EVOLUTIONARY ALGORITHM ASSISTED OPTIMAL PLACEMENT OF FACTS CONTROLLERS IN POWER SYSTEM

Thesis submitted in partial fulfillment of the requirements for the award of degree of

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CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled, **"Evolutionary Algorithm Assisted Optimal Placement of FACTS Controllers in Power System"**, in partial fulfillment of the requirements for the award of degree of Master of Engineering in ***Power Systems & Electric Drives*** submitted in Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Dr. Sanjay K. Jain, Assistant Professor, EIED.

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university

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This is to certify that the above statement made by the candidate is correct and true to best of my knowledge.

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ABSTRACT

With the increasing size of power system, there is a thrust on finding the solution to maximize the utilization of existing system and to provide adequate voltage support. For this the flexibility of power is needed. Flexible AC transmission system (FACTS) if placed optimally can be effective in providing voltage support, controlling power flow and in turn resulting into lower losses.

The algorithm to find the optimal location of TCSC and STATCOM based on genetic algorithm has been developed. The effect of these devices on line flows and bus voltage profile has been studied by placing at random location and placing them optimally with optimal ratings dictated by genetic algorithm. The effectiveness of developed algorithm has been tested on 5-bus and 30-bus systems.

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CHAPTER – 1

INTRODUCTION

1.1 OVERVIEW

The increasing Industrialization, urbanization of life style has lead to increasing dependency on the electrical energy. This has resulted into rapid growth of power systems. This rapid growth has resulted into few uncertainties. Power disruptions and individual power outages are one of the major problems and affect the economy of any country. In contrast to the rapid changes in technologies and the power required by these technologies, transmission systems are being pushed to operate closer to their stability limits and at the same time reaching their thermal limits due to the fact that the delivery of power have been increasing. The major problems faced by power industries in establishing the match between supply and demand are:

- Transmission & Distribution; supply the electric demand without exceeding the thermal limit.
- In large power system, stability problems causing power disruptions and blackouts leading to huge losses.

These constraints affect the quality of power delivered. However, these constraints can be suppressed by enhancing the power system control. One of the best method for reducing these constraints are FACTS devices.

With the rapid development of power electronics, *Flexible AC Transmission Systems* (FACTS) devices have been proposed and implemented in power systems. FACTS devices can be utilized to control power flow and enhance system stability. Particularly with the deregulation of the electricity market, there is an increasing interest in using FACTS devices in the operation and control of power systems. A better utilization of the existing power systems to increase their capacities and controllability by installing FACTS devices becomes imperative. FACTS devices are cost effective alternatives to new transmission line construction [1].

Reactive power compensation is provided to minimize power transmission losses, to maintain power transmission capability and to maintain the supply voltage. Series compensation is control of line impedance of a transmission line; with the change of impedance of a line either inductive or capacitive compensation can be obtained thus facilitating active power transfer or control. Thyristor Controlled Series Capacitor (TCSC) is a variable impedance type series compensator and is connected in series with the transmission line to increase the power transfer capability, improve transient stability, reduce transmission losses and dampen power system oscillations. Shunt compensation is used to increase the steady-state transmittable power and to control the voltage profile along the line. Static compensator (STATCOM) is a shunt compensator and one of the important members of FACTS family that are increasingly being applied to long transmission lines by the utility in modern power systems. They can have various applications concerned with operation and control of power system, such as scheduling power flow; decreasing unsymmetrical components damping the power oscillations and enhancing transient stability.

1.1.1 FLEXIBLE AC TRANSMISSION SYSTEM

The concept of Flexible AC Transmission Systems (FACTS) was first defined by N.G. Hingorani, in 1988 [2]. A Flexible Alternating Current Transmission System (FACTS) is a system comprised of static equipment used for the AC transmission of the electrical energy. It is meant to enhance controllability and increase power transfer capability of the network. It is generally a power electronic-based device. FACTS is defined by the IEEE as “a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability” [3].

The primary advantage of FACTS devices, over its conventional counterpart is the rapid control of current, voltage and/or impedance. The conventional solutions such as capacitor, reactor and phase shifting transformers are normally less expensive than FACTS devices, but limited in their dynamic behaviour and are less optimal. The review of various FACTS devices is summarized in Chapter 2.

1.1.2 LOAD FLOW SOLUTIONS

Load flow studies are the backbone of power system analysis and design. Load flow studies are necessary for planning, economic scheduling and exchange of power between utilities. In addition, power flow analysis is required for many analyses such as transient stability and contingency studies.

The load flow solution gives the nodal voltages and phase angles and hence the power injection at all the buses and power flows through interconnecting transmission lines.

Load flow equations are nonlinear and can be solved by an iterative method. In this thesis Newton Raphson method is used, as the number of iterations is independent of the size of the system**,** and convergence characteristic is independent of selection of slack bus. Details of Newton-Raphson method, load flow solution with TCSC and STATCOM are discussed in chapter 3.

1.1.3 EVOLUTIONARY ALGORITHM

Evolutionary algorithms (EA) are search methods that take their inspiration from natural selection and survival of the fittest in the biological world. EAs differ from more traditional optimization techniques in that they involve a search from a "population" of solutions, not from a single point. In an EA a number of artificial creatures search over the space of the problem. . EA also use objective function information, not derivatives or other auxiliary knowledge[4] .Genetic Algorithm is one of the several evolutionary search methods.

GA are search algorithms based on mechanics of natural selection and natural genetics. They emulate species evolution through generations. The main features of GA that differentiates it from other search methods are that it works with a coding of parameter instead of parameters themselves, it evaluates the fitness of each string to guide its search instead of the optimization function and is the algorithm is multipath search and hence reducing the possibility of local minimum trapping [5]. The three most important aspects of GA are:

- Definition of objective function
- Definition and implementation of genetic representation
- Definition and implementation of genetic operators

These aspects are discussed in detail in Chapter 4 in relation with the problem.

1.2 LITERATURE REVIE

The brief review on the placement of FACTS devices is presented here.

The concept of FACTS and FACTS controllers was first defined by Hingorani, 1988 in [2,3]. FACTS usually refer to the application of high-power semiconductor devices to control different parameters and electrical variables such as voltage, impedance, phase angles, currents, reactive and active power [11-12].

FACTS can provide versatile benefits to transmission utilities such as control of power flow, increasing capabilities of lines to their thermal limits, reducing loop flows, providing greater flexibility [9-10].The value of FACTS application lies mainly in the ability of the transmission system to efficiently transmit power or to transfer power under contingency conditions [6].

FACTS technology is a collection of controllers that can be applied to control electrical variables and parameters. In general FACTS controllers can be divided into four categories: 1) Series controllers mainly TCSC and SSSC 2) Shunt controllers mainly STATCOM and SVC 3) Series-series controllers such as IPFC and 4) Combined series-shunt controllers such as UPFC[1].

Reactive power compensation is an important issue in powers system. The purpose of reactive power compensation is mainly to improve the voltage profile in the system and to minimize the power loss. The reactive power compensation of AC system can be done using fixed series or shunt capacitor however the slow nature of control and limits on frequency are the drawback and can be overcome by using FACTS controllers [6-8]. Thyristor controlled series compensator is a variable impedance series compensator, which controls the effective line reactance by connecting a variable reactance in series with the line [16-18]. STATCOM is a second generation FACTS deivce used for shunt reactive compensation. It is applied to improve voltage security, provide interface with the real power source, higher response to system changes and mitigation of harmonics [19-20].

Hassan, Cheng and Zakaria presented steady state modelling of STATCOM and TCSC for power flow control studies. STATCOM is modelled as a controllable voltage source in series with impedance and proposed firing angle model for TCSC, Newton Raphson method algorithm was implemented to solve power flow equation in the presence of STATCOM and TCSC. The algorithm developed shows excellent convergence characteristics [20].

As FACTS devices are costly so type, number and location of the FACTS devices is very important, to decide the optimal location and parameters of FACTS devices the following objective functions are used in FACTS related researches: Transmission pricing issues by maximizing social welfare with or without [22] consideration of FACTS' costs; Better utilization of FACT by maximizing FACTS devices total transferred power [23] Reactive power or voltage control by minimizing transmission losses [24], or voltage fluctuation [25]. Increase system’s security under emergency by minimizing transmission lines loadability [15].

Thyristor-based FACTS are modelled as power injection, or controllable impedance (TCSC and SVC) or an ideal phase shifter (TCPST/TCPAR),FACTS devices can be embedded into power flow equations with modification of the network admittance matrix and the Jacobian matrix. Radman and Raje discussed power flow calculation of power system with multiple flexible AC transmission system (FACTS controller) by modifying and adding new entries in Jacobian equation with no FACTS controller and considered three major FACTS controllers STATCOM, SSSC and UPFC[21].

Esquiuel and Acha considered the issue of controllable branch model suitable for assessing the steady state response of FACTS devices and presented nodal admittance model for series compensators, phase shifter and unified power flow controller[26].

Genetic Algorithm is a well known evolutionary search technique that can result in feasible as well as an optimal solution[4]. GA starts with a random initial population in order to select the best individual. Crossover, mutation and selection all together are functions associated with GA. Crossover is the primary genetic operator, which promotes the exploration of new regions in the search space [27]. Mutation is a secondary operator and prevents the premature stopping of the algorithm in a local solution. Reproduction is based on the principle of survival of the better fitness. It is an operator that obtains a fixed number of copies of solutions according to their fitness value. GA provide several advantages over classical methods such as the algorithm work with a population of string as opposed to a single point, GA use objective function information instead of derivatives knowledge, GA has the potential to find solutions in many different areas of the search space simultaneously[5].Gerbex *et al.*, presented a genetic algorithm to optimally locate multi type FACTs devices in power system. The system loadability is used as a measure of power system performance. The optimization was performed on three parameters: the location of the devices, their type and their values [15].

Lu and Abur presented a systematic procedure to place and operate TCSC in a power system, Single sensitivity criterion for a given load if defined and is used to develop a branch’s priortizing index in order to rank branches for possible placement of TCSC’s[12].

1.3 OBJECTIVE OF THE THESIS

The work reported in this thesis has been carried out with the objective of studying the effect of FACTS controllers namely TCSC and STATCOM on load flow solution and also to develop the algorithm to decide their location in power system using Genetic Algorithm for loss minimization

1.4 ORGANIZATION OF THESIS

The thesis is organized into six chapters. The organization of thesis is as follows: The Chapter-1 highlights the brief overview, summary of work carried out by various researchers, the objective of the thesis and the outline of the thesis.

The Chapter-2 presents review on FACTS Controllers, series compensation, shunt compensation, opportunities and applications for FACTS.

The Chapter-3 presents the mathematical model of TCSC and STATCOM and algorithm to solve load flow with TCSC and STATCOM.

The Chapter-4 explores FACTS allocation of TCSC and STATCOM using GA, the objective function, coding structure are discussed.

The Chapter-5 summarizes the effect of allocation of TCSC and STATCOM on load flow solutions by considering the allocation at arbitrary location and locations identified by GA on 5-bus and 30-bus systems.

The chapter-6 summarizes the conclusions drawn and scope for the future work.

CHAPTER-2

REVIEW ON FLEXIBLE AC TRANSMISSION SYSTEM

2.1 INTRODUCTION

The FACTS is a generic term representing the application of power electronics based solutions to AC power system. These systems can provide compensation in series or shunt or a combination of both series and shunt. The FACTS can attempt the compensation by modifying impedance, voltage or phase angle.

The capability of FACTS in providing series or shunt compensation is explained with the help of transmission line. In the case of a no-loss transmission line, voltage magnitude at receiving end is the same as voltage magnitude at sending end: $V_1 = V_2 = V$. Transmission results in a phase lag δ that depends on line reactance X. Fig. 2.1 shows equivalent circuit and phasor diagram of no loss transmission line.

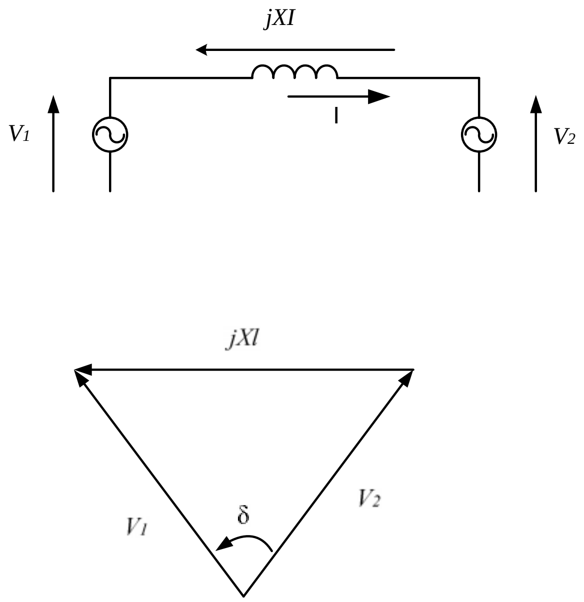

Figure 2.1 Transmission on a no-loss line and phasor diagram

$$V_1 = V\cos\left(\frac{\delta}{2}\right) + jV\sin\left(\frac{\delta}{2}\right) \tag{2.1}$$

$$V_2 = V\cos\left(\frac{\delta}{2}\right) - jV\sin\left(\frac{\delta}{2}\right) \tag{2.2}$$

$$I = \frac{V_s - V_r}{jX} = \frac{2V\sin\frac{\delta}{2}}{X} \quad (2.3)$$

As it is a no-loss line, active power P is the same at any point of the line is given by:

$$P_s = P_r = P = V\cos\left(\frac{\delta}{2}\right).\frac{2V\sin\frac{\delta}{2}}{X} = \frac{V^2}{X}\sin\delta \quad (2.4)$$

Reactive power at sending end is the opposite of reactive power at receiving end:

$$Q_s = -Q_r = Q = V\sin\left(\frac{\delta}{2}\right).\frac{2V\sin\frac{\delta}{2}}{X} = \frac{V^2}{X}(1 - \cos\delta) \quad (2.5)$$

As δ is very small, active power mainly depends on δ whereas reactive power mainly depends on voltage magnitude.

2.1.1 WITHOUT COMPENSATION

AC system mainly consists of inductive load so it requires reactive power for its operation and hence, the source must supply it, increasing the current from the generator and through power lines, Fig. 2.2 shows the representation of AC system. If reactive power is supplied near the load, the line current can be reduced or minimized resulting into lower losses and improving voltage regulation at the load terminals. Fig. 2.3 shows the phasor diagram of the system without compensation, the phase angle of the current has been related to the load side, which means that the active current I_P is in phase with the load voltage V_2 [2].

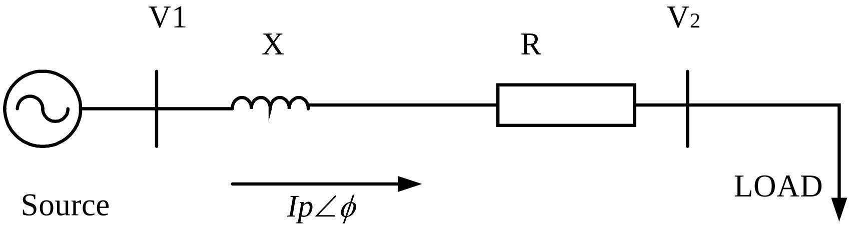

Figure 2.2 Representation of AC system

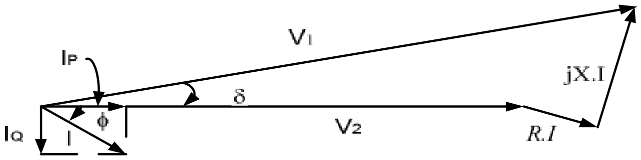

Figure 2.3 Phasor diagram without compensation

2.1.2 SERIES COMPENSATION

The conventional Series compensators employ switches to add inductive or capacitive reactance in transmission line. The conventional compensator emulates a static flow controller by means of mechanical switching [6,7].

Series compensation can also be implemented by injecting a voltage source in series with transmission line as shown in Fig. 2.4. The voltage source can inject voltage of controllable magnitude and phase. When the injected voltage is in phase quadrature leading to line current, series compensation emulates like an inductor, similarly when injected voltage is lagging to line current it emulates a capacitor. The results obtained with the series compensation through a voltage source, which has been adjusted again to have unity power factor operation at V_2 as shown in Fig.2.5. In this case, voltage V_{COMP} has been added between the line and the load to change the angle of V_2, which is now the voltage at the load side. As it can be seen from the phasor diagram of Fig. 2.5, V_{COMP} generates a voltage with opposite direction to the voltage drop in the line inductance because it lags the current I_P.

