CHAPTER-2

2.1 INTRODUCTION

FACTS is the acronym for Flexible AC Transmission Systems and refer to a group of resources used to overcome certain limitations in the static and dynamic transmission capacity of electrical networks. FACTS proved its mettle in the 1980s in demonstrations led by the power industry's Electric Power Research Institute (EPRI) [1] and grid equipment manufacturers, such as GE and Zurich-based ABB. Over the past decade, FACTS has gone commercial and is "penetrating the network everywhere”. Applications vary widely to fit local grid conditions and challenges. "Waking giant" countries such as China and India apply FACTS to maximize the power carried by every single new transmission line they install, thus minimizing the cost of grid expansion. The first FACTS controllers emerged in the 1980s as an improved means of balancing the two types of power that coexist on AC networks: active and reactive power [32].

The main purpose of these systems is to supply the network as quickly as possible with inductive or capacitive reactive power that is adapted to its particular requirements, while also improving transmission quality and the efficiency of the power transmission system. Traditionally, there are two ways of doing that: by patching banks of capacitors into a circuit to convert some of its megawatts into megaVArs, or by tuning the generators in conventional power stations to produce current waveforms that lead voltage. FACTS got started as a more dynamic solution, and it has become increasingly relevant as deregulation has progressively turned the electricity business into a kind of challenging game, whereby supply is changed or altered frequently to match demand, sometimes on an hourly basis, and without much regard for the capabilities of the transmission assets connecting those scattered centers of supply and demand. By means of such matchups, FACTS allows system managers to send more power over a line than it could otherwise support. The increase can be as high as 50 percent. Stability enhancement accounts for part of the boost, allowing grid operators to operate lines closer to their thermal limits.

The heart of a modern FACTS controller is an array of solid-state switches, often coupled with capacitors. Typically, the solid-state switches open to tap power from the line and charge a capacitor; then the switches fire in sequence to create a synthetic AC waveform with precisely the needed phase difference between current and voltage. That waveform is then applied to the grid. By precisely varying the phase difference, the FACTS controller can add or subtract reactive power in fine increments. Impressive as it is, such dynamic voltage regulation is the simplest of the FACTS grid control modes. FACTS innovators went further in the 1990s by exploiting newly developed high-power semiconductor switches that could switch at frequencies higher than the standard 50- or 60-hertz AC cycles.

With relatively advanced switches, such as insulated-gate bipolar transistors, FACTS controllers could simultaneously regulate voltage and surgically remove a variety of glitches in the AC signal. One such FACTS device, the static synchronous compensator, or STATCOM, has played a decisive role in the more than tenfold rise in wind power capacity worldwide over the past decade. A Siemens-built STATCOM, for example, is stabilizing flows from the world's largest offshore wind farm, completed this past September, whose 1003 MW wind turbines should Feed enough energy to the United Kingdom's grid during the year to supply more than 2,00,000 homes [33].

India and China, meanwhile, have applied FACTS as a cost-cutting tool to ensure that AC lines deliver their full potential and thus reduce the number of lines required. "Instead of building three lines, they may be able to build two and put in a FACTS device", According to a new study [15, 16].

Also, FACTS technology calls for new thinking on collaborative operation and planning among utilities because of the possibilities that the different owners of an integrated power system could be implementing contradictory control elements. However, one would expect that mutual interest will ensure the most optimum use of the power system as a whole [31, 34].

Several kinds of FACTS controllers have been commissioned in various parts of the world. The most popular are: load tap changers, phase-angle regulators, Static VAR Compensators (SVC), Thyristor-Controlled Series Compensators (TCSC), Interline Power Flow Controller (IPFC), Static Compensators (STATCOM), and Unified Power Flow Controllers (UPFC) [1].

The **IEEE** defines FACTS as “alternating current transmission systems incorporating power-electronics based and other static controllers to enhance controllability and power transfer capability.”

The significance of the power electronics and other static Controllers is that they have high speed response and there is no limit to the number of operations. Like a transistor leads to a wide variety of processors, power devices such as thyristors lead to a variety of FACTS Controllers and HVDC converters. These Controllers can dynamically control line impedance, line voltage, active power flow and reactive power flow. They can absorb or supply reactive power and when storage becomes economically viable storage they can supply and absorb active power as well, all this can be done at high speed [6, 7].

