APPLICATION OF IMPROVED BACTERIAL FORAGING ALGORITHM TO THE OPTIMAL SITING AND SIZING OF D-STATCOM IN RADIAL DISTRIBUTION NETWORKS

BY

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FEBRUARY, 2017

DECLARATION

I, Umar MUSA hereby declare that this Dissertation titled "Application of Improved Bacterial Foraging Algorithm to the Optimal Siting and Sizing of D-STATCOM in Radial Distribution Networks" has been carried out by me under the supervision of Professor G. A. Bakare and Professor B. Jimoh as part of the requirements for the award of the degree of Master of Science (M.Sc.) in Power Systems Engineering. To the best of my knowledge, this research has never been submitted anywhere for the award of any certificate. All literatures used are cited in this research and duly acknowledged by means of references.

Umar MUSA _____ _____

(Student) **Signature** **Date**

CERTIFICATION

This Dissertation titled "APPLICATION OF IMPROVED BACTERIAL FORAGING ALGORITHM TO THE OPTIMAL SITING AND SIZING OF D-STATCOM IN RADIAL DISTRIBUTION NETWORKS" meets the requirements for the award of the degree of Master of Science (M.Sc.) in Power Systems Engineering by Ahmadu Bello University, Zaria and is approved for its contribution to knowledge and literacy presentation.

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DEDICATION

This dissertation is dedicated to Almighty Allah; the Most Beneficient, the Most Gracious and the Most Merciful. Also, to the memory of my late father Alhaji Musa Sado Ekpoki. May his soul rest in Jannatul Firdaus. Ameen.

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ABSTRACT

Optimal siting and sizing of Distribution Flexible AC Transmission Systems (D-FACTS) devices in power distribution networks maximizes loadability, compensates reactive power, minimizes power loss and enhances voltage profile. The search for optimal size and locations of these devices in radial distribution networks is challenging and requires robust scheduling. This dissertation presents the application of improved bacterial foraging algorithm (IBFA) to the optimal siting and sizing of Distribution Static Compensator (D-STATCOM) in radial distribution networks for power loss minimization and voltage profile enhancement. Radial distribution network power flow model and algorithm was developed based on the Bus Injected to Branch Current matrix (BIBC) technique. The IBFA was modelled with three adaptive run-length units (linear, quadratic and exponential) and the cell-to-cell signalling mechanism was eliminated. A multi-objective function comprising of total active power loss and network bus voltage deviation was formulated for use in the IBFA. The effectiveness and applicability of the approach was demonstrated on standard IEEE 33-bus radial distribution network and the 50-bus Canteen Feeder in Zaria distribution network for steady-state constant load model. The results obtained are compared with those of the conventional BFA; and with Analytical and Bat Algorithm (BA) approaches reported in literature. For the standard IEEE 33-bus test network, the optimal location and size of D-STATCOM were determined respectively as bus 30 and 2577 kVar by the BFA method, while the IBFA approach obtained the optimal site and size of the D-STATCOM in the network to be bus 26 and 3351 kVar respectively. The BFA approach produced a 5.87 % reduction in overall network power losses and an 82.88 % improvement in voltage profile when compared with the base-case scenario. Similarly, the IBFA approach resulted in 5.83 % drop in total power losses of the network and 87.96 % improvement of the voltage profile. An average computational time of 7.2 seconds and 4.9 seconds were obtained for the BFA and IBFA approaches respectively. The results obtained using the IBFA approach showed a 28.5 % and 1.1 % reduction in active power loss and size of D-STATCOM respectively when compared with those of analytical approach. Also, when compared with the BA results, the IBFA approach showed a 50 % improvement in the overall network voltage profile. For the 50-bus Canteen Feeder, bus 41 and 227.8 kVar were found as the optimal site and size of D-STATCOM using BFA method, while for IBFA approach, the optimal site and size of the D-STATCOM in the network were determined as bus 22 and 138 kVar respectively. The overall network power loss was reduced by 22.8 % and the voltage profile improved by 6.10 % using the BFA approach while for the IBFA approach, a 26.53 % reduction in total power loss and a 6.21 % improvement in voltage profile were achieved as compared with the base-case results.

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LIST OF ABBREVIATIONS

BA	Bat Algorithm
BFA	Bacterial Foraging Algorithm
BIBC	Bus Injected to Branch Current
D-FACTS	Distribution Flexible AC Transmission Network System
D-STATCOM	Distribution Static Compensator
DVR	Dynamic Voltage Restorer
EABFA	Exponentially Adaptive Bacterial Foraging Algorithm
FACTS	Flexible AC Transmission Network System
GTO	Gate Turnoff Thyristor
IBFA	Improved Bacterial Foraging Algorithm
IEEE	Institute of Electrical and Electronics Engineering
IGBT	Insulated Gate Bipolar Transistor
KAEDCO	Kaduna Electricity Distribution Company
KCL	Kirchhoff's Current Law
kW	Kilo Watt
kVAr	Kilo Voltage Ampere Reactive
LABFA	Linearly Adaptive Bacterial Foraging Algorithm
MATLAB	Matrix Labouratory
PCC	Point of Common Coupling
p.u.	Per Unit
QABFA	Quadratic Adaptive Bacterial Foraging Algorithm
SSSC	Static Synchronous Series Compensator
STATCOM	Static Compensator
SVC	Static Var Compensator
TCSC	Thyristor Controlled Series Compensator
TCR	Thyristor Controlled Reactor
UPFC	Unified Power Flow Controller
UPQC	Unified Power Quality Conditioner
VSC	Voltage Source Converter
VSI	Voltage Source Inverter

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CHAPTER ONE

INTRODUCTION

1.1 Background Information

Technically, networks are categorized as either compact or large depending on their level of complexity. Large technical networks are known to be spatially extended with large number of structural components. Telecommunication networks, traffic networks, railroad networks and electric power networks are all classified as large technical systems (Tchokonte, 2009). Electric power networks are considered among the greatest and most sophisticated contemporary technological break-through comprising of generation, transmission and distribution networks (Murty, 2008). Electricity is generated at generating stations and transported via transmission networks to the final stage of power transfer (distribution networks) where power is directly delivered to consumers by electricity utilities (Murty, 2008). Figure 1.1 shows the major components that constitutes an electric power system.

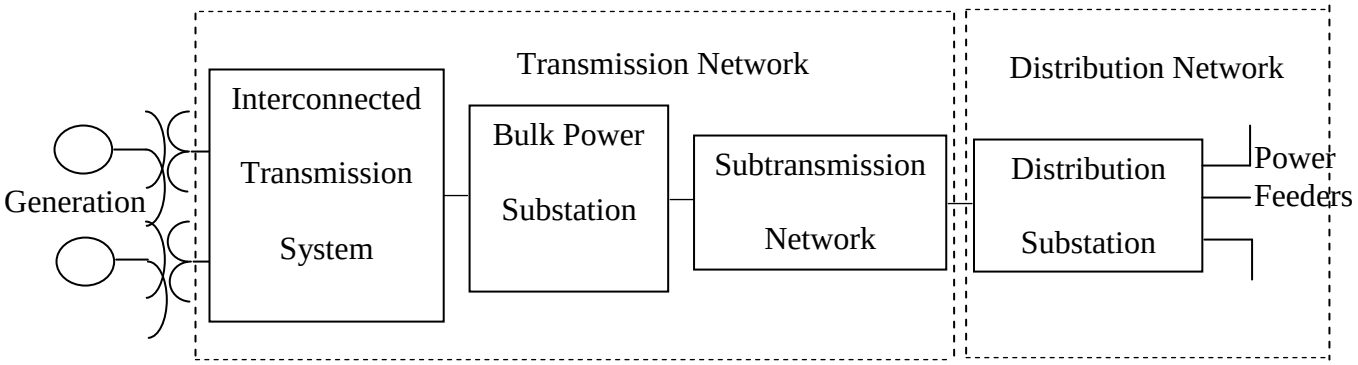


Figure 1.1: Major Components of an Electric Power System (Kersting, 2012)

Distribution networks are mostly radial in nature with very rare exceptions. A typical distribution network consists of distribution substation, feeders, switches, fuses, transformers, voltage regulators, meters and circuit breakers as shown in Figure 1.2.

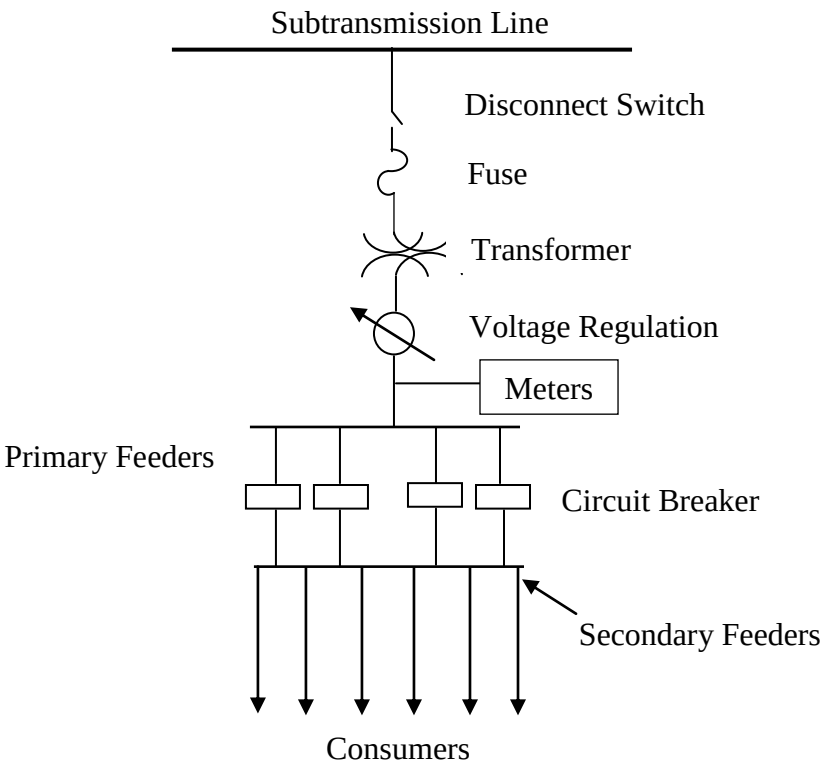


Figure 1.2: Schematic Diagram of a Simple Distribution Network (Kersting, 2012)

The deregulation of power networks to augment the imbalances between generation and consumption results in loss of the networks passive nature. This scenario subsequently results in technical issues that may affect the power quality of the entire network (Machowski *et al.*, 2011). Poor voltage quality in distribution networks which can be due to variations in consumers' demand forces electrical equipment to draw more than their rated current, resulting in excessive heating capable of inflicting severe damages (Watson andMiller, 2015). Practically, voltage quality remains the greatest threat to system stability considering the fact that electrical devices interact via the terminal voltage. Traditionally,load reduction, load shedding, series voltage regulators and shunt capacitors are among several techniques employed in arresting the issues of voltage quality in power networks.

The advent of power electronics based controllers, or Flexible AC Transmission System (FACTS) controllers such as Static VAR Compensator (SVC), Thyristor Controlled Reactor (TCR), Static Compensator (STATCOM) etc has led to improved ways of enhancing voltage profile and reducing losses in power networks (Singh *et al.*, 2012). Considering the fact that most electric loads draw lagging current, there is an increase in the demand for reactive power in distribution networks. Distribution Flexible AC Transmission Systems (DFACTS) devices such as Dynamic Voltage Restorer (DVR), Distribution Static Compensator (D-STATCOM), Unified Power Quality Conditioner (UPQC) and Static Synchronous Series Compensator (SSSC) have been developed for operation in distribution networks. The excellent features of D-STATCOM that includes less harmonic distortion, low power losses, zero resonance, compact size, low cost and high regulatory capability makes it superior over other DFACTS devices (Gupta andKumar, 2015).

Analytical and numerical techniques have been employed in the search for optimal position and size of FACTS devices in power networks. But their computational complexity and inability to fully incorporate the nonlinearity of the power networks prompted the search for better and more robust techniques (Ming *et al.*, 2014).

The evolution of meta-heuristics algorithms has led to a new, faster and robust approach of solving complex power system optimization problems (Binitha andSathya, 2012). Recently, a novel meta-heuristic optimization algorithm, known as Bacterial Foraging Algorithm (BFA) was developed by Passino in 2002. Inspired by the foraging behaviour of *Escherichia Coli* (E. Coli) bacteria found in human intestine, the algorithm is developed to mimic how bacteria forage over a landscape of nutrients to handle parallel non-gradient optimization problems (Xing andGao, 2014). The algorithm is highly recognised for its broad coverage of search area (global and local search

simultaneously) and multi-focused nature. However, the BFA, like all other meta-heuristic algorithms is characterized by high computational time, complexity and the possibility of getting trapped in local minima as shortcomings (Passino, 2012).

This research work applied an improved bacterial foraging algorithm (IBFA) to optimally site and size of D-STATCOM in radial distribution networks via a multi-objective function for power loss minimization and voltage profile enhancement.

1.2 Problem Statement

Due to the non-linear nature of most consumers' loads, there is an increased demand for reactive power in the distribution network of power systems. As such, up to 13% of total power generated is wasted in the distribution level depending on the network stability (Yuvaraj *et al.,* 2015). Highly sophisticated and efficient equipment (D-FACTS devices) have been developed specifically to mitigate these losses incurred at the distribution stage. Analytical (Eigen value analysis, Modal analysis, Index method, etc), conventional optimization (Liner Programming, Non-Linear Programming, Mixed Integer Non-Linear Programming, etc) and meta-heuristic optimization (Immune Algorithm, Firefly Algorithm, Bat Algorithm, etc) techniques have been deployed in the search for optimal placement and size of D-FACTS devices in distribution networks to resolve such problems. However, these techniques are characterised by multiple assumptions, inherent inaccuracy, complexity and high computational time as drawbacks (Ming *et al.,* 2014). With the recent evolution of meta-heuristics algorithms, some of these shortcomings (multiple assumptions and inherent inaccuracy) have been addressed. Although the bacterial foraging algorithm (BFA) has shown promising results when applied in solving complex power system optimization problems, it is insufficient due to its complexity, high computational time and possibility of being

trapped in local minima. This research seeks to apply an improved BFA for optimal siting and sizing of D-STATCOM in radial distribution networks.

1.3 Aim and Objectives

The aim of this research is to apply an improved bacterial foraging algorithm (IBFA) to the optimal siting and sizing of D-STATCOM in radial distribution networks for power loss minimization and voltage profile enhancement. In order to achieve this aim, the following objectives are set forth:

1. To apply the Improved Bacterial Foraging Algorithm (IBFA) to the optimal siting and sizing of D-STATCOM on standard IEEE 33-bus radial distribution network in MATLAB 2013a environment;
2. To validate the IBFA approach by comparison with conventional BFA and with the works of **Hussain and Subbaramiah, (2013)** and **Yuvaraj *et al.*, (2015)**; and
3. To implement and compare the BFA and IBFA approaches for 50-bus Canteen Feeder in Zaria distribution network.

1.4 Research Methodology

The objectives outlined in this research were actualized in line with the following procedures:

1. Acquire the relevant network data (line data, bus data, network base voltage, etc.);
2. Perform network base-case power flow analysis based on the Bus-Injected-to-Branch-Current matrix (BIBC);

3. Formulate the IBFA adaptive run-length units with appropriate tuneable and scaling factors, and also eliminating the cell-to-cell signalling mechanism in MATLAB 2013a environment;
4. Formulate a multi-objective function for the standard IEEE 33-bus radial distribution network comprising of the total network active power loss and bus voltage deviation to be used in the IBFA;
5. Represent the obtained results (voltage profile improvement, power loss reduction, etc.) in graphical, bar-chart and tabular form; and
6. Repeat the fourth and fifth procedures on the 50-bus Canteen Feeder in Zaria distribution network.

1.5 Research Limitations

The limitations of this research includes:

1. The use of D-STATCOM only for compensation;
2. Unavailability of data for other Feeders in the Zaria distribution network; and
3. Unavailability of resources for on-line application of the research resulting in virtual simulation platform only

1.6 Organisation of the Dissertation

Chapter One presents the general introduction of the dissertation while Chapter Two presents the fundamental concepts that includes all relevant assumptions, theories and modelling equations needed for the actualization of this research and a comprehensive review of similar works carried out. Chapter Three presents an elaborate procedure for the actualization of this research which comprises of all the materials and the methodology adopted. The results obtained from the application of the theoretical and modelling concepts presented in the two previous chapters and their discussions are presented in Chapter Four. Chapter Five covers the conclusion,significant contribution

of the research and recommendation for further research. Finally, relevant references and Appendices are presented at the end of this research.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The literature review in this research encompasses the fundamental concepts as well as the review of similar works carried out. All necessary assumptions, theories and equations needed for the actualization of this research have all been covered in the review of fundamental concepts; afterwards reviews of similar works are be presented.

2.2 Review of Fundamental Concepts

In this sub-section, a brief review on the fundamental concepts of Flexible AC Transmission System (FACTS) and Distribution Flexible AC Transmission System (DFACTS) Controllers are presented. An overview of the Distribution Static Compensator (D-STATCOM) is also considered. The optimal siting and sizing techniques, the standard IEEE 33-bus radial distribution network and the 50-bus Canteen Feeder in Zaria distribution network are equally presented. Finally, the bacterial foraging algorithm (BFA) and the improved bacterial foraging algorithm (IBFA) are discussed.

2.2.1 Flexible AC Transmission System (FACTS) Controllers

The word FACTS is an acronym for Flexible AC Transmission System. According to the IEEE PES Task Force of the FACTS working Group, the general and standard definitions for FACTS and FACTS Controllers respectively are stated as (Hingorani andGyugyi, 2000): *"Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability"* and *"a power electronic-based system and other static equipment that provides control of one or more AC transmission system parameters"*

2.2.1.1 Classification of FACTS Controllers

Basically, FACTS controllers are classified into (Singh *et al.*, 2012):

1. Thyristor controlled based FACTS controllers such as Thyristor Controlled Reactor (TCR), Thyristor Controlled Series Compensator (TCSC), Static Var Compensator (SVC), etc; and
2. Voltage source inverter (VSI) based FACTS controllers such as Static Synchronous Series Compensator (SSSC), Distribution Static Compensator (D-STATCOM), Unified Power Flow Controller (UPFC) etc.

The presence of resonance phenomena in thyristor controlled based FACTS Controllers remains a major disadvantage (Hingorani andGyugyi, 2000). Thus, the VSI based FACTS controllers have better performance in power networks due to the absence of resonance phenomena.

2.2.1.2 Categories of FACTS Controllers

Generally, FACTS controllers are categorised based on the nature of their connection in electric power systems. The four basic categories of FACTS controllers are as follows (Singh *et al.*, 2012):

1. Series connected;
2. Shunt connected;
3. Combined series-series connected; and
4. Combined series-shunt connected.

2.2.2 Distribution Flexible AC Transmission Systems (D-FACTS)

D-FACTS are highly advanced power-electronics based equipment with fast and authentic control strategies designed for use in the distribution networks. They are capable of providing reactive power compensation according to the network

requirements. These equipment operate in a similar mode to capacitor when the network is in need of reactive power, and operates like inductor when the network is experiencing excess of reactive power (Gupta andKumar, 2015). Among the recently developed D-FACTS equipment are the Dynamic Voltage Restorer (DVR), Unified Power Quality Conditioner (UPQC), Static Synchronous Series Compensator (SSSC) and Distribution Static Compensator (D-STATCOM). Aside the D-STATCOM, overview on other types of D-FACTS devices is out of the scope of this research.

2.2.3 Overview of Distribution Static Compensator (D-STATCOM)

According to IEEE, "D-STATCOM is defined as a static synchronous generator operating as a Static Var Compensator (SVC) connected in parallel with the output current (capacitive or inductive) which can be controlled independently of the AC voltage network" (Mokhtari *et al.*, 2014).

The basic functions of D-STATCOM include:

1. Mitigation of the impact of dips and peaks of voltage sensitivity loads;
2. Voltage regulation and reactive power compensation;
3. Compensation of harmonic currents;
4. Correction of power factor;
5. Mitigation of voltage flicker; and
6. Uninterrupted supply in case of use as an energy storage device.

The D-STATCOM is a three phase shunt connected Voltage Source Converter (VSC) designed for use in distribution network to compensate the bus voltage so as to provide better power factor and reactive power control (Yuvaraj *et al.*, 2015). The device is capable of injecting or absorbing both active and reactive current at the point of common coupling (PCC). The limit constraint attached to energy storage, makes it practically impossible for D-STATCOM to inject active power over a long period of

time. Thus, the operation is mostly in steady-state with reactive power being the power exchange between D-STATCOM and the system (Hussain andSubbaramiah, 2013). A typical model of D-STATCOM for steady-state operation consists of a coupling transformer with a leakage reactance, a GTO/IGBT, voltage source converter (VSC) and a DC capacitor. Figure 2.1 (a) and (b) shows a schematic diagram of D-STATCOM incorporated to a bus and its equivalent circuit respectively (Bagheri *et al.*, 2015).

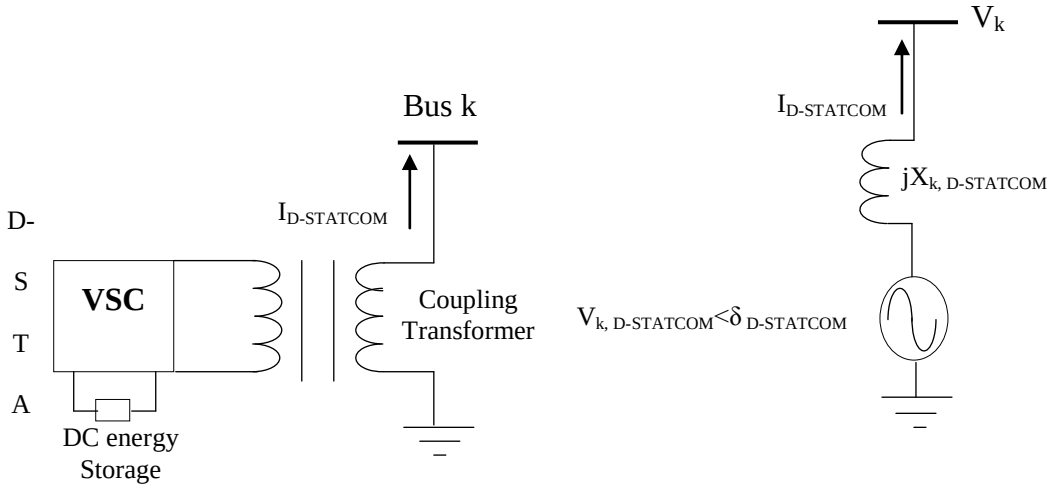


Figure 2.1: (a) Structure of D-STATCOM Connected to Bus k, (b) Equivalent Circuit (Bagheri *et al.*, 2015)

2.2.3.1 Basic Operating Principle of D-STATCOM

D-STATCOM operates in a similar manner as the synchronous machine, providing lagging current when under excited and leading current when over excited. The voltage of D-STATCOM is injected in phase with the line voltage and in this case there is no exchange of energy with the network, but only reactive power is to be injected (or absorbed) by the D-STATCOM as shown in Figure 2.2 (Hussain andSubbaramiah, 2013).