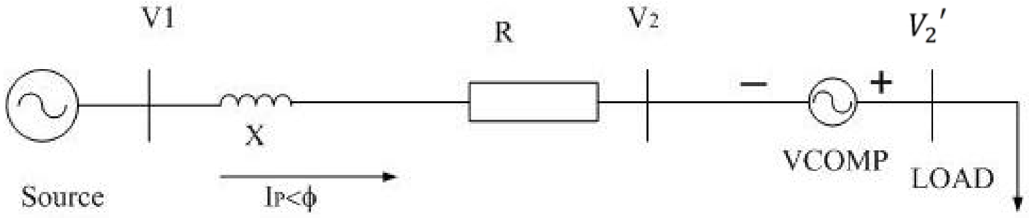

Figure 2.4 Representation of AC system with series compensation

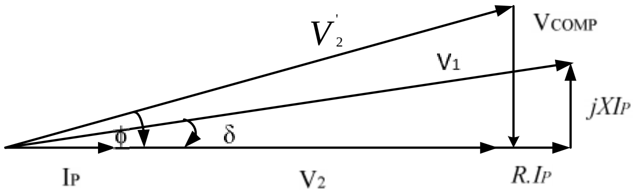

Figure 2.5 Phasor diagram with series compensation

By applying series compensations, the transmission line impedance X may be varied such that the line can be either more inductive or capacitive depending on the amount of compensations used. This is performed by inserting X_q which is either a series capacitor or series inductor depending on the type of compensation needed by the system. Under inductive compensation, X_q is defined as a positive value which increases the line impedance and for capacitive compensation; X_q is defined as a negative value which will decrease the line impedance. The variations in the impedance of transmission line can result in an increase or decrease in actual power flow P as well as the reactive power flow Q in the system.

Effective line impedance, $X_{eff} = X + X_q$

Real power, $$P = \frac{V_1 V_2}{X_{eff}} sin\delta \qquad (2.6)$$

Reactive power, $$Q = \frac{V_1 V_2}{X_{eff}} (1 - cos\delta) \qquad (2.7)$$

The power curve is attainable by using eq. (2.6). The outcome of the real power is dependent on effective line impedance X_{eff} and the phase difference δ between sending and receiving voltages [1].

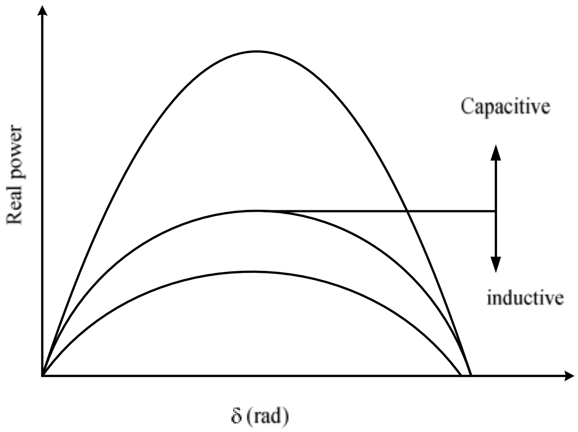

Figure 2.6 Influence of series compensation in power flow

The Fig.2.6 shows the characteristic for eq.(2.6), when X_q is providing inductive compensation, the effective line impedance $\boldsymbol{X_{eff}}$ increases, and real power in the line decreases. In capacitive mode, the effective line impedance $\boldsymbol{X_{eff}}$ decreases which resulted in real power increase in the power flow.

Series compensators are able to override the drawbacks of shunt compensators by providing dynamic control over those system variables In addition, static series compensation is able to provide dynamic compensation through:

- Reduction of load dependent voltage drops (Voltage Stability)
- Reduction of system transfer impedance
- Reduction of transmission angle (Improving Transient Stability)
- Load flow control for specified power paths
- Damping of active Power Oscillations

2.1.3 SHUNT COMPENSATION

Shunt compensation is used to influence the natural electrical characteristics of the transmission line to increase the steady-state transmittable power and to control the voltage profile along the line. The shunt compensator like STATCOM can be operated either to provide capacitive or inductive compensation depending on the specific requirement. The impedance of the shunt controller, which is connected to the line voltage, causes a variable current flow, and hence represents an injection of current into the line. As long as the injected current is in phase quadrature with the line voltage, the shunt controller only supplies or consumes variable reactive power. The ultimate objective of applying reactive shunt compensation in a transmission system is to increase the transmittable power capability from the generator to the load, which is required to improve the steady-state transmission characteristic as well as the stability of the system [6].

The shunt capacitive compensator is used to improve the power factor, most of the practical loads are inductive and results into lagging power factor. To compensate, a shunt capacitor is connected which draws current leading the source voltage. The net result is improvement in power factor.

The shunt inductive compensator is used either when charging the transmission line, or, when there is very low load at the receiving end. Due to very low, or no load, very low current flows through the transmission line. Shunt capacitance in the transmission line causes voltage amplification (Ferranti effect). At no load the receiving end voltage may increase abnormally high in very long transmission lines). To compensate, shunt inductors are connected across the transmission line.

In Fig. 2.7, a current source device is being used to compensate the reactive component of the load current (I_Q). As a result, the system voltage regulation is improved and the reactive current component from the source is reduced or almost eliminated as shown in Fig. 2.8. Also a current source or a voltage source can be used for inductive shunt compensation. The main advantages of using voltage or current source VAR generators (instead of inductors or capacitors) is that the reactive power generated is independent of the voltage at the point of connection[2].

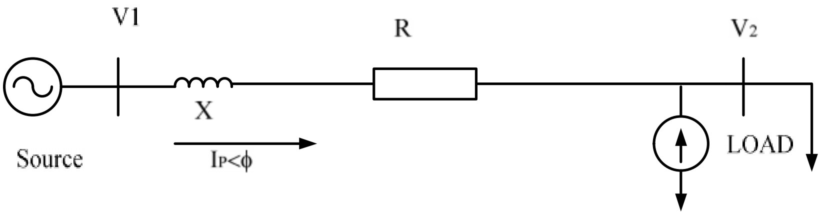

Figure 2.7 Representation of AC system with Shunt compensation

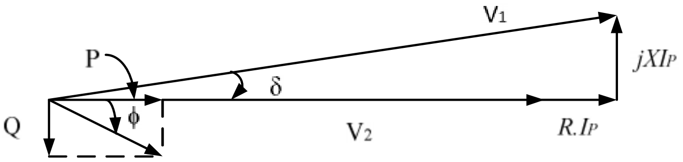

Figure 2.8 Phasor diagram of AC sytem with shunt compensation

The main purpose of shunt compensation is to provide the following:

- Steady state and dynamic voltage control.
- Reactive power control of dynamic loads.
- Damping of active power oscillations.
- Improvement of system stability.

2.2 SERIES COMPENSATORS

The series Compensator could be variable impedance, such as capacitor, reactor, etc., or a power electronics based variable source of main frequency to serve the desired need. Various Series connected FACTS devices are:

- Static Synchronous Series Compensator.
- Thyristor Controlled Series Capacitor.
- Thyristor Switched Series Capacitor.
- Thyristor Controlled Series Reactor.
- Thyristor Switched Series Reactor.

2.2.1 STATIC SYNCHRONOUS SERIES COMENSATOR (SSSC)

Static series compensator (SSSC) is generally implemented using GTO-based voltage source inverter that can provide controllable compensating voltage over an identical capacitive or inductive range independent of the line current as shown in Fig.2.9. The basic operation of SSSC is very much analogous to the conventional series compensation, except that it uses switching power converter as a synchronous voltage. SSSC is able to provide bi-directional compensation to the line by injecting compensating voltage into the series line. Therefore, SSSC is often used to enhance the dynamic behaviour of power system by providing temporarily increment and decrement of real power into the line as compensation.

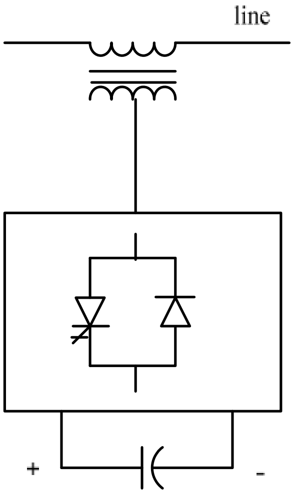

Figure 2.9 Schematic diagram of SSSC

2.2.2 THYRISTOR CONTROLLED SERIES COMPENSATOR (TCSC)

Thyristor controlled series compensator consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance as shown in Fig .2.10, the bi-directional thyristor valve that is fired with an angle α ranging between 90° and 180° with respect to the capacitor voltage.

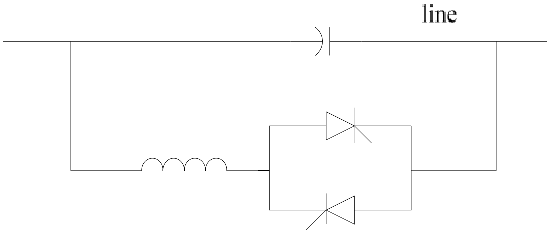

Figure 2.10 Schematic diagram of TCSC

The TCSC can be operated in bypass –thyristor mode, blocked-thyristor mode and vernier mode.

In bypass-thyristor mode, the thyristors are made to fully conduct with a conduction angle of 180^0.Gate pulses are applied as soon as the voltage across the thyristors reaches zero and becomes positive, resulting in a continuous flow of current through the thyristor valves. The TCSC module behaves like a parallel capacitor-inductor combination.

In blocked-thyristor mode, the firing pulses to the thyristor valves are blocked. If the thyristors are conducting and a blocking command is given, the thyristors turn off as soon as the current through them reaches a zero crossing. The net TCSC reactance is capacitive.

The vernier mode allows the TCSC to behave either as a continuously controllable capacitive reactance or as a continuously controllable inductive reactance. It is achieved by varying the thyristor-pair firing angle in an appropriate range.

2.2.3 THYRISTOR-SWITCHED SERIES CAPACITOR

It consists of a capacitor shunted by a pair of reversely parallel connected thyristor. The basic component that makes up a thyristor-switched series capacitor is shown in Fig 2.11.

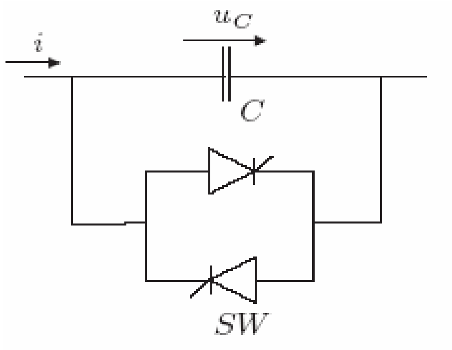

Figure 2.11 Schematic Diagram of TSSC

The operation of TSSC is to make use of a thyristor to act as a valve or switch for the capacitor connected parallel to it such that when thyristor is triggered the capacitor will be activated to start compensation.

2.2.4 THYRISTOR CONTROLLED SERIES REACTOR (TCSR)

TCSR is an inductive reactance compensator consists of a series reactor shunted by a thyristor controlled reactor in order to provide a smoothly variable series inductive reactance as shown in Fig. 2.12. When the firing angle of the thyristor controlled reactor is 180 degrees, it stops conducting, and the uncontrolled reactor acts as a fault current limiter. As the angle decreases below 180 degrees, the net inductance decreases until firing angle of 90 degrees, when the net inductance is the parallel combination of the two reactors. As in TCSC, the TCSR may be a single large unit or several smaller series units.

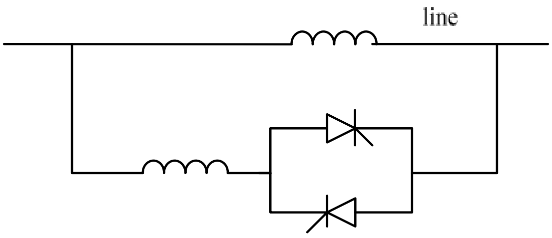

Figure 2.12 Schematic Diagram of TCSR

2.2.5 THYRISTOR-SWITCHED SERIES REACTOR (TSSR)

TSSR is an inductive reactance compensator which consists of a series reactor shunted by a thyristor-controlled switched reactor in order to provide a stepwise control of series inductive reactance. This is complement of TCSR, but with thyristor switches fully on or fully off to achieve a combination of stepped series inductance.

2.3 SHUNT COMPENSATORS

Shunt Controllers may be variable impedance, variable source, or a combination of these. In principle, all shunt Controllers inject current into the system at the point of connection. Various shunt connected controllers are:

- Static Synchronous Series Compensator
- Static VAR Compensator
- Thyristor Controlled Reactor
- Thyristor Switched Capacitor

2.3.1 STATIC SYNCHRONOUS SERIES COMPENSATOR (STATCOM)

STATCOM is a self commutated switching power converter supplied from an appropriate electric energy source and operated to produce a set adjustable multiphase voltage, which may be coupled to an AC power system for the purpose of exchanging independently controllable real and reactive power. The STATCOM is a solid-state-based power converter version of the SVC. Operating as a shunt-connected SVC, its capacitive or inductive output currents can be controlled independently from its terminal AC bus voltage. Basically, STATCOM is comprised of three main parts as shown in Fig. 2.13: a voltage source converter (VSC), a step-up coupling transformer, and a controller.

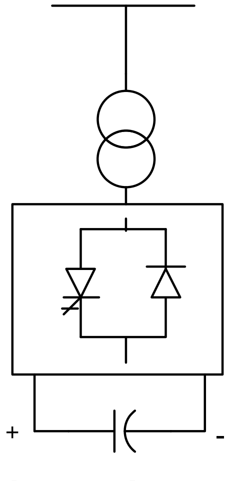

Figure 2.13 Schematic diagram of STATCOM

The advantages of STATCOM compared to other shunt compensators are equality of lagging and leading output, continuous reactive power control with fast response and possible active harmonic filter capability.

2.3.2 STATIC VAR COMPENSATOR (SVC)

SVC is “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”. Basically an SVC consists of a combination of fixed capacitors or reactors, Thyristor Switched Capacitors (TSC) and Thyristor Controlled Reactors (TCR) connected in parallel with the electrical system as shown in Fig.2.14. The basic structures and idea of the TSC is to split up a capacitor bank into sufficiently small capacitor steps and switch these steps on and off individually, using anti-parallel connected Thyristors as switching elements.

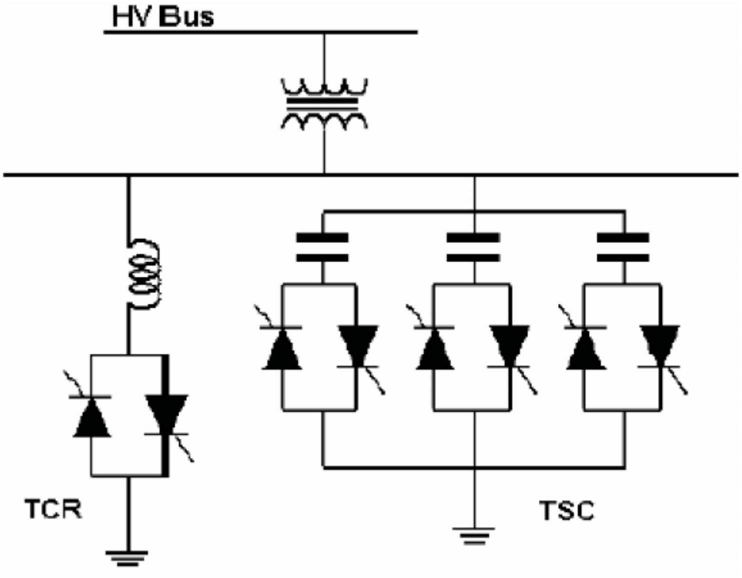

Figure 2.14 Schematic diagram of Static VAR Compensator (SVC)

2.3.3 THYRISTOR CONTROLLED REACTOR (TCR)

TCR is “A shunt connected, thyristor controlled inductor whose effective reactance is varied in a continuous manner by partial conduction control of the thyristor valve.” TCR is a subset of SVC, in which conduction time and hence, current in a shunt reactor is controlled by a thyristor based a.c. switch with firing angle control. The TCR consists of a fixed reactor of inductor L and a bi-directional Thyristor valve as shown in Fig.2.14, the schematic diagram of SVC Fig.2.14.

2.3.4 THYRISTOR SWITCHED CAPACITOR

TSC is a “A shunt-connected, thyristor-switched capacitor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve.” The TSC is different from TSR and TCR as its branch can be switched out at zero crossing of the current, as shown in Fig. 2.14 the schematic diagram of SVC.

2.4 COMBINED SERIES-SERIES CONTROLLERS

This may be a combination of separate series controllers, which are controlled in a coordinated manner, in a multi-line transmission system.

2.4.1 INTERLINE POWER FLOW CONTROLLER (IPFC)

The IPFC is the combination of two or more Static Synchronous Series Compensators which are coupled via a common dc link to facilitate bi-directional flow of real power between the ac terminals of the SSSCs as shown in Fig.2.15, and are controlled to provide independent reactive compensation for the adjustment of real power flow in each line and maintain the desired distribution of reactive power flow among the lines.

