CHAPTER 2

FLEXIBLE AC TRANSMISSION SYSTEM (FACTS) CONTROLLERS

2.1 Introduction

This chapter presents an overview of the most prominent characteristics of the power electronic equipment currently used in the electricity supply industry for the purpose of voltage regulation, active and reactive power flow control, and power quality enhancement. A study of the models and procedures with which to assess the steady-state operation of electrical power systems at the fundamental frequency is made. The modeling of FACTS controllers in both the phase domain and the sequence domain are addressed in this chapter. The focus is on steady-state operation and a distinction has been made between power electronic devices, which uses conventional power semiconductor equipments (i.e. thyristors) and the new generation of power system controllers, which use complete controllable semiconductor devices such as Gate Turn Off (GTO) thyristors and Insulated Gate Bipolar Tansistors (IGBTs). Also the latter devices work well with fast switching control techniques, such as the sinusoidal Pulse Width Modulation (PWM) control scheme, and, from the power system perspective, operate like voltage sources, having an almost delay-free response. Devices based on thyristors have a slower response, more than one cycle of the fundamental frequency, and use phase control instead of PWM control. From the power system point of view, thyristors-based controllers behave like controllable reactance as opposed to voltage sources. This chapter presents the structure, operation and the steady state characteristics of FACTS devices that depend in its operation on the Thyristor Controlled Reactor (TCR) or the Synchronous Voltage Source (SVS). Various optimization techniques used for location of FACTS controllers are also explained in this chapter.

2.2. Types, Modeling and Application of FACTS Controllers

2.2.1 Types of FACTS Controllers
The different types of FACTS Controllers are:

- Static VAR compensator (SVC)
FACTS controllers can be used in all the three states of the power system namely
1. Steady state
2. Transient state and
3. Post transient state.
However, the conventional devices find little application during system transient or contingency condition.
The main benefits of FACTS controllers are (a) Environmental benefit (b) Increased stability (c) Increased quality of supply (d) Flexibility (e) Financial benefit.

2.2.2. Modeling of FACTS Controllers
The modeling of FACTS controller is based on two main types.
1. The Thyristor controlled reactor and
2. Synchronous Voltage Source

2.2.2.1 The Thyristor Controlled Reactor (TCR)
The main components of the basic TCR has shown in Figure 2.1. The controllable element is the anti-parallel thyristor pair, Th1 and Th2, which conducts on alternate halfcycles of the supply frequency. The other key component is the linear (air-core) reactor of inductance L. In a practical valve, many thyristors (typically 10 to 40) are in series connection to handle the desired blocking voltage levels. A gate pulse is activated to all thyristors of a thyristor valve brings the valve into conduction. The valve will automatically block approximately at the zero crossing of the AC current, in the absence of the firing signal. Thus, the controlling element is the thyristor valve. The TCR current is essentially reactive, lagging the voltage by nearly 90°. The active component of the current is very small and the losses of the device are of the order of
0.5 – 2% of the reactive power. Therefore, one of the modeling assumptions is that the resistance of the inductor have neglected.

The firing angle is defined as the angle in electrical degrees between the positive going zero crossing of the voltage across the inductor and the positive going zero crossing of the current through it. The thyristors are to be fired symmetrically; therefore, the maximum possible firing angle is 180°. Complete conduction is achieved with an angle of gate of 90 degree. Partial conduction is achieved with angles of gates between 90° and 180° with zero current at 180°. Firing angles less than 90° is not allowed, as they generate unsymmetrical currents with a high DC component. The fundamental component of the reactor current is decreased as the firing angle increases. That means an increase in the reactor inductance, reduces both of its reactive power and its current. In Figure 2.2a, the voltage across the TCR inductor and the current through it is shown at full conduction. The equivalent reactance of the TCR is equal to the inductor reactance. In Figure 2.2b, the current waveform is shown for a firing angle of 100°. On lypart of the sinusoidal voltage has applied to the inductor, the current and the voltage are not sinusoidal anymore. The fundamental component of the current is less than that the current at a 90° firing angle, resulting in an equivalent reactance of the TCR higher than the inductor reactance. Figure 2.2c and 2.2d show the TCR current waveform for a firing angle of 130° and 150°. The fundamental component of the current through the inductor is very small, the equivalent reactance of the TCR is very high, and at 180° it becomes practically infinite[34].
Using the Fourier series, the fundamental component of the controllable reactance of the TCR (\(X_v\)) is

\[ x_v = x_l \frac{\pi}{2(\pi - \alpha) + \sin(2\alpha)} \]

(2.1a)

Inside a 3-Phase network, three numbers of single phase thyristors controlled reactors are utilized in delta connection. Subjecting to balanced conditions, the odd-order harmonic currents in zero sequence harmonic components flow in the delta linked TCRs and not flows to the power system. For the TCRs arranged in delta, the maximum total harmonic distortion coefficient is less than 10 %. For being used with shunt devices, a step-down transformer is required in high-voltage applications as the TCR voltages has a constraint for technical and economic reasons to values starting from 50 kV or below.
Among the devices that depend on the TCR is Static VAR Compensators (SVC) and Thyristor Controlled Series Capacitor (TCSC).

### 2.2.2.1 Static Var Compensators (SVCs)

The construction of the SVC consists of a TCR in parallel with a capacitors bank. From a technical perspective, the SVC operates as a shunt-connected variable reactance that can produces or draws reactive power to regulate the voltage level at the location of the connection to the system. It is used efficiently to supply fast reactive power and voltage regulation support. The firing angle control of the thyristor provides the SVC with an instantaneous speed of response.

A graphical illustration of the SVC is shown in Figure 2.3, where a three-phase, three winding transformer is utilized to connect the SVC to the system. The transformer has two identical secondary windings: the first is for the delta connection, six-pulse TCR and the second for the star connection, is a three-phase bank of capacitors, with its star point floating. The three transformer windings are also taken to be star-connected, with their starpoints floating.

![Fig 2.3 - Three-phase Static VAR Compensator (SVC)](image)

To regulate the transmission network voltage at a certain terminal is the main task of the compensator. Figure 2.4 clarifies the SVC V-I characteristic, indicating that regulation by a certain region near the nominal voltage can be done in the normal running range based on the maximum capacitive and inductive currents of the SVC while the maximum capacitive current reduces linearly and the produced reactive power in quadrature with the voltage of the system, where the SVC does as a fixed capacitor at the maximum capacitive output is presented. So the voltage support
ability of the traditional thyristor-controlled static Var compensator speedily impairs with reducing system voltage.

Moreover, to voltage support, SVCs are applied for transient first swing and steady state stability damping improvements. SVC behaves like an ideal mid-point compensator until the maximum capacitive admittance $BC_{\text{max}}$ is reached. From this point on, the power transmission curve becomes identical to that obtained with a fixed, mid-point shunt capacitor whose admittance is $BC_{\text{max}}$. The steady state stability enhancement of power oscillation damping can be achieved by changing the result of the SVC from required capacitive and inductive levels to reverse the angular acceleration and deceleration of the machines presented. The issue is to increase the transferred electrical power by raising the transmission line voltage, through capacitive amount, when the units accelerate and to reduce it by reducing the voltage, through inductive amount, when the units decelerate.

