OPTIMAL PLACEMENT OF STATCOM CONTROLLERS WITH METAHEURISTIC ALGORITHMS FOR NETWORK POWER LOSS REDUCTION AND VOLTAGE PROFILE DEVIATION MINIMIZATION

UNIVERSITY OF KWAZULU-NATAL

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Supervisor: Prof. A. K. Saha

CERTIFICATION

As the candidate's Supervisor, I agree to the submission of this dissertation.

Akshay Kumar Saha

Signed: ________________________________

Signed: Prof. A.K. Saha.

Date: 29 June, 2020

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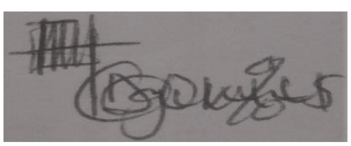

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Publication 3

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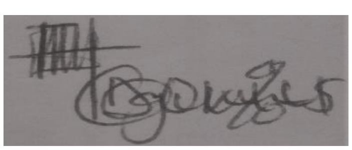
Publication 4

Emmanuel Idowu Ogunwole and Akshay Kumar Saha, “Optimal Placement of STATCOM with Fast Voltage Stability Index for Power Loss Reduction and Voltage Profile Improvement,” ***International Journal of Engineering Research in Africa (IJERA),*** (In review).

Signed: 

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ABSTRACT

Transmission system is a series of interconnected lines that enable the bulk movement of electrical power from a generating station to an electrical substation. This system suffers from unavoidable power losses and consequently voltage profile deviation which affects the overall efficiency of the system; hence the need to reduce these losses and voltage magnitude deviations. The existing methods of incorporation of static synchronous compensator (STATCOM) controllers to solve these problems suffer from incorrect location and sizing, which could bring about insignificant reduction in transmission network losses and voltage magnitude deviations. Hence, this research aims to reduce transmission network losses and voltage magnitude deviation in transmission network by suitable allocation of STATCOM controller using firefly algorithm (FA) and particle swarm optimization (PSO). A mathematical steady-state STATCOM power injection model was formulated from one voltage source representation to generate new set of equations, which was incorporated into the Newton-Raphson (NR) load flow solution algorithm and then optimized using PSO and FA. The approach was applied to IEEE 14-bus network and simulations were performed using MATLAB program. The results showed that the best STATCOM controller locations in the system after optimization were at bus 11 and 9 with the injection of shunt reactive power of 8.96 MVAr, and 9.54 MVAr with PSO and FA, respectively. The total active power loss for the network under consideration at steady state, with STATCOM only and STATCOM controller optimized using PSO and FA, were 6.251 MW, 6.075 MW, 5.819 MW and 5.581 MW, respectively. The corresponding reactive power were 14.256 MVAr, 13.857 MVAr, 12.954 MVAr and 12.156 MVAr, respectively. In addition, bus voltage profile improvement indicates the effectiveness of metaheuristic methods of STATCOM optimization. However, FA gave a better power loss and voltage magnitude deviations minimizations over PSO. The study concluded that FA is more effective as an optimization technique for suitably locating and sizing of STATCOM controller on a power transmission system.

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LIST OF ACRONYMS

ABC	Artificial Bee Colony
AC	Alternating Current
ANN	Artificial Neural Network
BESS	Battery Energy Storage System
BF	Bacterial Foraging
CIM	Current Injection Model
CRO	Chemical Reaction Optimization
CSA	Cuckoo Search Algorithm
DE	Differential Evolution
DP	Dynamic Programming
D-STATCOM	Distribution Static Synchronous Compensator
DVR	Dynamic Voltage Restorer
EHV	Extra High Voltage
EP	Evolution Programming
EPSs	Electrical Power Systems
E-STATCOM	Energy Storage Static Synchronous Compensator
FA	Firefly Algorithm
FACTS	Flexible Alternating Current Transmission Systems
FC-TCR	Fixed Capacitor – Thyristor Controlled Reactor
GA	Genetic Algorithm
GM	Gradient Method
GSA	Gravitational Search Algorithm
GTO	Gate Turn Off
HBCC	Hysteresis Band Current Controller
HCRO	Hybrid Chemical Reaction Optimization
HNN	Hopfield Neural Network
HS	Harmony Search
HVDC	High Voltage Direct Current
IAE	International Energy Agency
IEEE	Institute of Electronic and Electrical Engineering

IGBT	Insulated Gate Bi-polar Transistor
IP	Interior Point
IPFC	Interline Power Flow Controller
LP	Linear Programming
LRA	Lagrangian Relaxation Algorithm
MATLAB	Matrix Laboratory
MFO	Moth – Flame Optimization
NLP	Non - Linear Programming
NM	Newton Method
N-R	Newton – Raphson
OPF	Optimal Power Flow
PCC	Point of Common Coupling
PIM	Power Injection Model
PS	Pattern Search
PSO	Particle Swarm Optimization
QP	Quadratic Programming
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
STS	Static Transfer Switch
SVC	Static Var Compensator
TCSC	Thyristor Controlled Series Compensator
TCS-TCR	Thyristor Switched Capacitor–Thyristor Controlled Reactor
TS	Tabu Search
UPFC	Unified Power Flow Controller
UPS	Uninterrupted Power Supplies
VSC	Voltage Source Converter
VSM	Voltage Source Model

LIST OF SYMBOLS

Symbols	Definitions	Units
γ	Absorption coefficient	Dimensionless
$c_{1,}$ c_2	Acceleration coefficients	Dimensionless
P_i	Active power at bus i	Megawatt (MW)
δ_k	Angle at bus k	Degree (°)
β	Attractiveness	Dimensionless
G_{best}	Best fitness value	Dimensionless
$\Delta Q_i^{(k)}$	Change in reactive power	Megavolt-ampere reactive (MVAr)
$\Delta P_i^{(k)}$	Change in real / active power	Megawatt (MW)
$\Delta \delta_i^{(k)}$	Change in voltage angle	Degree (°)
$\Delta V_i^{(k)}$	Change in voltage magnitude	Volt (V)
x_i, x_j *and* y_i, y_j	Component of the spatial coordinate of the firefly	Meters (m)
G_{ij}	Conductance at buses i and j	Siemens (S)
$X^{\max}$	Control variable maximum limit	
$X^{\min}$	Control variable minimum limit	
E_1	Converter output voltage	Volt (V)
$iter$	Current iteration	Dimensionless
r_{ij}	Distance between fireflies	Meters (m)
F_p	Fitness function	
w	Inertial weight	
β_o	Initial attractiveness	
$U_{i(old)}$	Initial position of i^{th} firefly	Meters (m)
I	Line current	Ampere (A)
V	Line voltage	Volt (V)
$iter_{\max}$	Maximum number of iteration	Dimensionless
$w_{\max}$	Maximum number of weighing factors	
$w_{\min}$	Minimum number of weighing factors	
Y_{ij}	Mutual admittance at buses i and j	Siemens (S)
P_{best}	New fitness value	Dimensionless
I_N	Norton current	Ampere (A)
n	Number of iterations	Dimensionless
I_o	Original light intensity	
$q_{1,}$ $q_{2,}$ q_3	Penalty factors	
θ_{ij}	Phase angle at buses i and j	Degree (°)

P_D	Power demand	Megawatt (MW)
P_{Gi}	Power generated at bus i	Megawatt (MW)
P_L	Power loss	Megawatt (MW)
$P_{L,STC}$	Power loss with STATCOM.	Megawatt (MW)
$(rand)$	Random number generator uniformly distributed in the space	Dimensionless
α	Randomization parameter determined by the problem of interest	Dimensionless
Q	Reactive power	Megavolt-ampere reactive (MVAr)
Q_i	Reactive power at bus i	Megavolt-ampere reactive (MVAr)
Q_{Gi}	Reactive power compensator at bus i	Megavolt-ampere reactive (MVAr)
Q_{Di}	Reactive power demand at bus i	Megavolt-ampere reactive (MVAr)
P	Real power	Megawatt (MW)
I_r	Receiving end current	Ampere (A)
V_r	Receiving end voltage	Volt (V)
V_k^*	Reference voltage at bus k	Volt (V)
S_i	Sending end apparent power	Volt-ampere (VA)
I_s	Sending end current	Ampere (A)
V_s	Sending end voltage	Volt (V)
I_{sh}	Shunt current	Ampere (A)
G_{STC}	STATCOM conductance	Siemens (S)
I_{STC}	STATCOM current	Ampere (A)
$V_{STC}^{\max}$	STATCOM maximum voltage	Volt (V)
$V_{STC}^{\min}$	STATCOM minimum voltage	Volt (V)
δ_{STC}	STATCOM phase angle	Degree (°)
Y_{STC}^*	STATCOM reference admittance	Siemens (S)
I_{STC}^*	STATCOM reference current	Ampere (A)
B_{STC}	STATCOM susceptance	Siemens (S)
V_{STC}	STATCOM voltage	Volt (V)
$P_{L,normal}$	System power loss	Megawatt (MW)
T_{pi}	Transformer taping	dimensionless
V_k	Voltage at bus k	Volt (V)
V_{ij}	Voltage at buses i and j	Volt (V)

CHAPTER ONE

INTRODUCTION

1.1 Background

Modern power system is an interconnected sub-system which comprises a quite number of generators, transmission lines, transformers and variety of loads [1 – 3]. The power system is increasing in complexity due to increase in loop current flows, power demand and line losses [4, 5]. As a result of increase in power demand, modern day electrical power systems (EPSs) face crucial challenges. The power system is categorised into three sub-systems viz; generation system, transmission system and distribution system. In the generation system, electric power is produced, transmitted via the transmission system to the end users. Transmission system serves as a link between generation system and supply the end users [6 – 9].

1.1.1 Structure of Electrical Power Systems

Electrical power system is defined as a very large network that links power plants i.e. large or small to the loads, by means of an electric grid. Power system is divided into generation system (power generating stations), transmission system and distribution system [7]. The significant of a power network is to generate power in a reliable, secure, and economical manner. The six main power network parts are power generator, transmission transformer, transmission line, substations, distribution line, and distribution transformer [10]. The power generated in the power system is stepped up before being transferred to various substations via the transmission line. The power generated is transferred to the distribution transformer where it is being stepped down to the required value suitable for the end users. Power can be transported through the transmission and distribution networks. Power systems consist of a meshed transmission lines that cut across regions which numerous power generators and loads are connected [11, 12].

Transmission systems have the following advantages in power system [7, 11, 12]:

- A flattering of the load curve, which makes the use of generation plants more effective.
- Power generation economies of scale.
- A strong minimization of the reserve margins required at individual generator level, due to outage of a unit is compensated by all other connected generators in the network, which supply only a relatively small additional power.
- The possibility of minimizing the power cost by moving generation between units by the use of different prime movers (e.g. coal, gas and oil), depending on the energy source prices [13].

The above are the reasons that justify the financial viability of connecting huge power generators by a transmission and distribution networks so as to securely move the generated power to load, instead of having a disperse power generating station at every load center [12].

1.1.1.1 Power Generating Station

Fuels are transformed to electrical energy in generating station. The generated voltage which falls between 11 - 25 kV, is stepped up to be transmitted to a long distance. The plants in the generation system can be categorised into three viz; hydropower plant, thermal power plant, and nuclear power plant. Atomic nuclei serve as the primary source of energy to generate electrical power in a nuclear power plant; the nuclei are subjected to nuclear fission to free their energy. The energy released is utilized to produce steam at high pressure to power a prime mover. In a fossil, fuel powered electrical power generating station, coal, oil, and gas are fired to produce thermal energy that goes through a steam cycle process to produce electrical energy. In both cases, a synchronous prime mover, generator, or turbine is utilized to convert mechanical power to electrical power [7]. When electrical power is generated, the transmission network serve it purpose by conveying the generated electrical power energy to the loads.

In the last few years, there has been an improvement in the power generation by power system engineers and researchers due to the fact that the primary source of both modes of power generation discussed above are limited and they are not environmentally friendly. So, they came up with renewable electrical power generation which has an unlimited primary resource, with the advantage of being environmentally friendly. A synchronous prime mover at the renewable power generating station serve two purposes: it connects all the renewable power plants and it is also used to convert the generated energy to electrical power [14].

1.1.1.2 Power Transmission and Distribution

The transmission network bears the overhead or underground lines that transport the generated energy from generating station to the distribution substations [10, 15]. The transmitted voltage is operated at above 66 kV and it is standardized at 69, 115, 138, 161, 230, 345, 500, and 765 kV, line voltage. The voltage level greater than 230 kV is considered as extra-high voltage [7, 16]. The transmission line is terminated in sub-stations referred to as the primary sub-stations, high voltage sub-stations or receiving sub-stations. In these sub-stations, the voltage is stepped down to a value suitable for the subsequent flow of power to the end users. The two main functions of transmission systems are to transport the generated electrical power from the power generation stations to primary sub-stations and link two or more generating stations.

The distribution system is the power system part, linking the end users in a particular region to the power plants. The distribution system distributes the power generated to various power users. The main difference between the transmission and distribution systems is that power is transmitted at high voltage and over a long distance in transmission system compared to distribution systems, which distribute power at low voltage and over a short distance [11, 17]. This is as a result of the dependency of the capacity of transmitted power on current and voltage, and losses on the current and length of the line. Therefore, the active and reactive line losses on transmission network over a long distance are reduced by lowering the current and raising the magnitude of the voltage resulting in enhancement of power transfer capacity. Increase in voltage magnitude leads to increase in transmission and transmission component costs. Consequently, minimization of power loss cost more. This result in an existence of an option of capital expenditure for equipment to minimize losses for efficient power transfer.

In developing countries, majority of the transmission networks are loaded beyond their capacity than was planned, when constructed [18]. Availability of electricity is the most powerful vehicle driving economic development and social changes throughout the world. The supply of electricity involves a large inter-connection of generators and loads via a transmission systems consisting of transmission lines, transformers, and other necessary equipment [15].

Unlike in some communication systems where transmission of signals is based on wireless technology, electricity generated at various generating stations can only get to the consumers at the distribution system through a transmission network. The transmission system performs the roles of voltage transformation, power switching, measurement and control. It also provides for redundant system that helps in the smooth flow of power at a minimum cost with required reliability [19].

Transmission systems are either mesh or longitudinal in nature [20]. Meshed systems are located in high populated areas where building of generation stations close to the power users, is possible. Longitudinal networks are located where great quantities of power is required to be transfered over a long distance from generating stations to end users. Transmission line with low impedance ensures larger flow of power while the one with high impedance limits the flow of power. Transmission lines are long and have high impedance which give rise to various operational problems, such as high transmission line losses, voltage limit violations, loss of system stability and not being able to fully utilize power systems up to their thermal capacity [10].

Power outages, as a result of disruption of transmission lines, are increasing in the developing nations. This contributes to the educational dwarfism, economic down turn, technocrats and artisans gross dissatisfaction due to low business in-flow, consequently; a retrogressive national growth. Almost 1.3 billion people in the developing nations live with no power supply. With recent global increase in population in rural and urban areas, the demand for power is increasing and the availability of power systems supplies in developing countries are insufficient for the load. International energy agency (IEA) marked Sub-sahara Africa to have only 32% electricity supply. A large number of transmission lines are loaded beyond the capacity than was planned when constructed and there is an urgent need to meet the needs of the population without electricity [21].

The main objective of analysis of power flow is to obtain the magnitudes of active and reactive load flow in the transmission network and also, the voltage magnitudes at all the buses of the system for a given loading condition [2, 3]. Power flow control in power system, is an essential factor affecting the overall modern system development. As power demand substantially increases, the expansion of generation and transmission systems have been greatly hindered as a result of environmental restrictions and insufficient resources. Consequently, majority of the power systems are enomously loaded resulting in the stability of the system reaching its power transfer-limiting factor [22 – 24]. In contrast to the rapid boom in power network technologies, transmission networks are loaded to their thermal-limits and simultaneously, stability limits [18, 25].

Building new power plants and transmission lines as well as using traditional electromechanical devices, such as synchronous condenser, reactors, capacitor tap-changing transformers, and banks, have been employed to reduce the transmission systems operational problems [26]. However, long construction time and regulatory pressure hinder the construction of new transmission networks and generating stations while low speeds, mechanical wear and tear and high cost of implementation limit the use of traditional devices [19, 27]. Recently, FACTS devices were introduced in the transmission networks as a result of power electronic development [28]. FACTS devices control the network condition as fast as possible and this is exploited to control the system real and reactive power for minimizing losses and voltage magnitude deviations in transmission networks. These controllers facilitate power flow control, minimize generation cost, enlarge the power transfer capability, enhance and improve transmission network stability and security. FACTS devices are electronic based incorporated into the alternating current transmission networks to increase power transfer capability and enhance controllability [29, 30].

FACTS serves as an attractive means for maximizing the use of the existing power systems, the enhancement of which has not kept pace with the increase in the capacity of power transmitted through transmission networks. The power transfer problem is curbed by adding generating and additional transmission facilities. Interestingly, this problem can be curbed by FACTS controllers without necessarily altering the system configuration and this is mostly desired by transmission line management companies. FACTS devices is categorised into series connected, shunt connected and a combination of both [31]. Some of the shunt connected devices are static synchronous compensator (STATCOM) and static var compensator (SVC). The series connected comprises static synchronous series compensator (SSSC), thyristor controlled series compensator (TCSC) etc. While for combined shunt and series, unified power flow controller (UPFC) is a member of this type [32, 33]. STATCOM is use in this research due to it fast compensating / operating time and less cost of installation. These devices and their mode of operations were discussed fully in the next chapter.

1.2 Research Motivation and Problem Statement

Transmission systems are constructed in a way to respond to generation and varying load conditions. Transmission facilities are required to provide equal right to use for power migration to all participants at all times, ensure reliability and full capability at minimum technical loss and ensure equitable load allocation to consumers. Power transmission system has been shown to be connected to load centers through long fragile longitudinal transmission systems, which are subjected to frequent transmission network collapse due to bad system configuration, high transmission loss, voltage limit violation which does not allow system reliability [16, 19].

These problems have been solved using electromechanical devices and by power system reinforcement with construction of extra generating and transmission facilities [34]. Unfortunately, problems associated with the suggested methods cannot provide effective and immediate solution, hence the use of FACTS controllers which have been shown to be an alternative to strengthening the voltage profile, load flow and enhancing the interconnected power system stability [35].

The infinite length of longitudinal network is subjected to high power loss, poor voltage profile and power flow control. The solution to these problem, as power demanded increases continuously, is to either build more generation stations (which is expensive) or expand the available transmission infrastructure (which is not economical) or enhance the existing transmission facilities by incorporating FACTS devices like STATCOM, SVC and others. FACTS controllers proves as better alternatives for load flow variable control, voltage profile improvement, minimization of losses, and stability enhancement of the interconnected power systems. Enhancement of the existing transmission facilities by incorporating FACTS controllers to increase the power flow, and reduce losses rather than expanding the existing power generation stations is necessary.

Literature survey confirms that little has been done in applying FACTS controllers to solve the weaknesses manifested in the longitudinal power system [20]. Also, several researcher have incorporated different types of FACTS controllers for transmission line control [19], there is no known research that has explored load flow analysis of the longitudinal system, perform load flow solution by optimally incorporating STATCOM with meta-heuristic method for power flow control of system variables (active, reactive and voltage magnitude). Their researches were limited in scope to power flow analysis with Newton-Raphson, Gauss-Seidel, Fast decoupled method without the incorporation of STATCOM. The exchange of power in a network is facilitated by STATCOM in improving the power supplied to the loads.

1.3 Research Questions

Transmission network is the power system component linking the generated power at the generating stations to loads. It has been established that in power system, transmission networks account for a larger percentage of the total losses which increases the total transmission cost and this is undesirable. Therefore, minimization of losses and voltage magnitude deviations is imperative. Some of the questions that this research seeks to answer are:

- How can the voltage profile of transmission network be improved?
- How can the active and reactive losses be minimized on the transmission systems?
- What role does STATCOM play in achieving these?
- How can STATCOM be optimally sized and placed on the transmission networks?
- What methods can be used to optimally size and place STATCOM on transmission networks?
- What are the benefits of optimally sizing and placing STATCOM on transmission networks?

1.4 Aim and Objectives

This research aims at investigating the effectiveness of STATCOM device, been optimally sized and placed with particle swarm optimization (PSO) and firefly (FA) algorithms for power loss reduction and bus voltage magnitude deviation minimization on a transmission system.

The specific objectives of the study are to:

(a) formulate STATCOM power injection model.
(b) incorporate STATCOM power injection model in (a) into nonlinear algebraic load flow equations, solved using Newton Raphson power flow algorithm.
(c) simulate the Newton-Raphson load flow algorithm using MATLAB.
(d) determine the performance evaluation of the STATCOM model when optimally installed with meta-heuristic algorithms in the IEEE 14 bus standard network using voltage profile, active and reactive power as performance metrics.

1.5 Structure of the Dissertation

Chapter one gives a general introduction of the study, statements of the problem, aim and the objectives. Chapter two focuses on the literatures review. Chapter three presents the materials and the research methodology employed in the course of the study. Chapter four presents and discusses the preliminary results of the load flow analysis of IEEE 14-bus network and when STATCOM was manually placed.

Chapter five presents and discusses the simulation results when STATCOM was optimally sized and placed on IEEE 14 bus system, using PSO algorithm. Chapter six presents and discusses the simulation results when STATCOM was optimally sized and placed using firefly algorithm (FA). Chapter Seven presents the conclusion of the dissertation and provides recommendations, based on the research findings, for further future work.

1.6 Summary

This chapter introduced the subject matters of the research work, and the significance of the study, why it is expedient to investigate and evaluate the transmission losses and ways to minimize it were discussed. Moreover, all the methods and the devices used to minimize transmission power loss were briefly discussed. FACTS devices, which are power electronic based, are usually employed to minimize transmission power losses as well as to improve the system voltage profile. They are either placed in shunt or series or both on the transmission network to achieve those objectives. Thus, in respect of that, FACTS devices could be classified as SVC, STATCOM, TCSC, SSSC, UPFC etc. However, to achieve better results, FACTS device allocation must be optimally done using any of the meta-heuristic methods. In conclusion, the research motivation, problem statement, research questions, aim and objectives were stated.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

In transmission system networks, reactive power compensators are important in minimizing network voltage magnitude deviations and losses. The optimal location and size of compensator are very important to achieve these objectives. Therefore, this chapter discusses some of the devices used for voltage deviation minimization and power loss reduction in transmission systems. The methods utilized to determine the optimal location and reactive compensator capacities were discussed while the literatures relevant to this study were also reviewed.

2.2 Reactive Power Compensator

Reactive power compensators are electrical devices capable of absorbing or injecting reactive powers into the power network for transfer capability enhancement. They are usually connected at the suitable positions in the transmission system for voltage magnitude deviation minimization in the power network and also for minimizing losses. Different types of reactive power compensators are discussed in the following sections.

2.2.1 Capacitor

Capacitor placement in power system network, is an efficient way of improving the power delivery. When installed in shunt on the transmission line, it is referred to as shunt-compensator. A shunt-compensator generates the required reactive power into the network. Capacitors connected in shunt, are placed at a bus to hold the bus voltage levels, injecting required reactive power into network to do so. On the other hand, a capacitor connected in series is called a series compensator. A series compensator is placed between two buses in the transmission network to control the line reactive power flow [25, 29].

2.2.2 Flexible Alternating Current Transmission System

FACTS is a power electronics-based system made up of static equipment which is used in transmission of power. It facilitates the capability and controllability of the network to transfer power [29, 36, 37]. The Institute of Electronic and Electrical Engineering (IEEE) defined FACTS as equipment that is capable of controlling one or more transmission network control values to facilitate the capability and controllability of power transfer. FACTS devices reduces power delivery costs and improves systems reliability. They enhance the efficiency and quality of transmission system by injecting or absorbing required reactive power into the transmission network. FACTS devices are of various types among which are static synchronous compensator (STATCOM), static VAR compensator (SVC), unified power flow controller (UPFC), thyristor-controlled series capacitor (TCSC) and interline power flow controller (IPFC) [7, 10, 25].

2.3 Application of Power Electronics in Power System

Power electronics is the application of solid-state electronics for the control and conversion of electric power [38]. It is impossible to give a lists of power electronics applications in today's world; it has entered nearly all the fields where electrical energy is in use [39]. The ease of manufacturing has also led to availability of these devices in a vast range of ratings and has gradually appeared in power system. Power electronics devices used in power system are: high voltage direct current (HVDC) links and FACTS devices. The HVDC links is another way of transmitting electrical power, while FACTS controllers are applied for reactive power compensation and power system improvement. These devices used in the distribution system are employed to improve the system power quality and are usually called custom power devices, while the devices on the transmission system are optimized to reduce losses by balancing the reactive power [11, 40]. Figure 2-1 shows a brief diaspora of power electronics.

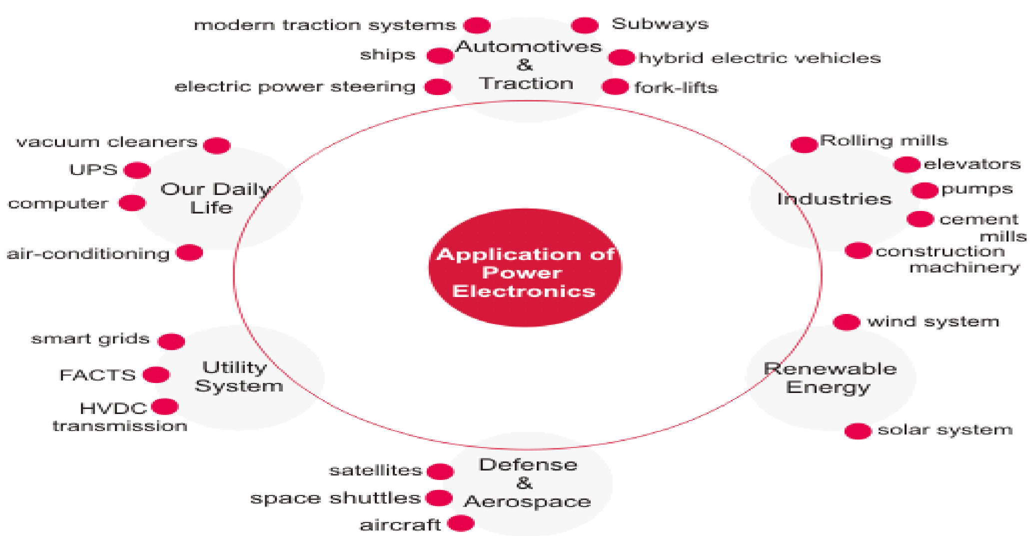

Figure 2-1: Diaspora of power electronics [25].