By using reliable, high-speed power electronic controllers, the technology offers utilities five opportunities for increased efficiency:

1. Greater control of power, so that it flows on the prescribed transmission routes.
2. Secure loading (but not overloading) of transmission lines to levels nearer their thermal limits.
3. Greater ability to transfer power between controlled areas, so that the generation reserve margin.
4. Prevention of cascading outages by limiting the effects of faults and equipment failure.
5. Damping of power system oscillations, this could damage equipment and/or limit usable transmission capacity.

2.2 TYPES OF FACTS CONTROLLERS [1, 2].

FACTS controllers can be broadly divided into four categories, which include series controllers, shunt controllers, combined series-series controllers, and combined series-shunt controllers. Their operation and usage are discussed below.

2.2.1 PRINCIPLE OF THE SERIES CONTROLLERS:

A series controller may be regarded as variable reactive or capacitive impedance whose value is adjusted to damp various oscillations that can take place in the system. This is achieved by injecting an appropriate voltage phasor in series with the line and this voltage phasor can be viewed as the voltage across impedance in series with the line. If the line voltage is in phase quadrature with the line current, the series controller absorbs or produces reactive power, while if it is not, the controllers absorb or generate real and reactive power. Examples of such controllers are Static Synchronous Series Compensator (SSSC), Thyristor-Switched Series Capacitor (TSSC), Thyristor-Controlled Series Reactor (TCSR), to cite a few. They can be effectively used to control current and power flow in the system and to damp oscillations of the system.

2.2.2 PRINCIPLE OF THE SHUNT CONTROLLERS:

Shunt controllers are similar to the series controllers the difference being that they inject current into the system at the point where they are connected. Variable shunt impedance connected to a line causes a variable current flow by injecting a current into the system. If the injected current is in phase quadrature with the line voltage, the controller adjusts reactive power while if the current is not in phase quadrature, the controller adjusts real power. Examples of such systems are Static Synchronous Generator (SSG), Static VAr Compensator (SVC). They can be used as a good way to control the voltage in and around the point of connection by injecting active or reactive current into the system.

2.2.3 PRINCIPLE OF THE COMBINED SERIES --SERIES CONTROLLERS:

A combined series-series controller may have two configurations. One configuration consists of series controllers operating in a coordinated manner in a multi line transmission system. The other configuration provides independent reactive power control for each line of a multi line transmission system and, at the same time facilitates real power transfer through the power link. An example of this type of controller is the Interline Power Flow Controller (IPFC), which helps in balancing both the real and reactive power flows on the lines.

2.2.4 PRINCIPLE OF THE COMBINED SERIES – SHUNT CONTROLLERS:

A combined series-shunt controller may have two configurations, one being two separate series and shunt controllers that operate in a coordinated manner and the other one being an interconnected series and shunt component. In each configuration, the shunt component injects a current into the system while the series component injects a series voltage. When these two elements are unified, a real power can be exchanged between them via the power link. Examples of such controllers are UPFC and Thyristor- Controlled Phase-Shifting Transformer (TCPST). These make use of the advantages of both series and shunt controllers and, hence, facilitate effective and independent power/current flow and line voltage control.

2.3 STATIC VAR COMPENSATOR (SVC):

The IEEE definition of the SVC is as follows: ―A shunt connected static VAR generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage)."

In other words, an SVC is a static VAR generator whose output is varied in order to maintain or control the specific parameters of an electric power system. SVCs are primarily used in power systems for voltage control or for improving system stability. Static VAR compensators (SVCs) are used primarily in power systems for voltage control as either an end in itself or a means of achieving other objectives, such as system stabilization. A typical SVC is shown below