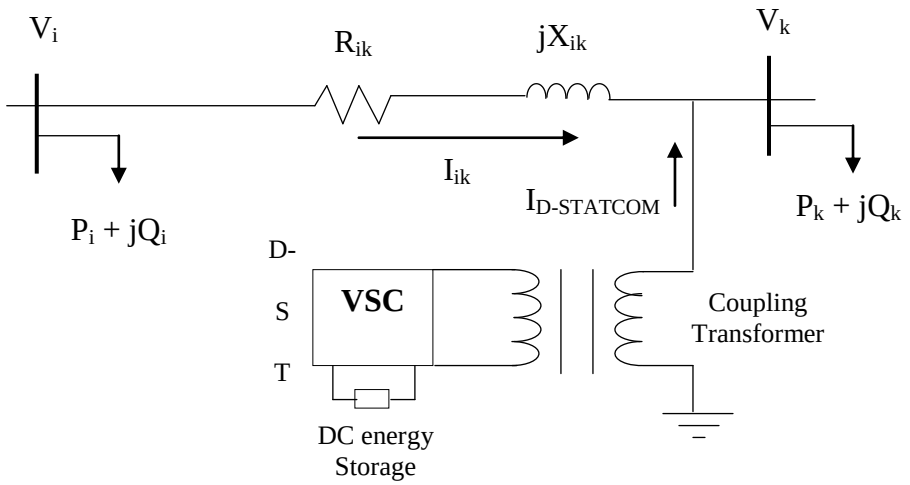


Figure 2.2: Single Line Diagram of 2-Bus with D-STATCOM Incorporated (Hussain andSubbaramiah, 2013)

The reactive power exchange with the network is achieved by varying the amplitude of the output voltages. The output voltage of the VSC V_{VSC} is controlled in phase with the system voltage V_S . If V_{VSC} is greater than V_S then the D-STATCOM will act as capacitor and generate reactive power (i.e. capacitive mode). On the other hand, if V_S is greater than V_{VSC} then the D-STATCOM will act as inductor and consume reactive power (i.e. inductive mode). But if V_{VSC} is equal to V_S then the D-STATCOM does not generate or absorb reactive power and the reactive power is zero (Ramakrishna andRao, 2014). The three operating modes of the D-STATCOM are shown in Figure 2.3.

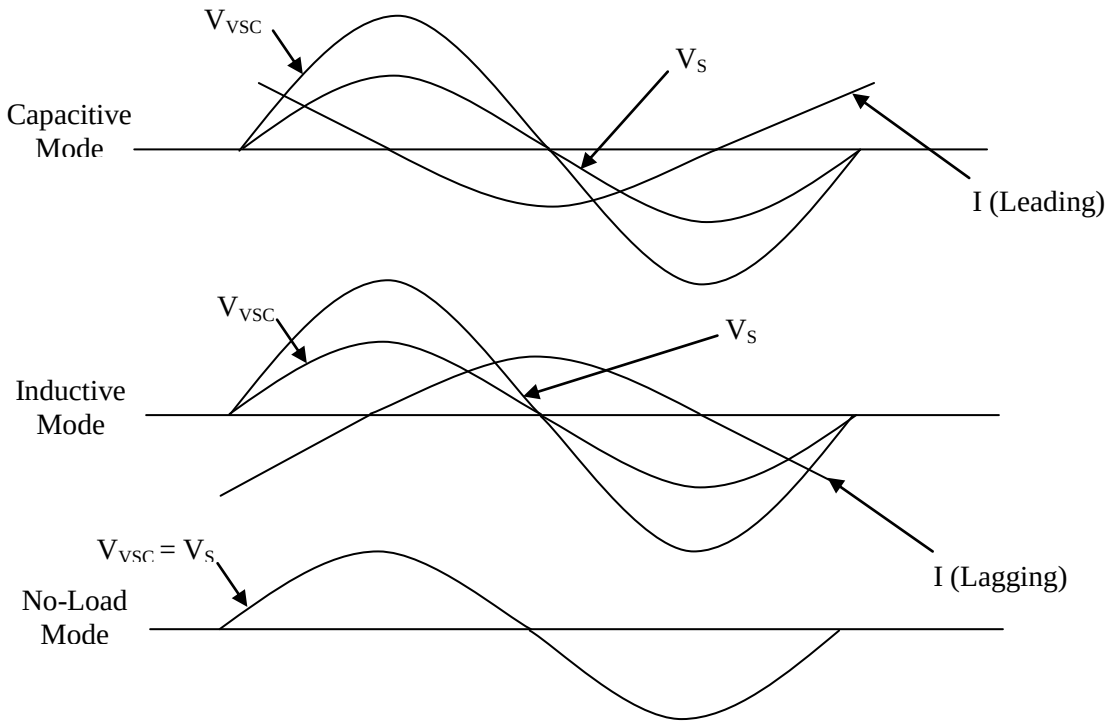
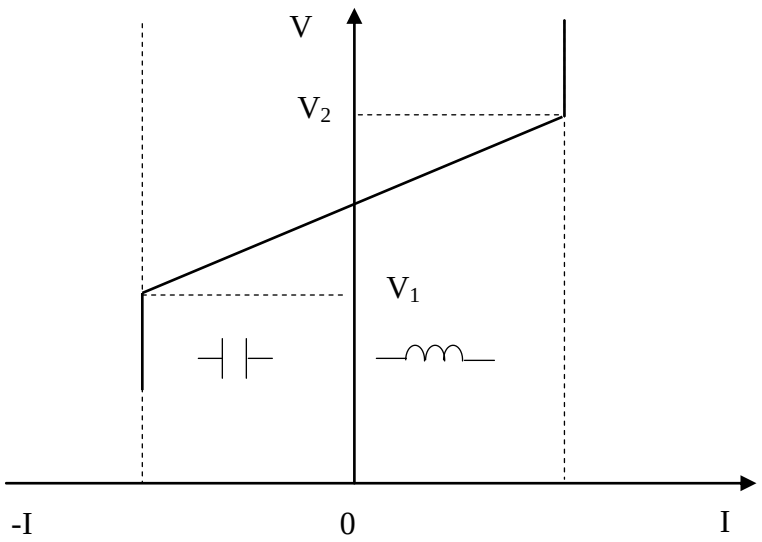


Figure 2.3: Operating Modes of D-STATCOM (Ramakrishna andRao, 2014)

The D-STATCOM smoothly and continuously controls voltage from V_1 to V_2 (Mokhtari *et al.*, 2014). However, if the system voltage V_S exceeds a low-voltage V_1 or high-voltage V_2, the D-STATCOM acts as a constant current source by controlling the VSC voltage V_{VSC}



appropriately as shown in Figure 2.4.

Figure 2.4: V-I Characteristics of D-STATCOM (Mokhtari *et al.*, 2014)

2.2.3.2 Modelling of the D-STATCOM

There exist three approaches to modelling of the D-STATCOM, which are (Mokhtari *et al.*, 2014):

1. Average modelling;
2. Detailed modelling; and
3. Phase-to-phase modelling.

Based on Figure 2.2, the active and reactive power exchanged with network at bus k can be computed by the equations (Mokhtari *et al.*, 2014):

$$P_{D-STATCOM} = \frac{V_k V_{D-STATCOM}}{X_{k,D-STATCOM}} \sin\ \delta_k - \delta_{D-STATCOM} \tag{2.1}$$

$$Q_{D-STATCOM} = -\frac{V_k\ \ V_{D-STATCOM} \cos\ \delta_k - \delta_{D-STATCOM}\ \ - V_k}{X_{k,D-STATCOM}} \tag{2.2}$$

where:

V_k is the absolute voltage at bus k,

$V_{D-STATCOM}$ is the absolute voltage of D-STATCOM,

$X_{k,D-STATCOM}$ is the line reactance,

δ_k is the voltage phase angle at bus k ,

$\delta_{D-STATCOM}$ is the voltage phase angle of D-STATCOM.

Assume $P_{D-STATCOM}$ and $Q_{D-STATCOM}$ to be constant and the values of V_k and δ_k are known, the values of $V_{D-STATCOM}$ and $\delta_{D-STATCOM}$ can be computed.

2.2.4 Optimal Siting and Sizing Techniques

Researchers have developed and applied several techniques for optimal siting and sizing of FACTS Controllers in electric power networks in order to enhance the network performance by reducing power loss and improving voltage profile. Some of the techniques are as follows:

2.2.4.1 Analytical Techniques

This approach is on the basis of simplified network assumptions. The techniques are employed for various sensitivity analysis for improving the dynamic stability in power networks. Some of the analytical techniques used for optimal siting and sizing of FACTS Controllers in power networks include (Singh *et al.*, 2015): Eigen Value Analysis (EVA), Modal Analysis (M.A), Residual Based Method (RBM), Index Method (IM), Sensitivity Based Method (SBM), etc.

2.2.4.2 Conventional Optimization Techniques

This method involves the application of conventional optimization analysis in determining the optimal position and size of FACTS Controllers in power networks. These techniques are developed to solve optimization problems with some theoretical assumptions, such as convexity, differentiability and continuity, which may not be suitable for use in complex network. Nevertheless, the convergence to global optimum solution is highly dependent on some selected initial guess (Ming *et al.*, 2014). Among

the various conventional optimization techniques developed and employed in this task include (Singh *et al.*, 2015): Linear Programming (LP), Non-Linear Programming (NLP), Mixed Integer Non-Linear Programming (MINLP), Dynamic Programming (DP), etc.

2.2.4.3 Meta-heuristic Optimization Techniques

Meta-heuristic optimization techniques represent a group of intelligent algorithms that make analogy of the natural evolution process based on Darwinian principles or mimic a certain natural phenomenon in search for an optimal solution. These techniques are capable of describing and solving complicated relationships from basic inherent conditions and rules with little or zero knowledge of the search domain (Binitha andSathya, 2012). They have been successfully applied to a wide range of power system optimization problems where non-differentiable regions exist and the global solutions are extremely difficult to be estimated (Ming *et al.*, 2014). Among the most popularly developed and applied meta-heuristics techniques in solving optimal location and sizing problems are (Singh *et al.*, 2015): Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Artificial Neural Network (ANN), etc.

2.2.5 Power Flow Analysis for Radial Distribution Networks

Classical power flow techniques such as Gauss-Seidel, coupled and fast-decoupled Newton-Raphson are more suitable for transmission systems. These techniques, in most cases, fail to converge when used for distribution systems power flow. The failure of classical techniques in a distribution system is clearly attributed to (Singh andGhose, 2013):

1. High R/X ratio;
2. Large number of buses and lines;

3. Uncertainties and imperfection of network parameters; and
4. Dynamic nature of connected loads.

For a balanced radial distribution network, line shunt capacitances are neglected due to their negligible values. Figure 2.5 shows a simplified radial distribution network used for power flow analysis. The method of analysis consist of computation of load current, formulation of Bus Injection to Branch Current matrix (BIBC) and performing forward sweep across the line (Jain *et al.*, 2014).

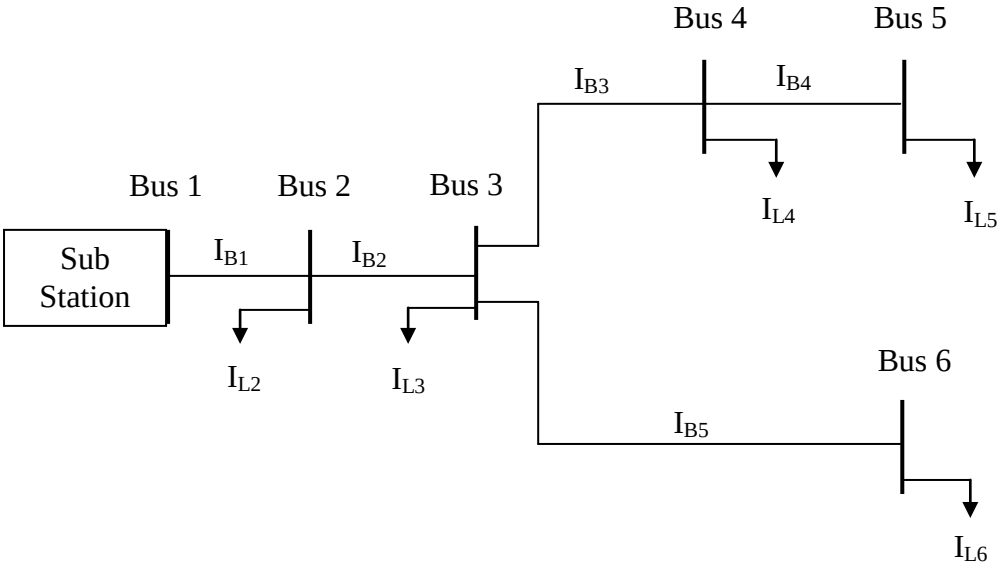


Figure 2.5: Simplified 6-Bus Radial Distribution Network (Jain *et al.*, 2014)

2.2.5.1 Computation of Load Current

Considering the k^{th} bus of a distribution power network, the load current at bus k is expressed as (Jain *et al.*, 2014):

$$I_{L\,k} = \frac{P_k - jQ_k}{V_k^*} \tag{2.3}$$

$for\ k = 1,2,3,...,N_{Bus}$

where:

N_{Bus} is the total number of buses,

P_k and Q_k are the real and reactive power demand at bus k respectively,

V_k^* is the voltage conjugate at bus k

2.2.5.2 BIBC Matrix Formation

The relationship between load currents I_L and branch currents I_B can be established by applying the Kirchhoff's current law (KCL) to the distribution network. The network branch currents are expressed as (Jain *et al.*, 2014):

$$I_{B1} = I_{L2} + I_{L3} + I_{L4} + I_{L5} + I_{L6} \tag{2.4}$$

$$I_{B2} = I_{L3} + I_{L4} + I_{L5} + I_{L6} \tag{2.5}$$

$$I_{B3} = I_{L4} + I_{L5} \tag{2.6}$$

$$I_{B4} = I_{L5} \tag{2.7}$$

$$I_{B5} = I_{L6} \tag{2.8}$$

Equations (2.4) to (2.8) can be expressed in a matrix form as follows (Jain *et al.*, 2014):

$$\begin{bmatrix} I_{B1} \\ I_{B2} \\ I_{B3} \\ I_{B4} \\ I_{B5} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_{L2} \\ I_{L3} \\ I_{L4} \\ I_{L5} \\ I_{L6} \end{bmatrix} \tag{2.9}$$

The above matrix can be written in a more compact form as (Jain *et al.*, 2014):

$$I_B = BIBC \quad I_L \tag{2.10}$$

$BIBC$ is the Bus Injection to Branch Current matrix and contains values of 0 and 1.

2.2.5.3 Forward Sweep

Since voltage values of source buses are known, the receiving end bus voltages can be determined by deducting the corresponding branch voltage drop from values of the sending end voltages. The voltage at bus k is given by (Jain *et al.*, 2014):

$$V_k = V_i - I_{B(ik)} * Z_{ik} \tag{2.11}$$

for $ik = 1,2,3,...,N_{Branch}$

where:

N_{Branch} is the total number of branches,

V_k and V_i are the receiving and sending end voltages of branch ik respectively,

$I_{B(ik)}$ is the current flowing in branch ik ,

Z_{ik} is the impedance of branch ik .

2.2.5.4 Power Losses

The active and reactive power losses of branch ik are calculated using (Jain *et al.*, 2014):

$$P_{ik\ loss} = \left| I_{B\ ik} \right|^2 * \Re\ Z_{ik} \tag{2.12}$$

$$Q_{ik\ loss} = \left| I_{B\ ik} \right|^2 * \Im\ Z_{ik} \tag{2.13}$$

Total active and reactive power losses of a radial distribution system can be determined by taking the summation of individual active and reactive power losses using equations (2.12) and (2.13) respectively.

2.2.6 The Standard IEEE and Zaria Distribution Networks

Different standard IEEE distribution test networks have been developed and made available for researchers to verify the effectiveness of their solutions. Most literatures in this area of research have either employed one or more standard sample distribution networks for analysis and validation. The line and bus data for 33-bus standard IEEE radial distribution networks has been adopted from(Taher andAfsari, 2014).

2.2.6.1 Standard IEEE 33-bus Distribution Network

This is a medium scale radial distribution network with 33-buses and 32-branches. Line and bus data for the network are given in Appendix A1. The line voltage, base MVA, real and reactive power loads of the radial distribution network are 12.66kV, 100MVA 3.72MW and 2.3MVAr, respectively. Figure 2.6 shows the single line diagram of the network (Yuvaraj *et al.*, 2015).

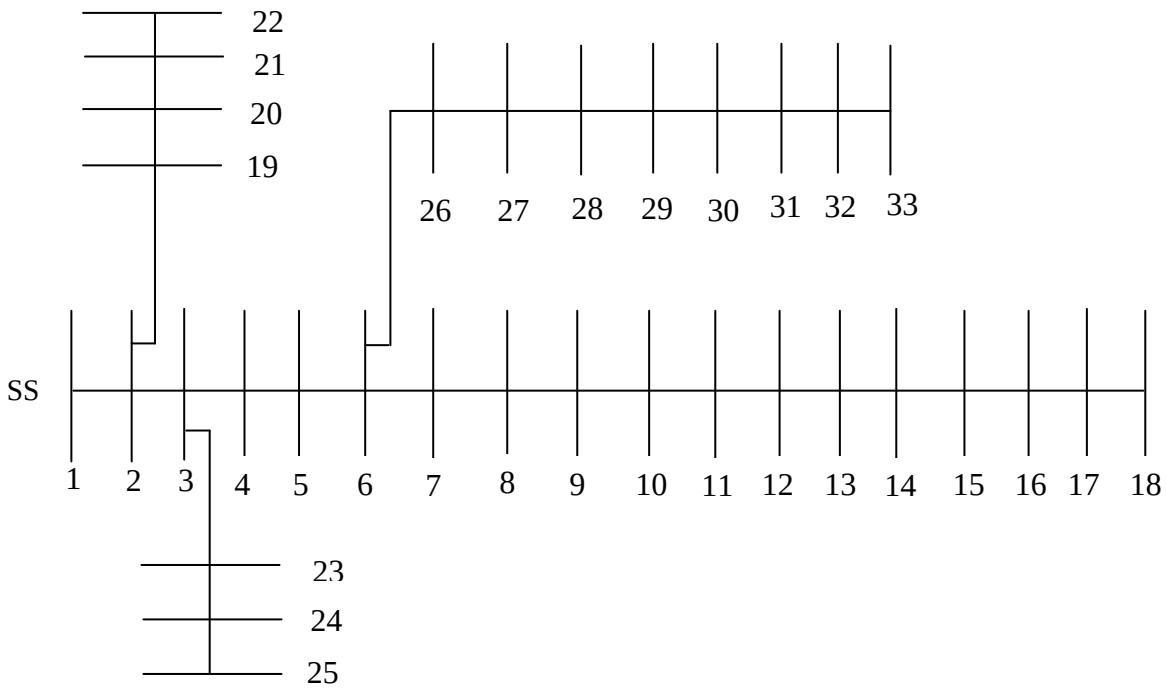


Figure 2.6: Single Line Diagram of IEEE 33-Bus Network (Yuvaraj *et al.*, 2015).

2.2.6.2 Zaria Distribution Network

The Zaria distribution network is a real network equipped with 8 Feeders namely: RLY/NTC Feeder, Sabon-Gari Feeder, Gaskiya Feeder, Canteen Feeder, Zaria-City Feeder, Wusasa Feeder, Kofar-Kibo Feeder and Teaching-Hospital Feeder. The 50-buses and 49-branches Canteen Feeder has been adopted in this research based on available historical records from Kaduna Electricity Distribution Company (KAEDCO) Zaria Business District. The network line voltage, base MVA, total real and reactive load are given as 11kV, 100MVA, 0.388MW and 0.294MVar respectively (Abubakar, 2014). The line and bus data of the network are presented in Appendix A2. Figure 2.7 shows the single line diagram of the network

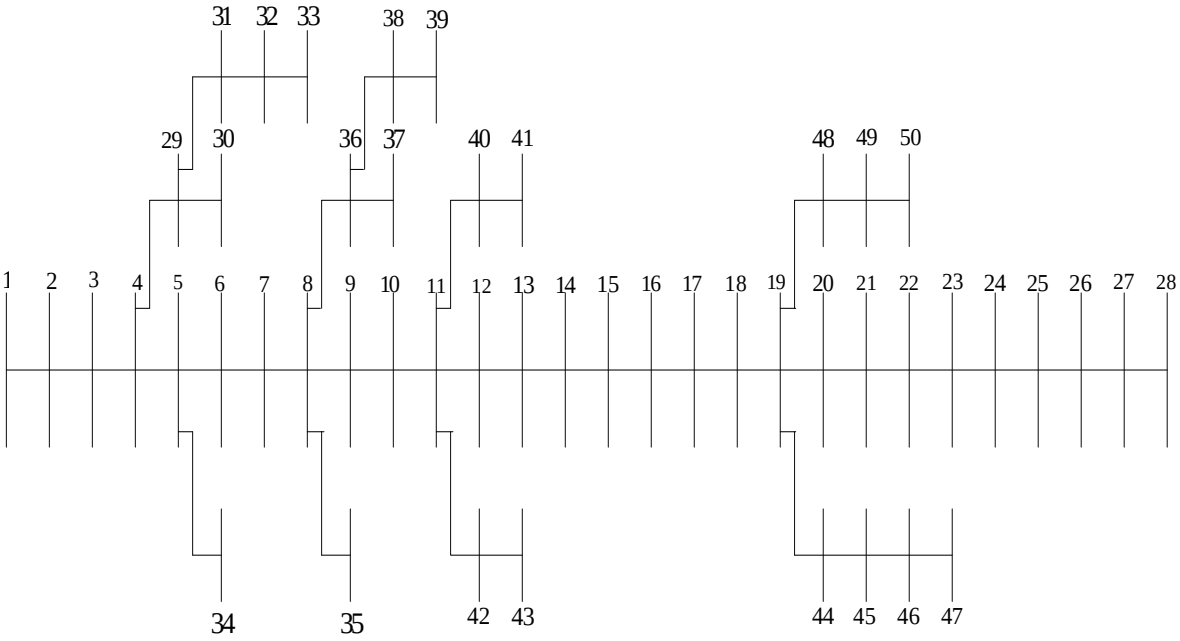


Figure 2.7: Single Line Diagram of 50-Bus Canteen Feeder, Zaria Distribution Network (Abubakar, 2014)

2.2.7 Concept of Bacterial Foraging Algorithm (BFA)

Originally proposed by Kevin Passino in 2002, the bacterial foraging algorithm (BFA) mimics the foraging behaviour of *Escherichia Coli* (E. Coli) bacteria found in the human intestines (Xing andGao, 2014). The algorithm is formulated on the basis of four principal processes, namely: chemotaxis, swarming, reproduction and elimination-dispersal (Boussaid *et al.*, 2013).

