Optimal Selection and Location of FACTS Devices for Enhancement of Power Transfer Capability using Bee Algorithm

Author

Emmanuel Mugiira Kinoti

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DECLARATION

This thesis is my original work and has not been submitted to any other university for examination.

Signature:................................. Date:........................

Student name: Emmanuel Mugiira Kinoti

This thesis report has been submitted for examination with our approval as University supervisors.

Signature:... Date:................................

Prof. G. N. Nyakoe (Dean, School of Mechanical, Manufacturing and Materials Engineering, Jomo Kenyatta University of Agriculture and Technology)

Signature:... Date:................................

Dr. C. Maina Muriithi (Lecturer, Department of Electrical and Electronic Engineering, Jomo Kenyatta University of Agriculture and Technology)

DEDICATION

I dedicate this work to my ailing mother. I wish her quick recovery and may the Almighty God restore her health.

ACKNOWLEDGEMENT

First of all, I would like to wholeheartedly give my thanks to the Almighty God for giving me the strength and the ability to complete the thesis. I would like to express my appreciation to my supervisors Prof. G. N. Nyakoe and Dr. C. Maina Muriithi for their valuable contributions, help and suggestions during this research. My sincere thanks to the African Union Commission for giving me scholarship for the research.

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LIST OF ABBREVIATIONS AND ACRONYMS

AI	Artificial Intelligence
BA	Bee Algorithm
BSA	Bacteria swarming algorithm
CPSO	Combinatorial Particle swarm optimization
DE	Differential Evolution
ECTs	Evolutionary control techniques
EED	Environment/economic dispatch
ELD	Economic Load Dispatch
ES	Evolution strategies
EPSO	Evolution particle swarm optimization
FACTS	Flexible Alternating Current Transmission System
GA	Genetic Algorithm
HVDC	High-Voltage Direct current
IPFC	Interline power flow controller
LP	Linear programming
MIP	Mixed Integer programming
NLP	Non Linear programming
NPSO	Neighborhood search assisted particle swarm optimization
NSGA	Non-dominated sorting genetic algorithm
PSO	Particle swarm optimization

SBM	Sensitivity based method
OBM	Optimization based Method
OPF	Optimal power flow
SSSC	Static synchronous series compensator
SVC	Static Var Compensator
SA	Simulated annealing
SOA	Swarm based optimization Algorithm
TS	Tabu search
TCSC	Thyristor Controlled Series Capacitor
UPFC	Unified Power Flow Controller

LIST OF SYMBOLS

α	Firing angle (radian) of the thyristor.
σ	Conduction angle (radian) of the thyristor.
θ_{ij}	Angle (degree) of the ij^{th} element in bus admittance matrix with TCSC.
∂_i, ∂_j	Voltage angle (degree) of bus i and bus j.
X_C	Capacitive reactance (farad).
X_L	Inductive reactance (henry).
V_i, V_j	Voltage magnitude (volt) at the buses i and j.
$P_{ij,}Q_{ij}$	Real power (Mw) and reactive power (Mvar) injections in line.
PG_i	Real power (Mw) generation at bus i
QG_i	Reactive power (Mvar) generation at bus i.
PD_i	Real loads (Mw) at bus i
QD_i	Reactive loads (Mvar) at bus i.
Q_{SVC}	Reactive power (Mvar) injected by SVC.
P_{Ui}	Injected real power (Mw) of UPFC at bus i
Q_{Ui}	Injected reactive power (Mvar) of UPFC at bus i.
r_{ij}, X_{ij}	Resistance (ohms) and reactance (ohms) of the line connected between the buses i and j.
$Y_{ij} X_s$	Magnitude of the ij^{th} element in bus admittance matrix with TCSC

ABSTRACT

Flexible Alternating Current Transmission System (FACTS) devices are solid state converters that have the capability of controlling various electrical parameters such as reactance, power angle and voltage in a power system. Optimal selection and location of FACTS devices play a vital role in improving the static and dynamic performance of the power system. However, finding the suitable location and selection of FACTS devices simultaneously is a complex and challenging task. There are several Artificial Intelligent (AI) approaches proposed concerning the location and selection of FACTS devices. A number of research works have been undertaken aimed at achieving optimal location and selection of FACTS devices based on different methods. Recent researches on multi-dimensional and non-linear engineering optimization problems are using a relatively new AI method known as Bee Algorithm (BA). Its performance, efficiency, precision, and speed of convergence in optimization has demonstrated its superiority compared to other AI methods.

In this thesis, the Bee Algorithm was used to develop a model for optimizing FACTS devices location and selection. The sensitivity of the system loading capability, corresponding to the active and reactive power balance equations was used to determine optimal location and selection of FACTS devices. The effectiveness of the model was tested by simulating on the IEEE 9 and 30-bus test systems operated under normal and contingency conditions using MATLAB®.

The resulting optimization model has shown improvement of the solutions of optimal location and selection of FACTS devices by increasing power transfer capability of power system network in comparison with other AI techniques.

CHAPTER 1

INTRODUCTION

1.1 Background

Long distance bulk power transfers are essential for an economic and secure supply of electric power. System transfer capability indicates how much inter-area power transfers can be increased without compromising system security. The concept of using solid state power electronic converters for power flow control at the transmission level has been known as Flexible Alternating Current Transmission Systems (FACTS). FACTS devices are solid state converters that have the capability of controlling various electrical parameters such as reactance, power angle and voltage in transmission networks. According to IEEE [1], FACTS is defined as follows:

Alternating current transmission systems incorporating power electronics based and other static controllers to enhance controllability and power transfer capability.

Power system security, congestion control and power quality are major concepts that draw the attention of power engineers. In a day to day operation, it may be beyond the operator scope to take preventive control during emergencies. However, the operator can use FACTS devices to control the system during various conditions [2]. In recent years, with the deregulation of the electricity market, the initial concepts and practices of power systems have been shifting. Better utilization of the existing transmission lines to enhance power transfer capability by installing FACTS devices has become common. This technology opens up new opportunities for controlling line power flows, minimizing losses, damping the oscillations, increasing the system stability, sensitivity and maintaining bus voltages at desired level in a power system. These are achieved by controlling one or more of the system parameters such as series impedance, shunt admittance, voltage at a bus and phase angle with the selection and insertion of appropriate FACTS controllers in a power system network [2]. Accurate identification of this capability provides vital information for both planning and operation of the bulk power system. Repeated estimates of transfer capabilities are needed to ensure that the combined effects of power transfers do not cause an undue risk of system overloads, equipment damage, or blackouts. However, an overly conservative estimate of transfer capability unnecessarily limits the power transfers and is a costly and inefficient use of the network. Power transfers are increasing both in amount and in variety as deregulation proceeds. Indeed, such power transfers are necessary for a competitive market for electric power. The practical computations of transfer capability are evolving. The computations presently being implemented are usually oversimplified and in many cases do not take sufficient account of effects such as interactions between power transfers, loop flows, nonlinearities, new FACTS technologies operating principles and voltage collapse blackouts [2].

The goal of the method described here is to improve the accuracy and realism of transfer capability computations. The power system must be operated with some conservatism to account for the effects of uncertainty in power system data. This uncertainty can be analyzed and quantified to provide a defensible basis for the conservatism. The limitations on power system performance that we consider in this thesis are transmission line flow limits, voltage magnitudes and voltage collapse. All these limits can be handled in an AC load flow power system model incorporating FACTS devices.

The FACTS devices allows the system operator to control the load flows as desired and has the capacity to improve line transfer capability up to certain limits. These devices may also be used in voltage control due to their ability to change the apparent impedance of a transmission line. Ability of FACTS devices to change some system parameters is believed to be one of key solutions to load flow problems within a power system network. However, finding the suitable placement, choice and sizing of FACTS is a complex and challenging task. The allocation of several FACTS devices in a transmission network can result in adverse interactions between them, a question of great importance that makes the optimal location of FACTS a critical area. Optimal placement is one of the most popular and main researches on these devices with aim of obtaining maximum benefits from them.

FACTS-devices provide a better adaptation to changing operational conditions and improve the usage of existing transmission lines in terms of loading capacity. The increasing system load makes the existing power system incapable of carrying sufficient power over long distances and rerouting within the network. The difficulties of obtaining new rights of way, as well as environmental protection requirements, constrain the building of new lines. One of the main approaches to meet the transmission requirements is to improve the usage and capacity of existing transmission lines. The improving manufacturing technology for high power electronic apparatus is leading to lower prices, which make FACTS a feasible solution for renovating existing grids. Rapid development in computation and control techniques, as well as the widespread use of computers, opens the way to FACTS implementation for fast, flexible, and secure control action.

The FACTS devices enable the transmission system to obtain one or more of the following general benefits [3]:

- Control of power flow. This is the main function of FACTS devices. The use of power flow control may be to meet the utilities' own needs, ensure optimum power flow during contingency conditions.

- Reduction of generation cost. One of the principal reasons for transmission interconnections is to utilize the lowest cost of generation. When this cannot be achieved, it follows that there is not enough cost-effective transmission and generation capacity.

- Dynamic stability enhancement. This FACTS peripheral function includes the transient stability improvement, power oscillation damping and voltage stability control.

- Increase in loading capability of lines to their thermal capabilities both in short term and long term demands.

- Provide secure tie-line connections to neighboring and regional utilities thereby decreasing overall generation reserve capacity on both sides.

1.2 Statement of the problem

Power system networks are being pushed to their operation limits as a consequence of increase in load demand on power system network due to increase in population and substantial industrial growth for the last few years. Therefore, it has been a complex task to operate the power system efficiently because the modern electrical system should compensate for the continually changing load demand and provide reliable energy of a high quality.

Notably, expansion of the existing transmission network has several limitations like environmental restrictions and limited resources. Due to these constraints, existing transmission lines are being abnormally loaded under varying operating conditions. For better utilization of available or present transmission lines without violating thermal limits, optimal selection and location of flexible AC transmission systems (FACTS) devices within the power system network needs to be addressed. With the help of optimal location and selection of multiple FACTS devices, we can easily control various parameters of transmission line such as line impedance, terminal voltage, and voltage angles under different operating conditions to enhance loadability of transmission lines in a power system network. However, finding the optimal placement, type and size of FACTS devices simultaneously is a complex and challenging task which needs to be addressed by a relatively new technique known as Bee Algorithm which is superior compared to other AI techniques.

1.3 Objectives

1.3.1 Main Objective

The main objective of this research is to enhance power transfer capability in an interconnected power network using the Bee Algorithm model for optimal location and selection of FACTS devices.

1.3.2 Specific Objectives

(i) To develop a Bee Algorithm model for optimal location and selection of FACTS devices.

(ii) To determine optimal location of different devices using the model under IEEE-9 and 30-bus test system.

(iii) To evaluate the power transfer capability of the system using the developed BA model and evaluate results with those of standard GA model.

1.4 Justification

Simultaneous optimization of the location and selection of the FACTS devices is a very complex and multi-dimensional problem in large interconnected power systems. The proposed BA algorithm is suitable for finding possible solution involving more than one parameters simultaneously by utilizing fewer control parameters compared to other AI methods. It always produces higher quality and precise solutions and it is faster compared to other AI methods in problems involving large power system. Furthermore, this algorithm is simple, robust, flexible and easy to implement in large and complex power systems.

1.5 Scope of Research

i. Development of a Bee algorithm model using C language and simulation in MATLAB platform to find the optimal location and best choice for the FACTS device.

ii. Simulations performed on IEEE 9 and 30 bus test system to test the effectiveness of the method and results will be evaluated using standard Genetic algorithm configured for the same.

1.6 Contributions of the Research

The thesis has made several contributions as described in the following:

(i) The incorporation of steady state model of three emerging types of FACTS devices namely; TCSC, SVC and UPFC in order to run the power flow studies of these devices was done successfully. The models have been used for steady state studies of FACTS devices in power system network.

(ii) The development of FACTS devices optimization method using BA for power transfer enhancement. The algorithm simultaneously searches the FACTS location, FACTS parameters and FACTS types for solving one or more nonlinear, multi-objective optimization problem. The algorithm addresses problem suffered by analytical methods such as slow convergence and the problem of dimensionality when solving complex optimization problems. The algorithm was developed based on two kinds of simulations: for single type of FACTS devices optimization and multi-type FACTS devices optimization. For single type, only one kind of FACTS devices was selected for optimization while for multi-type FACTS devices, all three types of FACTS devices were used simultaneously for optimization. The algorithm also identifies the optimal number of FACTS devices to be installed in the system.