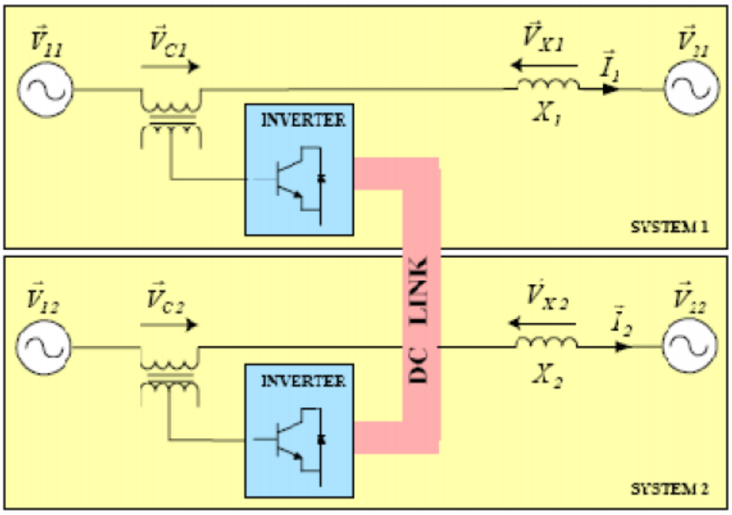

Figure 2.15 Schematic diagram of IPFC

2.5 COMBINED SERIES-SHUNT CONTROLLERS

This may be a combination of separate shunt and series controllers, which are controlled in a coordinated manner or a Unified Power Flow Controller with series and shunt elements. In principle, combined shunt and series controllers inject current into the system with shunt part of controller and voltage with the series part of controller. Various combined series shunt Controllers are:

- Unified Power Flow Controller
- Thyristor Controlled Phase Shifter

2.5.1 UNIFIED POWER FLOW CONTROLLER (UPFC)

Unified Power Flow Controller (UPFC) is “A combination of Static Synchronous Compensator (STATCOM) and a Static Synchronous Series Compensator (SSSC) as shown in Fig.2.16 which are coupled via a common d.c link to allow bi-directional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM; and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source.”

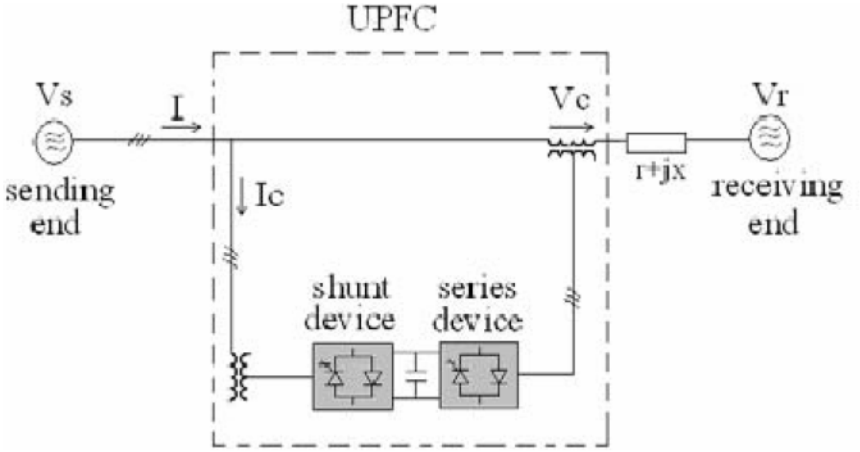

Figure 2.16 Basic Structure of UPFC

2.5.2 THYRISTOR CONTROLLED PHASE SHIFTING TRANSFORMER (TCPST)

Thyristor controlled phase shifting transformer is a phase shifting transformer adjusted by thyristor switches to provide a rapidly variable phase angle. In general, phase shifting is obtained by adding a perpendicular voltage vector in series with a phase as shown in Fig.2.17, the perpendicular series voltage is made variable with a variety of power electronic topologies.

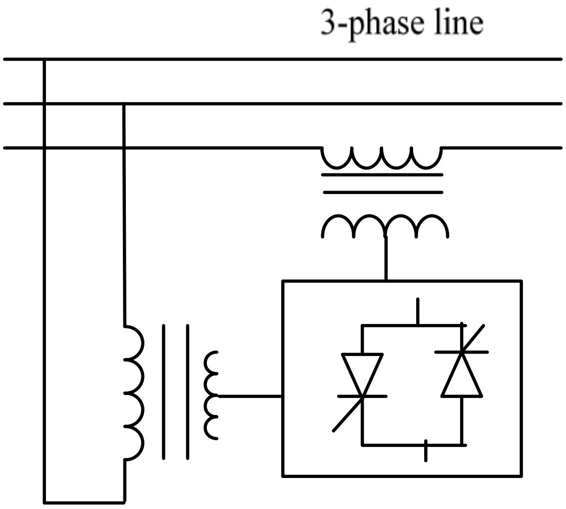

Fig.2.17 Schematic diagram of TCPST

2.6 OPPORTUNITIES FOR FACTS

The FACTS technology opens up new opportunities for controlling power and enhancing the usable capacity of present, as well as new and upgraded, lines. The FACTS controllers can enable a line to carry power closer to its thermal rating. FACTS device offers continuous control of power flow or voltage, against daily load changes. These opportunities arise through the ability of FACTS Controllers to control the interrelated parameters that govern the operation of transmission systems including series impedance, shunt impedance, current, voltage, phase angle, and the damping of oscillations at various frequencies below the rated frequency. Within the basic system security guidelines, the FACTS devices enable the transmission system to obtain one or more of the following benefits [9-10, 2]:

- Better utilization of existing transmission system assets:

Increasing the energy transfer capacity and controlling the load flow of transmission lines are is very important, especially in de-regulated power markets, where electricity supply and demand changes rapidly. Frequently, adding new transmission lines to meet increasing electricity demand is limited by economical and environmental constraints. FACTS devices help to meet these requirements with the existing transmission systems.

- Increased quality of supply for sensitive Industries:

Modern industries depend upon high quality electricity supply including constant voltage, and frequency and no supply interruptions. FACTS devices can help provide the required quality of supply.

- Increased Dynamic and Transient Stability:

Long transmission lines, interconnected grids, impacts of changing loads and line faults can create instabilities in transmission systems. These can lead to reduced line power flow, loop flows or even to line trips. FACTS devices stabilize transmission systems with resulting higher energy transfer capability and reduced risk of line trips.

- Increased transmission system reliability and availability:

Transmission system reliability and availability is affected by many different factors. Although FACTS devices cannot prevent faults, they can mitigate the effects of faults and provide more secure electricity by reducing the number of line trips. For example, a major load rejection results in an over voltage of the line which can lead to a line trip. SVC's or STATCOM's counteract the over voltage and avoid line tripping.

- Environmental Benefits:

FACTS devices are environmentally friendly. They contain no hazardous materials and produce no waste of pollutants

The FACTS controllers can be used for various purposes to enhance power system performance during steady state and dynamic state resulted due to transients and contingencies. Whereas, the conventional devices find little application during system transient or contingency condition [11-12].

2.6.1 APPLICATION OF FACTS UNDER STEADY STATE

Various steady state applications of FACTS controllers includes voltage control (low and high), increase of thermal loading, post-contingency voltage control, loop flows control, reduction in short circuit level and power flow control. The application of various FACTS controllers along with their conventional counterpart in addressing there limitations are summarized in Table 2.1. The primary advantage of FACTS controllers, over its conventional counterpart is the rapid control of current, voltage and/or impedance following disturbance. The conventional solutions are normally less expensive than FACTS devices, but limited in their dynamic behaviour. The steady state applications include-

- Reactive power and voltage control

- Increase thermal loading
- Post contingency and Voltage control
- Power flow balancing and control

Table 2.1 Application of Various FACTS devices

Issues	Problem	Corrective Action	Conventional Solution	New Equipment (FACTS)
Voltage Limits	Low voltage at heavy load	Supply reactive power	Shunt capacitor, Series capacitor	TCSC, STATCOM
	High voltage at light load	Remove reactive power supply	Switch EHV line and/or shunt capacitor	TCSC, TCR
		Absorb reactive power	Switch shunt capacitor, shunt reactor,SVC	TCR, STATCOM
	High voltage following outage	Absorb reactive power	Add reactor	TCR
		Protect equipment	Add arrestor	TCVL
	Low voltage following outage	Supply reactive power limit	Switch, shunt capacitor, reactor, SVC, switch series capacitor	STATCOM, TCSC
		Prevent over load	Series reactor, PAR	IPC, TCPAR, TCSC
	Low voltage and overload;	Supply reactive power and limit over load	Combination of two or more equipment	IPC, TCSC, UPFC, STATCOM
Thermal Limits	Line/transformer overload	Reduce overload	Add line/transformer	TCSC, TCPAR, UPFC
			Add series reactor	TCR, IPC
	Tripping of parallel circuit	Limit circuit loading		IPC,TCR, UPFC
Short-circuit levels	Excessive breaker fault current	Limit short-circuit current	Add series reactor, fuses, new circuit breaker	TCR, IPC, UPFC
		Change circuit breaker	Add new circuit breaker	
		Rearrange network	Split bus	IPC

- **REACTIVE POWER AND VOLTAGE CONTROL**

Under steady-state conditions, high loading and low voltage can be a limiting factor. The proper corrective action is to supply reactive power so as to correct the load power factor and to compensate for the reactive losses in lines and transformers. Traditionally, mechanically switched shunt capacitors (MSC) and reactors (MSR) were used for voltage control.

- **INCREASE THERMAL LOADING**

On a steady-state basis, equipment thermal limits represent a technical problem for which specific action is required. These hard limits can be removed only by adding transmission equipment or rearranging the network. Conventional solutions to transmission thermal overloads include a series reactor, series capacitors in parallel circuits.

- **POST-CONTINGENCY VOLTAGE CONTROL**

Depending on the change in network configuration caused by the outage, unacceptably high or low voltage conditions can result and thermal limits may be exceeded. Low voltage following an outage is one of the most widespread causes of transmission limitations. Indeed, most major transmission line loading levels are set by the maximum acceptable voltage drop and/or the minimum voltage a line loss would cause at other locations in the network, if not in neighbouring systems. The voltage drop due to the loss of a major line can be accompanied by circuit overloads, at the same voltage or at lower voltage levels. If only the final under voltage problem is of concern, the proper corrective actions to supply reactive power from mechanically switched shunt capacitors or to switch off shunt reactors. A STATCOM may offer better voltage support than a SVC. If a rapid solution to the voltage drop is needed to prevent load loss, the preferred FACTS controllers are those capable of supplying reactive power and controlling flows including IPC, UPFC and TCSC.

In the case of high post-contingency voltages, the rapid insertion of an overvoltage protective device such as the Thyristor Controlled Voltage Limiter (TCVL) may be the viable solution.

- **POWER FLOW BALANCING AND CONTROL**

FACTS controllers, especially TCSC, SSSC and UPFC, enable the load flow on parallel circuits and different voltage levels to be optimized and controlled, with a minimum of power wheeling, the best possible utilization of the lines, and a minimizing of overall system losses at the same time.

- **APPLICATION OF FACTS UNDER DYNAMIC STATE**

One of the most important capabilities expected of FACTS applications is to be able to reduce the impact of the primary disturbance. The impact reduction for contingencies can be achieved through dynamic voltage support (STATCOM), dynamic flow control (TCSC) or both with the use of UPFC. The typical applications in dynamic state include:

- Transient stability enhancement
- Oscillation damping
- Voltage stability enhancement
- SSR elimination

The above listed applications are explained briefly:

- **TRANSIENT STABILITY ENHANCEMENT:**

Transient instability is caused by large disturbances such as tripping of a major transmission line or a generator and the problem can be seen from the first swing of the angle. The conventional solutions for increasing synchronizing torques have been to equip generators with high response exciters and to shorten equivalent transmission distances with series capacitors. However, series capacitor compensated transmission network could be facing sub-synchronous resonance (SSR) problem. This can be overcome through an installation of appropriate FACTS controllers.

A SVC and STATCOM, near the electrical centre of the sending and receiving system can hold voltage or even raise voltage above nominal to transiently increase synchronizing power transfer. A TCPAR could control the effective angle between the sending and the receiving systems to extend the period over which synchronizing power is high. A UPFC, depending on the control strategy, can provide the benefits of a TCSC, PAR, SVC or a STATCOM. Moreover, a UPFC could also limit fault current (when the fault is downstream of the UPFC) by applying a series voltage that mimics a series reactor.

- **OSCILLATION DAMPING**

Electromechanical oscillations have been observed in many power systems worldwide and may lead to partial power interruption if not controlled. Initially, power system stabilizer (PSS) is used for oscillation damping in power system. Now this function can be more effectively handled by proper placement and setting of SVC, STATCOM and TCSC.

- **VOLTAGE STABILITY ENHANCEMENT**

Voltage stability (instability/collapse) is a totally different form of power system dynamic problem. Contrary to the loss of electromechanical stability, voltage instability is a possible consequence of progressive increase in load until the point of collapse is reached, beyond which little can be done except to prepare for system restoration. The collapse phenomenon is typically slow, over several minutes, depending on the time-varying behaviour of the loads. The following conventional corrective actions are possible;

- Reserve reactive support must be used, i.e. switched shunt capacitors and SVCs.
- Network control actions: coordinate system LTCs, recluse lines automatically; use HVDC station reactive power control capabilities.
- Load control: automatic undervoltage load shedding or operator initiated load shedding.
- Generator control action: remove generation to mitigate a transmission system overload, add local generation or trade real power for reactive power on critical generation.

- **SSR ELIMINATION**

Subsynchronous resonance (SSR) is a phenomenon which can be associated with series compensation under certain adverse conditions. TCSC have dynamic characteristics that differ drastically from conventional series capacitors especially at frequencies outside the operating frequency range and hence is used for the elimination of SSR in the power system.

CHAPTER-3

LOAD FLOW ANALYSIS WITH TCSC AND STATCOM

3.1 INTRODUCTION

Load flow studies are one of the most important aspects of power system planning and operation. The load flow provides us the sinusoidal steady state of the entire system - voltages, real, reactive powers and line losses. It provides solution of the network under steady state condition subjected to certain inequality constraints such as nodal voltages, reactive power generation of the generators. Load flow studies gives the voltage magnitudes and angles at each bus in the steady state. This is rather important as the magnitudes of the bus voltages are required to be held within a specified limit. Once the bus voltage magnitudes and their angles are computed, the real and reactive power flow through each line can be computed. Also based on the difference between power flow in the sending and receiving ends, the losses in a particular line can also be computed. Furthermore, from the line flow conditions of over and under load can be determined [13].

3.2 CLASSIFICATION OF BUSES

The system consists of three basic individual components: generators, transmission lines and loads. The system buses can be classified as slack bus, generator or voltage controlled buses and load buses as shown in Fig. 3.1. There are four system variables namely real power injection, P_i, reactive power injection, Q_i, voltage magnitude, V_i, and phase angle, δ_i are used to characterize each bus i; usually for each bus two system variables are controllable and other two are uncontrollable. Mathematically, a bus with largest generation is referred as a slack or swing bus compensates for system losses. A slack or swing bus, voltage controlled buses and load buses are distinguished by different set of controllable variables.

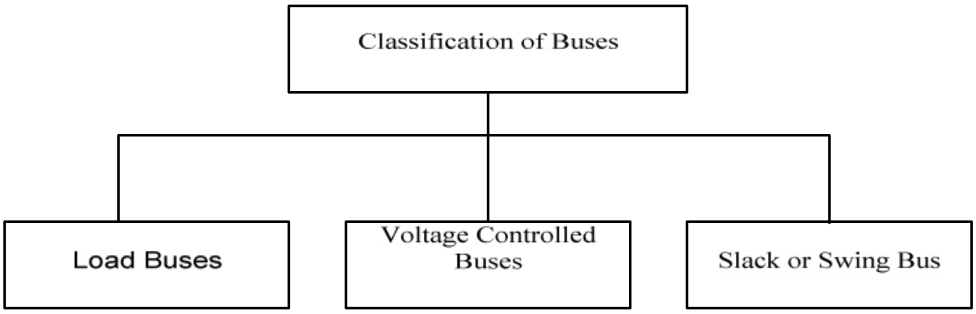

Figure 3.1 Classification of Buses

Slack or Swing bus: A power source of infinite power output capability. This bus takes the additional real and reactive power to supply transmission losses. Controllable variables are voltage magnitude, V, and phase angle δ.

Load buses: Controllable variables are real and reactive power injection P_i and Q_i respectively.

Voltage controlled buses: Controllable variables are real power injection, P_i, and voltage magnitude, V_i.