2.2.7.1 Chemotaxis

Chemotaxis explains the procedure in which the E. Coli bacteria conducts their movements towards certain chemicals within the surroundings. The bacteria moves in either of two ways: swimming or tumbling, with the sole purpose of finding nutrient-rich areas and avoiding toxic environments. Tumbling is the movement of the bacteria in a haphazard manner (random direction) whereas swimming is the movement in a specified direction mostly a unit walk in a previous tumble (Kiani *et al.*, 2013). The movement of the i th bacterium after one step is given by (Xing andGao, 2014):

$$\theta^i\ \ j+1,k,l\ =\theta^i\ \ j,k,l\ +C\ \ i\ \ \phi\ \ i \tag{2.14}$$

where:

$\theta^i\ \ j,k,l$ is the location of i th bacterium at j th chemotactic, k th reproductive, l th elimination and dispersal step,

$C\ \ i$ is the length of unit walk,

$\phi\ \ i$ is the direction angle of the j th step

The fitness function of the i th bacterium is determined based on its position and is represented by $J=J\ \ i,j,k,l$ (Kiani *et al.*, 2013). The direction angle $\phi\ \ i$ describes the tumble of the bacteria and is given by (Boussaid *et al.*, 2013):

$$\phi\ i\ = \frac{\Delta\ i}{\sqrt{\Delta^T\ i\ \Delta\ i}} \tag{2.15}$$

where:

$\Delta\ i\ \in \square^{p}$ is a randomly generated vector with elements within the interval $-1,1$,

^{T} is the transpose, and

$\square$ is a set of real numbers.

2.2.7.2 Swarming

The attractive and repulsive effects possessed by each bacterium are used as a medium of communication to others. The bacteria under the stresses circumstances, release attractants to signal bacteria to swarm together, while repellent are released to signal others to maintain a minimum distance from it (Xing andGao, 2014). The cell-to-cell signalling of the bacteria can be represented by (Xing andGao, 2014):

$$\begin{aligned} J_{cc} = \ \theta, P\ \ j,k,l\ \ &= \sum_{i=1}^{S} J_{cc}^{i}\ \ \theta, \theta^{i}\ \ \ j,k,l \\ &= \sum_{i=1}^{S}\left[-d_{attract} \exp\left(-\omega_{attract} \sum_{m=1}^{p}\ \theta_m - \theta_m^{i}\ ^{2} \right) \right] \\ &+ \sum_{i=1}^{S}\left[h_{repellant} \exp\left(-\omega_{repellant} \sum_{m=1}^{p}\ \theta_m - \theta_m^{i}\ ^{2} \right) \right] \end{aligned} \tag{2.16}$$

where:

$J_{cc} = \ \theta, P\ \ j,k,l\ \ $ is the swarming objective function value to be added to the actual objective function,

S is the total number of bacteria,

p is the number of variables to be optimized which are present in each bacterium,

$\theta = \left[\theta_1 \quad \theta_2 \quad \cdots \quad \theta_p \right]^T$ denotes a point in the p -dimensional search domain,

$d_{attract}$ is the depth of the attractant released by the cell,

$\omega_{attract}$ is a measure of the width of the attractant signal,

$h_{repellant}$ is the height of the repellent effect,

$\omega_{repellant}$ is a measure of the width of the repellent.

The fitness of each position is determined by (Boussaid *et al.*, 2013):

$$J\ i,j,k,l\ = J\ i,j,k,l\ + J_{cc}\ \theta, P\ j,k,l \tag{2.17}$$

2.2.7.3 Reproduction

The idea behind reproduction in E. Coli bacteria is that nature tends to eliminate animals with poor foraging strategies and retain those with better ones (Kiani *et al.*, 2013). After N_c chemotaxis steps, the reproduction step should be performed by sorting the health of all bacteria based on fitness described by a fitness function (Kiani *et al.*, 2013):

$$J^i_{health} = \sum_{j}^{N_c+1} J\ i,j,k,l \tag{2.18}$$

The S_r bacteria (the population of the bacteria divided into two equal halves) with least health due to insufficient nutrient eventually die leaving the healthiest to split into two identical bacteria and placed at the same location (Xing andGao, 2014).

2.2.7.4 Elimination and Dispersion

The process of elimination and dispersion is executed after N_{re} reproduction steps in order to avoid being involved in local optima. Each bacterium is subjected to elimination and dispersal within the environment according to a probability P_{ed} . N_{el} is the number of elimination and dispersal steps. If a bacterium is eliminated then it is

dispersed to a new (random) location of the nutrient environment in order to maintain the original bacteria population (Boussaid *et al.*, 2013).

Below is the complete pseudo-code for implementation of BFA as presented by(Boussaid *et al.*,2013) and (Ali andAbd-Elazim, 2013). The flow chart is shown in Figure 2.8.

[Step 1] Initialize parameters:

$p, S, N_s, N_c, N_{re}, N_{ed} P_{ed}, C\ i\ , \theta^i\ \ i = 1,2,...,S\ , d_{attract}, \omega_{attract}, h_{repelent}, \omega_{repelent}$

[Step 2] Elimination-dispersal loop:

for $l = l + 1$

[Step 3] Reproduction loop:

for $k = k + 1$

[Step 4] Chemotaxis loop:

for $j = j + 1$

4.1 ***for*** *each bacterium* $i = 1, 2, ..., S$,

4.2 *Compute cost function* $J\ \ i, j, k, l$ *using equation (2.17)*

4.3 $J_{last} = J\ \ i, j, k, l$

4.4 *Tumbling: Generate a random vector* $\Delta\ \ i\ \in \square^{\ p}$

4.5 *Move: Compute* $\theta^i\ \ j+1, k, l$ *using equation (2.14)*

4.6 *Compute cost function* $J\ \ i, j+1, k, l$ *using equation (2.17)*

4.7 *Swim:* $m = 0$ *(counter for swim length)*

while $m < N_s$

$m = m + 1,$

if $J\ \ i, j+1, k, l\ < J_{last}$ ***then***

$J_{last} = J\ \ i, j+1, k, l$

Move: Compute $\theta^i\ \ j+1, k, l$ *using equation (2.14)*

Compute cost function $J\ \ i, j+1, k, l$ *using equation (2.17)*

else

$m = N_s$

end

end

[Step 5] if $j < N_c$***,*** *go to step 4*

[Step 6] Reproduction:

for $i = 1, 2, ..., S$,

6.1Compute J_{health}^{i} *using equation (2.18)*

end

6.2 Sort bacteria in order of ascending J_{health} *(higher cost means lower health). The least healthy bacteria* S_r *die and other healthier bacteria split each into two bacteria, which are placed in the same location.*

end

[Step 7] if $k < N_{re}$ *go to step 3*

[Step 8] Elimination-dispersal:

for $m = 1, 2, ..., S$,

8.1 ***if*** $p_{ed} > rand$ *(Generate random number for each bacterium and if the generated random number is smaller than* p_{ed} *then eliminate/disperse the bacterium)*

Generate new random positions for bacteria

else

Bacteria keep their current position (bacteria are not dispersed)

end

end

if $l < N_{ed}$ ***,*** *go to step 2;*

else

end.

Yes

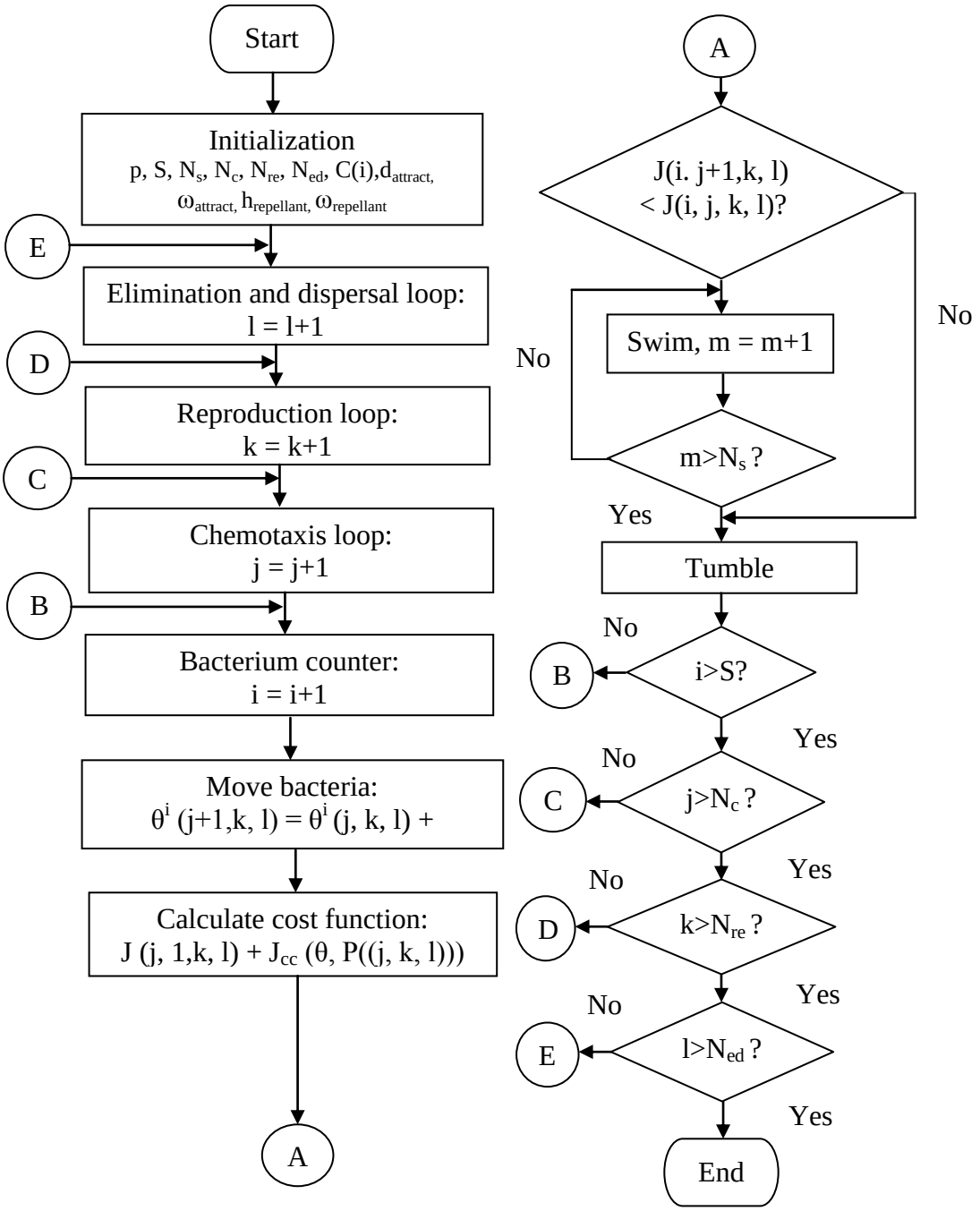


Figure 2.8: Flow Chart of Bacteria Foraging Algorithm (BFA) Passino (2002).

2.2.8 Improved Bacterial Foraging Algorithm (IBFA)

BFA has been used successfully in solving various complex power system optimization problems. As with all other meta-heuristic optimization algorithms, the BFA is also characterised with drawbacks among which are complexity, high computational time, parameters selection and the possibility of being trapped in local minima or even missing the optimum point. Researchers have proposed several improvements to the

BFA so as to enhance its performance by reducing the algorithm complexity and computational time. This research uses the IBFA as proposed by (Supriyono andTokhi, 2010).

To mitigate the drawbacks of complexity and high computational time associated with the BFA, two parameters are to be considered:

1. Run-length unit $C\ i$; and
2. Cell-to-cell signalling mechanism $J_{cc}\ \theta, P\ j,k,l$ used for swarming.

In order to locate the region with the highest concentration of nutrient, the BFA employs a fixed run-length unit all through the search process. A small value of the run-length unit will guarantee the optimum result at a higher computational time. On the other hand, a large run-length unit will result in the bacterium oscillating around the optimum point and probably risking the chance of missing the optimum value completely (Supriyono andTokhi, 2010). To balance the trade-off between high computational time and the possibility of the bacteria missing the optimum value, the run-length unit is made adaptive based on the fitness function. The idea is to apply a large run-length when the bacterium is far from the optimum point and a small run-length unit when the bacterium is close to the optimum point. To make the run-length unit adaptive, three different functions namely, linear, quadratic and exponential have been adopted due to their simplicity (Supriyono andTokhi, 2010).

2.2.8.1 Linearly Adaptive Bacterial Foraging Algorithm

The linearly adaptive bacterial foraging algorithm (LABFA) uses linear function for updating the run-length unit. The modified linear adaptive run-length unit is formulated as follows (Supriyono andTokhi, 2010):

$$C_l\ i\ = \frac{c_{max}}{1+\frac{\alpha}{\beta\left|J\ i\right|}} \tag{2.19}$$

where;

$C_l\ i$ is linearly adaptive run-length unit for each bacterium,

c_{max} is tuneable maximum run-length unit,

$\left|J\ i\right|$ is absolute of cost function of every bacterium,

α *and* β are tuneable positive factor and scaling factor respectively

2.2.8.2 Quadratic Adaptive Bacterial Foraging Algorithm

The quadratic adaptive bacterial foraging algorithm (QABFA) uses quadratic function for updating the run-length unit. The run-length unit is thus formulated as follows (Supriyono andTokhi, 2010):

$$C_q\ i\ = \frac{c_{max}}{1+\frac{\alpha}{\beta\ \left|J\ i\right|^2+\left|J\ i\right|}} \tag{2.20}$$ $C_q\ i$

is quadratic adaptive run-length for every bacterium

2.2.8.3 Exponentially Adaptive Bacterial Foraging Algorithm

The exponentially adaptive bacterial foraging algorithm (EABFA) uses an exponential function for updating the run-length unit, as follows (Supriyono andTokhi, 2010):

$$C_e\ i\ = \frac{c_{max}}{1+\frac{\alpha}{\beta e^{\left|J\ i\right|}}} \tag{2.21}$$

$C_e\ i$ is exponentially adaptive run-length for every bacterium

2.3 Review of Similar Works

Over the years, different techniques have been employed for optimal siting and sizing of D-STATCOM in radial distribution networks. Detailed reviews of some literatures on recent works accomplished in this area are presented in this sub-section.

Farhoodnea *et al.*, (2013)presented a novel approach to optimally locate Distribution Static Synchronous Compensators (D-STATCOMs) in radial distribution networks using Firefly Algorithm (FA). In this work, average voltage total harmonic distortion (THD_V), average voltage deviation and total investment cost are considered as the objective functions. The performance of the proposed technique was applied on a radial IEEE 16-bus test system and was reported to produce superior results when compared with PSO and GA. The values of the weighting factors used in the work were simply based on theoretical assumptions and cannot be guaranteed to provide optimal results when applied on real network. However, the research failed to consider total system power loss as part of its multi-objective function.

Hussain and Subbaramiah, (2013)proposed an effective analytical method for optimal location of D-STATCOM in radial distribution system for power losses minimization and voltage profile improvement. In this work, a backward forward sweep technique was applied for load flow analysis. The D-STATCOM was modelled and its size determined by assuming a voltage magnitude of 1p.u. at the candidate node. An objective function comprising of total system losses and system voltage profile was used for optimal location of D-STATCOM. The method was tested on a standard IEEE 33-bus radial distribution system. However, the cost of D-STATCOM and other associated benefits were not considered, and the work could not clearly present the necessary network constraints needed for the optimal placement of D-STATCOM.

Furthermore, the approach is only guaranteed for allocation of single D-STATCON in a given network.

Jain *et al.,* (2014)presented an improved method tothe analytical approach proposed by (Hussain &Subbaramiah, 2013). Here, the authors considered load current, BIBC matrix and forward sweep for power flow analysis using on a standard IEEE 33-bus radial distribution test system. The power flow was performed by implementing the compensating values for constant power (CP), constant current (CI), constant impedance (CZ) and finally composite load of 30% constant impedance, 20% constant current, 50% constant power load. A sensitivity based approach to optimal placement of D-STATCOM was adopted. Although the result of the improved method showed great reduction in system power loss and improvement in system voltage profile, the sensitivity analysis comes with the burden of mathematical complexity.

Repalle *et al.,* (2014) proposed an effective fuzzy logic based approach to identify the optimum location for D-STATCOM placement in radial distribution networks for losses minimization and voltage profile improvement. In this work, a backward forward sweep load flow program was used to perform the network load flow analysis. The optimal size of D-STATCOM was calculated by modelling it, to maintain the voltage magnitude as 1 p.u. A multi-objective function comprising of total network losses, voltage profile and cost of D-STATCOM was formulated and applied to determine the optimal location of D-STATCOM using fuzzy logic. Analysis was carried out on IEEE 33-bus radial distribution network with different sizes of D-STATCOM. However, the research failed to present any cost analysis of the D-STATCOM which results in inaccuracy in the values of annual energy savings. Also, the research failed to report the numerical values

of each weighting factor used because a wrong weighting factor impact negatively on the accuracy of the approach.

Taher and Afsari, (2014)proposed a novel approach to the optimal location and sizing of D-STATCOM for power loss reduction in radial distribution systems by immune algorithm (IA) . In their work, the backward/forward sweep technique was used for load flow calculations. An objective function comprising of total cost of power loss, D-STATCOM installations and deviation of node's voltage and line's current was formulated. The D-STATCOM was modelled with an assumed voltage magnitude of 1p.u. at the candidate node, while the IA was employed to determine the optimal size of D-STATCOM. Three load levels (Light, Medium and Peak) were selected for annual load profile modelling at different time duration. The results of the proposed approach as tested on standard IEEE 33 and 69-bus radial distribution systems was found to perform better when compared to GA. However, the research is restricted to only reactive power exchange between D-STATCOM and the network.

Devi and Geethanjali, (2014a)proposed a Modified Bacterial Foraging Optimization (MBFO) algorithm for optimal placement and sizing of distributed generation in radial distribution systems. The work focuses on improving the drawback of slow convergence in BFO algorithm by modifying the elimination and dispersal step using the knowledge of worst and best bacterium instead of P_{ed},which is time consuming. The proposed algorithm was tested on standard IEEE 12, 34 and 69-bus distribution system with an objective of reducing total power loss and improving voltage profile. It was found that MBFO algorithm provides better results in terms of accuracy and high convergence speed when compared to BFO. However, the research failed to consider

the complexity of the BFO. Also, no scientific justification was given for the choice of parameters used for both the BFO and MBFO algorithm.

Devi and Geethanjali, (2014b)proposed a Particle Swarm Optimization (PSO) approach for optimal location and sizing of Distributed Generation (DG) and D-STATCOM in radial distribution systems based on Loss Sensitivity Factor (LSF). In this work, it is considered that the real power is provided by DG and the reactive power is compensated by D-STATCOM. A slightly modified LSF was used to determine the best possible buses for the placement of DG and D-STATCOM and the optimal location and sizing of DG and D-STATCOM is done using PSO. A performance analysis was carried out on three different IEEE standard test buses (12, 34 and 69-bus) for five different cases. The results of the analysis revealed better improvement in voltage profile and reduction in total power loss of the systems for some cases. However, the work did not consider the possibility of using multiple DGs with D-STATCOM for total power loss reduction and voltage profile improvement in radial systems.

Bagheri *et al.,* (2015)presented a new fuzzy-ACO-based algorithm for simultaneous reconfiguration and optimal allocation of PV and D-STATCOM units in radial distribution networks for mitigating power loss (P_{loss}), improving voltage profile (VP), and increasing feeder load balancing (LB) in radial distribution networks. The proposed approach was applied on two test systems at load levels of 0.5 (light), 1.0 (nominal), and 1.6 (heavy) for five different cases. Results obtained from the proposed method was compared with two other techniques of fuzzy –GA and fussy-PSO. It was found that among the three terms P_{loss}, VP, and LB, the improvement in P_{loss} is more significant as compared to VP and LB. Also, the simultaneous reconfiguration and optimal placement of PV and D-STATCOM units has greatly improved system VP for all three methods on

both test systems. However, the research failed to consider the optimum cost of PV and D-STATCOM as part of its multi-objective function. Also, maintaining the total number of tie switches after reconfiguration is tasking and time consuming in real networks, hence require complex mathematical computation and precise choice of parameters respectively.

Gupta and Kumar, (2015)presented an analytical approach for determining optimal location and size of D-STATCOM for radial distribution networks with the aim of reducing loss, improving voltage profile and overall energy saving. Two different sensitivity methods: the power loss index (PLI) and voltage stability index (VSI) were applied to determine the optimal location of D-STATCOM. Optimal size of D-STATCOM was calculated using variational technique. The approach was carried out on standard IEEE 33-bus test system. It was observed that the size of D-STATCOM was lower as compared to results obtained from other approaches. The size of D-STATCOM used in the variational technique ranges from 0-2000KVA with a step size of 50KVR. However, for every increase in the value of D-STATCOM, a new power flow analysis must be performed which is time consuming and computationally complex to execute.

Devabalaji *et al.*, (2015) proposed a Bat algorithm (BA) based optimal sizing and placement of capacitor banks in radial distribution network for power loss minimization. Loss Sensitivity Factor (LSF) is employed to pre-identify the optimum location of the capacitor banks while the bat algorithm was used in the search for optimal size. Analysis was performed on IEEE 34-bus radial distribution network considering network net savings. The results of the proposed approach was found to be better when compared with those of PSO, PGSA and DE-PS approaches respectively.

However, the process of incorporating the capacitor banks in each of the possible locations predetermined by LSF to obtain the optimum location is time consuming and computationally complex.

Devabalaji and Ravi, (2015)proposed a novel approach to optimal location and sizing of multiple DGs and D-STATCOM in radial distribution systems based on the combination of LSF and BFOA. The research considered a predetermined location for DGs and D-STATCOM using LSF, while optimal size is determined using BFOA. A multi-objective function comprising of power loss, voltage profile index and operational cost of the system is minimized. Analysis with eight different cases was carried out on two standard IEEE test networks (33 and 169-bus) using the proposed method. Results obtained from the different analysis indicated a better superiority of the proposed approach over others used in past works. However, the trial and error method adopted in sorting for the candidate bus for location of DG and D-STATCOM is characterized by computational complexity, high computational time and has no proven scientific basis.

Yuvaraj *et al.,* (2015) proposed a harmony search algorithm based approach for optimal location and sizing of D-STATCOM in radial distribution networks for power loss minimization and voltage profile improvement. In this work, a direct approach based on the Bus Injected to Branch Current (BIBC) matrix was applied for distribution system load flow analysis. The total annual cost saving, cost of D-STATCOM and annual investment cost analysis are considered. An objective function comprising of the network total active power loss is formulated for use in the harmony search algorithm. The effectiveness and performance of the proposed method was tested on standard IEEE 33-bus system and compared with Immune Algorithm (IA) approach. Although

the results of the proposed approach outperforms those of IA, the work failed to consider multiple D-STATCOM in reducing losses.

Yuvaraj *et al.,* (2015) proposed a new method of scheduling for optimal placement and sizing of Distribution Static Compensator (D-STATCOM) in radial distribution networks to minimize power loss. In this work, Voltage Stability Index was used to search the optimal place for installation of D-STATCOM, while bat algorithm was employed in the search for optimal size of D-STATCOM. A step size of 1% was used to vary the feeder loads of test networks from light (0.5) to peak (1.6). The optimal size of D-STATCOM at each of the load level is determined using Curve fitting technique (CFT). Analysis was carried out for single D-STATCOM and multiple D-STATCOMs placements on standard IEEE 33 and 69-bus radial distribution networks. The results of their work showed improvement in terms of active and reactive power reduction as well as the total annual cost saving for both test networks. However, the work could not justify the use of two different methods in the search for optimal size of D-STATCOM in the test networks. Also, the choice of 1% step size in the variation of feeder loads lacks any scientific justification.

