CHAPTER I
FLEXIBLE AC TRANSMISSION SYSTEM (FACTS) TECHNOLOGY – AN OVERVIEW

1.1. Introduction

Electrical power system is a network of electrical components to supply, transmit and use electrical power. Electrical Power Transmission lines are responsible for the bulk transfer of electrical energy from generating stations to electrical substations located near the demand centres. The transmission lines in order to meet the required power delivery, carry bulk power flowing in a desired direction on the various links of the transmission system. Power system obviously is exposed to various disturbances, which depending on their nature, may cause sudden and large variations in the active and reactive power balance of the system and consequently result into some problem in certain machines. The power system capability of recovering from an adverse situation created due to such disturbances and regains the original or very near the original condition under stipulated contingencies is called the power system stability. The attribute of power system stability calls for special efforts in order to create a suitable condition for maintaining the continuous power flow in the transmission line to its fullest capacity. Power system stability has always been a major concern in system operation.

Power system stability is broadly divided in two categories namely [1]:

- Steady state stability
- Transient stability.

**Steady state stability** A power system is said to be steady state stable for a particular operating condition if, following a small and gradual disturbance, the system reaches a steady state operating condition which is either identical or close to the pre-disturbance operating condition.

**Transient stability** is the capability of the power system to maintain synchronism under the condition of a severe and sudden disturbance in the system. Transient stability is a condition that characterizes the dynamics of a
power system subjected to a fault, the initial state preceding the fault being a balanced one. The system is said to possess transient stability, if it is able to maintain synchronism and return to its initial state or a state close to it even after the occurrence of a sudden and major fault. Transient stability of a system depends on number of factors such as time, type and location of fault, fault clearance time, re-closing time after fault clearance and also on the stability improvement measures adopted.

The maximum amount of steady state power that the system can transmit after being subjected to a fault for specified operating conditions without losing synchronism is known as the transient stability limit of the system [2]. Power system stability limits constrain the generation and transmission of active and reactive power in the system. The power or load-angle becomes uncontrollable in case a system is unstable, reaches high magnitudes and rapidly varies over a wide range. The system thus, may lose its capability of control and power transfer. In such a situation, the stability limits are imposed to ensure that the system power-angle may fall within the controllable range and thus, enabling the system to transfer maximum power. The power system thus, must call for flexibility so that it can adapt to momentary changes in system conditions. This need of the power system has given birth to the nomenclature called Flexible AC Transmission System (FACTS). The idea of FACTS was introduced way back in 1980s by N.G.Hingorani.

1.2. FACTS Technology

Flexible AC Transmission System (FACTS) technology by virtue of its flexible and rapid technique of control over the ac transmission parameters and network topology is capable of: (i) facilitating the power control, (ii) raising the power transfer capacity, (iii) decreasing the line losses and generation costs, and (iv) enhancing the stability and security of the power system. The concept of FACTS implies the use of high power electronic devices in order to control power flow in a transmission network, thereby allowing the transmission lines to be loaded to their full capacity. Single-line diagram of a transmission line carrying electrical power is shown in
The active power (P) transmitted through a transmission line connecting a generating station to a load located at a bus as shown in Fig. 1.1, is given by:

\[ P = \frac{V_s V_r}{X_i} \sin \delta \]  

(1.1)

where, \( V_s \) and \( V_r \) are the voltages at the sending end and receiving end respectively, \( \delta \) is the angle between \( V_s \) and \( V_r \) and \( X_i \) is the line reactance [3].

Fig. 1.1 Single-Line Diagram of a Transmission Line Carrying Electrical Power

The transmission line can be utilized only to a level well below that corresponding to 90°, without controlling any of the parameters \( V_s \), \( V_r \), \( X_i \) and \( \delta \). This is necessary, in order to maintain an adequate margin needed for transient and dynamic stability and to ensure that the system does not collapse following the outage of the largest generator and/or a line. Increase/decrease of the value of \( X \) will increase/decrease the maximum power flow. Varying \( X \) for a given power flow, will correspondingly vary the angle between the voltages at the two ends.

Power/current flow can also be controlled by regulating magnitude of the voltage phasor \( V_s \), or the voltage phasor \( V_r \). However, with change in magnitude of \( V_s \), the magnitude of the driving voltage phasor \( V_s-V_r \) does not change much, but its phase-angle does. This also means that regulation of magnitude of the voltage phasor \( V_s \), and/or \( V_r \), has much more influence over the reactive power flow as compared to that on the active power flow.

Current flow and hence, power flow can also be changed by injecting voltage in series with the line. When the injected voltage is in phase quadrature with the current, it directly influences the magnitude of the current flow and with small angle influences substantially the active power flow.

Alternatively, the voltage injected in series can be a phasor with variable magnitude and phase relationship with the line voltage. By varying the magnitude and the
phase-angle of the voltage injected in series, both active and reactive power flow can be influenced.