3.3 YBUS FORMULATION

For a interconnected system, if the value of admittance for each interconnecting circuit are known, the admittance matrix may be assembled as follows:

- The diagonal element of each node is the sum of the admittance connected to it.
- The off-diagonal element is the negated admittance between the nodes.

If any shunt branch is present then shunt admittance are added to the diagonal elements corresponding to the nodes at which they are connected[14].

The π-equivalent model shown in fig 3.2 is often used to describe transmission line ij.

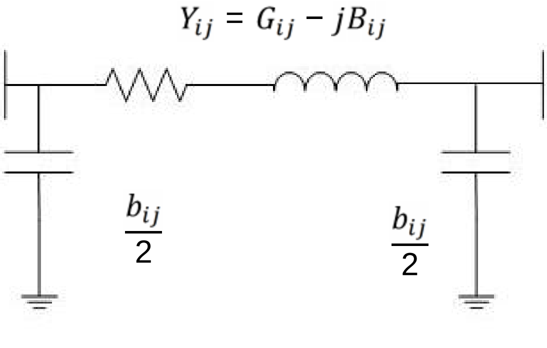

Figure 3.2 π-equivalent model of transmission line

Admittance Y is used to describe the topological properties of transmission network.

The entries of Y, y_{ij} are given by:

$$y_{ii} = \sum_{j\neq i} Y_{ij} \qquad (3.1)$$

$$y_{ij} = -Y_{ij}$$

where Yij is the admittance of transmission line *ij* as shown in Fig.3.2, Y provides a convenient notation of relating various system variables. For example, the network bus voltages, V and currents, I, are related simply by:

$$I = \begin{bmatrix} I_1 \\ I_2 \\ \cdot \\ \cdot \\ \cdot \\ I_{l+g} \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} & \cdot & \cdot & \cdot & y_{1(l+g)} \\ y_{21} & y_{22} & \cdot & \cdot & \cdot & y_{2(l+g)} \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ y_{(l+g)1} & y_{(l+g)2} & \cdot & \cdot & \cdot & y_{(l+g)(l+g)} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \cdot \\ \cdot \\ \cdot \\ V_{(l+g)} \end{bmatrix} = YV$$

3.4 POWER FLOW EQUATIONS

Complex power at bus *i*, S_i is given by,

$$S_i = V_i I_i^{*} \qquad (3.2)$$

$$S_i = V_i \sum_{j=0}^{l+g} Y_{ij}^{*} V_j^{*} \qquad i = 0,1,\ldots,l+g \qquad (3.3)$$

Let $V_i = V_i e^{j\delta_i}$

$$\delta_{ij} = \delta_i - \delta_j$$

$$Y_{ij} = G_{ij} + jB_{ij}$$

Where G_{ij} = conductance of transmission line *ij*.

B_{ij} = susceptance of transmission line *ij*

l = number of load buses and

g = number of generator buses

Then Eq.(3.3) becomes

$$S_{ij} = \sum_{j=0}^{l+g} V_i V_j e^{j\delta_{ij}} (G_{ij} - jB_{ij})$$

$$= \sum_{j=0}^{l+g} V_i V_j \left(\cos\delta_{ij} + j\sin\delta_{ij}\right)\left(G_{ij} - jB_{ij}\right) \qquad i = 0,1,\ldots,l+g. \qquad (3.4)$$

The power flow equations for a bus *i* of the power system are given by

$$P_i = \sum_{j=1}^{N} |V_i||V_j||Y_{ij}| \cos\left(\delta_i - \delta_j - \theta_{ij}\right) \qquad (3.5)$$

$$Q_i = \sum_{j=1}^{N} |V_i||V_j||Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) \qquad (3.6)$$

Where *l* = number of load buses

g = number of generator buses

Thus, the load flow equations are of the form:

$$\begin{cases} P = P(V, \delta) \\ Q = Q(V, \delta) \end{cases} \qquad (3.7)$$

Given the controllable system variables, the objective is to solve eq. (3.7) for the uncontrollable system variables. This is a nonlinear problem and the solution cannot be found analytically in most case. Newton-Raphson method is normally preferred because of its quadratic convergence characteristic.

3.5 JACOBIAN MATRIX

Newton-Raphson method is an iterative method which approximates the set of non linear simultaneous equations to a set of linear simultaneous equations using Taylor's series expansion and the terms are limited to first approximation.

Let the unknown variables be (x1, x2,…..xn) and the specified quantities are y1, y2,...yn.

These are related by set of non-linear equations:

$$\begin{aligned} y_1 &= f_1(x_1, x_2, \dots, x_n) \\ y_2 &= f_2(x_1, x_2, \dots x_n) \qquad (3.8) \\ &\square \\ y_n &= f_3(x_1, x_2, \dots x_n) \end{aligned}$$

To solve these equations, start with an approximate solution $(x_1^0, x_2^0, \dots x_n^0)$. Here superscript zero means zeroth iteration in the process of solving the above non-linear Eq.(3.8).The equations are linearized about the initial guess.

Assume $\Delta x_1^0, \Delta x_2^0, \dots \Delta x_n^0$ are the correction required for $x_1^0, x_2^0, \dots x_n^0$ respectively for the next better solution.

$$\begin{aligned} y_1 &= f_1(x_1^0 + \Delta x_1^0, x_2^0 + \Delta x_2^0, \dots x_n^0 + \Delta x_n^0) \\ &= f_1(x_1^0, x_2^0, \dots x_n^0) + \Delta x_1^0 \frac{\partial f_1}{\partial x_1}\bigg|_{x^0} + \Delta x_2^0 \frac{\partial f_1}{\partial x_2}\bigg|_{x^0} + \cdots \square_1 \end{aligned}$$

Where $\square_1$ are higher order derivatives and are neglected according to Newton-Raphson method.

If all the equations are linearized and arranged in a matrix form as given below:

$$\begin{bmatrix} y_1 - f_1(x_1^0, x_2^0, \dots x_n^0) \\ y_2 - f_2(x_1^0, x_2^0, \dots x_n^0) \\ \vdots \\ y_n - f_n(x_1^0, x_2^0, \dots x_n^0) \end{bmatrix} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} \\ \vdots & \vdots \\ \frac{\partial f_n}{\partial x_1} & \frac{\partial f_n}{\partial x_2} \end{bmatrix} \begin{bmatrix} \Delta x_1^0 \\ \Delta x_2^0 \\ \vdots \\ \Delta x_n^0 \end{bmatrix} \tag{3.9}$$

eq.(3.9) can be represented as

$$B = J.C$$

Where

J is the first derivative matrix known as the Jacobian matrix.

B is difference of the specified quantities and calculated quantities.

The better solution is obtained as follows:

$$\begin{aligned} x_1^1 &= x_1^0 + \Delta x_1^0 \\ x_2^1 &= x_2^0 + \Delta x_2^0 \\ x_n^1 &= x_n^0 + \Delta x_n^0 \end{aligned} \tag{3.10}$$

When referred to power system problem, considering first bus as slack bus, the above set of linearized eq.(3.10) becomes

$$\begin{bmatrix} \Delta P_2 \\ \Delta P_3 \\ \vdots \\ \Delta P_n \\ \Delta Q_2 \\ \Delta Q_3 \\ \vdots \\ \Delta Q_n \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2}{\partial e_2} & \frac{\partial P_2}{\partial e_3} & \cdots & \frac{\partial P_2}{\partial e_n} & \frac{\partial P_2}{\partial f_2} & \frac{\partial P_2}{\partial f_3} & \cdots & \frac{\partial P_2}{\partial f_n} \\ \frac{\partial P_3}{\partial e_2} & \frac{\partial P_3}{\partial e_3} & \cdots & \frac{\partial P_3}{\partial e_n} & \frac{\partial P_3}{\partial f_2} & \frac{\partial P_3}{\partial f_3} & \cdots & \frac{\partial P_3}{\partial f_n} \\ \vdots & \vdots & \cdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ \frac{\partial P_n}{\partial e_2} & \frac{\partial P_n}{\partial e_3} & \cdots & \frac{\partial P_n}{\partial e_n} & \frac{\partial P_n}{\partial f_n} & \frac{\partial P_n}{\partial f_3} & \cdots & \frac{\partial P_n}{\partial f_n} \\ \frac{\partial Q_2}{\partial e_2} & \frac{\partial Q_2}{\partial e_3} & \cdots & \frac{\partial Q_2}{\partial e_n} & \frac{\partial Q_2}{\partial f_2} & \frac{\partial Q_2}{\partial f_3} & \cdots & \frac{\partial Q_2}{\partial f_n} \\ \frac{\partial Q_3}{\partial e_2} & \frac{\partial Q_3}{\partial e_3} & \cdots & \frac{\partial Q_3}{\partial e_n} & \frac{\partial Q_3}{\partial f_2} & \frac{\partial Q_3}{\partial f_3} & \cdots & \frac{\partial Q_3}{\partial f_n} \\ \vdots & \vdots & \cdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ \frac{\partial Q_n}{\partial e_2} & \frac{\partial Q_n}{\partial e_3} & \cdots & \frac{\partial Q_n}{\partial e_n} & \frac{\partial Q_n}{\partial f_2} & \frac{\partial Q_n}{\partial f_3} & \cdots & \frac{\partial Q_n}{\partial f_n} \end{bmatrix} \begin{bmatrix} \Delta e_2 \\ \Delta e_3 \\ \vdots \\ \Delta e_n \\ \Delta f_2 \\ \Delta f_3 \\ \vdots \\ \Delta f_n \end{bmatrix}$$

In short form it can be written as

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta e \\ \Delta f \end{bmatrix}$$

Where J_1, J_2, J_3 and J_4 are Jacobian elements.

3.6 MODELLING OF TCSC

Power flow calculations are performed in power systems for planning, operational planning, and operation/control. Flexible AC transmission system (FACTS) controllers are able to change the network parameters in a fast and effective way in order to achieve better system performance. These controllers are used for enhancing dynamic performance of power systems in terms of voltage/angle stability while improving the power transfer capability and voltage profile in steady state [15-18].

The mathematical models of the FACTS devices are developed mainly to perform the steady-state research. Therefore the TCSC is modelled to modify the reactance of the transmission directly. The function of the TCSC is to alter the value of the transmission line reactance by adding either a capacitive or inductive component to the main transmission line reactance as shown in Fig. 3.4.

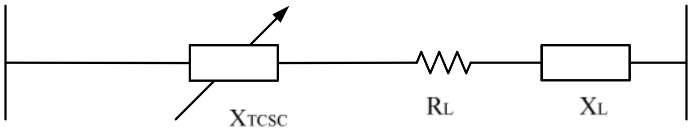

Figure 3.3 The effect of TCSC on transmission line reactance

The reactance of the line where TCSC is placed is given by:

$$X_{ij} = X_L + X_{TCSC} \qquad (3.11)$$

where X_L is the reactance of the transmission line and X_{TCSC} is the reactance of TCSC. To avoid overcompensation, the working range of TCSC is selected between $-0.7X_L$ and $0.2\ X_L$.

After adding TCSC on the line between bus i and bus j of a general power system, the new system admittance matrix Y'_{bus} can be updated as:

$$Y'_{bus} = Y_{bus} + \begin{array}{cc} \left[\begin{array}{ccccccc} 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & \Delta y_{ij} & 0 & \dots & 0 & -\Delta y_{ij} & 0 \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & -\Delta y_{ij} & 0 & \dots & 0 & \Delta y_{ij} & 0 \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 \end{array}\right] & \begin{array}{l} \\ \textit{row-i} \\ \\ \\ \\ \textit{row-j} \\ \\ \end{array} \\ \begin{array}{ccccccc} & \textit{col-i} & & & & \textit{col-j} & \end{array} & \end{array}$$

Because the Y_{bus} has to be updated for each of different locations and the amount of compensation of TCSC, the above formulation is applied at each iteration.

3.7 MODELLING OF STATCOM

The static compensator (STATCOM) is one of the most prominent members in the family of FACTS devices, which is connected in shunt to the transmission grid. It is usually used to control transmission voltage by reactive power compensation. In ideal steady state analysis, it can be assumed that active power exchange between the AC system and the STATCOM can be neglected, and only the reactive power can exchanged between them [19-21].

The presence of FACTS controllers is accommodated and accounted for by adding new equations to the set of the power flow equations and modifying some of the existing power flow equations as needed. The Jacobian equation is modified accordingly. Fig. 3.5 shows the circuit model of a STATCOM connected to Bus *k* of an *N*-Bus power system; the subscript '*p*' means the STATCOM is connected in parallel with the power system. The STATCOM is modelled as a controllable voltage source (E_p) in series with impedance.

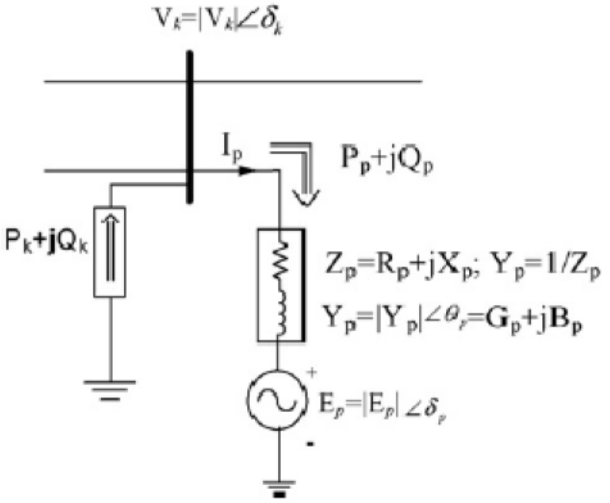

Figure 3.4 Steady state model of STATCOM

The power flow equations for a bus i of the power system with no FACTS controller is given by:

$$P_i = \sum_{j=1}^{N} |V_i||V_j||Y_{ij}|\cos(\delta_i - \delta_j - \theta_{ij}) \quad (3.12)$$

$$Q_i = \sum_{j=1}^{N} |V_i||V_j||Y_{ij}|\sin(\delta_i - \delta_j - \theta_{ij}) \quad (3.13)$$

Where V*i* represents complex voltage of a bus *i* and Yij represents (i,j)-entry of the Y matrix. With the addition of STATCOM connected at bus k the power flow equations of the system remain same as the power flow equation of the system without STATCOM for all buses given by Eqs. (3.12) and (3.13), except for bus k which are given below.

$$P_p = G_p|V_k^2| - |V_k||E_p||Y_p|\cos(\delta_k - \delta_p - \theta_p) \quad (3.14)$$

$$Q_p = -B_p|V_k^2| - |V_k||E_p||Y_p|\sin(\delta_k - \delta_p - \theta_p) \quad (3.15)$$

where $|E_p|$,δ_p,$|Y_p|$ and θ_p are defined in Fig 3.5.

Addition of STATCOM introduces two new variables ($|E_p|$ and δ_p). Thus one more equation needed to solve the power flow problem. This equation is found using the fact that power consumed by the source E_p (called P_{Ep}) must be zero in steady state and is given by eq.(3.16)

$$\begin{aligned} P_{Ep} &= Real\left[E_p I_p^*\right] \quad (3.16) \\ &= -(G_p)\left|E_p^2\right| + |E_p||V_k||Y_p|\left(cos\,(\delta_p - \delta_k - \theta_p)\right) = 0 \end{aligned}$$

A row and a column related to P_{Ep} and δp are added to Jacobian matrix.. The modified Jacobian elements are as given below:

$$\frac{\partial P_{Ep}}{\partial \delta_k} = +|E_p||V_k||Y_p|\sin(\delta_p - \delta_k - \theta_p) \quad (3.17)$$

$$\frac{\partial P_{Ep}}{\partial |E_p|} = -2G_p|E_p| + |V_k||Y_p|\cos(\delta_p - \delta_k - \theta_p) \quad (3.18)$$

$$\frac{\partial P_{Ep}}{\partial |\delta_p|} = -E_p||V_k||Y_p|\sin(\delta_p - \delta_k - \theta_p) \quad (3.19)$$

$$\frac{\partial P_k}{\partial \delta_p} = \frac{\partial P_p}{\partial \delta_p} \quad (3.20)$$

$$\frac{\partial Q_k}{\partial \delta_p} = \frac{\partial Q_p}{\partial \delta_p} \quad (3.21)$$

$$\frac{\partial P_k}{\partial \delta_k} = \frac{\partial P_p}{\partial \delta_p} + \frac{\partial P_k}{\partial \delta_k}(original) \quad (3.22)$$

$$\frac{\partial P_k}{\partial \delta_k} = \frac{\partial P_p}{\partial |E_p|} \qquad (3.23)$$

$$\frac{\partial Q_k}{\partial \delta_k} = \frac{\partial Q_p}{\partial \delta_k} + \frac{\partial Q_k}{\partial \delta_k}(original) \qquad (3.24)$$

$$\frac{\partial Q_k}{\partial |E_p|} = \frac{\partial Q_p}{\partial |E_p|} \qquad (3.25)$$

And the following terms are found from eqs. (3.14) and (3.15):

$$\frac{\partial P_p}{\partial |\delta_p|} = -|V_k||E_p||Y_p|\sin(\delta_k - \delta_p - \theta_p) \qquad (3.26)$$

$$\frac{\partial P_p}{\partial |\delta_k|} = -\frac{\partial P_p}{\partial |\delta_p|} \qquad (3.27)$$

$$\frac{\partial P_p}{\partial |E_p|} = -|V_k||Y_p|\cos(\delta_k - \delta_p - \theta_p) \qquad (3.28)$$

$$\frac{\partial Q_p}{\partial |\delta_k|} = -|V_k||E_p||Y_p|\cos(\delta_k - \delta_p - \theta_p) \qquad (3.29)$$

$$\frac{\partial Q_p}{\partial |E_p|} = -|V_k||Y_p|\sin(\delta_k - \delta_p - \theta_p) \qquad (3.30)$$

3.8 ALGORITHM FOR LOAD FLOW SOLUTION

The algorithm for Newton-Raphson procedure is as follows:

Step1: Read system database for line data, bus data and limits for reactive power and voltage.