They are widely applied in power system, and promotes development of power system towards a more intelligent and sustainable direction. The power electronic converter processed 60% of the final electric energy used in developed country at least one time according to the data. Which means, power electronics contributes greatly in power system to the power generation, power transmission, power system harmonics control, power supply stability, etc. [19, 29].

2.3.1 Distribution Level

As power electronics controllers are utilized to improve stability in transmission networks and control power flow, likewise are the custom power devices used to enhance quality of power in distribution system. Problems with harmonics, damages related to transient over-voltages, or tripping of equipment as a result of voltage dips has led to the use of adjustable and dynamic devices to curb these problems [7]. Unlike FACTS devices, custom power devices are also placed in different ways: series-connection, shunt-connection, combine series-shunt connection [13]. Type of customs devices used in the distribution system are discuss below:

2.3.1.1 Distribution Static Synchronous Compensator

D-STATCOM comprises of a VSC and a small DC-capacitor. The distribution system and D-STATCOM exchange reactive power between themselves [41]. D-STATCOM is the reformation or adaptation of STATCOM for application of FACTS devices on the distribution system and only supplies reactive power into the system. D-STATCOM find it application on the distribution grid to control voltage during transient and voltage dip, filter the system to reduce current harmonics level and for load balancing. Figure 2-2 shows the connections of D-STATCOM in a distribution network.

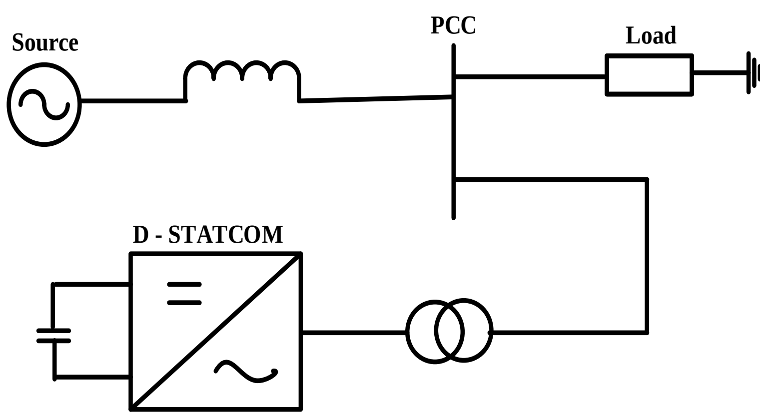

Figure 2-2: D-STATCOM on a distribution system [41].

2.3.1.2 Energy Storage Static Synchronous Compensator

E-STATCOM is a device placed in shunt, which is capable of absorbs or injects reactive and real current. Figure 2-3 shows how it is connected in a distribution system. It comprises of a VSC and energy-storage. This E-STATCOM model is capable of supplying real and reactive power. However, it is unable to inject real power for a long time due to its energy storage limit capacity. E-STATCOM has a similar use to D-

STATCOM, with the exception of its energy storage capacity which exchanges active power with the system [11].

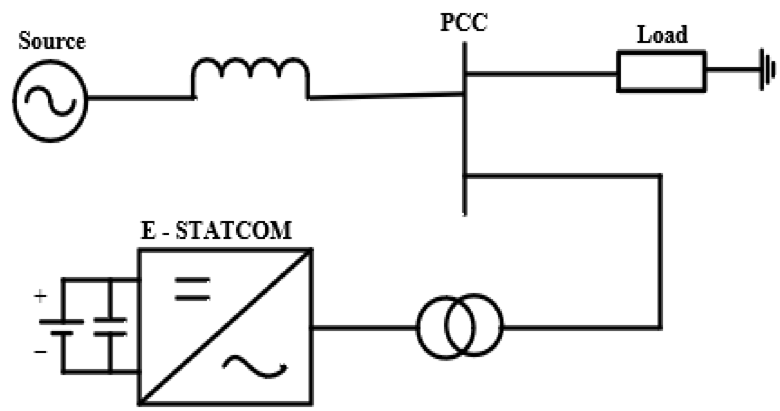

Figure 2-3: E-STATCOM on a distribution system [12].

2.3.1.3 Dynamic Voltage Restorer

Dynamic voltage restorers (DVR) are series devices comprising of a VSC which produces injected a.c. voltages for voltage sag improvement via injection transformers [41]. The major advantage of the use of the DVR to mitigate the voltage drop is its dynamic performance, which is not dependent on the source impedance. Likewise, it can be deployed to compensate for unbalanced voltage and filter voltage harmonics. The only draw back of DVR is the increase in cost as a result of the requirement of an advanced protection system if a short circuit fault occurs [12]. Figure 2-4 presents the configuration of a DVR in a distribution network.

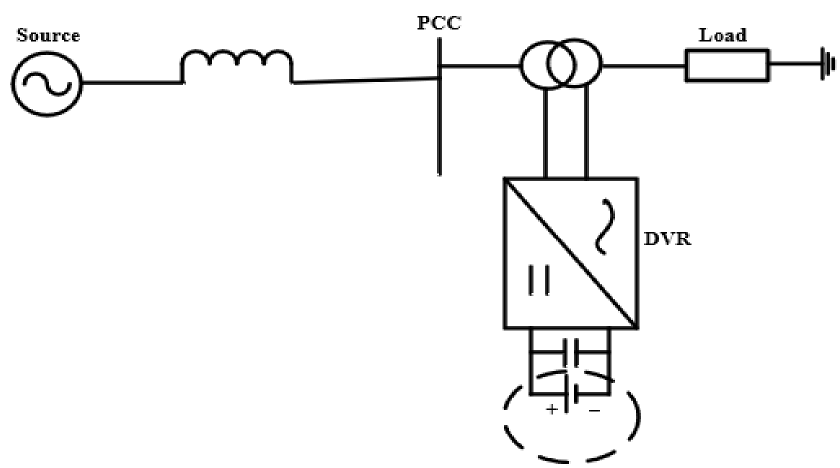

Figure 2-4: DVR connected to a distribution system [41]

2.3.1.4 Static Transfer Switch

Static transfer switches (STS) is another means of protecting a sensitive load from voltage dip. Either the primary or secondary feeder can feed a load with static transfer switch. The thyristor switches the device from the primary feeder to the secondary feeder in cases of voltage dip. The STS only protects equipment in the distribution system; if there is a voltage dip in the transmission system, both feeders of this device will be affected [11]. Figure 2-5 shows the connection in a distribution network.

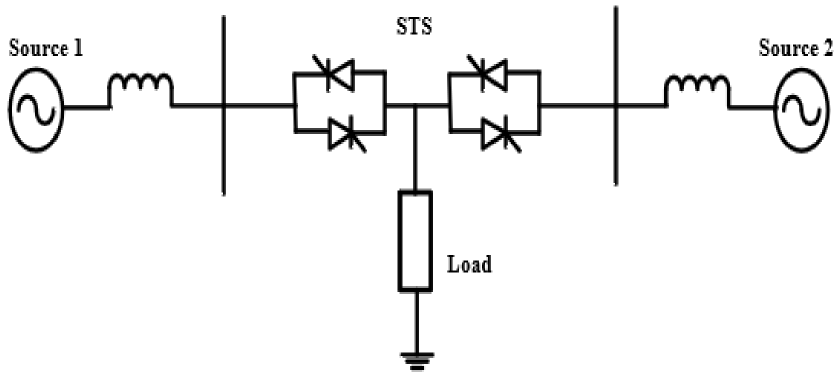

Figure 2-5: STS connected on a distribution system [12].

2.3.1.5 Uninterrupted Power Supplies

Uninterrupted power supplies (UPS) come in various structures but the common denominator of all UPS is that its energy storage can supply active power. The size of the UPS energy storage determines its capacity to mitigate power interruption, voltage drop, and other power quality problems. UPS of about 5000 kVA can be deployed for low power equipment that is sensitive, such as computers and servers [11]. Its connection with distribution system is shown in Figure 2-6.

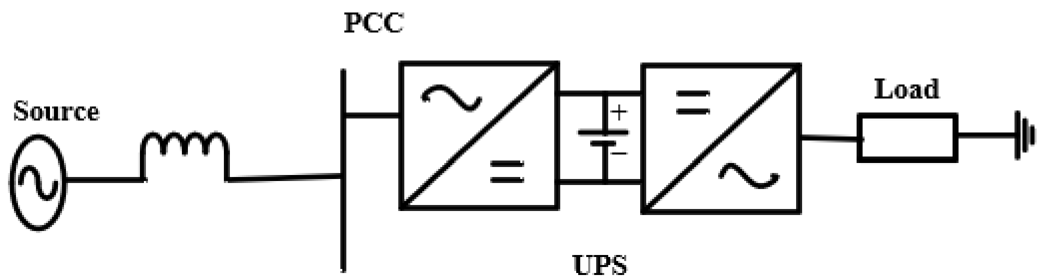

Figure 2-6: UPS connected on a distribution system [12].

2.3.2 Transmission Level

HVDC is the first power electronics technology to be used in power network, which began with the use of mercury ionic valves [11]. The HVDC finds more use in long distance overhead and underground transmission systems, as an alternative means to transport power. It is also used to connect AC systems of different frequencies [29]. The transmission capacity of transmission networks is increased to their thermal capacity limit by using FACTS devices,. FACTS facilitates control of voltage when there is contingencies and stop the flow of loop currents which is responsible for unnecessary loading of transmission network facilities [42].

Also, FACTS devices are applied to compensate and improve on an existing AC transmission system where there is a need to enhance the capacity of the system on power delivery. It has been proven that there is a significant increasing demand for electrical power leading to the complexities of the transmission system [21]. Considering the time and cost to build a new transmission line, FACTS comes in as a viable and attractive alternative [19, 24]. FACTS devices could be placed in series, parallel, or combined mode.

2.4 Overview of Flexible Alternating Current Transmission Systems Devices

FACTS controllers are power electronic controller circuit configuration which are very effective in regulating power flow on a.c. transmission lines. FACTS devices are an evolving technology to help electric utility companies. Load flow in the transmission network and bus voltage profile are easily controlled with FACTS technology applications. Iincrease in the useable transmission system power capacity and flow control over the transmission routes is the main goal of FACTS controllers [25]. FACTS devices are divided into two generations based on the technological features viz; the first and the second generations [26]. In the first generation, FACTS devices use thyristor as the power semiconductor switching device in conjuction with a large reactor or capacitor banks for absorbing or injecting reactive power from or into the transmission network. In second generation, FACTS devices use GTO or IGBT as the power semiconductor switching device in conjuction with small capacitors. The ability to interchange and generate real and reactive power is the main difference between the two generations of the FACTS devices [27].

The most advanced type of the controller among the FACTS controllers, are those which use VSC as synchronous sources. STATCOM controllers are of the VSC type, which are connected in shunt, so also are the SSSC controllers which are series connected and UPFC, which is a series/shunt type controller. Of all the VSC the most widely used is the STATCOM [28]. Figure 2-7 shows the classification of member of each generation.

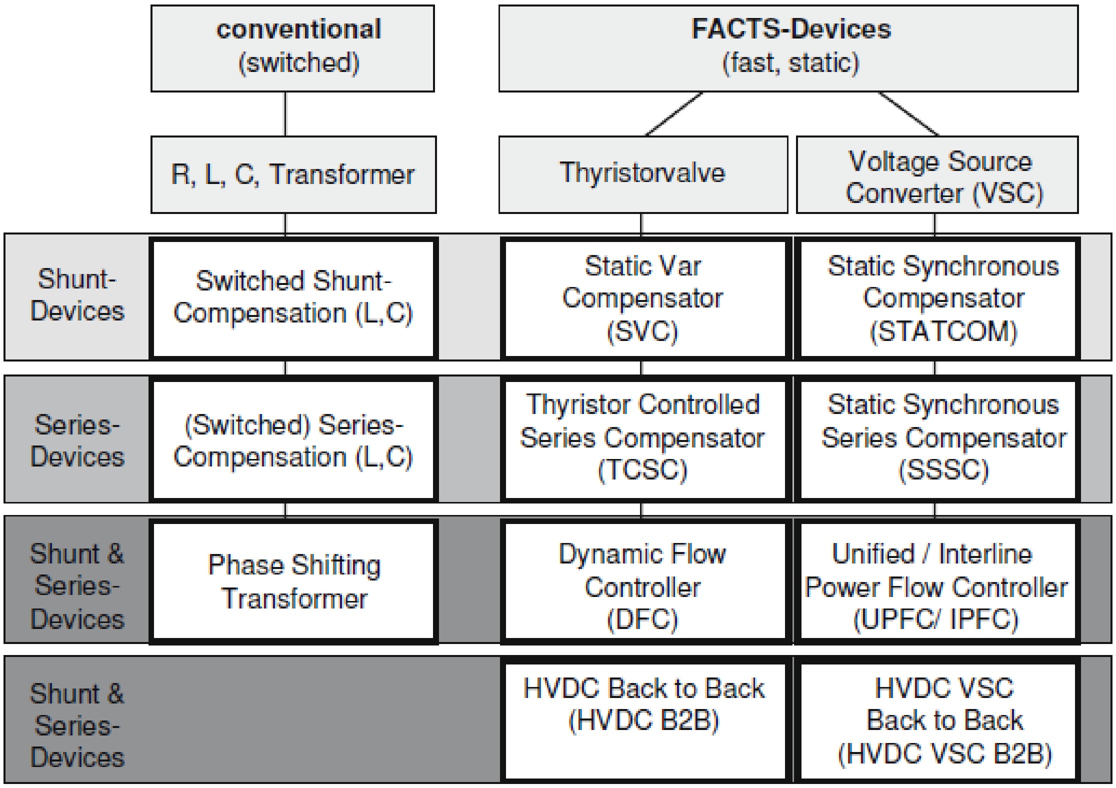

Figure 2-7: Overview of member FACTS generation [43].

FACTS devices are applied as follows [43]:

(i) increase of transmission capability

(ii) power flow control

(iii) power conditioning.

(iv) compensation of reactive power,

(v) voltage control

(vi) improvement of network stability

(vii) improvement of power quality

2.5 Basic Types of Flexible Alternating Current Transmission System

FACTS controllers are classified to four categories depending on how their connections in the transmission system bus. Electronics-based FACTS devices have replaced many mechanically controlled reactive power compensators. Furthermore, they play a role in the control and operation of transmission networks [7, 10, 29, 44 – 46].

- Shunt controllers
- Series controllers

- Combine series-series controllers
- Combine series-shunt controllers

2.5.1 Series Controllers

The series controller is either a variable impedance for examples, a reactor, thyristor switched, capacitor or a power-electronics based variable voltage source that supplies series voltage. Figure 2-8 depicts the connections of this controller on transmission network. The current flowing through the variable impedance is multiplied by the impedance, which inject series voltage on the transmission network. In this case, the device requires a energy source connected externally to it. This device either injects or absorbs reactive power when the voltage is more or less than 90^0 out of phase with the line current.

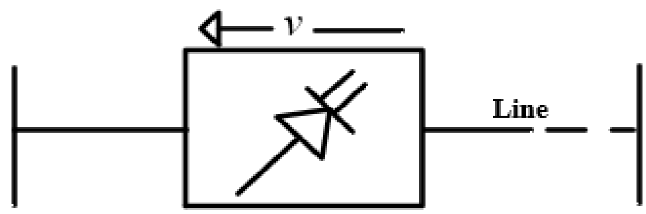

Figure 2-8: Basic series controller [29].

2.5.2 Shunt Controllers

The shunt device can either have a variable current and impedance or voltage source in addition to a reactor, or capacitor, placed in shunt in the transimission network to produce reactive power into the line as depicted in Figure 2-9. The shunt device either injects or absorbs reactive power when the current injected is more or less than 90^0 and is out of phase with respect to the voltage.

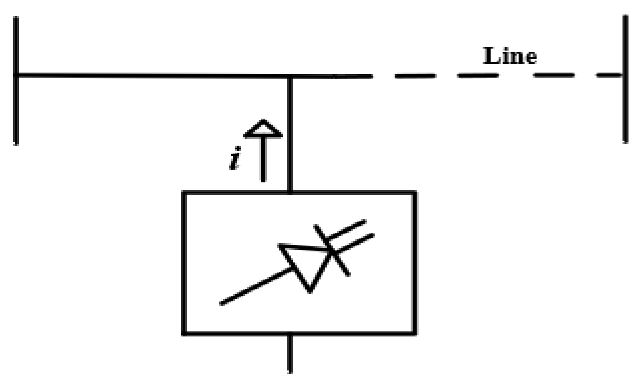

Figure 2-9: Basic shunt FACTS controller [29].

2.5.3 Combined Series Series Controllers

Combined series series controller is a combination of two or more separate series devices on a transmission network, which are controlled in a coordinated manner. These controllers possess the capacity to balance the flow of power in the network through the DC link whereby the transmission network is maximally utilized. For real power transfer, the DC-terminal of all the device is connected, therefore it is called UPFC. Figure 2-10 shows this controller type.

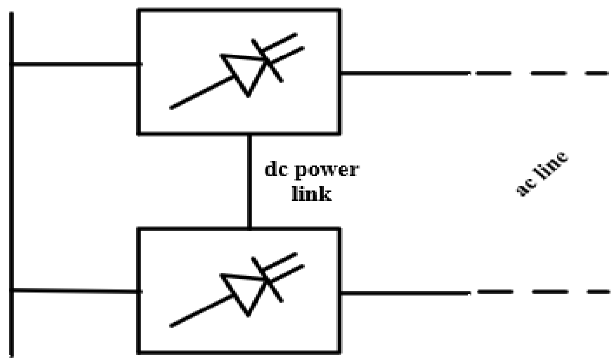

Figure 2-10: Basic series series FACTS controller [29].

2.5.4 Combined Series Shunt Controllers

The combined series-shunt controllers utilize both series and shunt devices on a transmission network, controlled in coordinated manner. The combined series- shunt devices supply series line voltage with the series part of the device and supply current to the network with the shunt part as depicted in Figure 2-11.

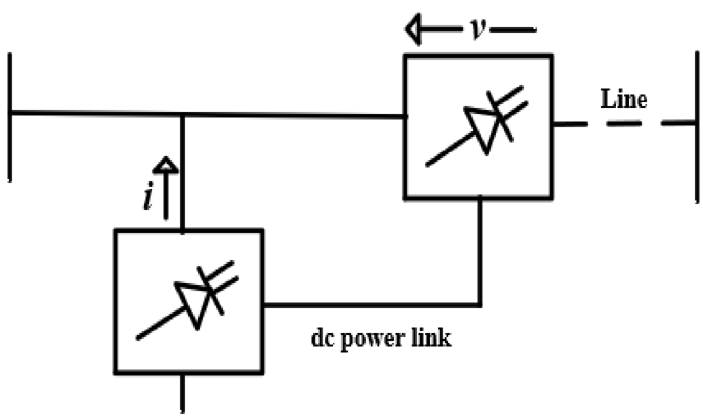

Figure 2-11: Basic series-shunt FACTS controller [29].

2.6 Shunt Devices and Operational Principle

The basic operational principle of shunt device is the injection of the reactive power which the load required. I_{sh} could be controlled by varying the shunt controller impedance for adjusting the current $\boldsymbol{I}$ in the line. The transmission line voltage-drop is related to current $\boldsymbol{I}$ in the line. When the sending end voltage V_s assumes a constant magnitude, the shunt devices is utilize for adjusting the receiving end-voltage value $|V_r|$ as depicted by Figure 2-12 [47].

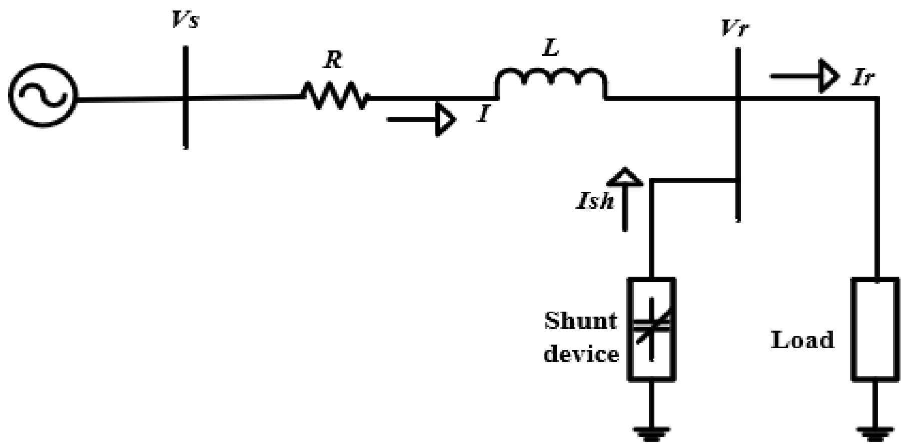

Figure 2-12: Operating principle of shunt controller [47].

This relationship I_{sh} and V_r is expressed as in Equation (2-1):

$$\boldsymbol{V_r} = \boldsymbol{V_s} - \boldsymbol{IZ}$$

$$\boldsymbol{V_r} = \boldsymbol{V_s} - (\boldsymbol{I_r} - \boldsymbol{I_{sh}})\boldsymbol{Z} \tag{2-1}$$

The current I_{sh} compensated the load current I_r partly, which reduce the line current $\boldsymbol{I}$ when the line is heavily loaded which results in low voltage-drop. Through varying the impedance, the voltage magnitude is controlled accordingly by the shunt device. Shunt devices are distinguished into three types viz; SVC devices, switched shunt-capacitor and inductor devices and STATCOM. The switched shunt-capacitor and inductor controller has only two status (high and low). Its simplicity in mode of operation and principles are too simple, which makes it not to be relatively used. Its configuration is shown in Figure 2-13. The remaining two shunt devices are discussed below.

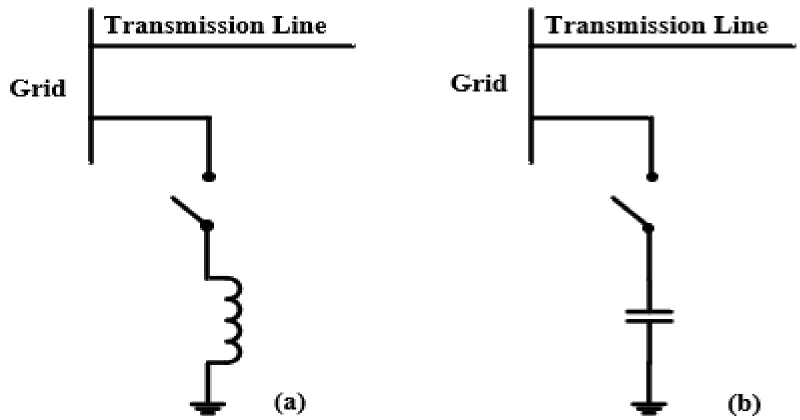

Figure 2-13: Configuration of switched-shunt capacitor and inductor [47]: (a) capacitor; (b) inductor.

2.6.1 Static VAR Compensator

This device provides fast-acting reactive power on high-voltage electricity transmission networks. The term "static" signifies that the device has no moving components. Basically, SVC divided into two type [10, 29, 46]:

- Fixed Capacitor Thyristor Controlled Reactor (FC-TCR)
- Thyristor Switched Capacitor Thyristor Controlled Reactor (TSC-TCR).

TSC-TCR is frequently used than FC-TCR due to its flexibility and that it requires reactor of smaller rating which produce smaller harmonics [31]. Figure 2-14 depicts a typical SVC connection. The TSC-TCR SVC type comprises a series capacitor or an inductor with inverse-parallel thyristor. Inverse-parallel thyristors is used in TSC to quickly switch the capacitor on and off instead of mechanical connectors. The inrush currents are limited by a small series inductor when severe transience happens, especially during the process when the capacitor begin to charge initially.

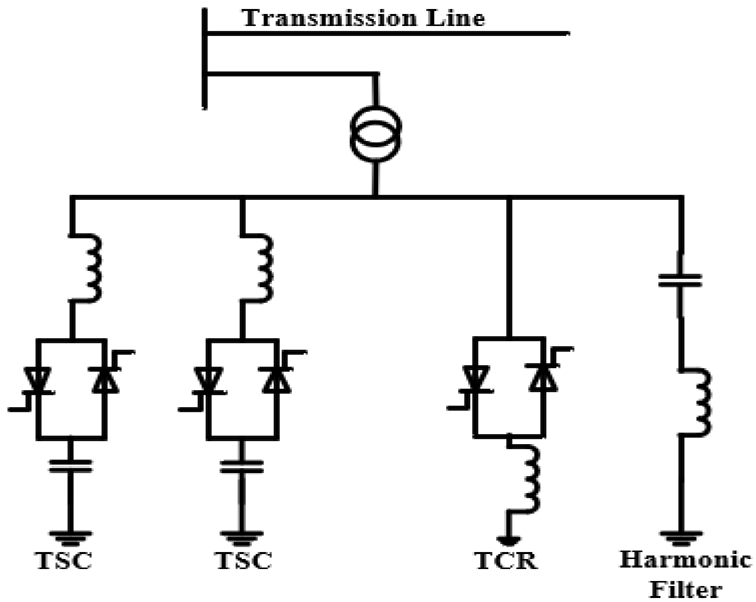

Figure 2-14: Typical configuration of SVC [47].