Series connected capacitors and shunt connected inductors and capacitors are normally employed either to absorb or to generate reactive power. Another approach to control power flow is by injecting appropriate level of voltage. The above mentioned voltage injection methods which thereby, incorporate active and reactive power control form the most important portfolio of the FACTS controllers.

1.3. FACTS Controllers

FACTS controllers are basically high power thyristor switches and are capable of taking extremely fast control actions. Because of their fast operating capability they can enlarge the safe operating limits of a transmission system without risking its stability [4]. FACTS devices enable the transmission system to obtain one or more of the following benefits:

(i) Control of power flow.
(ii) Increment of loading capability of lines.
(iii) Increment of system security through raising transient stability limit, limiting short circuit currents and overloads, managing cascading blackouts and damping electromechanical oscillations of power systems and machines.
(iv) Provision of secured tie line connections to neighbouring utilities and regions thereby decreasing overall generation reserve requirements on both sides.
(v) Provision of greater flexibility in transmission.
(vi) Reduction of reactive power flows, thus allowing the lines to carry active power.
(vii) Reduction of loop flows.
(viii) Enhancement of utilization of lowest cost generation.
(ix) Balancing the power flow over a wide range of operating conditions, thereby using the power system network most efficiently.
(x) Balancing the power flow in parallel networks operating at different voltage levels.
Details of FACTS controllers have been discussed in the following paragraphs:

1.4. Classification of FACTS Controllers

FACTS controllers are broadly divided into four categories: (i) shunt controllers, (ii) series controllers, (iii) shunt-series controllers and (iv) series-series controllers [5]. Shunt controllers are connected in parallel with the line, inject current into the system at the point of connection, whereas, series controllers are connected in series with the line to inject voltage in the system. Fig.1.2 (a) shows the line-diagram of a shunt controller and Fig.1.2 (b) shows the line-diagram of a series controller.

A shunt controller is like a current source, which draws/injects current from/into the line. On the other hand, a series connected controller directly affects the driving voltage and hence, the current and the power flow. As long as the voltage is in phase quadrature with the line current, the series controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well. In other words, as long as the injected current is in phase quadrature with the line voltage, the shunt controller only supplies or consumes variable reactive power whereas, different phase relationship will involve handling of real power also.

Shunt controllers include: (i) Static VAR Compensator (SVC) (ii) Static Synchronous Compensator (STATCOM)

On the other hand, series controllers include:

(i) Thyristor-Controlled Series Capacitor (TCSC)  
(ii) Thyristor-Switched Series Capacitor (TSSC)  
(iii) Static Synchronous Series Compensator (SSSC)
There are certain situations where not an individual but, a combination of more than one controller is preferred due to obvious reasons. The combination may be formed either between a shunt and a series (shunt-series) controller or between two series (series-series) controllers. Combined shunt and series controllers inject current into the system with the shunt part of the controller and voltage in series in the line with the series part of the controller. When the shunt and series controllers are unified, there can be real power exchange between them via a power link. Series-series controllers when incorporated in the system can provide independent series reactive compensation for each line and also transfer real power among the lines via the power link. Real power transfer capability enables the system to balance both real and reactive power flow in the lines and thereby, enhancing the utilization of the transmission system to its maximum capacity. Fig.1.3 (a) shows the line-diagram of a shunt-series controller and Fig.1.3 (b) shows the line-diagram of a series-series controller.

![Fig. 1.3 Line-Diagram of (a) Shunt-Series Controller (b) Series-Series Controller](image)

Thyristor-Controlled Phase Shifting Transformer (TCPST) and Unified Power Flow Controller (UPFC) are the few examples of shunt-series FACTS Controllers whereas Inter-line Power Flow Controller (IPFC) is one of the examples of a series-series controller. The classification of FACTS Controllers is shown in Fig.1.4. FACTS Controllers can also be classified on the basis of the type of high power electronic devices employed in the control process as:

(i) variable impedance type controllers
(ii) voltage source converter based controllers.

This classification of FACTS Controllers is shown in Fig.1.5.
FACTS Technology - An Overview

Fig. 1.4 Classification of FACTS Controllers Based on the Method of Connection

Fig. 1.5 Classification of FACTS Controllers Based on the Type of High Power Electronic Devices Used
Thyristor switches (formed by implementing anti-parallel connection of two thyristors) are connected in series or in shunt along with reactors or capacitors to form variable impedance type thyristor based FACTS Controllers. Such controllers are employed to control the reactive power in the system [6]. Static VAR Compensator (SVC), Thyristor-Controlled Series Capacitor (TCSC), Thyristor-Switched Series Capacitor (TSSC), Thyristor-Controlled Phase Shifting Transformer (TCPST), etc. are some of the examples of such FACTS Controllers. The basic building block of a Voltage Source Converter (VSC) is a three-phase converter bridge. When a VSC is interfaced with a transmission system, it enables the system to vary the magnitude and the phase-angle of its output voltage with respect to that of the system voltage, thus exchange active and reactive power with the transmission system. Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC), Interline Power Flow Controller (IPFC) are the well-known VSC based FACTS Controllers.