Step 2: Form Y_{bus} using line data. Choose the initial values of the voltage magnitudes V_i of all n_p (number of load buses) and $(n - 1)$ angles δ_i of the voltages of all the buses (n) except the slack bus. Let $V_i = 1+j0$.

Step 3: Set convergence criterion equal to ε.

Step 4: Set bus count i=2.

Step 5: Calculate real and reactive powers Pi and Qi using eq. (3.31) and eq. (3.32),

$$P_i = \sum_{j=1}^{n} |V_i|\,|V_j||Y_{ij}|\cos\,(\theta_{ij} - \delta_i + \delta_j) \qquad (3.31)$$

$$Q_i = -\sum_{j=1}^{n} |V_i|\,|V_j||Y_{ij}|sin\,(\theta_{ij} - \delta_i + \delta_j) \qquad (3.32)$$

$$\Delta P_i = P_i^{sp} - P_i^{k} \qquad (3.33)$$

$$\Delta Q_i = Q_i^{sp} - Q_i^{k} \qquad (3.34)$$

where

P_i^{sp}= net real power

Q_i^{sp} =net reactive power

For load buses *Pi*,*Qi*, Δ*Pi* and Δ*Qi* are calculated using eq. (3.33) and eq. (3.34).

For voltage controlled buses *Pi* and Δ*Pi* are calculated.

Step 6: Check type of bus, if the bus is generator bus PV then check the reactive power limits, if it exceeds the limit, fix the reactive power generation to the corresponding limit.

Step 7: Advance bus count i= i+1.

Step 8: determine the largest of the absolute of the residue using eq.(3.35) and if less than the convergence criterion then compute line flows and slack bus power and terminate the process.

$$\begin{cases} |\Delta P_i| \le \varepsilon \\ |\Delta Q_i| \le \varepsilon \end{cases} \tag{3.35}$$

Step9: Compute elements of Jacobian matrix.

For the load flow problem, this equation is of the form

$$J\begin{bmatrix} \Delta\delta_2 \\ \vdots \\ \Delta\delta_n \\ \frac{\Delta|V_2|}{|V_2|} \\ \vdots \\ \frac{\Delta|V_{1+np}|}{|V_{1+no}|} \end{bmatrix} = \begin{bmatrix} \Delta P_2 \\ \vdots \\ \Delta P_n \\ \Delta Q_2 \\ \vdots \\ \Delta Q_{1+np} \end{bmatrix} \tag{3.36}$$

where J is given by

$$J = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix}$$

It can be seen that the size of Jacobian matrix is (n+n_p-1) x (n+n_p-1).The size of the submatrices are as follows:

J_{11}: (n-1) x (n-1)

J_{12}: (n-1) x n_p

J_{21}: $n_p \times (n-1)$

J_{22}: $n_p \times n_p$

The submatrices are:

$$J_{11} = \begin{bmatrix} \frac{\partial P_2}{\partial \delta_2} & \cdots & \frac{\partial P_2}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n}{\partial \delta_2} & \cdots & \frac{\partial P_n}{\partial \delta_n} \end{bmatrix}$$

$$J_{12} = \begin{bmatrix} |V_2| \frac{\partial P_2}{\partial |V_2|} & \cdots & |V_{1+np}| \frac{\partial P_2}{\partial |V_{1+np}|} \\ \vdots & \ddots & \vdots \\ |V_2| \frac{\partial P_n}{\partial |V_2|} & \cdots & |V_{1+np}| \frac{\partial P_n}{\partial |V_{1+np}|} \end{bmatrix}$$

$$J_{21} = \begin{bmatrix} \frac{\partial Q_2}{\partial \delta_2} & \cdots & \frac{\partial Q_2}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_{1+np}}{\partial \delta_2} & \cdots & \frac{\partial Q_{1+np}}{\partial \delta_n} \end{bmatrix}$$

$$J_{22} = \begin{bmatrix} |V_2| \frac{\partial Q_2}{\partial |V_2|} & \cdots & |V_{1+np}| \frac{\partial Q_2}{\partial |V_{1+np}|} \\ \vdots & \ddots & \vdots \\ |V_2| \frac{\partial Q_n}{\partial |V_2|} & \cdots & |V_{1+np}| \frac{\partial Q_n}{\partial |V_{1+np}|} \end{bmatrix}$$

and find out ΔVi and $\Delta\delta_i$ by solving eq.(3.36)

Step 10: Obtain the updates from eq.(3.37) and eq.(3.38).

$$\delta i = \delta i + \Delta \delta i \qquad (3.37)$$

$$|Vi| = |Vi| + \Delta|Vi| \qquad (3.38)$$

Step 11: Evaluate cos δ and sin δ of all voltages

Step 12: Check for voltage limits and set the voltages to their limits.

Step 13: advance the iteration counter K=K+1

The process of Newton- Raphson method is depicted in Fig. 3.6.

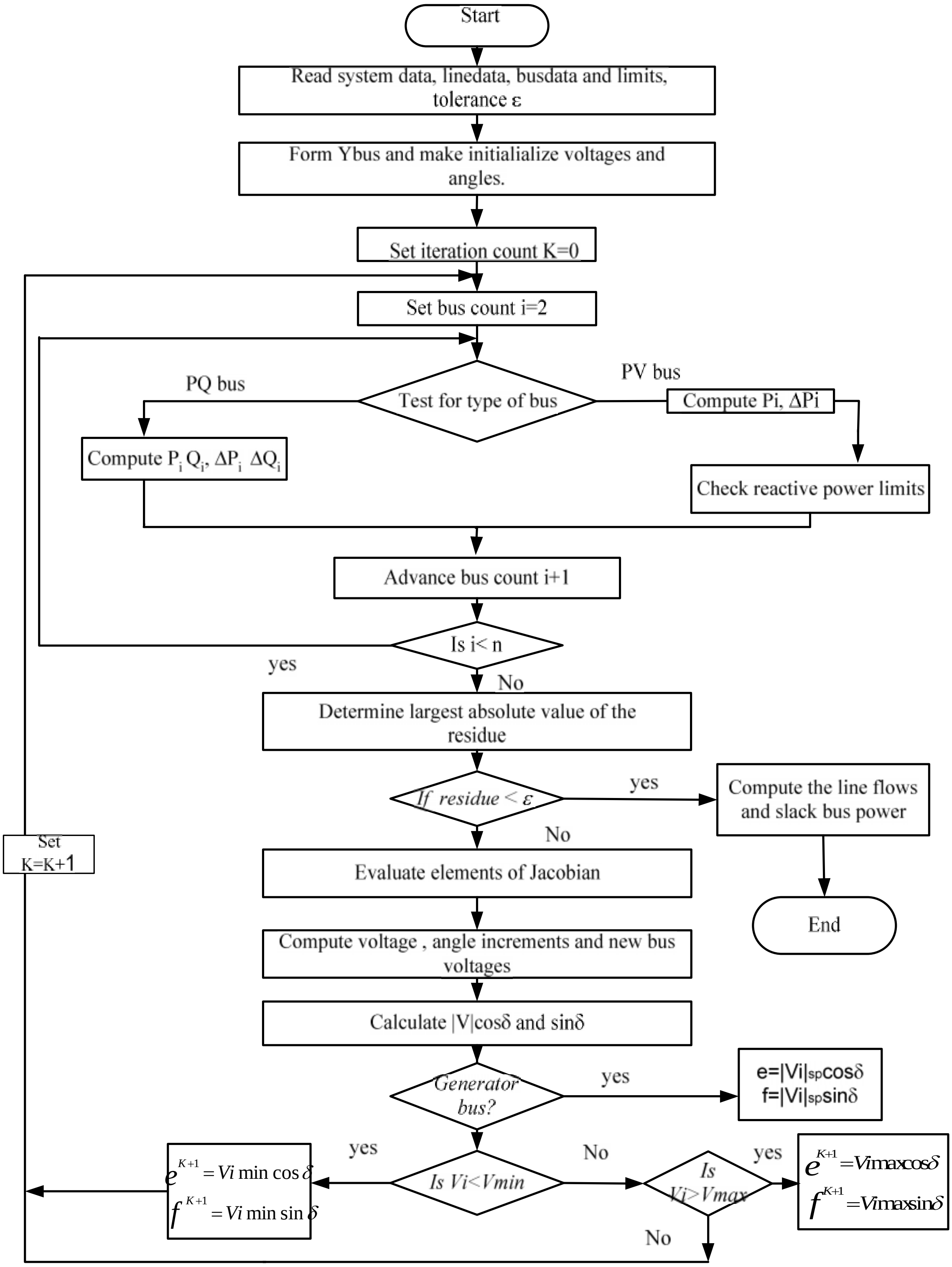

Figure 3.5 Flow chart for Newton-Raphson method

3.8.1 ALGORITHM FOR LOAD FLOW WITH TCSC

The steps to incorporate TCSC in the system are as follows:

Step1: Read system database for linedata, busdata and limits.

Step2: Reactance of TCSC X_{TCSC} is generated in the working range, working range selected is

$$-0.7X_L \leq X_{TCSC} \leq 0.2X_L$$

This range is selected to avoid overcompensation.

Step3: Modify the reactance of line using Eq.():

$$X_{ij} = X_L + X_{TCSC}$$

Step4: Carry Newton-Raphson method as described in section 3.8.

3.8.2 ALGORITHM FOR LOAD FLOW WITH STATCOM

The steps to incorporate STATCOM are as follows:

Step 1: Read the system database.

Step 2: The system buses, at which STATCOM are assumed to be placed are made PV buses.

Step 3: The specified real power and reactive power at which STATCOM is placed is calculated using eq. (3.14) and eq. (3.15).

Step 4: On the buses with STATCOM, the specified voltage is set according to the desired voltage and upper and lower limits of reactive power are set according to the STATCOM ratings.

Step 5: Modify Jacobian elements as described in section 3.6 and using eq.(3.17) to eq.(3.30).

Step 6: Carry Newton-Raphson load flow with modified Jacobian elements.

Step 7: Voltages and angles of system and STATCOM are updated.

CHAPTER-4

FACTS ALLOCATION USING EVOLUTIONARY ALGORITHM

4.1 INTRODUCTION

Genetic Algorithm is one of the Evolutionary Algorithms search technique. The method was developed by John Holland. Genetic Algorithms are global search techniques based on the mechanism of natural selection and genetics. They can search several possible solutions simultaneously and produces high quality solutions. The goal of optimization is to find out the best optimal location of TCSC(s) and STATCOM(s) in power system using genetic algorithm [5]. The genetic algorithm follows the following steps:

Step1: Generate an initial population of binary string.

Step2: Calculate fitness value of each member of population based on the problem type (minimization or maximization).

Step3: Generate offspring string through reproduction, crossover and mutation and evaluate.

Step4: Calculate fitness value for each string.

Step5: Terminate the process if required solution is obtained or number of generation is attained. The above process is represented in flow chart as shown in Fig.4.1

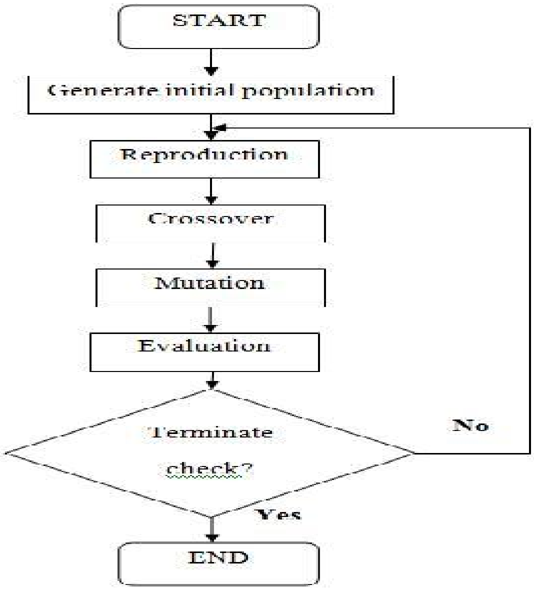

Figure 4.1 Flow Chart for Genetic Algorithm

4.2 OPTIMAL PLACEMENT OF TCSC

Thyristor-controlled series compensators (TCSC) are connected in series with the lines. The effect of a TCSC on the network can be seen as a controllable reactance inserted in the related transmission line that compensates for the inductive reactance of the line. This reduces the transfer reactance between the buses to which the line is connected. This leads to an increase in the maximum power that can be transferred on that line in addition to a reduction in the power losses. The series capacitors also contribute to an improvement in the voltage profiles. To find out the optimal location of TCSC, the objective function used is minimization of losses [15].

4.2.1 OBJECTIVE FUNCTION

As the main objective of this work is to determine the optimal location of the FACTS devices (TCSC and STATCOM) in the power network to minimize the losses, the following performance index is selected:

$$min\ F_l = \sum_{k=1}^{ntl} P_{Ltl} \tag{4.1}$$

where

F_l is the objective function to minimize active power losses.

P_{Ltl} is the active power loss in tl^{th} line.

ntl is the number of transmission lines in the system.

Subjected to constraints:

$$P_i^{min} \le P_i \le P_i^{max} \quad i = 1,2, \dots ng$$

$$Q_i^{min} \le Q_i \le Q_i^{max} \quad i = 1,2, \dots ng$$

$$V_i^{min} \le V_i \le V_i^{max} \quad i = 1,2, \dots n$$

$$\delta_i^{min} \le \delta_i \le \delta_i^{max}$$

For TCSC

$$-0.7X_L \le X_{TCSC} \le 0.2X_L$$

For STATCOM

$$Q_{smn} \le Q_s \le Q_{smx}$$

where

Q_s is the reactive power injected by the STATCOM into the system.

Q_{smn} is the minimum limit of reactive power injected.

and Q_{smx} is the maximum limit of reactive power injected.

Where ng= number of generator buses

n= number of buses

X_{TCSC}= reactance of TCSC

X_L= reactance of line.

To find optimal location of TCSC load flow using Newton-Raphson method is run to evaluate active power losses i.e objective function and then GA is applied.
The steps to solve the Genetic Algorithm to find out optimal location of TCSC with the coding structure and 5-bus example is described as follows:

4.2.2 ENCODING AND INTIALIZATION

Genetic Algorithms operate with a set of strings instead of a single string. This set of strings is known as a population and is put through the process of evolution to produce new individual strings. The population size depends on the nature of the problem, but typically contains several hundreds or thousands of possible solutions. Initial population is generated on the basis of population size and stringlength.

For 5-bus system, initialization is done as follows:

Step1: First generated random values for the TCSC reactance in the working range ($-0.7\ X_L < X_{TCSC} < 0.2X_L$)

Step2: Then generated a set of random number equal to number of transmission lines consists of 0's and 1's.

Step3: Multiply the values of TCSC reactance generated with the set of random numbers generated in step 2.

For 5-bus problem, number of transmissions lines are seven so the initial population will be of the form

TCSC1	TCSC2	TCSC3	TCSC4	TCSC5	TCSC6	TCSC7
0.032	0	-0.542	0.034	-0.656	0	-0.346

where TCSC1, TCSC2…..TCSC7 shows the value parameter of TCSC (i.e reactance) connected to the line. The value of TCSC reactance represents that TCSC is present and 0 represents that TCSC is not present. The bit number from the left gives the line in which TCSC is located or not. Negative value emulates capacitive reactance and positive value emulates inductive reactance.

4.2.3 FITNESS FUNCTION CALCULATION

After initialization, the fitness is evaluated for each individual of the population. The fitness is measure to of quality which is used to compare different solutions In general, a fitness function F(x) is first derived from the objective function and used in successive genetic operations, here objective function is loss minimization as given by eq.(4.1).