**Fig 2.4 Current V-I Characteristics of a SVC**

### 2.2.2.1.2. Thyristor Controlled Series Capacitor (TCSC)

A basic TCSC module consists of a TCR in parallel with a capacitor. An actual TCSC comprises one or more modules. Figure 2.5 shows the layout of one phase of the TCSC installed in the Slatt substation in USA. The TCSC basically comprises a capacitor bank inserted in series with the transmission line, a parallel metal oxide varistor (MOV) to protect the capacitor against over-voltage and a TCR branch, with a thyristor valve in series with a reactor, in parallel with the capacitor.
Mechanically bypass breakers are provided in parallel with the capacitor bank and in parallel with the thyristor valve. During normal operation, the bypass switch is open, the bank disconnect switches (1 and 2) are closed and the circuit breaker is open. When it is required to disconnect the TCSC, the bypass circuit breaker is switched on first, and then the bypass switch is switched on. The damping circuit is used to limit the current when the capacitor is switched on or when the bypass circuit breaker is switched on. Minimum series compensation is achieved when the TCR is off. The TCR can be selected to achieve the ability to restrict the voltage at the capacitor at faults and other system contingencies of similar effect.

Fig 2.5 Thyristor Controlled Series Capacitor (TCSC)

The operating range curve of TCSC impedance against the line current is shown in Fig 2.6. The different operating limits of the TCSC can be explained as follows:

For low line current, the TCSC can provide maximum capacitive and inductive compensation according to the resonant firing angle. In the capacitive region, the minimum firing angle allowed is above the resonant firing angle (limit A). On the other hand, in the inductive region, the maximum firing angle allowed is lower than the resonant firing angle(limit E). In the capacitive region, as the line current increases, the voltage drop across the TCSC increases too. To prevent over-voltage across the TCSC during normal operation, the firing angle increases towards 180 degrees to reduce the equivalent capacitive reactance of the TCSC, hence the voltage drop across it (limit c). In the inductive region, as the magnitude of the line current increases, the firing angle decreases to reduce the equivalent inductive reactance of the TCSC, hence the voltage drop across it (limit e).
increases, the harmonic heating limit of the thyristor valves is reached. The firing angle should be reduced to reduce the equivalent inductive reactance of the TCSC so as not to exceed this limit (limit F). Limit G presents the thyristors current limits.

Figure 2.7 shows the block diagram for the TCSC operation under current control mode. The line current is measured and the magnitude of it is compared with the desired value of the line current, the error signal is passed to the TCSC controller to obtain the appropriate firing angle, which can be measured from the zero crossing of the line current. The model for balanced, fundamental frequency operation is shown in Figure 2.8[34].

The overall impedance of the TCSC is given as:

$$X_{TCSC} = \frac{\pi X_c X_L}{X_c [2(\pi - a) + \sin 2\alpha]} - \pi X_L$$  \hspace{1cm} (2.1b)

The problem of the last equation is that the harmonic analysis has only been conducted for the TCR while the analysis of the capacitor charging has been neglected. The total impedance has been obtained by paralleling the TCR equivalent impedance at the fundamental frequency and the fixed capacitor. This makes equation (2.1) only valid for the first cycle of the current. The reason is that after the first cycle has elapsed, the capacitor stores charge, leading to higher steady state voltages compared to cases when the capacitor charging effect is neglected.

![Fig 2.6 Operating Range of TCSC.](image)
Fig. 2.7 Block Diagram of TCSC Operating in Current Control

Figure 2.8 - Dynamic Model of a TCSC
The derivation of the TCSC impedance is started by examining the voltages and currents in the TCSC under the full range of operating conditions. The basic equation is:

\[ Z_{TCSC}(1) = \frac{V_{TCSC(1)}}{I_{line}} \]  

(2.2)

\( V_{TCSC(1)} \) is the fundamental frequency voltage across the TCSC model, \( I \) is the fundamental frequency line current. The voltage \( V \) is equal to the voltage across the TCSC capacitor and equation (2.2) can be written as:

\[ Z_{TCSC(1)} = \frac{-jX_C I_{cap(1)}}{I_{line}} \]  

(2.3)

If the external power network is represented by an idealized current source, as seen from the TCSC terminals, this current source is equal to the sum of the currents following through the TCSC capacitor and inductor. The TCSC can then be expressed as:

\[ Z_{TCSC(1)} = \frac{-jX_C (I_{line} - I_{TCR(1)})}{I_{line}} \]  

(2.4)

The fundamental component of the TCR current can be found by the following:

The line current is,

\[ i_{line} = \cos(\omega t - \sigma) = \cos \omega t \cos \sigma + \sin \omega t \sin \sigma \]  

(2.5)

The voltage across the TCSC,

\[ L \frac{dI_{TCR}}{dt} = \frac{1}{C} \int i_{cap} dt + V_C^o \]  

(2.6)

Where \( V_C^o \) is the voltage across the capacitor when the thyristor turns on. In Laplace form equation (2.5) and (2.6) are

\[ I_{line} = \cos \sigma \frac{S}{S^2 + \omega^2} + \sin \sigma \frac{\omega}{S^2 + \omega^2} \]  

(2.7)

\[ I_{cap} = S^2 L C I_{TCR} - CV_C^o \]  

(2.8)

Applying Kirchhoff current law,

\[ I_{TCR} = I_{line} - I_{cap} \]  

(2.9)

Substituting (2.7) and (2.8) into (2.9), and solving for \( I_{TCR} \).
\[ I_{TCR} = \omega_o^2 \cos \sigma \frac{S}{(S^2 + \omega^2)(S^2 + \omega_o^2)} + \omega_o^2 \omega \sin \sigma \frac{1}{(S^2 + \omega^2)(S^2 + \omega_o^2)} + \frac{\omega_o^2 CV_C^o}{S^2 + \omega_o^2} \]  

(2.10)

Where \( \omega_o^2 = \frac{1}{LC} \)  

(2.11)

Substituting the expression for \( I_{TCR(1)} \) (The fundamental component of the TCR current) into (2.4) and assuming \( I_{line} = I_m \cos \omega t \), leads to the fundamental frequency TCSC equivalent reactance, as a function of the TCSC firing angle \( \alpha \) as:

\[ X_{TCSC} = -X_C + C_1(\pi - \alpha + \sin(2(\pi - \alpha))) - C_2 \cos^2(\pi - \alpha)(\frac{1}{\omega} \tan(\omega(\pi - \alpha)) - \tan(\pi - \alpha)) \]  

(2.12)

Where,

\[ \bar{\omega} = \frac{\omega_o}{\omega}, \quad \omega_o^2 = \frac{1}{LC}, \quad C_1 = \frac{X_C + X_{LC}}{\pi}, \quad C_2 = \frac{4X^2_{LC}}{X_L \pi}, \quad X_{LC} = \frac{X_C X_L}{X_C - X_L} \]

Comparing Equations 2.1 and 2.12, the resonant firing angle in the two equations are not the same. Depending on the ratio between \( X_C \) and \( X_L \), there could be more than one resonant angle for the TCSC expressed by Equation 2.5. Figure 2.9 shows the TCSC equivalent reactance’s as a function of the firing angle. The TCSC capacitive and inductive reactance values should be chosen carefully in order to ensure that just one resonant point is present in the range of \( \pi/2 \) to \( \pi \).