(iii) The integration and modification of equations for setting the BA parameters used for simulation purposes based on several testing on a variety of IEEE test bus system. The equations are implemented in the algorithm and the parameters for simulations using BA calculated accordingly based on the number of lines and number of FACTS devices that are installed in the system. Hence, the developed program can be used to run any power system network as long as the main two items are known; i.e. number of lines in the system and number of FACTS devices that are to be installed in the system.

1.7 Thesis Outline

A brief description of the problem to be solved, proposed approach, and main contributions of this research are described in this chapter. The rest of the thesis is divided into four parts:

- Chapter 2 provides a literature survey on essential topics of this research. It starts with a general overview of techniques for solving FACTS devices optimization problems, Bee algorithm overview, FACTS devices modeling followed by BA application in power system optimization and specific methods to solve the problem of optimal location and selection of FACTS devices in the power network.

- Chapter 3 focuses on the methodology. The Bee algorithm and model development are adequately addressed.
- Chapter 4 Analyses, discuses and compares the results of the BA and GA optimization techniques and demonstrates the superior performance of the proposed bee algorithm.
- Chapter 5 highlights conclusions and recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Types of FACTS devices.

FACTS devices can be divided into four categories [1]:

- Series FACTS devices. Series FACTS devices could be variable impedance, such as capacitor, reactor, etc., or power electronics based variable source of main frequency, sub synchronous and harmonic frequencies or a combination to serve the desired need. In principle, all series FACTS devices inject voltage in series with the transmission line.
- Shunt FACTS devices. Shunt devices may be variable impedance, variable source, or a combination of these. They inject current into the system at the point of connection.
- Combined series-series FACTS device. It is a combination of separate series FACTS devices, which are controlled in a series coordinated manner.
- Combined series-shunt FACTS device. Combined series-shunt FACTS device is a combination of separate shunt and series devices, which are controlled in a coordinated manner or one device with series and shunt elements.

There are various applications of FACTS controllers/devices in restructured multi-machine power systems to enhance power system performance. One of the greatest advantages of utilizing FACTS controllers in power system is that, FACTS controller can be used in three states of the power system namely steady state, transient and post-transient steady state. However, the conventional devices find little application during system transient or contingency conditions. Various steady state applications of FACTS controllers include: Power flow balancing and control, Available Transfer Capability (ATC) improvement, loading margin improvement, congestion management, Reactive Power and Voltage Control. Various Dynamic applications of FACTS controllers include: Dynamic Voltage Control, Oscillation Damping, Transient Stability Enhancement, Sub synchronous Resonance (SSR) Elimination, and Power Systems Interconnection. The development of FACTS-devices started with the growing capabilities of power electronic components. Devices for high power levels have been made available in converters for voltage levels. The overall starting points are network elements influencing the reactive power the parameters of power system. Fig 2.1 shows a number of basic devices separated into the conventional ones and the FACTS-devices.

2.2 FACTS devices modeling

The development of FACTS devices started with the growing capabilities of power electronic components. Devices for high power levels have been made available in converters for high and even highest voltage levels. Flexible AC transmission systems (FACTS) devices are installed in power systems to increase the power flow transfer capability of the transmission systems, to enhance continuous control over the voltage profile and/or to damp power system oscillations [3]. The ability to control power rapidly can increase stability margins as well as minimize losses. Transmission efficiency is greatly improved by a device that varies parameters (reactance, power angle and voltage) of the line, thus allowing power to be transmitted with acceptable losses.

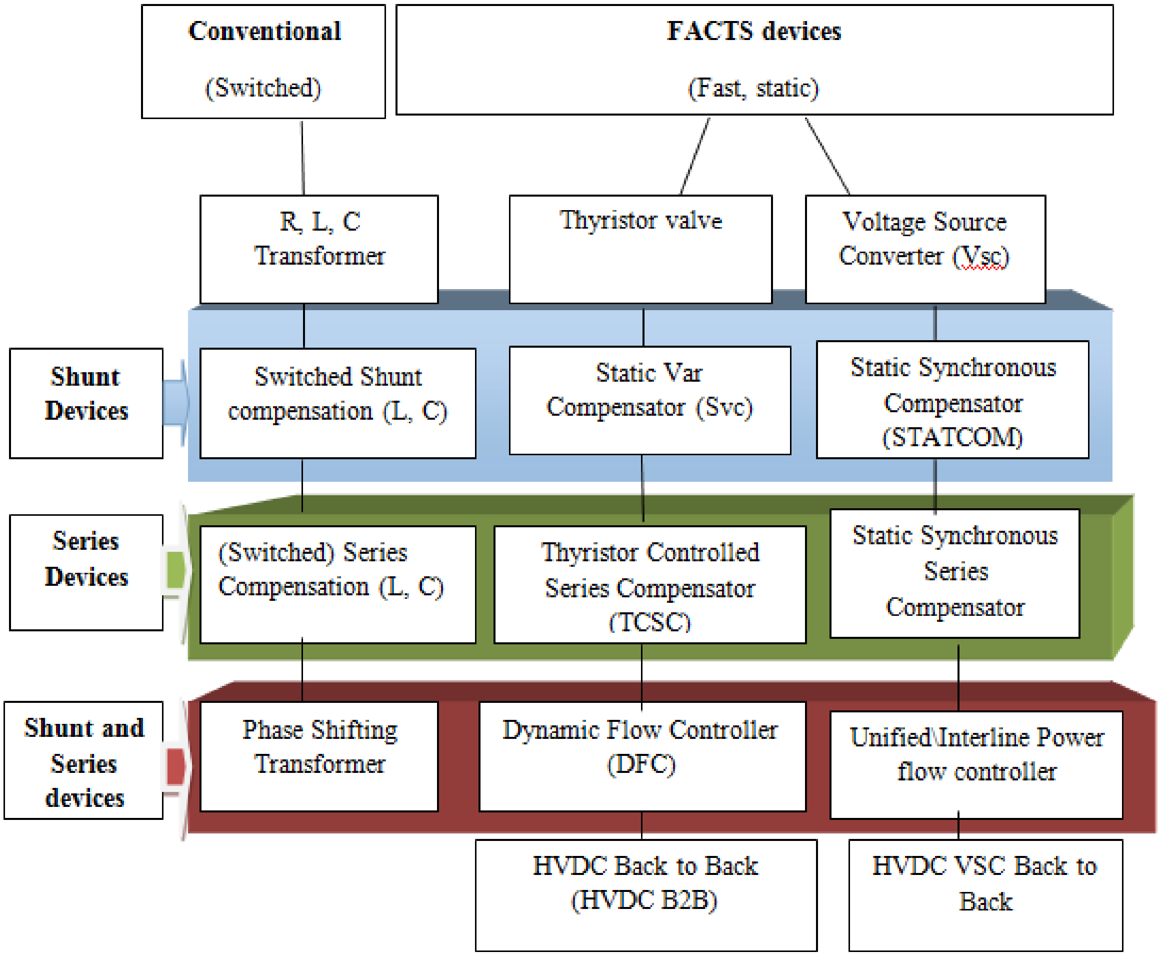

Fig 2.1 FACTS devices Classification.

2.2.1 Modeling of Static Var Compensator

Electrical load both generates and absorbs reactive power. Since the transmitted power varies considerably from one time to another, the reactive power balance in a power grid varies as well. This can result to unacceptable voltage variations or at the extreme, a voltage collapse. A rapidly operating Static Var Compensator (SVC) can continuously provide the reactive power required to control dynamic voltage oscillations under various system operating conditions and thereby improve the power system transmission capability [4]. Installing an SVC at one or more suitable points in the network can increase transfer capability and reduce losses while maintaining a smooth voltage profile under different network operating conditions. In addition an SVC can put in check active power oscillations through voltage amplitude modulation. In order to improve the total transfer capability and to minimize the transmission loss by using SVC, the static model of the SVC as shown in Fig 2.2 has been considered.

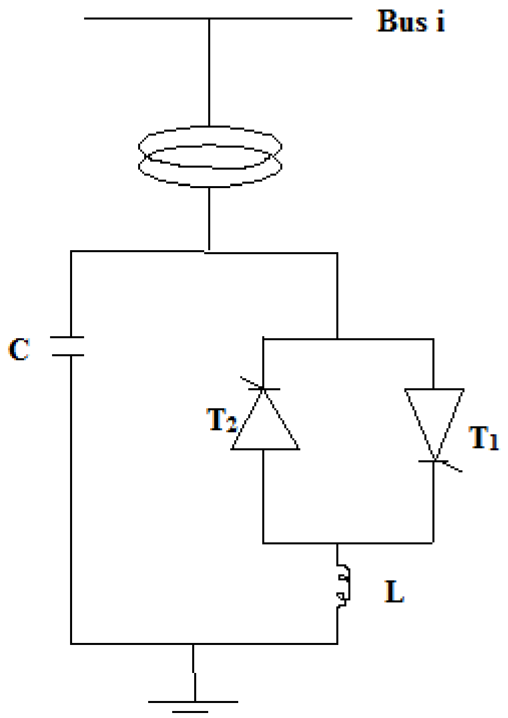

Fig 2.2 Basic SVC topology

The SVC consists of a fixed capacitor and a Thyristor controlled reactor (TCR) connected in parallel. SVC is connected in shunt with the bus. SVC is modeled as a reactive power source added or connected at the bus. In practice the SVC can be seen as an adjustable reactance that can perform both inductive and capacitive compensation. A shunt- connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage).

This is a general term for a Thyristor Controlled Reactor (TCR) or Thyristor Switched Reactor (TSR) and/or Thyristor Switched Capacitor (TSC). The term, "SVC" has been used for shunt connected compensators, which are based on Thyristor without gate turn-off capability. It includes separate equipment for leading and lagging Vars. The thyristor –controlled or switched reactor for absorbing reactive power and thyristor – switched capacitor for supplying the reactive power. SVC can be used for both inductive and capacitive compensation. In this work, the SVC is modeled as an ideal reactive injection at bus i. Fig 2.3 represents susceptance model of an SVC.

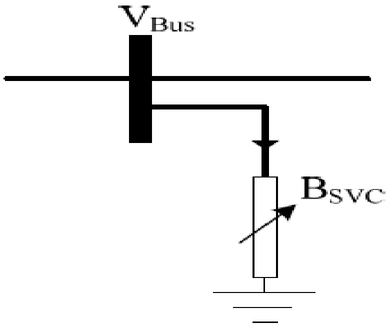

Fig 2.3 Variable Susceptance Model of SVC

$$\Delta Q_i = Q_{SVC} \qquad [2.1]$$

The equivalent reactance of TCR at the fundamental frequency X_L is given as

$$X_{TCR} = \frac{\pi X_L}{2(\pi - \alpha) + \sin 2\alpha} \qquad [2.2]$$

Where,

$$X_L = \omega L \qquad [2.3]$$

α : Firing angle of the thyristor

σ : Conduction angle of the thyristor.

At $\alpha = 90^\circ$, TCR conducts fully and the equivalent reactance, $X_{TCR} = X_L$ .When $\alpha = 180^\circ$,TCR is blocked and its equivalent reactance becomes infinite. The equivalent reactance of SVC at the fundamental frequency X_{SVC} is the parallel combination of capacitive reactance in terms of delay angle, α is given by Equation 2.4.

$$X_{SVC} = \frac{\pi X_C X_L}{X_C\left[2(\pi-\alpha)+\sin 2\alpha\right]-\pi X_L} \qquad [2.4]$$

The equivalent susceptance of SVC at the fundamental frequency is given by Equation 2.5.

$$B_{svc} = \frac{X_L - \frac{X_C}{\pi}\left(2(\pi-\alpha)+\sin(2\alpha)\right)}{X_C X_L} \qquad [2.5]$$

The equivalent reactive power injected or absorbed by SVC is given by Equation 2.6 and 2.7.

$$Q_i^{SVC} = -V_i B_{SVC} \qquad [2.6]$$

$$Q_{sh} = -V_i^2 b_{sh} - V_i V_{sh}(\sin(\theta_i - \theta_{sh}) - b_{sh}\cos(\theta_i - \theta_{sh}) \qquad [2.7]$$

A changing susceptance B_{SVC} model represents the fundamental frequency equivalent of all shunt models making up the SVC. This model is an improved version of SVC models. This is giving the shunt compensation for the system. The SVC acts as an unregulated voltage compensator whose production or absorption reactive power capabilities will be a function of the nodal voltage at the SVC point of connection to maintain the voltage profile. Fig 2.4 shows voltage and current characteristics when SVC is capacitive and inductive.