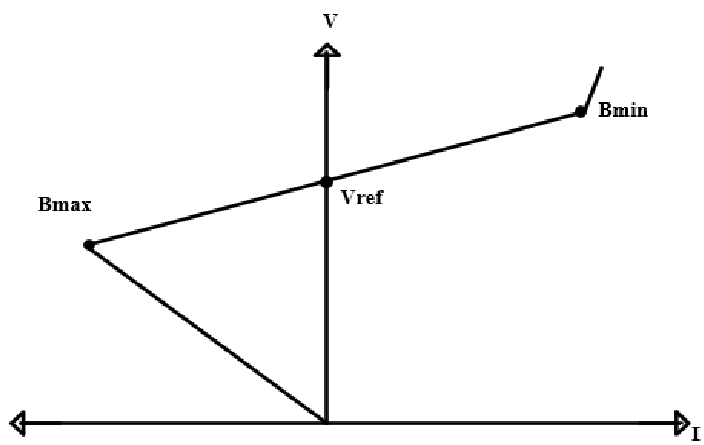

Figure 2-15: Terminal V-I characteristics of SVC [43].

Firing angle control is employed in TCR to fire the thyristors to change the current which results in control of the shunt TCR reactance. The firing angle is delayed by 90^0 delay to 180^0 delay to ensure uninterrupted conduction. SVC can function as a controllable capacitor or inductor, to inject or consume required reactive power to the transmission bus. When it is effectively located, it gives optimum performance on transmission line. The main disadvantages of SVC are that firstly, in terms of supplying required reactive power, it is less effective for low bus voltage. Secondly, SVC produces current with great number of harmonics, thereby requiring a low cutoff frequency filter to reduce these harmonics in the current [47].

2.6.2 Static Synchronous Compensator

STATCOM is a power electronics based VSC which could inject or absorb reactive power from the transmission system. It comprises a DC capacitor, a VSC and a coupling transformer [8]. Leading or lagging quadrature a.c. current can be injected by the STATCOM into the grid voltage, emulating a capacitive or an inductive impedance at where it is connected [48 – 50].

Figure 2-16 shows the one-line diagram of STATCOM controller in which a magnetic coupling is connects a transmission network bus to a VSC. By changing the magnitude of the converter 3-phase output voltage, E_1, the reactive power exchange between the a.c. network and the converter can be adjusted. Increase in output voltage magnitude above the transmission network bus voltage, V, will result in flow of current through the converter reactance to the a.c. network. This makes the converter to injects reactive power into the a.c. system. Decrease in the output voltage magnitude below the transmission network bus voltage, will result in flow of current from the a.c. network to the converter and thus consuming reactive power from the network [51]. The reactive power exchange is nil when the a.c. network voltage equals the converter output voltage. Furthermore, STATCOM performs the following [46, 52];

(i) It occupies a small footprint, i.e. compact electronic converters replace passive banks of circuit elements;
(ii) It provides modularity, factory-built equipment, thereby minimizing site work and commissioning time;
(iii) It utilizes encapsulated electronic converters, thereby reducing its environmental impact.

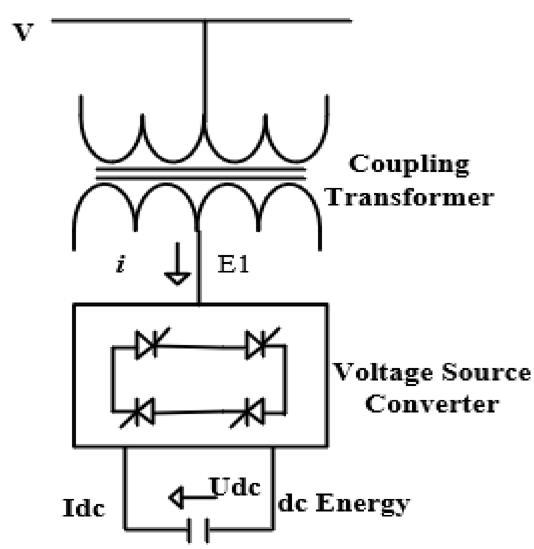

Figure 2-16: STATCOM configuration [7].

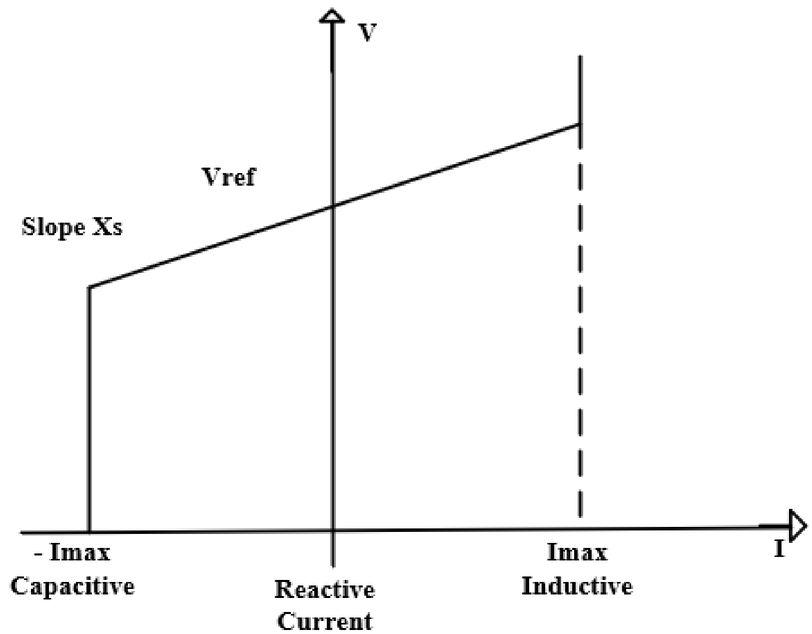

Figure 2-17: Terminal V-I characteristics of STATCOM [10].

Incorporation of STATCOM into load flow studies needs adequate STATCOM modelling in the load flow algorithms. STATCOM have two well tested models viz; the current injection model (CIM) and the power injection model (PIM). In CIM, a current source is placed in parallel whereas in PIM, a voltage source behind an equivalent reactance, is connected in paralle on the transmission network for adjusting the voltage. Steady state STATCOM power injection model reliability is very high when it is incorporated into the transmission network and is well documented [30, 43, 53, 54].

2.7 Advantages of STATCOM Over SVC

The major purpose of shunt connected FACTS devices on the system (transmission network) is to provide adequate reactive power compensation that is needed for effective operation of the system. Both SVC and STATCOM are important or elegant member of first and second generations shunt connected FACTS devices. Each of them plays a vital role in solving or mitigating problems in transmission network, especially in voltage magnitude minimization, loss minimization, system stability and security. To stabilize the voltage level in a transmission network, compensation of reactive power is required, since imbalance reactive power can cause breakdown of the power system. STATCOM operation advantage can be applied to minimize and compensate for such reactive power imbalances. As a result of fast-switching times of IGBTs (self-commutating power semiconductor) of the VSC. STATCOM responds faster than SVC and its harmonic emissions are lower. STATCOM requires less space because of its elimination of large passive components; it requires less maintenance without the problem of loss of synchronism [12, 38, 52].

Another merit of STATCOM is that compensating current is independent of the system bus voltage magnitude at the connection point, unlike SVC that experience lower compensating current as the voltage dips [39]. By comparing the cost of SVC to that of STATCOM, it becomes obvious that it is relatively cheap to install and maintain and when connected in transmission systems, it provides the voltage needed for stability, but it is poor in terms of voltage regulation - voltage regulated by the SVC maybe greater than 1.05 p.u. A VSC PWM based STATCOM was investigated in this dissertation to mitigate power losses in a transmission network. Tables 2-1 and 2-2, below shows the different basic operational principles and cost of both shunt FACTS devices respectively.

Table 2-1: Different basic operational principles of SVC and STATCOM [55].

SVC (Thyristor based shunt compensator)	STATCOM (VSC based shunt compensator)
SVC operates as a shunt connected reactive admittance control	STATCOM functions as a shunt connected synchronous voltage source
SVC does not provide active power compensation	STATCOM provide active power and reactive compensation

Table 2-2: Comparison of cost of shunt devices [55].

SHUNT DEVICES	**COST (US $)**
Shunt capacitor	8 / kVar
SVC	40 / kVar
STATCOM	50 / kVar

Table 2-1, shows the differences that account for STATCOM's superiority over SVC, for greater application flexibility and better performance. STATCOM increases flexibility and boosts power system performance, provides instant detection of voltage disturbance, and rapidly compensates by injecting leading or lagging reactive power. STATCOM provide fast recover time for utilities, from system voltage collapse events and eliminates stability-related power transfer limitations, with advanced controls. More importantly, it is a cost effectives solution with minimal footprint. STATCOM performed better than SVC when incorporated on the transmission network to mitigate power system problems.

2.8 Optimal Power Flow

Optimal power flow (OPF) is an essential tool for network operators in operating and planning stages. In order to optimize an objective function in an OPF, there is a need to find the values of all the control variables. The problem must be defined with objectives given at the onset, being stated clearly. Objective function can take different forms such as transmission losses, reactive source allocation and fuel cost [43, 56, 57].

The total production cost of scheduled generating units is the objective function to be minimized. It is mostly utilized because current economic dispatch practice is reflected and importantly cost related aspect is always ranked high among operational requirements in Power Systems. The aim of OPF is to minimize an objective, with the system load flow equations and operating limits of the equipment being the constraints that it is subjected to. The optimum solution is obtained by adjusting the controls to optimize an objective function subject to security requirements and specified operating [7, 58].

2.9 Solution Methodologies for Optimal Power Flow

A quite number of algorithms for solving optimal power flow have been proposed and applied on power network. Two major categories are recognised viz; the intelligent and conventional methods. In conventional method, the solution approaches have some disadvantages which make artificial intelligent algorithms to be used [43]. The broad views of the above itemized methods are subsequently presented.

2.9.1 The Conventional Solution Methodologies

The conventional or classical approaches are otherwise known as deterministic approach optimization methods. Examples are Gradient Method (GM), Dynamic Programming (DP), Linear Programming (LP), Quadratic Programming (QP), Newton Methods (NM), Lagrangian Relaxation Algorithm (LRA), Non-Linear Programming (NLP), Interior Point (IP) Methods and Hessian Methods. Many of these conventional techniques are employed most especially when the search space is non-linear [30].

Despite the scholarly advancements that have been made in classical approaches, yet classical approach presents some limitations in its implementation. The identified limitations among others include [10]:

(i) Poor convergence.
(ii) The solution is highly computationally expensive.
(iii) Finding a single optimized solution and the treatments of operational constraints are somehow tedious.

Most deterministic optimization methods are viewed as local search methods because they are known for producing the same set of solutions if the algorithm starts under the same initial conditions [47].

2.9.2 Intelligent Solution Methodologies

Intelligent methods also known metaheuristic optimization methods which are based on artificial intelligence. Examples are Cuckoo Search Algorithm (CSA), Bacterial Foraging (BF), Particle-Swarm Optimization (PSO), Artificial Bee Colony (ABC), Pattern Search (PS), Evolution Programming (EP), Firefly Algorithm (FA), Differential Evolution (DE), Harmony Search (HS), , Hopfield Neural Network (HNN), Gravitational Search Algorithm (GSA), Genetic Algorithm (GA) and Tabu Search (TS)among others. Researchers had shown that these algorithms are endowed with [59 – 61];

(i) Faster convergence rate.
(ii) Ability to attain global solution within shortest time possible.
(iii) Efficient capabilities for handling complex system.

A comparison of various intelligent methods for solving OPF problems showing their strengths and weaknesses is presented in Table 2-3.

This research aims to determine optimal placement and sizing of STATCOM in minimizing power losses and voltage magnitude deviations on the transmission lines. STATCOM is a VSC based controller that offers support to power system by providing reactive power compensation and rapid voltage control in power system. STATCOM increases the transmission line capacity, enhances the voltage profile, angle stability and dampens the oscillation mode of the system. In recent years, STATCOM attracts the mind of power researchers and operators for supporting the system by supplying the required reactive power and for voltage profile improvement on the transmission networks. The placement of STATCOM is an optimization problem which requires reducing the system loss and voltage magnitude deviation and satisfying system constraints.

Table 2-3: Comparison of Meta-Heuristic Optimization Algorithms [37, 59, 60, 62 – 66].

Meta-heuristic Optimization Algorithm	Merits	Demerits
Particle Swarm Optimization (PSO)	• The concept is simple and easy to implement. • Parameter control is robust and requires lesser memory. • Application to non-linear, discontinuous problem is easy.	• When handling heavily constraint problems, It is trapped in local optima as a result of limited local/global searching capabilities. • It can be easily updated without solutions quality consideration.

Ant Colony Optimization	• Applicable to a broad range of optimization problems. • Since ants move simultaneously and independently without supervision, it can be used in dynamic parallel applications. • Positive feedback favoring most taken path leads to discovering good solution rapidly. • It avoids premature convergence when computation is distributed	• Theoretical analysis is difficult so research is experimental instead of theorectical. • Although convergence is guaranteed, but it takes uncertain time to achieve this. • Applied only to discrete-problems
Artificial Bee Colony	• Requires few values. • It is used globally. • High flexibility	• High computational time
BAT Algorithm	• High flexibility and simple to implement. • Requires few control parameters. • Initial convergence is fast. • Application to non-linear discontinuous functions.	• It could lead to stagnation after initial stage, if it is rapidly switched from exploration to exploitation stage.
Grey Wolf Optimization	• Easy implementation as a result of its structure. • Converges rapidly. • Requires few number of parameter. • Local optima are avoided.	• The algorithm is still under research and development.

Meta-heuristic Optimization Algorithm	Merits	Demerits
Bacterial Foraging Optimization Algorithm	• Adapt automatically. • It converges globally thus avoiding premature convergence. • Computation is very fast. • Less memory requirement. • Wide application to nonlinear functions and handling of more objective functions.	• Swarming effect is unsatisfactory for ELD problem as a result of its biased random walk.
Shuffled Frog Leaping Algorithm	• It is accurate, robust and efficient. • It combines the profits of the local search tool of PSO and mixing information idea from parallel local searches to toward a global solution.	• Gets trapped in local optima. • The convergence to proper target is very late.
Firefly Algorithm	• It only includes self-improving process with the current space but also include. • It improves its own space • Computation to reach optima is rapid. • Rate of convergence is high and much easier. • It is a hybridized version of APSO, HS, SA and DE. • Automatic division of the whole population in subgroup. • Has inherent ability to deal with multi-modal optimization.	• May be trapped into local optima if the values are not well set. • Parameters are fixed. • No memory of previous iterations better solutions.

	• It has high periodicity and diversity in the solution.	
Genetic Algorithm	• It can easily handle the integer or discrete variables since it works with coding of parameter set. • It uses only objective function information, not derivatives or other auxiliary knowledge.	• It is time consuming. • It has many control parameters. • It is difficult to formally specify convergence criteria being a stochastic algorithm.

Various nature inspired meta-heuristic algorithms as mentioned in Table 2-3, are used to solve the problem of STATCOM placement. This dissertation proposes the use of PSO and FA for STATCOM placement to reduce power losses and voltage magnitude deviations. The choice of FA and PSO are driven by their computational efficiency, quick convergence, control parameters lustiness, easy deployment and simple concepts. The algorithms identify the parameters of the STATCOM and the most suitable STATCOM location. Simulations were carried out on standard IEEE 14-bus network using Matlab computer program.

2.10 Review on Previous Works

Several researches have been conducted in the area of optimal determination of the most suitable reactive power compensators location in a transmission network for voltage magnitude and power loss reduction. The two most popular solution methods which are reported in literature are the sensitivity techniques and mathematical optimization. The mathematical optimization approach consists of both analytic and heuristic techniques. The sensitivity technique predicts buses/areas where compensators could best located by using certain characteristic of the network. This section of the dissertation reviews some of the works conducted in this area.

ANN based STATCOM and conventional PI based STATCOM model of 132 kV transmission network were simulated with comparison by authors in [67]. Result after simulation showed that the power factor was restored into unity by STATCOM which enhanced the transmission network transfer capability by either injecting or consuming required value of reactive power. STATCOM with ANN controller gave a rapid response time when compared with PI Controller. In addition, ANN controlled STATCOM enhanced system stability and dynamic response of the network better than conventional PI based STATCOM.

A control strategy was proposed by authors in [68] for PSO based STATCOM, adjusting the parameter of PI control loop online adaptively. A small scale STATCOM controller incorporated grid was developed and simulated using a model based on electromagnetic transient. STATCOM with a control utilizing a conventional double closed-loop and PSO based intelligent control system were also designed, analyzed and the results compared. The grid voltage was significantly improved by PSO as revealed by the result showed the validity of PSO based STATCOM control strategy.

Determination of the appropriate STATCOM location and parameter setting using the Moth Flame Optimization (MFO) algorithm was proposed by authors in [32]. Incorporation of STATCOM in transmission network was done to reduce voltage deviations, enhance system stability and minimize loss. The algorithm was validated on IEEE 30-bus system. Comparison of the optimization algorithm which include a simplified STATCOM model was made with the conventional PSO. The OPF problems formulated to verify the device effectiveness, was solved with and without STATCOM incorporation. The simulation results revealed that the developed algorithm was superior in optimal STATCOM location determination.

System voltage deviation was reduced by authors in [69], using STATCOM controller allocation. The fitness value which comprises total voltage deviation and real power loss was reduced by placement of UPFC controller. This results in decrement in the total loading of the network line. Differential Evolution (DE) was chosen for optimally sizing and placing of FACTS controllers. Simulation was performed on IEEE 30-bus network. The results further showed reduction in total deviation of the voltage with increased in load by 90%. Differential Evolution algorithm also reduced congestion significantly after placement of UPFC.

Hybrid STATCOM comprising of active inverter part and thyristor-controlled LC part was used by authors in [70] to overcome the shortcoming of reactive power compensation. Simulation of Hybrid STATCOM was completed using the MATLAB/Simulink. From the simulation, the performance of the hybrid STATCOM was determined. Testing of the Hybrid STATCOM was performed during unbalanced current conditions and voltage dip. The hybrid STATCOM was found to have higher compensation capability than conventional STATCOM.

Simulation of STATCOM and SVC was carried out by the authors in ref. [31], using MATLAB/SIMULINK and a comparative analysis was done. The results showed STATCOM effectively stabilized the voltage. When the breaker closes, the device supplies reactive power to the system. As soon as the breaker closes, the voltage profile suffers a change but is recovered soon with the application of STATCOM that injects reactive power into the network. The regulated rms voltage showed a reasonably smooth profile in spite of sudden load changes, where the transient overshoots are almost nonexistent. The transients were kept at a very small values with respect to the reference voltage.

The STATCOM principle structures and its midpoint voltage regulation impact was explained by authors in [39]. The STATCOM performance with that of conventional SVC under different fault conditions were compared. MATLAB/SIMULINK software was simulated used as simulation tool and the results revealed that STATCOM is more effective in regulation of midpoint voltage on the network.

Reduction of transmission power loss was performed by authors in [71] using hysteresis band current (HBC) controller-based STATCOM. The authors designed and analyzed a STATCOM controller for linear and non-linear loads. Simulation was performed by the use of MATLAB software and the results showed mitigation in losses in the system.

A control strategy for limiting fault-current by the use of dual STATCOM was used by authors in [72], to reduce power oscillations and minimize the voltage- dip as a result of a serious symmetrical fault. This was achieved by divertion of the fault current to the capacitor using the dual-STATCOM controller. They observed that it was best suitable to maintain stability with uninterrupted power supply, effective power transfer capability and rapid reactive power support and to reduce inter-area oscillations. The SG and DFIG effectiveness as a result of symmetrical short-circuit fault in the network was investigated. The author observed that voltage magnitude deviations were mitigated and surge-current was minimized in both areas. The power oscillations were reduced, and SG q-axis voltage was regulated to nearly the same magnitude before, during and after the fault. From the results, dual STATCOM proved to be a better device than single STATCOM.

The practical and theoretical applications of STATCOM controller for controlling voltage and optimizing active power losses was described by the authors in [73]. They used STATCOM controller to vary the bus voltage and to reduce active power losses. PSO application revealed the potentials of this technique in transmission system to enhance their operation.

A micro grid system which could deliver power to dynamic loads was investigated in [74]. The system comprises a photovoltaic and a constant power micro-hydro system, connected via a fuzzy controlled STATCOM controller together with an energy-storage system. The STATCOM injected the required reactive power to the network to regulate the voltage and frequency and to also ensure good power quality in the network. The performance of the hybrid microgrid system was evaluated using various types of loads among which are nonlinear load, dynamic load, and linear load. MATALB/Simulink software was used for simulation. The results revealed that device capability in stabilizing the network parameters various load conditions.

A differential-evolution and chemical-reaction optimization hybrid chemical-reaction optimization approach was proposed by author in [75], to determine the appropriate location and STATCOM parameter settings to ensure optimal performance of network. Optimal STATCOM allocation was done by the use of hybrid chemical reaction optimization, for reducing the network loss and improve the voltage profile in a transmission network. The algorithm was successfully applied to IEEE 30-bus network. The HCRO technique is superior to other discussed algorithms discussed by the authors.

STATCOM was used by the authors in [76], to connect hybrid-power network to the grid. In their work, they use wind and solar power source for the hybrid network. The sources were not connected directly to grid because the power output of these two sources are not constant,. By the use of STATCOM, the hybrid power network output of was regulated. Although, STATCOM input varied continuously but its output was regulated with the aid of $I\cos\phi$ current component. MATLAB software was used to simulate system to obtain good waveforms.

A coordinating scheme for ULTC and STATCOM was presented by the authors in [77]. In their work, some manipulations were made in the STATCOM control system to coordinate ULTC and STATCOM. On the basis of the proposed scheme, STATCOM capacity was minimized and hence some compensating margins provided for control purposes in emergency situations. The major merit of the technique is the modification of STATCOM control system to some extent but and the control of ULTC is unchanged.

Consideration of optimal allocation method which focuses on return of investment index of high cost STATCOM and involves huge economic loss of the voltage sags was proposed by author in [78]. Firstly, voltage-sag-severity index and voltage-sag-economic loss index based on quality engineering theory, were presented. Secondly, the author puts forward STATCOM return on investment index to assess the economic benefit of different installation capacity by comparing the voltage sag economic losses before and after the installation of STATCOM controller. Finally, an optimal reactive compensation allocation technique which is based on above economic benefit evaluation indexes was presented. The method presented ensures safe reliability of network and achievement of the optimal economic benefit.

Active and reactive power loss reduction in network was proposed by authors in [79] using STATCOM based on hysteresis band current (HBC) controller. The active and reactive power losses in the transmission system was reduced by compensating load reactive power. The STATCOM controller design and analysis for nonlinear and linear loads were done. The analysis was performed for a 3ϕ induction motor, a 3ϕ battery charger and a 3ϕ transformer. The results showed that losses were greatly minimized that the STATCOM based hysteresis band-current controller is more effective than the conventional controllers in minimizing losses.

The topology and performance of T 3-level inverter based on the principle and topology of three level traditional NPC inverter was analyzed by authors in [80]. They proved T three level inverter superiority and also built T 3-level inverter-based D-STATCOM model. By the use of hysteresis control method, D-STATCOM compensation effect under three modes of dynamic switching, constant reactive compensation and sudden load variation was analyzed by the authors. The working characteristics of T three level-based D-STATCOM inverter were verified. Results showed fast-dynamic response of hysteresis control T type three level STATCOM. This new type of STATCOM supplied the reactive power demanded.

Authors in [81], dealt with the use of STATCOM PV farm inverter to stabilize the voltage where it is connected which improves the stability. The solar farm normally produces real power during the day but remains inactive at night time. The proposed solar system working as a STATCOM is known as PV STATCOM. This scheme uses total capacity of inverter during night time and that remaining after real power production during the day for carrying out various STATCOM operations. The entire system modelling and analysis were done on a single machine system having midpoint connected PV-STATCOM using Matlab software. This PV-STATCOM in the field of PV-solar gives rise to new opportunities to earn profit in the nighttime and daytime along with the sale of active power during the day

The oscillations system operation in inter-area mode was investigated and analyzed by authors in [82]. They used Kundur model which is a power system with two area with implementation of each of selected FACTS devices which were implemented to a specific place in the network to noté the dynamic performances of STATCOM, TCSC and SSSC on inter-area. The simulation results showed that power oscillation damping of the specific power network and contingency conditions was enhanced with adequate FACTS controller sitting and parameter settings.

2.11 Summary

An overview of the most salient characteristics of the power electronic equipment used in regulation of voltage, active and reactive load flow control, and power quality enhancement has been presented. The applications and performance of TCR, TCSC, SVC, UPFC, SSSC, and STATCOM among other FACTS devices were discussed. It was observed that STATCOM has some advantages in terms of reactive power injection, response time, and cost of implementation as earlier presented. Therefore, STATCOM forms the major FACTS device used in this research work and has been extensively discussed and properly reviewed. Besides, in all the reviewed and mostly the available articles, there has not been applications of particle swarm optimization and firefly algorithms concurrently, for optimization of STATCOM device for the purpose of power loss reduction and bus voltage profile deviation minimization, hence this work. The achievement of the above mention objectives via implementation of an optimally placed STATCOM device, through independent and comparative optimization algorithms, involving FA and PSO formed the vantage of inference deduced from the review of the literature in this chapter.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Research Approach

This research is based on the basic principles and theories of constrained optimization problems. The problems to be minimized are the power losses, while bus voltage magnitude minimization is also considered as part of objectives. These are to be achieved with optimal STATCOM controller placement and sizing by the use of PSO and FA. A single-objective solution method was used to find the optimum size and most suitable location of STATCOM controller that will reduce the losses of the network and minimize voltage magnitude deviation. Mathematical modeling of STATCOM power injection was formulated appropriately for incorporation into the standard IEEE 14-bus. Newton-Raphson (N-R) power flow method was used, because of its fast quadratic convergence. PSO and FA were chosen as optimization methods for allocation of STATCOM controller as they only require minimum manipulation to solve optimization problems and their ability to attain global optimum solution.

STATCOM data were obtained from published open access literatures on the concept. The STATCOM power injection model (PIM) was included in the Newton Raphson algorithm and simulations were carried out using Matlab programme. The modified N-R was then implemented on a standard IEEE 14-bus. PSO and FA were evaluated with real and reactive power loss minimization and voltage magnitude minimization as performance metrics.