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**Fig. 2.9 - Thyristor-Controlled Series Capacitor (TCSC) Fundamental Frequency Impedance**
Although of the effective enhancement on transmittable power, high levels of series compensation are not typically used. The feasible upper boundary to the limit of series compensation is about 70%, as more steady state compensation may produce uncontrollable variations in the power for low alteration in terminal voltages or angles, and large transient currents and voltages during disturbances at series resonance conditions.

2.2.2.2. Synchronous Voltage Source (SVS)

Controllable solid-state synchronous voltage sources are employed for compensating the dynamic and controlling real-time the power flow in transmission systems. This method, when compared to conventional compensation approaches employing thyristor switched capacitors and thyristor-controlled reactors, controls performance characteristics and regular applicability for transmission voltage, reactance, and angle capability. It also gives the powerful tool to direct exchange active power with the AC grid, in addition to the independently controllable reactive power compensation, thereby giving a powerful new option for the counter action of dynamic disturbances. A functional model of the solid-state synchronous voltage source is shown in Figure 2.10. Reference signals \( Q_{\text{ref}} \) and \( P_{\text{ref}} \) define the output voltage amplitude with its phase angle of the generated voltage and also the reactive and real power flow between the reference mentioned voltage source and the grid. If the goal of dynamic true power flow is not achieved, \( P = 0 \), the SVS gets a self-sufficient reactive power source as an ideal synchronous condenser, and the external energy storage device can be disposed of. Various switching power converters can implement the solid-state synchronous voltage source, although of the switching converter mentioned as the voltage-sourced inverter. This particular DC to AC switching power converter, which is based on gate turn-off (GTO) thyristors in appropriate multi-pulse circuit configurations, is presently applied in the most practical for high power utility applications. The functional and operating characteristics of this type of inverter, which saves the basic functional building block for the comprehensive compensation and power flow control approach, are explained below.

An elementary, six-pulse, voltage-sourced inverter is shown in Figure 2.11. It consists of six self-commutated semiconductor (GTO) switches, each of which is shunted by an inverse-parallel connected diode. It should be noted that in a high power
inverter, each solid-state switch consists of a number of series-connected GTO thyristor/diode pairs. With a DC voltage source (which may be a charged capacitor), the inverter can produce a balanced set of three quasi-square voltage wave-forms of a given frequency, as illustrated in Figure 2.12, by connecting the DC source sequentially to the three output terminals via the appropriate inverter switches. There is exchange between the reactive power of the inverter and the AC system, which can be controlled by varying the magnitude of the produced three-phase output voltage. When the amplitude of the output voltage is raised over the system voltage, then the current flows via the reactance from the inverter to the AC system and the inverter produces capacitive power for the AC grid. If the output voltage amplitude is decreased under that of the AC grid, then the reactive current flows from the AC system to the inverter and the inverter draws inductive power. When the output voltage is balanced with the AC grid voltage, the reactive power flow becomes zero.

In the same way, the real power transfer between the SVS and the AC grid may be controlled by shifter of the phase voltage of the inverter related to the AC system voltage. That is, the inverter from its DC energy storage provides real power to the AC network if the voltage of the inverter is leading the corresponding AC network voltage. This is because this phase advancement results in a real component of current through the tie reactance that is in anti-phase with the AC network voltage. By the same way, the inverter draws real power from the AC grid for DC energy storage, when the voltage of the inverter is lagging the AC network voltage. The real component of current flowing through the tie reactor is now in-phase with the AC system voltage.
The mechanism by which the inverter internally generates reactive power can be explained simply by considering the relationship between the output and input powers of the inverter. The base of the explanation depends on the physical rule that the process of energy transfer through the inverter, consisting of nothing but arrays of solid-states witches, is absolutely direct. Thus, it is clear that the resultant power at
the AC output ports are always equal to the net resultant power at the DC input terminals when neglecting the losses.

Assume that the inverter is operated to supply only reactive output power. In this case, the active input power provided by the DC source has to be zero. Furthermore, where reactive power, at frequency equals zero, by basics will be zero, the DC source generates no input power and therefore it clearly has no part in the supplying of the reactive output power. In another meaning, the inverter connects internally the three output terminals, like a method, which the reactive currents may move easily between them. Concerning this with the terminals of the network, it could be seen that the inverter produces an exchanged circulating power among the phases.

Although reactive power is inherently produced by the action of the solid-state switches, it is still essential to have a relatively small DC capacitor connected across the input terminals of the inverter.

The importance for the DC capacitor is primarily requested to satisfy the above stipulated the balance input power and output power. The waveform of the inverter output voltage is not a pure sine wave. It is a staircase approximation of a sine wave. However, the multi-pulse inverter absorbs a smooth, almost sinusoidal current from the network through the tie reactance. As a result, the resultant three-phase instantaneous apparent power(VA) at the output terminals of the inverters lightly fluctuates. Thus, for not violating the balance between of the real input power and output power, the inverter must draw a ripple current from the DC capacitor that keeps a regulated terminal voltage at the input.

The existence of ripple part of input current is mainly due to the ripple components of the output voltage, which depend on the used technique in the output waveform fabrication. In a high power inverter, using a sufficiently high pulse number, the output voltage distortion and, thereby, capacitor ripple current can be mainly decreased to any desired degree [34].

Thus, a perfect inverter would produce sinusoidal output voltage and draw pure DC input current without harmonics. To achieve purely reactive output, the input current of the perfect inverter is zero. Because of system unbalance and other unbalances like economic considerations, those ideal conditions are not practical, but approximated satisfactorily by inverters of sufficiently high pulse numbers (24 or higher).
Among the SVS based Facts devises are the STATCOM, the SSSC and the UPFC.

2.2.2.2.1 Static Compensator (STATCOM)

The STATCOM consists of one VSC and its associated shunt-connected transformer. It is the static form of the rotating synchronous condenser but it supplies or draws reactive power with a fast rate because there are no moving parts inside it. In principle, it performs the same voltage regulation function as the SVC but in a more robust manner because, unlike the SVC, its operation is not impaired by the presence of low voltages. A schematic representation of the STATCOM and the equivalent circuit are indicated in Figure 2.13.

If the energy storage is of suitable rating, the SVS can exchange both active and reactive power with the network. The active and reactive power supplied or drawn by the SVS, can be controlled independently of each other, and any combination of active power, generated or absorbed, with active power, generated or absorbed, is possible. The active power that the SVS exchanges at its network terminals with the grid must, of course, be supplied to, or absorbed from, its DC terminals by the energy storage unit. In other way, the reactive power flow is internally developed by the SVS, without the DC energy storage device playing any significant part in it.

The bi-directional real power exchange capability of the SVS, that is, the ability to absorb energy from the AC system and deliver it to the DC energy storage device (large storage capacitor, battery, superconducting magnet) and to reverse this process and deliver power for the AC system from the energy storage device, makes complete, temporary system support possible. Specifically, this capability may be used to improve system efficiency and prevent power outages. In addition, in combination with fast reactive power control, dynamic active power exchange is considered as an extremely powerful method for transient & dynamic stability enhancement.
When the SVS is applied in strict way for reactive shunt compensation, as a conventional static Var compensator, the DC energy storage device can be replaced by a relatively small DC capacitor, as shown in Figure 2.13. In this case, the steady-state power flow between the SVS and the AC grid become only in reactive form.