The detailed explanations of each of these FACTS Controllers are given in the following sections:

### 1.5. Static VAR Compensator (SVC)

Static VAR Compensator (SVC) is the first FACTS device used in power transmission lines. Prior to the development of SVC, the adjustment of voltage level in transmission system, was made possible only by mechanically switched shunt reactors and capacitors. Mechanical switching of shunt reactors and capacitors was found to be a crude method, resulting abrupt voltage level deviations thus, causing voltage and current transients.

The Static VAR Compensator being capable in providing rapid and fine adjustment of voltage level, which is extremely important and very much desirable in power system control and operation. Implementation of SVC can also incorporate dynamic shunt compensation. SVC can instantaneously and automatically adjust the reactive power output smoothly by maintaining the voltage at the required level. It can thus,
enhance transient stability of the power system by damping oscillations evolving in the power system. SVC uses thyristor valves to rapidly add or remove shunt connected reactors and/or capacitors often in coordination with mechanically controlled reactors and/or capacitors. There are two popular configurations of SVCs. They are: (i) Fixed Capacitor (FC) and Thyristor Controlled Reactor (TCR) configuration and (ii) Thyristor Switched Capacitor (TSC) and TCR configuration [7]. The two configurations of SVC are shown in Fig.1.6.

Fig. 1.6. Static VAR Compensator
(a) FC-TCR Configuration
(b) TSC-TCR Configuration
The fixed capacitor C provides a permanently connected source of reactive power and also serves the purpose of a harmonic suppressor. TCR is a reactor connected in series with a bi-directional switch. The bi-directional switch comprises an anti-parallel connection of two SCRs. Triac is also a bi-directional thyristor. But they are not available in such high power ratings as SCR. Therefore for many switching applications, ac switches using two SCRs in anti-parallel connection are used instead of triacs. TCR can be considered as a shunt-connected, thyristor-controlled inductor whose effective reactance is varied in a continuous manner by partial-conduction control of the thyristor (SCR). The magnitude of the current in the reactor can be controlled from maximum to zero by the method of firing-delay-angle (α) control. Evidently, the effective reactive admittance varies with α in the same manner as the current and thus, provides fully adjustable control over the full range of the rated reactive power absorption.

The thyristor switched capacitor (TSC) also comprises a bi-directional thyristor switch connected in series with a capacitor and a small current limiting reactor. The maximum possible delay in switching ON a capacitor bank is one full cycle of the applied ac voltage. It is well known that firing-delay-angle control is not applicable to the capacitors; hence, the capacitor switching must take place at that specific instant at which the conditions for minimum transients are satisfied. A TSC branch of the SVC can provide only a step like change in the reactive current it draws. In other words it can be said that, TSC is a single-capacitive admittance which is either connected to or disconnected from the system.

In the FC-TCR configuration of SVC, as shown in Fig.1.6(a), fixed capacitor (FC) banks shown by C in Fig.1.6(a) are connected in shunt with the TCR in order to extend the dynamic controllable range to the leading power factor domain. This is because TCR provides continuously controllable reactive power only in the lagging power factor range. The operation of the TCR results in a non-sinusoidal current wave-form in the reactor and thus, generates harmonics. Filters are employed to reduce these TCR generated harmonics.
The TSC-TCR configuration usually comprises more than one TSC banks and a single TCR connected in parallel as shown in Fig.1.6(b). The capacitors can be switched ON in discrete steps, whereas, continuous control within the reactive-power span of each step is provided by the TCR. The TSC-TCR SVC enhances the operational flexibility of the compensator during large disturbances and also reduces the steady state losses. FC-TCR behaves like a parallel LC circuit that tends to set up a resonance with the ac system impedance during large disturbances. The main problem faced here is that the system experiences severe voltage swings followed by load rejection. In the occurrence of such an event, TSC-TCR can quickly operate to disconnect all the capacitors from the compensator, thus, precluding the resonant oscillations. This feature of disconnecting the capacitor in exigencies is not available with FC-TCR SVC [7].

SVC modeling is important for power flow, transient stability, long term dynamics simulation etc. SVC can be modeled as a variable susceptance device whose value depends on the firing-angle of the thyristors [8]. The equivalent susceptance \( B_{svc} \) of the FC-TCR SVC is given by:

\[
B_{svc} = \frac{B_0 (B_0 + B_{TCR})}{B_0 + B_c + B_{TCR}} \tag{1.2}
\]

where, \( B_0 \) is the susceptance of the step down transformer, \( B_c \) is the susceptance of the FC, and \( B_{TCR} \) is the susceptance of the TCR. A SVC is usually connected to the high-voltage power system by means of a step-down coupling transformer.

\( B_c \) is given by:

\[
B_c = \omega L \tag{1.3}
\]

and \( B_{TCR} \) is given by:

\[
B_{TCR} = \frac{1}{\omega L} \left[ 1 - \frac{2\alpha}{\pi} - \frac{\sin 2\alpha}{\pi} \right] \tag{1.4}
\]

where, \( \alpha \) is the firing-angle of the thyristor.