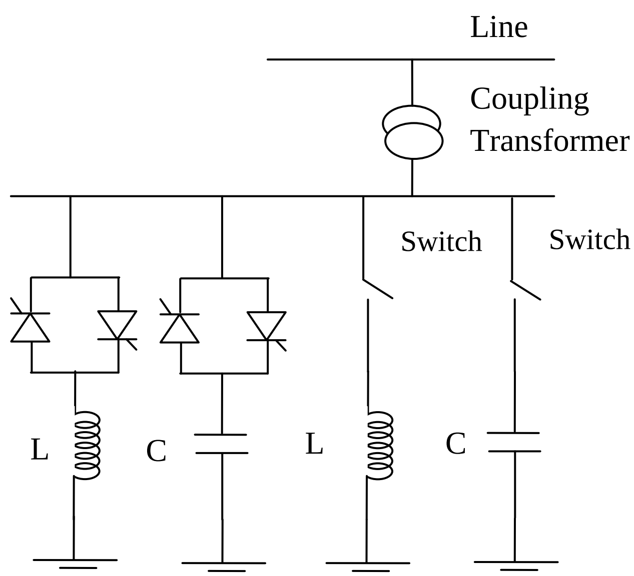

Fig 2.1 A Basic SVC module

2.4. THYRISTOR CONTROLLED SERIES COMPENSATOR (TCSC):

The basic conceptual TCSC module comprises a series capacitor, *C*, in parallel with a thyristor-controlled reactor L, as shown in Fig.2.2. However, a practical TCSC module also includes protective equipment normally installed with series capacitors. A metal-oxide varistor (MOV), essentially a nonlinear resistor, is connected across the series capacitor to prevent the occurrence of high-capacitor over- voltages. Not only does the MOV limit the voltage across the capacitor, but it allows the capacitor to remain in circuit even during fault conditions and helps improve the transient stability.

Also installed across the capacitor is a circuit breaker, CB, for controlling its insertion in the line. In addition, the CB bypasses the capacitor if severe fault or equipment-malfunction events occur. A current-limiting inductor, L is incorporated in the circuit to restrict both the magnitude and the frequency of the capacitor current during the capacitor-bypass operation. An actual TCSC system usually comprises a cascaded combination of many such TCSC modules, together with a fixed-series capacitor *C*. This fixed series capacitor is provided primarily to minimize costs [19, 21].

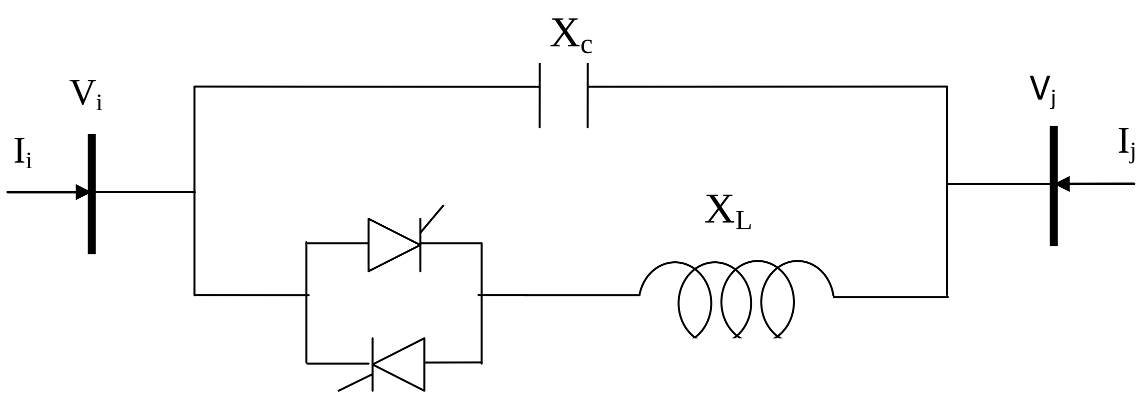

Fig .2.2 A TCSC Basic Module

2.5 STATIC SYNCHRONOUS COMPENSATOR (STATCOM):

The STATCOM is a shunt-connected reactive-power compensation device that is capable of generating and/or absorbing reactive power and in which the output can be varied to control the specific parameters of an electric power system. It is in general a solid-state switching converter capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an energy source or energy-storage device at its input terminals. Specifically, the STATCOM is a voltage-source converter that, from a given input of dc voltage, produces a set of 3-phase ac-output voltages, each in phase with and coupled to the corresponding ac system voltage through a relatively small reactance (which is provided by either an interface reactor or the leakage inductance of a coupling transformer). The dc voltage is provided by an energy-storage capacitor. A Typical STATCOM is shown below in Fig 2.3