Devabalaji *et al.,* (2016) proposed an efficient method for optimal placement and sizing of capacitor banks in radial distribution networks using cuckoo search algorithm (CSA). In this work, an objective function to minimize power losses and improve voltage profile of the network subject to equality and inequality constraint was formulated. Candidate buses for possible placement of capacitors in the network were determined using Voltage Sensitivity Index (VSI). The CSA was employed to determine the optimal size of the capacitor. The effectiveness of the proposed approach was tested on two standard IEEE test networks, the 34 and 69-bus radial distribution system, and the

results were compared with those obtained from other certain classical approaches. However, the calculation of VSI which depends on the topology, configuration and loading nature of the network is characterised with the burden of complex mathematical computation.

Shanmugasundaram and Babu, (2016) presented the application of D-STATCOM for loss minimization in radial distribution systems. In this work, the forward backward technique was employed in power flow analysis. The optimal location of D-STATCOM was determined using the bus sensitivity factor analysis. Analysis were performed with three capacitors and three D-STATCOMs on IEEE 33-bus radial distribution system. A comparison of network losses and savings between capacitors and D-STATCOMs was performed. However, the work failed to state the technique employed for sizing the capacitors and D-STATCOMS used for minimizing the network losses.

Chabok and Ashouri, (2016) proposes an optimal placement of D-STATCOMs in radial distribution networks in the presence of Distributed generations using a hybrid Discrete Imperialistic Competition and Nelder-Mead (DICA-NM) algorithm. In this work, Forward-Backward method is applied for power flow analysis. The network voltage control and reactive power management in annual scheduling time interval are considered. A weighted objective function defined in terms of network active power losses and voltage stability level at each bus is formulated. Voltage Stability Index (VSI) was applied in identifying weak buses, while the DICA-NM hybrid algorithm is used for sizing of D-STATCOMs. Analysis are conducted for three cases on IEEE 30-bus radial distribution test feeder to validate the performance and effectiveness of the proposed DICA-NM hybrid algorithm. However, the approach is characterised by

complex mathematical computation associated with the VSI analysis and slow convergence nature of the NICA-NM hybrid algorithm.

2.3.1 Summary of Literature

Apparently, it can be observed from the literatures reviewed so far that all the researches showed promising results in determining the locations and optimal size of D-STATCOM in radial distribution networks. However, none of the literatures reported the use of a single technique for determination of both the optimal site and size of D-STATCOM in the test networks, as all researchers have employed one technique forlocation and another for size. These approaches are characterised by rigorous mathematical analysis, algorithm complexity and high computational time. Furthermore, the literatures focus only on standard test networks and failed to consider the implementation of D-STATCOM on real power distribution networks.

In this research, improved bacterial foraging algorithm (IBFA) has been applied to the optimal siting and sizing of D-STATCOM in radial distribution networks to minimize power loss and enhance voltage profile.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

In this chapter, an elaborate procedure for the actualization of this research is discussed. The materials employed, optimal parameters settings used for both the conventional BFA and IBFA, the minimum and maximum voltage limits as well as the D-STATCOM limits are presented. Also, a comprehensive methodology adopted for this research is given.

3.2 Materials

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

3.2.1 Personal Computer

All simulations analyses were carried out using HP EliteBook 6930p personal computer with the following specifications:

1. Intel(R) Core(TM) 2Duo CPU P8700;
2. 2.53GHz 64-based processor;
3. 4.00GB installed memory (RAM); and
4. 32-bit windows 8 Operating System (OS).

3.2.2 MATLAB 2013a Software

Simulations are performed under virtual platform using MATLAB 2013a for analyses (Mathworks Corporation). The details of the program developed are provided in Appendix B.

3.2.3 Distribution Network Parameters

The standard IEEE 33-bus and a dedicated 50-bus Canteen Feeder in Zaria distribution network with the following network parameters: slack bus, active and reactive powers, bus voltages and bus voltage angles have been adopted for this research.

3.3 Methodology

The objectives as outlined are achieved in line with the following procedures:

3.3.1 Acquisition of Relevant Data

Data about the standard IEEE 33-bus radial distribution network and the 50-bus Canteen Feeder in Zaria distribution network used include:

1. Line data (resistance and reactance of each line in ohms);
2. Bus data (active and reactive power demand at each bus in kW and $kVAr$ respectively);
3. Network base voltage; and
4. Sending and receiving end buses

3.3.2 Base-case Power Flow Analysis

The pseudo-code used in developing the algorithm for running the base-case power flow analysis of the distribution networks are presented in this section; and the complete flow chart is shown in Figure 3.1. In addition to this, the MATLAB code is given in Appendix B1.

1. Load the network line and bus data;
2. Compute the load current at each bus of the network using equation (2.3);
3. Formulate the Bus Injected to Branch Current matrix (BIBC);
4. Assume a standard flat start voltage profile of $1.0 \angle\ 0^0$ p.u at all buses;

5. Compute the current flow $I_{B\,ik}$ at each branch of the network using equation (2.10);
6. Formulate the network Z-bus as presented by Elsaiah *et al,*. (2012);
7. Calculate the voltage and phase angle at each bus of the network using equation (2.11); and
8. Compute the line losses ($P_{ik\ loss}$ and $Q_{ik\ loss}$) using equations (2.12) and (2.13)

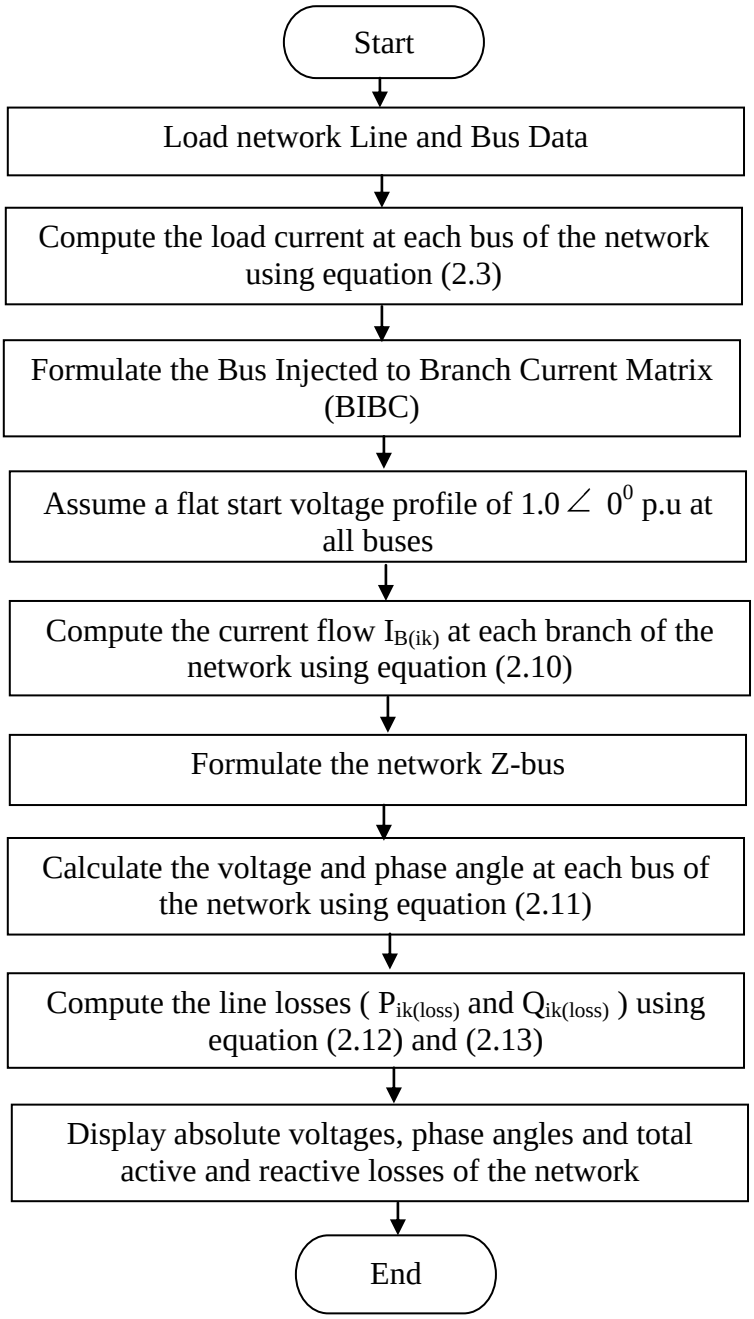


Figure 3.1: Flow Chart for Base Case Power Flow

3.3.3 Multi-Objective Algorithm Formulation

The essence of this research is to find a set of optimal trade-off between several conflicting objectives by introducing D-STATCOM into electric power networks at the distribution level. Consider a multi-objective problem with m decision variables (parameters) and n objectives:

$$Minimize\ y = f_1(x), f_2(x), ..., f_n(x) \tag{3.1}$$

$$x = x_1, x_2, ..., x_m \tag{3.2}$$

where;

x and y are the decision and objective vectors respectively.

3.3.3.1 Problem Formulation

Here, the objective is to accomplish two goals:

1. Minimize total active power loss, $P_{T\ loss}$; and
2. Minimize voltage deviation, V_D.

The network total active power loss function as modelled in equation (2.12) is given by:

$$P_{T\ loss} = \sum_{ik=1}^{N_{Branch}} \left| I_{B\ ik} \right|^2 * \Re\ Z_{ik} \tag{3.3}$$

The voltage deviation function is expressed by:

$$V_D = \sum_{k=1}^{N_{Bus}} V_k - V_k^{ref}\ ^2 \tag{3.4}$$

where V_k and V_k^{ref} are the per-unit (p.u) voltage values at bus k and the reference bus respectively.

The multi-objective function J can be formulated mathematically using the weighted sum of equations (3.3) and (3.4) to give:

$$min\ J = min\ \omega_1 P_{T\ loss} + \omega_2 V_D \tag{3.5}$$

Where ω_1 and ω_2 are the weighting metrics used for adjusting the network total active power loss and voltage deviation functions respectively. Due to the equal importance attached to both objectives in equation (3.5), a unit weighting metric was assigned to both objective functions. Thus, $\omega_1 = \omega_2 = 1$.

3.3.3.2 Constraints

The optimal siting and sizing of D-STATCOM is considered as a constrained optimization problem that deals with both equality and inequality constraints.

Equality Constraints

The equality constraints represent the power flow equations expressed as:

$$\sum_{k=1}^{N_{Bus}} P_{Gk} - P_{Dk} = P_L \tag{3.6}$$

$$\sum_{k=1}^{N_{Bus}} Q_{Gk} - Q_{Dk} = Q_L \tag{3.7}$$

where:

P_{Gk} and Q_{Gk} are the total active and reactive power generation at bus k respectively,

P_{Dk} and Q_{Dk} are the total active and reactive power demand at bus k respectively,

P_L and Q_L are the total active and reactive power losses.

Inequality Constraints

The inequality constraints represent the network load bus number, bus voltage and D-STATCOM size limits respectively given by:

$$\lambda_n^{\min} \le \lambda_n \le \lambda_n^{\max} \tag{3.8}$$

$$V_k^{\min} \le V_k \le V_k^{\max} \tag{3.9}$$

$$Q_n^{\min} \le Q_n \le Q_n^{\max} \tag{3.10}$$

The network voltage constraint limits has been set as 0.95 p.u. and 1.05 p.u. for $V^{\min}$ and $V^{\max}$, while the D-STATCOM was sized between 0 and 10,000 kVAr (Taher andAfsari, 2014).

3.3.4 Replication of the Improved Bacterial Foraging Algorithm

The IBFA was modelled based on the principle of chemotaxis, swarming, reproduction and elimination-dispersal. In order to improve computational time and avoid the possibility of being trapped in local minima, the IBFA was modelled using equations (2.19), (2.20) and (2.21) with appropriate tuneable and scaling factors respectively. Also, the cell-to-cell signalling mechanism explained by equation (2.16) was eliminated, as its performance in this work will only increase the algorithm complexity and reduce its accuracy. Below is a complete pseudo-code for implementation of the IBFA and the flow chart is shown in figure 3.2

[Step 1] Initialize parameters:

$p, S, N_s, N_c, N_{re}, N_{ed} P_{ed}, C\ i\ , \theta^i\ \ i = 1,2,...,S$

[Step 2] Elimination-dispersal loop:

for $l = l+1$

[Step 3] Reproduction loop:

for $k = k+1$

[Step 4] Chemotaxis loop:

for $j = j+1$

4.1 ***for*** *each bacterium* $i = 1,2,...,S$,

4.2 *Compute cost function* $J\ \ i, j, k, l$ *using equation (2.17) without the cell-to-cell signalling mechanism*

4.3 $J_{last} = J\ \ i, j, k, l$

4.4 *Tumbling: Generate a random vector* $\Delta\ \ i \in \square^{\ p}$

4.5 *Move: Compute* $\theta^i\ \ j+1, k, l$ *using equation (2.14)*

4.6 *Compute cost function* $J\ \ i, j+1, k, l$ *using equation (2.17)*

4.7 *Swim:* $m = 0$ *(counter for swim length)*

while $m < N_s$

$m = m + 1,$

if $J\ i, j+1, k, l\ < J_{last}$ ***then***

$J_{last} = J\ i, j+1, k, l$

Move: Compute $\theta^i\ j+1, k, l$ *using equation (2.14)*

Compute cost function $J\ i, j+1, k, l$ *using equation (2.17) without the cell-to-cell signalling mechanism*

else

$m = N_s$

end

end

[Step 5] if $j < N_c$***,*** *go to step 4*

[Step 6] Reproduction:

for $i = 1, 2, \ldots, S$,

6.1Compute J^i_{health} *using equation (2.18)*

end

6.2 Sort bacteria in order of ascending J_{health} *(higher cost means lower health). The least healthy bacteria* S_r *die and other healthier bacteria split each into two bacteria, which are placed in the same location.*

end

[Step 7] if $k < N_{re}$ *go to step 3*

[Step 8] Elimination-dispersal:

for $m = 1, 2, \ldots, S$,

8.1 ***if*** $p_{ed} > rand$ *(Generate random number for each bacterium and if the generated random number is smaller than* p_{ed} *then eliminate/disperse the bacterium)*

Generate new random positions for bacteria

else

Bacteria keep their current position (bacteria are not dispersed)

end

end

if $l < N_{ed}$ ***,*** *go to step 2;*

else

end.

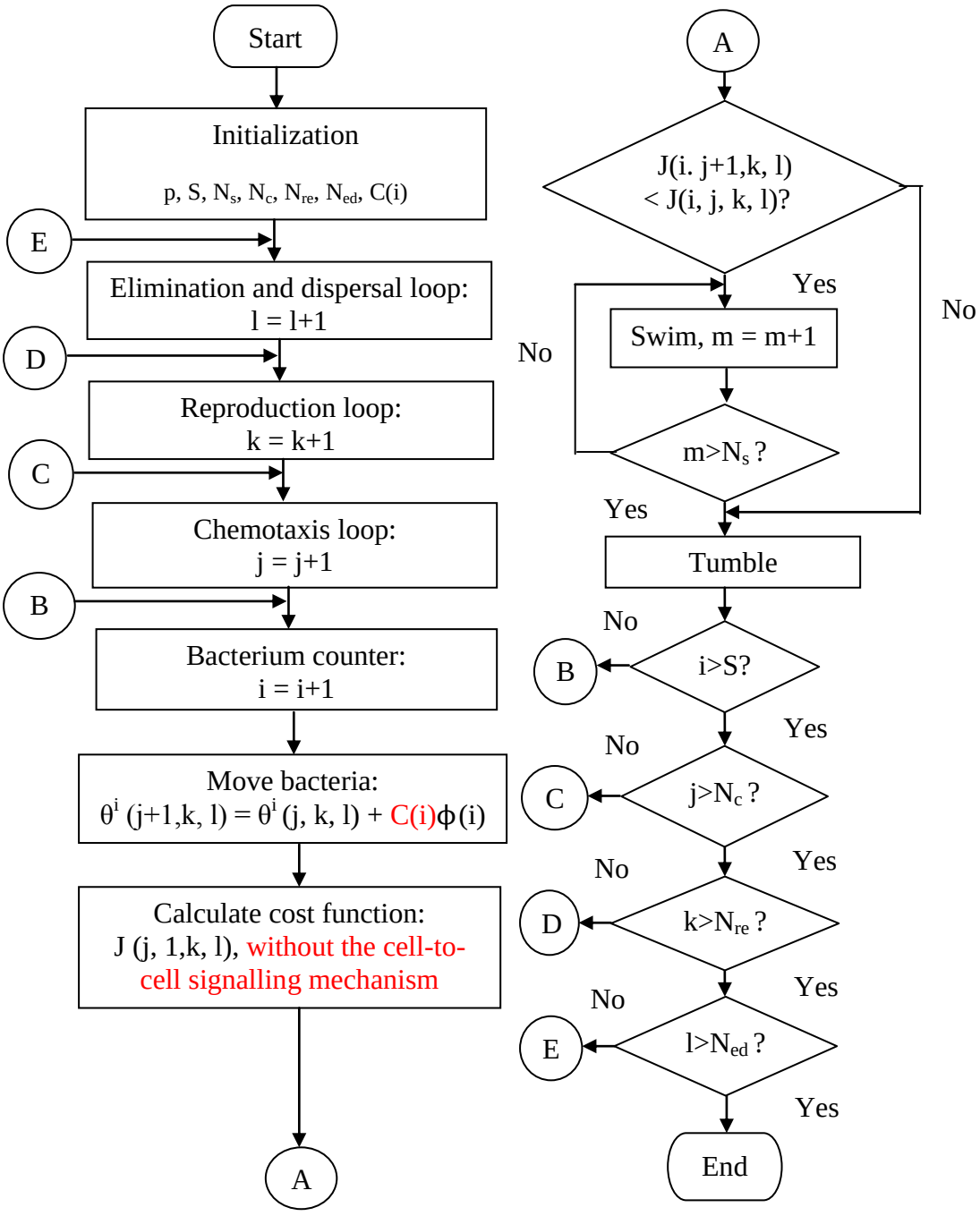


Figure 3.2: Flow Chart of the Improved Bacteria Foraging Algorithm (IBFA).

3.3.4.1 Parameter Selection

For the purpose of this research, the initialization and user-defined parameters for both the conventional BFA and IBFA are presented in table 3.

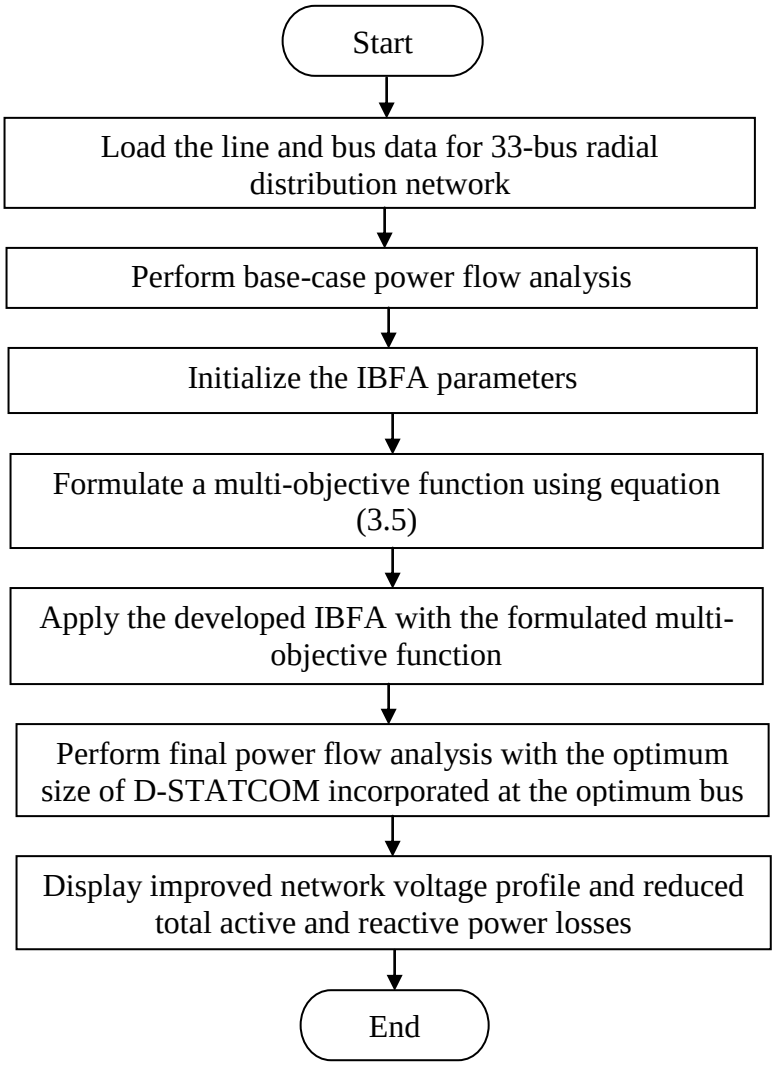
Table 3.1: Parameters Setting for BFA and IBFA (Supriyono andTokhi, 2010)

Parameters	**Values**
Dimension of search space, p	2
Number of bacteria, S	10
Number of chemotactic steps, N_c	4
Number of swim steps, N_s	4
Number of reproductive steps, N_{re}	4
Number of elimination-dispersal steps, N_{ed}	3
Run-length unit $C\ i$	0.1
Number of bacteria reproductions (splits) per generation, S_r	S/2
The probability that each bacteria will be eliminated/dispersed, P_{ed}	0.25
Depth of attractant, $d_{attract}$	0.1
Width of attractant, $\omega_{attract}$	0.2
Height of repellent, $h_{repellant}$	0.1
Width of repellent, $\omega_{repellant}$	10
Tuneable factor, α	1
Scaling factor, β	0.01

3.3.5 Implementation

The steps involved in implementing the developed IBFA are presented in this section. Figure 3.3 shows the flow chart of the algorithm and the MATLAB code is presented in Appendix B2.

1. Load the line and bus data of the 33-bus radial distribution network;
2. Perform base-case power flow analysis for the 33-bus radial distribution network;
3. Initialize the IBFA parameters;
4. Formulate a multi-objective function using equation (3.5);
5. Apply the replicated IBFA with the formulated multi-objective function;and



6. Perform final power flow analysis with the optimum size of D-STATCOM incorporated at the optimum bus

Figure 3.3: Flow Chart for Power Flow with D-STATCOM Incorporated in Network

3.3.6 Comparison of Results

The results obtained after implementation of the approach are compared with those of the conventional BFA, and with the analytical and bat algorithm (BA) approaches by:

1. Graphical representation (voltage profile improvement);
2. Bar-chart representation (active power loss reduction); and
3. Tabular representation (percentage active and reactive power loss reduction, bus location, size of D-STATCOM, etc.)

The complete MATLAB codes for representations of all voltage profile and power loss analysis are presented in Appendix B4.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, results and discussion of the theoretical concepts from the previous two chapters are presented. The effectiveness of the developed IBFA is validated on the standard IEEE 33-bus radial distribution network and compared with the conventional BFA, analytical and bat techniques. A practical 50-bus Canteen Feeder in Zaria distribution network was considered for implementation of the proposed technique. In both networks, two different cases were considered for analysis:

Case I: Network without D-STATCOM (Base-case)

Case II: Network with D-STATCOM installed

4.2 The Standard IEEE 33-Bus Radial Distribution Network

The standard IEEE 33-bus radial distribution network discussed in sub-section 2.2.6.1 with line and bus data given in Appendix A1 is modelled based on the theoretical concepts presented in chapter two. The results obtained from Case I and Case II are used for comparison with existing results reported in literatures.