Similarly, the equivalent susceptance \( B_{svc} \) of the TSC-TCR SVC is given by:

\[
B_{svc} = \frac{B_0 (B_0 + B_{TCR})}{B_0 + B_{tcn} + B_{TCR}} \tag{1.5}
\]
where, \( n \) is the number of TSC branches in operation and \( B_{cn} \) is the total susceptibility of \( n \) TSC branches.

It is a common practice to consider the centre or midpoint of a line as the optimal location of reactive power support or shunt FACTS controllers.

### 1.6. Thyristor Controlled Series Compensator (TCSC)

The Thyristor Controlled Series Capacitor (TCSC), uses thyristors to manage a capacitor bank connected in series with the line, enabling the system to transfer more power on a particular transmission line. TCSC controllers employ thyristor-controlled reactor (TCR) in parallel with capacitor segments of series capacitor bank as shown in Fig. 1.7. The reactor impedance is designed to be much lower as compared to the series capacitor impedance. The combination of TCR and capacitor allows the capacitive reactance to be smoothly controlled over a wide range by varying the thyristor-pair firing-angle in an appropriate range. When the firing-angle of the thyristors is 180 degrees, the reactor connected in the circuit gets disconnected from the circuit and the series capacitor poses its normal impedance. The TCSC is said to be in the bypassed thyristor mode or thyristor switched reactor (TSR) mode.

![Fig. 1.7 Thyristor Controlled Series Compensator (TCSC)](image)

As the firing-angle is reduced from 180 to 150 degrees, the capacitive impedance increases, the TCSC behaves as continuously controllable capacitive impedance and is said to be in the capacitive-vernier control mode. This mode causes the TCR current direction to be reversed that is opposite that of the capacitor current, thus, resulting in the flow of a loop current in the TCSC controller. This loop current increases the voltage across \( C \), effectively enhancing the equivalent capacitive
reactance and the series-compensation level for the same values of line current. At
the other end, when the firing-angle of the thyristors forming the TCR is increased
from 90 to 120 degrees, the reactor starts conducting fully, and the total impedance
becomes inductive in nature. In this case the TCSC can be operated by having a
high level of thyristor conduction which is known as inductive-vernier control mode.
Direction of the circulating current is reversed in this mode, and the controller starts
presenting net inductive impedance. It can thus, be said that the TCSC helps in
limiting the fault current at the firing-angle value of 90 degrees [7]. TCSC thus, offers
a continuous control of capacitive or inductive reactance.

Thyristor Switched Series Compensator (TSSC), is another configuration of series
compensators. TSSC uses thyristor switches in parallel with segments of the series
capacitor bank in order to rapidly insert or remove portions of the capacitor bank in
discrete steps. TSSC controllers have the capability to switch capacitor segments
between the bypassed and the blocked conditions in order to achieve two levels of
compensation on the transmission line. A TSSC scheme consists of a series
connection of multiple TCSC modules with capacitor segments. The thyristor pairs
operate either in the blocked mode or in the bypassed mode, thus acting as a
switch. The series capacitor is either inserted or removed from the transmission-line
circuit for each switching operation. The thyristor switches being static in nature
allow an unlimited number of operations without any wear and tear. This capability is
utilized to alter the degree of line compensation more frequently and to achieve a
greater control over the power flow [7]. Exact switching instants can be selected and
fixed with thyristors, which can minimize the switching transients significantly. The
TSSC scheme can function quite satisfactorily in case only stepwise control of
transmission-line reactance is considered adequate. For continuous control, TCSC
is employed.

The variable reactance of TCSC, \( X_{TCSC} \) has been determined by [9]:

\[
X_{TCSC}(\sigma) = X_c - \frac{X_c^2}{(X_c - X_p)} \left( \frac{\sigma + \sin \sigma}{\pi} \right) + \frac{4X_c^2}{(X_c - X_p)} \frac{\cos^2(\sigma/2)}{(k^2 - 1)} \frac{k \tan(k\sigma/2) - \tan(\sigma/2)}{\pi}
\]

(1.6)
where, conduction-angle $\sigma$ is related to the firing-delay-angle $\alpha$ by:

$$\sigma = 2(\pi - \alpha). \quad (1.7)$$

1.7. Static Synchronous Compensator (STATCOM)

The STATic synchronous COMpensator (STATCOM), previously referred to as a STATic synchronous CONdensor (STATCON), is based on the principle of voltage-source converter. STATCOM converts dc input voltage into ac output voltage at the fundamental frequency, in order to compensate the level of active and reactive power needed by the system. A STATCOM is a controlled reactive-power source. It implements the provision of generation and/or absorption of reactive power entirely by means of electronic processing of voltage and current waveforms in a voltage-source converter (VSC). Reactive power compensation is the main function of a STATCOM. A STATCOM is seen as an adjustable voltage-source behind a reactance. Capacitor banks and shunt reactors are not needed for reactive-power generation and absorption, thereby giving STATCOM a compact design, small footprint, as well as low noise and low magnetic impact.