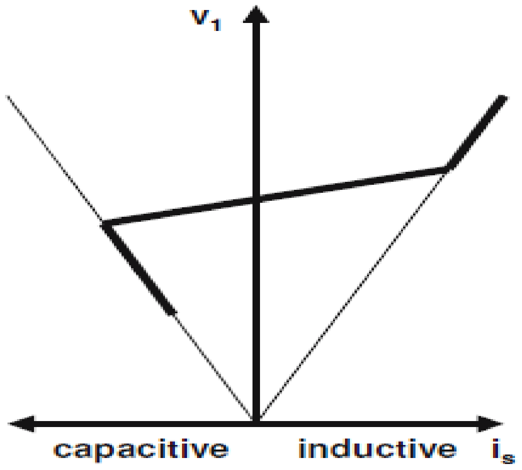

Fig 2.4 Voltage/current characteristics.

2.2.2 Modeling of Thyristor Controlled Series Compensator.

The static model of TCSC as shown in Fig 2.5 has been considered in this work.

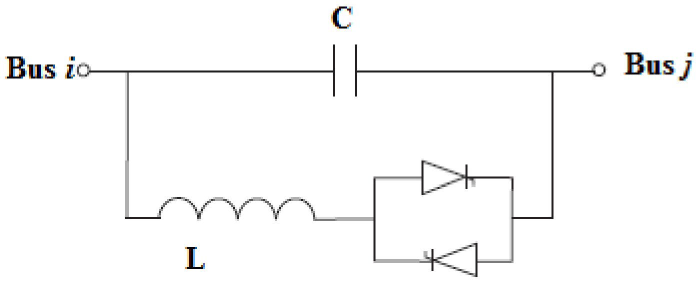

Fig 2.5 Basic TCSC topology

TCSC has been modeled as a variable reactance inserted in the transmission line connecting buses [5]. TCSC may have one of the two possible characteristics, capacitive or inductive to decrease or increase the impedance of the branch respectively. The TCSC consists of a capacitor bank and a thyristor controlled reactor (TCR) connected in parallel and it is connected in series with the transmission line as shown in Fig 2.6. The effect of the TCSC on a network can be seen as a controllable reactance inserted in a transmission line. The equivalent reactance of TCSC at the fundamental frequency is the parallel combination of capacitive reactance and is given by the following equation.

$$X_{TCSC} = \frac{X_C X_L}{\frac{X_C}{\pi}\left[2\left(\pi - \alpha\right) + \sin 2\alpha\right] - X_L} \qquad [2.8]$$

where,

X_{TCSC} Value is a function of the transmission line reactance X_{ij} , where the device is located. It is in the range of $-0.7X_{ij} \le X_{TCSC} \ge 0.2X_{ij}$ to regulate compensation of the transmission line.

$$X_{ij} = X_{line} + X_{TCSC} \qquad [2.9]$$

$$X_{TCSC} = r_{tcsc} \times X_{line} \qquad [2.10]$$

Fig 2.6 TCSC located in a transmission line.

The power flow equations with TCSC is given by,

$$P_{ij} = V_i^2 g_{ij} - V_i V_j \left(g_{ij}\cos\left(\delta_i - \delta_j\right) + b_{ij}\sin\left(\delta_i - \delta_j\right)\right) \qquad [2.11]$$

$$Q_{ij} = V_i^2 b_{ij} - V_i V_j \left(g_{ij} \sin\left(\delta_i - \delta_j\right) - b_{ij} \cos\left(\delta_i - \delta_j\right)\right) \qquad [2.12]$$

where,

$$g_{ij} = \frac{r_{ij}}{r_{ij}^2 + (X_{ij} + X_{TCSC})^2} \qquad [2.13]$$

$$b_{ij} = -\frac{X_{ij} + X_{TCSC}}{r_{ij}^2 + (X_{ij} + X_{TCSC})^2} \qquad [2.14]$$

X_C, X_L : Inductive and capacitive reactance.

V_i, V_j : Voltage magnitude at the buses i and j.

$P_{ij,} Q_{ij}$: Real and reactive power injections in line.

r_{ij}, X_{ij} : Resistance and reactance of the line connected between the buses i and j.

g_{ij}, b_{ij} : Conductance and susceptance of the line connected between buses i and j.

2.2.3 Modeling of Unified Power Flow Controller

UPFC can be represented in the steady-state by two voltage sources representing fundamental components of output voltage waveforms of the two converters and impedances being leakage reactance of the two coupling transformers [6]. The static model of UPFC as shown in Fig 2.7 has been considered in this work

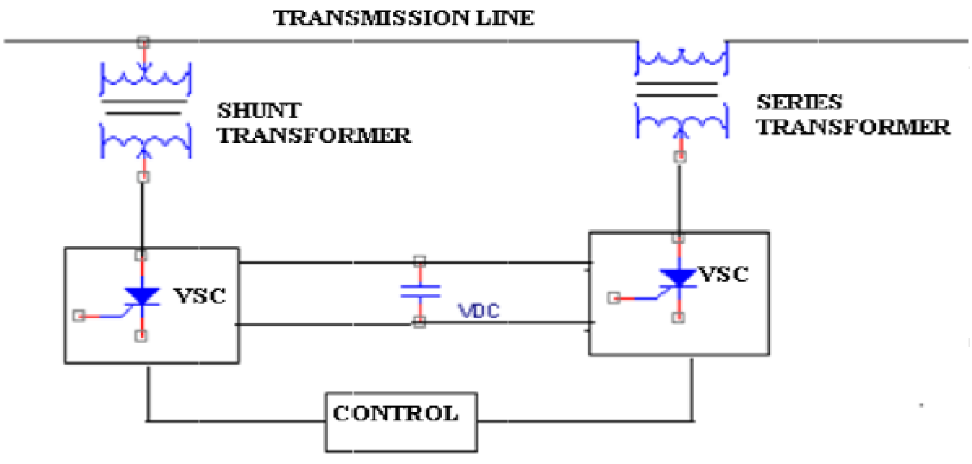

Fig 2.7 Two voltage source model of UPFC.

The UPFC is a device which can control all three parameters of line power flow (line impedance, voltage and phase angle) simultaneously. It is a one of the FACTS family that is used for optimum power flow in transmission. The UPFC is presented as a combination of SVC and TCSC as shown in Fig 2.8. Both converters are operated from a common dc link with a dc storage capacitor. The real power can freely flow in either direction between the two branches. Each converter can independently generate or absorb reactive power at the output terminals. The controller provides the gating signals to the converter valves to provide the desired series voltages and simultaneously drawing the necessary shunt currents. In order to provide the required series injected voltage, the inverter requires a dc source with regenerative capabilities. The possible solution is to use the shunt inverter to support the dc bus voltage. The function of converter1 is to supply or absorb the real power demanded by converter 2 at the common dc link. The power of the dc link is converted back to ac and coupled to the transmission line via a shunt-connected transformer. If reactive power is required then inverter 1 can also generate or absorb controllable reactive power, so it can provide independent shunt reactive compensation for the line.

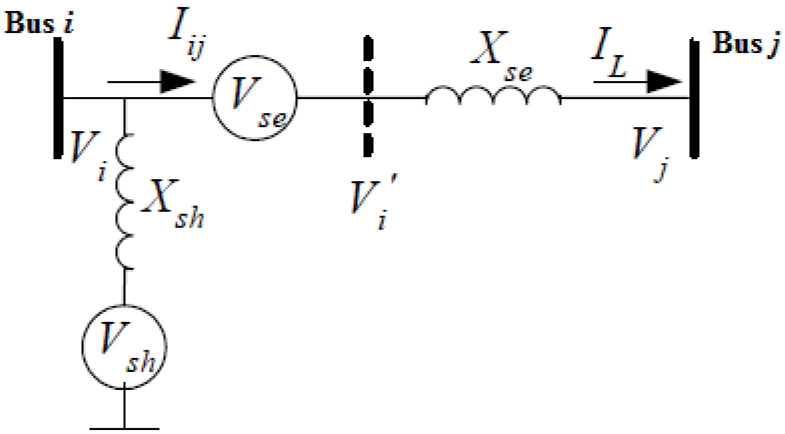

Fig 2.8 UPFC power injection model.

In UPFC, the shunt branch is used mainly to provide both the real power, P_{series} which is injected to the system through the series branch, and the total losses within the UPFC.

The power flow equations with UPFC is given by,

$$P_{ij} = V_i^2 b_{ij} - V_i V_j \left(g_{ij} \sin\theta_{ij} - b_{ij} \cos\theta_{ij} \right) - V_i V_{se} \left(g_{ij} \sin\left(\theta_i - \theta_{se}\right) - b_{ij} \cos\left(\theta_i - \theta_{se}\right)\right) \quad [2.15]$$

$$Q_{ij} = V_i^2 b_{ij} - V_i V_j \left(g_{ij} \sin\theta_{ij} - b_{ij} \cos\theta_{ij} \right) - V_i V_{se} \left(g_{ij} \sin\left(\theta_i - \theta_{se}\right) - b_{ij} \cos\left(\theta_i - \theta_{se}\right)\right) \quad [2.16]$$

The above novel and complete steady state models for the SVC, TCSC, and UPFC can be directly implemented in any software package that has some external programming capabilities, or can be readily integrated in any power flow programs. It should be noted that the models are independent of the type of control used in any of these FACTS devices.

The proposed models include and properly represent the alternating current power flow so that operating and control limits can be properly represented in these models. The models can be used in balanced and fundamental frequency studies of power system, such as steady state, small signal and voltage stability analysis.

The electric power grid is the largest man-made interconnected network in the world. It consists of synchronous generators, transformers, transmission lines, switches, relays and compensators. Various control objectives, operation actions in such a system require solving an optimization problem. For such a nonlinear non-stationary system with possible uncertainties, as well as various operational constraints, the solution to the optimization problem is by no means trivial. Moreover, the following issues need attention. An appropriate optimization technique has to be selected that suits the nature of the power transfer problem best. All the system constraints and FACTS devices parameters should be perfectly addressed, and a comprehensive yet not too complicated objective function should be defined and formulated [7].

2.3 Methods for Solving Complex Optimization Problems

In general, for a simple case where the possible decisions can be parameterized by finite-dimensional vectors and the quality of these decisions can be characterized by a finite set of computation criteria, the solution of the Kuhn- Tucker system of equations and inequalities provides all optimal solutions to a nonlinear and complex problem. However, to solve this system in an analytical fashion is not always possible, so that numerical routines (algorithms that numerically approximate the solutions of the problem) are vital [8].

From this point of view, the methods are divided into:

- Zero-order routines using only values of the objective function and the constraints and not using their derivatives.

- First-order routines using the values and the gradients of the objective function and constraints.
- Second-order routines using the values, the gradients and the Hessians (i.e. matrices of the second order derivatives) of the objective function and the constraints.

In principle it could be possible to use higher order derivatives, however these are not used in practice because of the difficulties encountered in programming, computational time, and memory volume required [9]. In addition to nonlinear conditions, often some or all variables are constrained to take on integer values, and the technique is then referred to as mixed integer programming (MIP) or strictly integer programming (IP). MIP and IP problems are difficult to solve, in fact, no efficient general algorithm is known for their solution. There are three main categories of algorithms that can be applied to this type of problem [10]:

- Exact algorithms that are guaranteed to find an optimal solution but may take an exponential number of iterations,
- Approximation algorithms that provide in polynomial time a suboptimal solution.
- Heuristic algorithms that provide a suboptimal solution relatively fast, but without a guarantee on its quality.

While deterministic optimization problems are formulated with known parameters, real world problems almost invariably include some unknown and vague parameters. This necessitates the introduction of stochastic programming models that incorporate the probability distribution functions of various different variables into the problem formulation. In its most general case, the method is referred to as DP. Although the method has been mathematically proven to find an optimal solution, it has its own disadvantages. Solving the DP algorithm in most of the cases is not feasible. Even a numerical solution requires overwhelming computational effort, which increases exponentially as the size of the problem increases (dimensionality problem). These restrictive conditions lead the solution to a sub-optimal control scheme with limitation of moving ahead [11]. The complexity level is even further exacerbated when moving from finite horizon to infinite horizon problems, while also considering the probabilistic effects and model imperfections.