4.2.1 Case I: Network without D-STATCOM (Base Case)

The network base case power flow is performed using the modelling equations given in sub-section 2.2.5. Results of the analysis (voltage magnitude, phase angle and power loss) for each bus are presented in table 4.1. The total active power loss of the network is obtained as 201.8125 kW.

Table 4.1: 33-Bus IEEE Radial Distribution Network Base Case Power Flow Results

Bus Number	Voltage Magnitude (p.u)	Phase angle (degree)	Power Loss (kW)
1	1.0000	0	12.1927
2	0.9970	0.0148	51.5711
3	0.9830	0.0985	19.7934
4	0.9755	0.1658	18.5931
5	0.9682	0.2341	38.0256
6	0.9498	0.1446	1.9131
7	0.9463	-0.0872	4.8342
8	0.9415	-0.0539	4.1773
9	0.9352	-0.1312	3.5575
10	0.9294	-0.1980	0.5531
11	0.9286	-0.1914	0.8802
12	0.9271	-0.1812	2.6638
13	0.9210	-0.2778	0.7286
14	0.9187	-0.3585	0.3569
15	0.9173	-0.3976	0.2813
16	0.9160	-0.4223	0.2515
17	0.9140	-0.5017	0.0531
18	0.9134	-0.5120	0.1610
19	0.9965	0.0039	0.8322
20	0.9929	-0.0636	0.1008
21	0.9922	-0.0831	0.0436
22	0.9916	-0.1036	3.1812
23	0.9794	0.0673	5.1432
24	0.9727	-0.0220	1.2873
25	0.9694	-0.0662	2.5940
26	0.9479	0.1858	3.3211
27	0.9453	0.2443	11.2766
28	0.9339	0.3386	7.8180
29	0.9257	0.4249	3.8881
30	0.9222	0.5338	1.5928
31	0.9180	0.4534	0.2131
31	0.9171	0.4312	0.0132
33	0.9168	0.4237	12.1927

4.2.2 Case II: Network with D-STATCOM

After the network base case power flow analysis, the conventional BFA and IBFA developed in sub-section 2.2.7 and 2.2.8 are applied to determine both the optimal size and site of D-STATCOM to be incorporated into the test network. The average optimal size of D-STATCOM were found to be 2577 kVAr and 3351 kVAr respectively, while the optimal site were at bus 30 and 26. The results obtained after final power flow

analysis with D-STATCOM installed showed a reduction of the total active power loss to 190.5254 kW and 191.0473 kW for both approaches. A clear picture of the effect of D-STATCOM on the voltage profile, phase angle and power loss for each bus of the network is given in table 4.2 and 4.3 for the conventional BFA and IBFA approaches respectively.

Table 4.2: 33-Bus IEEE Radial Distribution Network Power Flow Results with

D-STATCOM using Conventional BFA

Bus Number	**Voltage Magnitude (p.u)**	**Phase angle (degree)**	**Power Loss (kW)**
1	1.0000	0	7.9829
2	0.9980	-0.0749	33.4526
3	0.9890	-0.4764	13.7107
4	0.9853	-0.7711	13.4553
5	0.9818	-1.0822	27.9835
6	0.9772	-1.9661	1.8006
7	0.9742	-2.1988	4.5473
8	0.9695	-2.1883	3.9264
9	0.9635	-2.2882	3.3431
10	0.9580	-2.3764	0.5196
11	0.9571	-2.3740	0.8269
12	0.9557	-2.3711	2.5017
13	0.9499	-2.4890	0.6841
14	0.9478	-2.5748	0.3350
15	0.9465	-2.6177	0.2641
16	0.9452	-2.6471	0.2360
17	0.9434	-2.7306	0.0498
18	0.9428	-2.7429	0.1606
19	0.9975	-0.0858	0.8306
20	0.9939	-0.1539	0.1006
21	0.9932	-0.1735	0.0435
22	0.9925	-0.1941	3.1416
23	0.9854	-0.5114	5.0790
24	0.9788	-0.6075	1.2712
25	0.9755	-0.6551	4.4773
26	0.9774	-2.1225	6.2382
27	0.9778	-2.3401	23.1856
28	0.9842	-3.2282	17.4988
29	0.9895	-3.8808	11.3077
30	0.9913	-4.2544	1.3756
31	0.9877	-4.3605	0.1840
31	0.9869	-4.3877	0.0114

33	0.9867	-4.3966	7.9829

Table 4.3: 33-Bus IEEE Radial Distribution Network Power Flow Results with D-STATCOM using IBFA

Bus Number	**Voltage Magnitude (p.u)**	**Phase angle (degree)**	**Power Loss (kW)**
1	1.0000	0	8.7849
2	0.9982	-0.1010	38.7180
3	0.9904	-0.6432	19.2030
4	0.9875	-1.0419	19.4440
5	0.9851	-1.4610	41.0596
6	0.9840	-2.5729	1.7743
7	0.9811	-2.8060	4.4802
8	0.9764	-2.8016	3.8677
9	0.9705	-2.9076	3.2929
10	0.9650	-3.0016	0.5118
11	0.9642	-3.0004	0.8144
12	0.9628	-2.9994	2.4638
13	0.9571	-3.1231	0.6738
14	0.9550	-3.2103	0.3299
15	0.9538	-3.2543	0.2600
16	0.9525	-3.2849	0.2324
17	0.9507	-3.3695	0.0491
18	0.9501	-3.3825	0.1606
19	0.9977	-0.1120	0.8302
20	0.9941	-0.1803	0.1005
21	0.9934	-0.1999	0.0435
22	0.9928	-0.2205	3.1325
23	0.9868	-0.6794	5.0643
24	0.9802	-0.7774	1.2675
25	0.9770	-0.8260	8.5261
26	0.9847	-2.7837	3.0671
27	0.9822	-2.7451	10.4115
28	0.9711	-2.7277	7.2170
29	0.9632	-2.6992	3.5887
30	0.9596	-2.6214	1.4694
31	0.9557	-2.7217	0.1965
31	0.9549	-2.7479	0.0121
33	0.9546	-2.7565	8.7849

An average computational time of 7.145422 seconds was recorded for the conventional BFA, while 4.881136, 4.958691 and 4.956823 seconds were recorded for the linearly, quadratic and exponentially adaptive run-length units of the IBFA respectively.

4.2.2.1 Network Voltage Profile with D-STATCOM using BFA and IBFA

The application of both conventional BFA and IBFA to the optimal siting and sizing of the D-STATCOM in the network has improved the voltage profile of the entire network as shown in table 4.2 and 4.3. The voltage magnitudes shown in table 4.1, 4.2 and 4.3 are plotted against their corresponding bus numbers. A clear improvement in voltage profile of the network after incorporating D-STATCOM using the conventional BFA and IBFA is shown in Figure 4.1.

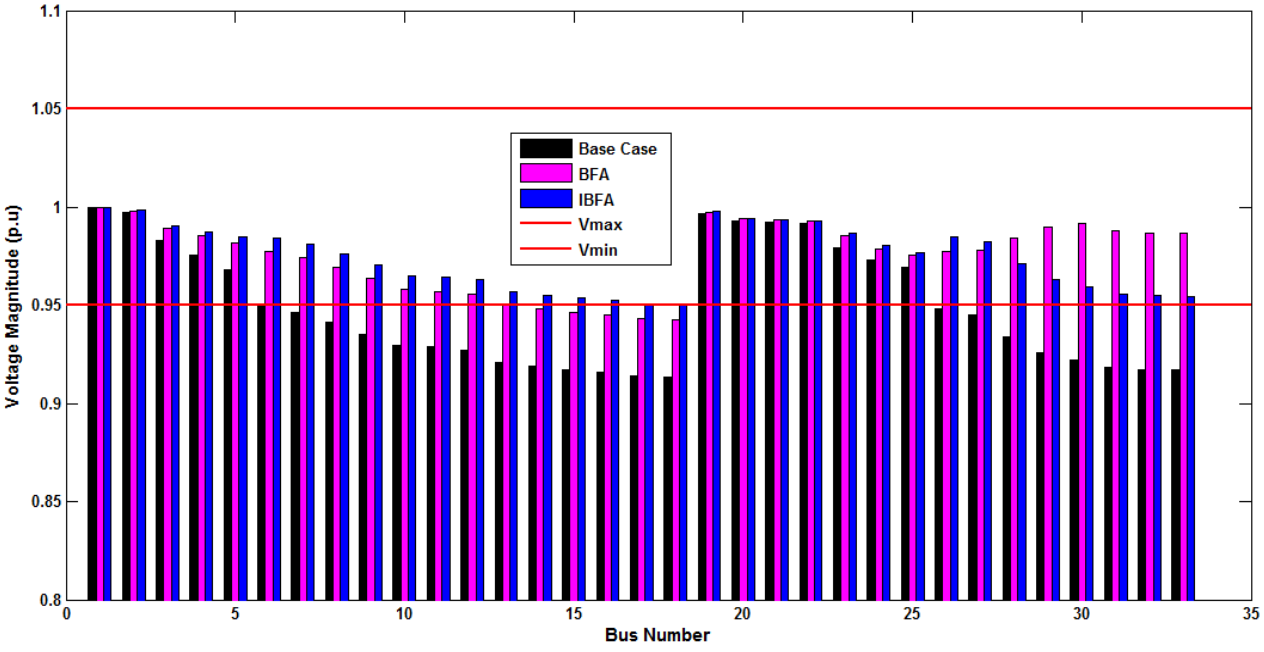
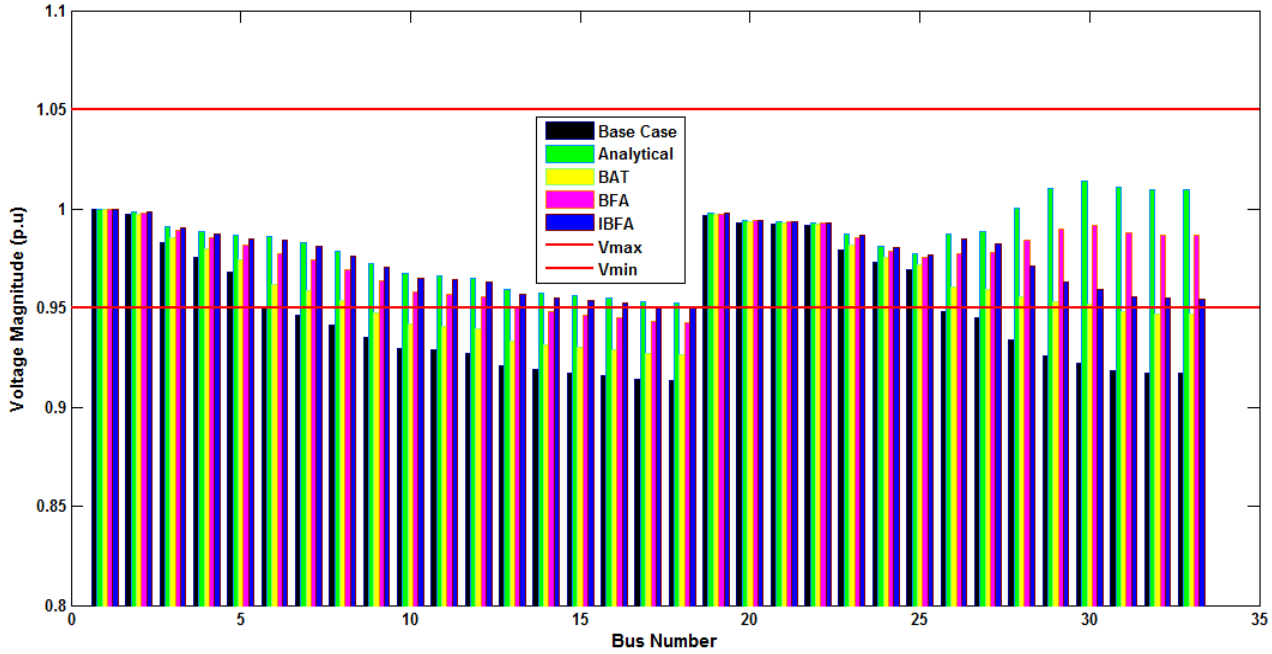


Figure 4.1: Voltage Profile Improvement for 33-Bus IEEE Radial Distribution Network with D-STATCOM using BFA and IBFA

The entire voltage profile of the network with D-STATCOM has been improved by 82.88 % using the conventional BFA and 87.96 % using IBFA as compared to the base case voltage profile.



4.2.2.2 Performance Comparison for Voltage Profile Improvement

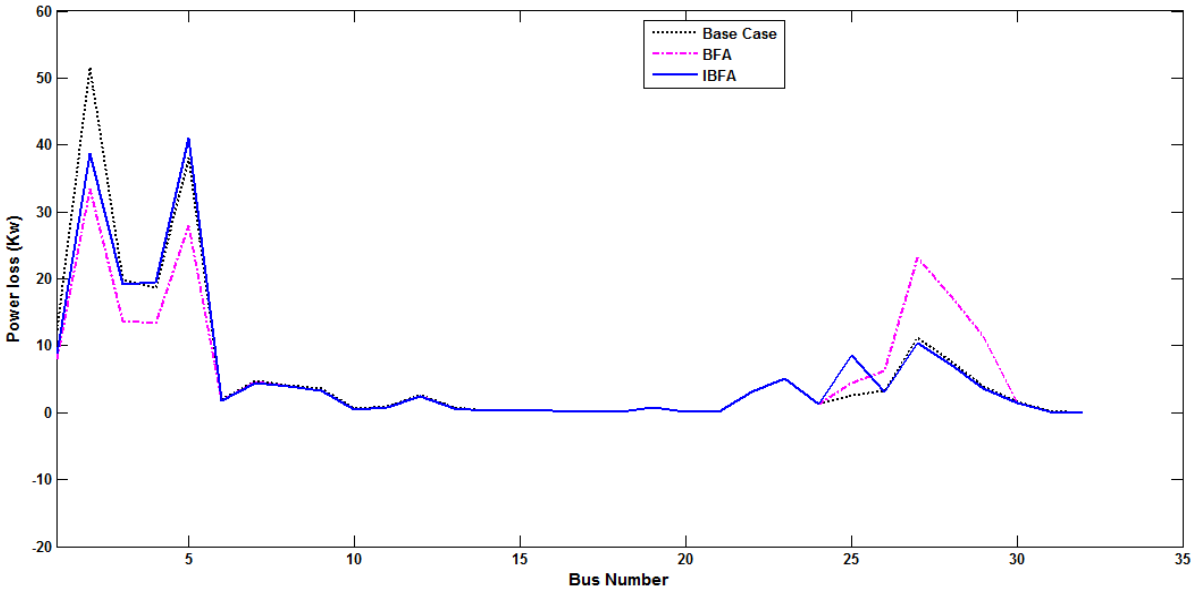
A plot of the overall voltage profile improvement results using BFA, analytical, Bat Algorithm (BA) and IBFA approaches for optimal siting and sizing of D-STATCOM in the network is shown in Figure 4.2.

Figure 4.2: Voltage Profile Improvement for 33-Bus IEEE Radial Distribution Network with D-STATCOM using Analytical, BAT, BFA and IBFA

From Figure 4.2, it can be observed that the optimal siting and sizing of D-STATCOM in the test network has improved the network voltage profile. Bus 18 which has the least value of voltage magnitude (0.9134 p.u) has been improved to 0.9523 p.u, 0.9262 p.u, 0.9428 p.u and 0.9501 p.u after incorporating D-STATCOM into the network using analytical, BA, BFA and IBFA approaches respectively. Obviously, it can be seen that the trend of voltage profile for both the BA and IBFA approaches are in conformity with that of the base case, while the same cannot be said of the analytical and conventional BFA approaches. An overall voltage profile improvement of 115.07 %,

37.96 %, 82.88 % and 87.96 % was recorded for analytical, BA, BFA and IBFA approaches respectively with respect to the base case.

The total number of buses out of constraint limits for analytical, BA, BFA and IBFA are



0, 13, 6 and 0 respectively as compared to the base-case value of 21.

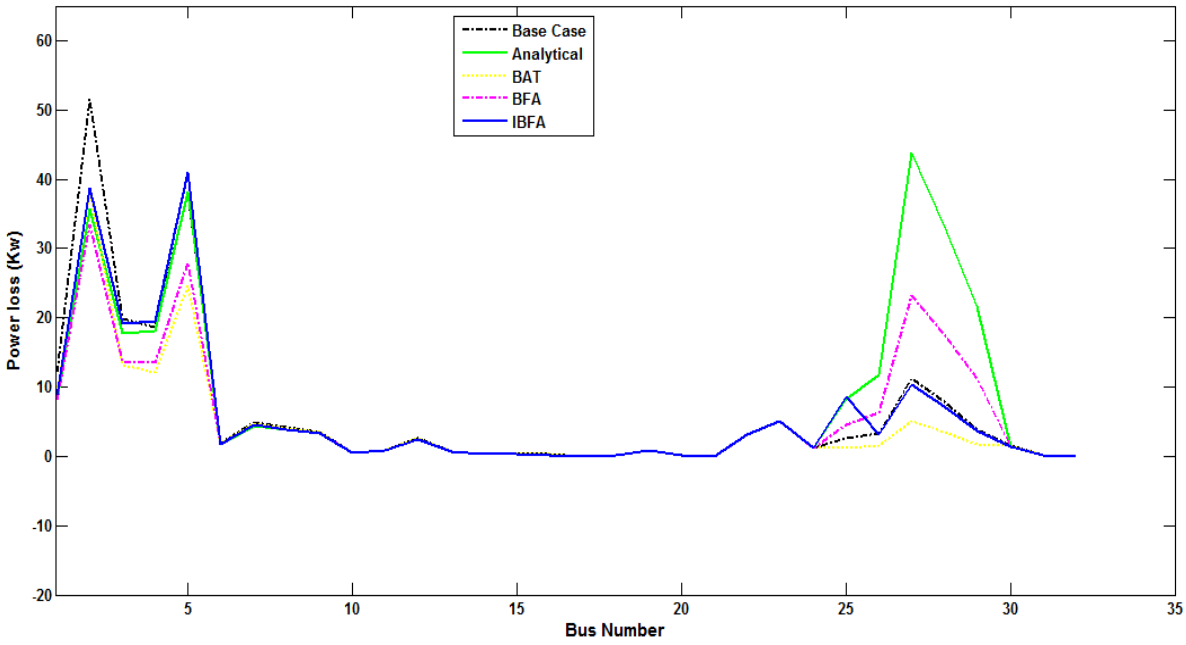
4.2.2.3 Network Power Loss with D-STATCOM using BFA and IBFA

The results of network power losses for both cases as presented in Tables 4.1, 4.2 and 4.3 are plotted against their respective bus numbers and shown in Figure 4.3.

Figure 4.3: Power Loss Minimization for 33-Bus Radial Distribution Network with D-STATCOM using BFA and IBFA

It can clearly be observed from Figure 4.3 that the highest power loss as shown by the peak curves is obtained at bus 2 of the network with approximate values of 51.5711 kW and 33.4526 kW for base-cases and BFA respectively. For the IBFA, the highest loss is experienced at bus 5 with an approximate value of 41.0596 kW. The overall network active power loss has been minimized from 201.8125 kW to 190.5254 kW and

191.0473 kW using the BFA and IBFA approaches at an average computational time of 7.2 seconds and 4.9 seconds respectively.



4.2.2.4 Performance Comparison for Power Loss Reduction

The plots of power loss against bus number of the network for Case I and Case II using analytical, Bat Algorithm (BA), conventional BFA and IBFA approaches are shown in Figures 4.4.

Figure 4.4: Power Loss Minimization for 33-Bus Radial Distribution Network with D-STATCOM using Analytical, BAT, BFA and IBFA

The effect of incorporating D-STATCOM into the network can be seen by a relative drop in the curves. It can be observed from Figures 4.4 that the power loss at each bus

for both BA and IBFA approaches represented by yellow and blue curve follows the same trend as that of the base case shown by red curve. The highest loss for both approaches occurred at bus 2 and 5 with relative values of 33.4526 kW and 41.0596 kW respectively. However, a sudden increase in loss which can be attributed to improper sizing and siting of D-STATCOM in the network was observed at bus 26, 27, 28 and 29 for the analytical approach as can be seen by the green curve in Figure 4.4. Bus 27 experiences the highest loss with an approximate value of 43.7725 kW. The total network power loss realized from the analytical, BA, BFA and IBFA were 267.2220 kW, 143.9700 kW, 190.5254 and 191.0473 kW respectively. The percentage reduction in power loss obtained for BA, conventional BFA and IBFA as compared with the base case are 29.32 %, 5.87 % and 5.37 %; whereas for the analytical approach, a 24.45 % increase in loss was recorded.

4.2.3 Summary of Simulation Results

The active and reactive power losses, voltage profile, total number of buses out of constraint limits, computational time as well as the optimal site and size of D-STATCOM in both Case I and Case II of the 33-bus radial distribution network are presented in Table 4.4 for the conventional BFA and IBFA.

Table 4.4: Summary of Simulation Results for the 33-Bus IEEE Radial Distribution Network using BFA and IBFA

Performance Index	**Case I**	**Case II**	
		BFA	**IBFA**
Optimal Site (bus)	-	30	26
Optimal Size of D-STATCOM (kVAr)	-	**2577**	3351
Minimum Voltage (p.u)	0.9134	0.9428	**0.9501**
Voltage Profile Improvement (%)	-	82.88	**87.96**

Overall Active Power Loss (kW)	201.8925	**190.5254**	191.0473
Percentage Reduction in Active Power Loss (%)	-	**5.87**	5.37
Overall Reactive Power Loss (kVAr)	134.6413	132.6283	**128.9875**
Percentage Reduction in Reactive Power Loss (%)	-	1.50	**4.20**
Total number of buses out of constraint limits	21	6	**0**
Computational time (seconds)	-	7.2	**4.9**

The values presented in bold explains the significance of a particular approach regarding a parameter. Based on the results of the performance analysis presented in sub-section 4.2.2 and the number of bolded parameters in Table 4.4, it is evident that the IBFA approach outperforms the conventional BFA.

The performance results for both cases of the network using the analytical, BA and IBFA are summarized in Table 4.5.

Table 4.5: Summary of Simulation Results for the 33-bus IEEE Radial Distribution Network using Analytical, BA and IBFA

Performance Index	**Case I**	**Case II**		
		Analytical	**BA**	**IBFA**
Optimal Site (bus)	-	30	30	26
Optimal Size of D-STATCOM (kVAr)	-	3386.5	**1150**	3351
Minimum Voltage (p.u)	0.9134	0.9523	0.9244	**0.9501**
Voltage Profile Improvement (%)	-	115.07	37.96	**87.96**
Overall Active Power Loss (kW)	201.8925	267.2220	**143.9700**	191.0473
Percentage Reduction in Active Power Loss (%)	-	-24.45	**28.69**	5.37

Overall Reactive Power Loss (kVAr)	134.6413	188.4901	**96.4700**	128.9875
Percentage Reduction in Reactive Power Loss (%)	-	-28.57	**28.35**	4.20
Total number of buses out of constraint limits	21	0	13	**0**

From the results presented in Table 4.5, it can be observed that the analytical approach has rather increased the overall active power loss of the network by 24.45 % as against the 30 % reduction reported in the work of Hussain and Subbaramiah,(2013). However, a 115.07 % improvement in the overall network voltage profile was obtained as compared to 37 % and 87.96% improvements by the BA and IBFA approaches. Aside the minimum size of the D-STATCOM, the BA approach also produced the least total power loss while all other parameter results are better with the IBFA approach.