The basic voltage-source inverter representation for reactive power generation is shown schematically in Fig.1.8.

![Fig.1.8 Single-Line Diagram of STATCOM](image-url)
The STATCOM basically consists of a step-down transformer with a leakage reactance, a three-phase GTO or IGBT voltage source converter (VSC), and a dc capacitor. The converter produces a set of controllable three-phase output voltages with the frequency of the ac power system derived from a dc input voltage source, provided by the charged capacitor C. Each output is in phase with, and coupled to the corresponding ac system voltage via a relatively small tie reactor which in practice is provided by the per phase leakage inductance of the coupling-transformer. The ac voltage difference across the leakage reactance produces reactive power exchange between the STATCOM and the power system. The STATCOM can supply real power to the power system by adjusting the phase-angle of the STATCOM terminals and the phase-angle of the ac power system.

The reactive power exchange between the converter and the ac power system can be controlled by varying the amplitude of the output voltage. If the value of the output voltage is increased beyond that of the ac system voltage, the converter starts generating reactive power which can be used by the ac power system. If the value of the output voltage is decreased below that of the ac power system, the converter starts absorbing the reactive power [10]. In case the output voltage is equal to the ac power system voltage, the reactive power exchange becomes zero, in which case the STATCOM is said to be in a floating state.

The real power exchange between the converter and the ac power system can be controlled by altering the phase-angle between the inverter output and the ac power system voltage. The converter starts supplying real power to the ac power system if the inverter output voltage is made to lead the corresponding ac power system voltage. Conversely, the converter starts absorbing real power from the ac power system, if the inverter output voltage is made to lag the ac power system voltage. Various literature available, demonstrate that a STATCOM improves transient stability considerably and also compensates the reactive power in steady state [11]. The STATCOM improves the desired power-system performance, including power-oscillation damping, sub-synchronous resonance (SSR) mitigation, dynamic voltage control etc.
1.8. Static Synchronous Series Compensator (SSSC)

Static Synchronous Series Compensator (SSSC) is the series version of a STATCOM. This series connected device could perform the functions of a TCSC for increasing or decreasing the power flow along a specific transmission line.

A typical SSSC connected in a transmission line is shown in Fig. 1.9. The controller comprises a VSC which along with a coupling transformer is connected in series with the transmission line. The SSSC injects a voltage (almost sinusoidal in nature) in series with the transmission line, thus, emulates a reactance in series with the transmission line. When this injected voltage is leading the line current almost in quadrature, it emulates an inductive reactance in series with the transmission line causing the power flow and the line current to decrease as the level of compensation increases. The SSSC at this moment is considered to be operating in inductive mode.

When the SSSC injects a voltage lagging the line current, almost in quadrature, it emulates a capacitive reactance in series with the transmission line causing the power flow and the line current to increase as the level of compensation increases. The SSSC at this moment is considered to be operating in capacitive mode [12].

The series compensator exchanges real power with the transmission line in case the injected voltage is in phase with the line current. In general, it can be concluded that the SSSC can be used to enhance transient stability, dampen sub-synchronous
resonance where other fixed capacitors are used, and increase line power capability.

A performance comparison between STATCOM and SSSC in improving the stability limit has been reported in [13]. The authors have concluded that a STATCOM is more effective as compared to a SSSC in improving the first swing stability limit. However, the SSSC has been found to be more effective in improving damping of the subsequent swings.

1.9. Unified Power Flow Controller (UPFC)

A Unified Power Flow Controller (UPFC) combines the static compensator and the synchronous series capacitor into a single device with a common control system. It has the unique ability to simultaneously control all the three parameters viz. line voltage, line reactance and phase-angle of the power flow.

The UPFC can thus, be considered to be consisting of two identical voltage-source converters, namely (i) the shunt converter and (ii) the series converter. These converters operate through a common dc link along with a dc storage capacitor. These two converters allow the UPFC to independently control active and reactive power flows on the line and also the bus voltage. A schematic single-line diagram of a UPFC is shown in Fig.1.10.

Active power can flow freely in either direction between the ac terminals of the two converters through the dc link. Each of the converters can generate or absorb reactive power at their own ac output terminals. However, the converters cannot internally exchange reactive power through the dc link. It is obvious that the operation of UPFC has its own significance as the device affects both the transmission line flow and the line voltage magnitude [14].

The series converter is controlled to inject a voltage \( V_{pq} \) in series with the line, which can be varied from 0 to \( V_{pq\text{max}} \). The phase-angle of \( V_{pq} \) can be independently varied from 0° to 360°. In this process, the series converter can exchange both the real and the reactive power with the transmission line. Although the reactive power is internally generated/absorbed by the series converter, the real power generation/absorption is made feasible by the capacitor.
The shunt converter is used mainly to supply or absorb the real power demanded by the series converter, which it derives from the transmission line itself. The shunt converter maintains constant voltage at the dc bus. Thus, the net real power drawn from the ac system comes out to be equal to the losses of the two converters and their coupling transformers.