Computational intelligence based techniques can be solutions to the above problems. Computational intelligence combines elements of learning, adaptation, and natural evolution to create methods that are intelligent [12]. BA is a relatively new subset of computational intelligence, and generic population based metaheuristic algorithm for global optimization applications [13]. Candidate solutions to the optimization problem play the role of individuals in a population, and the objective function determines the environment where the solutions exist. Evolution of the population then takes place after the repeated application of operators for social communication and cultural learning for those methods based on swarm intelligence [14]. Evolutionary computation algorithms are not largely affected by the size and nonlinearity of the problem, and they can perform well in highly constrained and integer optimization problems.

2.4 Current Trends on FACTS Devices Optimization.

Optimal location of FACTS devices, when considering the installation in transmission grids, is of extreme importance. Since 1990s, researchers have investigated the effects of FACTS devices in the power system under various operating conditions. Steady state performance as well as dynamic and transient stability have been key focus areas of study. The problem of optimal location and selection of FACTS devices, considering technical criteria and cost functions, is still in a relatively early stage of research. Frequently, only technical criteria have been considered and the solutions found are not proven to be the global optimum.

In [15], optimal location of given phase shifter in the French network is carried out via MILP in order to reduce the flow in the heavily loaded lines and to reduce cost of production. In [16], the authors provide an idea regarding the optimal locations of FACTS devices, considering the cost of FACTS device, system loadability and their impact on the generation cost. In [17], Genetic Algorithm (GA) was used to optimally locate a given number of phase shifters. The behavior of the phase shifters is studied on the influence they have on one another. This model was successfully applied to a study network and to the French power system network. The optimization was made in order to find the most economical generation pattern by taking advantage of phase shifters optimal placement.

An optimal location of multi-type FACTS devices is presented in [18]. The authors based their study on a Genetic Algorithm method to perform the optimization based on three parameters: location, type and size. Simulations were made on IEEE 118 bus test system, where the system loadability was applied as a measure of system performance. Results revealed that a multi-type FACTS devices approach was a better solution than the single-type device.

In [19], a simple and efficient model for the optimal location of FACTS devices for congestion management is presented. A sensitivity-based approach was developed where the choice to allocate the devices was based on the reduction of the cost associated with congestion. The success of the proposed method was demonstrated by using an IEEE 5-bus test system.

Particle Swarm Optimization (PSO) is also a very popular algorithm used to allocate FACTS devices [20]. It is used in to optimally allocate FACTS devices with the objective of achieving maximum system load ability and minimum cost of installation. Simulations performed on IEEE 6 and 30-test bus systems were successfully done for single and multi-type FACTS devices using PSO.A hybrid meta-heuristic method is proposed in [21] to allocate FACTS devices. The method combines TS with Evolutionary Particle Swarm Optimization (EPSO). It determines the optimal allocation of devices with TS and evaluates the output variables of the devices with EPSO. This technique was successfully applied to the IEEE 30- bus test system. The method was also compared with a TS-PSO strategy giving consistently and better results.

In [22], the Static Var Compensator (SVC) and Thyristor Controlled Series Capacitor (TCSC) based FACTS device are employed to minimize the losses and power flow in long distance transmission line. The problem of determining the optimal SVC and TCSC parameters is formulated as an optimization problem. A steady state mathematical model for the SVC and TCSC can be controlled to satisfy simultaneously power flow regulation through a transmission line and minimization of power losses without generation rescheduling. In [23], the Combined Evolutionary Algorithm (CEA) was presented to find the optimal location and optimal capacity of UPFC. The method aided in the improvement of reactive power to meet the voltage stability improvements requirements.

In [24], the application of Bacterial Foraging Algorithm to find optimal location of Flexible AC Transmission System (FACTS) devices to achieve voltage stability improvement in power system with minimum cost of installation of FACTS devices is presented. While finding the optimal location, thermal limit for the lines and voltage limit for the buses are taken as constraints. Comparison between UPFC, SVC, TCSC, and SSSC for power system stability enhancement under large disturbance for inter-area power system demonstrates a considerable improvement in the system performance. In [25] , a genetic algorithm based optimal power flow is proposed for optimal location and rating of the UPFC in power systems and also simultaneous determination of the active power generation for different loading condition is studied. The UPFC is employed to evaluate the power system performance verifying that by using UPFC the power flow in transmission lines is improved, the voltage magnitudes are increased and also the real power losses in the system are minimized. In [26], the study investigated the transient characteristic of STATCOM, and summarized the switch strategy of internal and external fault based on two generating station. The simulation result shows that STATCOM can damp power oscillation efficiently, and different switch modes result different effect especially when in internal fault. In [27], the study is aimed at utilizing FACTS devices with the purpose of improving the operation of an electrical power system. Performance comparison of different FACTS controllers has been discussed. In addition, some of the utility experience and semiconductor technology development have been reviewed and summarized. Applications of FACTS to power system studies have also been discussed.

In [28], a model of the power system equipped with an SVC is systematically derived and the parameters of the SVC are modeled into the power flow equations and used in the control strategy, the SVC is modeled in a 5-bus system and a 30-bus system and implemented in Newton-Raphson load flow algorithm in order to control the voltage of the bus to which the SVC is connected to in a MATLAB platform, the contribution of the SVC to transient stability was tested and verified. In [29], the power system stability improvement of a multi-machine power system by various FACTS devices such as SVC and UPFC is analyzed for a two area system. The dynamics of the system is studied at the event of a major disturbance. Then the performance of the devices for power system stability improvement is compared. The simulation results demonstrate the effective and robustness of the proposed UPFC for transient stability improvement of the system for two area system. Transient stability, as an important issue in the study of power systems, is investigated. In [30], investigation on IPFC is done to determine a feasible solution for paired transmission lines. A line-to-ground fault is introduced and the response of the test system with and without IPFC is studied and found that the IPFC not only increase the transmission capacity but also improve the transient performance of the system. The small signal studies are carried out to investigate the performances of the IPFC and UPFC in [31]. Findings obtained indicate that the series branch has strong capability to change the low oscillation mode and further to change the small signal stability of the system. The comparison of UPFC and the IPFC performance, Since the IPFC has on more series branches than the UPFC provides greater damping improvement.

2.5 Bee Algorithm Overview

In social insect colonies, each individual seems to have its own role and yet the group as a whole appears to be highly organized and coordinated. The algorithms based on swarm intelligence and social insects begin to show their effectiveness and efficiency to solve complex and difficult optimization problems [32], [33]. In the real world, many optimization problems have to deal with the simultaneous optimization of two or more objectives. In some cases, however, these objectives are in contradiction with each other. While in single-objective optimization the optimal solution is usually clearly defined, this does not hold for multi-objective optimization problems. Instead of a single optimum, there is rather a set of alternative trade-offs, generally known as Pareto optimal solutions. These solutions are optimal in the wider sense that no other solutions in the search space are superior to them when all objectives are considered.

The BA is a swarm based, meta-heuristic algorithm based on the foraging behavior of honey bee colonies. BA algorithm is simple in concept, easy to implement, and has fewer control parameters. The artificial bee colony contains three groups: scouts, onlooker bees and employed bees. The bee carrying out random search is known as scout. The bee which is going to the food source which is visited by it previously is employed bee. The bee waiting on the dance area is an onlooker bee. The onlooker bee with scout also called unemployed bee .The BA has both local and global search capability utilizing exploitation and exploration strategies respectively. The performance of the BA is very sensitive to the control parameter choices. During initialization, it is ensured that all the artificial bees are within the feasible solution space, since randomly initialized artificial bees are not always confined to the feasible solution space. The BA parameters are the same for each swarm and for all simulation runs.

The BA uses the set of parameters given in Table 2.1.

Table 2.1: BA parameters description

Parameter	**symbol**
Number of individuals in a population	pn
Employed bees	$\frac{pn}{2}$
Onlookers bees	$\leq \frac{pn}{2}$
Number of iterations	Iter

2.5.1 Natural World of Bees

A colony of honey bees can exploit a large number of food sources in big fields and they can fly up to 11 km to exploit food sources [33]. The colony employs about a quarter of its members as forager bees. The foraging process begins with searching out promising flower patches by scout bees. The colony keeps a percentage of the scout bees during the harvesting season. When the scout bees have found a flower patch, they will look further in hope of finding an even better one. The scout bees search for the better patches randomly. The scout bees inform their peers waiting in the hive as to the quality of the food source, based amongst other things, on sugar levels. The scout bees deposit their nectar and go to the dance floor in front of the hive to communicate to the other bees by performing their dance, known as the waggle. The waggle dance is named based on the wagging run (in which the dancers produce a loud buzzing sound by moving their bodies from side to side), which is used by the scout bees to communicate information about the food source to the rest of the colony. The scout bees provide the following information by means of the waggle dance: the quality of the food source, the distance of the source from the hive and the direction of the source. Typically, Power system network is divided into two areas. Area 1 is a generator (hive/source) while area 2 is a load (nectar/sink) as indicated in Fig 2.9.

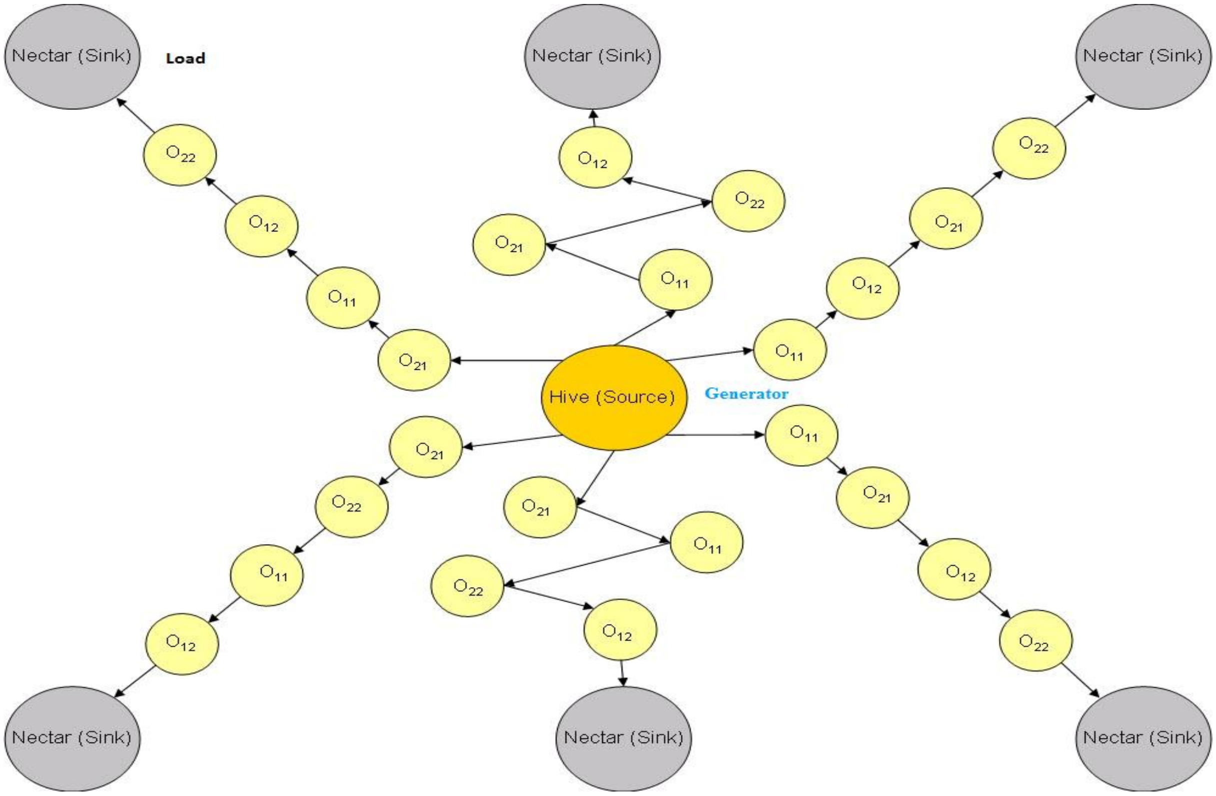

Fig 2.9 Bee Swarm Analogy

BA consists of four main phases:

Initialization phase:

The food sources are randomly generated. Each food source, represented by x_f is an input vector to the optimization problem. x_f has D variables and D is the dimension of searching space of the objective function to be optimized. The initial food sources are randomly generated via the expression below.

$$p_i = \frac{fit_i(x_i)}{\sum_{i=1}^{pn} fit_i(x_i)} \qquad [2.17]$$

Employed Bee Phase

Employed bees' flies to a food source and finds a new food source within the neighborhood of the food source. The higher quantity and quality is memorized by the employed bees. The food source information stored by employed will be shared with onlooker bees. A neighbor food source v_{ij} is determined and calculated by the equation below.

$$v_{ij} = x_{ij} + \phi_{ij}\left(x_{ij} - x_{ik}\right) \qquad [2.18]$$

Where i is a randomly selected parameter index, x_k is a randomly selected food source, ϕ_i is a random number within the range [-1, 1].The range of this parameter can make an appropriate an appropriate adjustment on specific issues. The fitness of food sources is essential in order to find the global optimal. The fitness is calculated by the equation below.

$$fit_i(x_i) = \begin{pmatrix} \frac{1}{1+f_i(x_i)},\ f_i\left(x_i\right) > 0 \\ 1+f_i(x_i),\ f_i(x_i) < 0 \end{pmatrix}. \qquad [2.19]$$

Where $f_i(x_i)$ is the objective function value of x_i .