When the SVS is applied for reactive power supplying, the inverter itself can maintain the capacitor charged to the desired voltage level. This is achieved by making lagging in the output voltages of the inverter and the system voltages by a little angle. In this way, the inverter draws a small amount of active power from the grid to rebalance the inner losses and save the voltage of the capacitor at the required level. The same control procedure can be applied to raise or reduce the capacitor voltage, and then the inverter voltage magnitude, for achieving the control of the reactive power generation or absorption. The DC capacitor also owns a task of establishing a balance between the input energy and output energy at the dynamic changes of the VAR output.

The STATCOM V-I characteristic is indicated in Figure 2.14. As can be seen, the STATCOM can act as both capacitive and inductive compensators and it is able to control its output current independently over the maximum range of the capacitive or inductive of the network voltage. That is, the STATCOM can produce complete capacitive output current at any grid voltage level. On the other side, the SVC can supply only output current with reducing system voltage as calculated by its
maximum equivalent capacitive admittance. So the STATCOM is superior to the SVC in applying voltage support.

![V-I Characteristic of a STATCOM](image)

**Fig. 2.14 V-I Characteristic of a STATCOM.**

### 2.2.2.2 Static Series Synchronous Compensator (SSSC)

The Static Synchronous Series Compensator (SSSC) is a series connection FACTS controller dependent on VSC and can be considered as advanced kind of controlled series compensation, just as a STATCOM is an advanced SVC. A SSSC own several merits over a TCSC such as (a) elimination of bulky passive components (capacitors and reactors), (b) improved technical characteristics (c) symmetric capability in both inductive and capacitive operating modes (d) the connection availability of an energy source on the DC port to exchange active power with the AC grid. A solid-state synchronous voltage source, consisting of a multi-pulse, voltage-sourced inverter and a DC capacitor, is shown in series with the transmission line in Figure 2.15.
In general, the active and reactive power exchange is controlled by the phase displacement of the injected voltage related to the current. For example, when the injected voltage is in phase with the line current, then only active power is exchanged, and if it is in quadrature with the line current then only reactive power is exchanged.

The series-connected synchronous voltage source is an extremely powerful tool for power flow control and, it is able to control both the transmission line impedance and angle. Its capability to exchange active power with the grid makes it very effective in enhancing dynamic stability by means of alternately inserting a virtual positive and negative damping resistance in series with the line by the disturbed generators angular deceleration and acceleration.

The idea of the solid-state synchronous voltage source for compensation of series reactive depends on the rule that the characteristic of the impedance with the frequency of the practically employed series capacitor, which is different than the filter techniques, has no role in achieving the required line compensation. The goal of the series capacitor is summarized to generate a suitable voltage at the fundamental AC network frequency in series with the line to eliminate the voltage drop produced via the inductive impedance of the line by the fundamental part of the line current. So that the resulting total voltage drop of the compensated line becomes electrically equivalent to that of a shorter line. Therefore, if an AC voltage supply with
fundamental frequency, which has a quadrature lagging following to the line current and the magnitude depends on the line current is flowed in series with the line. A series compensation is equal to the one developed by a series capacitor during the fundamental frequency is supplied.

The voltage source can be described in mathematical form as follows:

\[ V_n = -jkXI \]

\( V_n \) is the compensating value of the injected voltage, \( I \) is the phasor of the line current, \( X \) is the impedance of the series reactive line, and \( k \) is the series compensation degree.

For conventional series compensation, \( k \) is defined as \( X_C /X \), where \( X_C \) is the impedance of the series capacitor.

For regular capacitive compensation, the output voltage must lag the line current by 90 degrees, in order to directly oppose the inductive voltage drop of the line impedance. However, the output voltage of the inverter will be opposed by a proper control method to direct it to be leading the line current with 90 degrees. Then, the inserted voltage is in phase with the voltage developed by the inductive reactance of line. Therefore, the series compensation owns the equivalent effect as if the reactive impedance was raised. This capability can be invested to increase the effectiveness of power oscillation damping and, with sufficient inverter rating; it can be used for fault current limitation. Series compensation by a synchronous voltage source that can be limited to the fundamental frequency is worthy to that provided with series capacitive compensation in that it cannot produce undesired electrical resonances with the transmission grid, and for this reason, it cannot cause sub-synchronous resonance. However, by appropriate control it can damp sub-synchronous oscillations, which may happen because of present series capacitive compensations by inserting non-fundamental voltage components with proper magnitudes, phase angles and frequencies, in addition to the fundamental component, in series with the line.

Due to the stipulated 90-degree phase relationship between the inverter output voltage and the line current, this, via the series insertion transformer, flows through the inverter as the load current, the inverter in the solid-state voltage source theoretically exchanges only reactive power with the AC system. As explained previously, the inverter can internally generate all the reactive power exchanged and thus can be operated from a relatively small
DC storage capacitor charged to an appropriate voltage. In practice, however, the semiconductor switches of the inverter are not loss-less, and so the energy saved in the DC capacitor would be balanced through the inverter internal losses. Those losses will be provided by the AC system itself by acting the voltage of the inverter lags the current by less than 90 degrees. The typical deviation from 90 degrees is a fraction of a degree. In this way, the inverter draws a small value of active power from the AC network to balance the internal losses and save the DC capacitor voltage at the required level. That control procedure can also be applied to raise or reduce the DC capacitor voltage by making the inverter voltage lag the line current by an angle smaller or greater than 90 degrees. Thereby, control the magnitude of the AC output voltage of the inverter and the degree of series compensation.

2.2.2.2.3. Unified Power Flow Controller (UPFC)

The UPFC may be considered to be constructed of two VSCs sharing a common capacitor on their DC side and a unified control system. A simplified schematic representation of the UPFC is given in Figure 2.16.

The UPFC gives simultaneous control of real and reactive power flow and voltage amplitude at the UPFC terminals. Additionally, the controller may be adjusted to govern one or more of these criteria in any combination or to control none of them. This technique permits with the combined application of controlling the phase angle with controlled series reactive compensations and voltage regulation, but also the real-time change from one mode of compensation into another one to handle the actual system contingencies more effectively. For instance, series reactive compensation may be altered by phase-angle control or vice versa. This can become essentially important at relatively big numbers of FACTS devices will be applied in interconnected power grids, and compatibility and coordination control can own to be save in the face of devices failures and system changes.

The technique would also give significant flexible operation by the inner adaptability to power network expansions and changes no real hardware alterations. The implementation problem of the unrestricted series compensation is simply that of supplying or absorbing the real power that it exchanges with the AC system at its AC terminals, to or from the DC input sides of the inverter applied in the solid-state synchronous voltage source. The implementation in the proposed configuration called unified power flow controller (UPFC) employs two voltage source inverters applied
with a common DC connected capacitor; it is shown schematically in Figure 2.16. That arrangement is practically an achievement of an AC to DC power converter within dependently controllable input and output parameters. Inverter 2 in the arrangement shown is used to generate voltage \( V_B(t) = V_B \sin(\omega t - \delta_B) \) at the fundamental frequency with variable amplitude \( 0 \leq V_B \leq V_B^{\text{max}} \) which is added to the AC system terminal voltage by the series connected coupling (or insertion) transformer. With these stipulations, the inverter terminal voltage injected in series way with the line will be applied for direct voltage control, series compensation, and phase-shift.