3.2 Problem Formulation

The STATCOM power injection model was incorporated in Newton-Raphson (N-R) for load flow analysis and treated as an optimization problem and formulated as a single-objective optimization problem to reduce the total active and reactive power losses and voltage magnitude deviation of transmission network subject to series of equations that characterize the flow of power in the transmission network and STATCOM controller. The objective is to find the appropriate STATCOM controller location and size to reduce the active and reactive losses and consequently improves the system voltage profile. The control values are the generator voltage magnitude, transformer-tap setting and STATCOM controller VAr outputs. In OPF problems the control variables are varied to reduce losses.

The objective function is the sum of line losses as shown in Equation (3.1):

$$P_L = \sum_{K=1}^{NL} G_{ij} (V_i^2 + V_j^2 - V_i V_j \cos(\delta_i - \delta_j)) \tag{3-1}$$

This is expressed as;

$$f = \min(P_L) \tag{3-2}$$

$$= \min \sum_{K=1}^{NL} G_{ij}(V_i^2 + V_j^2 - V_i V_j \cos(\delta_i - \delta_j)) \tag{3-3}$$

The voltage deviation

The STATCOM optimal location and size is obtained such that the voltage deviation is regulated to be equal to the nominal value. Thus, voltage deviation is expressed as:

$$VD = \sum_{k=1}^{NL} \left| \left(V_i - V_j^{ref} \right) \right| \tag{3-4}$$

Constraints

The problem is subjected to the following constraints:

Equality constraints

The equality constraints are load flow equations expressed as:

$$P_{Gi} - P_{Di} - \sum_{j=i}^{NB} V_i V_{ij} Y_{ij} \cos(\delta_i - \gamma_i - \gamma_j) = 0 \tag{3-5}$$

$$Q_{Gi} - Q_{Di} - \sum_{j=i}^{NB} V_i V_{ij} Y_{ij} \sin(\delta_i - \gamma_i - \gamma_j) = 0 \tag{3-6}$$

Inequality Constraints

The inequality constraints on real power flow;

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \tag{3-7}$$

Reactive power generation limit (Size) of STATCOM;

$$Q_{STC}^{\min} \le Q_{STC} \le Q_{STC}^{\max} \quad ; \quad i \in N_{STC} \tag{3-8}$$

Voltage constraints

$$V_{STC}^{\min} \le V_{STC} \le V_{STC}^{\max} \quad ; \quad i \in N_B \tag{3-9}$$

Flow limit

$$S_i \le S_i^{\max} \quad ; \quad i \in N_i \tag{3-10}$$

Tap position constraints

$$T_{pi}^{\min} \le T_{pi} \le T_{pi}^{\max} \quad ; \quad i \in N_T \tag{3-11}$$

where,

NL = the number of transmission line.

VD = the voltage deviation.

V_{ij} = the voltage at the buses i and j of k^{th} lines.

G_{ij} = the conductance at the buses i and j of k^{th} line.

$V_i\angle\delta_i$ and $V_j\angle\delta_j$ are the voltage at the buses i and j of k^{th}, respectively.

$V_{STC}^{\min}$ and $V_{STC}^{\max}$ are the STATCOM's minimum and maximum voltages, respectively.

P_D = the power demand.

P_L = the total power loss.

P_{Gi} = the power generated at bus i.

Q_{Di} = the reactive power demand at bus i.

Q_{Gi} = the reactive power compensator at bus i.

S_i = the sending end apparent power.

T_{pi} = the sending end transformer tapings.

Fitness Function Formation

This can be written as [7]

$$F_P = \sum_{q\in N} P_{qloss} + Penalty\ Function \tag{3-12}$$

The Penalty Function is given by

$$q_1 \times \sum_{i=1}^{N_G} f(Q_{gi}) + q_2 \times \sum_{i=1}^{N} f(V_i) + q_3 \times \sum_{m=1}^{N_L} f(S_{lm}) \tag{3-13}$$

where,

q_1, q_2, q_3 are penalty factors

$$f(x) = \begin{cases} 0\ if\ \ x^{\min} \le x \le x^{\max} \\ (x - x^{\max})^2\ if\ \ x > x^{\max} \\ (x^{\min} - x)^2\ if\ \ x < x^{\min} \end{cases} \tag{3-14}$$

where,

$x^{\min}$ and $x^{\max}$ are the limits for the control variables.

3.3 Power Flow

Power flow is very importance in system design, planning and expansion. With power flow analysis, the voltage values of all the buses in a network, under specified network condition of operation can be computed. Other quantities, such as current values, power values, and power losses, is easily calculated when the bus voltages are known. This is needed for system planning and control [58].

Power flow analysis is fundamental to power systems study. Several numerical solution methods are used to solve load flow equations. The Newton Raphson, Fast Decoupled, and Gauss-Seidel methods are the most common iterative methods [43].

The N-R increases in quadratic progression, Gauss-Seidel method increases in arithmetic progression, while the Fast-decoupled increases in geometric progression. However, the most reliable and effective of the three power flow techniques is the Newton-Raphson due to its accurate and fast convergence [15].

3.3.1 Newton Raphson Load Flow

The technique starts with the initial guess of the unknown values follows by Taylor series expansion of the power balanced equations ignoring the higher order terms. Newton Raphson load flow method converges rapidly provided the initial are correctly guessed. However, longer times is required to execute each iteration

Expressing the current in terms of Y-bus gives [43, 58, 83]:

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \tag{3-15}$$

In polar form

$$I_i = \sum_{j=1}^{n} |Y_{ij}||V_j| \angle \theta_{ij} + \delta_j \tag{3-16}$$

At bus i , the complex power is expressed as:

$$P_i - jQ_i = V_i^* I_i \tag{3-17}$$

Substituting Equation (3.16) into Equation (3.17) gives,

$$P_i - jQ_i = V_i^* \sum_{j=1}^{n} |Y_{ij}||V_j| \angle \theta_{ij} + \delta_j \tag{3-18}$$

By separation of Equation (3-18),

$$P_i = \sum_{j \neq i} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{3-19}$$

$$Q_i = -\sum_{j \neq i} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i - \delta_j) \tag{3-20}$$

where,

I_i = current at bus i .

Y_{ij} = mutual admittance between buses i and j .

V_i and V_j are calculated voltage of bus i and j .

θ_{ij} = phase angle at bus i and j .

P_i = active and reactive power at bus i .

Equations (3-19) and (3-20) are the set of non-linear-algebraic equations.

3.3.2 The Jacobian Matrix

The Jacobian matrix generalizes the scalar-valued function gradient of multiple variables, which in turn generalizes the derivative of the scalar-valued function of a single-variable [10, 56]. This implies that the Jacobian matrix for a scalar-valued multivariate and single-variable functions are the gradient and derivative, respectively. The Jacobian can also be thought of as describing the amount of "stretching", "rotating" or "transforming" that a transformation imposes locally. In vector calculus, first-order partial derivative of a vector valued function is referred to as the Jacobian matrix. The Taylor series expansion of Equations (3-19) and (3-20) about the initiate value ignoring terms of higher order gives the linear Equation set as follows:

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \hline \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \left[\begin{array}{ccc|ccc} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial V_n} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} & \frac{\partial P_n^{(k)}}{\partial V_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial V_n} \\ \hline \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} & \frac{\partial Q_2^{(k)}}{\partial V_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial V_n} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} & \frac{\partial Q_n^{(k)}}{\partial V_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial V_n} \end{array}\right] \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \\ \hline \Delta \left|V_2^{(k)}\right| \\ \vdots \\ \Delta \left|V_n^{(k)}\right| \end{bmatrix} \tag{3-21}$$

The Jacobian matrix equation expresses the linearized relationship between changes in voltage magnitude $\Delta V_i^{(k)}$ and angle $\Delta \delta_i^{(k)}$ with the changes in real and reactive power $\Delta P_i^{(k)}$and $\Delta Q_i^{(k)}$. The partial derivatives

Equations (3-19) and (3-20) evaluate at $\Delta\delta_i^{(k)}$and $\Delta\left|V_n^{(k)}\right|$ gives the Jacobian matrix elements. In compact form, the expression is given by Equation (3-22) [10].

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \tag{3-22}$$

where,

ΔP and ΔQ = power residuals

J = Jacobian matrix

$$J = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial |V_i|} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial |V_i|} \end{bmatrix} \tag{3-23}$$

Voltage values of the voltage-control buses are given. If there are 'm' voltage-controlled buses in the transmission network, then 'm' ΔV and ΔQ equations and the corresponding columns in the Jacobian matrix are eliminated using Gaussian-elimination method. Gaussian elimination is an operation performed on the corresponding coefficients matrix.

Accordingly, there are $n-1$ real power constraints and n – 1 – m reactive power constraints and the Jacobian matrix is of order (2n – 2 – m) × (2n – 2 – m).

The diagonal and the off-diagonal of J_1 are

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{j \neq i} |V_i||V_j||Y_{ij}| Sin(\theta_{ij} - \delta_i - \delta_j) \tag{3-24}$$

$$\frac{\partial P_i}{\partial \delta_i} = -|V_i||V_j||Y_{ij}| Sin(\theta_{ij} - \delta_i - \delta_j) \quad j \neq i \tag{3-25}$$

The diagonal and off-diagonal elements of J_2 are

$$\frac{\partial P_i}{\partial |V_i|} = 2|V_i||Y_{ii}| Cos\theta_{ii} + \sum |V_i||V_j||Y_{ij}|(\theta_{ij} - \delta_i - \delta_j) \tag{3-26}$$

$$\frac{\partial P_i}{\partial |V_j|} = -|V_i||Y_{ij}| Cos(\theta_{ij} - \theta_i - \theta_j) \quad j \neq i \tag{3-27}$$

The diagonal and off-diagonal elements of J_3 are

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{j \neq i} |V_i||V_j||Y_{ij}| Cos(\theta_{ij} - \delta_i - \delta_j) \tag{3-28}$$

The diagonal and off-diagonal elements of J_4 are

$$\frac{\partial P_i}{\partial |V_j|} = -|V_i||Y_{ij}|Cos(\theta_{ij} - \theta_i - \theta_j) \quad j \neq i \tag{3-29}$$

The power mismatch is expressed as:

$$\Delta P_i^{(K)} = P_i^{(sch)} - P_i^{(K)} \tag{3-30}$$

$$\Delta Q_i^{(K)} = Q_i^{(sch)} - Q_i^{(K)} \tag{3-31}$$

The estimated values of voltage magnitudes and angle are:

$$\delta_i^{(K+1)} = \delta_i^{(K)} + \Delta\delta_i^{(K)} \tag{3-22}$$

$$|V_i^{(K+1)}| = |V_i^{(K)}| + \Delta|V_i^{(K)}| \tag{3-33}$$

where,

$\Delta P_i^{(k)}$and $\Delta Q_i^{(k)}$= difference in calculated and scheduled values.

$P_i^{sch}$and Q_i^{sch} are scheduled real and reactive power at bus *i*.

$P_i^{(k)}$and $Q_i^{(k)}$ = calculated real and reactive power at bus *i*.

$\delta_i^{(k)}$ = calculated angle.

$\Delta\delta_i^{(k)}$ = change in calculated angle.

$|V_i^{(k+1)}|$ = the different between voltage value at bus *i*.

$|V_i^{(k)}|$ = most recently voltage bus value.

K and *(k+1)* denote previous and next iteration respectively.

The process is repeated until a stopping condition is met.

3.4 Power Flow Algorithm of Newton-Raphson

This section presents the Newton-Raphson load flow solution procedure while the flowchart is depicted in Figure 3-1.

(i) For load buses, the voltage magnitudes and angles are set equal to 1.0 and 0.0.

(ii) Equation (3-19) and Equation (3-20) compute $P_i^{(k)}$ and $Q_i^{(k)}$ for load buses and Equation (3-30) and Equation (3-31) compute $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$.

(iii) Equation (3-19) and Equation (3-30) compute $P_i^{(k)}$ and $\Delta P_i^{(k)}$ for voltage controlled-buses.

(iv) Calculate the Jacobian matrix elements (J_1, J_2, J_3, and J_4).

(v) The simultaneous Equation (3-19) is solved using triangular factorization and Gaussian elimination methods.

(vi) Equation (3-32) and Equation (3-33) calculate the updated voltage values and angles from.

(vii) The process continues till the $\Delta Q_i^{(k)}$ and $\Delta P_i^{(k)}$ are smaller than the tolerance.

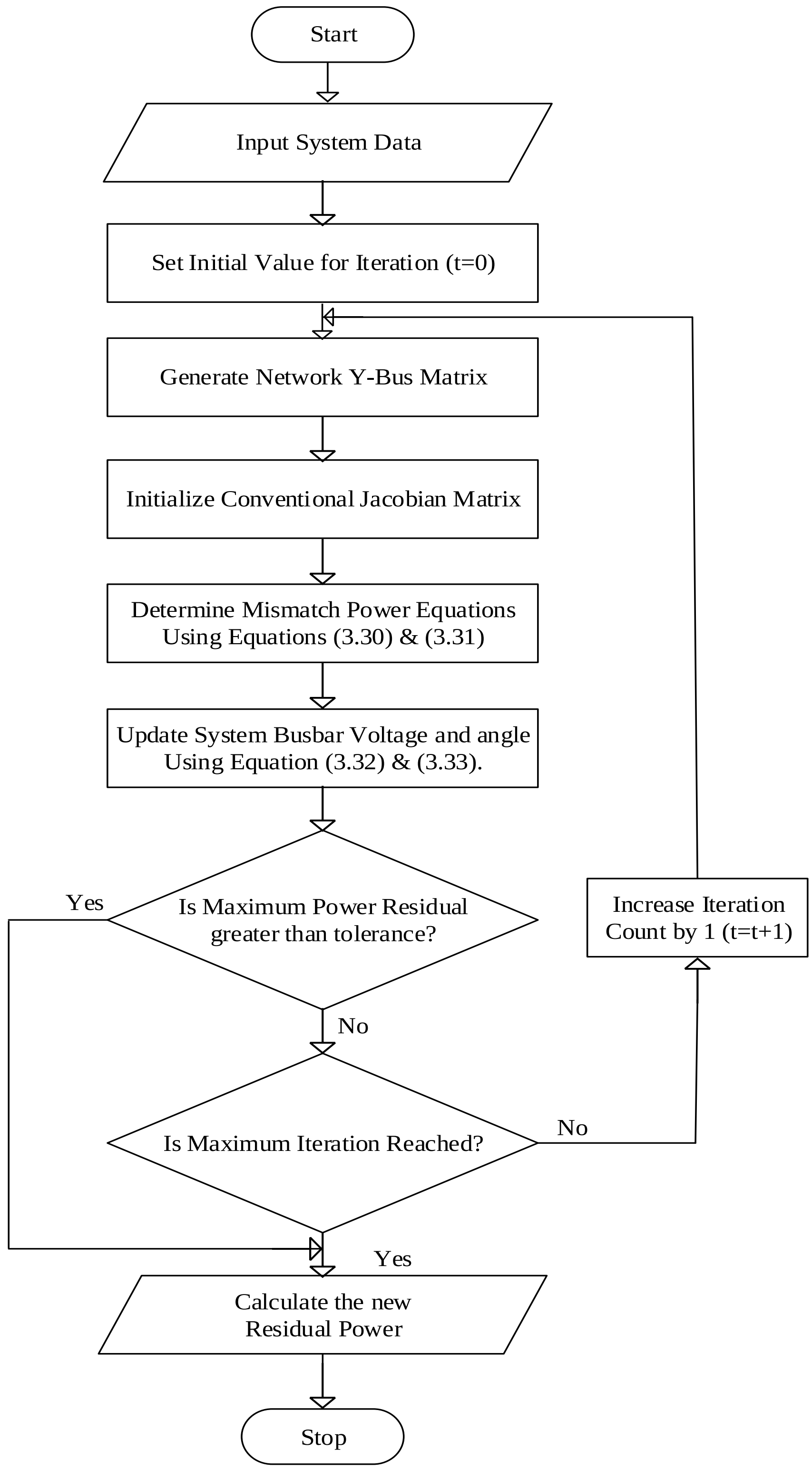

Figure 3-1: Newton Raphson Load Flow Flowchart [30].

3.5 Modeling of STATCOM for Load Flow Analysis

Power flow analysis incorporating STATCOM requires an accurate model in the solution algorithm. This model is of two main categories as applicable to transmission networks. These are the power injection model (PIM) and the current injection model (CIM). A current source is placed in parallel for controlling the voltage values in CIM model. The PIM model has a parallel-connected voltage source behind a reactance. The STATCOM steady-state-power-injection model is more reliable when incorporated in transmission network and is well documented in literatures [30, 53, 54].

The model was generated by connecting the STATCOM into the transmission network using power as mismatch calculation termination criteria to compute the active and reactive losses. The generated model was included in the Newton Raphson power algorithm to formulate new set of equations.

This STATCOM model to be included in the load flow algorithm was obtained from STATCOM equivalent diagram in Figure 3-2. The power injected mathematical STATCOM model reduces the computer power flow codes complexity and this mathematical equations are given as follow [30, 53]:

$$V_{STC} = V_k + Z_{SC} I_{STC} \tag{3-34}$$

Expressing Equation (3-34) in Norton Equivalent form;

$$I_{STC} = I_N - Y_{SC} V_k \tag{3-35}$$

where,

$$I_N = Y_{SC} V_{STC} \tag{3-36}$$

Converting Equation (3-35) into Equations (3-37) and (3-39):

$$S_{STC} = V_{STC} I^{*}_{STC} \tag{3-37}$$

$$= V^{2}_{STC} Y^{*}_{SC} - V_{STC} Y^{*}_{STC} V_k \tag{3-38}$$

$$S_k = V_k I^{*}_{STC} \tag{3-39}$$

$$= V_{STC} V^{*}_{SC} V^{*}_{k} - V_k^{2} Y^{*}_{SC} \tag{3-40}$$

From Figure 3-2, the voltage source representation is given as:

$$E_{STC} = V_{STC} \left(Cos\delta_{STC} + jSin\delta_{STC} \right) \tag{3-41}$$

The active and imaginary components for the STATCOM source at bus *k*, are:

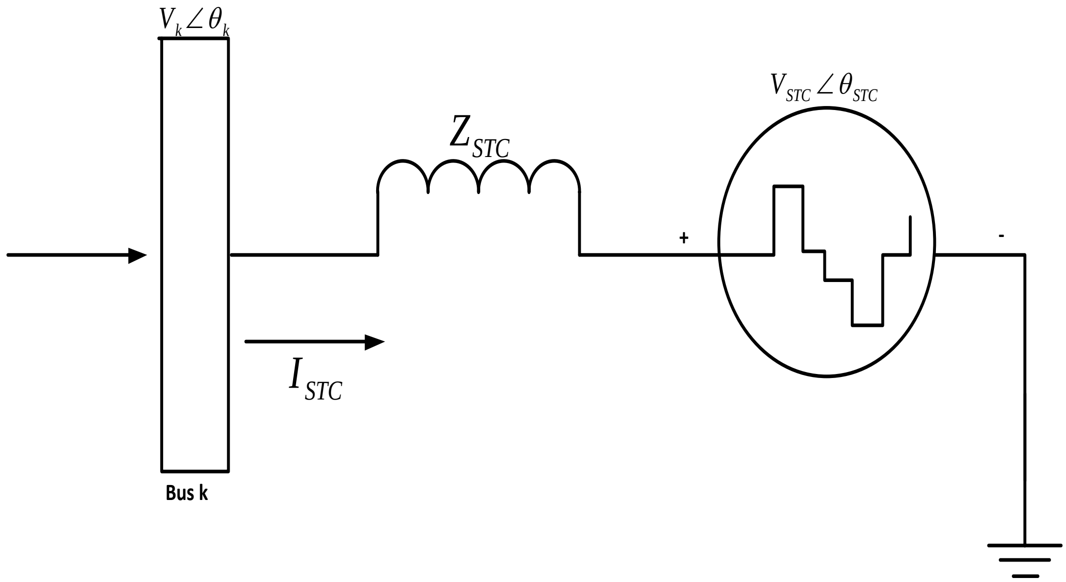

Figure 3-2: STATCOM Equivalent Circuit [43].

$$P_{STC} = V_{STC}^2 G_{STC} + V_{STC} V_k \left[G_{STC} Cos(\delta_{STC} - \theta_k) + B_{STC} Sin(\delta_{STC} - \theta_k) \right] \tag{3-42}$$

$$Q_{STC} = -V_{STC}^2 G_{STC} + V_{STC} V_k \left[G_{STC} Sin(\delta_{STC} - \theta_k) + B_{STC} Cos(\delta_{STC} - \theta_k) \right] \tag{3-43}$$

$$P_k = V_k^2 G_{STC} + V_k V_{STC} \left[G_{STC} Cos(\theta_k - \delta_{STC}) + B_{STC} Sin(\theta_k - \delta_{STC}) \right] \tag{3-44}$$

$$Q_k = -V_k^2 G_{STC} + V_k V_{STC} \left[G_{STC} Sin(\theta_k - \delta_{STC}) + B_{STC} Cos(\theta_k - \delta_{STC}) \right] \tag{3-45}$$

From the above power equations, the STATCOM linearized Newton-Raphson load solution model is expressed as:

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \\ \Delta P_{STC} \\ \Delta Q_{STC} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial \delta_{STC}} & \frac{\partial P_k}{\partial V_{STC}} V_{STC} \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial \delta_{STC}} & \frac{\partial Q_k}{\partial V_{STC}} V_{STC} \\ \frac{\partial P_{STC}}{\partial \theta_k} & \frac{\partial P_{STC}}{\partial V_k} V_k & \frac{\partial P_{STC}}{\partial \delta_{STC}} & \frac{\partial P_{STC}}{\partial V_{STC}} V_{STC} \\ \frac{\partial Q_{STC}}{\partial \theta_k} & \frac{\partial Q_{STC}}{\partial V_k} V_k & \frac{\partial Q_{STC}}{\partial \delta_{STC}} & \frac{\partial Q_{STC}}{\partial V_{STC}} V_{STC} \end{bmatrix} \cdot \begin{bmatrix} \Delta \theta_k \\ \frac{\Delta V_k}{V_k} \\ \Delta \delta_{STC} \\ \frac{\Delta V_{STC}}{V_{STC}} \end{bmatrix} \tag{3-46}$$

From Equation (3-44), the STATCOM Voltage magnitude, 'V_{STC}' and angle 'δ_{STC}' are the values incorporated.

$$\left| V_{STC}^{(i+1)} \right| = \left| V_{STC}^{(i)} \right| + \Delta \left| V_{STC}^{(i)} \right| \tag{3-47}$$

$$\delta_{STC}^{(i)} = \delta_{STC}^{i} + \Delta\delta_{i}^{i} \tag{3-48}$$

The power residuals are given by

$$\Delta P_k^{(i)} = P_k^{sch} - P_k^{i} \tag{3-49}$$

$$\Delta Q_k^{(i)} = Q_k^{sch} - Q_k^{i} \tag{3-50}$$

The power loss in the system is given as:

$$P_{loss} = \sum_{k=1}^{NL} G_k \left(V_i^2 + V_{STC}^2 - 2V_i V_{STC} Cos\delta_i \right) \tag{3-51}$$

where,

V_{STC} = STATCOM voltage magnitude.

Y_{STC} = STATCOM admittance.

δ_{STC} = STATCOM phase angle.

I_{STC}^{*} = STATCOM reference current.

Y_{STC}^{*} = STATCOM reference admittance.

V_{STC}^{*} = STATCOM reference voltage.

V_k^{*} = reference bus voltage at bus *k*.

G_{STC} = STATCOM conductance.

I_N = Norton current.

I_{STC} = STATCOM current.

B_{STC} = STATCOM susceptance.

θ_k = firing angle at bus *k*.

V_k = bus voltage at bus *k*.

The formulation above is a system of nonlinear equations that is solved by iterative techniques.

3.6 Simulation of Test Network without and with STATCOM

A script was written in MATLAB environment for load flow analysis of transmission network without and with the placement of the steady-state power injection model of the STATCOM device. The procedures for load flow solution is as follows while the flowchart is shown in Figure 3-3.

Step 1: Input system data for power flow calculation.

Step 2: Form the system admittance matrix and conventional Jacobian matrix with incorporation of STATCOM.

Step 3: Modify the Jacobian matrix and power flow mismatched equations.

Step 4: Update the voltage after every iteration.

Step 5: Check the convergence and Jacobian matrix modification. Power mismatched occurs until convergence is reached.

Step 6: Display the results if convergence is achieved .

3.7 Particle Swarm Optimization Algorithm Implementation of OPF with STATCOM

PSO is a population based optimization method which was first proposed by Dr. James Kennedy and Dr. Russell Eberhart in the year 1995 [28, 35, 84, 85]. This method determines the optimum value using particles populations. Each of the particles is considered as candidate solution in the search process. The aim is to obtain the best performing individual among the group. PSO find application in different optimization problems which include maximization, minimization and training of neural network.

The PSO algorithm randomly generate a number of particles in the search space domain of the function. In the search space, each particle i, has current position x, velocity v and personal best positions. Each particle track these positions represented in a d-dimensional space; $x_i = (x_{i1}, x_{i2}, ..., x_{id})$, $v_i = (v_{i1}, v_{i2}, ..., v_{id})$, and $P_{besti} = (P_{besti,1}, P_{besti,2}, ..., P_{besti,d})$. The P_{best} refers to the particle that leads to least error in a minimization problem while the g_{best} is the best particle in the search space which signifies the position that produces smallest error among the personal bests. Each particle position in the swarm is modified in each iteration depending on its own P_{best}, g_{best}, and the previous velocity vector [86].

3.7.1 Particle Swarm Optimization Algorithm

The followings are the definition of PSO [84]:

(i) Each particle i possesses the following parameters: a current position, x_i, current velocity, v_i, and personal best position, y_i in the search space.

(ii) The personal best position, y_i, corresponding to the search space position, where particle i gives lowest error as obtained by the objective function f.

(iii) The global best position $\hat{y}$ representing the position that yield smallest error among all y_i.

Equations (3-52) and (3-53) update the global and personal best at time t.