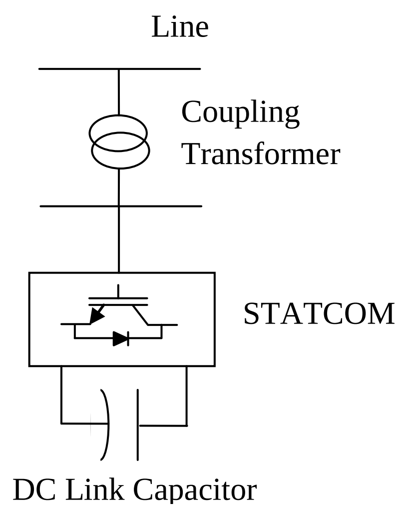

Fig 2.3 Typical STATCOM connected in a line

2.6 STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC)

SSSC is a voltage-sourced converter-based series compensator, proposed by Gyugyi in 1989 using the concept of converter-based technology uniformly for shunt and series compensation and for transmission angle control. The series capacitive compensation acts as a means of reducing the line impedance (maximum power transfer) as well as means of increasing the voltage across the given impedance of the line (voltage stability). By making the output voltage of the synchronous voltage source (SVS) a function of the line current, the similar compensation is provided by the series capacitor. However, in contrast to the real series capacitor, the SVS is able to maintain a constant compensating voltage in the presence of variable line current, or control the amplitude of injected compensating voltage independent of the amplitude of the line current. The series reactive scheme using a switching power converter (voltage-sourced converter) as a SVS is, per IEEE and CIGRE definition, termed the Static Synchronous Series Compensator (SSSC).The Fig 2.4 shown below shows the SSSC.

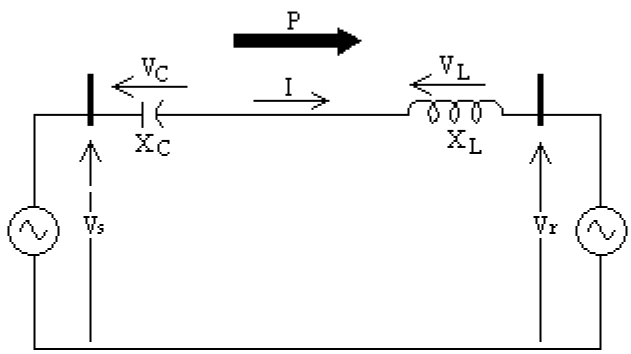

Fig 2.4 The Static Synchronous Series Compensator (SSSC) used for series compensation

2.7 UNIFIED POWER FLOW CONTROLLER (UPFC):

The UPFC is the most versatile FACTS controller with capabilities of voltage regulation, series compensation, and phase shifting. The UPFC is a member of the family of compensators and power flow controllers. The latter utilize the synchronous voltage source (SVS) concept to provide a unique comprehensive capability of transmission system control. The UPFC is able to control simultaneously or selectively all the parameters affecting power flow patterns in a transmission network, including voltage magnitudes and phases, and real and reactive powers. These basic capabilities make the UPFC the most powerful device in the present day transmission and control systems.

As shown in Fig 2.5, the UPFC consists of two voltage-sourced converters, one in series and one in shunt, both using Gate Turn-Off (GTO) thyristor valves and operated from a common dc storage capacitor. This configuration facilitates free flow of real power between the ac terminals of the two converters in either direction while enabling each converter to independently generate or absorb reactive power at its own ac terminal.

The series converter, referred to as Converter 2, injects a voltage with controllable magnitude Vpq and phase ρ in series with the line via an insertion transformer, thereby providing the main function of the UPFC. This injected voltage phasor acts as a synchronous ac voltage source that provides real and reactive power exchange between the line and the ac systems.

The reactive power exchanged at the terminal of series insertion transformer is generated internally while the real power exchanged is converted into dc power and appears on the dc link as a positive or negative real power demand. By contrast, the shunt converter, referred to as Converter 1, supplies or absorbs the real power demanded by Converter 2 on the common dc link and supports the real power exchange resulting from the series voltage injection. It converts the dc power demand of Converter 2 into ac and couples it to the transmission line via a shunt connected transformer.

Converter 1 can also generate or absorb reactive power in addition to catering to the real power needs of Converter 2; consequently, it provides independent shunt reactive compensation for the line. It is to be noted that the reactive power exchanged is generated locally and hence, does not have to be transmitted by the line. On the other hand, there exists a closed path for the real power exchanged by the series voltage that is injected through the converters back to the line. Thus, there can be a reactive power exchange between Converter 1 and the line by controlled or unity power factor operation. This exchange is independent of the reactive power exchanged by Converter 2.