![Fig. 2.16. Schematic Diagram for the UPFC](image)

The inverter output voltage inserted in series with the line is considered mainly as an AC voltage source. The current flowing through the injected voltage source is the transmission line current; it depends on the transferred electric power and the transmission line impedance. The total of the maximum injected voltage defines the VA rating of the injected voltage source for Inverter 2 and the maximum line current during the power flow control is still developed.

### 2.2.3 FACTS Controller Applications in Transmission system

The applications of FACTS controllers in electric power systems are given below.

- Steady state voltage regulation and control
- Steady state control of power flow on a transmission line
- Transient stability enhancement
- Damping of transmission system oscillation frequencies (0.2 -2 Hz)
- Improving steady state/dynamic stability limits
• Improving voltage stability
• Reducing the problem of sub-synchronous resonance
• Improving HVDC link performance

2.3 Location of FACTS controller

In competitive electric power systems, electric utilities have to operate close to their limits (thermal, voltage etc.). With the advent of power electronics technology, flexible AC transmission system (FACTS), utilities are able to control power flow, increase transmission, line stability limits, improve security of transmission systems and enhance utilization of the existing power system. The application of power electronics based devices called FACTS (flexible AC Transmission system) gives promising solutions because of their high speed and flexible controllability. **Better controls can increase the stability limit, and then the system can be loaded at a higher level. This provides better utilization of the existing transmission network. Power transfer along a line has limited by stability & any increase in this limit has a direct economic benefit by enabling more transactions between generators and customers.**

In recent years, the impacts of FACTS devices on power transfer capability enhancement and system loss minimization have been a major issue in the competitive electric power system. In this regard, many optimization techniques are available to control the power system parameters. However the optimum power flow, stability limit problem is generating non-linear and non-convex optimization problem and as a result, many local solutions may exist especially in power system with embedded FACTS devices. Moreover conventional optimization methods are highly sensitive to starting points and may converge to local optimum solutions or diverge altogether.

The solution techniques for optimum power flow and enhancement of system stability involves mathematical and computational characteristics. The solution techniques available are a) Conventional methods b) Classical methods c) Computational intelligence methods and d) Heuristic methods. The purpose of this chapter is to present some general background on optimization theory and discuss the current optimization methods to solve the problem of optimal allocation of FACTS devices in the power system.
FACTS make the application of a large amount of \textit{var} compensation. By proper choice of the FACTS devices at suitable locations, it is possible to control the system parameters and thus will improve the system stability. Right location and right sizing of reactive power compensators, considering technical and economic needs, are the major criteria in present research work.

2.4 Methods of Location of FACTS Controllers

FACTS sizing and allocation constitutes a milestone problem in power system. In this regard, various methods of location of FACTS controllers have been discussed below.

2.4.1 Conventional Methods

Generally, location of FACTS devices in the power system have obtained based on static and / or dynamic performances. There are several methods for finding optimal location of FACTS devices in vertically integrated system as well as unbundled power system. The objective of the series device placement may be reduction in the real power loss of a particular line, reduction in the total system real power loss, reduction in the total system reactive power loss and maximum power transfer in the system.

Sensitivity analysis is a widely used terminology to describe the analysis based on the evaluation of the rate of change of one group of variables in a system with respect to another group. There are many different ways to perform the analysis depending on the selected variables and methodologies used to calculate the sensitivities.

The loss sensitivity approaches were available to determine the optimal placement of TCSC, TCPAR, and SVC to minimize the total system real power loss. In this research work, VAR indices method has been proposed for placement of series capacitor compensators. The real power flow performance index (RPPI) method has also been used in this research work to determine the overloaded lines for locations of TCSC for congestion management. However, these methods may not lead to the optimal solution because of the dependency to system topology and loading conditions. Therefore, using conventional methods may be stuck into local optimal solutions, insecure convergence, long execution time and algorithmic complexity. To overcome the above problems Artificial Intelligence (AI) techniques are essential.
The various conventional methods used in the present research work are as given below.

a) **Loss Sensitivity Index Method or VAR indices Method:**

Loss sensitivity index is a method based on the sensitivity of total system reactive power loss with respect to control variable of the FACTS devices. In this research work, a method based on the sensitivity of the total system reactive power loss with respect to a control variable of the TCSC has been carried out. For TCSC placed between the buses i and j, we consider net line series reactance as a control parameter. Loss sensitivity index with respect to this control parameter of TCSC placed between buses i and j can be written as,

\[
a_{ij} = \frac{\partial Q_L}{\partial X_{ij}}
\]

(2.13)

These factors can computed at a base load flow solution as given below. Consider a line connected between buses i and j and having a net series impedance of \(X_{ij}\) and \(Q_i\) is the net reactive power injected in the bus i. The bus sensitivity index with respect to \(X_{ij}\) computed as

\[
\frac{\partial Q_L}{\partial X_{ij}} = \left[ V_i^2 + V_j^2 - 2V_iV_j \cos(\delta_i - \delta_j) \right] \frac{r_{ij}^2 - X_{ij}^2}{(r_{ij}^2 + X_{ij}^2)^2}
\]

(2.14)

For optimal placement of TCSC in reactive power loss reduction method the criteria used is TCSC should be placed in a line having the positive loss or the value nearer to the origin sensitivity index[55].

b) **Line Utilization Factor (LUF)**

In the present research work, two approaches have been derived. These approaches involved two new factors. With the help of these factors, the level of congestion in transmission line can be determined.

LUF is the measure of utilization of a particular line or overall system. It gives an idea about how much percentage of the line has used for the power flow. If the value of utilization is less, it means that less power has been transferred and the system will be less congested and vice-versa.

\[
LUF_{ij} = \frac{MVA_{ij}}{MVA_{ij}^{MAX}}
\]

(2.15)
Where,
LUF\(_{ij}\) is the Line Utilization Factor (LUF) of the line connected to bus-i and bus-j.
MVA\(_{ij}^{\text{MAX}}\) is the Mega Volt Ampere (MVA) rating of the line between bus-i and bus-j.
MVA\(_{ij}\) is the actual MVA rating of the line between bus-i and bus-j.

c) Real Power Performance Index (RPPI)

An index for quantifying the extent of line overloads defined in terms of real power performance index is given as

\[
\text{RPPI} = \sum_{l=1}^{NL} \epsilon_l \left[ \frac{P_l}{P_l^{\text{Lim}}} \right]^{2n}
\]

(2.16)

Where,
\(P_l\) = Mega Watt flow of line l.
\(P_l^{\text{Lim}}\) = Mega Watt capacity of the line.
\(NL\) = Number of lines in the system.
\(n\) = Specified exponent.
\(\epsilon_l\) = Weighting factor, which may be used to reflect the importance of some lines.

In this work, we consider that \(n=1\) and \(\epsilon_l=1\). RPPI will be small when all the lines are within their limits and reach a high value where there are overloads. Thus, it provides a good measure of severity of line overloads for a given state of the power system.

2.4.2 Classical Methods

The classical methods provide different techniques such as linear programming (LP), non linear programming (NLP), quadratic programming (QP), integer and mixed integer programming (IP and MIP respectively), and dynamic programming (DP). Classical optimization theory has been applied in the literature to the FACTS allocation problem in the form of MILP and MINLP.