For minimization problems, the fitness function is an equivalent maximization problem chosen such that the optimum point remains unchanged. The following fitness function for loss minimization problems can be expressed as:

$$F(X) = \frac{1}{1 + F_l}$$

As it is easy to find the maximum value of objective function using GA, so inverse function is selected to convert the objective function into a maximum one.

4.2.4 REPRODUCTION

Reproduction is a process where the individual is selected to move to a new generation according to its fitness. In reproduction process the fittest individual is selected. The various methods to select individuals are Roulette-wheel selection,Boltzmann selection, Tournament selection and Rank selection.In this problem formulation Roulette-wheel selection criterion is used and detailed as follows:

Each individual in the population has its interval. The size of each interval corresponds to the fitness of the individual and can be defined as:

$$P_i = F_i / \sum_{i} F_i$$

Where
P*i* = probability for selecting *ith* string.
F*i*= the fitness of *ith* individual.

To select an individual, a random number is generated in the interval and the individual whose segment spans the random number is selected. The probability of an individual's reproduction is proportional to its fitness.

4.2.5 CROSSOVER

Crossover is applied after reproduction, purpose of crossover is to exchange information among the strings of mating pool to create new strings. There are three forms of crossover: one point crossover, multipoint crossover and uniform crossover.

One point crossover is applied for the implementation of GA and is described as follows:

Two individual strings (parent1 and parent 2) are selected at random from the mating pool. Next select a crossover site (cpoint), suppose site 3 is selected at random along the stringlength. Then, from the point of crossover, elements of the strings of both individuals are exchanged [27].

parent1 {0.192 -0.456 -0.678 0.023 -0.567 -0.667 -0.566}
parent2 {-0.578 -0.666 0.050 -0.435 -0.622 -0.448 0.156}

then offsprings generated for cpoint=3 will be:

offspring 1 {0.192 -0.456 -0.678 **-0.435 -0.622 -0.448 0.156**}
offspring 2 {**-0.578 -0.666 0.050** 0.023 -0.567 -0.667 -0.566}

Crossover rate p_c is the probability of crossover and varies from 0 to 1.Typically crossover rates vary from 0.7 to 1 for a population of 30 to 200.

4.2.6 MUTATION

Mutation is used to introduce some sort of diversification in the population to avoid premature convergence to local optimum. Mutation involves just flipping of the bit for binary structure i.e 1 to 0 or 0 to 1 and alteration of number in case of real value structure.

For example for 5-bus system, a string is selected and let mutation point (i.e mpoint) is equal to 3 then string generated after mutation will be

String {0.156 -0.654 **-0.567** 0.123 0.111 -0.677 -0.455}
After mutation string {0.156 -0.654 -0.444 0.123 0.111 -0.677 -0.455}

In above example during mutation the number at third position i.e mpoint is replaced by a number generated between $-0.7X_L$ to $0.2X_L$.

Mutation rate is the probability of mutation. Mutation helpsin preserving lost information to the population. Typically mutation rate varies from 0.001 to 0.5 for a population size of 30 to 200.

4.2.7 ALGORITHM AND FLOW CHART

The steps to optimally locate TCSC with Genetic Algorithm are as follows:

Step 1: Read system data

Step 2: Run load flow using Newton Raphson method to find losses in the system.

Step 3: Assume suitable population size, maximum number of generation.

Step 4: Set counter =0

Step 5: Randomly generate chromosomes.

Step 6: Modify admittance matrix with the help of randomly generated values.

Step 7: Run load flow with modified admittance matrix for each generating pattern. Calculate losses using eq. (4.1) and evaluate fitness value.

Step 8: Increment counter i.e counter= counter +1

Step 9: Select new population using Roulette-wheel selection criterion as detailed in section 4.2.4

Step 10: Perform crossover and evaluate objective function.

Step 11: Perform mutation and evaluate objective function and add offsprings generated by crossover and mutation to the population generated by selection and replace initial population.

Step 12: Repeat this process until convergence is achieved or maximum number of generation is reached. The flow chart for above process is depicted in Fig. 4.2.

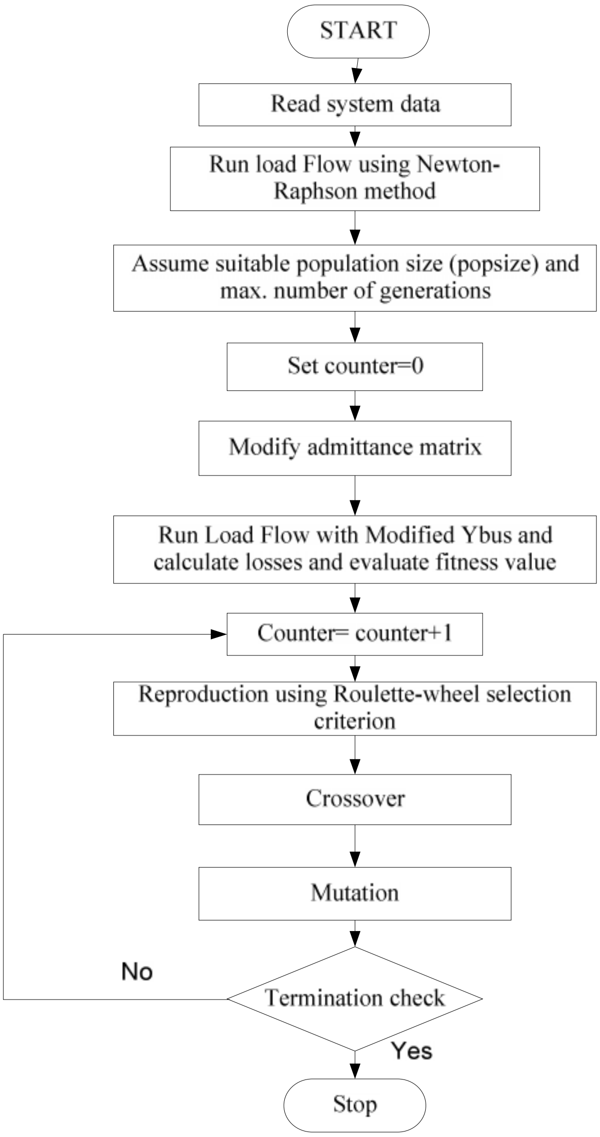

Figure 4.2 Flow chart for optimal placement of TCSC

4.3 OPTIMAL PLACEMENT OF STATCOM

FACTS controllers are able to change the network parameters in a fast and effective way in order to achieve better system performance. Theses controllers are used for enhancing dynamic performance of system in terms voltage stability while improving the power transfer capability and voltage profile. STATCOM compensates the reactive power from and to the power system. STATCOM is a shunt controller and is connected in shunt with the power system. To find the location of STATCOM, Genetic Algorithm is used.

The steps involved to find optimal location of STATCOM using Genetic Algorithm are as follows:

4.3.1 ENCODING AND INITIALIZATION: generate a set of random number equal to the number of load buses which consists of string of 1's and 0's for example in case of 5-bus system there are 3 load buses so random numbers generated will be of the form:

Load bus 1	Load bus 2	Load bus 3
1	0	1

where 1 represents the presence of STATCOM and 0 represents no device.

4.3.2 FITNESS FUNCTION CALCULATION

Fitness function for STATCOM is evaluated in the similar manner as in the case of TCSC.

4.3.3 REPRODUCTION

Roulette- wheel selection is used for copying chromosomes according to its fitness value i.e. chromosome with higher probability have higher chances of selection.

4.3.4 CROSSOVER

The process of crossover for optimal allocation of STATCOM is illustrated with 5-bus example.

Assume the strings parent1 and parent2 as :

parent 1{1 0 1}

parent 2{0 1 0}

Let the crossover site (cpoint) is equal to 2 then offsprings generated will be:

offspring1 {**1 0** 0}

offspring 2 {0 1 **1**}

4.3.5 MUTATION

The process of mutation is illustrated with 5-bus example:

Assume a string and let mutation site (mpoint) site is 2:

String {0 **1** 1}

New string {0 0 1}

In this case bit at the mutation site is flipped. The bits of mutation are independently mutated, that is, the mutation of a bit does not affect the probability of mutation of other bits.

The steps of the process of Genetic Algorithm applied to find the allocation of STATCOM is same except instead of modifying admittance matrix as in TCSC and then carry the Newton-Raphson method, Jacobians are modified to calculate the load flow. In GA, the difference in coding scheme has already been explained

CHAPTER-5

RESULT AND DISCUSSIONS

5.1 INTRODUCTION

This chapter presents the results obtained on the performance of power system with the placement of TCSC and STATCOM. The installation of TCSC and STATCOM, has been studied for their placement at arbitrary location and optimal location decided by GA. The performance has been studied on 5-bus and 30-bus systems the data used for these case studies is given in Appendix-1 and Appendix-2.

First, Newton-Raphson-Method is run without any FACTS devices with following parameters are used:

Base MVA= 100
accuracy = 0.0001
max iterations = 10

Initial values for STATCOM considered are E_p=1 and δ_p=0, it works in voltage control mode and is used to regulate the bus voltages to unity Following parameters are used for Genetic Algorithm:

Population size = 100
Maximum number of generation = 50
Crossover probability =0.9
Mutation probability = 0.1

5.2 ANALYSIS OF 5-BUS SYSTEM

The 5-bus system, consists of two generators and seven transmission lines as shown in Fig 5.1.

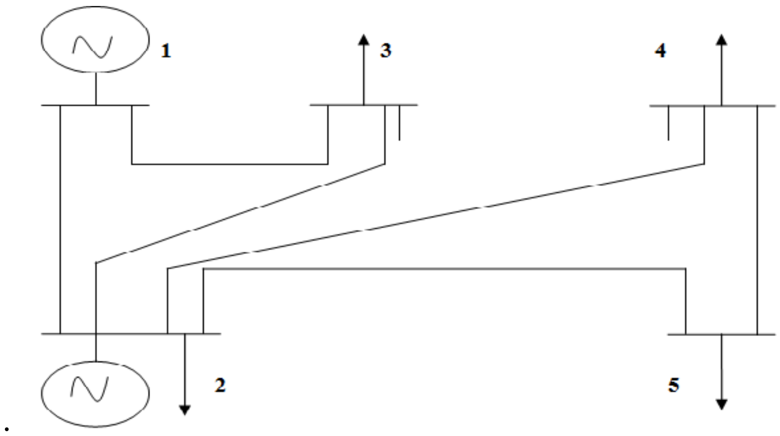

Figure. 5.1 5- bus system network

Table 5.1(a) and Table 5.1 (b) summarizes base case load flow solutions resulted by Newton-Raphson Method for 5-bus system. The base case load flow solution corresponds to network without FACTS.

Table 5.1: Base case load flow for a 5-bus system

(a) Voltage magnitude and Angle

Bus No.	Voltage magnitude (pu)	Angle (degree)
1	1.06	0
2	1.00	-2.0612
3	0.9872	-4.6367
4	0.9841	-4.9570
5	0.9717	-5.7649

(b) Line Flows and line losses

Line no.	Line flows				Line losses	
	Sending End		Receiving End			
	Psend (pu)	Qsend (pu)	Prec (pu)	Qrec (pu)	Real power Losses (pu)	Reactive Power Losses (pu)
1-2	0.8933	-0.7568	-0.8685	0.7141	0.0249	- 0.0427
1-3	0.4179	-0.1822	-0.4027	0.1629	0.0152	- 0.0193
2-3	0.2447	0.0152	-0.2411	- 0.0062	0.0036	0.0090
2-4	0.2771	0.0072	-0.2725	- 0.0014	0.0046	0.0059
2-5	0.5466	- 0.0631	-0.5344	0.0412	0.0122	- 0.0219

3-4	0.1939	- 0.0335	-0.1935	0.0420	0.0004	0.0085
4-5	0.0660	- 0.0173	-0.0656	0.0399	0.0004	0.0226

Total active power loss =0.0612 (p.u)

5.2.1 TCSC PLACEMENT

- **RANDOM LOCATION AND RATING**

A random location and rating of TCSC is selected to study its effect. The results are prepared for placing TCSC in line 1-3, the results are presented in Table 5.2(a) and Table 5.2(b) where TCSC is operated in inductive mode and capacitive modes respectively. The results are presented Table 5.2(a) and Table 5.2 (b), the value of TCSC reactance is 0.6142

Table 5.2 : Effect of TCSC at line 1-3 operating in inductive mode

(a)Voltage magnitude and Angle with TCSC at random location

Bus No.	Voltage magnitude	Angle
1	1.06	0
2	1.00	-2.2056
3	0.9855	-4.9572
4	0.9827	-5.2434
5	0.9712	-5.9580

(b) Line Flows with TCSC at random location

Line no.	Line flows With FACTS devices (TCSC)				Line losses with FACTS Devices (TCSC)	
	Sending End		Receiving End		Real Power Losses P_L (pu)	Reactive Power Losses Q_L (pu)
	Psend(pu)	Qsend	PQrec(pu)			
1-2	0.9338	- 0.7450	-0.9080	0.6992	0.0259	- 0.0457
1-3	0.3771	- 0.1745	-0.3644	0.1565	0.0127	- 0.0180
2-3	0.2626	0.0108	-0.2584	- 0.0035	0.0041	0.0073
2-4	0.2915	0.0035	-0.2864	0.0008	0.0051	0.0044
2-5	0.5539-	-0.0653	-0.5414	0.0425	0.0125	- 0.0229
3-4	0.1728	- 0.0298	-0.1725	0.0385	0.0003	0.0087
4-5	0.0589	- 0.0159	-0.0586	0.0387	0.0004	0.0228

Total active power loss: 0.0609

As the value of reactance of TCSC is inductive, the active power flows through the line decreases, however the flow through other line also changes as total load remains same. If the value of reactance of TCSC is capacitive then the active power flow through the line will increase, this can be shown by considering X_{TCSC} = -0.1642 for the above case, result obtained are shown in Table 5.3. The main objective of TCSC is to divert flow, it helps in diverting the flow from heavily loaded lines. There is reduction in loss by a factor of 0.49% (approximately 0.5%).

Table 5.3 line flows and losses with capacitive reactance of TCSC at line 1-3 in 5-bus system

Line no.	Line flows With FACTS devices (TCSC)				Line losses with FACTS Devices (TCSC)	
	Sending End		Receiving End		Real Power Losses P_L (pu)	Reactive Power Losses Q_L (pu)
	Psend(pu)	Qsend	PQrec(pu)			
1-2	0.8706	- 0.7635	-0.8463	0.7224	0.0243	- 0.0411
1-3	0.4411	- 0.1786	-0.4246	0.1553	0.0165	0.0233
2-3	0.1793	- 0.0030	-0.1774	0.0134	0.0019	0.0103
2-4	0.3060	0.0129	-0.3004	- 0.0101	0.0056	0.0028
2-5	0.5610	- 0.0610	-0.5482	0.0373	0.0128	- 0.0238
3-4	0.1520	- 0.0455	-0.1517	0.0544	0.0003	0.0089
4-5	0.0521	- 0.0209	-0.0518	0.0439	0.0003	0.0230

- **LOCATION AND RATING DECIDED BY GA**

Table 5.4(a) and Table 5.4(b) shows the results of placement of TCSC using Genetic Algorithm and Table 5.4(c) summarizes the optimal location and rating of TCSC using GA.

Table 5.4: (a) Voltage and Angle magnitude of TCSC at Location specified by GA

Bus No.	Voltage magnitude (pu)	Angle (degree)
1	1.06	0

2	1.00	-2.3033
3	0.9873	-4.7154
4	0.9842	-5.0478
5	0.9721	-5.7640

Table 5.4(b) Line Flows and Losses with TCSC at location specified by GA

Line no.	Line flows With FACTS devices (TCSC)				Line losses with FACTS Devices (TCSC)	
	Sending End		Receiving End			
					Real Power Losses P_L (pu)	Reactive Power Losses Q_L (pu)
	Psend(pu)	Qsend	PQrec(pu)			
1-2	0.8865	-0.7088	-0.8631	0.6655	0.0234	0.0434
1-3	0.4234	-0.1807	-0.4079	0.1605	0.0155	0.0202
2-3	0.2459	0.0170	-0.2423	-.0074	0.0036	0.0096
2-4	0.2641	0.0041	-0.2599	0.0030	0.0042	0.0071
2-5	0.5531	-0.0602	-0.5407	0.0403	0.0124	-0.0199
3-4	0.2002	-0.0299	-0.1998	0.0383	0.0004	0.0084
4-5	0.0597	-0.0179	-0.0593	0.0408	0.0004	0.0228

Total active power loss=0.0599 (pu)

Table 5.4 (c) Result Analysis of 5-bus system with and without TCSC

Line number	X_{TCSC}	Active power without TCSC (pu)	Active power with TCSC (pu)
1-2	0.0732	0.8933	0.8865
2-3	-0.0699	0.2447	0.2459
2-5	-0.0748	0.5466	0.5531

From Table 5.4 (c),it is clear that the value of reactance of TCSC in case of line 1-2 is inductive so there is increase in active power flow whereas in case of line 2-3 and 2-5 , the reactance of TCSC generated randomly using Genetic Algorithm in the working range are capacitive so there is increase in active power flow. There is reduction of

2.124% in the losses. Results obtained using Genetic Algorithm are better than the selecting the line randomly.