Onlooker Bee phase:

Onlooker bees calculates the probability of food sources by observing the waggle dance in the dance area and then select a higher food source randomly. Fig 2.10 describes the Bees Algorithm.

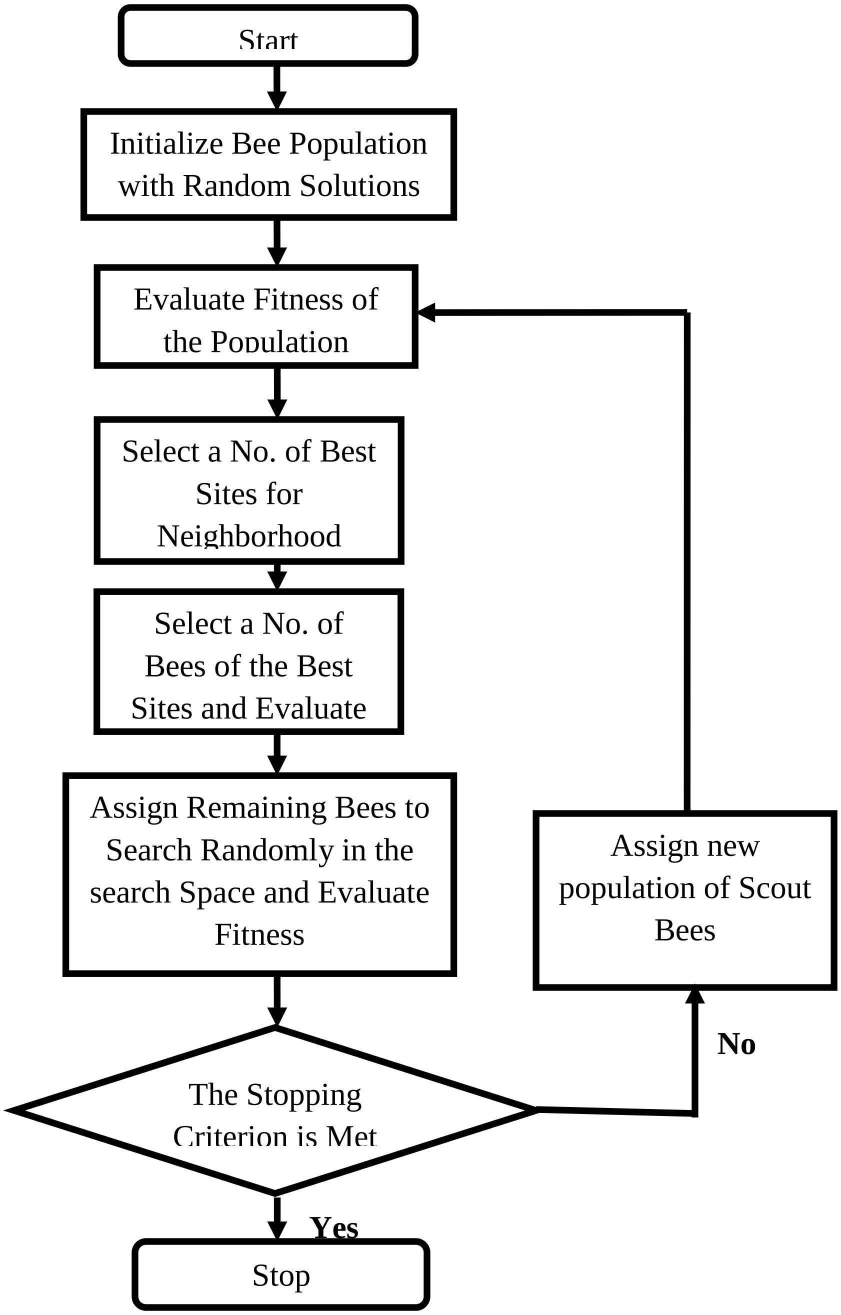

Fig 2.10 Flow chart of Bees Algorithm

Scout phase:

If the quality of food source cannot be improved and the times of unchanged are greater than the predetermined number of trials, the solutions will be abandoned by scout bees. Then, the new solutions are randomly searched by the scout bees.

2.5.2 Bee Algorithm Application in Power System Optimization

In power systems, many problems were addressed using this algorithm though not in sufficient numbers. Other artificial intelligence methods were applied to almost every field of power system but since the bees' algorithm is a comparatively newer member, it was not explored extensively in power system optimal modeling. Network configuration and reconfiguration of distributed power system applying BA was done quite successfully in [34]. In this work, the authors proposed artificial bee colony algorithm based technique to solve the network reconfiguration problem in a radial distribution system on 14, 33, and 119-bus systems and compared with different approaches. The main objectives were minimization of real power loss, voltage profile improvement and feeder load balancing subject to the radial network structure. The results on 14-bus were compared with Simulated Annealing (SA) and Differential Evolution (DE), for 33-bus compared with GA and Refined GA and for 119-bus compared with Tabu Search (TS). Simulation results obtained by the proposed method were better in terms of quality of the solution and computation efficiency.

Bees Algorithm and its variants were tested on Economic Load Dispatch problem in [35] and quite few times compared to the other field of power system. The proposed BA optimization to constrained economic load dispatch problem was tested on three different power systems comprising 6, 15 and 18 generators systems. Different constraints were considered like Power

Balance Constraints, Generator Constraints, prohibited operating zones and ramp rate limits. The obtained results are compared with the results obtained from Particle Swarm Optimization (PSO), GA, Neighborhood PSO (NPSO) and Combinatorial Particle Swarm Optimization (CPSO) methods. Results were either better or comparable with other techniques and the proposed methodology was found to be robust, fast converging and more proficient compared to the other techniques.

BA for nonlinear constrained multi-objective optimization Environmental/Economic power Dispatch problem was proposed in [36]. In this paper the authors tried to minimize both fuel cost and nitrogen oxides emission simultaneously. In this work, simulated results obtained from the standard IEEE 30-bus 6 generator test system using the Bees Algorithm with Weighted Sum were compared to Linear Programming, Multi-Objective Stochastic Search Technique, Non-dominated Sorting Genetic Algorithm, Niched Pareto Genetic Algorithm and Strength Pareto Evolutionary Algorithm and proved to be better and conferred the potentiality to solve the multi-objective Environment and Economic Dispatch (EED) problem. In [37], [38], Bee Colony Optimization based algorithm was tested on power systems with 6 and 15 units for ELD. The results were compared with the other conventional approaches, such as SA, GA, TS algorithm and PSO. The work addresses the constrained static and dynamic Economic Load Dispatch (ELD) problem of 6 unit and 15 unit system with artificial bee colony optimization algorithm approach while satisfying the system load demand and generator operation constraints, transmission losses, dynamic operation constraints. Here the algorithm was simulated in different size of power systems of various daily load curves. The results for ELD and dynamic ELD of six units and fifteen unit systems were compared with GA, PSO and some modified version of PSO (CPSO, APSO and NPSO-LRS). In ELD problem queen bee concept, they presented queen-bee evolution algorithm for solving the optimization problem of economic power dispatch. In this work, the attention was to schedule the committed generating unit outputs so as to meet the load demand at minimum operating cost while satisfying all units and system equality and inequality constraints. BA emerged as proficient, robust and fast convergent. In [39], the author proposes optimal position of unified power flow controller (UPFC) in a power system network using BA and then used to find the optimal dispatch of the generating units and the optimal value of Interline Power Flow Controller (IPFC) parameters. The Static VAR Compensator (SVC) FACTS devices is used in [40] with BA to study economic power dispatch of power system. In [41], the work presents an intelligent artificial bee algorithm for achieving the optimal power flow problem solution incorporating FACTS device which is the static synchronous series compensator (SSSC). Results show that the BA gives better solution to enhance the system performance with SSSC compared to without SSSC. In [21], maintenance of voltage stability and available transfer capability by using UPFC is presented.

2.6 Summary

From the foregoing literature survey, it is noted BA technique is capable of providing more optimal solutions since it exhibit improved efficiency, excellent solution quality, prompt responsiveness, fast convergence, less execution time and robustness compared to other AI methods. Bee algorithm is free from local optimal trapping and goes for global solution for any non-linear complex problem like placement of FACTS devices. It doesn’t require crossover and mutation rate like GA and it works quite efficiently utilizing fewer control parameters with its neighborhood search characteristic. Its potential advantage of being easily hybridized with different meta-heuristic algorithms and components makes it robustly viable for continued utilization for more exploration and enhancement possibilities in many more years to come.

There is therefore need to investigate the suitability of using BA for location and selection of FACTS devices for optimizing power transfer in a power system network.

CHAPTER 3

METHODOLOGY

The current problem has been framed as a multi-objective optimization problem of having to maximize system load ability and select best location, size and type of FACTS devices simultaneously so that it satisfies the specified criteria. The decision variables considered are IEEE 9 and 30 –bus test system power flow constraints and FACTS devices limits. It has been clearly illustrated in the following sections that these variables have very wide ranges and are associated with a number of different constraints. Thus, this problem falls under the class of constrained non-linear optimization problem with a vast solution space. FACTS devices constrained non-linear optimization problem is made up of three basic components; a set of variables, objective function to be optimized and a set of associated constraints that define the feasible solution space. The goal is to find the values of the variables within the feasible space that optimizes the objective function while satisfying the constraints. BA has been successfully used for many standard optimization problems and has established itself as a very effective optimization tool.

3.1 Development of BA model for FACTS devices Optimization

Initially, the problem to be solved is described in detail by considering the characteristics of the power system, the objective function and the system constraints Then, an exhaustive search is performed in order to identify the global optimum of the problem. This exhaustive search also provides useful information about the problem hyperspace, it’s feasible regions (areas that contain solutions which satisfy all the system constraints), and the total computational effort involved, which can later on be used as a point of comparison for the computational times obtained by the optimization algorithms.

The objective is to maximize power flow while optimizing selection and location of FACTS devices based on the function formulated below [43]. The objective function is dependent on the variables which represent the typical load flow equations and a set of the control variables representing the operating limit of FACTS devices and power system limits. Basically, the problem is stated as optimize:

$$f(x, u) \tag{3.1}$$

subject to $g(x, u) = 0$ and $h(x, u) \leq 0$

In accordance with $x = [\, PG_i, PD_i, V_g, V_l \,]$ and $u = [\, i, N, P_{inj}, Q_{inj} \,]$

Where x indicates the state variables and u represents the vector of the control variables. f represents the objective function i.e. Total power transferred, g represents the load flow equations and h indicates the parameter limits of the system and FACTS devices. For optimal selection and location of FACTS devices, total power transferred $f(x, u)$ has to be maximized and is expressed as:

$$f = PG_i + \sum_{k=1}^{N(i)} P_{injUi} - \sum_{j=1}^{N} P_{injTi} + Q_{injSi} \tag{3.2}$$

Where:

f : Total power transmitted

i : Location Bus number

PG_i : Real power generation at bus i

QG_i : Reactive power generation at bus i .