4.3 The 50-bus Canteen Feeder

The 50-bus Canteen Feeder which is a real network is discussed in sub-section 2.2.6.2 and its line as well as bus data are given in Appendix A2. Just like the standard IEEE 33-bus radial distribution network, the network is modelled based on the theoretical concepts presented in chapter two. The conventional BFA and IBFA approaches were applied in Case II to determine the reduction in overall network power loss and improvement in voltage profile. The MATLAB code in given in Appendix B3.

4.3.1 Case I: Network without D-STATCOM (Base Case)

The modelling equations expressed in sub-section 2.2.5 are employed for power flow analysis. Table 4.6 presents the analysis results of voltage magnitude, phase angle and active power loss for individual bus of the network. The total active power loss of the network was determined as 2.8066 kW.

Table 4.6: 50-Bus Canteen Feeder Base Case Power Flow Results

Bus Number	Voltage Magnitude (p.u)	Phase angle (degree)	Power Loss (kW)
1	1.0000	0	0.7792
2	0.9981	0.0084	0.1669
3	0.9977	0.0102	0.4753
4	0.9964	0.0163	0.3095
5	0.9954	0.0206	0.0673
6	0.9952	0.0215	0.0323
7	0.9951	0.0220	0.0617
8	0.9949	0.0229	0.0133
9	0.9949	0.0232	0.0248
10	0.9947	0.0238	0.0116
11	0.9947	0.0241	0.0429
12	0.9945	0.0252	0.0103
13	0.9944	0.0254	0.2569
14	0.9929	0.0324	0.1233
15	0.9921	0.0358	0.0619
16	0.9917	0.0376	0.0245
17	0.9916	0.0384	0.0465
18	0.9912	0.0400	0.0619
19	0.9907	0.0424	0.0193
20	0.9905	0.0433	0.0265
21	0.9902	0.0448	0.0130
22	0.9900	0.0456	0.0337
23	0.9895	0.0478	0.0103
24	0.9893	0.0488	0.0023
25	0.9893	0.0491	0.0011
26	0.9892	0.0494	0.0004
27	0.9892	0.0496	0.0185
28	0.9974	0.0116	0.0059
29	0.9973	0.0122	0.0038
30	0.9972	0.0126	0.0021
31	0.9971	0.0129	0.0002
31	0.9971	0.0130	0.0005
33	0.9971	0.0131	0.0005
34	0.9971	0.0133	0.0000
35	0.9971	0.0133	0.0003
36	0.9964	0.0164	0.0001
37	0.9964	0.0164	0.0000
38	0.9964	0.0164	0.0000
39	0.9964	0.0164	0.0159
40	0.9948	0.0237	0.0028
41	0.9948	0.0238	0.0103
42	0.9946	0.0243	0.0022
43	0.9946	0.0244	0.0301
44	0.9942	0.0262	0.0091
45	0.9941	0.0268	0.0068
46	0.9940	0.0272	0.0134
47	0.9937	0.0285	0.0015
48	0.9937	0.0286	0.0049

49	0.9934	0.0309	0.0006
50	0.9934	0.0313	0.7792

4.3.2 Case II: Network with D-STATCOM

After the base case analysis, the conventional BFA and IBFA presented in sub-section 2.2.7 and 2.2.8 were comprehensively employed in the search for optimal size and location of D-STATCOM in the real network. The optimal size of D-STATCOMwere determined as 227.8 kVAr and 138 kVAr respectively, while the optimal sites were found to be buses 41 and 22 respectively. The final power flow results after incorporating D-STATCOM into the network indicated a decrease in the overall active power loss to 2.1655 kW and 2.0620 kW for the conventional BFA and IBFA approaches respectively. The results presented in Tables 4.7 and 4.8 clearly depict the consequences of D-STATCOM on the network in terms of voltage profile, phase angle and active power loss for individual bus for the earlier stated approaches.

Table 4.7: 50-bus Canteen Feeder Power Flow Results with D-STATCOM using Conventional BFA

Bus Number	**Voltage Magnitude (p.u)**	**Phase angle (degree)**	**Power Loss (kW)**
1	1.0000	0	0.5115
2	0.9986	-0.0337	0.1095
3	0.9983	-0.0410	0.3044
4	0.9974	-0.0711	0.1975
5	0.9967	-0.0940	0.0429
6	0.9966	-0.0991	0.0206
7	0.9965	-0.1017	0.0394
8	0.9964	-0.1068	0.0133
9	0.9963	-0.1065	0.0247
10	0.9962	-0.1060	0.0115
11	0.9961	-0.1057	0.0428
12	0.9959	-0.1047	0.0103
13	0.9958	-0.1044	0.2562
14	0.9943	-0.0979	0.1229
15	0.9936	-0.0947	0.0617
16	0.9932	-0.0930	0.0244
17	0.9930	-0.0922	0.0464
18	0.9927	-0.0907	0.0617
19	0.9921	-0.0884	0.0193

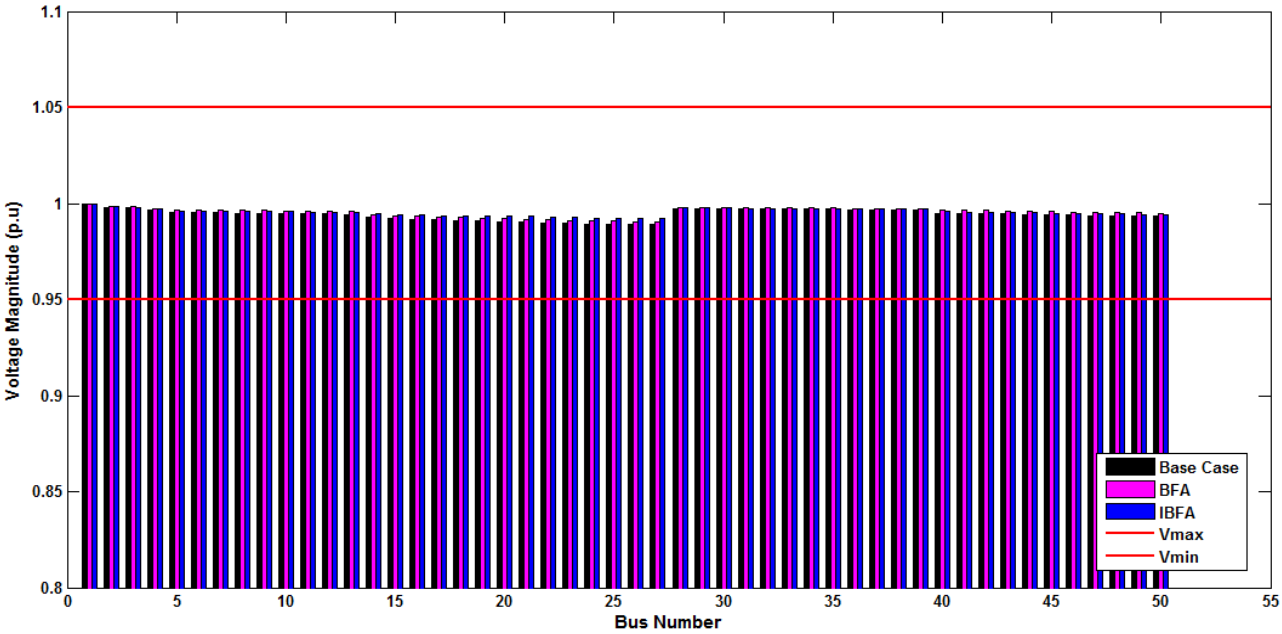
20	0.9920	-0.0876	0.0264
21	0.9916	-0.0862	0.0129
22	0.9915	-0.0855	0.0336
23	0.9910	-0.0834	0.0103
24	0.9908	-0.0825	0.0023
25	0.9907	-0.0822	0.0011
26	0.9906	-0.0819	0.0004
27	0.9906	-0.0817	0.0185
28	0.9980	-0.0396	0.0059
29	0.9979	-0.0390	0.0038
30	0.9978	-0.0386	0.0021
31	0.9977	-0.0383	0.0002
31	0.9977	-0.0383	0.0005
33	0.9977	-0.0382	0.0005
34	0.9976	-0.0380	0.0000
35	0.9976	-0.0380	0.0003
36	0.9973	-0.0710	0.0001
37	0.9973	-0.0710	0.0000
38	0.9973	-0.0710	0.0000
39	0.9973	-0.0710	0.0386
40	0.9964	-0.1211	0.0078
41	0.9964	-0.1240	0.0102
42	0.9963	-0.1235	0.0022
43	0.9962	-0.1234	0.0300
44	0.9959	-0.1217	0.0091
45	0.9957	-0.1212	0.0068
46	0.9956	-0.1207	0.0134
47	0.9954	-0.1196	0.0015
48	0.9953	-0.1195	0.0049
49	0.9951	-0.1173	0.0006
50	0.9950	-0.1169	0.5115

Table 4.8: 50-bus Canteen Feeder Power Flow Results with D-STATCOM using IBFA

Bus Number	**Voltage Magnitude (p.u)**	**Phase angle (degree)**	**Power Loss (kW)**
1	1.0000	0	0.5750
2	0.9984	-0.0173	0.1231
3	0.9981	-0.0210	0.3361
4	0.9970	-0.0370	0.2150
5	0.9962	-0.0493	0.0466
6	0.9961	-0.0521	0.0222
7	0.9960	-0.0535	0.0423
8	0.9958	-0.0563	0.0085
9	0.9958	-0.0578	0.0158
10	0.9957	-0.0609	0.0074
11	0.9957	-0.0625	0.0274

12	0.9955	-0.0688	0.0066
13	0.9955	-0.0703	0.1657
14	0.9945	-0.1150	0.0799
15	0.9941	-0.1374	0.0409
16	0.9938	-0.1503	0.0171
17	0.9937	-0.1569	0.0330
18	0.9936	-0.1701	0.0493
19	0.9933	-0.1934	0.0186
20	0.9932	-0.2036	0.0345
21	0.9932	-0.2242	0.0198
22	0.9931	-0.2362	0.0335
23	0.9927	-0.2343	0.0103
24	0.9925	-0.2335	0.0023
25	0.9924	-0.2332	0.0011
26	0.9923	-0.2329	0.0004
27	0.9923	-0.2328	0.0185
28	0.9978	-0.0196	0.0059
29	0.9976	-0.0191	0.0038
30	0.9976	-0.0186	0.0021
31	0.9975	-0.0183	0.0002
31	0.9975	-0.0183	0.0005
33	0.9974	-0.0182	0.0005
34	0.9974	-0.0180	0.0000
35	0.9974	-0.0180	0.0003
36	0.9970	-0.0370	0.0001
37	0.9970	-0.0369	0.0000
38	0.9970	-0.0369	0.0000
39	0.9970	-0.0369	0.0159
40	0.9957	-0.0556	0.0028
41	0.9956	-0.0554	0.0102
42	0.9955	-0.0549	0.0022
43	0.9955	-0.0548	0.0301
44	0.9951	-0.0531	0.0091
45	0.9950	-0.0526	0.0068
46	0.9949	-0.0521	0.0134
47	0.9946	-0.0509	0.0015
48	0.9945	-0.0508	0.0049
49	0.9943	-0.0485	0.0006
50	0.9943	-0.0482	0.5750

The computational time of the IBF with the linear, quadratic and exponential adaptive run-length units were obtained as 5.69 seconds, 5.64 seconds and 5.63 seconds respectively.

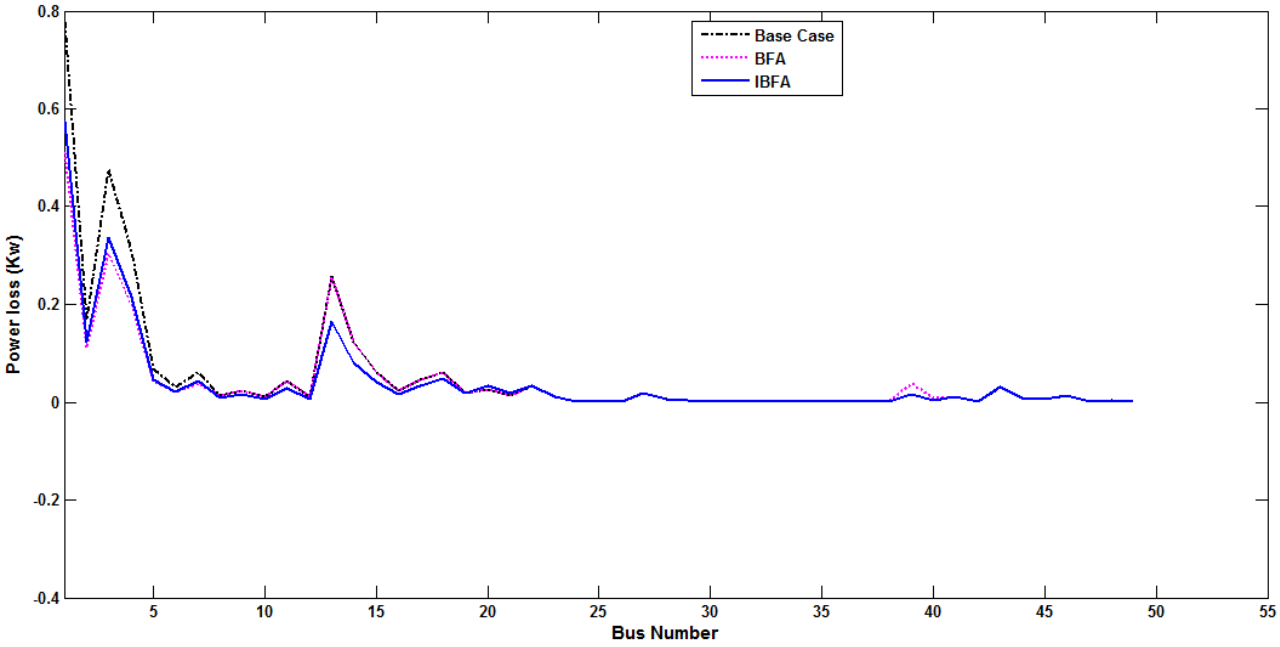


4.3.2.1 Network Voltage Profile with D-STATCOM using BFA and IBFA

Apparently, the results presented in Tables 4.7 and 4.8 shows improvement in voltage profile of the entire network when compared to that of the base case. A plot of the voltage magnitudes in Tables 4.6, 4.7 and 4.8 against their respective bus numbers is shown in Figure 4.5.

Figure 4.5: Voltage Profile Improvement with D-STATCOM using BFA and IBFA

After incorporating the D-STATCOM, the overall voltage profile of the network has been improved by 6.1 % and 6.2 % for both the conventional BFA and IBFA approach respectively as compared to the overall network base case voltage profile. The effect of the D-STATCOM on voltage profile can be seen by the magenta and blue bars in Figure



4.5 which follow the same pattern as the base bars curve in red. The minimum voltage (0.9892 p.u) obtained at bus 27 from the base case analysis has been improved to 0.9906 p.u and 0.9923 p.u with the proposed conventional BFA and IBFA techniques.

4.3.2.2 Network Power Loss with D-STATCOM using BFA and IBFA

The network active power losses given in Tables 4.6, 4.7 and 4.8 are plotted against their respective bus numbers as shown in Figure 4.6

Figure 4.6: Power Loss Minimization with D-STATCOM using BFA and IBFA

As can be seen from Figure 4.6, the highest power loss is experienced at bus 1 with approximate value of 0.7792 kW for Case I; and relative values of 0.5115 kW and 0.5750 kW for Case II using the conventional BFA and IBFA techniques respectively. The total active power loss of the network have been slightly reduced from 2.8066 kW

to 2.1655 kW and 2.0620 kW at an average computational time of 8.9 seconds and 5.65 seconds respectively. The percentage reduction in active power loss for the conventional BFA and proposed IBFA techniques are approximately 22.8 % and 26.53 % as compared to the base case.

4.3.3 Summary of Simulation Results

As presented in sub-section 4.2.3, the active and reactive power losses, voltage profile, computational time as well as the optimal site and size of D-STATCOM in Case I and II of the 50-bus Canteen Feeder in Zaria distribution network are given in Table 4.9.

Table 4.9: Summary of Simulation Results for the 50-Bus Canteen Feeder

Performance Index	**Case I**	**Case II**	
		BFA	**IBFA**
Optimal Site (bus)	-	41	22
Optimal Size of D-STATCOM (kVAr)	-	227.8	**138**
Minimum Voltage (p.u)	0.9934	0.9906	**0.9943**
Voltage Profile Improvement (%)	-	6.1	**6.2**
Overall Active Power Loss (kW)	2.8066	2.1655	**2.0620**
Percentage Reduction in Active Power Loss (%)	-	22.80	**26.53**
Overall Reactive Power Loss (kVAr)	1.7799	1.3731	**1.3075**
Percentage Reduction in Reactive Power Loss (%)	-	22.86	**26.54**
Computational time (seconds)	-	8.9	**5.7**

The values presented in bold explains the superiority of the IBFA approach over the conventional BFA with regards to a specific parameter. From the performance analysis results presented in sub-section 4.3.2 and the summary of simulation results given in

table 4.9, the IBFA approach has clearly demonstrated its superiority over the conventional BFA approach in terms of power loss minimization, voltage profile enhancement and reduced computational time.

The results obtained so far for both radial distribution networks (33-bus and 50-bus) clearly indicates the effectiveness and applicability of the proposed IBFA approach to the optimal siting and sizing of D-STATCOM in radial distribution networks for power loss minimization and voltage profile improvement.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Summary

This Chapter presents a detailed summary of the research findings. The research concentrated on the application of improved BFA with better accuracy and reduced computational time. Performance analysis of results obtained using the IBFA, conventional BFA, analytical and BA approaches for a standard IEEE 33-bus test network are highlighted. Similarly, results obtained for the real 50-bus network using BFA and IBFA approaches are presented. Also, the significant contribution of the research are given, before recommendations for further works are finallydrawn.

5.2 Conclusion

This dissertation has proposed the application of improved bacterial foraging algorithm (IBFA) to the optimal siting and sizing of D-STATCOM in radial distribution networks for power loss minimization and voltage profile improvement. Radial distribution network power flow model was developed based on Bus Injected to Branch Current matrix (BIBC) technique. The IBFA was modelled with three adaptive run-length units (linear, quadratic and exponential) without the swarming process. A multi-objective function comprising of total active power loss and network bus voltage deviation was formulated for use in the IBFA.

The effectiveness and applicability of the approach has been demonstrated on standard IEEE 33-bus radial distribution network and the 50-bus Canteen Feeder in Zaria distribution network for steady-state constant load model. The results obtained have been compared with those of the conventional BFA; and with analytical and Bat Algorithm (BA) approaches. For the standard IEEE 33-bus test network, the optimal

location and size of D-STATCOM were determined respectively as bus 30 and 2577 kW by the BFA method, while the IBFA approach obtained the optimal site and size of the D-STATCOM in the network to be bus 26 and 3351 kW respectively. The BFA approach causes a 5.87 % reduction in overall network power losses and an 82.88 % improvement in voltage profile when compared to the network base-case scenario. Similarly, the IBFA approach resulted in 5.83 % drop in total power loss of the network and 87.96 % improvement of the voltage profile. An average computational time of 7.2 seconds and 4.9 seconds were obtained for the BFA and IBFA approaches respectively.

The results obtained using the IBFA approach showed a 25.5 % and 1.1 % reduction in active power loss and size of D-STATCOM respectively when compared with those of analytical approach reported in the work of Hussain and Subbaramiah, (2013). Also, when compared with the BA results reported by Yuvaraj *et al.*, (2015), the IBFA approach showed a 50 % improvement in the overall network voltage profile.

For the 50-bus Canteen Feeder, bus 41 and 227.8 kW were found as the optimal site and size of D-STATCOM using BFA method, while the optimal site and size of the D-STATCOM in the network for IBFA approach were bus 22 and 138 kW respectively. The overall power loss was reduced by 22.8 % and the voltage profile improvement by 6.10 % using the BFA approach while for the IBFA approach, a 26.53 % reduction in total power loss and a 6.21 % improvement in voltage profile were achieved as compared to the network base-case results.

The general comparative assessment conducted demonstrated the superiority of the IBFA over the conventional BFA, analytical, and BA approaches in determining the optimal site and size of D-STATCOM in radial distribution for power loss minimization and over all voltage profile enhancement.

5.3 Significant Contributions

Numerous research works on the optimal location and sizing of D-STATCOM in radial distribution networks have been carried out and reported in literatures. Also, a significant number of researches have employed different approaches in actualizing the optimum results. The significant contributions of this research are:

1. The application of conventional BFA and IBFA for determination of both the optimal site and size of D-STATCOM in radial distribution networks. The approaches (BFA and IBFA) have resulted in significant power loss reduction (5.87 % and 5.37 %) and enhanced voltage profile (82.88 % and 87.96 %); and
2. Implementation of the IBFA approach on practical 50-bus Canteen Feeder in Zaria distribution network as a case study. This has led to 26.53 % reduction in power loss and better quality of supply with 6.2 % improvement in overall voltage profile.

5.4 Recommendations for Further Work

The following area are recommended for further research:

1. The research can be extended to other members of the D-FACTS devices, such as the UPQC, DVR, SSSC, etc.,
2. The effect of multiple D-STATCOMs and their associated costs in distribution networks can be considered,
3. The possibility of hybridizing two or more D-FACTS devices can also be considered, and
4. Further analysis can be performed considering network reconfiguration and load dispatch.