5.2.2 STATCOM PLACEMENT

- **RANDOM LOCATION**

A random location of STATCOM is selected to study its effect. The results are prepared for placing STATCOM at bus 4. STATCOM is working in voltage control mode and is used to improve the voltage profile of the bus. Observation of Table 5.5(a) and Tables 5.5(b) shows that voltage profile of bus has improved and also there is improvement in the voltages of bus 3 and 5. With the placement of STATCOM in the system, there is improvement in the real power losses of the system, there is reduction of 0.5% in the losses. Table 5.5(c) shows the data of STATCOM.

Table 5.5 Effect of STATCOM at bus 5 operating in voltage control mode

(a) Voltage magnitude and Angle

Bus No.	Voltage magnitude (pu) (Without STATCOM)	Bus Angle (Degree) (Without STATCOM))	Voltage magnitude (pu) (With STATCOM)	Angle (degree) (With STATCOM)
1	1.0600	0.0000	1.0600	0.0000
2	1.0000	-2.0612	1.0000	-2.0568
3	0.9872	-4.6367	0.9996	-4.8319
4	0.9841	-4.9570	1.0000	-5.2144
5	0.9717	-5.7649	0.9771	-5.8292

(b) Line Flows and Losses with STATCOM at random location

Line no.	Lines Flows with STATCOM				Line losses with STATCOM	
	Sending End		Receiving End		Real power losses(P_L)	Reactive power losses(Q_L)
	Psend (pu)	Qsend (pu)	Prec (pu)	Qrec (pu)		
1-2	0.8921	- 0.7572	-0.8672	0.7145	0.0248	- 0.0426
1-3	0.4194	- 0.1287	-0.4057	0.1115	0.0140	- 0.0154

2-3	0.2446	0.0827	-0.2407	- 0.0744	0.0039	0.0083
2-4	0.2779	0.0942	-0.2729	- 0.0894	0.0051	0.0048
2-5	0.5447	- 0.0194	-0.5329	0.5328	0.0119	- 0.0212
3-4	0.1962	0.0837	-0.1957	- 0.0750	0.0004	0.0087
4-5	0.0680	- 0.0605	-0.0672	0.0825	0.0008	0.0220

(c) STATCOM data

STATCOM bus no.	E_p	δ_p	Q_p
4	1.0247	-5.3561	-0.2474

Total active power losses= 0.0609 (pu)

- **LOCATION DECIDED BY GA**

In this case location of STATCOM is decided by using GA and the load flow results obtained are shown in Table 5.6(a) and Table 5.6(b)

Table 5.6(a) Voltage and Angle with STATCOM using GA

Bus No.	Voltage magnitude (pu) (without STATCOM)	Angle(degree) (without STATCOM)	Voltage magnitude (pu) (With STATCOM)	Angle (degree) (with STATCOM)
1	1.0600	0.0000	1.0600	0.0000
2	1.0000	-2.0612	1.0000	-2.0543
3	0.9872	-4.6367	1.0000	-4.8403
4	0.9841	-4.9570	0.9944	-5.1094
5	0.9717	-5.7649	0.9752	-5.7988

Table 5.6(b) Line Flows with STATCOM using GA

Line no.	Lines Flows with STATCOM				Line losses with STATCOM	
	Sending End		Receiving End		Real power losses(P_L)	Reactive power losses(Q_L)
	Psend (pu)	Qsend (pu)	Prec (pu)	Qrec (pu)		
1-2	0.8914	- 0.7574	-0.8666	0.7148	0.0248	- 0.0426
1-3	0.4196	- 0.1268	-0.4057	0.1115	0.0140	- 0.0153
2-3	0.2450	0.0851	-0.2411	- 0.0769	0.0039	0.0082
2-4	0.2767	0.0632	-0.2719	- 0.0576	0.0048	0.0056

2-5	0.5449	- 0.0350	-0.5329	0.0137	0.0119	- 0.0212
3-4	0.1963	- 0.1170	-0.1958	0.1253	0.0005	0.0083
4-5	0.0677	- 0.0449	-0.0671	0.0672	0.0006	0.0223

Total active power loss = 0.0606 (pu)

Table 5.6(c) STATCOM data

STATCOM bus	E_p (pu)	δ_p (pu)	Q_{sh} (pu)
3	1.0205	-4.9577	-0.2049

From Table 5.6(a) and Table 5.6(b) it is clear that with the placement of STATCOM, voltage profile of bus 3 has improved and also there is improvement in the voltage profile of bus 4 and 5. Also there is reduction in the total active power losses in the system, there is reduction of 0.98% in the losses. Table 5.6(c) shows the data of STATCOM.

5.3 ANALYSIS OF 30-BUS SYSTEM

The 30 bus system consists of 30 buses and 41 transmission lines.

Results of Newton-Raphson method for 30 bus system are shown in Table 5.7(a) and Table 5.7(b)

Table 5.7(a) Voltage and Angle without FACTS devices

Bus No.	Voltage magnitude	Angle
1	1.0600	0
2	1.0430	-5.3543
3	1.0196	-7.5308
4	1.0104	-9.2840
5	1.0100	-14.1738
6	1.0096	-11.0581
7	1.0020	-12.8649
8	1.0100	-11.8193
9	1.0392	-14.0644
10	1.0215	-15.6706
11	1.0820	-14.0644
12	1.0496	-15.1245
13	1.0710	-15.1245
14	1.0320	-16.0018

15	1.0251	-16.0084
16	1.0304	-15.6251
17	1.0188	-15.8687
18	1.0114	-16.6067
19	1.0066	-16.7658
20	1.0095	-16.5502
21	1.0082	16.2178
22	1.0120	-15.9811
23	1.0085	-16.2294
24	0.9991	-16.3007
25	1.0032	-16.0720
26	0.9852	-16.5038
27	1.0145	-15.6559
28	1.0078	-11.7163
29	0.9944	-16.9077
30	0.9828	-17.8067

Table 5.7(b) Line Flows and Losses

Line no.	Lines Flows without FACTS device				Line losses without FACTS device	
	Sending End		Receiving End		Real power losses(P_L) (pu)	Reactive power losses(Q_L) (pu)
	Psend (pu)	Qsend (pu)	Prec (pu)	Qrec (pu)		
1-2	1.7336	0.1964	-1.6817	- 0.3227	0.0519	- 0.1263
1-3	0.8780	- 0.0637	-0.8468	- 0.0284	0.0312	- 0.0921
2-4	0.4376	- 0.0563	-0.4273	0.0445	0.0103	- 0.0119
3-4	0.8228	0.0276	-0.8142	- 0.0480	0.0086	- 0.0204
2-5	0.8241	- 0.0289	-0.7945	- 0.0732	0.0295	- 0.1021
2-6	0.6030	- 0.0184	-0.5836	- 0.0210	0.0195	- 0.0394
4-6	0.7132	0.1751	-0.7069	- 0.1923	0.0063	- 0.0172
5-7	-0.1475	- 0.1255	0.1492	0.1314	0.0018	0.0059
6-7	0.3810	0.0286	-0.3772	- 0.0318	0.0038	- 0.0031
6-8	0.2961	0.0949	-0.2949	- 0.0943	0.0011	0.0006
6-9	0.2645	0.1371	-0.2645	- 0.1552	0.0000	- 0.0181
6-10	0.1492	0.0156	-0.1492	- 0.0279	0.0000	- 0.0123
9-11	0.0000	0.2136	0.000	- 0.2224	0.0000	- 0.0088
9-10	0.2705	- 0.1717	-0.2705	0.1613	0.0000	- 0.0105

4-12	0.4216	0.1331	-0.4216	- 0.1821	0.0000	- 0.0490
12-13	0.000	0.1605	0.000	- 0.1638	0.0000	- 0.0033
12-14	0.0810	- 0.0336	-0.0801	0.0318	0.0009	- 0.0018
12-15	0.1812	- 0.1062	-0.1786	0.1010	0.0027	- 0.0052
12-16	0.0781	- 0.0643	-0.0773	0.0624	0.0009	- 0.0018
14-15	0.0181	- 0.0158	-0.0180	0.0157	0.0001	- 0.0001
16-17	0.0423	- 0.0444	-0.0420	0.0438	0.0003	- 0.0007
15-18	0.0653	- 0.0321	-0.0648	0.0310	0.0005	- 0.0011
18-19	0.0328	- 0.0220	-0.0327	0.0218	0.0001	- 0.0002
19-20	-0.0623	0.0122	0.0624	- 0.0124	0.0001	- 0.0003
10-20	0.0851	- 0.0210	-0.0844	0.0194	0.0007	- 0.0015
10-17	0.0481	- 0.0144	-0.0480	0.0142	0.0001	- 0.0002
10-21	0.1774	- 0.0993	-0.1760	0.0963	0.0014	- 0.0030
10-22	0.0557	- 0.0379	-0.0554	0.0372	0.0003	- 0.0007
21-23	0.0010	0.0157	-0.0010	- 0.0157	0.0000	0.000
15-23	0.0492	- 0.0596	-0.0487	0.0584	0.0006	- 0.0011
22-24	0.0554	- 0.0372	-0.0549	0.0365	0.0005	- 0.0008
23-24	0.0177	- 0.0267	-0.0176	0.0264	0.0001	- 0.0003
24-25	-0.0145	0.0041	0.0145	- 0.0042	0.0000	- 0.0001
25-26	0.0355	- 0.0237	-0.0350	0.0230	0.0005	- 0.0007
25-27	-0.0500	0.0279	0.0504	- 0.0285	0.0004	- 0.0007
28-27	0.1774	0.0109	-0.1774	- 0.0232	0.0000	- 0.0123
27-29	0.0619	- 0.0167	-0.0610	0.0151	0.0009	- 0.0017
27-30	0.0710	- 0.0167	-0.0693	0.0136	0.0017	- 0.0031
29-30	0.0370	- 0.0061	-0.0367	0.0054	0.0003	- 0.0006
8-28	-0.0051	- 0.0019	0.0051	0.0236	0.0000	0.0217
6-28	0.1889	0.0551	-0.1883	0.0089	0.0006	0.0640

Total real power losses = 0.1776(pu)

Without any compensation (use of FACTS device) the total active power loss in the system is 0.1776 pu.

5.3.1 TCSC PLACEMENT

For the placement of TCSC in 30-bus system using Genetic Algorithm, maximum number TCSC used are four and out of four, three are optimally placed by GA. In this case random location is not selected as the system is large.

Results of Newton-Raphson for 30-bus system with TCSC are shown in Table 5.8(a) and Table 5.8(b).

Table 5.8(a) Voltage and angle with TCSC at location specified by GA

Bus No.	Voltage magnitude (pu)	Angle (degree)
1	1.06	0.00
2	1.0430	-5.4134
3	1.0234	-7.3744
4	1.0105	-9.0849
5	1.0100	-12.6408
6	1.0160	-10.7637
7	1.0057	-12.0631
8	1.0200	-11.5724
9	1.0473	-13.7580
10	1.0281	-15.3574
11	1.0620	-13.7580
12	1.0528	-14.8110
13	1.0710	-14.8111
14	1.0359	-15.631
15	1.0295	-15.7027
16	1.0352	-15.3118
17	1.0249	-15.5538
18	1.0173	-16.2205
19	1.0127	-16.3978
20	1.0158	-16.1955
21	1.0145	-15.9001
22	1.0186	-15.6632
23	1.0147	-15.9123
24	1.0058	-15.9771
25	1.0103	-15.7446
26	0.9925	-16.1702
27	1.0218	-15.3296
28	1.0150	-11.4278
29	1.0019	-16.5631
30	0.9838	-17.4809

Table 5.8(b) Line Flows and Losses with TCSC

Line no.	Lines Flows with TCSC				Line losses with TCSC	
	Sending End		Receiving End		Real power losses(P_L) (pu)	Reactive power losses(Q_L) (pu)
	Psend (pu)	Qsend (pu)	Prec (pu)	Qrec (pu)		
1-2	1.7519	-0.2007	-1.6988	0.3303	0.0530	0.1296
1-3	0.8578	0.0431	-0.8280	0.0433	0.0297	0.0865
2-4	0.4059	0.0377	-0.3972	-0.0305	0.0088	0.0072
3-4	0.8040	-0.0425	-0.7959	0.0615	0.0082	0.0191
2-5	0.9150	-0.0141	-0.8787	0.1035	0.0363	0.0893
2-6	0.5609	-0.0089	-0.5441	0.0401	0.0168	0.0312
4-6	0.6702	-0.2092	-0.6645	0.2244	0.0057	0.0151
5-7	0.0633	0.0579	0.0636	-0.0673	0.0004	0.0095
6-7	0.2939	0.0305	-0.2916	-0.0322	00023	-0.0017
6-8	0.2969	-0.1822	-0.2955	0.1824	0.0014	0.0002
6-9	0.2672	-0.1461	-0.2672	0.1648	0.0000	0.0187
6-10	0.1505	-0.0162	-0.1505	0.0285	0.0000	0.0123
9-11	0.0000	-0.2362	0.0000	0.2395	0.0000	0.0033
9-10	0.2732	0.1863	-0.2732	-0.1753	0.0000	0.0110
4-12	0.4165	-0.1294	-0.4163	0.1767	0.0000	0.0473
12-13	0.0000	-0.1366	0.0000	0.1389	0.0000	0.0024
12-14	0.0801	0.0317	-0.0793	-0.0300	0.0008	0.0017
12-15	0.1792	0.0983	-0.1767	-0.0934	0.0025	0.0049
12-16	0.0755	0.0580	-0.0747	-0.0564	0.0008	0.0016
14-15	0.0173	0.0140	-0.0172	-0.0139	0.0001	0.0001
16-17	0.0397	0.0384	-0.0395	-0.0378	0.0002	0.0005
15-18	0.0667	0.0291	-0.0661	-0.0281	0.0005	0.0009
18-19	0.0341	0.0191	-0.0340	-0.0189	0.0001	0.0002
19-20	0.0610	-0.0151	0.0611	0.0153	0.0001	0.0003
10-20	0.0838	0.0238	-0.0831	-0.0223	0.0007	0.0015
10-17	0.0506	0.0204	-0.0505	-0.0202	0.0001	0.0002
10-21	0.1803	0.1042	-0.1789	-0.1011	0.0014	0.0031
10-22	0.0558	0.0382	-0.0555	-0.0376	0.0003	0.0006
21-23	0.0039	-0.0109	-0.0039	0.0109	0.0000	0.0000
15-23	0.0452	0.0532	-0.0448	-0.0522	0.0005	0.0009
22-24	0.0555	0.0376	-0.550	-0.0368	0.0005	0.0008
23-24	0.0167	0.0254	-0.0166	-0.0251	0.0001	0.0002

24-25	-0.0154	-0.0050	0.0155	0.0051	0.0000	0.0001
25-26	0.0355	0.0237	-0.0350	-0.0230	0.0005	0.0007
25-27	-0.0509	-0.0288	0.0513	0.0295	0.0004	0.0007
28-27	0.1782	-0.0113	-0.1782	0.0235	0.0000	0.0123
27-29	0.0619	0.0167	-0.0610	-0.0151	0.0009	00016.
27-30	0.0709	0.0166	-0.0693	-0.0136	0.0016	0.0031
29-30	0.0370	0.0061	-0.0367	-0.0054	0.0003	0.0006
8-28	-0.0045	0.0157	0.0046	-0.0377	0.0000	-0.0220
6-28	0.1893	-0.0699	-0.1887	0.0050	0.0006	-0.0649

Total real active power loss= 0.1756(pu)

Table 5.8(c) Result Analysis of 30-bus system with and without TCSC

Line number	X_{TCSC}	Active power without TCSC (pu)	Active power with TCSC (pu)
2-5	-0.0536	0.8241	0.9155
9-11	-0.1429	0	0.0000
15-18	-0.0298	0.0653	0.0667

From Table 5.8(c), it is clear that the value of reactance of TCSC in all the three cases is capacitive so there is increase in active power flow in all the , value of the reactance of TCSC generated randomly using Genetic Algorithm in the working range are capacitive so there is increase in active power flow. There is reduction of 1.126% in the losses.