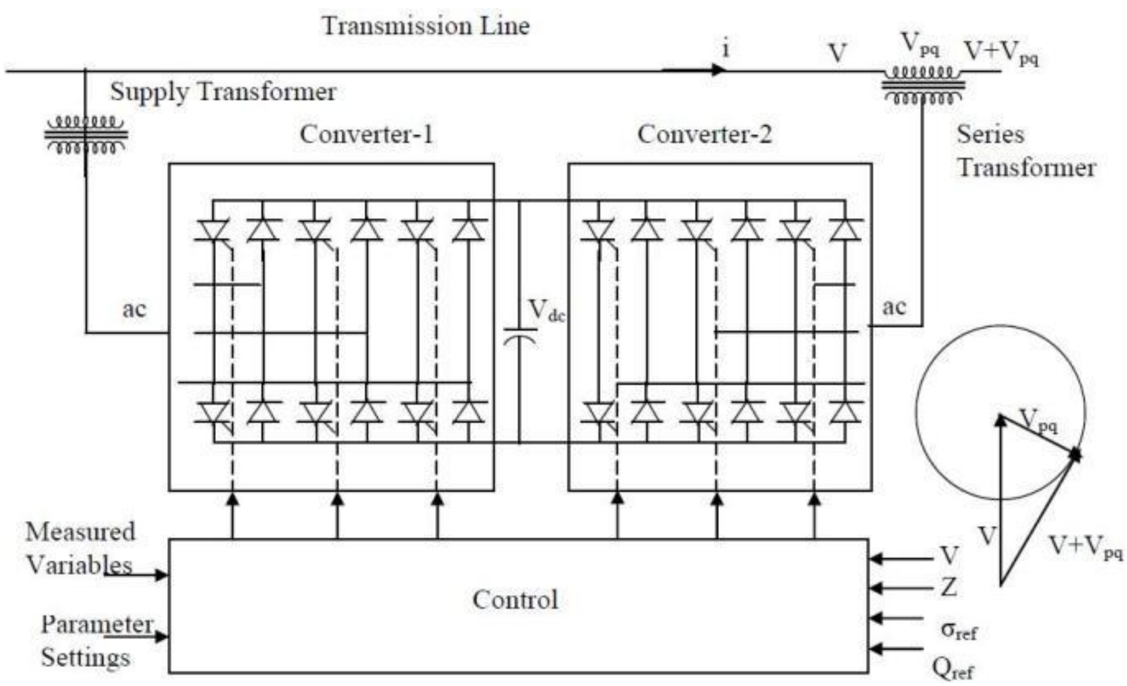

Fig 2.5 UPFC implemented by using two converters

2.8 INTERLINE POWER FLOW CONTROLLER (IPFC)

The Interline Power Flow Controller (IPFC) proposed is a new concept for the compensation and effective power flow management of multi-line transmission systems. In its general form, the IPFC employs a number of inverters with a common dc link, each to provide series compensation for a selected line of the transmission system[35]. Because of the common dc link, any inverter within the IPFC is able to transfer real power to any other and thereby facilitate real power transfer among the lines of the transmission system. Since each inverter is also able to provide reactive compensation, the IPFC is able to carry out an overall real and reactive power compensation of the total transmission system. This capability makes it possible to equalize both real and reactive power flow between the lines, transfer power from overloaded to under loaded lines, compensate against reactive voltage drops and the corresponding reactive line power, and to increase the effectiveness of the compensating system against dynamic disturbances. In other words, the IPFC can potentially provide a highly effective scheme for power transmission management at a multi-line substation.

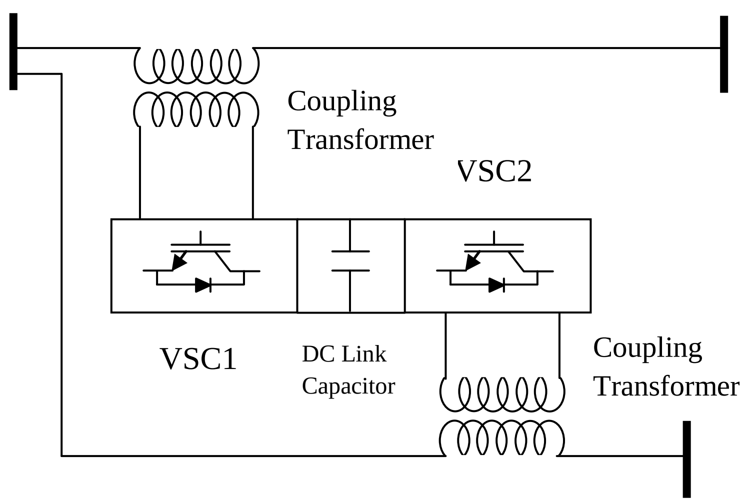

Fig 2.6 The Interline Power Flow Controller (IPFC)