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APPENDICES

Appendix A1: Line and Bus Data for Standard IEEE 33-bus Distribution Network

Branch Number ik	Sending Bus i	Receiving Bus k	R_{ik} Ω	X_{ik} Ω	P_{Dk} kW	Q_{Dk} $kVAr$
1	1	2	0.0922	0.0470	100	60
2	2	3	0.4930	0.2511	90	40
3	3	4	0.3660	0.1864	120	80
4	4	5	0.3811	0.1941	60	30
5	5	6	0.8190	0.7070	60	20
6	6	7	0.1872	0.6188	200	100
7	7	8	0.7114	0.2351	200	100
8	8	9	1.0300	0.7400	60	20
9	9	10	1.0440	0.7400	60	20
10	10	11	0.1966	0.0650	45	30
11	11	12	0.3744	0.1238	60	35
12	12	13	1.4680	1.1550	60	35
13	13	14	0.5416	0.7129	120	80
14	14	15	0.5910	0.5260	60	10
15	15	16	0.7463	0.5450	60	20
16	16	17	1.2890	1.7210	60	20
17	17	18	0.7320	0.5740	90	40
18	18	19	0.1640	0.1565	90	40
19	19	20	1.5042	1.3554	90	40
20	20	21	0.4095	0.4784	90	40
21	21	22	0.7089	0.9373	90	40
22	22	23	0.4512	0.3083	90	50
23	23	24	0.8980	0.7091	420	200
24	24	25	0.8960	0.7011	420	200
25	25	26	0.2030	0.1034	60	25
26	26	27	0.2842	0.1447	60	25
27	27	28	1.0590	0.9337	60	20
28	28	29	0.8042	0.7006	120	70
29	29	30	0.5075	0.2585	200	600
30	30	31	0.9744	0.9630	150	70
31	31	32	0.3105	0.3619	210	100
32	32	33	0.3410	0.5302	60	40

Appendix A2: Line and Bus Data for Zaria Distribution Network

(50-bus Canteen Feeder)

Branch Number ik	Sending Bus i	Receiving Bus k	R_{ik} Ω	X_{ik} Ω	P_{Dk} kW	Q_{Dk} $kVAr$
1	1	2	0.3871	0.2456	0	0
2	2	3	0.0829	0.0526	6.48	4.86
3	3	4	0.3318	0.2105	3.24	2.43
4	4	5	0.2489	0.1579	3.24	2.43
5	5	6	0.0553	0.0351	6.48	4.86
6	6	7	0.0277	0.0175	6.48	4.86
7	7	8	0.0553	0.0351	6.48	4.86
8	8	9	0.0277	0.0175	6.48	4.86
9	9	10	0.0553	0.0351	6.48	4.86
10	10	11	0.0277	0.0175	6.48	4.86
11	11	12	0.1106	0.0702	3.24	2.43
12	12	13	0.0277	0.0175	9.72	7.29
13	13	14	0.7742	0.4912	3.24	2.43
14	14	15	0.3871	0.2456	9.72	7.29
15	15	16	0.2212	0.1403	16.20	12.15
16	16	17	0.1106	0.0701	3.24	2.43
17	17	18	0.2212	0.1403	16.20	12.15
18	18	19	0.3871	0.2456	16.20	12.15
19	19	20	0.1659	0.1052	16.20	12.15
20	20	21	0.3318	0.2105	6.48	4.86
21	21	22	0.1936	0.1228	6.48	4.86
22	22	23	0.6083	0.3859	16.20	12.15
23	23	24	0.3318	0.2105	16.20	12.15
24	24	25	0.1659	0.1052	16.20	12.15
25	25	26	0.3318	0.2105	6.48	4.86
26	26	27	0.3595	0.2281	9.72	7.29
27	3	28	0.4701	0.2982	9.72	7.29
28	28	29	0.2212	0.1403	6.48	4.86
29	29	30	0.1935	0.1228	9.72	7.29
30	30	31	0.1935	0.1228	3.24	2.43
31	31	32	0.0277	0.0175	6.48	4.86
32	32	33	0.1106	0.0701	6.48	4.86
33	33	34	0.2212	0.1403	6.48	4.86
34	34	35	0.0553	0.0351	6.48	4.86
35	4	36	0.0553	0.0351	6.48	4.86
36	36	37	0.0553	0.0351	6.48	4.86
37	37	38	0.0553	0.0351	3.24	2.43

38	38	39	0.0277	0.0175	3.24	2.43
39	8	40	0.1382	0.0877	6.48	4.86
40	40	41	0.0277	0.0175	3.24	2.43
41	41	42	0.1106	0.0702	6.48	4.86
42	42	43	0.0277	0.0175	3.24	2.43
43	43	44	0.4148	0.2631	9.72	7.29
44	44	45	0.1659	0.1053	3.24	2.43
45	45	46	0.1382	0.0877	16.20	12.15
46	46	47	0.4977	0.3158	16.20	12.15
47	47	48	0.1383	0.1000	9.72	7.29
48	48	49	1.0000	0.5000	9.72	7.29
49	49	50	0.5000	0.3000	9.72	7.29