The simplest technique is linear programming (LP) that concerns the case where the objective function \(f\) is linear and the set \(A\) is specified using only linear equality and inequality constraints. In general, the objective function or the constraints or both contain nonlinearities, raising the concept of nonlinear
programming (NLP). A particularly well studied case is the one where the objective function \( f \) is nonlinear but all the constraints \( g \) and \( h \) are linear. This problem has been referred to as linearly constrained optimization. If in addition to linear constraints, the objective function is quadratic then the optimization problem has been called as quadratic programming (QP). In principle it could be possible to use higher order derivatives, however these methods has not been used in practice because of the difficulties that arise due to multiple local minima and overwhelming computational effort and memory required.

In addition to nonlinear conditions, often some or all variables have constrained to take on integer values, and the technique has then referred to as mixed integer programming (MIP) or strictly integer programming (IP). MIP and IP problems are difficult to solve, in fact, no efficient general algorithm is known for their solution.

The deterministic optimization problem has been formulated with known parameters; real world problems almost invariably include some unknown parameters. This necessitates the introduction of stochastic programming models that incorporate the probability distribution functions of various variables into the problem formulation.

In its most general case, Dynamic Programming (DP) has been mathematically proven to find an optimal solution but it has its own disadvantages. Solving the dynamic programming algorithm in most of the cases is not feasible. Even a numerical solution requires overwhelming computational effort, which increases exponentially as the size of the problem increases (curse of dimensionality). These restrictive conditions lead the solution to a suboptimal control scheme with limited look-ahead policies. In the Mixed Integer Linear Programming (MILP) formulation, the approach has based on DC power flow that allows the power system to represent in a linear manner. The performance of the system has analyzed in steady state conditions considering maximum load ability of the system and total transfer capability.

2.4.3. Computational Intelligence Method

Computational intelligence (CI) is a new and modern tool for solving complex problems that are difficult to solve by the conventional techniques. Heuristic optimization techniques are general-purpose methods that are very flexible and can
applied to many types of objective functions and constraints. Recently, these new heuristic tools have combined among themselves and new methods have emerged that combine elements of nature-based methods or which have their foundation in stochastic and simulation methods. Developing solutions with these tools offers two major advantages: development time is much shorter than when using more traditional approaches, and the systems are very robust, being relatively insensitive to noisy and/or missing data/information known as uncertainty.

Due to environmental, right-of-way and cost problems, there is an increased interest in better utilization of available power system capacities in both bundled and unbundled power systems. Patterns of generation that results in heavy flows, tend to incur greater losses, and to threaten stability and security, ultimately make certain generation patterns economically undesirable. Hence, new devices and resources such as flexible ac transmission systems (FACTS), distributed generations, smart grid technologies, etc. are being utilized. In the emerging area of power systems, computation intelligence plays a vital role in providing better solutions of the existing and new problems.

There are several problems in the power systems that cannot be solved using the conventional approaches as these methods are based on several requirements, which may not be true all the time. In those situations, computational intelligence techniques are only choice however these techniques are not limited to these applications. The following areas of power system utilize the application of computational intelligence.

- **Power system operation** (including unit commitment, economic dispatch, hydro-thermal coordination, maintenance scheduling, congestion management, load/power flow, state estimation, etc.)
- **Power system planning** (including generation expansion planning, transmission expansion planning, reactive power planning, power system reliability, etc.)
- **Power system control** (such as voltage control, load frequency control, stability control, power flow control, dynamic security assessment, etc.)
- **Power plant control** (including thermal power plant control, fuel cell power plant control, etc.)
- **Network control** (location and sizing of facts devices, control of facts devices, etc.)
- **Electricity markets** (including bidding strategies, market analysis and clearing, etc.)
• Power system automation (such as restoration and management, fault diagnosis and reliability, network security, etc.)

• Distribution system application (such as operation and planning of distribution system, demand side management & demand response, network reconfiguration, operation and control of smart grid, etc.)

• Distributed generation application (such as distributed generation planning, operation with distributed generation, wind turbine plant control, solar photovoltaic power plant control, renewable energy sources, etc.)

• Forecasting application (such as short term load forecasting, electricity market forecasting, long term load forecasting).

Computational intelligence (CI) methods, which promise a global optimum or nearly so, such as expert system (ES), artificial neural network (ANN), genetic algorithm (GA), evolutionary computation (EC), fuzzy logic, etc. have been emerged in recent years in power systems applications as effective tools. These methods are also known as artificial intelligence (AI) in several works. In a practical power system, it is very important to have the human knowledge and experiences over a period of time due to various uncertainties, load variations, topology changes, etc. This section presents the overview of CI/AI methods (ANN, GA, fuzzy systems, EC, ES, ant colony search, Tabu search, etc.) used in power system applications.

However, to find the best location for each device an exhaustive evaluation of all possible locations is required. Therefore, the basis of these methodologies is deficient in the formulation and implementation of an appropriate search process to avoid the exhaustive search and corresponding computational burden. In addition, these methodologies evaluate the sensitivity indices independently for each FACTS device. In this way, it is not possible to evaluate the combined effect of several of these devices installed in the system.

In this research work presented, fuzzy logic method has used to relieve congestion by properly locating FACTS controllers in power system. The details of fuzzy logic methods are as follows.

2.4.3.1 Fuzzy Logic Control

Fuzzy logic was developed by Zadeh in 1964 to address uncertainty and imprecision which widely exist in the engineering problems and it was first introduced in 1979 for solving power system problems. Fuzzy set theory can be considered as a generation of the classical set theory. In classical set theory, an
element of the universe either belongs to or does not belong to the set. Thus, the
degree of associations of an element is crisp. In a fuzzy set theory, the association of
an element can be continuously varying. Mathematically, a fuzzy set is a mapping
(known as membership function) from the universe of discourse to the closed interval
[0, 1]. The membership function has been usually designed by taking into
consideration the requirement and constraints of the problem. Fuzzy logic implements
human experiences and preferences via membership functions and fuzzy rules. Due to
the use of fuzzy variables, the system can made understandable to a non-expert
operator. In this way, fuzzy logic can be used as a general methodology to incorporate
knowledge, heuristics or theory into controllers and decision makers.

![Diagram](image)

**Fig.2.17. Shows the Block Diagram of Fuzzy Controller for TCSC which has
used in this Research Work.**

Fuzzy control system design is based on empirical methods, basically a methodical
approach to trial-and-error. The general process is as follows:

- Document the system's operational specifications and inputs and outputs.
- Document the fuzzy sets for the inputs.
- Document the rule set.
- Determine the defuzzification method.
- Run through test suite to validate system, adjust details as required.
- Complete document and release to production

Fuzzification is a process whereby the input variables hasbeen mapped onto
fuzzy variables (linguistic variables). In this block diagram, line flow in MW without
FACTS device and change in line flow in MW after placing FACTS device are
considered as inputs and change in power loss after placing device is considered as
system output. In this work for both the inputs \( P_{\text{line}} \) and \( \Delta P_{\text{line}} \) and the output \( \Delta P_{\text{loss}} \),
five fuzzy subsets have been used. They are S (small), SM (Small Medium), M
(Medium), MH (Medium High) and H (High). The triangular membership functions
are used for the above sub-sets. 25 control rules yield by these fuzzy sub-sets which are shown in table 2.1.