$i \in 1......s$. $$y_i(t+1) = \begin{cases} y_i(t) & if \quad f(y_i(t) \le f(x_i(t+1))) \\ x_i(t+1) & if \quad f(y_i(t) > f(x_i(t+1))) \end{cases} \tag{3-52}$$

$$\hat{y}(t) = \min \{ f(y), \quad f(\hat{y}(t)) \}$$

$$y \in \{ y_0(t), \; y_1(t), ..., \; y_s(t) \} \tag{3-53}$$

Equations (3-52) and (3-53) update all the particles in the swarm during each iteration. For all dimension $j \in 1...\mathrm{n}$, let x_{ij} , y_{ij} , and v_{ij} be the current position, current personal best position and velocity of the jth dimension of the ith particle. The velocity is updated using Equation (3-54).

$$v_{i,j}(t+1) = wv_{i,j}(t) + c_1 r_{1,j}(t)[y_{i,j}(t) - x_{i,j}(t)] + c_2 r_{2,j}(t)[\hat{y}_{i,j}(t) - x_{i,j}(t)] \tag{3-54}$$

To get the next particle position, the new velocity and the current position of the particle are sumed up:

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{3-55}$$

To minimize the particle likelihood of leaving the search space, each dimension variable of all the vector velocity v_i are clamped $[-v_{\max}, v_{\max}]$ The $v_{\max}$ value is given as

$$v_{\max} = k \times x_{\max}, \;\; where\; 0.10 \le k \le 1.00$$

where,

$x_{\max}$ = search space domain.

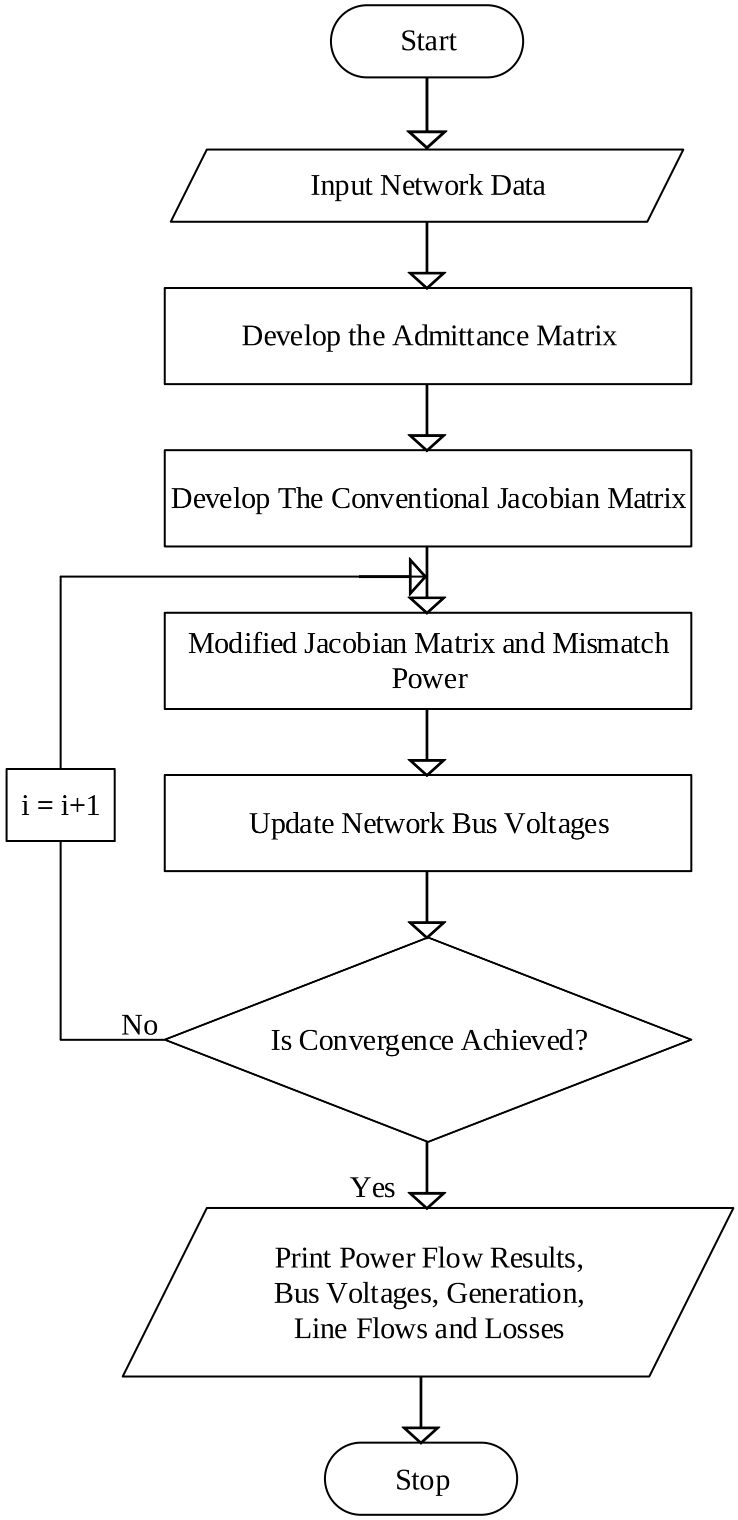

Figure 3-3: Flowchart of power flow solution by the Newton-Raphson without and with STATCOM controller [61].

This parameter restrict not x_i to $[-v_{\max}, v_{\max}]$. It only restricts the particle maximum distance in the search space. c_1 and c_2 are the coefficients of acceleration which control the distance of the particle in one iteration. Typically, c_1 and c_2 set to 2.0. c_2 must be greater than c_1 for unimodal problems and c_1 must be greater than c_2 for multimodal problems. However, c_1 and c_2 must be low and for more acceleration, or high for smooth particle trajectories, [85]. The inertia weight, w which controls PSO convergent behaviour is expressed as in Equation (3-56) :

$$w = w_{\max.} - \frac{w_{\max} - w_{\min}}{iteration_{\max}} . iteration \tag{3-56}$$

where,

$iteration_{\max}$ = maximum iteration.

$iteration$ = current iteration.

$w_{\max}$ and $w_{\min}$ are the maximum and minimum number of weighting factors.

3.7.2 PSO Algorithm Application Transmission Network

PSO implementation was done on the IEEE 14-bus network. The initial control-variable-limits randomly initialize the positions of the particles. Equation (3-12) compute the given problem fitness function to evaluate the control system variables to attain the reduced global best. The PSO algorithm procedure applied to IEEE 14-bus network is given below:

1. The size of the population, all control variables, and iteration number are defined. Including parameters of PSO and 14-bus data.
2. Set iteration = 0.
3. Particles population and their velocities are randomly generate.
4. Determine the losses by running N-R power flow.
5. Use Equation (3-12) to compute each particle fitness function.
6. Determine P_{best} and g_{best} for all the particles.
7. Increase the iterations by one.
8. Calculate each particle velocity by using Equation (3-54) and adjust if limit violation occurs.
9. Each particle new position is calculated using Equation (3-55).
10. Find the losses by running N-R power flow.
11. Use Equation (3-12) to calculate each particle fitness function.
12. Set $P_{best} = P$ if each particle present fitness P is better than P_{best}.
13. Set g_{best} to P_{best}.

14. Step 7 is repeated until the iteration maximum number is reached.

Figure 3-4 shows the flow chart applied to transmission network.

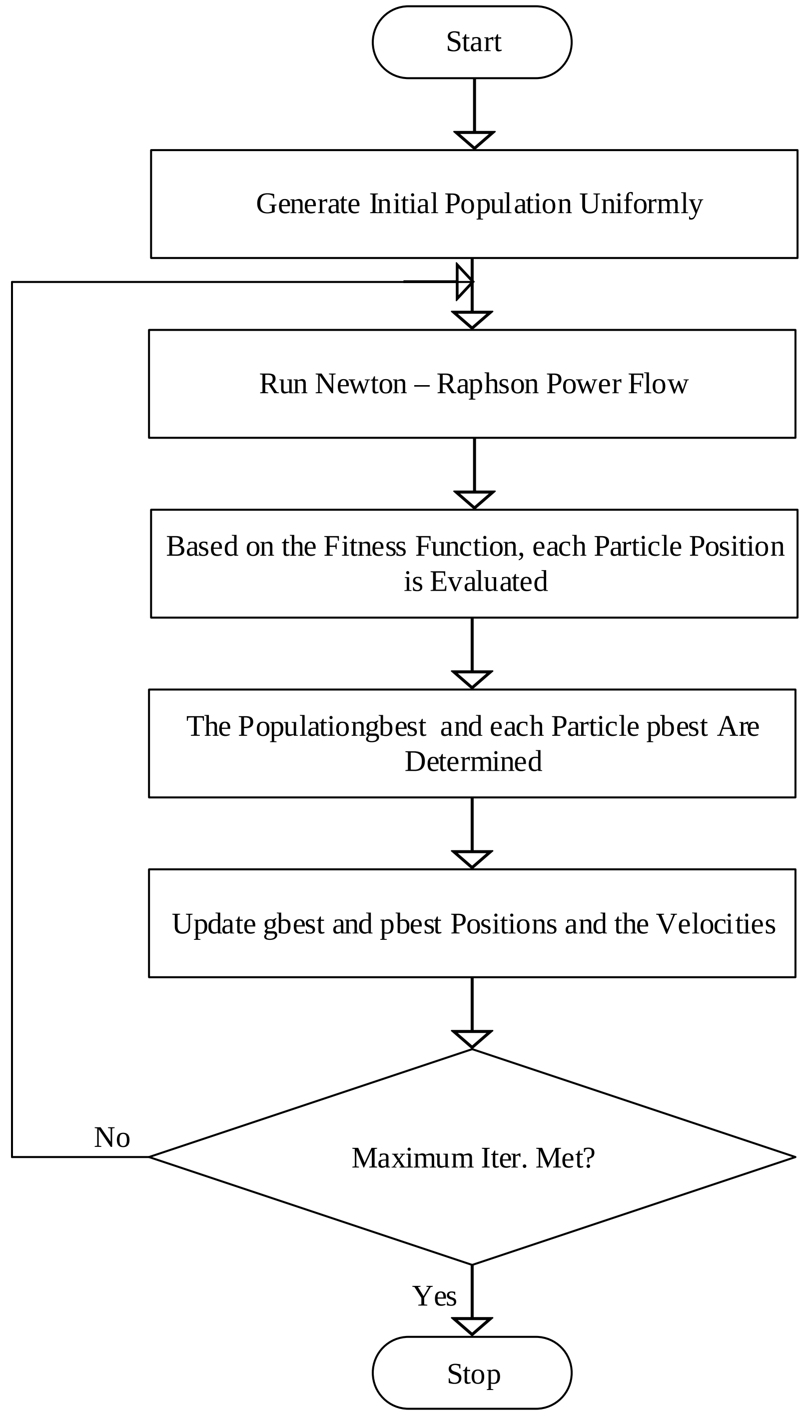

Figure 3-4: PSO algorithm flow chart for transmission network [85].

3.8 Implementation of Firefly Algorithm for OPF with STATCOM

For the optimization of power flow with STATCOM controller, FA was implemented to place the controller in a suitable location and determine the appropriate size of the controller to minimize system real and reactive power loss. FA is a meta-heuristic, nature-inspired optimization algorithm which is based on the social flashing behavior of fireflies [87 – 90]. To minimize problem, each firefly brightness exhibits inversely relationship with the objective function value. A firefly swarm which is randomly located in the search space is initially produced by FA. A uniform random distribution usually produces initial distribution and each firefly position represents a potential optimization problem solution. The number of the parameters in the given optimization problem is equivalent to the dimension of the search space.

The firefly input position is taken by the fitness function to produce a single numerical output which denote the effectiveness of the potential solution. Each of the firefly is assigned a fitness value and each firefly brightness is dependent on that firefly fitness value. The other firefly brightness attract each of the fireflies by moving towards it. The firefly velocity to another firefly is dependent on the attractiveness which in turn depends on the relative fireflies distance which could also depends on the firefly brightness [91]. The brightness and each firefly relative attractiveness are computed by FA in each iterative step. Firefly positions are updated depending on these values. All the fireflies converges to the best possible position on the search space after certain iteration number is reached.

The two paramount issues in the FA are the light intensity variation and attractiveness formulation. The brightness of the firefly determines its attractiveness and is associated with the objective function. To minimize optimization problems, the firefly brightness I at a specific position x is given as $I(x)$ and is proportional to the objective function, $f(x)$. The attractiveness β varies with the distance r_{ij} two fireflies. Additionally, intensity of light reduces with the source distance and therefore, the attractiveness is varied with the degree of absorption.

For a given medium, the light intensity I is a function of the distance ‘ r ’ as [91 – 93]:

$$I = I_0 e^{-\gamma r} \tag{3-57}$$

where,

γ = fixed light absorption coefficient

I_0 = intensity of the original light.

Flashing light was formulated based on objective function of Equation (3-1) and a script was written in MATLAB environment to solve the resulting optimization procedures.

The following parameters were considered:

(i) The optimal STATCOM controller location in the system was considered as the first step of optimization process. The network variables such as voltage changes, power loss and system balance condition were incorporated with the optimization algorithm.

(ii) The size of the STATCOM controller was obtained according to network working range in which the shunt voltage source converter injected voltage range is obtained.

(iii) The power injection model of STATCOM controller and the system stability examined.

Once these three conditions are satisfied, firefly algorithm is initiated and the attractiveness, distance, position movement and fitness value of firefly are calculated.

The firefly attractiveness function can be expressed as [88, 91, 92]:

$$\beta(r) = \beta_0^* e^{-\lambda r_{ij}} \qquad n \geq 1 \tag{3-58}$$

There is a decrease in attractiveness when the distance increases. Therefore, this distance of attraction of brightest firefly is calculated by:

$$r_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{3-59}$$

which corresponds to:

$$r_{ij} = G_{best}FV - P_{best}FV \tag{3-60}$$

The attraction of i^{th} firefly towards brighter j^{th} firefly depends on the attractiveness and distance between them and expressed as:

$$U_{i(new)} = U_{i(old)} + \beta_0 e^{-\lambda r_{ij}^2}(x_i - x_j) + \alpha(rand_i^k) \tag{3-61}$$

The firefly fitness function for maximum loss reduction is expressed as:

$$FV = P_{L,normal} - P_{L,STC} \tag{3-62}$$

The position of firefly is given as:

$$P_{i,k+1} = P_{i,k} + U_{i(new)} \tag{3-63}$$

where,

β_0 = initial attractiveness at $r = 0$.

r = distance between any two fireflies.

λ = absorption coefficient.

x_i, x_j and y_i, y_j = firefly spatial coordinate component.

$U_{i(old)}$ = Initial position of i^{th} firefly.

α = random parameter

$(rand)$ = uniformly distributed random number generated in the space between 0 and 1.

$P_{L,normal}$ = system power loss.

$P_{L,STC}$ = power loss with STATCOM.

G_{best} = best fitness value.

P_{best} = new fitness value.

r_{ij} = best fitness value difference.

n = number of iterations.

Firefly moves randomly if no brighter firefly is found. The processes are repeated until a stopping criterion is reached. Optimal STATCOM location and size are estimated by the brightest firefly position.

The steps involved in the FA for OPF with STATCOM is as follows.

Step 1: Read the system data while satisfying OPF inequality and equality constraints.

Step 2: Initialization of the parameters and firefly algorithm constants.

Step 3: Fireflies ‘ n ’ number is randomly generated and iteration count set to 1.

Step 4: Run base case load flow.

Step 5: Determine the firefly fitness value using the mathematical representation of objective function for loss reduction.

Step 6: Obtain the fireflies P_{best} values from the fitness values and identify the best value as G_{best}.

Step 7: Determine the distance of attraction of each firefly using Equation (3-60)

Step 8: Equation (3-61) calculates the new fireflies values

Step 9: Update the position of firefly using Equation (3-63)

Step 10: New fitness values are calculated for the new positions of all the fireflies. If the new fitness value for any firefly is better than previous P_{best} value, then P_{best} value for that firefly is set to present fitness value. Similarly, G_{best} value is identified from the latest P_{best} values.

Step 11: Increment in the iteration count and if iteration count has not reached maximum then go to step 3 except convergence is achieved.

Step 12: Rank the fireflies according to the current global best. G_{best} which determine the STATCOM sizes in ‘ n ’ candidate with the position indicating the locations and display the results.

Figure 3.5 presents the flow chat of these step by step algorithm.

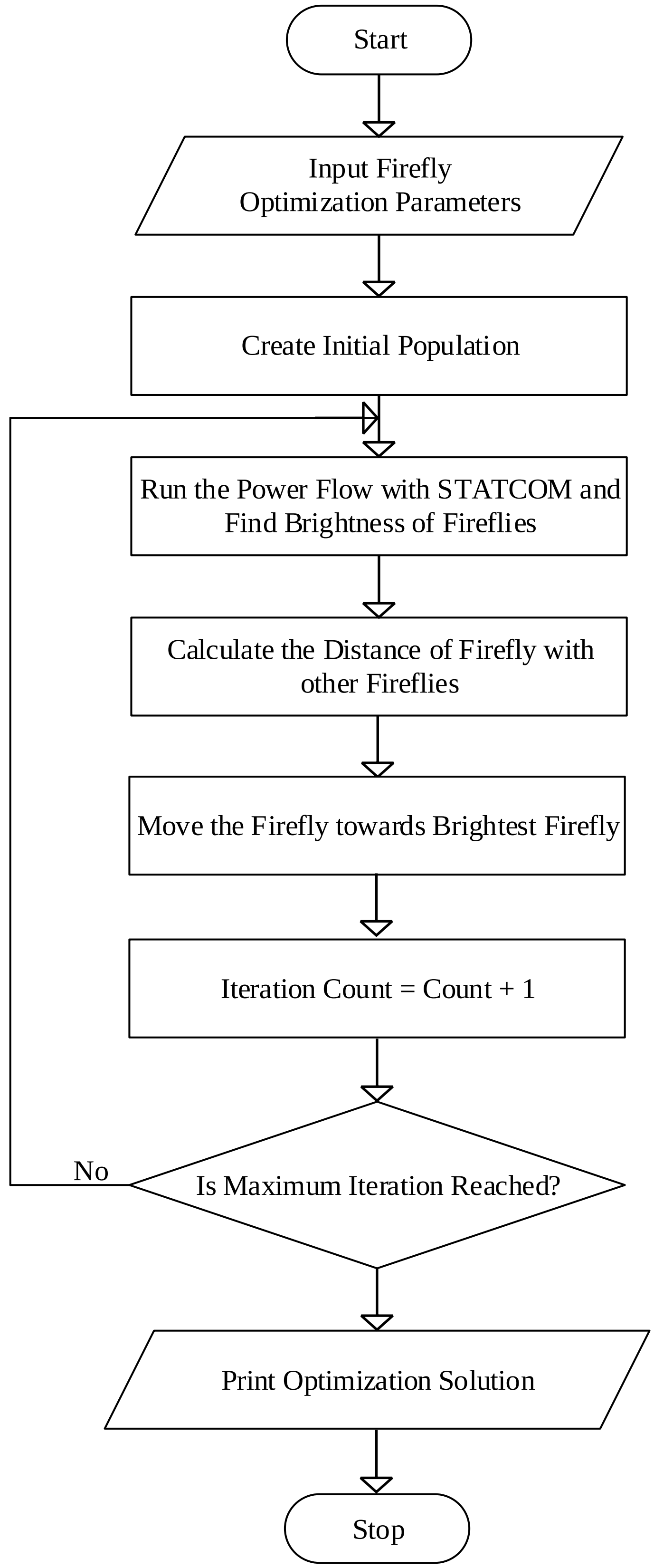

Figure 3-5: Firefly algorithm flow chart [66].

3.9 Summary

This chapter presents the methods used in the research. The suitable STATCOM controllers location and size were obtained using a single objective solution function method. Mathematical modeling of STATCOM power injection was formulated and incorporated into the standard IEEE 14-bus transmission network. Network load flow analyses were solved by the use of Newton-Raphson method. PSO and FA were the optimization solution methods employed in this research to optimally locate and size STATCOM controller.

Also, IEEE 14-bus and STATCOM data required to carry out the research were sourced from IEEE website and published open access literatures, respectively. Simulations were carried out on the STATCOM power injection Newton-Raphson power flow algorithm incorporated model using Matlab software. The modified N-R was then implemented the IEEE 14-bus network. Power loss reduction and voltage magnitude minimization were used as performance metric to evaluated the system performance with PSO and FA were discussed. Therefore, the simulation results were presented and discussed in the subsequent chapters.

CHAPTER FOUR

PRELIMINARY RESULTS

4.1 Introduction

The study basic results prior to optimization of the test network are presented. Data for this research were obtained from published open access literatures. Mathematical modeling of static synchronous compensator (STATCOM) was carried out. Newton-Raphson (N-R) load flow technique was employed for power flow analysis of the system because it converges fastly.

Load flow analysis of IEEE 14-bus network was done in MATLAB environment to determine the system steady state and corresponding results were noted and recorded. Newton-Raphson power flow algorithm was then modified for accommodating STATCOM power injection model (PIM) and simulation was also performed. The corresponding results were noted and recorded to determine the effect of the STATCOM PIM model on the network.

4.2 Description of IEEE 14-Bus Test System

Test systems are available for the analysis of transmission network. They are standard feeders approved by the IEEE standards association [94]. It comprises of basic standard data such as load data, shunt capacitor data, overhead spacing data, underground spacing data, conductor data and cable data. For the purpose of this work, IEEE 14-bus network was used. The network comprises five (5) generator connected at buses 1, 2, 3, 6 and 8 respectively, with bus one (1) acting as the swing bus. To improve power flow, the voltage limit on all the buses were set to be between 0.95 to 1.05 p.u. because, the maximum allowable voltage deviation is $\pm 5\%$ of the nominal voltage for system stability and reliability realization [95]. Appendix A contains generator data, system network parameters as well as the bus voltage profile data. Figure 4-1 is a standard IEEE 14-bus network which was used for conducting the investigation of STATCOM functionalities in the research.

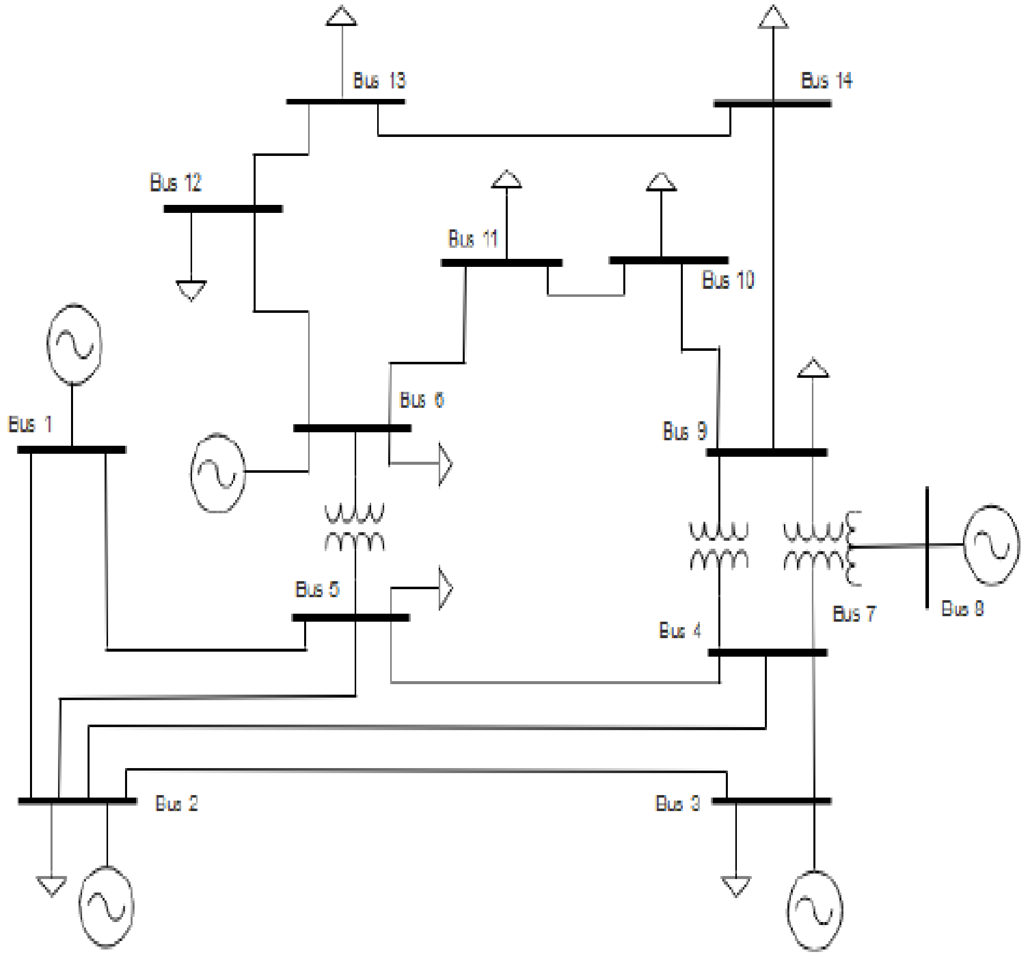

Figure 4-1: One line of IEEE 14-bus network [12].

4.3 Simulation Results

Tests were conducted on the system before and after the incorporation of the STATCOM controller. Two case studies are presented. The first case is the network initial condition determination while the second case is the STATCOM controller effect determination on the network.

4.3.1 Case Study 1: Load Flow Analysis of the IEEE 14-bus System

IEEE 14-bus line and bus data are presented in Appendices A and B. These data were used to model the system. Newton-Raphson power flow was employed to analyze and obtain the steady state bus voltages, active and reactive flow in the network. The line losses and voltage magnitude were noted for discussion and are subsequently presented. Table 4-1 reveals voltage magnitude and angle results for the power flow analysis of the network.

Table 4-1: Bus voltage magnitudes and angles of IEEE 14-bus network

Bus No	Bus Type	Voltage Magnitude (p.u.)	Voltage Angle (degree)
1	Swing	1.0600	0.0000
2	PV	1.0450	4.9800
3	PV	0.9600	2.2530
4	PQ	0.9690	4.8505
5	PQ	0.9630	3.1320
6	PV	1.0200	5.6104
7	**PQ**	**1.0680**	**3.0510**
8	PV	0.9900	5.7723
9	PQ	1.0270	1.0515
10	PQ	1.0330	4.1083
11	PQ	1.0300	3.8934
12	PQ	1.0330	4.1246
13	**PQ**	**1.0670**	**1.1922**
14	PQ	1.0470	1.9534

It was noted in Table 4-1, that the voltage magnitudes at buses 7 and 13 are out of voltage limit. This was not unconnected with lack of load connection at bus 7 and reactive power compensation at bus 13. This situation must be prevented to avoid cascading bus voltage violation which might lead to system collapse. Therefore, there is need to incorporate STATCOM to control this bus voltage deviation, hence, these buses whose terminal voltages are violated are the candidates for STATCOM controller placements.