The UPFC can fulfill three basic compensation functions of power transmission namely (i) phase-angle control (ii) voltage control and (iii) line reactance control. These are achieved through the control of the magnitude and phase-angle of the series injected voltage $V_{pq}$. Voltage control is effected if $V_{pq}$ ($= \Delta V$) is generated in phase with $V$. A combination of voltage regulation and line reactance control, equivalent to series compensation is implemented where $V_{pq}$ is the sum of $\Delta V$ and a series compensating voltage component $V_c$ that lags behind the line current by 90°.

In the phase shifting process, the UPFC generated voltage $V_{pq}$ is a combination of $\Delta V$ and a phase shifting voltage component $V_s$ which is in phase quadrature with $V$. It is also possible to achieve all the above three power control functions simultaneously [15].
1.10. Characteristic Features of Different FACTS Controllers

The different FACTS Controllers such as STATCOM, SVC, SSSC, TCSC and UPFC have been simulated and their characteristics have been reported in the literature. A comparison of these FACTS controllers are as follows:

1.10.1. SSSC vs TCSC
(i) SSSC is capable of internally generating a controllable compensating voltage over an identical capacitive and inductive range independently of the magnitude of line current.
(ii) The compensating voltage of TCSC over a given control range is proportional to the line current.
(iii) SSSC has the inherent ability to provide compensation for the line resistance by the injection of real power as well as for the line reactance by the injection of reactive power.
(iv) TCSC cannot exchange real power with the transmission line and can provide reactive compensation.
(v) TCSC employs conventional thyristors which are more rugged, with higher voltage and current ratings.
(vi) SSSC have considerably lower voltage and current ratings.
(vii) TCSC can be coupled directly with the transmission line and hence can be installed on a high voltage platform whereas SSSC requires a coupling transformer.

1.10.2 STATCOM vs SVC
(i) STATCOM is superior to SVC in providing voltage support under large system disturbances as it has the ability to maintain full capacitive output current independent of the ac system voltage.
(ii) SVC which comprises capacitors and reactors becomes a fixed capacitive admittance at full output, hence maximum attainable compensating current of SVC decreases linearly with the ac system voltage.
(iii) STATCOM is more effective than SVC in improving transient stability.
(iv) STATCOM is capable of drawing controlled real power from an energy source at its dc terminal and deliver it as ac power to the system.
(v) SVC is not capable to exchange real power.
(vi) STATCOM has smaller physical size as compared to SVC.
(vii) STATCOM is suitable for installation in areas where land cost is high and for applications where anticipated system changes may require the relocation of the installation.

1.10.3 UPFC

(i) The UPFC is able to control simultaneously or selectively all the parameters affecting power flow in the transmission line, i.e. voltage, impedance and phase-angle.
(ii) UPFC has a superior power flow control characteristic as compared to other FACTS controllers
(iii) UPFC can control both real and reactive power flow in either direction and its control range in terms of real and reactive power is independent of the transmission angle.
(iv) UPFC offers the possibility of operating the shunt and series converters independently of each other by disconnecting the common dc terminals and splitting the capacitor bank.

1.10.4 Disadvantages of UPFC

Thyristor-controlled FACTS devices, such as SVC, TCSC etc., require fully rated capacitor/reactor banks to supply/absorb reactive power. Devices of large sizes with substantial cost and additional significant labour cost for installation are thus required.

The main disadvantage of the topology of UPFC is that it is entirely converter based. Transmission systems need distributed reactive power support for efficient operation. This is generally accomplished by installing capacitor banks at strategic locations within the system, and by switching these banks in and out as per the
need. The UPFC can make limited use of such hardware. By definition it uses the shunt converter to supply the active power coupled with the series converter, and once the shunt converter is in place it is also used to supply the required reactive power [16].

VSC based devices using GTOs lead to reduction in equipment size and also improved performance, but the considerable price of such FACTS Controllers (STATCOM, UPFC etc.) remains as the major impediment to their widespread use. The equipment appropriation for converter based FACTS Controllers is a further setback by the existence of classical equipment such as SVC for voltage support, and TCSC for line impedance control. These compensators in many applications were installed to mitigate critical contingency conditions and while improvements in their performance would be worth considering their complete replacement is prohibitive. Novel and cost effective converter based FACTS topologies are proposed in [17] by Bebic et al, which build upon existing equipment and provide improved control performance. These devices make use of converters in addition to the (presumably existing) passive components, and can be regarded as hybrid in nature. Such FACTS controllers are named Hybrid Power Flow Controller (HPFC). The key benefit of the new topology is that it fully utilizes existing equipment (switched capacitors or SVC) and thereby the required ratings of the additional converters are substantially lower as compared to the ratings of the comparable UPFC. HPFC has been discussed in the following section:

1.11. Hybrid Power Flow Controller (HPFC)

The Hybrid Power Flow Controller (HPFC) uses two equally rated voltage source converters or static VAR compensators. Such a power flow controller is considered to be hybrid in nature because of the use of static converters along with passive devices. Functionality of switched capacitors and SVCs can be changed from reactive power support to the generalized power flow control by using appropriate converter control.
Two topologies have been presented by Bebic et al in [17]. The first one consists of a shunt connected controllable source of reactive power, and two series connected voltage sourced converters, one on each side of the shunt device as shown in Fig.1.11.