PD_i : Real power at bus i

QD_i : Reactive loads at bus i.

P_{injUi}, Q_{injU_i} **:** Injected real and reactive power of UPFC at bus i.

$V_{i\min}, V_{i\max}$: Lower and upper limit of voltage magnitude at bus i

Q_{Vi} : Reactive power injected by SVC.

N: Type of FACTS device. [0 for no device, 1 for SVC, 2 for TCSC and 3 for UPFC]

The equality constraints, typical load flow equations *g*(*x*, *u*) are given as:

$$PG_i - PD_i + \sum_{k=1}^{N(i)} P_{injUi} - \sum_{j=1}^{N} P_{injTi} + Q_{injSi} = 0 \qquad [3.3]$$

$$QG_i - QD_i + \sum_{k=1}^{N(i)} Q_{Uinj} + Q_{Sinj} - \sum_{j=1}^{N} Q_{Tinj} = 0 \qquad [3.4]$$

The parameter constraint limits, *h(x, u)* including the typical load flow constraints are given as,

$$PG_{i\min} \le PG_i \le PG_{i\max}$$

$$QG_{i\min} \le QG_i \le QG_{i\max}$$

$$Q_{Vi\min} \le Q_{Vi} \le Q_{Vi\max}$$

$$\phi P_{i\min} \le \phi P_i \le \phi P_{i\max}$$

$$-\pi \le \phi_{Ui} \le \pi$$

Three different types of devices (SVC, TCSC and UPFC) have been chosen to be optimally selected and located. Each of them is able to change the line parameters as follows:

- TCSC permits the decrease or increase of the reactance of the line.
- SVC is used to absorb or inject reactive power at the midpoint of the line.
- UPFC controls voltage magnitude and the phase angle of the sending end buses of the lines where major active power flow takes place.

For a given power system of several transmission lines, the initial bee population is generated from the following parameters:

- The number of FACTS devices to be located optimally.
- The different types of devices to be located.
- The number of possible location for device.

The initial population is generated from the following parameters;

- N_{facts} - Number of FACTS devices to be simulated
- T -Types of FACTS devices (SVC, UPFC, TCSC)
- $L_{locations}$ - Possible locations for FACTS devices

The number of individual in a population pn is calculated using the following equations:

$$pn = T \times N_{facts} \times L_{locations} \qquad [3.5]$$

Where;

Employed bees= $\frac{pn}{2}$ **(**number of solutions).

Onlooker bees $\leq \frac{pn}{2}$

Scout bees $\leq \frac{pn}{2}$

For IEEE 30-bus system, possible locations are bus 6, 8, 28 and transmission lines 6-28 and 6-8.

$$pn = 4_{facts} \times 2 \times 5_{locations}$$

The BA parameters used for the model development are summarized in Table 3.1.

Table 3.1: BA parameter settings

Serial No	BA parameters	Values
1	Swarm size	40
2	Number of employed bees	20
3	Number of onlooker bees foragers	20
4	Trial limit	100
5	Number of iterations	500

3.1.1 FACTS parameter settings.

FACTS devices contain three sets of parameters.

i. The first set corresponds to the values of the devices. It takes discrete values contained between -1 and +1 p.u. corresponding to the minimum and maximum value that the device respectively.
   - TCSC ranges between $-0.7X_{ij}\,p.u \leq X_{t\text{csc}} \leq 0.2X_{ij}\,p.u$
   - SVC is chosen between -1Mvar p.u. and 1Mvar p.u.
   - UPFC in this thesis is modeled as a combination of TCSC and SVC.

ii. The second set is related to the types of the FACTS devices. A value is assigned to each type of modeled FACTS device: 0 for no device, 1 for SVC, 2 for TCSC and 3 for UPFC. By this way new other types of FACTS may be easily added.

iii. The third set is related to the location of the devices. It contains the numbers of the lines where the FACTS are possible to be located. Each line appears at maximum once in the set.

The problem formulation is based on repeated power flow with FACTS devices to evaluate the feasible inter-tie flow value. The overall aim is to maximize the power that can be transferred from a specific set of generators in a source area to loads in a sink area subject to power system limit values and FACTS devices operation limits. The model was developed and initialized as detailed in Fig 3.1

3.1.2 Classification of Buses

In power flow study, buses were classified into the following categories:

Slack bus:

At a slack bus, the voltage angle and magnitude are specified while the active and reactive power injections are unknown. The voltage angle of the slack bus is taken as the reference for the angles of all other buses. Usually there is only one slack bus in a system. However, in some production grade programs, it may be possible to include more than one bus as distributed slack buses. FACTS devices are not located in a slack bus or any line connected to a slack bus

P-V buses:

At a PV bus, the active power injection and voltage magnitude are specified while the voltage angle and reactive power injection are unknown. Usually buses of generators, synchronous condensers are considered as PV buses.

P-Q buses:

At a PQ bus, the active and reactive power injections are specified while the voltage magnitude and angle at the bus are unknown. Usually a load bus is considered as a PQ bus.

The system data and FACTS devices have been expressed in per unit.

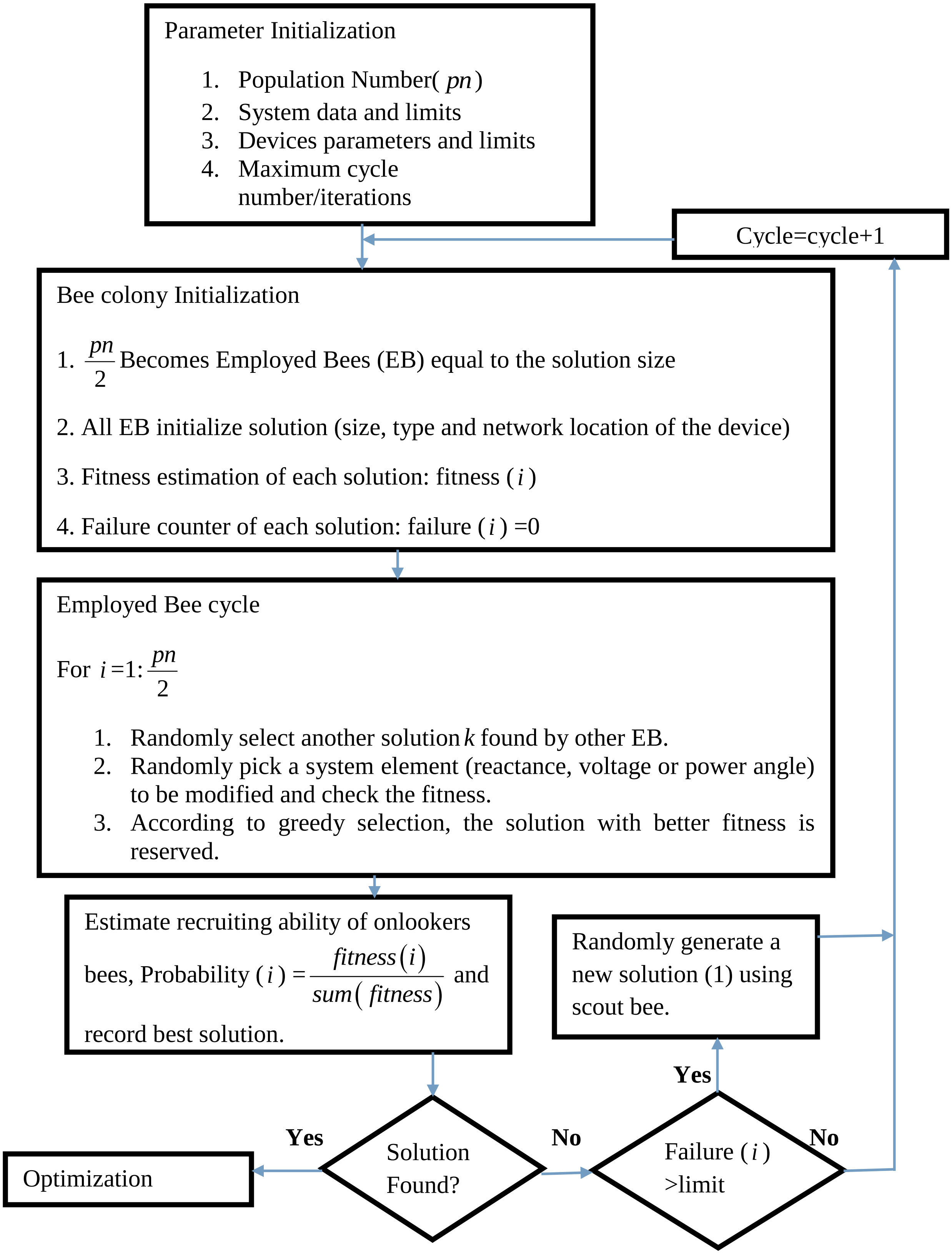

Fig 3.1 FACTS devices Optimization Bee Algorithm

3.2 Optimal Selection and Location of FACTS Devices.

The modified IEEE 9 and 30-bus test system attached in appendices A1 and A4 was used to check the effectiveness of the developed bee algorithm model optimization and whose line data and bus data can be found out from the appendices. The sensitivity analysis is applied to the power system with the purpose of determining bus number which is the most sensitive to the change in power system balance in order to establish the best locations. Shunt compensation is effective in improving voltage stability and *V-Q* sensitivity analysis is required to specify the location of shunt devices in order to achieve the best efficiency. Sensitivity analysis is not applied to slack bus. The developed model effectiveness was tested by simulating on a Matlab platform to optimally locate and select FACTS devices in IEEE9 –Bus test system and IEEE 30-bus test system. In order to perform the simulations and evaluation studies, the following were carried out:

(i) The test system was divided into two areas. Area 1 is a generator while area 2 is a load.
(ii) The test system voltage range is between 0.95 to 1.50 p.u
(iii) The active and reactive power of source area was varied as well as the loads in sink area, so that the power is transferred from source to sink via the tie-line.
(iv) The active powers of all the generators are kept constant except for the slack bus, so that the power increase in load is drawn from the slack bus.

The system was simulated under two operating conditions:

(i) Normal case (without any contingency) to give the base case values without FACTS devices.
(ii) Contingency case, taking into account line outage, voltage variation, angle variation and reactance variation to provide optimal selection and location of FACTS devices in IEEE 30-bus test system in single type and multi type.

IEEE 30 bus system was used to assess the effectiveness of BA model developed in this thesis to enhance power flow capability by optimal selection and location of FACTS devices. Appendix A3 show the single line diagram of the system, with 100MVA base. This system comprises of one slack bus, 5 PV buses, 24 PQ buses and 41 lines. Several cases have been considered for the optimization objectivity. For power flow capability enhancement, TCSC, SVC and UPFC are employed separately first and in similar and different device combinations to enhance inter-tie flow. The system was tested under two FACTS devices installation scenarios: single type and multi-type of FACTS devices. For each case, a total of five FACTS devices were installed in order to enhance the transferred power from source area to sink area. The location, setting and type of FACTS devices are obtained under different operating conditions. Inter-tie flow value at the base case without employing FACTS device is determined. Determination is further done by employing FACTS devices in single and multi-type device combinations. The limiting lines are obtained for this analysis. In the multi-type, similar devices combination are placed in the first limiting lines. For the UPFC, the placement of TCSC and SVC was done simultaneously.

3.2.1 IEEE 9-bus test system Simulation

9-bus test system is used to assess the effectiveness of BA models developed in this thesis. Appendix A1 show the single line diagram of the system, with 230 kV and 100MVA base has been considered. Four cases are considered along the limiting lines and buses, SVC is connected at bus 8 and, then at bus6, TCSC connected between line 7-8 and, then between line 9-8.

Case I:

SVC is connected to bus 8 to keep the voltage at that bus at 1.0 p.u and for susceptance value optimization.

Case II:

SVC is connected to bus 6, to keep the voltage at bus 6 at 1.0 p.u.

Case III:

TCSC is connected between bus7 and bus8. The objective is to increase the active power flow of that line.

Case IV:

TCSC is connected between bus 9 and bus 8 in order to increase the real power flows in line 9-8.

3.2.2 IEEE 30-bus test system Simulation

Case I: SVC is connected to bus 8 and 28 separately with the objective of maintaining the voltage profile of the system at a defined level and for susceptance value optimization.

Case II: TCSC is connected between limiting lines 6-28 and 6-8 separately to with the objective of enhancing inter-tie flow within the system.