2.4.3.2 Fuzzy Control Rules

<table>
<thead>
<tr>
<th>$\Delta P_{\text{lin}}$</th>
<th>S</th>
<th>SM</th>
<th>M</th>
<th>MH</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{lin}}$</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>SM</td>
<td>S</td>
<td>SM</td>
<td>SM</td>
<td>SM</td>
<td>SM</td>
</tr>
<tr>
<td>M</td>
<td>S</td>
<td>SM</td>
<td>M</td>
<td>MH</td>
<td>M</td>
</tr>
<tr>
<td>MH</td>
<td>S</td>
<td>SM</td>
<td>M</td>
<td>MH</td>
<td>MH</td>
</tr>
<tr>
<td>H</td>
<td>S</td>
<td>SM</td>
<td>M</td>
<td>MH</td>
<td>H</td>
</tr>
</tbody>
</table>

In the beginning, line flow in MW without device $P_{\text{lin}}$ and change in line flow in MW after placing device $\Delta P_{\text{lin}}$, values will be converting to fuzzy variables. After this fuzzification, fuzzy inputs enter to inference mechanism level and with considering membership function and rules; outputs are sent to defuzzification to calculate the final output.

After evaluating inputs and applying them to the rule base, a control signal will be generated by the fuzzy-logic controller. The output variables of the inference system are linguistic variables.

They will be evaluated for the derivation of the output control signal. This process is the defuzzification. The defuzzification is achieved using the centre of gravity (COG) method and the output of the fuzzy coordinated controller is

Centre of gravity (set of real numbers)

$$COG(A) = \frac{\sum_{X_{\min}}^{X_{\max}} x \cdot A(x)}{\sum_{X_{\min}}^{X_{\max}} A(x)} \tag{2.17}$$

Where $X_{\min}=1$ and $X_{\max}=25$

$A(x)=P_{\text{loss}}$

Corresponds to the value of control output for which the membership values in the output sets are equal to unity.
x=Membership function.

The advantages of fuzzy set theory are more accurately represents the operational constraints of power systems, and fuzzified constraints are softer than traditional constraints.

2.4.4. Evolutionary Computation Techniques

Many areas in power systems, including the FACTS devices placement, sizing and control, require solving one or more nonlinear, multi-objective optimization problems. While analytical methods might suffer from slow convergence and the curse of dimensionality, heuristics based evolutionary computation techniques can be an efficient alternative to solve these complex optimization problems.

Evolution of the population then takes place after the repeated application of operators such as inheritance, mutation, natural selection and crossover for evolutionary biologically inspired algorithms, or social communication and cultural learning for those methods based on swarm intelligence. Evolutionary computation algorithms consistently perform well to approximate solutions to all types of problems because they do not make any assumption about the underlying fitness landscape. They are not largely affected by the size and nonlinearity of the problem, and they can perform well in highly constrained and integer (or mixed integer) optimization problems.

Computational intelligence combines elements of learning, adaptation, and biological evolutions to create methods that are, in some sense, intelligent. GA, EP, TS, SA and PSO, are a subset of computational intelligence, and generic population based meta heuristic algorithms for global optimization applications. Candidate solutions to the optimization problem play the role of individuals in a population, and the cost function determines the environment where the solutions exist.

Simple heuristic approaches have traditionally applied to find the size and location of FACTS devise in a small power system. However, more scientific methods are required for placing them in a large power network. In this research work, Genetic algorithm and Particle swarm optimization have been tested for finding the optimal allocation as well as the type of devices and their sizes, and this has given better results than classical techniques and with less computational effort. These heuristic methods have proved that it does converge to the optimal solution with high degree of probability. The basic model of Genetic Algorithm and Particle Swarm Optimization methods used in this work has been explained below.
2.4.4.1 Simple Genetic Algorithm Method

The major advantage of GA lies in their computation simplicity, powerful search ability to reach the global optimum and has been extremely robust with respect to the complexity of the problem.

Genetic Algorithms (GA) are powerful domain independent search technique inspired by Darwinian Theory of evolution [1]. It was invented by John Holland and his colleagues in 1970s [2] and was successfully applied to many engineering and optimization problems [2] and to various areas of power system such as economic dispatch [3, 4], unit commitment [5], reactive power planning [6,7], power plant control [8,9], and Generation expansion planning [10].

GA is an adaptive learning heuristic that imitate the natural process of evolution to progress toward the optimum by performing an efficient and systematic search of the solution space. A set of solutions, described as a population of individuals, has encoded as binary strings, termed as Chromosomes. This population represents points in the solution space. A new set of solutions, called offsprings, has been created in a new generation (iteration) by crossing some of the strings of the current generation. This process has called Crossover. Furthermore, the Crossover repeated at every generation and new characteristics will introduce to add diversity. The process of altering some of the strings of the offsprings randomly is known as Mutation.

The basic steps of GA can described as follows:

**Step 1**: Generation of Initial population of solutions represented by Chromosomes.

**Step 2**: Evaluation of the solutions generated using the fitness function, which is usually the objective function of the problem under study.

**Step 3**: Selection of individual solutions that have higher fitness value. There are different selection methods such as Roulette wheel selection, stochastic selection, and Ranking-based selection [2].

**Step 4**: Generation of new offsprings from the selected individual solutions. This is done for certain number of generations using two main operations:

- Crossover: There are various Crossover operators; the most common is the one point crossover. In one point Crossover, one bit in each solution, of two given binary coded solutions, is determined randomly and then swapped to generate two new solutions.
- Mutation: Incremental random changes applied in the selected off springs by altering randomly some of its bits. Mutation will usually probabilistically apply to only few members of the population and therefore has a small value.

**Step 5:** Steps 2 to 4 will repeat until a predefined number of generations have been produced.

![Flow chart of GA algorithm](image)

**Fig 2.18. The Flow Chart of GA Algorithm has Shown Above.**

Table 2.2. Presents the analogy between genetic terminology and the corresponding GA terminology.
Genetic algorithms are different from normal search methods encountered in engineering optimization in the following ways:

1. GA work with a coding of the parameter set not the parameters themselves.
2. GA search from a population of points, not a single point.
3. GA use probabilistic transition rules, not deterministic transition rules.

### 2.4.4.2 Coding of Parameters

Genetic Algorithms require the natural parameter set of the optimization problem to be coded as a finite-length string. As an example, consider the linear optimal control Problem shown in Figure 2.19. For this optimization problem, the two parameters \( K_1 \) and \( K_2 \) has discretized by mapping from a smallest possible parametric set \( K_{\text{min}} \) to a largest possible parametric set \( K_{\text{max}} \). This mapping uses a 10-bit binary unsigned integer for both \( K_1 \) and \( K_2 \). In this coding string code 0000000000 maps to \( K_{\text{min}} \) and 1111111111 maps to \( K_{\text{max}} \) with a linear mapping in between. Next, the two 10-bit sets are chained together to form a 20-bit string representing a particular controller design. A single 20-bit string represents one of the \( 2^{20} = 1,048,576 \) alternative solutions.

<table>
<thead>
<tr>
<th>Genetics Terminology</th>
<th>GA Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual, String or Chromosome</td>
<td>A coded parametric set</td>
</tr>
<tr>
<td>Population</td>
<td>A Collection of search points</td>
</tr>
<tr>
<td>Generation</td>
<td>Next iteration</td>
</tr>
<tr>
<td>Gene</td>
<td>Feature or character</td>
</tr>
<tr>
<td>Allele</td>
<td>Feature value</td>
</tr>
<tr>
<td>Fitness function or objective</td>
<td>Function to be optimized</td>
</tr>
<tr>
<td>Function or Performance index</td>
<td></td>
</tr>
<tr>
<td>Schemata or similarity templates</td>
<td>Building blocks</td>
</tr>
</tbody>
</table>

Table B-1 GA terminology
Fig. 2.19 An Example of Linear Optimal Control.