Table 4-2: STATCOM settings for the devices at bus 7 and 13.

Test Cases	STATCOM LOCATION	Voltage Profile (p.u.)	Angle (degree)	Shunt Reactive Power (MVAr)
Case 1 (Manual Placement)	7	1.0000	2.6335	3.68
	13	1.0000	1.1491	5.43

Figure 4-2 depicts the graphical interpretation of bus voltage profile after the simulation without STATCOM device. The peak bus voltage occurs at bus 7 and 13 as earlier stated. Besides these, buses 3 and 5 whose bus terminal voltages are at the verge of violating lower limit bound are prone to lower limit violation and should be controlled. Apart from swing bus whose value remains constant at 1.06 volts even after the simulation, other bus voltages are within the allowable limits.

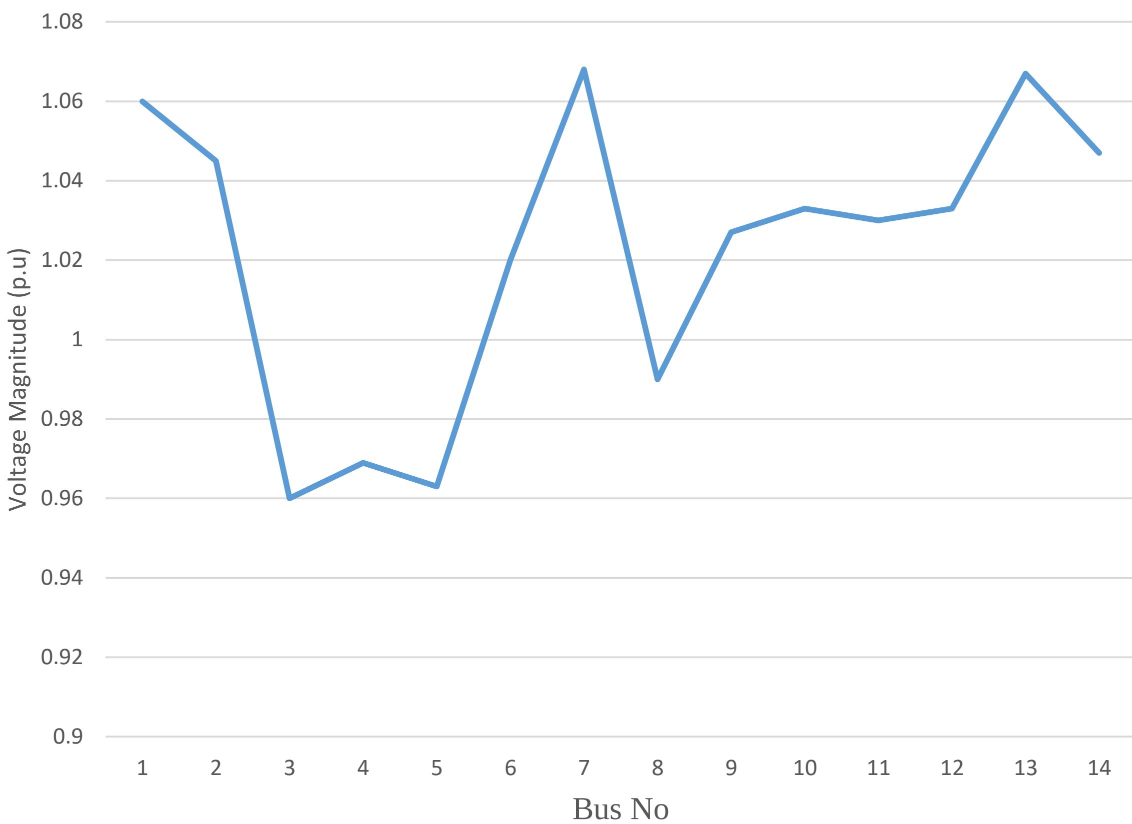

Figure 4-2: Voltage Profile of 14-Bus System Before STATCOM Placement

Another point of interest is the active and reactive losses on the test network. These values are presented in Table 4-2 as follows. The highest power loss occurred on the lines 1 – 2 and 1 – 5 while the total real power loss stands at 6.251 MW, reactive power loss recorded is 14.256 MVAr. These losses must also be minimized for optimal operation of the test network.

The graphical illustration of losses in Table 4-3 is presented in Figure 4-3 for a better understanding. The reactive power loss is very high at lines 1 – 2, 1 – 5, 2 – 3, 2 – 5, 4 – 5, 4 – 7, 4 – 9, 5 – 6 and 7 – 9. These losses are impacting on the network performance.

4.3.2 Case Study 2: Load Flow Study of STATCOM Incorporated IEEE 14-bus Network

In order to incorporate STATCOM with the test system, the Newton Raphson load flow analysis was modified to accommodate the STATCOM power injection model. N-R power flow equations which was developed in MATLAB software environment was modified to accommodate the injected model of the device. Two STATCOM controllers were placed at buses number 7 and 13 to stabilized the voltage magnitudes to 1.0 p.u. The voltage magnitudes, and losses were noted for discussion and are subsequently presented. The results of the load flow analysis is shown in Table 4-3.

It was noted that buses 7 and 13 were now regulated to 1.0 p.u. voltage magnitudes as a result of STATCOM devices placement and the entire bus voltage magnitudes were improved except bus 4 whose voltage magnitude is now 0.9490 p.u.

Table 4-3: Line Losses of IEEE 14-Bus Transmission Network (Without STATCOM)

Bus Number		**Steady State**	
From Bus	**To Bus**	**MW**	**MVAr**
1	**2**	**2.366**	**4.390**
1	5	1.275	2.492
2	3	1.052	2.008
2	4	0.729	0.313
2	5	0.388	0.736
3	4	0.221	0.158
4	5	0.222	0.703
4	7	0.000	0.731
4	9	0.000	0.651
5	6	0.000	1.898
6	11	0.019	0.041
6	12	0.029	0.062
6	13	0.086	0.170
7	8	0.000	0.087
7	9	0.000	0.522
9	10	0.007	0.019
9	14	0.052	0.111
10	11	0.004	0.009
12	13	0.002	0.001
13	14	0.019	0.039
TOTAL		**6.251**	**14.256**

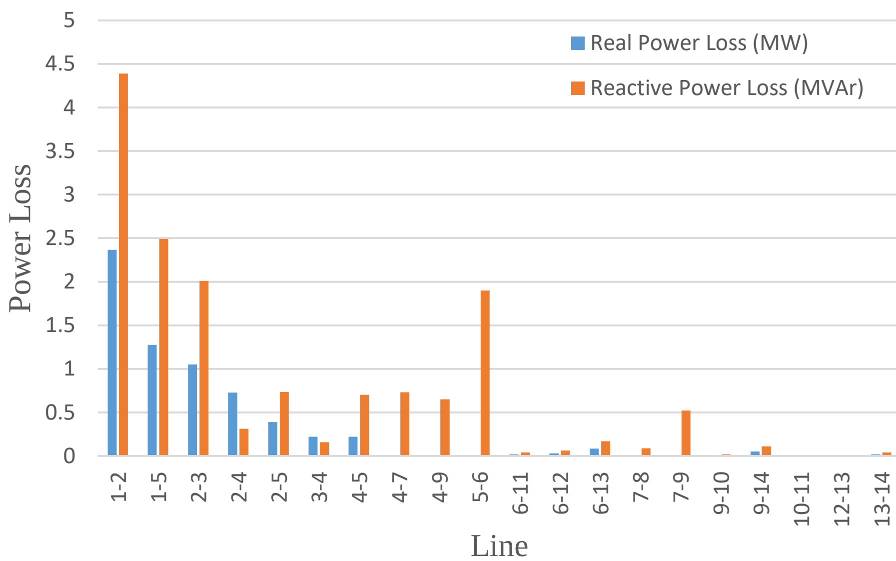

Figure 4-3: Real and Reactive Power Loss Before STATCOM Placement

Table 4-4: Voltage magnitude results of IEEE 14 bus transmission nnetwork (With STATCOM)

Bus No	Bus Type	Voltage Magnitude (p.u.)	Voltage Angle (degree)
1	Swing	1.0600	0.0000
2	PV	1.0350	3.9641
3	PV	0.9800	1.3563
4	**PQ**	**0.9490**	**3.8543**
5	PQ	0.9760	2.5160
6	PV	1.0100	3.3620
7	PQ	1.0000	2.6335
8	PV	0.9700	4.2340
9	PQ	1.0240	1.0031
10	PQ	1.0290	4.0970
11	PQ	1.0230	3.8069
12	PQ	1.0240	4.1200
13	PQ	1.0000	1.1491
14	PQ	1.0420	1.9518

It should be noted here that the device placement was done manually meaning that optimal location was achieved hence, bus voltage profile improvement with an exception of bus 4, hence the need to optimize the device placement. A clear presentation of the bus voltage profile with STATCOM device incorporation is depicted by Figure 4-4 below. All the bus voltage magnitudes except bus 4 are within the allowable limits.

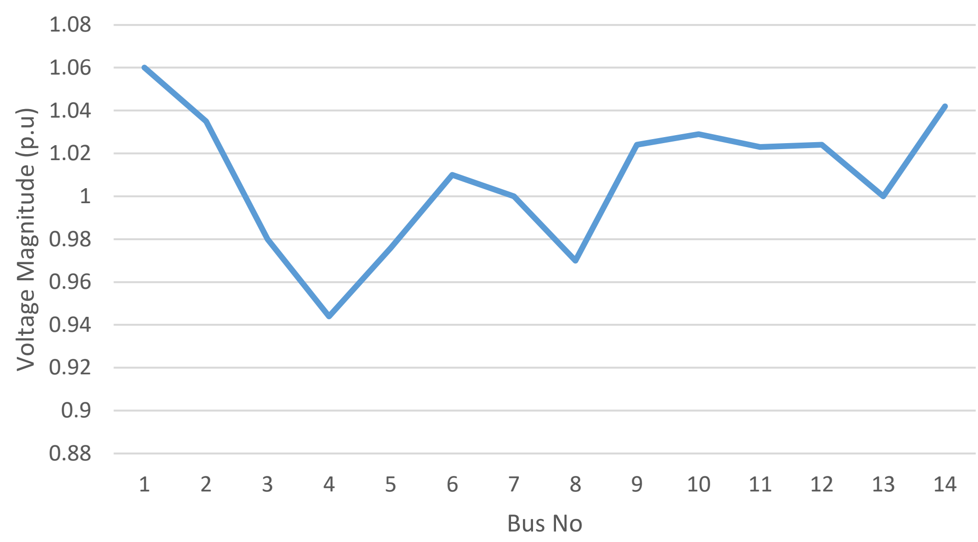

Figure 4-4: Voltage Profile of 14-Bus System after STATCOM Placement

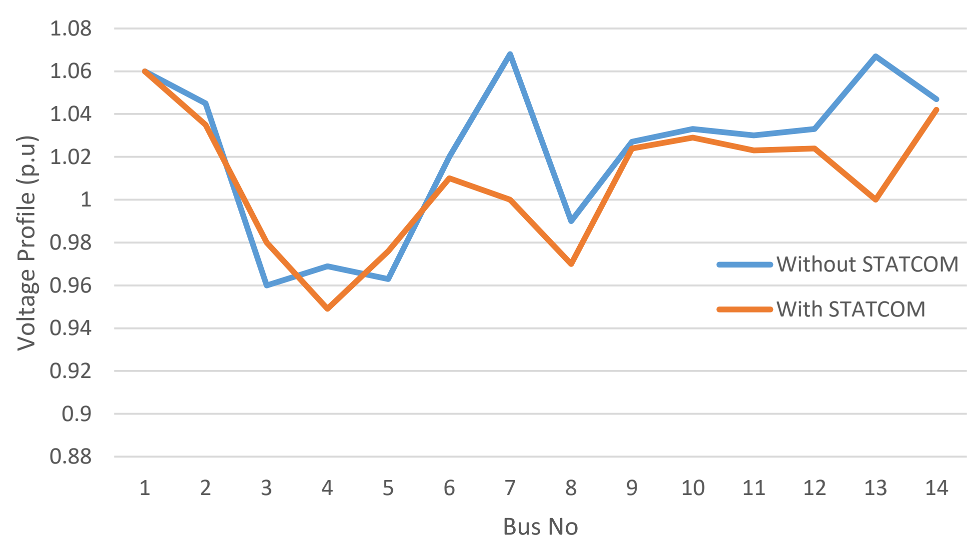

Figure 4-5: Voltage Profile Comparison Without and With STATCOM Placements

The voltage profile comparison before and with STATCOM device placement is presented in Figure 4-5. The distinction of the device performance can be seen as depicted in red colour line. The results of the line losses for power flow analysis of the system are presented in Table 4-5. The line connecting bus 1 and 2 exhibited the highest active power loss of 2.146 MW. The total loss was reduced from 6.251 to 6.075 MW. With this manual placement, a real power loss reduction of 176 kW was achieved. This was as a result of incorporation of STATCOM controller in the system which generated required reactive power to control the load flow and loss minimization.

Table 4-5: Results of the Line Losses with STATCOM

Bus Number		With STATCOM	
From Bus	**To Bus**	**MW**	**MVAr**
1	**2**	**2.346**	**4.370**
1	5	1.164	2.456
2	3	1.044	2.116
2	4	0.726	0.415
2	5	0.372	0.676
3	4	0.161	0.247
4	5	0.200	0.698
4	7	0.030	0.671
4	9	0.030	0.601
5	6	0.030	1.688
6	11	0.004	0.023
6	12	0.002	0.038
6	13	0.065	0.158
7	8	0.030	0.281
7	9	0.030	0.530
9	10	0.024	0.014
9	14	0.020	0.077
10	11	0.024	0.016
12	13	0.027	0.027
13	14	0.006	0.017
TOTAL		**6.075**	**13.857**

Likewise, there was a reactive power loss reduction of 399 kVAr when STATCOM was incorporated in the network. This was possible because of capability of STATCOM to generate or consume reactive power on any connected network. The graphical presentation losses of all the lines is shown in Figure 4-6.

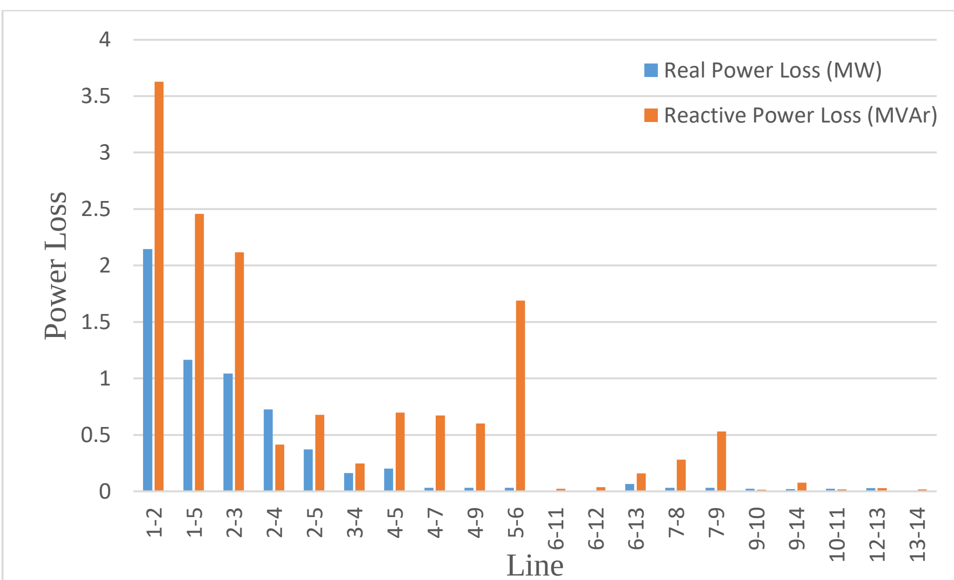

Figure 4-6: Real and Reactive Power Loss After STATCOM Placement

The total loss before and during the incorporation of STATCOM devices are presented in Figure 4-7. In this exercise, 40% of reactive power loss reduction was achieved with STATCOM device. This reactive power control practically enhanced network performance because, bus terminal voltage directly related to quality of network reactive power. Likewise, active power loss minimization of 2.82% was achieved at the same time. The release of 176 kW active power back to the network is an advantage for a system that is being operated at threshold. It is worthy of note that reactive power loss reduction is quite significant compare to active power loss reduction, howbeit, this is in accordance to the shunt FACTS device used whose operations directly rely on reactive power manipulations. Nevertheless, the focus of the exercise which is the minimization of transmission line losses with STATCOM placement was achieved.

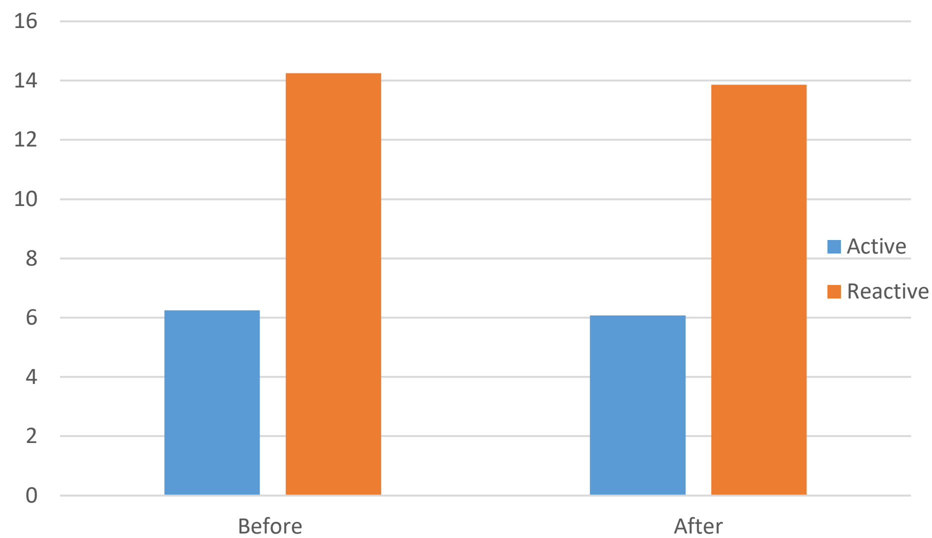

Figure 4-7: Total Active and Reactive Power Loss

Despite bus voltage profile improvement recorded after the incorporation of the STATCOM controller, the voltage limit violation which was observed at bus 4, is a testament that the system can be further improved upon in order to eliminate the issues of voltage limit violation and further reduced the total system power losses. This is achievable by placing STATCOM device optimally in the test network. With this placement method, efficiency and reliability of the electrical power system will be improved.

In line with the above desire however, efforts were made in the subsequent chapters to place STATCOM device optimally in the test network using artificial intelligence algorithm called PSO to place the device optimally in the test system. This was with a view to improving on/above the achievement of performance of the device as recorded in this current chapter.

4.4 Summary

In this chapter, results of the test system before and after STATCOM manual placement after simulations were discussed. When the test system was simulated without incorporation of STATCOM, buses 7 and 13 violated the maximum voltage limit. Buses 3 and 5 were at the verge of violating the lower voltage limit. Similarly, It was also observed after simulation that transmission lines 1-2 and 1-5 exhibited the highest losses, while the total losses were 6.251 MW and 14.256 MVAr.

To minimize losses and voltage magnitude deviations, STATCOM devices were manually placed at buses 7 and 13 so as to control and stabilize the voltage values at 1.0 p.u. After simulation, the voltages at 7 and 13 buses, which violated the voltage limits without STATCOM placement were stabilized at 1.0 p.u. and STATCOM placement effect was felt on the voltage magnitudes of the remaining buses except bus 4 which now violated the lower voltage limit due to fact that STATCOM devices were manually placed.

In conclusion, the line loses were significangly reduced except that of line 1-2 which showed little reduction. Similarly, the losses were minimized 6.075 MW and 13.857 MVAr. But manual placement of STATCOM devices does not give satisfactorily results in term of the overall network voltage profile, hence the need for optimizing device placement. Thus, the optimization of STATCOM placement is presented and discussed in the subsequent chapters.

CHAPTER FIVE

OPTIMAL LOCATION OF STATCOM DEVICE WITH PARTICLE SWARM OPTIMIZATION ALGORITHM

5.1 Particle Swarm Optimization Algorithm Implementation

The optimization algorithm known as PSO was implemented for optimal setting of STATCOM in this chapter. PSO method determines the optimal solution using a population of particles with each particle representing a candidate solution to the problem. It is considered as a famous, powerful and well-established metaheuristic optimization algorithm utilized frequently to proffer solution to FACTS device optimal allocation problem on transmission network. PSO is a method based on the population inspired by the graceful behavior of a school of fishes and flock of birds.

The control variables to be optimized are bus voltage magnitude of the generator, tap setting of the transformer and STATCOM controller VAR output. Table 5-1 presents the values of these parameters. The steady state power injection STATCOM model was incorporated into the load flow codes written in MATLAB software for the analysis. The algorithm was implemented on earlier described IEEE 14 bus network to check for its effectiveness.

Table 5-1: Control Variable Limits

S/N	Control Variable	Limit
1	Generator Voltage (V_{Gi})	(0.95 – 1.05) p.u.
2	Transformer Tap Settings (T_{Pi})	(0.90 – 1.10) p.u.
3	MVAr by Static Compensator (Q_{STC})	(0.00 – 100) MVAr

5.2 Incorporation of STATCOM Controller with IEEE 14-Bus Test System

The data were used in modeling the system is presented in Appendices A and B. Bus voltage profile deviation minimization and power loss reduction are the major focus of this research work hence, voltage magnitude, line flows and line losses that have direct bearing with the objectives of this work were noted and recorded accordingly. Three test cases were presented for the performance evaluation of the PSO algorithm on the optimal STATCOM controller location and sizing,

Test case one (Base case): Test system load flow without the incorporation of the device is referred to as Base case which reveals the status of the network.

Test case two (STATCOM): The outcome of test case one (base case) study gives test system voltage profile and power loss. This status of network was then used to locate and determine numbers of STATCOM devices to improve the network performance. This test case is similar to case one except that two STATCOM controllers whose parameters were manually obtained were installed at buses where there were voltage limit violations.

Test case three (STATCOM set with PSO): This test case is like test case two except that PSO algorithm was utilized to locate and size STATCOM controller. Optimal setting of STATCOM with PSO algorithm enhances the performance of the device.

5.3 Simulation Results

Newton-Raphson power flow was employed for each case, to obtain the bus voltage and to analyze the load flow. In all cases, voltage magnitudes, line flow and total losses were noted for comparison. The subsequent sections present the obtained results for the described three different case studies. The presentations were done in line with bus voltage deviation minimization, active and reactive power loss reduction. Table 5-2 presents used STATCOM parameters for the test cases.

Table 5-2: STATCOM Parameters used

Test Cases	Location Bus No.	Voltage profile (p.u.)	Angle (degree)	Shunt Reactive Power (MVAr)
Case 1	7	1.000	2.6335	3.68
Case 1	13	1.000	1.1491	5.43
Case 2	11	1.025	3.7689	8.96

5.4. Bus Voltage Profiles

Table 5-3 presents the results of voltage magnitudes and angles for load flow solutions of the test system for the three test cases. From the table, the magnitudes of voltage at buses 7 and 13 for test case one, are 1.068 and 1.067 p.u., respectively and these are out of upper voltage limit due to inadequate reactive power compensation and are therefore the locations for STATCOM placements. Two STATCOM controllers were placed at these buses to regulate the voltages to 1.0 p.u.

With STATCOM controller incorporation at 7 and 13buses, the voltages at these buses were regulated to 1.0 p.u. compared to their initial values of 1.0680 and 1.0670 p.u., respectively when the system was without STATCOM controllers. The incorporated STATCOM controller improved network voltage profile by having voltage magnitudes at majority of the buses within range of $\pm 5\%$. However, the magnitude of voltage at bus number 4 for this test case was reduced to 0.949 from 0.969 p.u. This bus terminal voltage was affected adversely and violated the permissible lower bus voltage limit. Hence, in order to restore this terminal voltage within the limit, PSO algorithm was then used to optimally locate and size STATCOM controller.