5.3.2 PLACEMENT OF STATCOM

Results of Newton-Raphson Method for 30-bus system with STATCOM using Genetic Algorithm are shown in Table 5.9(a) and Table 5.9(b)

Table 5.9(a) Voltage magnitude and Angle

Bus No.	Voltage magnitude (Withoue STATCOM)	Angle (Degree) (Without STATCOM)	Voltage magnitude (With STATCOM)	Angle (With STATCOM)
1	1.06	0	1.06	0
2	1.043	-5.6952	1.043	-5.3530
3	1.0209	-7.8266	1.0198	-7.5311
4	1.0111	-8.9381	1.0107	-9.2841
5	1.0100	-13.0176	1.0100	-14.1706

6	1.0108	-10.9148	1.0099	-11.0603
7	1.0026	-12.3128	1.0021	-12.8647
8	1.0100	-11.4534	1.0100	-11.8171
9	1.0382	-13.9687	1.0399	-14.0572
10	1.0305	-14.6046	1.0227	-15.6569
11	1.0820	-13.9687	1.0820	-14.0572
12	1.0530	-14.1119	1.0501	-15.1044
13	1.0710	-14.1119	1.0710	-15.1044
14	1.0361	-15.1318	1.0327	-15.9810
15	1.0313	-14.8969	1.0260	-15.9922
16	1.0357	-14.6276	1.0312	-15.6078
17	1.0267	-14.8338	1.0199	-15.8536
18	1.0199	-15.3323	1.0125	-16.5899
19	1.0155	-15.4985	1.0077	-16.7491
20	1.0182	-15.4011	1.0106	-16.5342
21	1.0190	-14.8854	1.0097	-16.2072
22	1.0209	-14.8969	1.0140	-15.9786
23	1.0187	-14.9370	1.0101	-16.2204
24	1.0080	-15.2005	1.0022	-16.3196
25	1.0088	-15.2234	1.0101	-16.1719
26	0.9961	-15.2062	1.0000	-16.8830
27	1.0166	-15.0917	1.0195	-15.6826
28	1.0091	-11.4362	1.0085	-11.7300
29	0.9960	-16.4553	1.0000	-16.9324
30	0.9838	-17.4809	0.9883	-17.8169

Table 5.9(b) Line Flows and losses with STATCOM

Line no.	Lines Flows with STATCOM				Line losses with STATCOM	
	Sending End		Receiving End		Real power losses(P_L)	Reactive power losses(Q_L)
	Psend (pu)	Qsend (pu)	Prec (pu)	Qrec (pu)		
1-2	1.7332	0.1963	-1.6813	- 0.3225	0.0519	- 0.1262
1-3	0.8779	- 0.0624	-0.8467	- 0.0296	0.0312	- 0.0920
2-4	0.4374	- 0.0549	-0.4271	0.0431	0.0102	- 0.0118
3-4	0.8227	0.0288	-0.8141	- 0.0492	0.0086	- 0.0204
2-5	0.8239	- 0.0289	-0.7944	- 0.0731	0.0295	- 0.1020

2-6	0.6030	- 0.0167	-0.5835	- 0.0226	0.0195	- 0.0393
4-6	0.7141	0.1764	-0.7078	- 0.1937	0.0063	- 0.0173
5-7	-0.1476	- 0.1240	0.7078	- 0.1937	0.0063	- 0.0173
6-7	0.3812	0.0272	-0.1494	0.1299	0.0017	0.0059
6-8	0.2963	0.0880	-0.3774	- 0.0303	0.0038	- 0.0031
6-9	0.2640	0.1390	-0.2951	- 0.0873	0.0011	0.0007
6-10	0.1489	0.0173	-0.2640	- 0.1571	0.0000	- 0.0182
9-11	0.0000	0.2104	0.0000	- 0.2189	0.0000	- 0.0122
9-10	0.2699	- 0.1667	-0.2699	0.1546	0.0000	- 0.0102
4-12	0.4204	0.1344	-0.4204	- 0.1832	0.0000	0.0488
12-13	0.0000	0.1567	0.0000	- 0.1598	0.0000	- 0.0031
12-14	0.0807	- 0.0329	-0.0798	0.0312	0.0008	- 0.0018
12-15	0.1806	- 0.1036	-0.1780	0.0984	0.0026	- 0.0051
12-16	0.0778	- 0.0629	-0.0769	0.0611	0.0009	- 0.0018
14-15	0.0178	- 0.0152	-0.0177	0.0151	0.0001	- 0.0001
16-17	0.0419	- 0.0431	-0.0417	0.0425	0.0003	- 0.0007
15-18	0.0652	- 0.0317	-0.0646	0.0306	0.0005	- 0.0011
18-19	0.0326	- 0.0216	-0.0325	0.0214	0.0001	- 0.0002
19-20	-0.0625	0.0126	0.0626	- 0.0129	0.0001	- 0.0003
10-20	0.0853	- 0.0214	-0.0846	0.0199	0.0007	- 0.0015
10-17	0.0484	- 0.0157	-0.0483	0.0155	0.0001	- 0.0002
10-21	0.1772	- 0.0963	-0.1758	0.0934	0.0014	- 0.0029
10-22	0.0547	- 0.0326	-0.0544	0.0321	0.0003	- 0.0006
21-23	0.0008	0.0186	-0.0008	- 0.0186	0.0000	0.0000
15-23	0.0486	- 0.0568	-0.0480	0.0557	0.0005	- 0.0011
22-24	0.0544	- 0.0321	-0.0539	0.0314	0.0004	- 0.0007
23-24	0.0168	- 0.0211	-0.0167	0.0210	0.0001	- 0.0002
24-25	-0.0163	0.0147	0.0164	- 0.0148	0.0001	- 0.0002
25-26	0.0353	- 0.0035	-0.0350	0.0030	0.0003	- 0.0005
25-27	-0.0517	0.0183	0.0521	- 0.0189	0.0003	- 0.0006
28-27	0.1790	0.0219	-0.1790	- 0.0346	0.0000	- 0.0127
27-29	0.0619	- 0.0158	-0.0610	0.0142	0.0009	- 0.0016
27-30	0.0709	0.0163	-0.0693	0.0132	0.0016	- 0.0031
29-30	0.0370	- 0.0064	-0.0367	0.0058	0.0003	- 0.0006
8-28	-0.0049	0.0019	0.0049	0.0199	0.0000	0.0218
6-28	0.1904	0.0628	-0.1898	0.0012	0.0006	0.0640

Total active power losses= 0.1771 (p.u)

Table 5.9(c) STATCOM data

STATCOM bus	E_p (pu)	δ_p (pu)	Q_{sh} (pu)
26	1.0200	-16.8945	-0.0200
29	1.001	-16.9331	-0.0012

From Table5.9 (a)and Table 5.9(b), it is clear that voltage profile of bus 26 and 29 has improved and also there is reduction total active power losses of the system. Table 5.9(c) shows the STATCOM data used.

CHAPTER-6

CONCLUSIONS AND SCOPE FOR FUTURE WORK

6.1 CONCLUSIONS

The work on ‘Evolutionary Algorithm assisted Optimal Placement of FACTS Controllers in Power System’ has been carried out to find optimal location of TCSC and STATCOM to improve the losses and voltage profile of the system. The optimal placement of FACTS controllers has been attempted using Genetic Algorithm. The study has been carried out on 30-bus and 5-bus system. From the study following conclusions are drawn.

- The developed algorithm is effective in deciding the placement of FACTS devices.
- TCSC helps in diverting flow from heavily loaded lines and results in reduction in active power losses.
- STATCOM helps in improving voltage profile of the system and also results in reduced active power losses.

6.2 SCOPE FOR FUTURE WORK

The completion of one research project opens the avenues for work in many other related areas. The following areas are identified for future work:

1. The allocation can be carried out accounting the cost of FACTS devices and other economic consideration.
2. The speed can be enhanced by reducing search space by incorporating some sensitivity index

APPENDIX-1

TABLE (A1) BUS DATA FOR 5-BUS SYSTEM [28]

Bus Generator no.	Voltage (|v|,θ)	Load (MW, Mvar)	Generator		Injected MVAR
			(MW, Mvar)	Qmin, Qmax (Mvar)	
1	1.06,0	0,0	0,0	-50,50	0
2	1,0	20,10	40,0	-30,30	0
3	1,0	45,15	0,0	0,0	0
4	1,0	40,5	0,0	0,0	0
5	1,0	60,10	0,0	0,0	0

TABLE (A2) LINE DATA FOR 5-BUS SYSTEM

Sending Bus	Receiving Bus	Line resistance pu	Line Reactance pu	Line suseptance pu
1	2	0.02	0.06	0.06
1	3	0.08	0.24	0.05
2	3	0.06	0.18	0.04
2	4	0.06	0.18	0.04
2	5	0.04	0.12	0.03
3	4	0.01	0.03	0.02
4	5	0.08	0.24	0.05

APPENDIX-2

TABLE (A3): BUS DATA FOR 30 BUS SYSTEM [14]

Bus no.	Bus Code	Voltage Mag. (Volts)	Angle (Degree)	Load		Generator				Injected MVAr
				MW	MVAr	MW	MVAr	Qmin	Qmax	
1	1	1.06	0	0	0	0	0	0	0	0
2	2	1.043	0	21.7	12.7	40	0	-40	50	0
3	0	1.0	0	2.4	1.2	0	0	0	0	0
4	0	1.06	0	7.6	1.6	0	0	0	0	0
5	2	1.01	0	94.2	19	0	0	-40	40	0
6	0	1.0	0	0	0	0	0	0	0	0
7	0	1.0	0	22.8	10.9	0	0	0	0	0
8	2	1.01	0	30	30	0	0	-10	40	0
9	0	1.0	0	0	0	0	0	0	0	0
10	0	1.0	0	5.8	2	0	0	0	0	19
11	2	1.082	0	0	0	0	0	-6	24	0
12	0	1.0	0	11.2	7.5	0	0	0	0	0
13	2	1.071	0	0	0	0	0	-6	24	0
14	0	1.0	0	6.2	1.6	0	0	0	0	0
15	0	1.0	0	8.2	2.5	0	0	0	0	0
16	0	1.0	0	3.5	1.8	0	0	0	0	0
17	0	1.0	0	9	5.8	0	0	0	0	0
18	0	1.0	0	3.2	0.9	0	0	0	0	0
19	0	1.0	0	9.5	3.4	0	0	0	0	0
20	0	1.0	0	2.2	0.7	0	0	0	0	0
21	0	1.0	0	17.5	11.2	0	0	0	0	0
22	0	1.0	0	0	0	0	0	0	0	0
23	0	1.0	0	3.2	1.6	0	0	0	0	0
24	0	1.0	0	8.7	6.7	0	0	0	0	4.3
25	0	1.0	0	0	0	0	0	0	0	0
26	0	1.0	0	3.5	2.3	0	0	0	0	0
27	0	1.0	0	0	0	0	0	0	0	0
28	0	1.0	0	0	0	0	0	0	0	0
29	0	1.0	0	2.4	0.9	0	0	0	0	0
30	0	1.0	0	10.6	1.9	0	0	0	0	0

TABLE (A4): LINE DATA FOR 30 BUS SYSTEM

Bus nl	Bus nr	R Pu	X pu	½ B	Tap Setting values
1	2	0.0192	0.0575	0.02640	1
1	3	0.0452	0.1852	0.02040	1
2	4	0.0570	0.1737	0.01840	1
3	4	0.0132	0.0379	0.00420	1
2	5	0.0472	0.1983	0.02090	1
2	6	0.0581	0.1763	0.01870	1
4	6	0.0119	0.0414	0.0045hj	1
5	7	0.0460	0.1160	0.0000	1
6	7	0.0267	0.0820	0.0000	1
6	8	0.0120	0.0420	0.0000	1
6	9	0.0000	0.2080	0.0000	0.978
6	10	0.0000	0.5560	0.0000	0.969
9	11	0.0000	0.2080	0.0000	1
9	10	0.0000	0.1100	0.0000	1
4	12	0.0000	0.2560	0.0000	0.932
12	13	0.0000	0.1400	0.0000	1
12	14	0.1231	0.2559	0.0000	1
12	15	0.0662	0.1304	0.0000	1
12	16	0.0945	0.1987	0.0000	1
14	15	0.2210	0.1997	0.0000	1
16	17	0.0824	0.1923	0.0000	1
15	18	0.1073	0.2185	0.0000	1
18	19	0.0639	0.1292	0.0000	1
19	20	0.0340	0.0680	0.0000	1
10	20	0.0936	0.209	0.0000	1
10	17	0.0324	0.0845	0.0000	1
10	21	0.0348	0.0749	0.0000	1
10	22	0.0727	0.1499	0.0000	1
21	22	0.0116	0.0236	0.0000	1
15	23	0.1000	0.2020	0.0000	1
22	24	0.1150	0.1790	0.0000	1
23	24	0.1320	0.2700	0.0000	1
24	25	0.1885	0.3292	0.0000	1
25	26	0.2544	0.3800	0.0000	1
25	27	0.1093	0.2087	0.0000	1
28	27	0.0000	0.3960	0.0000	0.968
27	29	0.2198	0.4153	0.0000	1
27	30	0.3202	0.6027	0.0000	1
29	30	0.2399	0.4533	0.0000	1
8	28	0.0636	0.2000	0.0214	1
6	28	0.0169	0.0599	0.065	1

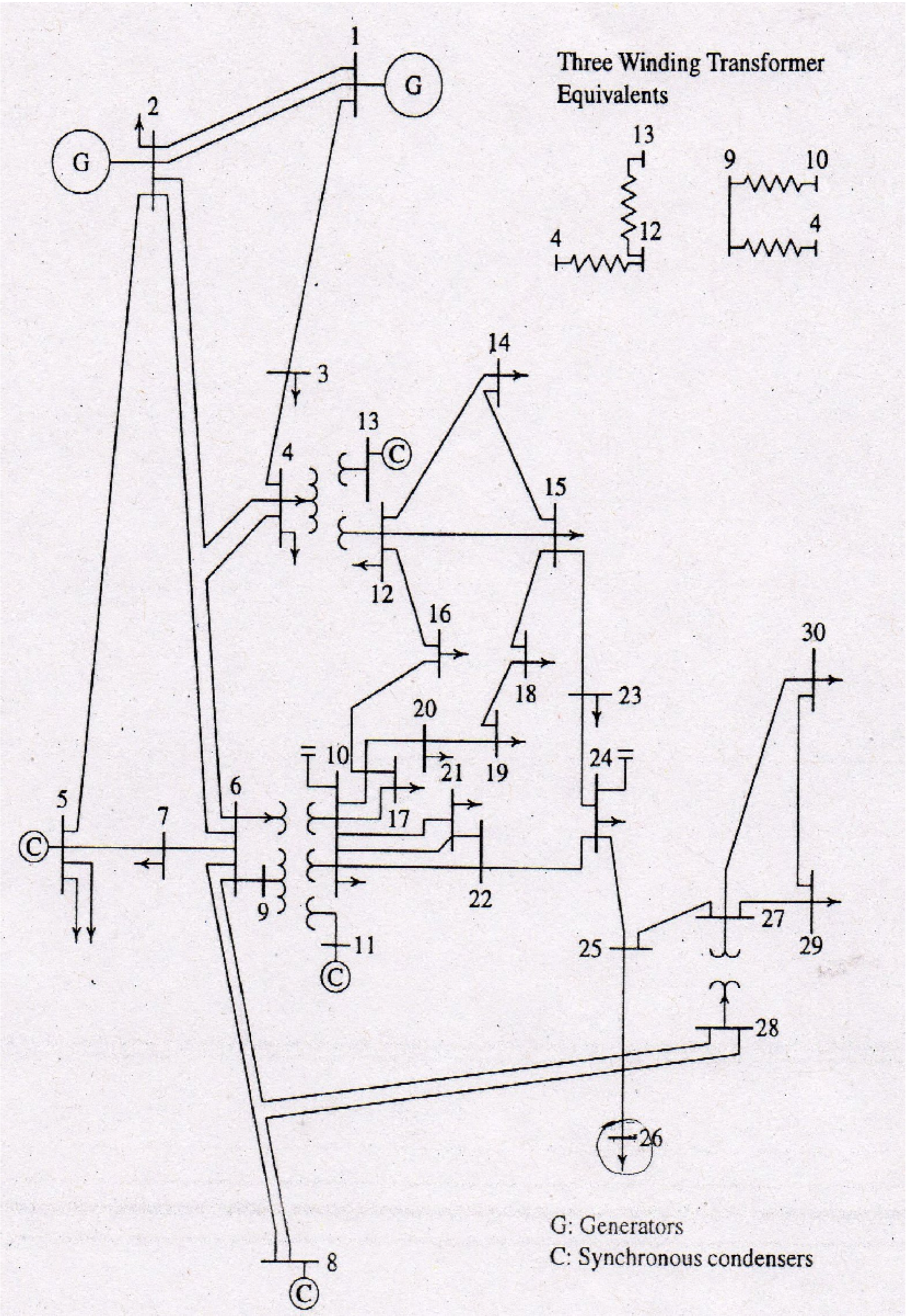

Figure (A1): 30-bus system

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