![Fig.1.11 Hybrid Power Flow Controller – First Topology](image)

The second topology is a dual of the first. It is based on two shunt connected current sourced converters around a series connected reactive compensator as shown in Fig.1.12. The converters can exchange active power through a common dc circuit in both the cases. The analysis carried out by the authors verifies that the HPFC offers performance characteristics similar to those of the UPFC.

The shunt connected source of reactive power denoted by $B_m$ as shown in Fig.1.11 can either be a switched capacitor bank or an SVC. The two voltage-sourced converters $VSC_x$ and $VSC_y$ are connected in series with the associated line segments using coupling transformers. The converters share a common dc circuit, coupling each other’s dc terminals. The dc circuit enables exchange of active power between the two converters. Flow of active power through the line and the amount of reactive power supplied to each line segment can be simultaneously and
independently controlled by regulating the magnitudes and angles of the voltages supplied by the converters. Control of the shunt connected reactive element is coordinated with the control of converters to supply the bulk of the total required reactive power.

On making a comparison of the topology of a UPFC with that of an HPFC, it is observed that in case of HPFC, the shunt converter of UPFC is substituted by a presumably existing switched capacitor, while its series converter has been split into two half-sized ones, installed on each side of the shunt device. Such topological configuration has finally resulted in attaining operating characteristics similar to those of the UPFC, at the same time achieving considerable savings in the total converter MVA ratings required.

The dual topology as shown in Fig.1.12, has been configured by replacing the shunt connected variable susceptance by two half sized current sourced converters. The two VSCs have been combined together and replaced by a variable series connected reactance.

![Figure 1.12. Hybrid Power Flow Controller - Dual Topology](image)

Concept of hybrid power flow controller (HPFC) has been proposed, but no model has been simulated and no stability studies carried out till date. Computer simulations have become a useful practice of mathematical modeling. Continuous development of appropriate software packages makes simulation of power engineering problems more and more effective. However, these analysis
tools differ from each other considerably from the point of view of the applicability to a special problem.

1.12. Development Environments or Tools Used

The tools or development environments used are LabVIEW and MATLAB/SIMULINK. The different FACTS controllers have been simulated using these development environments and the transient stability analysis have been carried out. Brief descriptions of these tools have been incorporated in the following paragraphs:

1.12.1. LabVIEW

LabVIEW stands for Laboratory Virtual Instrumentation Engineering Workbench. It is a powerful and flexible instrumentation and analysis software development application created by National Instruments. LabVIEW is a major player in the field of testing, measurements, industrial automation, data analysis etc. LabVIEW finds lots of applications in power systems and instrumentation engineering.

LabVIEW is different from text-based programming languages in the way that it uses a graphical programming language, known as the G programming language. LabVIEW uses graphic symbols to describe the entire programming actions. Such programs are called Virtual Instruments (VI) as they have the look and feel of the physical systems or instruments. A VI mainly consists of two objects (i) an interactive user interface and (ii) the source code. Both of these are represented in graphical form.

The front panel is the interactive user interface of a VI comprising graphical objects. These are the G programming elements. Controls and indicators built on the front panel enables an operator to input/extract data into/from a running virtual instrument. However, the front panel can also serve as a program interface [18].

The block diagram window contains the program code that exists in a graphical form. The block diagram also contains terminals corresponding to the front panel
controls and the indicators. It also houses the constants, functions, sub VIs, structures, and wires that carry data from one object to another. These icons are wired together to allow the data flow.

The most advanced LabVIEW development systems offer the possibility of building stand-alone applications. Furthermore, it is possible to create distributed applications, which communicate by a client/server scheme, and are therefore easier to implement due to the inherently parallel nature of G-code.

1.12.2. Benefits and Characteristics of LabVIEW

One major benefit of LabVIEW over other development environments is the extensive support for accessing instrumentation hardware. Drivers and abstraction layers for various types of instruments and buses are either already included or are available for inclusion. These present themselves as graphical nodes. The abstraction layers offer standard software interfaces to communicate with the hardware devices. The provided driver interfaces save program-development time. A new hardware driver topology (DAQmx-Base) provides platform independent hardware access to numerous data acquisition and instrumentation devices.