Case III: UPFC is formulated by simultaneous connection of SVC and TCSC in two sets.

(i) TCSC between line 6-28 and SVC at bus 28 with the objective of maintaining voltage profile within predefined magnitude and enhance inter-tie flow.

(ii) TCSC between line 6-8 and SVC at bus 8 to achieve voltage profile and enhance power flow capability.

Case IV: UPFC, SVC and TCSC are simultaneously connected with the objective of enhancing inter-tie flow while maintaining system parameters within the desired limits.

3.3 Evaluating results Obtained using BA algorithm.

Case I: SVC is connected to limiting bus 8 and 28 separately with the objective of maintaining the voltage profile of the system at a defined level and for susceptance value optimization in order to optimize power flow enhancement. Power flow results are evaluated against optimally located SVC using GA at bus 24.

Case II: TCSC is connected between limiting lines 6-28 and 6-8 separately to with the objective of enhancing inter-tie flow within the system. Power flow results are evaluated against TCSC located between lines 2-5 using GA.

Case III: UPFC is formulated by simultaneous connection of SVC and TCSC in two sets.

(i) TCSC between line 6-28 and SVC at bus 28 with the objective of maintaining voltage profile within predefined magnitude and enhance inter-tie flow. Power flow results are evaluated against TCSC located between lines 2-5 and SVC at bus 24 using GA.

(ii) TCSC between line 6-28 and SVC at bus 6 to achieve voltage profile and enhance power flow capability. Power flow results are evaluated against TCSC located between lines 2-5 and SVC at bus 24 using GA.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Simulation Results

4.1.1. IEEE 9-Bus Test System Simulation Results.

Table 4.1 Voltage magnitude for 9-bus test system with and without SVC

Bus	**Without FACTS**	**SVC at bus 6** Q_{sh} =-0.1372	**SVC at bus 8** Q_{sh} =-0.2186
1	1.09	1.04	1.04
2	1.03	1.03	1.03
3	1.03	1.03	1.03
4	1.03	1.02	1.02
5	0.99	0.99	0.99
6	1.01	1.01	1.00
7	1.03	1.02	1.02
8	1.02	1.00	1.01
9	1.03	1.03	1.03

Table 4.1 shows the results for SVC connected at bus 6 and 8.

i). SVC connected at bus 8, the convergence is obtained after 0.16 seconds. SVC absorbs 0.2186 Mvar from bus 8 in order to keep the voltage magnitude at 1 p.u, with Q_{sh} equal to -0.2186 p.u.

ii). SVC connected at bus 6, the convergence is obtained after 0.18 seconds. SVC absorbs 0.1372 Mvar from bus 6 in order to keep the voltage magnitude at 1 p.u, with Q_{sh} equal to -0.1372 p.u.

One of the major causes of low capacity of power transfer is voltage instability due to reactive power limits of the power systems. BA location and selection of SVC improves voltage stability of the power systems by improving the systems reactive power handling capacity and increase power transfer.

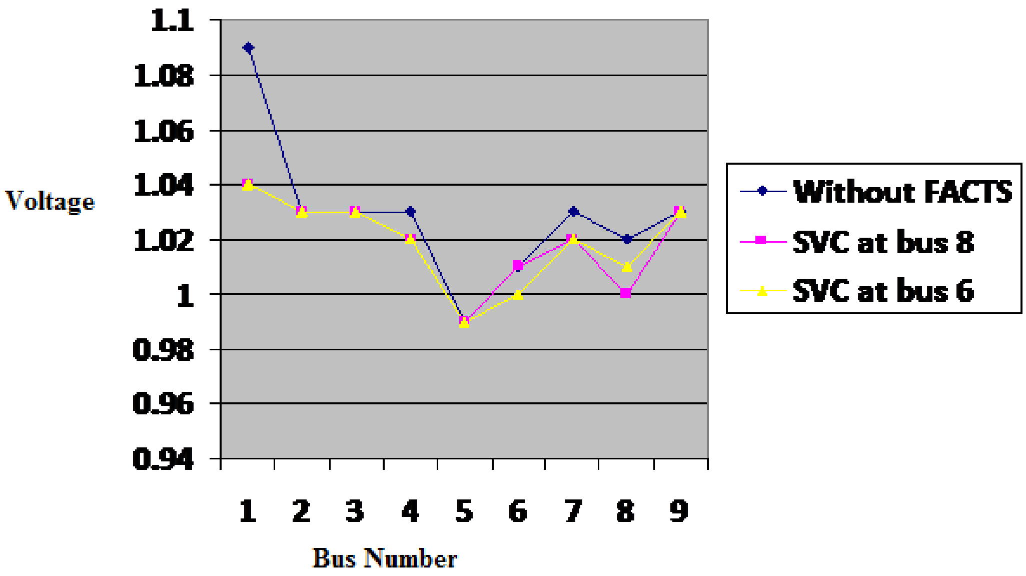

Fig 4.1 Voltage Profile chart for IEEE 9-Bus system

Fig 4.1 presents a voltage profile chart. The chart indicates that the voltage profile is achieved to its predefined range of 1 p.u when SVC is incorporated in the system hence improving power transfer.

Table 4.2 Power flow results of 9-bus test system with and without TCSC

	Lines	
	7-8	**9-8**
$X_{t\mathrm{csc}}$	-0.0319	-0.0439
Active power without TCSC(mw p.u)	0.76	0.24
Active power with TCSC(mw p.u)	0.80	0.26

TCSC was connected between bus 7 and bus 8. The objective was to increase the active power flow of that line. After running load flow program, $X_{t\mathrm{csc}}$ is equal to -0.0319 p.u. TCSC is connected between bus 9 and bus 8 in order to increase the real power flows in line 9-8. After running load flow program, $X_{t\mathrm{csc}}$ is equal to -0.0439.

The above results were used to evaluate the developed BA model in location and selection of FACTS to enhance power transfer. FACTS devices can boost the power transfer substantially. The considerable difference between voltages values with and without FACTS devices for the considered transactions justifies that the FACTS technology can offer an effective and promising solution to enhance the usable power transfer capability, thereby improving transmission capacity of the power system network without constraints.

The effect of FACTS devices on power transfer enhancement is system dependent.

4.1.2 IEEE30- Bus Test System Simulation Results.

Table 4.3 Power flow results of IEEE 30-bus test system with and without SVC

	Buses	
	8	**28**
Q_{sh}	-0.5	-1
Inter-tie flow without SVC	51.0	
Inter-tie flow with SVC	50.7	50.9

Table 4.4 Power flow results of IEEE 30-bus test system with and without TCSC

	Lines	
	6-28	**6-8**
X_{tcsc}	0.2	0.6
Inter-tie flow without TCSC	51.0	
Inter-tie flow with TCSC	52.1	52.0

Table 4.5 Power flow results of IEEE 30-bus test system with and without UPFC

	Line 6-28	**Bus 28**
X_{tcsc}	0.2	
Q_{sh}		-0.5
Inter-tie flow without UPFC	51.0	
Inter-tie flow with UPFC	52.2	

Table 4.6 Power flow results of IEEE 30-bus test system with and without UPFC

	Line 6-8	**Bus 8**
$X_{t\mathrm{csc}}$	0.6	
Q_{sh}		-0.5
Inter-tie flow without UPFC	51.0	
Inter-tie flow with UPFC	52.1	

Table 4.7 Power flow results of IEEE 30-bus test system with and without Multi-type FACTS Devices

	SVC	**TCSC**	**UPFC**	
	Bus 28	**Line 6-28**	**Bus 8**	**Line 6-8**
$X_{t\mathrm{csc}}$ p.u		0.2		0.6
Q_{sh} p.u	-1		-0.5	
Inter-tie flow without FACTS devices(Mw)	51.0			
Inter-tie flow with Multi-type FACTS devices(Mw)	54.6			

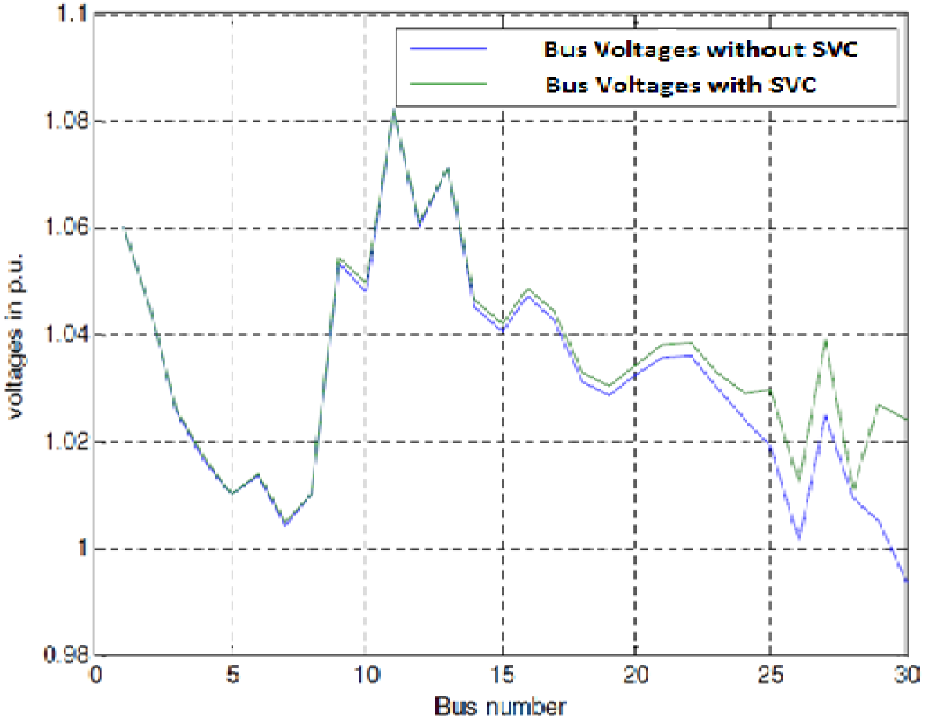

Fig.4.2 IEEE 30 Bus system Voltage profile chart for BA

For the proposed system, the inter-tie flow power that can be transferred from all generators to loads without placing the FACTS devices is 51.0 MW. To enhance inter-tie flow with the FACTS devices, we need to place devices at the optimal location. After performing the simulations to place the single type devices in the system to improve inter-tie flow, it was observed that the bus 28 is the best suitable locations for the SVC to maintain voltage profile at the desired level. TCSC is best located in line 6-28 to enhance inter tie flow to 52 MW. UPFC is best connected at bus 28 and line 6-28. In the single device type, UPFC is providing maximum enhancement of inter-tie flow. Considering similar and different device combinations, two UPFCs are providing maximum inter-tie flow. Voltage magnitudes of critical buses are fixed to 1 p.u by converging to the best susceptance values of SVC devices. The results show the effectiveness of the new approach in optimizing the FACTS placement in terms of more optimal solution. In the case of multi-type FACTS devices, the type of device to be placed is also considered as a parameter in the optimization. The results show that simultaneous use of several types of FACTS devices is the most efficient method to increase the inter-tie flow. Several cases have been considered for this system.

4.2 Evaluation of Simulation results

Table 4.8 Power flow values for IEEE 30-bus system with and without FACTS devices using BA and GA algorithm.

