while i<=200   % maximum iterations
     for j=1:Size_load_power(1,2)-1
         I(j,1)=conj(load_power(1,j+1)/V_bus(j,1));
     end
     I_test(:,i)=I;
     V_bus= V1-(DLF*I);
     V_test(:,i)=V_bus;


     if i<=1
         telorance= 1;   % convergence condition

     else
         telorance= abs(abs(I_test(line_number,i))-abs(I_test(line_number,i-
1)));


     end
     if abs(telorance) <= 1e-5
         %fprintf('Power flow solution found for %gth sample in "%g"
iterations\n',jj,i)
         break
     end
        i=i+1;
 end
```

```
 if i==201
     fprintf('No solution, the algorithm did not converge\n')
     break
 end

 V_bus_size=size(V_bus);
 v_bus_shift=zeros(V_bus_size(1,1)+1,1);
 v_bus_shift(1,1)=1;

for i=2: V_bus_size(1,1)+1
    v_bus_shift(i,1)=V_bus(i-1,1);
end

 V_bus=v_bus_shift;

 I_bus_shift=zeros(V_bus_size(1,1)+1,1);
 I_bus_shift(1,1)=(V_bus(1,1)-V_bus(2,1))/line(1,1);

 for i=2: V_bus_size(1,1)+1
    I_bus_shift(i,1)=I(i-1,1);
 end

 I_bus=I_bus_shift;

 V_bus;
 size(V_bus);
 I_bus;
 sizeIbus=length(I_bus);
 sizeline=size(line);
 I_node_wo1=I_bus(2:sizeIbus,1);
 %PowerlossPU=sum((abs(I_node_wo1).^2)*real(line));
 powerlossPU=sum((real(line))'*(BIBC)*(abs(I_node_wo1).^2));
 qowerlossPU=sum((imag(line))'*(BIBC)*(abs(I_node_wo1).^2));
%%%%%%  calculate the loads Impedance   %%%%%%%%%%%

V_bus_size=size(V_bus);
Z_loads=zeros(Size_load_power(1,2),1);

for i=1:V_bus_size(1,1)
    if load_power(1,i) ~= 0
        Z_loads(i,1)=(V_bus(i,1))/conj(load_power(1,i)/V_bus(i,1));
    else
        Z_loads(i,1)=0;
    end
end

P_LOSS=powerlossPU;
Q_LOSS=qowerlossPU;
Vi=V_bus(2:end);
Ii=I_node_wo1;
S_source=zeros(Size_load_power,1);
S_Demand=load_power;
S_injected=S_source-S_Demand;

S_source=transpose(S_source(2:end));
```

```
S_Demand=transpose(S_Demand(2:end));
S_injected=transpose(S_injected(2:end));
end
```