Evaluate $K_1$ and $K_2$ for $\min J = \int_0^T f(Y_1, Y_2, U) dt$

Table B-2 Coding example

<table>
<thead>
<tr>
<th>String Number</th>
<th>K1 (Population Size = 5)</th>
<th>Coding</th>
<th>K2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K1</td>
<td>K2</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-25.00 ($K_{\text{min}}$)</td>
<td>0000000000 0000000000</td>
<td>-25.00 ($K_{\text{min}}$)</td>
</tr>
<tr>
<td>2</td>
<td>8.3</td>
<td>1010101010 1010111101</td>
<td>9.23</td>
</tr>
<tr>
<td>3</td>
<td>19.43</td>
<td>1110001110 0001101101</td>
<td>-19.67</td>
</tr>
<tr>
<td>4</td>
<td>15.57</td>
<td>1100111111 0000110111</td>
<td>-22.31</td>
</tr>
<tr>
<td>5</td>
<td>25.00 ($K_{\text{max}}$)</td>
<td>1111111111 1111111111</td>
<td>25.00 ($K_{\text{max}}$)</td>
</tr>
</tbody>
</table>

Example of coding

Range of parameter $K$ (-25 to 25)

Number of states for 10 bits string $= 2^{10} = 1024$ state

$Q$ (Quantitization) = $50 / 1024 = 0.048828$

For string # 2 $K_1 = 682 \times 0.048828 - 25 = 8.3$
  where $(1010101010)_2 = (682)_{10}$

For string # 3 $K_2 = 109 \times 0.048828 - 25 = -19.67$
  where $(0001101101)_2 = (109)_{10}$

Genetic Algorithms (GA), approach to tune the parameters of a TCSC for power system stability improvement are described in the reference (11) and heuristic methods are in (12, 13).
2.4.5 Particle Swarm Optimization (PSO)

The Particle swarm optimization (PSO) is an evolutionary computation technique developed by Eberhart and Kennedy [14] inspired by social behaviour of bird flocking or fish schooling. Similar to Genetic Algorithms (GA), PSO is a population based optimization tool. The system is initialized with a population of random solutions and searches for optima by updating generations. However, unlike GA, PSO has no evolution operators such as crossover and mutation. In PSO, the potential solutions, called particles $x$, are "flown" through the problem space by following the current optimum particles. Each Particle keeps track of its coordinates in the problem space, which are associated with the best solution (fitness) it has achieved so far. The fitness value is also stored. This value has called particle best, $pbest$, and the particle(s) associated with it has denoted by $xpbest$. Another “best” value that has tracked by the global version of the particle swarm optimizer is the overall best value, and its location, obtained so far by any particle in the population. This value has been called global best, $gbest$, and the particle(s) is $xgbest$. The particle swarm optimization concept consists, at each time step $t$, updating the velocity, accelerating each particle towards pbest and gbest locations. Acceleration is weighted by a random term, with separate random numbers being generated for acceleration toward pbest, and $gbest$ locations. The PSO algorithm can be described briefly as follows:

**Step 1:** Initialize a population (array) of particles with random positions and velocities $v$ on $d$ dimension in the problem space. The particles are generated by randomly selecting a value with uniform probability over the $d$th optimized search space $[x^d_{min}, x^d_{max}]$.

Set the time counter $t = 0$.

**Step 2:** For each particle $x$, evaluate the desired optimization fitness function, $J$, in $d$ variables.

**Step 3:** Compare particles fitness evaluation with $xpbest$, which is the particle with best local fitness value. If the current value is better than that of $xpbest$, then set $xpbest$ equal to the current value and $xpbest$ locations equal to the current locations in $d$-dimensional space.

**Step 4:** Compare fitness evaluation with population overall previous best. If current value is better than $xgbest$, the global best fitness value then reset $xgbest$ to the current particle’s array index and value.
**Step 5:** Update the time counter $t$, inertia weight $w$, velocity $v$, and position of $x$ according to the following equations

**Step 6:** Loop to 2, until a criterion is met, usually a good fitness value or a maximum number of iterations (generations) $m$ is reached. Another criteria used is to terminate the search process if there is no more improvement in fitness value for the last $n$ iterations. In this case $n < m$.

The following equations has utilized in this research, in computing the position and velocities, in the X-Y plane:

$$v_i^{k+1} = w \times v_i^k + c_1 \times \text{rand}_1 \times (P_{\text{best}_i} - s_i^k) + c_2 \times \text{rand}_2 \times (G_{\text{best}} - s_i^k) \quad (2.18)$$

$$s_i^{k+1} = s_i^k + v_i^{k+1} \quad (2.19)$$

Where

$v_i^{k+1}$ Velocity of $i^{th}$ individual at $(k + 1)^{th}$ iteration;

$v_i^k$ Velocity of $i^{th}$ individual at $k^{th}$ iteration;

$w$ Inertial weight;

$c_1, c_2$ Positive constants both equal to 2;

$\text{rand}_1$ Random number selected between 0 and 1;

$\text{rand}_2$ Random number selected between 0 and 1;

$P_{\text{best}_i}$ Best position of the $i^{th}$ individual;

$G_{\text{best}}$ Best position among the individuals (group best);

$s_i^k$ Position of $i^{th}$ individual at $k^{th}$ iteration;

The velocity of each agent has modified according to (2.18), and the position has modified according to (2.19). The inertia weight ‘$W$’ is modified using (2.20), to enable quick convergence.

$$W = W_{\text{max}} - \frac{(W_{\text{max}} - W_{\text{min}})}{\text{iter}_{\text{max}}} \times \text{iter} \quad (2.20)$$

Where

$W_{\text{max}}$ Initial value of inertia weight;

$W_{\text{min}}$ Final value of inertia weight;

$\text{iter}_{\text{max}}$ Maximum iteration number

### 2.5 Conclusions
This chapter presents a general overview on optimization techniques and more details on those methods that have been applied to solve the specific problem of optimal allocation of FACTS devices in a power system.

The work published by others indicates that there are some disadvantages in using classical optimization theory, particularly considering the size of the system and non-convexity problems. In addition, there are a number of techniques for allocating FACTS devices that are based on technical criteria. Even though, excellent improvements have been made in classical methods, but they suffer with limitations of weak in handling qualitative constraints, poor convergence and may get into local optimum solutions. Sometimes they are computationally expensive for solution of a large system. Whereas, the advantage of the CI methods is, they are versatile for handling various qualitative constraints. In most cases, they can find the global optimum solution. The advantages of Fuzzy method are accurately represents the operational constraints. However, fuzzified constraints are softer than traditional constraints. The advantages of GA methods are it only uses the values of the objective function and less likely to be trapped at a local optimum. Nevertheless, computational time is the main disadvantage. PSO intelligent method is the recent entry in the field of optimization. PSO can be used to solve complex optimization problems, which are non-linear, non-differentiable and multi-model. The main merits of PSO are its fast convergence speed and it can be realized easily by considering less parameters.

In this research work, technical feasibility has been considered, and there is an improvement in the power system performance verified from the simulation results.