Power Flow With No FACTS(Mw)	FACTS TYPE	AI Techniques	Settings and Placement of FACTS devices				Power flow with FACTS devices(Mw)
			TCSC	**SVC**	**UPFC**		
51.0	**SVC**	**BA**		-1(Bus 28)			50.9
				-0.5(Bus 8)			50.7
		GA		0.1 (Bus 24)			51.0
	TCSC	**BA**		0.2(Line 6-28)			52.1
				0.6(Line			52.0

				6-8)			
		GA		0.2(Line 2-5)			51.0
	UPFC	**BA**	0.2 (Line 6-28)	-0.5(Bus 28)			52.2
		GA	0.23(Line 2-5)	0.1(Bus 24)			51.5
	SVC **TCSC** **UPFC**	**BA**	0.2(Line 6-28)	-1(Bus 6)			54.6
		GA	0.2(Line 2-5)	0.1(Bus 24)			52.1

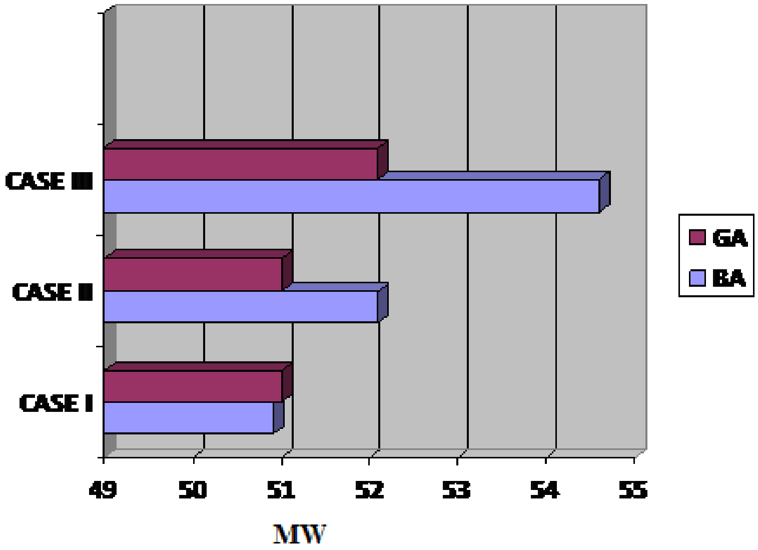

Fig.4.3 Result comparison chart for BA and GA

The evaluation of the proposed BA method considers two important factors:

- Convergence into feasible regions.
- Analysis of global optimality.

In the two cases, the performance of the BA is compared with other optimization technique, in particular genetic algorithm (GA).The BA method is used to aid the convergence into feasible regions(solutions that satisfy all the constraints of the problem). The performance of the proposed BA is compared with the GA.

The assessment of the capability of achieving global optimality is addressed by analyzing how accurately each algorithm enhances power transfer capability of an interconnected power system network by optimal selection and location of FACTS devices. Finally, the scalability of the BA is analyzed by comparing results for different power system sizes. Table 4.8 compares simulations result of BA and GA.

These results show that installation of multi-type FACTS devices lead to improvement in voltage stability index and reduction in power system losses simultaneously. So multi-type FACTS devices should be placed in optimal location to both improve stability margins and enhance power transfer. The selection of types and location of FACTS devices for power flow enhancement depends on the violation of the system elements. For the case of bus voltage violation, it is understood that SVC is always the best choice and it is installed at the bus where violation occur. Besides, FACTS technology can also improve the voltage profile at the buses which are near to where it is installed.BA presents several optimal locations and more optimal solutions compared to GA.

The performance was analyzed considering the role played separately by TCSC, SVC and UPFC for boosting voltage profile and power transfer in single device type and multi-type three similar and three different devices combinations using both GA and BA. Effective single device and effective combination of devices have also been suggested for the considered test system. The main objective was to find optimal locations, sizes and control parameters FACTS devices, such that a maximum benefit is obtained over the entire power system, instead of focusing on local neighborhoods. In particular, this study focuses on enhancing inter-tie flow of the system during normal and contingency operation modes while maintaining system parameters limit.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Several major achievements have been accomplished through the course of this thesis:

i). The incorporation of steady state model of three emerging types of FACTS devices namely; TCSC, SVC and UPFC in order to run the power flow studies of these devices was done successfully. The models have been used for steady state studies of FACTS devices in power system network. The power injection models of the Thyristor Controlled Series Capacitor (TCSC), Unified Power Flow Controllers (UPFC) and Static VAR Compensator (SVC) with their power flow controllers have been demonstrated. The injection models are very simple to implement and they have been appropriate for the kind of investigation carried out in this thesis. The software for both steady-state study and dynamic study of large power systems embedded with FACTS devices has been developed.

ii). The development of a BA model suitable to locate and select FACTS devices in an interconnected power system. The resulting optimization shown improvement in power transfer compared to GA.

iii). The confirmation of BA as a successful heuristic method to optimize the location of FACTS devices in power networks and enhance power transfer improvement compared to GA.

From the perspective of the model developed, a significant contribution is given on the development of multi-objective model to locate FACTS devices. This research work led to the suggestion of a BA based model to optimally locate FACTS devices in power system. The model allowed the optimal location and selection of FACTS devices on a realistic power network given a set of various system operating conditions. The results demonstrated improved power transfer compared to GA.

The BA model has been effectively evaluated, giving consistent results for the optimal location of FACTS devices. New variants of BA were proposed and used in the optimal location of FACTS devices, resulting in important progresses on the algorithmic field of this thesis.

In general, the optimal location of the FACTS devices obtained according to the dynamic criteria is not the same as the one obtained according to the static criteria. A compromise has to be found for each particular case, considering multiple tasks, for example power flow control and power transfer enhancement. The procedure for considering the FACTS devices location and selection in order to satisfy the mentioned requirements has been presented. Verification by simulation matched predicted locations as optimally selected FACTS devices location with respect to both control objectives.

5.2 Recommendations

The work developed throughout this thesis is a contribution to future work aiming to study the location and selection of FACTS devices in transmission networks and also some of the methodologies proposed.

Suggestions are now presented to develop new work taking as starting point the results presented in this thesis through Hybridization of BA with other heuristic search algorithm to improve the results presented here.

The future work should include introduction of the developed steady state models of FACTS devices to voltage, transient stability and power flow programs. The models should be further used in stability studies for planning and operation of actual power systems.

Publications

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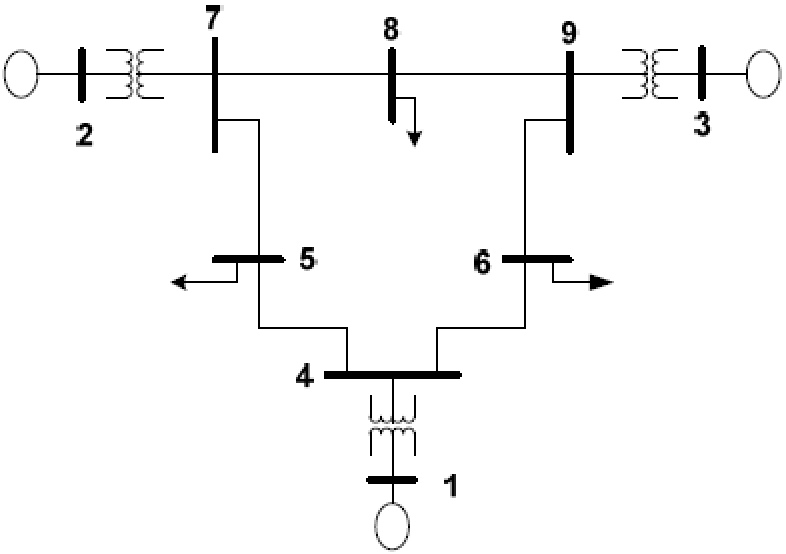
Appendices

A1.Single line Diagram of IEEE 9-bus system.



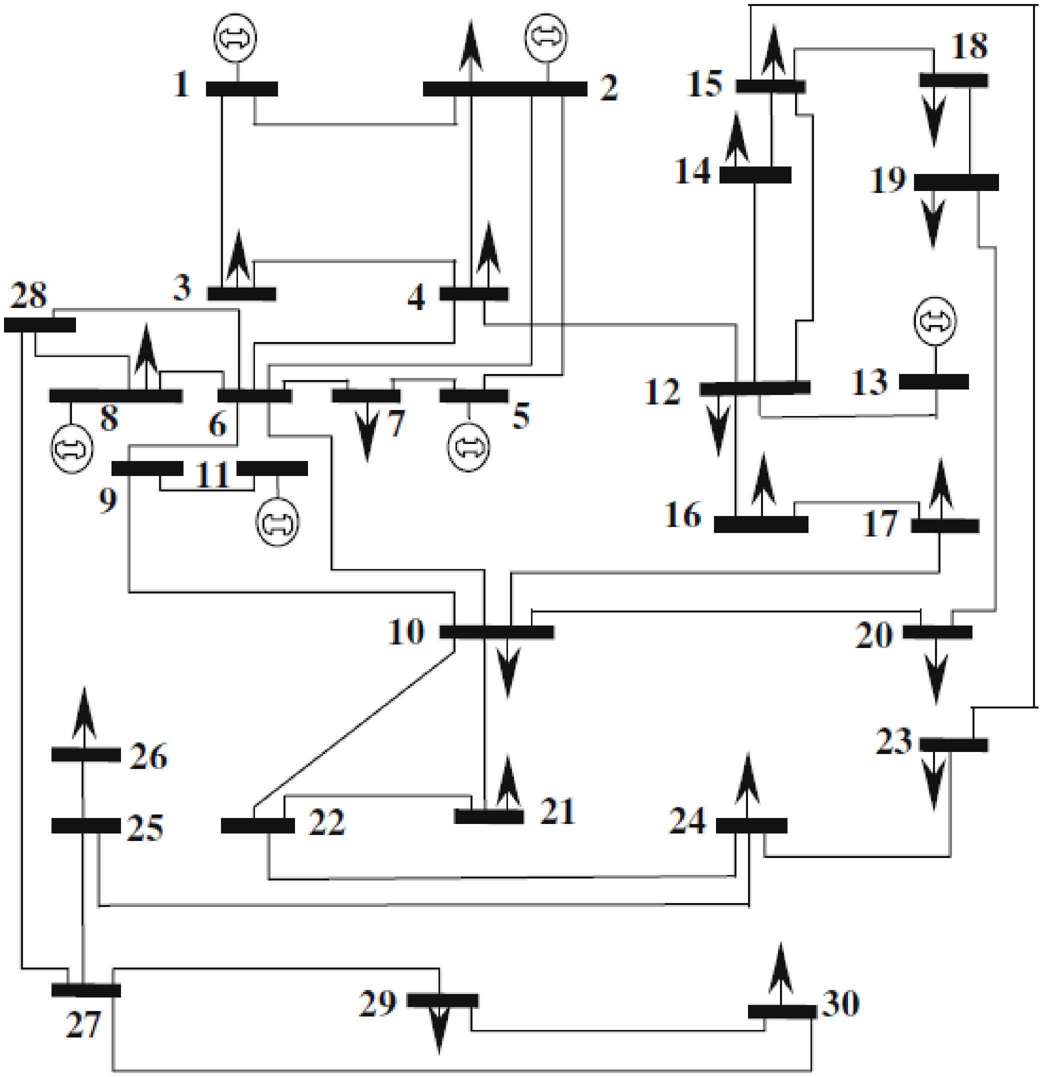
A2. Data of IEEE 9-Bus Test System.

Bus	V	P_D	Q_D
1	0.97	0.0	0.0
2	1.05	3.27	0.43
3	0.96	0.0	0.0
4	0.93	0.0	0.0
5	0.95	0.0	0.0
6	1.05	1.0	1.5
7	0.96	0.0	0.0
8	1.05	2.5	0.5
9	0.98	0.0	0.0

A3. Data of IEEE 9-Bus Test System.

Bus	P_G	Q_G
1	0.0	-
2	1.63	0.0
3	0.85	0.0
4	0.0	0.0
5	0.0	0.0
6	0.0	0.0
7	0.0	0.0
8	0.0	0.0
9	0.0	0.0

A4. Single line Diagram of IEEE 30-bus system.



A5.Bus Load and Injection Data of IEEE 30-Bus System.

Bus	**Load(MW)**	**Bus**	**Load(MW)**
1	0.0	16	3.5
2	21.7	17	9.0
3	2.4	18	3.2
4	67.6	19	9.5
5	34.2	20	2.2
6	0.0	21	17.5
7	22.8	22	0.0
8	30.0	23	3.2
9	0.0	24	8.7
10	5.8	25	0.0
11	0.0	26	3.5
12	11.2	27	0.0
13	0.0	28	0.0
14	6.2	29	2.4
15	8.2	30	1.6

A6.Reactive power limits IEEE 30-Bus System.

Bus	**Qmin (p.u)**	**Qmax (p.u)**	**Bus**	**Qmin (p.u)**	**Qmax (p.u)**
1	-0.2	0.0	16		
2	-0.2	0.2	17	-0.05	0.05
3			18	0.0	0.055
4			19		
5	-0.15	0.15	20		
6			21		
7			22		
8	-0.15	0.15	23	-0.05	0.055
9			24		
10			25		
11	-0.1	0.1	26		
12			27	-0.055	0.055
13	-0.15	0.15	28		
14			29		
15			30		