LabVIEW includes a compiler that produces native code for the CPU platform. The graphical code is translated into executable machine code by interpreting the syntax and by compilation. The LabVIEW syntax is strictly enforced during the editing process and compiled into the executable machine code when requested to run or upon saving. The executable runs with the help of the LabVIEW run-time engine. The run-time engine reduces compile-time and also provides a consistent interface to various operating systems, graphic systems, hardware components, etc. The run-time environment makes the code portable across platforms [19].

Several libraries comprising a large number of functions for data acquisition, signal generation, mathematics, statistics, signal conditioning, analysis, etc., along with numerous graphical interface elements are provided in various LabVIEW package options. The number of advanced mathematic blocks for operations such as
integration, filtration, and other special features usually associated with data capture from hardware sensors are in plenty.

In addition, LabVIEW also includes a text-based programming component called MathScript with additional inbuilt functionality for signal processing, analysis and mathematics. MathScript can be integrated with graphical programming using "script nodes". It makes use of .m file script syntax that is generally compatible with MATLAB.

The fully object-oriented character of LabVIEW code allows code reuse without modifications as long as the data types of input and output are consistent. The LabVIEW Professional Development System allows creating stand-alone executables and the resultant executables can be distributed for unlimited number of times. The run-time engine and its libraries can be provided freely along with the executables.

LabVIEW 8.6 was used by the investigator which is its recent version. LabVIEW 8.6 has several toolkits and modules in the areas of control, signal processing, system identification, simulation, mathematics etc. The LabVIEW Control and Simulation Module has been employed in the present work for simulation of different FACTS Controllers incorporated in the Electric Power System.

1.12.3. SIMULINK

SIMULINK, a simulation tool associated with MATLAB, is a very widely used software package for modeling simulating, analyzing dynamic systems. It supports linear as well as non-linear systems. Simulations are interactive in nature which provides an opportunity to the user to change the parameters and verify results. SIMULINK provides an instant access to all the analysis tools in MATLAB, so results can be taken for analysis and visualization. SIMULINK for the purpose of modeling, provides a graphical user interface (GUI) for building models as block diagrams, using click-and-drag operations. SIMULINK
includes a comprehensive block library of sinks, sources, linear and non-linear components, and connectors.

Models are hierarchical in nature, so, they can be built using both top-down and bottom-up approaches. The system can be viewed at a high level, then double-click blocks to go down through the levels to see increasing levels of model details. This approach provides an insight into how a model is organized and how its parts interact [20].

A model after it is defined, can be simulated using a choice of integration methods, either from the SIMULINK menus or by entering commands in the MATLAB Command Window. The menus are particularly convenient for interactive work, while the command-line approach is very useful for running a batch of simulations. The simulation results can be put in the workspace for post processing and visualization. Model analysis tools include linearization and trimming tools, which can be accessed from the MATLAB command line, plus the several tools in MATLAB and its application tool boxes. Since, MATLAB and SIMULINK are integrated to each other; models can be simulated, analyzed and revised in either environment at any point of time.

The SimPowerSystems Blockset in SIMULINK is a tool for modeling and simulating generation, transmission, distribution and consumption of electrical power. It provides models of many components used in these systems including three-phase machines, electric drives and libraries of application specific models such as FACTS and wind power generation. FACTS Blockset consists of STATCOM, SSSC, SVC and UPFC blocks.

1.13. Organization of the Present Thesis Report

The present thesis is organized as follows:
Chapter I discusses in detail the power system stability and the transient stability. This chapter also gives details of different types of FACTS Controllers such as SVC, TCSC, STATCOM, SSSC, UPFC and HPFC.
Chapter II presents the detailed literature review regarding applications of various types of FACTS controllers being used for enhancing power system stability.

Chapter III discusses in detail the modeling and simulation of variable impedance type FACTS Controllers such as SVC and TCSC being incorporated in Single Machine Infinite Bus (SMIB) and Multi Machine (MM) Power systems for transient stability enhancement.

Chapter IV presents in detail the modeling and simulation of voltage source converter based FACTS Controllers such as STATCOM, SSSC and UPFC being incorporated in SMIB and MM Power systems for improving transient stability.

Chapter V discusses in detail the simulation of different configurations of HPFC employing the discrete solution method and the phasor simulation method available in SimPowerSystems in MATLAB/SIMULINK. These configurations termed as HPFCD1, HPFCD2, HPFCD3, HPFCP4, HPFCP5 and HPFCP6 have been implemented on SMIB power system and the performance characteristics have been investigated.

Chapter VI presents the details of the simulation results when the above mentioned configurations of HPFC are implemented in a MM power system.

Chapter VII details out the simulation of HPFC in LabVIEW and the performance analysis of SMIB and MM power systems implementing HPFC.

Chapter VIII discusses the simulation results based on the comparison of HPFC with other FACTS Controllers.

Lastly a concise report on the different inferences drawn out of the entire thesis work has been incorporated in the Conclusions. The scope for future research in the area of HPFC has been identified and reported under the heading future scope.

1.14. Conclusion

Taking note of the introductory details given in this chapter, a detailed literature review of the present state of the art research going on in this field has been carried out by the investigator in the next chapter.