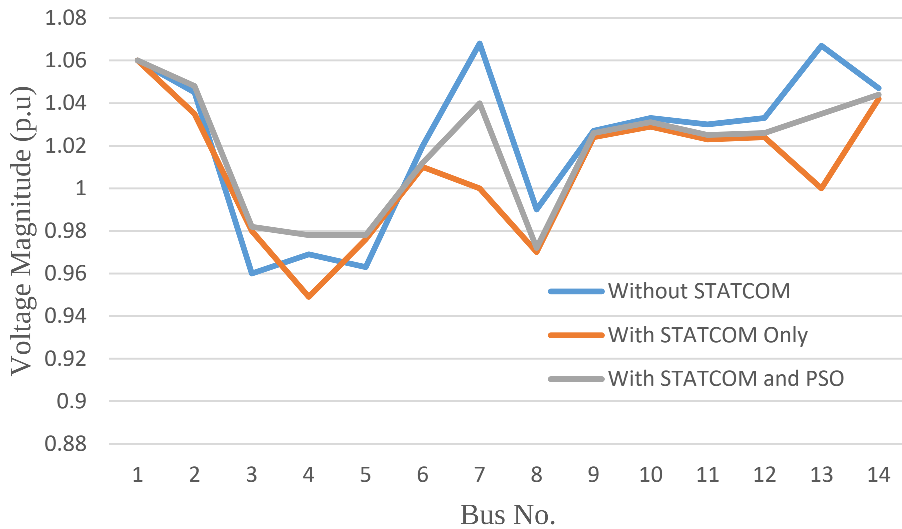

Figure 5-1: Bus voltage profile for all the three test cases

Table 5-3: Bus Voltage Magnitudes Results of IEEE 14-Bus Transmission Network

Bus Description		**Steady State (Base case)**		**STATCOM manually placed)**		**STATCOM (PSO placed)**	
Bus No.	**Bus Type**	**Voltage Magnitude (p.u.)**	**Voltage Angle (deg)**	**Voltage Magnitude (p.u.)**	**Voltage Angle (deg)**	**Voltage Magnitude (p.u.)**	**Voltage Angle (deg)**
1	Swing	1.060	0.000	1.060	0.000	1.060	0.000
2	PV	1.045	4.980	1.035	3.964	1.048	3.726
3	PV	0.960	2.253	0.980	1.356	0.982	2.287
4	**PQ**	**0.969**	**4.851**	**0.949**	**3.854**	**0.978**	**4.054**
5	PQ	0.963	3.132	0.976	2.516	0.978	1.847
6	PV	1.020	5.610	1.010	3.362	1.012	0.342
7	**PQ**	**1.068**	**3.051**	**1.000**	**2.634**	**1.040**	**2.714**
8	PV	0.990	5.772	0.970	4.234	0.972	4.385
9	PQ	1.027	1.052	1.024	1.003	1.026	2.855
10	PQ	1.033	4.108	1.029	4.097	1.031	0.948
11	PQ	1.030	3.893	1.023	3.807	1.025	3.768
12	PQ	1.033	4.125	1.024	4.120	1.026	4.045
13	**PQ**	**1.067**	**1.192**	**1.000**	**1.149**	**1.035**	**1.101**
14	PQ	1.047	1.953	1.042	1.952	1.044	1.452

The incorporation of STATCOM with PSO ensures no further bus voltage limits violation at any of the buses. The implementation of this improve the overall network voltage profile further. The voltage profile comparison of the three test cases is depicted in Figure 5-1.

The improvement recorded with manual selection of STATCOM parameter resulted into an improvement of bus voltage profile but bus voltage enhancement when STATCOM was optimally incorporated with artificial intelligent method, referred to as PSO is tremendous. The implication is that though, STATCOM can improve bus voltage but it must be properly optimized for optimal performance. All the terminal voltage of test case three lie inbetween 0.950 to 1.050 p.u., resulting into a more stable network operation and performance.

5.5. Minimization of Active Power Loss

Active losses for the three cases considered are given inTable 5-4. The total loss without any device stood at 6.251 MW which reduced to 6.075 MW when STATCOM was incorporated though manually. The reduction of 0.432 MW was achieved when the STATCOM was incorporated with PSO optimization algorithm. 6.90% reduction in active power loss was recorded when PSO was used to incorporate STATCOM device as against 2.82% reduction in active power loss that was obtained with manual placement. Notwithstanding, in case two and three, this FACTS device minimized the real power losses.

Table 5-4: Active Power Losses Results for all the three Cases

Bus Number		Steady State (Base case) (MW)	STATCOM (manually placed) (MW)	STATCOM (PSO placed) (MW)
From	**To**			
1	**2**	**2.366**	**2.346**	**2.336**
1	5	1.165	1.129	1.130
2	3	0.942	0.819	0.792
2	4	0.729	0.726	0.689
2	5	0.388	0.372	0.358
3	4	0.221	0.161	0.142
4	5	0.222	0.200	0.143
4	7	0.000	0.030	0.024
4	9	0.000	0.030	0.028
5	6	0.000	0.030	0.020
6	11	0.019	0.004	0.019
6	12	0.029	0.002	0.002
6	13	0.086	0.065	0.046
7	8	0.000	0.030	0.020
7	9	0.000	0.030	0.020
9	10	0.007	0.024	0.017
9	14	0.052	0.020	0.012
10	11	0.004	0.024	0.014
12	13	0.002	0.027	0.002
13	14	0.019	0.006	0.003
Total		**6.251**	**6.075**	**5.819**

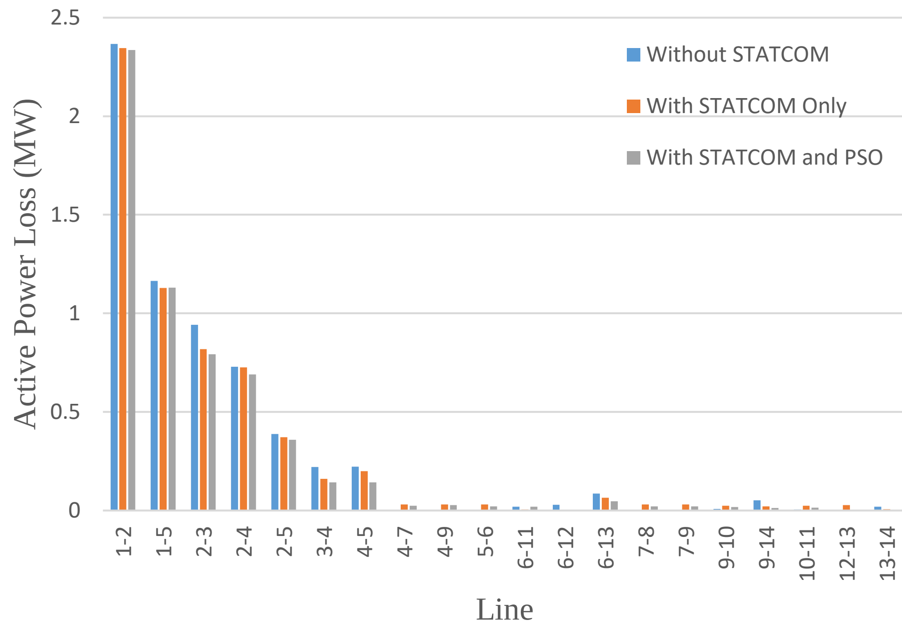

Figure 5-2: Active loss reduction of the three cases

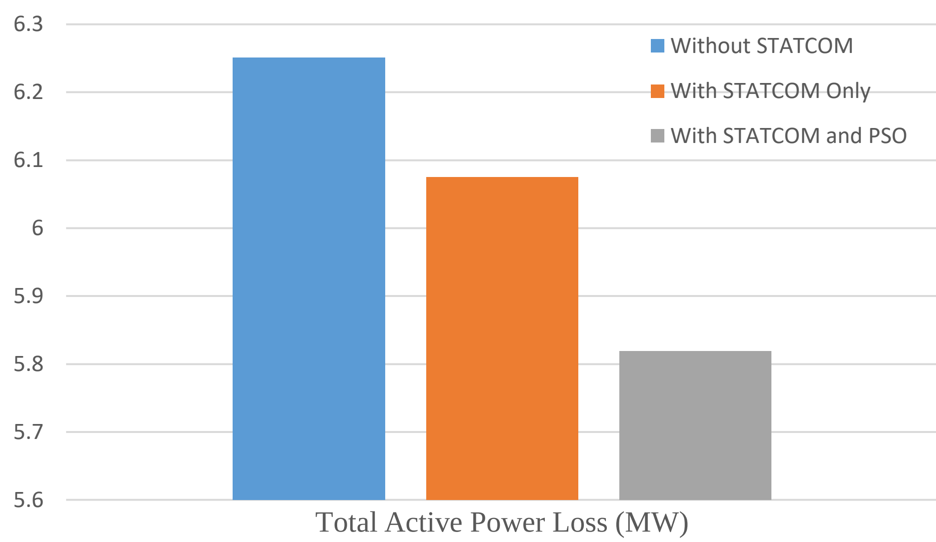

Figure 5-3: Total active power loss for all the three cases

This loss minimization was achieved by the redistribution of line flows on the network, which was made possible by STATCOM device, through the provision of reactive power. Figure 5-2, compares STATCOM device achievement on active power loss reduction based on manual and optimally placed methods is depicted for a better understanding.

It is clearly obvious that the network recorded loss minimization when STATCOM was placed with PSO technique. This is indicated in green colour on the graph. The reduction here supersede that indicated in red colour which is the case two for which the device was placed manually. The total loss reduction is presented in Figure 5-3, to better appreciate the performance of STATCOM when it was optimally incorporated into a test network.

5.6. Reactive Power Loss Reduction

Table 5- 5 presents the reactive losses results for the test system without STATCOM as well as with manually and optimally placed STACOM. The reactive loss which was 14.256 MVAr without the device was reduced to 13.857 MVAr when STATCOM was manually placed under case two study. This was further reduced to 12.954 MVAr when STATCOM was optimally incorporated using PSO. There was an achievement of 0.399 and 1.302 MVAr, corresponding to 2.80% and 9.13% total reduction respectively, when PSO was used to place the device and when the device was placed manually. By extension, optimally placed STATCOM with PSO was able to minimize the system loss with 0.903 MVAr corresponding to 6.52% total loss reduction. It is of interest that an optimally placed FACTS device will result into an optimal achievement of the desired objectives. The corresponding reduction of reactive power loss along different transmission lines is obvious as presented in the table.

Figure 5-4 depicts graphically, the comparison of the two approaches used in STATCOM placement for a clearer presentation. The overall reactive loss reduction before STATCOM, after manually and optimally placed STATCOM is presented in Figure. 5-5. Here, the overall benefits of using optimization algorithm in FACTS location can be visualized and better appreciated. This has tremendously minimized the system reactive loss.

Table 5-6 aggregates real and reactive power loss results of all the test cases. Active and reactive losses for network with test case one are presented in columns three and four, respectively. Columns five and six present results for all lines during test case two while columns seven and eight indicate the results obtained during test case three for active and reactive power losses, respectively. This is to better appreciate line by line reduction as achieved by the devices. The performance of PSO cannot be over emphasized because, not only that the device achieved better loss minimization results for active and reactive power, voltage profile improvement, but also minimized the cost.

Table 5-5: Reactive Power Loss Results for all the three Cases

Bus Number From	Bus Number To	Steady State (Base case) (MVAr)	STATCOM (manually placed) (MVAr)	STATCOM (PSO placed) (MVAr)
1	**2**	**4.39**	**4.370**	**4.228**
1	5	2.049	1.787	1.792
2	3	1.565	0.947	1.006
2	4	0.313	0.415	0.314
2	5	0.736	0.676	0.637
3	4	0.158	0.247	0.128
4	5	0.703	0.698	0.603
4	7	0.731	0.671	0.631
4	9	0.651	0.601	0.551
5	6	2.265	2.245	1.999
6	11	0.041	0.023	0.041
6	12	0.062	0.038	0.062
6	13	0.170	0.158	0.169
7	8	0.087	0.281	0.087
7	9	0.522	0.530	0.522
9	10	0.019	0.014	0.019
9	14	0.111	0.077	0.111
10	11	0.009	0.016	0.009
12	13	0.001	0.027	0.002
13	14	0.039	0.017	0.039
Total		**14.256**	**13.857**	**12.954**

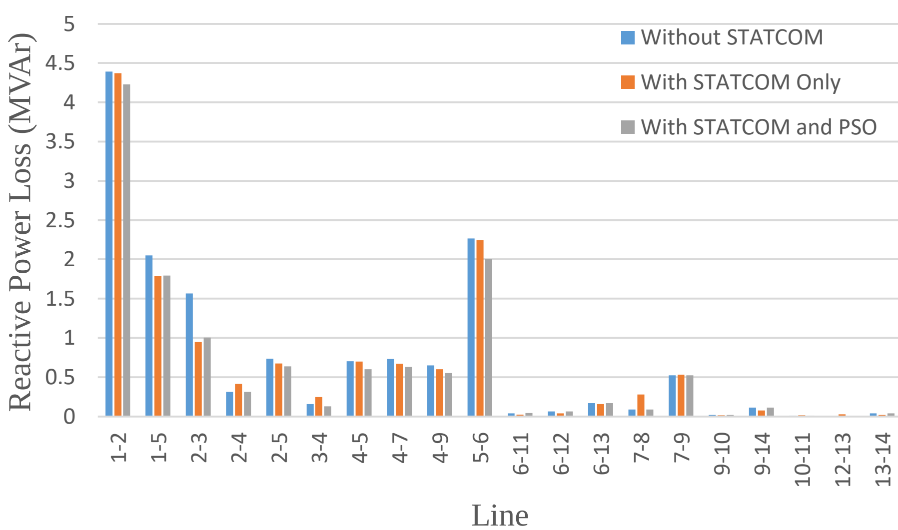

Figure 5-4: Reactive power reduction for all the three cases

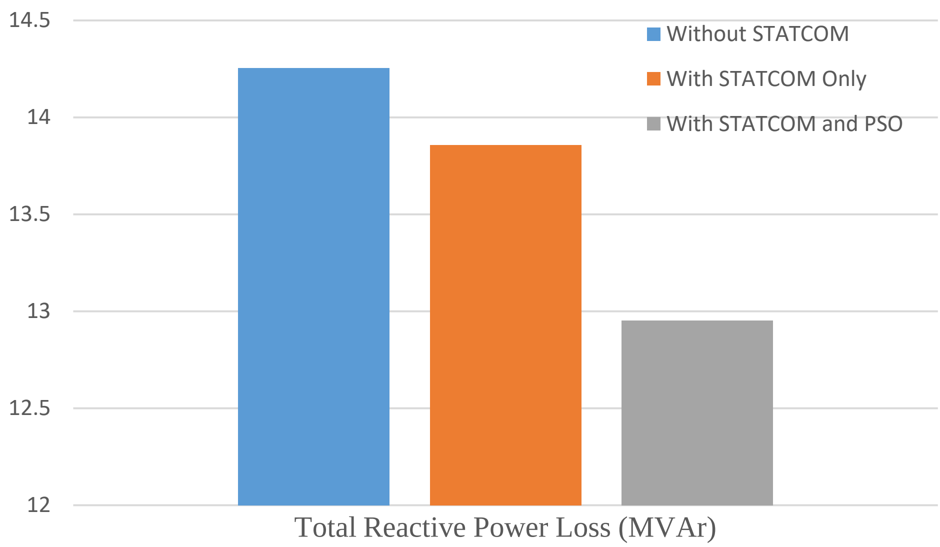

Figure 5-5: Total reactive power loss for all the three cases

Table 5-6: Line Loss Results of Test Network

Bus Number		Steady State (Base case)		STATCOM (manually placed)		STATCOM (PSO placed)	
From	To	(MW)	(MVAr)	(MW)	(MVAr)	(MW)	(MVAr)
1	**2**	**2.366**	**4.390**	**2.346**	**4.370**	**2.336**	**4.228**
1	5	1.165	2.049	1.129	1.787	1.130	1.792
2	3	0.942	1.565	0.819	0.947	0.792	1.006
2	4	0.729	0.313	0.726	0.415	0.689	0.314
2	5	0.388	0.736	0.372	0.676	0.358	0.637
3	4	0.221	0.158	0.161	0.247	0.142	0.128
4	5	0.222	0.703	0.200	0.698	0.143	0.603
4	7	0.000	0.731	0.030	0.671	0.024	0.631
4	9	0.000	0.651	0.030	0.601	0.028	0.551
5	6	0.000	1.898	0.030	2.265	0.020	1.999
6	11	0.019	0.041	0.004	0.023	0.019	0.042
6	12	0.029	0.062	0.002	0.038	0.002	0.062
6	13	0.086	0.170	0.065	0.158	0.046	0.169
7	8	0.000	0.087	0.030	0.281	0.020	0.087
7	9	0.000	0.522	0.030	0.530	0.020	0.522
9	10	0.007	0.019	0.024	0.014	0.017	0.019
9	14	0.052	0.111	0.020	0.077	0.012	0.111
10	11	0.004	0.009	0.024	0.016	0.014	0.009
12	13	0.002	0.001	0.027	0.027	0.002	0.002
13	14	0.019	0.039	0.006	0.017	0.003	0.039
Total		**6.251**	**14.256**	**6.075**	**13.857**	**5.819**	**12.954**

This is because two STATCOM devices were used during test case two, but this has been limited to only one device through particle swarm optimization algorithm. Optimally placed STATCOM injected in total, 8.96 MVAr into the network which is more than the sum of the two reactive powers injected by the two STATCOM devices earlier incorporated manually into the test network. Cost reduction forms major achievement of the algorithm. Table 5-7 gives the summary at a glance, the total loss reduction obtained with STATCOM device incorporation.

Table 5-7: Results of Total Active and Reactive Loss of the Test Network

Total Power Loss	**Steady State (Base case)**	**STATCOM (manually placed)**	**STATCOM (PSO placed)**
P (MW)	6.251	6.075	5.8195
Q (MVAr)	14.256	13.857	12.9542

The distributions of the flow of energy on power network during the three test cases are presented in Table 5-8. The STATCOM device achieved improvement in network performance through redistribution of energy (power flow) on the network. In a power network system, more power flow is usually accompanied by corresponding losses however, the creation of alternate path flow for energy along less loaded line by the device will lessen the corresponding losses on such heavy loaded transmission lines. This has resulted into reduction of power losses on network system.

A critical look into columns five, six, seven and eight as compared to columns three and four of the Table 5-8 reveals how the line flows for both active and reactive have been redistributed with the presence of STATCOM as against when the devices were not incorporated. The reactive power compensation of STATCOM dislodged power flow by injecting reactive power to compensate for system reactive power hitherto being consumed to maintained bus voltage profile. The contribution of loss reduction consequent of this reactive power compensation can be seen in columns five and seven for active power flow and columns six and eight for reactive power flow. The device(s) adjusted appropriately as necessary to present a more stable tested power network.

The total active power flow in the network, which was 621.466 MW without STATCOM, was increased to 622.967 MW and 623.381 MW with manually and optimally placed STATCOM device, respectively. Correspondingly, the reactive power which stood at 201.711 MVAr, without the device got increased to 248.515 MVAr and 250.786 MVAr with manually and optimally incorporated STATCOM device, respectively. It is of interest that the network was able to support an increase in both active and reactive flow with FACTS device incorporation. STATCOM paved way for loss minimization with an increase in network power flow.

Table 5-8: Line Flow Result of the Test Network

Bus Number		**Steady State (Base case)**		**STATCOM (Manually placed)**		**STATCOM (PSO placed)**	
From	**To**	**(MW)**	**(MVAr)**	**(MW)**	**(MVAr)**	**(MW)**	**(MVAr)**
1	2	135.719	75.7495	136.715	93.8467	138.065	96.2140
1	5	69.9246	18.1396	69.7698	26.7010	69.8589	27.0550
2	3	68.7359	10.6289	68.7191	10.8519	68.7203	10.9960
2	4	51.8444	3.41780	52.0954	8.24311	52.1509	8.36960
2	5	38.2318	0.9358	38.4929	5.27455	38.5039	5.34660
3	4	23.3152	14.7861	23.3758	9.99670	23.1738	9.83530
4	5	61.4815	4.49210	61.6044	6.51721	61.3006	6.31630
4	7	27.8024	6.92250	28.0672	1.57644	27.7524	1.54640
4	9	16.3042	4.16420	16.3595	1.16854	16.2542	1.14850
5	6	43.1095	11.2655	42.8319	20.9215	43.0595	20.8920
6	11	7.10061	2.07250	6.93040	3.48098	7.07607	3.48550
6	12	7.57962	2.02230	7.53480	2.19209	7.54242	2.18930
6	13	17.2293	5.67910	17.1667	6.38178	17.1875	6.31610
7	8	0.00000	11.0213	0.00000	20.1737	0.00000	20.1440
7	9	27.8024	19.4067	28.0672	20.0010	27.7524	20.0310
9	10	5.32541	5.38670	5.50730	3.95473	5.28126	3.97890
9	14	9.28119	3.93097	9.41940	2.99817	9.28171	2.77770
10	11	3.66289	0.37382	3.47780	1.81421	3.50722	1.78990
12	13	1.54522	0.54639	1.49447	0.72863	1.49792	0.75590
13	14	5.47130	0.76900	5.33791	1.69230	5.41454	1.59910

Table 5-9 summarizes the total power flow and corresponding total loss values in the network for decipherment purpose. By extension, the algebraic sum of both the active power flow and loss in each case implies that the network system was able to accommodate and cope with more power with the incorporation of FACTS device. This was also the case for reactive power as can be inferred in Table 5-9.

Table 5-9: Summary of Total Power Flow and Total Power Loss in the Network

	Power Flow			**Power Loss**		
	Steady State	**STATCOM (manually placed)**	**STATCOM (PSO placed)**	**Steady State**	**STATCOM (manually placed)**	**STATCOM (PSO placed)**
P (MW)	621.466	622.967	623.381	6.251	6.075	5.819
Q (MVAr)	201.711	248.515	250.786	14.256	13.857	12.954
Total (MVA)	**653.381**	**670.707**	**671.936**	**15.566**	**15.130**	**14.201**

5.7 Summary

The optimization of STATCOM devices was presented and discussed in this chapter. PSO was utilized for the determination of the optimal location of STATCOM controller. Voltage profile improvement and loss minimization results obtained using STATCOM device optimized by PSO, were compared with the base case and manually placed STATCOM devices, which were presented earlier.

It was noted that implementation of PSO further improved the overall network voltage profile, Also, real power loss was reduced by 0.432 MW when the STATCOM was incorporated with PSO optimization algorithm. This means that active power was reduced by 6.90% when STATCOM device was optimized by using PSO as against 2.82% reduction obtained with manual placement. Similarly, Reactive power was reduced by 0.399 and 1.302 MVAr, corresponding to 2.80% and 9.13% total reduction respectively, when STATCOM were manually and optimally placed, respectively. PSO gave better loss minimization and voltage profile improvement resulting in cost minimization.

CHAPTER SIX

OPTIMAL LOCATION AND SETTING OF STATCOM DEVICE WITH FIREFLY ALGORITHM

6.1 Firefly Algorithm Implementation

The optimization algorithm known as firefly algorithm (FA) earlier described in chapter three was implemented for optimal setting of STATCOM in this chapter. FA operates by finding the minimized network active power losses and corresponding reactive power settings of the STATCOM controller. In this chapter, STATCOM optimal location and parameter setting was achieved with FA. Codes were written in Matlab software for load flow analysis in which steady state power injection of the STATCOM controller model was incorporated just as in the case of PSO. The network power flow analyses without and with the controller placement were performed. The algorithm was implemented on earlier described IEEE 14-bus network to check for its effectiveness. The performance of FA in optimal setting of STATCOM device in this contest was then compared to that of PSO setting. This was with a view to identifying the best out of these algorithms in terms of device parameter settings and subsequent network performance in response to device incorporation.

6.2 STATCOM Controller Placement with Test System

Like previous chapters, the bus and line data of IEEE 14 bus in Appendices A and B were used in modeling the system. Also, bus voltage profile deviation minimization and minimization of losses are the focus of this research work hence, voltage magnitude, line flows and line losses that have direct bearing with the objectives of this work were noted and recorded accordingly. The performance evaluation of FA on the optimal STATCOM controller placement and size was done by comparing the results of FA with those obtained in chapter five (PSO set STATCOM device). The process involved here is similar to test case two of chapter five, except that FA was applied to obtain optimal STATCOM controller location and size. It should be observed that bus voltage deviation minimization, system active and reactive power regulations were enhanced by optimal setting of STATCOM device with firefly algorithm.

6.3 Results of Simulations

The subsequent sections present the obtained results for the described algorithm when FA was used for optimal setting of STATCOM. Newton-Raphson load flow was employed in each case, to obtain the voltage magnitude and analyze active and reactive flow. In all cases, voltage magnitudes, line flow, active and reactive power losses were noted and presented for comparison. The presentations were done in line with voltage deviation and power loss reduction. Table 6-1 presents the STATCOM parameters as indicated by FA.

Table 6-1: STATCOM Parameters used

Optimization Algorithm	Location Bus No.	Voltage profile (p.u.)	Angle (degree)	Shunt Reactive Power (MVAr)
FA	9	1.029	0.9257	9.54

6.4 Bus Voltage Profiles

Table 6-2 presented the voltage magnitudes and angles for power flow solutions of the test network. Columns 3, 5, and 7 give magnitudes while columns 2, 4, and 6 present the corresponding voltage angles, respectively for the base case, PSO placed and FA placed STATCOM device. Arising from columns 5 and 7, the voltage profile in each case has been improved but a critical look at column 7 revealed a better improvement over that of voltage profile in column 5. This implies that when STATCOM device was optimized with FA, there was an improvement in bus voltage profile in comparison with when PSO algorithm was used for this same device setting. This can be understood better in Figure 6-1. Bus voltage profile with FA is represented in green colour while colour red indicates the voltage profile when PSO was used. The base case voltage profile is presented in blue. All the terminal voltages of test system are lie between 0.95 to 1.05 p.u., resulting into a more stable network operation and performance. These two algorithms minimized the deviation however, the greatest achievement of bus voltage deviation minimization was achieved with FA in this case.

A good justification for this performance can be pointed out from buses 2 and 3. At steady state, the p.u. bus voltage at bus 2 was 1.045 where after the optimization with PSO, it increased to 1.048 p.u. but decreased to 1.046 p.u. upon optimization of STATCOM with FA. Also, at bus 3, steady state bus voltage p.u. which was 0.960 p.u. increased to 0.982 p.u. and later to 0.985 p.u. upon optimization with PSO and FA, respectively. Since the expected rated bus terminal value is 1.0 p.u., then, it implies that the optimization algorithm whose impacts on the network tends to restore the terminal voltage to expected rated value is the most appropriate optimization algorithm.