Appendix B1: m-File for Network Base-Case PowerFlow Analysis

```
% Power Flow Code for Standard IEEE 33-bus Radial Distribution Network
% and the 50-bus Canteen Feeder in Zaria Distribution Network
% Umar Musa (umarnadada@yahoo.co.uk)
% MSc Student, Department of Electrical and Computer Engineering,
% Ahmadu Bello University Samaru-Zaria, Nigeria
% August, 2016.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Based on the Bus Injected to Branch Current (BIBC) Matrix and
% Forward Sweeptechnique on section II ofJain A., Gupta A.R., &
% Kumar A."An Efficient Method of D-STATCOM Placement in Radial
% Distribution System"Paper presented at the Energy Efficient
% Technologies for Sustainability (ICEETS), 2013
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The power flow code is basically programmed to provide the Active
% and Reactivepower losses (PLoss & QLOSS) as well as Voltage drop
% and Phase angle ineach load bus of the networks (IEEE 33-bus & 50-
& bus Canteen Feeder)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clc;
clear all;
format short;
tic
a=load('linedata33bus.m');
b=load('loaddata33bus.m');
%a=load('linedata50bus.m');
%b=load('loaddata50bus.m');
MVAb=100; % Network base power
KVb=12.66; % Network base voltage
%KVb=11.00; % Network base voltage
m=length(a);
n=length(b);
Zb=(KVb^2)/MVAb; % Network base impedance
% Per-unit Values
for i=1:m
    R(i,1)=(a(i,4))/Zb;
    X(i,1)=(a(i,5))/Zb;
end
for k=1:n
    P(k,1)=((b(k,2))/(1000*MVAb));
    Q(k,1)=((b(k,3))/(1000*MVAb));
end

R,X,P,Q
% Voltage-Current Program

for k=1:n
    Vb(k,1)= 0.984; % Flat start voltage at load bus
end

Vb;
for k=1:n-1
    IL(k,1)=conj(complex(P(k,1),Q(k,1)))/(Vb(k,1)); % Network Load
Current
end
```

```
IL;
% BIBC matrix program
BIBC=zeros(m,m);
for i=1:m
if a(i,2)==1
        BIBC(a(i,3)-1,a(i,3)-1)=1;
else
        BIBC(:,a(i,3)-1) = BIBC(:,a(i,2)-1);
        BIBC(a(i,3)-1,a(i,3)-1)=1;
end
end
BIBC;
IB=BIBC*IL; % Network Branch Current
IB;
% Z-Bus program
Z=zeros(m,n);
for i=1:m
for k=1:n
        d=a(i,2);
        e=a(i,3);
if d==i
if e==k
               Z(i,k)=complex(R(i,1),X(i,1));
end
end
end
end

Z;

% Bus voltage program for IEEE 33-bus network

V= ones(n,1);
for i=1:m
for k=1:n
    d=a(i,2);
    e=a(i,3);
if 1==i
           V(i)= 1.0;
end
if e==k
if d==i
              V(k)=(V(i)-(IB(i,1)*Z(i,k)));
end
end
if 2==i
if 19==k
              V(k)=(V(i)-(IB((k-1),1)*Z(i,k)));
end
end
if 3==i
if 23==k
                V(k)=(V(i)-(IB((k-1),1)*Z(i,k)));
end
end
if 6==i
if 26==k
                V(k)=(V(i)-(IB((k-1),1)*Z(i,k)));
end
end
end
```

```
end
V
% Bus voltage program for 50-bus Canteen Feeder
% V= ones(n,1);
% for i=1:m
%     d=a(i,2);
%     e=a(i,3);
%     for k=1:n
%         if 1==i
%             V(i)=1.0;
%         end
%         if e==k
%             if d==i
%                V(k)=(V(i)-(IB(i,1)*Z(i,k)));
%             end
%         end
%         if 4==i
%            if 29==k
%                V(k)=(V(i)-(IB(k-1,1)*Z(i,k)));
%            end
%         end
%         if 5==i
%             if 34==i
%                 V(k)=(V(i)-(IB(k,1)*Z(i,k)));
%             end
%         end
%         if 8==i
%             if 35==k
%                 V(k)=(V(i)-(IB(k,1)*Z(i,k)));
%             end
%             if 36==k
%                 V(k)=(V(i)-(IB(k,1)*Z(i,k)));
%             end
%         end
%         if 11==i
%            if 40==k
%                V(k)=(V(i)-(IB(k,1)*Z(i,k)));
%            end
%            if 42==k
%                V(k)=(V(i)-(IB(k,1)*Z(i,k)));
%            end
%         end
%         if 19==i
%             if 44==k
%                 V(k)=(V(i)-(IB(k,1)*Z(i,k)));
%             end
%             if 48==k
%                 V(k)=(V(i)-(IB(k,1)*Z(i,k)));
%             end
%         end
%         if 29==i
%             if 31==k
%                 V(k)=(V(i)-(IB(k,1)*Z(i,k)));
%             end
%         end
%         if 36==i
%             if 38==k
%                 V(k)=(V(i)-(IB(k,1)*Z(i,k)));
%             end
%         end
%     end
```

```
% end
%
% V

Vrp=[abs(V) angle(V)*180/pi] % Recieving end bus voltages and phase
angles
toc;
%
% Network active and reactive power losses program
PL=zeros(n,1);QL=zeros(n,1);
for i=1:m
    d=a(i,2);
    e=a(i,3);
for k=1:n
if d==i
if e==k
                PL(k,1)=((real(Z(i,k)))*((abs(IB(i,1))).^2));
                QL(k,1)=((imag(Z(i,k)))*((abs(IB(i,1))).^2));
end
end
end
end

PL,QL % Active and reactive power losses in p.u
for k=1:n
  PLT=sum(PL);
  QLT=sum(QL);
end

PLTkw=PLT*100
QLTkw=QLT*100
PLOSS=PLTkw*1000
QLOSS=QLTkw*1000

voltage=Vrp(:,1)
angle=Vrp(:,2)*(pi/180)

plot(1:n,voltage,'-or');
axis([1 35 0.91 1.013])
xlabel('Bus Number');
ylabel('Voltage Magnitude (p.u.)');

% plot(1:n,voltage,'-or');
% axis([1 55 0.985 1.002])
% xlabel('Bus Number');
% ylabel('Voltage Magnitude (p.u.)');


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Appendix B2: m-File for Optimal Siting and Sizing of D-STATCOM in Standard IEEE 33-Bus Radial Distribution Network

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Code for Validation of Improved Bacterial Foraging Algorithm (IBFA)
% to theOptimal Siting and Sizing of D-STATCOM in Standard IEEE 33-
% bus Radial Distribution Network.
% Umar Musa (umarnadada@yahoo.co.uk)
% MSc Student, Department of Electrical and Computer Engineering,
% Ahmadu Bello University Samaru-Zaria, Nigeria
% January, 2016.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The Code is basically programmed to provide the optimum Site (bus)
% and Size (Q_D-STATCOM) of D-STATCOM in Standard IEEE 33-bus Radial
% Distribution Network. Also, the network final power flow results
% (active and reactive power losses, voltage magnitudes and phase
% angles) after incorporating the D-STATCOM
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%

function [OPTIMUM_BUS Q_DSTSTCOM] = UMARNADADAIBFADSS33

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clc;
clear all;
format short;
tic
a=load('linedata33bus.m');
b=load('loaddata33bus.m');
MVAb=100; % Network base power
KVb=12.66; % Network base voltage
m=length(a);
n=length(b);
Zb=(KVb^2)/MVAb; % Network base impedance
% Per-unit Values
for i=1:m
    R(i,1)=(a(i,4))/Zb;
    X(i,1)=(a(i,5))/Zb;
end
for k=1:n
    P(k,1)=((b(k,2))/(1000*MVAb));
    Q(k,1)=((b(k,3))/(1000*MVAb));
end

R;X;P;Q;
% Voltage-Current Program
for k=1:n
    Vb(k,1)= 0.984; % Flat start voltage at load bus
end

Vb;
for k=1:n-1
    IL(k,1)=conj(complex(P(k,1),Q(k,1)))/(Vb(k,1)); % Network Load
Current
end
IL;
% BIBC matrix program
BIBC=zeros(m,m);
```

```
for i=1:m
if a(i,2)==1
        BIBC(a(i,3)-1,a(i,3)-1)=1;
else
        BIBC(:,a(i,3)-1) = BIBC(:,a(i,2)-1);
        BIBC(a(i,3)-1,a(i,3)-1)=1;
end
end
BIBC;
IB=BIBC*IL; % Network Branch Current
IB;
% Z-Bus program
Z=zeros(m,n);
for i=1:m
for k=1:n
        d=a(i,2);
        e=a(i,3);
if d==i
if e==k
               Z(i,k)=complex(R(i,1),X(i,1));
end
end
end
end
Z;

% Bus voltage program
V= ones(n,1);
for i=1:m
    d=a(i,2);
    e=a(i,3);
for k=1:n
if 1==i
           V(i)=1.0;
end
if e==k
if d==i
               V(k)=(V(i)-(IB(i,1)*Z(i,k)));
end
end
if 2==i
if 19==k
               V(k)=(V(i)-(IB(18,1)*Z(i,k)));
end
end
if 3==i
if 23==k
                 V(k)=(V(i)-(IB(22,1)*Z(i,k)));
end
end
if 6==i
if 26==k
                 V(k)=(V(i)-(IB(25,1)*Z(i,k)));
end
end
end
end
V;
Vrp=[abs(V) angle(V)*180/pi] % Recieving end bus voltages and phase
angles
%
```

```
% Network active and reactive power losses program
PL=zeros(n,1);QL=zeros(n,1);
for i=1:m
    d=a(i,2);
    e=a(i,3);
for k=1:n
if d==i
if e==k
               PL(k,1)=((real(Z(i,k)))*((abs(IB(i,1))).^2));
               QL(k,1)=((imag(Z(i,k)))*((abs(IB(i,1))).^2));
end
end
end
end

P;QL; % Active and reactive power losses in p.u
for k=1:n
  PLT=sum(PL);
  QLT=sum(QL);
end

PLTkw=PLT*100;
QLTkw=QLT*100;
PLOSS=PLTkw*1000
QLOSS=QLTkw*1000

voltage=Vrp(:,1)
%angle=Vrp(:,2)*(pi/180)
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% Improved Bacterial Foraging Algorithm (IBFA)
% ------------------------------------------------------------------------
% (1) Initialization
p  =  2;           % Dimension of search space
S  = 10;           % Number of bacteria in the colony
Nc =  4;           % Number of chemotactic steps
Ns =  4;           % Number of swim steps
Nre=  4;           % Number of reproductive steps
Ned=  3;           % Number of elimination and dispersal steps
Sr =S/2;           % The number of bacteria reproductions (splits) per
generation
Ped=0.25;          % The probability that each bacteria will be
eliminated/dispersed
n = 33;

ca(:,1)=0.01*ones(S,1);   % the run length unit (the size of the step
taken in each run or tumble)
% Initial positions
for m=1:S                     % the initital posistions
    B(1,:,1,1,1)= 2 + (n-2)*rand(S,1)';
    B(2,:,1,1,1)= 0.5 + (2-0.5)*rand(S,1)';
%format short,B(2,:,1,1,1);

end
%% Loops
% (2) Elimination-dispersal loop
for l = 1:Ned
```

```
% (3) Reproduction loop
for k = 1:Nre
% (4) Chemotaxis (swim/tumble) loop
for j=1:Nc
% (4.1) Chemotatic step
for i=1:S
% (4.2a) Fitness function
                J(i,j,k,l) = fitnessIBFADSS33(B(:,i,j,k,l));
% (4.2b) Add on cell-to-cell attraction effect

J(i,j,k,l)=J(i,j,k,l)+cell_to_cell_func(B(:,i,j,k,l),B(:,:,j,k,l),S);
% (4.3) Jlast
                Jlast=J(i,j,k,l);
% (4.4) Tumble
                Delta(:,i) = unifrnd(-1,1,p,1);
% (4.5) Move

B(:,i,j+1,k,l)=B(:,i,j,k,l)+ca(i,k)*Delta(:,i)/sqrt(Delta(:,i)'*Delta(
:,i)); % with the original run length unit
%
B(:,i,j+1,k,l)=B(:,i,j,k,l)+(ca(i,k)/(1+(1/(0.01*(abs(J(i,j,k,l)))))))
*Delta(:,i)/sqrt(Delta(:,i)'*Delta(:,i)); % with linear adaptive run
length unit
%
B(:,i,j+1,k,l)=B(:,i,j,k,l)+(ca(i,k)/(1+(1/(0.01*(((abs(J(i,j,k,l)))^2
) + (abs(J(i,j,k,l)))))))*Delta(:,i)/sqrt(Delta(:,i)'*Delta(:,i)); %
with quadratic adaptive run length unit
%
B(:,i,j+1,k,l)=B(:,i,j,k,l)+(ca(i,k)/(1+(1/(0.01*(exp(abs(J(i,j,k,l)))
)))))*Delta(:,i)/sqrt(Delta(:,i)'*Delta(:,i)); % with exponential
adaptive run length unit
% (4.6a) New fitness function
                J(i,j+1,k,l)= fitnessIBFADSS33(B(:,i,j+1,k,l));
% 4.6b) Add on cell-to-cell attraction effect

J(i,j+1,k,l)=J(i,j+1,k,l)+cell_to_cell_func(B(:,i,j+1,k,l),B(:,:,j+1,k
,l),S);
% (4.7) Swimming
                m=0; % counter for swim length
while m < Ns
                    m=m+1;
if J(i,j+1,k,l)<Jlast
                        Jlast=J(i,j+1,k,l);

B(:,i,j+1,k,l)=B(:,i,j+1,k,l)+ca(i,k)*Delta(:,i)/sqrt(Delta(:,i)'*Delt
a(:,i)) ;
                        J(i,j+1,k,l)=
fitnessIBFADSS33(B(:,i,j+1,k,l));
else
                        m=Ns;
end
end
                J(i,j,k,l)=Jlast; %???
end% (4.8) Next bacterium
            OPTIMUM_BUS = B(1,:,j,k,l);
            Q_DSTATCOM = B(2,:,j,k,l);
%format short,Q_DSTATCOM;

%               if OPTIMUM_BUS <=1;
%                   OPTIMUM_BUS = round((abs(OPTIMUM_BUS))+1);
%               end
```

```
end% (5) if j < Nc, chemotaxis
% (6) Reproduction
% (6.1) Health
        Jhealth=sum(J(:,:,k,l),2);      % Set the health of each of
the S bacteria
        [Jhealth,sortind]=sort(Jhealth);% Sorts bacteria in order of
ascending values
        B(:,:,1,k+1,l)=B(:,sortind,Nc+1,k,l);
        ca(:,k+1)=ca(sortind,k);          % Keeps the chemotaxis
parameters with each bacterium at the next generation
% (6.2) Split the bacteria
for i=1:Sr % Sr??
                B(:,i+Sr,1,k+1,l)=B(:,i,1,k+1,l); % The least fit do
not reproduce, the most fit ones split into two identical copies
                ca(i+Sr,k+1)=ca(i,k+1);
end
end% (7) Loop to go to the next reproductive step
% (8) Elimination-dispersal
for m=1:S
if  Ped>rand % % Generate random number
                B(1,:,1,1,1)= 2 + (n-2)*rand(S,1)';
                B(2,:,1,1,1)= 0.5 + (10-0.5)*rand(S,1)';
%format short,B(2,:,1,1,1);
else
                B(:,m,1,1,l+1)=B(:,m,1,Nre+1,l); % Bacteria that are
not dispersed
end
end
end
%% Results
           reproduction = J(:,1:Nc,Nre,Ned);
           [jlastreproduction,O] = min(reproduction,[],2);  % min cost
function for each bacterial
           [Y,I] = min(jlastreproduction);
           pbest = B(:,I,O(I,:),k,l);
           Jcost=jlastreproduction;
           OPTIMUM_BUS = round(pbest(1,:));% Return the optimal
positions as Kp and Kd
           Q_DSTATCOM = pbest(2,:);
%
%%%%%%%%%%%%%%%%%% End of IBFA Code %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

a=load('linedata33bus.m');
b=load('loaddata33bus.m');
c=load('BIBC33bus.m');
% To take care of the D-STATCOM siting and

OPTIMUM_BUS = real(round(pbest(1,:)))%30; %mat2str(pbest(1),2); %
Q_DSTATCOM = real(abs(pbest(2,:)))%1.376; %mat2str(pbest(2),2); %

if OPTIMUM_BUS <=1;
     OPTIMUM_BUS = round((abs(OPTIMUM_BUS))+2);
end
 b(OPTIMUM_BUS,3) = b(OPTIMUM_BUS,3) + (-Q_DSTATCOM * 1000);
  fprintf('D-STATCOM should be sited at bus %3.0f\n',OPTIMUM_BUS)
  fprintf('With Value of D-STATCOM = %7.3f VAr\n',Q_DSTATCOM)

MVAb=100; % Network base power
```

```
KVb=12.66; % Network base voltage
m=length(a);
n=length(b);
Zb=(KVb^2)/MVAb; % Network base impedance
% Per-unit Values
for i=1:m
    R(i,1)=(a(i,4))/Zb;
    X(i,1)=(a(i,5))/Zb;
end
for k=1:n
    P(k,1)=((b(k,2))/(1000*MVAb));
    Q(k,1)=((b(k,3))/(1000*MVAb));
end

R;X;P;Q;
% Voltage-Current Program
for k=1:n
    Vb(k,1)= 0.984; % Flat start voltage at load bus
end

Vb;
for k=1:n-1
    IL(k,1)=conj(complex(P(k,1),Q(k,1)))/(Vb(k,1)); % Network Load
Current
end

IL;
IB=c*IL; % Network Branch Current
IB;
% Z-Bus program
Z=zeros(m,n);
for i=1:m
for k=1:n
        d=a(i,2);
        e=a(i,3);
if d==i
if e==k
              Z(i,k)=complex(R(i,1),X(i,1));
end
end
end
end

Z;
% Bus voltage program
V= ones(n,1);
for i=1:m
    d=a(i,2);
    e=a(i,3);
for k=1:n
if 1==i
           V(i)=1.0;
end
if e==k
if d==i
              V(k)=(V(i)-(IB(i,1)*Z(i,k)));
end
end
if 2==i
if 19==k
```

```
                V(k)=(V(i)-(IB(18,1)*Z(i,k)));
end
end
if 3==i
if 23==k
                  V(k)=(V(i)-(IB(22,1)*Z(i,k)));
end
end
if 6==i
if 26==k
                  V(k)=(V(i)-(IB(25,1)*Z(i,k)));
end
end
end
end
V;
Vrp=[abs(V) angle(V)*180/pi] % Recieving end bus voltages and phase
angles
%
% Network active and reactive power losses program
PL=zeros(n,1);QL=zeros(n,1);
for i=1:m
    d=a(i,2);
    e=a(i,3);
for k=1:n
if d==i
if e==k
                PL(k,1)=((real(Z(i,k)))*((abs(IB(i,1))).^2));
                QL(k,1)=((imag(Z(i,k)))*((abs(IB(i,1))).^2));
end
end
end
end

PL;QL; % Active and reactive power losses in p.u
for k=1:n
  PLT=sum(PL);
  QLT=sum(QL);
end

PLTkw=PLT*100;
QLTkw=QLT*100;
PLOSS=PLTkw*1000
QLOSS=QLTkw*1000

voltage3 = Vrp(:,1)
%angle=Vrp(:,2)*(pi/180)
toc;
%plot for 33-bus
plot(1:n,voltage,'-^r',1:n,voltage3,'-ob');
axis([0 35 0.91 1.01])
xlabel('Number of Bus');
ylabel('P.U. Voltage');
legend('Case Case','IBFA')
return;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Appendix B3: m-File for Optimal Siting and Sizing of D-STATCOM in 50-Bus Canteen Feeder

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Code for Implementation of Improved Bacterial Foraging Algorithm
% (IBFA) to the Optimal Siting and Sizing of D-STATCOM in Real 50-bus
% Canteen Feeder in Zaria Distribution Network.
% Umar Musa (umarnadada@yahoo.co.uk)
% MSc Student, Department of Electrical and Computer Engineering,
% Ahmadu Bello University Samaru-Zaria, Nigeria
% August, 2016.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The power flow code is basically programmed to provide the optimum
% Site (bus) and Size (Q_D-STATCOM) of D-STATCOM in Standard IEEE 33-
% bus Radial Distribution Network. Also, the network final power flow
% results (active and reactive power losses, voltage magnitudes and
% phase angles) after incorporating the D-STATCOM
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [OPTIMUM_BUS Q_DSTSTCOM] = UMARNADADAIBFADSS50
clc;
clear all;
format short;
tic
a=load('linedata50bus.m');
b=load('loaddata50bus.m');
c=load('BIBC50bus.m');
MVAb=100; % Network base power
KVb=11.00; % Network base voltage
m=length(a);
n=length(b);
Zb=(KVb^2)/MVAb; % Network base impedance
% Per-unit Values
for i=1:m
    R(i,1)=(a(i,4))/Zb;
    X(i,1)=(a(i,5))/Zb;
end
for k=1:n
    P(k,1)=((b(k,2))/(1000*MVAb));
    Q(k,1)=((b(k,3))/(1000*MVAb));
end

R;X;P;Q;
% Voltage-Current Program
for k=1:n
    Vb(k,1)= 1.05; % Flat start voltage at load bus
end

Vb;
for k=1:n-1
    IL(k,1)=conj(complex(P(k,1),Q(k,1)))/(Vb(k,1)); % Network Load
Current
end
IL;
% BIBC matrix program
BIBC=zeros(m,m);
for i=1:m
if a(i,2)==1
```

```
        BIBC(a(i,3)-1,a(i,3)-1)=1;
else
        BIBC(:,a(i,3)-1) = BIBC(:,a(i,2)-1);
        BIBC(a(i,3)-1,a(i,3)-1)=1;
end
end
BIBC;
IB=BIBC*IL; % Network Branch Current
IB;
% Z-Bus program
Z=zeros(m,n);
for i=1:m
    d=a(i,2);
    e=a(i,3);
for k=1:n
if e==k
        Z(i,k)=complex(R(i,1),X(i,1));
end
end
end
Z;
% Bus voltage program
V= ones(n,1);
for i=1:m
    d=a(i,2);
    e=a(i,3);
for k=1:n
if 1==i
           V(i)=1.0;
end
if e==k
if d==i
              V(k)=(V(i)-(IB(i,1)*Z(i,k)));
end
end
if 4==i
if 29==k
              V(k)=(V(i)-(IB(k-1,1)*Z(i,k)));
end
end
if 5==i
if 34==i
               V(k)=(V(i)-(IB(k,1)*Z(i,k)));
end
end
if 8==i
if 35==k
               V(k)=(V(i)-(IB(k,1)*Z(i,k)));
end
if 36==k
               V(k)=(V(i)-(IB(k,1)*Z(i,k)));
end
end
if 11==i
if 40==k
              V(k)=(V(i)-(IB(k,1)*Z(i,k)));
end
if 42==k
              V(k)=(V(i)-(IB(k,1)*Z(i,k)));
end
end
```

```
if 19==i
if 44==k
                V(k)=(V(i)-(IB(k,1)*Z(i,k)));
end
if 48==k
                V(k)=(V(i)-(IB(k,1)*Z(i,k)));
end
end
if 29==i
if 31==k
                V(k)=(V(i)-(IB(k,1)*Z(i,k)));
end
end
if 36==i
if 38==k
                V(k)=(V(i)-(IB(k,1)*Z(i,k)));
end
end
end
end
V;

Vrp=[abs(V) angle(V)*180/pi]  % Recieving end bus voltages and phase
angles

% Network active and reactive power losses program
PL=zeros(n,1);QL=zeros(n,1);
for i=1:m
    d=a(i,2);
    e=a(i,3);
for k=1:n
if d==i
if e==k
               PL(k,1)=((real(Z(i,k)))*((abs(IB(i,1))).^2));
               QL(k,1)=((imag(Z(i,k)))*((abs(IB(i,1))).^2));
end
end
end
end
PL;QL; % Active and reactive power losses in p.u
for k=1:n
  PLT=sum(PL);
  QLT=sum(QL);
end

PLTkw=PLT*100;
QLTkw=QLT*100;
PLOSS=PLTkw*1000
QLOSS=QLTkw*1000

voltage=Vrp(:,1)
%angle=Vrp(:,2)*(pi/180)


%% Improved Bacterial Foraging Algorithm (IBFA)
% ------------------------------------------------------------------------
% (1) Initialization
p  =  2;           % Dimension of search space
S  = 10;           % Number of bacteria in the colony
Nc =  4;           % Number of chemotactic steps
```

```
Ns =  4;            % Number of swim steps
Nre=  4;            % Number of reproductive steps
Ned=  3;            % Number of elimination and dispersal steps
Sr =S/2;            % The number of bacteria reproductions (splits) per
generation
Ped=0.25;           % The probability that each bacteria will be
eliminated/dispersed
n = 50;

ca(:,1)=0.01*ones(S,1);   % the run length unit (the size of the step
taken in each run or tumble)
% Initial positions
for m=1:S                       % the initital posistions
    B(1,:,1,1,1)= 2 + (n-2)*rand(S,1)';
    B(2,:,1,1,1)= 0 + (1-0)*rand(S,1)';
%format short,B(2,:,1,1,1);

end
%% Loops
% (2) Elimination-dispersal loop
for l = 1:Ned
% (3) Reproduction loop
for k = 1:Nre
% (4) Chemotaxis (swim/tumble) loop
for j=1:Nc
% (4.1) Chemotatic step
for i=1:S
% (4.2a) Fitness function
                J(i,j,k,l) = fitnessIBFADSS50(B(:,i,j,k,l));
% (4.2b) Add on cell-to-cell attraction effect

J(i,j,k,l)=J(i,j,k,l)+cell_to_cell_func(B(:,i,j,k,l),B(:,:,j,k,l),S);
% (4.3) Jlast
                Jlast=J(i,j,k,l);
% (4.4) Tumble
                Delta(:,i) = unifrnd(-1,1,p,1);
% (4.5) Move

B(:,i,j+1,k,l)=B(:,i,j,k,l)+ca(i,k)*Delta(:,i)/sqrt(Delta(:,i)'*Delta(
:,i)); % with the original run length unit
%B(:,i,j+1,k,l)=B(:,i,j,k,l)+(ca(i,k)/(1+(1/(0.01*(abs(J(i,j,k,l))))))
)*Delta(:,i)/sqrt(Delta(:,i)'*Delta(:,i)); % with linear adaptive run
length unit
%B(:,i,j+1,k,l)=B(:,i,j,k,l)+(ca(i,k)/(1+(1/(0.01*(((abs(J(i,j,k,l)))^
2) + (abs(J(i,j,k,l))))))))*Delta(:,i)/sqrt(Delta(:,i)'*Delta(:,i)); %
with quadratic adaptive run length unit
%B(:,i,j+1,k,l)=B(:,i,j,k,l)+(ca(i,k)/(1+(1/(0.01*(exp(abs(J(i,j,k,l))
))))))*Delta(:,i)/sqrt(Delta(:,i)'*Delta(:,i)); % with exponential
adaptive run length unit
% (4.6a) New fitness function
                J(i,j+1,k,l)= fitnessIBFADSS50(B(:,i,j+1,k,l));
% 4.6b) Add on cell-to-cell attraction effect

J(i,j+1,k,l)=J(i,j+1,k,l)+cell_to_cell_func(B(:,i,j+1,k,l),B(:,:,j+1,k
,l),S);
% (4.7) Swimming
                m=0; % counter for swim length
while m < Ns
                    m=m+1;
if J(i,j+1,k,l)<Jlast
                        Jlast=J(i,j+1,k,l);
```

```
B(:,i,j+1,k,l)=B(:,i,j+1,k,l)+ca(i,k)*Delta(:,i)/sqrt(Delta(:,i)'*Delt
a(:,i)) ;
                          J(i,j+1,k,l)=
fitnessIBFADSS50(B(:,i,j+1,k,l));
else
                          m=Ns;
end
end
                J(i,j,k,l)=Jlast; %???
end% (4.8) Next bacterium
            OPTIMUM_BUS = B(1,:,j,k,l);
            Q_DSTATCOM = B(2,:,j,k,l);
%format short,Q_DSTATCOM;

%               if OPTIMUM_BUS <=1;
%                   OPTIMUM_BUS = round((abs(OPTIMUM_BUS))+1);
%               end
end% (5) if j < Nc, chemotaxis
% (6) Reproduction
% (6.1) Health
        Jhealth=sum(J(:,:,k,l),2);      % Set the health of each of
the S bacteria
        [Jhealth,sortind]=sort(Jhealth);% Sorts bacteria in order of
ascending values
        B(:,:,1,k+1,l)=B(:,sortind,Nc+1,k,l);
        ca(:,k+1)=ca(sortind,k);          % Keeps the chemotaxis
parameters with each bacterium at the next generation
% (6.2) Split the bacteria
for i=1:Sr % Sr??
                B(:,i+Sr,1,k+1,l)=B(:,i,1,k+1,l); % The least fit do
not reproduce, the most fit ones split into two identical copies
                ca(i+Sr,k+1)=ca(i,k+1);
end
end% (7) Loop to go to the next reproductive step
% (8) Elimination-dispersal
for m=1:S
if  Ped>rand % % Generate random number
                B(1,:,1,1,1)= 2 + (n-2)*rand(S,1)';
                B(2,:,1,1,1)= 0 + (1-0)*rand(S,1)';
%format short,B(2,:,1,1,1);
else
                B(:,m,1,1,l+1)=B(:,m,1,Nre+1,l); % Bacteria that are
not dispersed
end
end
end
%% Results
           reproduction = J(:,1:Nc,Nre,Ned);
           [jlastreproduction,O] = min(reproduction,[],2);  % min cost
function for each bacterial
           [Y,I] = min(jlastreproduction);
           pbest = B(:,I,O(I,:),k,l);
           Jcost=jlastreproduction;
           OPTIMUM_BUS = round(pbest(1,:));% Return the optimal
positions as Kp and Kd
           Q_DSTATCOM = pbest(2,:);

%%%%%%%%%%%%%%%%%% End of IBFA Code %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% Final power flow
a=load('linedata50bus.m');
b=load('loaddata50bus.m');
c=load('BIBC50bus.m');

% To take care of the D-STATCOM siting

OPTIMUM_BUS = 22; %mat2str(pbest(1),2); %real(round(pbest(1,:)))%
Q_DSTATCOM = 0.138; %mat2str(pbest(2),2); %real(abs(pbest(2,:)))%

if OPTIMUM_BUS <=1;
     OPTIMUM_BUS = round((abs(OPTIMUM_BUS))+2);
end
 b(OPTIMUM_BUS,3) = b(OPTIMUM_BUS,3) + (-Q_DSTATCOM * 1000);
  fprintf('D-STATCOM should be sited at bus %3.0f\n',OPTIMUM_BUS)
  fprintf('With Value of D-STATCOM = %7.3f VAr\n',Q_DSTATCOM)

MVAb=100; % Network base power
KVb=11.00; % Network base voltage
m=length(a);
n=length(b);
Zb=(KVb^2)/MVAb; % Network base impedance
% Per-unit Values
for i=1:m
    R(i,1)=(a(i,4))/Zb;
    X(i,1)=(a(i,5))/Zb;
end
for k=1:n
    P(k,1)=((b(k,2))/(1000*MVAb));
    Q(k,1)=((b(k,3))/(1000*MVAb));
end

R;X;P;Q;
% Voltage-Current Program
for k=1:n
    Vb(k,1)= 1.05; % Flat start voltage at load bus
end

Vb;
for k=1:n-1
    IL(k,1)=conj(complex(P(k,1),Q(k,1)))/(Vb(k,1)); % Network Load
Current
end
IL;
% BIBC matrix program
BIBC=zeros(m,m);
for i=1:m
if a(i,2)==1
        BIBC(a(i,3)-1,a(i,3)-1)=1;
else
        BIBC(:,a(i,3)-1) = BIBC(:,a(i,2)-1);
        BIBC(a(i,3)-1,a(i,3)-1)=1;
end
end
BIBC;
IB=BIBC*IL; % Network Branch Current
IB;
% Z-Bus program
Z=zeros(m,n);
for i=1:m
```

```
    d=a(i,2);
    e=a(i,3);
for k=1:n
if e==k
        Z(i,k)=complex(R(i,1),X(i,1));
end
end
end
Z;
% Bus voltage program
V= ones(n,1);
for i=1:m
    d=a(i,2);
    e=a(i,3);
for k=1:n
if 1==i
           V(i)=1.0;
end
if e==k
if d==i
              V(k)=(V(i)-(IB(i,1)*Z(i,k)));
end
end
if 4==i
if 29==k
              V(k)=(V(i)-(IB(k-1,1)*Z(i,k)));
end
end
if 5==i
if 34==i
               V(k)=(V(i)-(IB(k,1)*Z(i,k)));
end
end
if 8==i
if 35==k
               V(k)=(V(i)-(IB(k,1)*Z(i,k)));
end
if 36==k
               V(k)=(V(i)-(IB(k,1)*Z(i,k)));
end
end
if 11==i
if 40==k
              V(k)=(V(i)-(IB(k,1)*Z(i,k)));
end
if 42==k
              V(k)=(V(i)-(IB(k,1)*Z(i,k)));
end
end
if 19==i
if 44==k
               V(k)=(V(i)-(IB(k,1)*Z(i,k)));
end
if 48==k
               V(k)=(V(i)-(IB(k,1)*Z(i,k)));
end
end
if 29==i
if 31==k
               V(k)=(V(i)-(IB(k,1)*Z(i,k)));
end
```

```
end
if 36==i
if 38==k
                V(k)=(V(i)-(IB(k,1)*Z(i,k)));
end
end
end
end
V;

Vrp=[abs(V) angle(V)*180/pi]  % Recieving end bus voltages and phase
angles

% Network active and reactive power losses program
PL=zeros(n,1);QL=zeros(n,1);
for i=1:m
    d=a(i,2);
    e=a(i,3);
for k=1:n
if d==i
if e==k
               PL(k,1)=((real(Z(i,k)))*((abs(IB(i,1))).^2));
               QL(k,1)=((imag(Z(i,k)))*((abs(IB(i,1))).^2));
end
end
end
end
PL;QL; % Active and reactive power losses in p.u
for k=1:n
  PLT=sum(PL);
  QLT=sum(QL);
end

PLTkw=PLT*100;
QLTkw=QLT*100;
PLOSS=PLTkw*1000
QLOSS=QLTkw*1000

voltage3 = Vrp(:,1)
%angle=Vrp(:,2)*(pi/180)
toc;

plot(1:n,voltage,'-^r',1:n,voltage3,'-ob');
axis([0 55 0.986 1.002])
xlabel('Number of Bus');
ylabel('P.U. Voltage');
legend('Base Case','Proposed')
return
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Appendix B4: m-File for Bar-Charts and Graphical Representations of Voltage Profiles and Power Losses

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Bar-charts and Graphical Representations of Voltage Profiles and
% and Power Losses for the IEEE 33-bus and 50-bus Canteen Feeder.
% Umar Musa (umarnadada@yahoo.co.uk)
% MSc Student, Department of Electrical and Computer Engineering,
% Ahmadu Bello University Samaru-Zaria, Nigeria
% August, 2016.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%% PLOTS FOR 33-BUS IEEE NETWORK %%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%% VOLTAGE PROFILE AGAINST BUS NUMBER %%%%%%%%%%%%%%%%%%%%%%%%

%PLOT1: VOLTAGE PROFILE IN CONTIOUS FORM FOR BASE-CASE, BFA AND IBFA

y1 = 1.05*ones(33,1); y2 = 0.95*ones(33,1);
plot(1:n,y2,'r');
hold on
plot(1:n,voltage,'-^k',1:n,voltage3,'-dm',1:n,voltage4,'-ob');
axis([1 35 0.91 1.014])
xlabel('Bus Number');
ylabel('Voltage Magnitude (p.u)');
legend('Vmin','Base Case','BFA','IBFA')

%PLOT2: VOLTAGE PROFILE IN DISCRETE FORM FOR BASE-CASE, BFA AND IBFA

x=1:n; y1=voltage; y4=voltage3; y5=voltage4
y=[y1 y4 y5];
h = bar(x,y,'grouped');
set(h(1),'FaceColor','k')
set(h(2),'FaceColor','m')
set(h(3),'FaceColor','b')
hold on
ymax = 1.05*ones(36,1); ymin = 0.95*ones(36,1);
plot(0:35,ymax,'r',0:35,ymin,'r');
axis([0 35 0.8 1.1]),xlabel('Bus Number'); ylabel('Voltage Magnitude
(p.u)');legend('Base Case','BFA','IBFA','Vmax','Vmin'); %grid on

%PLOT3: VOLTAGE PROFILE IN CONTIOUS FORM FOR BASE-CASE, ANALYTICAL,
BAT, BFA AND IBFA

y1 = 1.05*ones(33,1); y2 = 0.95*ones(33,1);
plot(1:n,y2,'r');
hold on
plot(1:n,voltage,'-^k',1:n,voltage1,'-*g',1:n,voltage2,'-
sy',1:n,voltage3,'-dm',1:n,voltage4,'-ob');
axis([1 35 0.91 1.014])
xlabel('Bus Number');
ylabel('Voltage Magnitude (p.u)');
legend('Vmin','Base Case','Analytical','BAT','BFA','IBFA')

%PLOT4: VOLTAGE PROFILE IN DISCRETE FORM FOR BASE-CASE, ANALYTICAL,
BAT, BFA AND IBFA
```

```
x=1:n; y1=voltage; y2=voltage1; y3=voltage2; y4=voltage3; y5=voltage4
y=[y1 y2 y3 y4 y5];
h = bar(x,y,'grouped');
set(h(1),'FaceColor','k')
set(h(2),'FaceColor','g')
set(h(3),'FaceColor','y')
set(h(4),'FaceColor','m')
set(h(5),'FaceColor','b')
hold on
ymax = 1.05*ones(36,1); ymin = 0.95*ones(36,1);
plot(0:35,ymax,'r',0:35,ymin,'r');
axis([0 35 0.8 1.1]),xlabel('Bus Number'); ylabel('Voltage Magnitude
(p.u)');legend('Base
Case','Analytical','BAT','BFA','IBFA','Vmax','Vmin'); %grid on

%%%%%%%%%%%% POWER LOSSES AGAINST BUS NUMBER %%%%%%%%%%%%%%%%%%%%%%

%PLOT1: POWER LOSSES IN CONTIOUS FORM FOR BASE-CASE, BFA AND IBFA

plot(1:n-1,Plosskw,':k',1:n-1,Plosskw3,'-.m',1:n-1,Plosskw4,'-b');
axis([1 35 -20 60])
xlabel('Bus Number');
ylabel('Power loss (Kw)');
legend('Base Case','BFA','IBFA')

%PLOT2: POWER LOSSES IN DISCRETE FORM FOR BASE-CASE, BFA AND IBFA

x=1:n-1; y1=Plosskw; y4=Plosskw3; y5=Plosskw4
y=[y1 y4 y5];
h = bar(x,y,'grouped');xlabel('Bus Number'); ylabel('Power loss
(Kw)');legend('Base Case','BFA','IBFA'); grid on
set(h(1),'FaceColor','k')
set(h(2),'FaceColor','m')
set(h(3),'FaceColor','b')

%PLOT3: POWER LOSSES IN CONTIOUS FORM FOR BASE-CASE,ANALYTICAL, BAT,
BFA AND IBFA

plot(1:n-1,Plosskw,'-.k',1:n-1,Plosskw1,'-g',1:n-1,Plosskw2,':y',1:n-
1,Plosskw3,'-.m',1:n-1,Plosskw4,'-b');
axis([1 35 -20 65])
xlabel('Bus Number');
ylabel('Power loss (Kw)');
legend('Base Case','Analytical','BAT','BFA','IBFA')

%PLOT4: POWER LOSSES IN DISCRETE FORM FOR BASE-CASE,ANALYTICAL, BAT,
BFA AND IBFA

x=1:n-1; y1=Plosskw; y2=Plosskw1; y3=Plosskw2; y4=Plosskw3;
y5=Plosskw4
y=[y1 y2 y3 y4 y5];
h = bar(x,y,'grouped');xlabel('Bus Number'); ylabel('Power loss
(Kw)');legend('Base Case','Analytical','BAT','BFA','IBFA'); grid on
set(h(1),'FaceColor','k')
set(h(2),'FaceColor','g')
set(h(3),'FaceColor','y')
set(h(4),'FaceColor','m')
set(h(5),'FaceColor','b')
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%% PLOTS FOR THE 50-BUS CANTEEN FEEDER %%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%% VOLTAGE PROFILE AGAINST BUS NUMBER %%%%%%%%%%%%%%%%%%%%%%%

%PLOT1: VOLTAGE PROFILE IN CONTIOUS FORM FOR BASE-CASE, BFA AND IBFA

plot(1:n,voltage,'-^k',1:n,voltage3,'-dm',1:n,voltage4,'-ob');
axis([1 55 0.988 1.002])
xlabel('Bus Number');
ylabel('Voltage Magnitude (p.u)');
legend('Base Case', 'BFA', 'IBFA')

%PLOT2: VOLTAGE DISCRETE FORM IN CONTIOUS FORM FOR BASE-CASE, BFA AND
IBFA

x=1:n; y1=voltage; y4=voltage3; y5=voltage4
y=[y1 y4 y5];
h = bar(x,y,'grouped');
set(h(1),'FaceColor','k')
set(h(2),'FaceColor','m')
set(h(3),'FaceColor','b')
hold on
ymax = 1.05*ones(56,1); ymin = 0.95*ones(56,1);
plot(0:55,ymax,'r',0:55,ymin,'r');
axis([0 55 0.8 1.1]),xlabel('Bus Number'); ylabel('Voltage Magnitude
(p.u)');legend('Base Case','BFA','IBFA','Vmax','Vmin'); %grid on

%%%%%%%%%%%%%% POWER LOSSES AGAINST BUS NUMBER %%%%%%%%%%%%%%%%%%%%%%%%%%

%PLOT1: POWER LOSSES IN CONTIOUS FORM FOR BASE-CASE, BFA AND IBFA

plot(1:n-1,Plosskw,'-.k',1:n-1,Plosskw3,':m',1:n-1,Plosskw4,'-b');
axis([1 55 -0.4 0.8])
xlabel('Bus Number');
ylabel('Power loss (Kw)');
legend('Base Case','BFA','IBFA')

%PLOT2: POWER LOSSES IN DISCRETE FORM FOR BASE-CASE, BFA AND IBFA

x=1:n-1; y1=Plosskw; y4=Plosskw3; y5=Plosskw4
y=[y1 y4 y5];
h = bar(x,y,'grouped');xlabel('Bus Number'); ylabel('Power loss
(Kw)');legend('Base Case','BFA','IBFA'); grid on
set(h(1),'FaceColor','k')
set(h(2),'FaceColor','m')
set(h(3),'FaceColor','b')
```