2.9 APPLICATIONS OF FACTS DEVICES:

Flexible AC Transmission Systems, called FACTS, got in the recent years a well-known term for higher controllability in power systems by means of power electronic devices. Several FACTS-devices have been introduced for various applications worldwide [9]. A number of new types of devices are in the stage of being introduced in practice.

In most of the applications the controllability is used to avoid cost intensive or landscape requiring extensions of power systems, for instance like upgrades or additions of substations and power lines. FACTS-devices provide a better adaptation to varying operational conditions and improve the usage of existing installations. The basic applications of FACTS-devices are:

- power flow control,
- increase of transmission capability,
- voltage control,
- reactive power compensation,
- stability improvement,
- power quality improvement,
- power conditioning,
- flicker mitigation,
- Interconnection of renewable and distributed generation and storages.

In all applications the practical requirements, needs and benefits have to be considered carefully to justify the investment into a complex new device. Figure 1.1 shows the basic idea of FACTS for transmission systems. The usage of lines for active power transmission should be ideally up to the thermal limits. Voltage and stability limits shall be shifted with the means of the several different FACTS-devices.

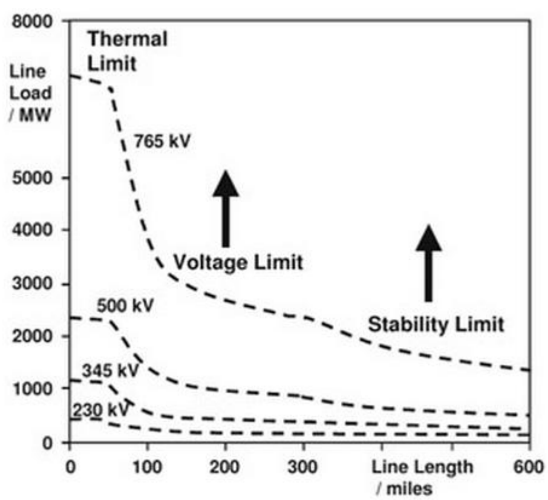

Fig 2.7 Operational limits of transmission lines for different voltage levels

Many FACTS Devices are installed worldwide with majority for improving the performance of operation and increasing the capacity of the lines. The following table 2.1 shows some of the projects installed [9]

Table 2.1 List of some of the FACTS Devices installed worldwide

Device	Country	kV	Purpose	Place
Series Capacitors	India	6 capacitors rated 1100MVAr	enhancement of transmission capacity	Lucknow, Bareilly, Unnao Substations
Series Capacitors	Argentina	4 capacitors rated 430 MVAr	Increase overall power transmission capacity	Transener´s power transmission corridor
SVC	Saudi Arabia	380kV,150 MVAr	Reactive power compensation, increase the stability limit of the generators	SEC-CRB Transmission grid
SVC	India	33kV,0-200 MVAr	To mitigate problems in power quality in plant as well as feeding grid	Jindal Steel & Power Ltd(JSPL)
SVC	Australia	132kV,600 MVAr(9SVC's)	achieve dynamic load balancing	Railway network for located in east Central Queensland.
STATCOM	Japan	154kV,80MVAr	Power system and voltage stabilization	Inumaya substation
STATCOM	USA	138 kV,100MVAr	To maintain adequate voltage stability margin	Austin utility, Texas
UPFC	China	154kV,80MVA	To vary different operational parameters	Kang-Jin Sub-station
UPFC	USA	138kV,320 MVA	Reliable power supply, effective voltage support	Inez substation
TCSC	China	220kV, 86.7MVAr	Increase Stability margin, suppress low frequency oscillation	North-West China Power System
TCSC	India	400kV,1.7 GVAr	To increase power transfer capability, To enhance the transient stability.	Purnea-Gorakhpur
TCSC	USA	230kV,165 MVAr	To increase power transfer capability	Kayenta substation, Arizona