6.5 Active Power Loss Minimization

With the application of optimization algorithms for placement technique, STATCOM device was able to minimize real power losses. The real power loss details for the base case, PSO and FA placed STATCOM device are shown in Table 6-3. During the base case, the total loss without any device stood at 6.251 MW which reduced to 5.819 and 5.518 MW when STATCOM was incorporated with PSO and FA, respectively. With the use of PSO, the gross loss was reduced by 0.432 MW, while the gross loss was

Table 6-2: Results of the Test Network Voltage Magnitudes and Angles

Bus Description		**Steady State (Base case)**		**STATCOM (PSO placed)**		**STATCOM (Firefly placed)**	
Bus No.	**Bus Type**	**Voltage Magnitude (p.u.)**	**Voltage Angle (degree)**	**Voltage Magnitude (p.u.)**	**Voltage Angle (degree)**	**Voltage Magnitude (p.u.)**	**Voltage Angle (degree)**
1	Swing	1.060	0.000	1.060	0.000	1.060	0.000
2	PV	1.045	4.980	1.048	3.726	1.046	3.547
3	PV	0.960	2.253	0.982	2.287	0.985	0.492
4	**PQ**	**0.969**	**4.851**	**0.978**	4.054	**0.981**	**3.854**
5	PQ	0.963	3.132	0.978	1.847	0.981	2.048
6	PV	1.020	5.610	1.012	0.342	1.015	3.097
7	**PQ**	**1.068**	**3.051**	**1.040**	2.714	**1.043**	**2.513**
8	PV	0.990	5.772	0.972	4.385	0.975	4.187
9	PQ	1.027	1.052	1.026	2.855	1.029	0.926
10	PQ	1.033	4.108	1.031	0.948	1.034	3.729
11	PQ	1.030	3.893	1.025	3.768	1.028	3.671
12	PQ	1.033	4.125	1.026	4.045	1.029	3.945
13	**PQ**	**1.067**	**1.192**	**1.035**	1.101	**1.038**	**1.099**
14	PQ	1.047	1.953	1.044	1.452	1.047	1.572

Figure 6-1: Bus voltage profile for test system

Table 6-3: Active Power Losses Results for all the three Cases

Bus Number From	To	Steady State (Base case) (MW)	STATCOM (PSO placed) (MW)	STATCOM (Firefly placed) (MW)
1	**2**	**2.366**	**2.336**	**2.146**
1	5	1.165	1.130	0.982
2	3	0.942	0.792	0.672
2	4	0.729	0.689	0.606
2	5	0.388	0.358	0.352
3	4	0.221	0.142	0.141
4	5	0.222	0.143	0.180
4	7	0.000	0.024	0.050
4	9	0.000	0.028	0.050
5	6	0.000	0.020	0.050
6	11	0.019	0.019	0.024
6	12	0.029	0.002	0.017
6	13	0.086	0.046	0.045
7	8	0.000	0.020	0.050
7	9	0.000	0.020	0.050
9	10	0.007	0.017	0.044
9	14	0.052	0.012	0.005
10	11	0.004	0.014	0.044
12	13	0.002	0.002	0.047
13	14	0.019	0.003	0.026
Total		**6.251**	**5.819**	**5.581**

minimized with 0.733 MW when STATCOM was incorporated with FA. The corresponding minimization at each transmission lines are presented in the Table 6-3. This loss minimization was achieved by the redistribution of line flows on the network, which was made possible by STATCOM device, through the provision of reactive power. While FA resulted into 11.73% loss minimization, PSO yielded 6.9% loss reduction. This implies that FA outperformed PSO in real power loss minimization for the test network.

Figure 6-2, depicts a clearer comparison of the performance of the two algorithms for the target objective of loss minimization. It is obvious that the network recorded loss minimization in all the lines when STATCOM was placed with FA and PSO technique. However, the magnitude of loss reduction differs for both algorithms. The lines indicated in green colour (STATCOM with FA) on the graph, are far more reduced in magnitude than the red colour profiles which represents losses with PSO algorithm. It is clear that these reductions with FA placement supersede that indicated in red colour which is PSO placement method. The total loss reduction is presented in Figure 6-3, to better appreciate the performance of FA and PSO for STATCOM optimization.

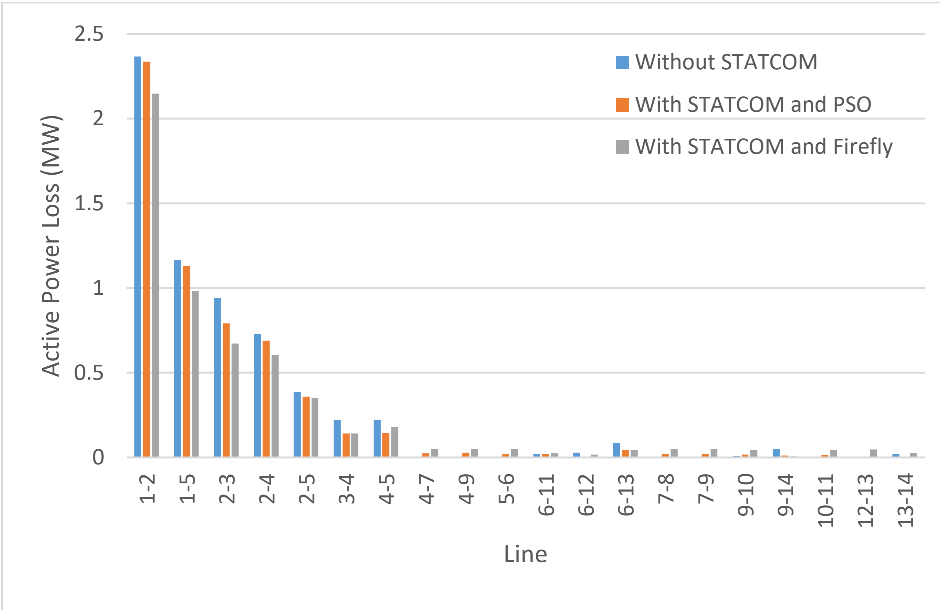

Figure 6-2: Active power loss reduction for all the three cases

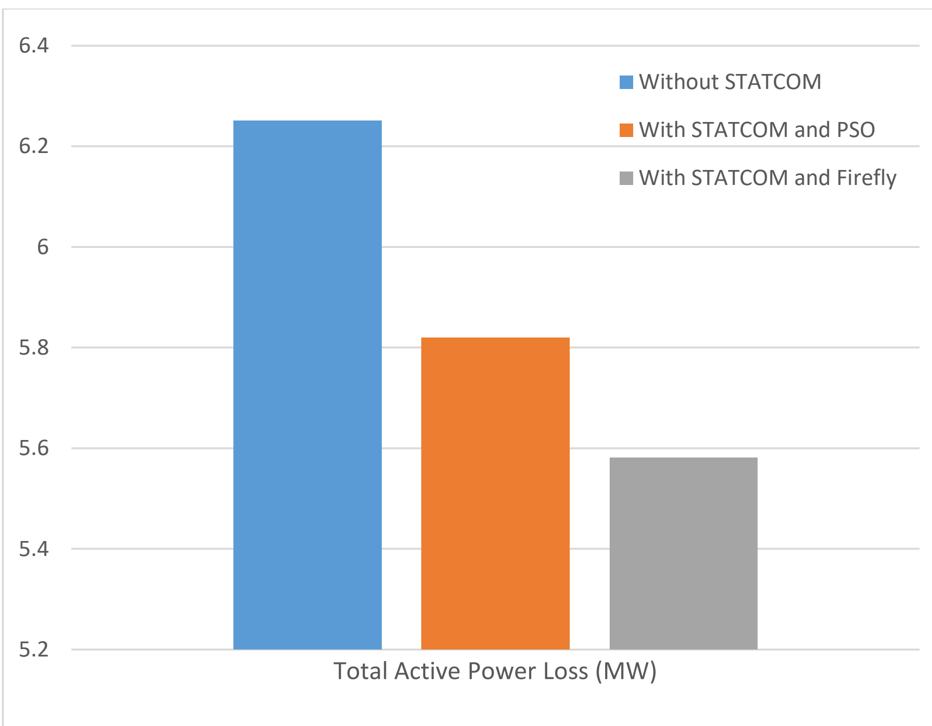

Figure 6-3: Total real power loss

6.6 Reactive Power Loss Minimization

Table 6-3 presents the results of the line losses for the test network before and after optimally placed STACOM. Without the device, the total loss was 14.256 MVAr however, this was reduced to 12.594 MVAr when optimal setting of STATCOM was achieved with PSO. This loss was further abridged to 12.156 MVAr when STATCOM was optimally incorporated using FA. With the incorporation of STATCOM device with PSO and FA, there was an achievement of 1.622 and 2.100 MVAr, corresponding to 11.37% and 14.73% total reduction, respectively. Performance comparison of the two optimization methods reveals that FA surpasses PSO in reactive power loss minimization. From Table 6-3, columns 4 and 5 present the comparative transmission lines losses for both PSO and FA.

The reduction in the lines' losses are better explained graphically in Figure 6-4. In all the transmission lines, saves line 3 – 4, there were loss minimization with STATCOM optimized FA. The differences in magnitude of reactive power loss for optimally placed STATCOM with PSO and FA indicate the advantage of FA over PSO for loss minimization. Figure 6-5 presents the total reactive power loss minimization for the test network without and with optimally placed STATCOM, is presented in. Overtly, the FA performance to optimize STATCOM controller can be visualized and better appreciated.

Table 6-4: Reactive Power Loss Results

Bus Number From	 To	Steady State (Base case) (MVAr)	STATCOM (PSO placed) (MVAr)	STATCOM (Firefly placed) (MVAr)
1	**2**	**4.390**	**4.228**	**3.628**
1	5	2.049	1.792	1.692
2	3	1.565	1.006	0.852
2	4	0.313	0.314	0.305
2	5	0.736	0.637	0.616
3	4	0.158	0.128	0.267
4	5	0.703	0.603	0.600
4	7	0.731	0.631	0.611
4	9	0.651	0.551	0.581
5	6	2.265	1.999	1.898
6	11	0.041	0.041	0.003
6	12	0.062	0.062	0.018
6	13	0.170	0.169	0.138
7	8	0.087	0.087	0.261
7	9	0.522	0.522	0.510
9	10	0.019	0.019	0.034
9	14	0.111	0.111	0.057
10	11	0.009	0.009	0.036
12	13	0.001	0.002	0.047
13	14	0.039	0.039	0.002
Total		**14.256**	**12.954**	**12.156**

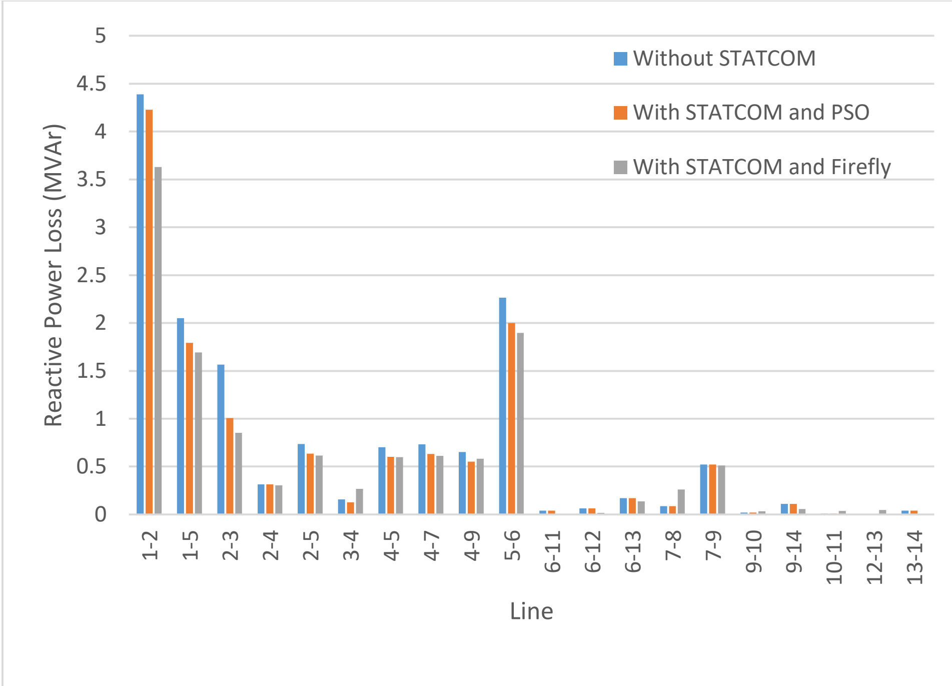

Figure 6-4: Reactive power reduction for all the three cases

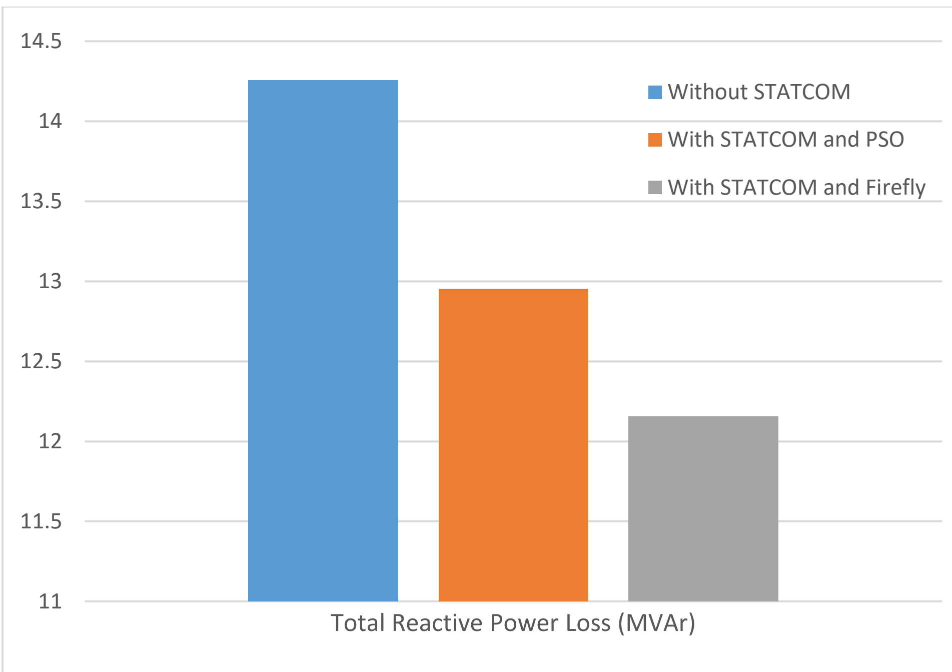

Figure 6-5: Total reactive power loss for all the three cases

This has tremendously minimized the system reactive power loss of the test system better than PSO algorithm. This minimization contributed immensely to bus voltage profile deviation minimization and thereby improving system stability and security. Table 6-5 presents the real and reactive power loss results for the test system. Real and reactive power losses the whole transmission lines during base case study are presented in columns three and four, respectively. The active power loss with PSO placed STATCOM is contained in column five while that of FA placed SATCOM is contained in column seven. Their corresponding reactive power loss are contained in columns six and eight. This gives a holistic line by line reduction for both real and reactive power as achieved by the device through the two algorithms during the test.

The performance of FA cannot be over emphasized when place side by side with PSO algorithm. With this performance, FA achieved better minimization results for active and reactive power losses and voltage deviations, leading to cost minimization. Table 6-6 summarizes the total loss minimization for the two optimization algorithms. In this case also, FA outperformed PSO for both active and reactive power loss reduction. There was an improvement in flow of energy as designated by power flow distribution in the network when the device was optimized by the two algorithms as presented in Table 6-7. This improvement in network performance was as a result of energy redistribution in the network as a result of the presence of STATCOM device. This device created an alternative flow path for energy along less loaded line leading to corresponding loss reduction on the initial transmission lines.

Table 6-5: Results of the Line Loss of the Test Network

Bus Number		**Steady State (Base case)**		**STATCOM (PSO placed)**		**STATCOM (Firefly placed)**	
From	**To**	**(MW)**	**(MVAr)**	**(MW)**	**(MVAr)**	**(MW)**	**(MVAr)**
1	**2**	**2.366**	**4.390**	**2.346**	**4.370**	**2.146**	**3.628**
1	5	1.165	2.049	1.129	1.787	0.982	1.692
2	3	0.942	1.565	0.819	0.947	0.672	0.952
2	4	0.729	0.313	0.726	0.415	0.706	0.395
2	5	0.388	0.736	0.372	0.676	0.352	0.696
3	4	0.221	0.158	0.161	0.247	0.141	0.267
4	5	0.222	0.703	0.200	0.698	0.180	0.678
4	7	0.000	0.731	0.030	0.671	0.050	0.651
4	9	0.000	0.651	0.030	0.601	0.050	0.581
5	6	0.000	1.898	0.030	2.265	0.050	2.245
6	11	0.019	0.041	0.004	0.023	0.024	0.003
6	12	0.029	0.062	0.002	0.038	0.017	0.018
6	13	0.086	0.170	0.065	0.158	0.045	0.138
7	8	0.000	0.087	0.030	0.281	0.050	0.261
7	9	0.000	0.522	0.030	0.530	0.050	0.510
9	10	0.007	0.019	0.024	0.014	0.044	0.034
9	14	0.052	0.111	0.020	0.077	0.005	0.057
10	11	0.004	0.009	0.024	0.016	0.044	0.036
12	13	0.002	0.001	0.027	0.027	0.047	0.047
13	14	0.019	0.039	0.006	0.017	0.026	0.002
Total		**6.251**	**14.256**	**5.819**	**12.954**	**5.518**	**12.156**

Table 6-6: Total Active and Reactive Power Loss

Total Power Loss	Steady State (Base case)	STATCOM (PSO placed)	STATCOM (Firefly placed)
MW	6.251	5.819	5.581
MVAr	14.256	12.954	12.156

The reactive power which were 18.1396, 3.4178, 0.9358, 11.2655, and 11.0213 MVAr on transmission lines 1-5, 2-4, 2-5, 5-6, and 7-8 were increased to 27.055, 8.3696, 5.3466, 20.892 and 20.144 MVAr using PSO and 28.0556, 8.9696, 5.6466, 20.8915 and 20.1437 MVAr respectively with FA optimization. This redeployment of reactive power impacted positively on the corresponding bus voltage profile of the test system.

Table 6-7: Results of the Line Flow of the Test Network

Bus Number		Steady State (Base case)		STATCOM (PSO placed)		STATCOM (Firefly placed)	
From	To	(MW)	(MVAr)	(MW)	(MVAr)	(MW)	(MVAr)
1	2	135.719	75.7495	138.065	96.214	138.065	96.2135
1	5	69.9246	18.1396	69.8589	27.055	71.2589	28.0554
2	3	68.7359	10.6289	68.7203	10.996	69.7603	11.8963
2	4	51.8444	3.41780	52.1509	8.3696	52.5509	8.96961
2	5	38.2318	0.93580	38.5039	5.3466	38.5839	5.64659
3	4	23.3152	14.7861	23.1738	9.8353	23.1738	9.83527
4	5	61.4815	4.49210	61.3006	6.3163	61.3006	6.31630
4	7	27.8024	6.92250	27.7524	1.5464	27.7524	1.54644
4	9	16.3042	4.16420	16.2542	1.1485	16.2542	1.19854
5	6	43.1095	11.2655	43.0595	20.892	43.0595	20.8915
6	11	7.10061	2.07250	7.07607	3.4855	7.07607	3.48551
6	12	7.57962	2.02230	7.54242	2.1893	7.56242	2.18929
6	13	17.2293	5.67910	17.1875	6.3161	17.2750	6.31605
7	8	0.00000	11.0213	0.00000	20.144	0.00000	20.1437
7	9	27.8024	19.4067	27.7524	20.031	27.7524	20.0310
9	10	5.32541	5.38670	5.28126	3.9789	5.28126	3.97888
9	14	9.28119	3.93097	9.28171	2.7777	9.28171	2.97765
10	11	3.66289	0.37382	3.50722	1.7899	3.70722	1.78988
12	13	1.54522	0.54639	1.49792	0.7559	1.49792	0.75594
13	14	5.47130	0.76900	5.41454	1.5991	5.44454	1.69907

The total active power flow increased from 621.466 to 623.381 MW with PSO algorithm and 626.638 MW with FA placed STATCOM device. In the same way, the reactive power which stood at 201.710 MVAr, without the device got increased to 250.787 and 253.936 MVAr when STATCOM was optimally incorporated with PSO and FA, respectively. Table 6-8 summarizes the total power flow in the network and the corresponding total loss values for decipherment purpose.

From this table, the network accommodated 653.381 MVA total power without STATCOM device. However, this total power increased to 671.936 and 676.135 MVA with PSO and FA placed STATCOM device, respectively. With this total network power increase, the network loss decreased from 15.566 to 13.813 MVA as shown Table 6-8.

Table 6-8: Summary of Total Power Flow and Losses in the Network

	Power Flow			**Power Loss**		
	Steady State	**STATCOM (PSO placed)**	**STATCOM (Firefly placed)**	**Steady State**	**STATCOM (PSO placed)**	**STATCOM (Firefly placed)**
MW	621.466	623.381	626.638	6.251	5.819	5.681
MVAr	201.711	250.787	253.936	14.256	12.954	12.591
Total (MVA)	**653.381**	**671.936**	**676.135**	**15.566**	**14.201**	**13.813**

The disparity in terms of device rating is presented in Table 6-9. The injected reactive power is in column five while column three and four contain the device voltage magnitude and angle while the location is in column two of the Table 6-9. The resultant parameters setting and location of STATCOM device that resulted into system performance as explained above for both FA and PSO are presented here for comparison.

Table 6-9: FA and PSO STATCOM Location and Parameters settings

Optimization Algorithm	**Location Bus No.**	**Voltage profile (p.u.)**	**Angle (degree)**	**Shunt Reactive Power (MVAr)**
FA	9	1.029	0.9257	9.54
PSO	11	1.025	3.7689	8.96

6.7 Summary

This chapter presented and compared the results obtained with optimally placed STATCOM with PSO and that with FA. The two algorithms minimized the improved the voltage profile however, the voltage profile was significantly improved when STATCOM device was optimized with firefly algorithm compared to when PSO algorithm was used to optimized the same device settings. In other words, FA contributed immensely to bus voltage profile deviation minimization thereby improving the system stability and security better than PSO.

In terms of active power loss minimization, FA gave 11.73% loss minimization compared with PSO, which yielded 6.90% loss reduction. This implies that FA outperformed PSO in active power loss minimization for the test system. Similarly, with FA optimized STATCOM, total reactive power was reduced by 14.73% compared with PSO algorithm which gave 11.37% loss reduction. This has tremendously minimized the network reactive power loss better than PSO algorithm. Therefore, FA surpasses PSO in power loss minimization., when the performance of the two optimization methods were compared.

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

An optimization approach to minimize power transmission network losses, and control bus voltage deviation through appropriate location and sizing of STATCOM controller has been presented in this thesis. Particle swarm optimization (PSO) and firefly algorithm (FA) are the optimization techniques adopted for device allocation in the investigation conducted. Basically, the steady-state Newton-Raphson power flow algorithm of the IEEE 14 bus network test system was modified to accommodate STATCOM power injection model (PIM). A script was written in MATLAB environment to perform load flow analysis of the network before and after STATCOM placement, using PSO and FA for device allocation.

The successful independent implementation of FA and PSO revealed the suitability of these algorithms for STATCOM location and parameter settings for the achievement of set objectives. Also, STATCOM played substantive roles in network power loss reduction and bus voltage profile control. However, the results showed that optimization of STATCOM controller using PSO and FA enhanced the efficiency of the transmission system without the need for physical power infrastructure expansion. Meanwhile, in performance comparison, FA yielded better results than PSO and is considered more effective for STATCOM device optimization to minimize power loss and bus voltage deviations. It has been demonstrated that various research questions have been properly addressed and besides, the implemented PSO and FA methods proved to be effective for optimal placement of STATCOM device as compared uncompensated placement approach. The performance of FA supersedes that of PSO for the same objectives as achieved in this study.

7.2 Contribution to Knowledge

This research reveals the effectiveness of PSO and FA to locate and size STATCOM controller optimally in transmission networks for minimizing losses and voltage magnitude deviations. Hence, PSO and FA can be used by power system engineers to optimise STATCOM controller within the power system for reliability and efficiency improvement of the existing transmission network.

7.3 Recommendation for Future Work

The suggested recommendations for further research are:

(i) The performance of an optimized STATCOM device in network power loss reduction and bus voltage deviation minimization revealed the innate ability and the competence of this controller in influencing network parameters to achieve target system objectives in steady state conditions. Therefore, future work on STATCOM controller performance analysis under different fault conditions should be considered.

(ii) Various optimization techniques for locating and sizing STATCOM controller optimally for example, cuckoo search algorithm, ant colony, genetic algorithm, tabu search algorithm among others on power transmission system should be investigated, analyzed and compared with the results of this work.

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APPENDIX A

Line Data for IEEE 14 Bus System

From Bus	To Bus	R (p.u.)	X (p.u.)	½ B (p.u.)	Tap
1	2	0.01938	0.05917	0.0264	1
1	5	0.05403	0.22304	0.0219	1
3	2	0.04699	0.19797	0.0187	1
2	4	0.05811	0.17632	0.0246	1
2	5	0.05695	0.17388	0.017	1
4	3	0.06701	0.17103	0.0173	1
4	5	0.01335	0.04211	0.0064	1
4	7	0	0.20912	0	0.978
4	9	0	0.55618	0	0.969
6	5	0	0.25202	0	0.932
6	11	0.09498	0.1989	0	1
6	12	0.12291	0.25581	0	1
6	13	0.06615	0.13027	0	1
7	8	0	0.17615	0	1
7	9	0	0.11001	0	1
9	10	0.03181	0.0845	0	1
9	14	0.12711	0.27038	0	1
10	11	0.08205	0.19207	0	1
12	13	0.22092	0.19988	0	1
13	14	0.17093	0.34802	0	1

APPENDIX B

Bus Data for IEEE 14 Bus System

Bus No.	Bus Code	V (p.u.)	P (MW)	Q (MVAR)	LOAD (MW)	LOAD (MVAR)	$Q_{min.}$ (MVAR)	$Q_{max.}$ (MVAR)
1	1	1.06	0	0	0	0	0	0
2	2	1.045	40	42.4	21.7	12.7	-40	50
3	2	1.01	0	23.4	94.2	19	0	40
4	0	1	0	0	47.8	-3.9	0	0
5	0	1	0	0	7.6	1.6	0	0
6	2	1.07	0	12.2	11.2	7.5	-6	24
7	0	1	0	0	0	0	0	0
8	2	1.09	0	17.4	0	0	-6	24
9	0	1	0	0	29.5	16.6	0	0
10	0	1	0	0	9	5.8	0	0
11	0	1	0	0	3.5	1.8	0	0
12	0	1	0	0	6.1	1.6	0	0
13	0	1	0	0	13.5	5.8	0	0
14	0	1	0	0	14.9	5	0	0