POWER SYSTEM PERFORMANCE ENHANCEMENT USING FLEXIBLE AC TRANSMISSION SYSTEM DEVICES

by

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Abstract

The objective of this research is to investigate the performance enhancement of a power system using Flexible AC Transmission System (FACTS) devices. It is intended to show how the reliability and performance of the power system is improved. The focus is to enhance the understanding of the system operating with and without these devices.

Power transmission can always be improved by upgrading or adding new transmission circuits. But this is not a practical solution. FACTS devices are feasible alternatives for optimizing the transmission systems. Providing reactive shunt compensation with shunt-connected capacitors and reactors is a well-established technique to get a better voltage profile in a power system. Shunt capacitors lack dynamic capabilities, and so dynamically controlled reactive power compensation is essential. This feature is provided by FACTS devices. Implementation of new equipment consisting high power electronics based technologies such as FACTS becomes essential for improvement of operation and control of power systems.

FACTS promote the use of static controllers to enhance the controllability and increase the power transfer capability. Three software tools were used in this thesis, such as, MATLAB, PSCAD and PowerWorld. Thyristor Controlled Reactors (TCR), Thyristor Controlled Series Capacitors (TCSC), Static Var Compensators (SVC) are used as FACTS devices for consideration in the power system study. This thesis aims at examining the ability of FACTS devices and distributed FACTS devices for power flow control and reactive power compensation in a power system.

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Dedicated to my parents Mr. Rajendran & Ms. Rajamani

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List of Abbreviations

(in alphabetical order)

AC – Alternating Current

DFACTS – Distributed Flexible Alternating Current Transmission System

FACTS – Flexible Alternating Current Transmission System

MOV – Metal Oxide Varistor

MVA – Mega Volt Ampere

MVAR – Mega Volt-Ampere Reactive

MW – Mega Watt

p.u. – per unit

SSSC – Static Synchronous Series Compensator

STATCOM – Static series Compensator

SVC – Static Var Compensator

TCR – Thyristor Controlled Reactor

TCSC – Thyristor Controlled Series Capacitor

TSC – Thyristor Switched Capacitor

VAR – Volt Ampere reactive

δ – power angle

° - degrees

Chapter 1

Introduction

1.1 Background of the research

With power demand on the rise, power transmission needs to be developed at a corresponding pace. A traditional approach to transmission network development would simply be building more and more powerful lines. This, however, is not the best way, as power transmission lines over distances and of large power transmission capability cost a lot of money, take considerable time to build, and need several modifications in the existing urban landscape. A more useful way is to take a fresh look at facilities already in place in the system, and find better ways of using those facilities. Planning of reactive power compensation has changed the way the utility industry handles the increased load and extremely low voltages.

1.2 Objectives of the research

At the present time, power systems are forced to operate at almost full capacity. More often, generation patterns result in heavy flows that tend to incur greater losses as well as threaten stability and security of the system. This ultimately creates increased risk of unwanted power outages from mild to severe levels. For this reason, there is a general consensus that the power grid has to be reinforced, to make it smart, fault tolerant and self-healing, dynamically and statically controllable.

A traditional alternative to reinforce the power network consists of upgrading the electrical transmission system infrastructure through the addition of new transmission lines, substations, and associated equipment. However, the process to permit, site, and construct new transmission lines has become difficult, expensive, time consuming, and many times even controversial.

The utilization of the existing power system can be improved through the application of advanced power electronics technologies. Flexible AC Transmission Systems (FACTS) provide technical solutions to address the new operating challenges being presented today. Devices, such as a STATCOM, SVC, SSSC, and UPFC, can be connected in series or shunt (or a combination of the two) to achieve numerous control functions, including voltage regulation, power flow control, and system damping.

1.3 Organization of the thesis

The objective of this thesis is to demonstrate the enhancement in power system operation by the application of FACTS devices, which are used to control the power flow in energy systems. Chapter 2 provides some background theory and current installations on the Flexible AC Transmission Systems (FACTS) devices. Chapter 3 discusses the theoretical reactive power compensation by a case study solving for the mid-point compensation in a long transmission line. Chapter 4 presents the application of Thyristor Controlled Reactor

(TCR) and Thyristor Controlled Series Capacitor (TCSC) in a test system. PSCAD software is used to model the test system. Chapter 5 extends an insight on the newly developing D-FACTS devices. Its advantages over the regular FACTS devices and their application in a power system are briefly discussed. Chapter 6 presents the summary of the thesis, highlighting the key contribution of the research and suggestions for future work are outlined.

Chapter 2

Overview of Flexible AC Transmission Systems (FACTS)

2.1 Introduction

This chapter aims at describing the main features of flexible alternating current transmission systems (FACTS). These power electronics based devices offer the possibility to increase the transmission network capacity as well as the system flexibility, reliability, security and controllability with a limited environmental impact. FACTS provide effective solutions to several grid connected problems. This chapter provides information about how FACTS devices are classified based on their construction and operation. The configuration, operating principle, working, and applications of various FACTS devices are presented in this chapter.

2.2 Motivation for the development of FACTS Technology

The traditional solution for any network problem is by increasing its capacity by installing new transmission or distribution lines. But implementing this solution has become increasingly difficult due to various aspects such as environmental impacts, economic considerations and political obstacles. Therefore, an effective way to cope with this situation is to use the existing power system more efficiently by utilizing the transmission lines to prevent any possible congestions.

The increasing progress in Thyristor-based technology has resulted in the development of advanced FACTS. FACTS devices are able to address most of the discomforts in the power system needs, if not all, making utility networks more reliable, more controllable and more efficient. FACTS devices are typically high-power high-voltage power converters, operating at 138–500 kV and 0–300 MVA that are used to control power flow in the transmission and distribution network.

Following are some of the key advantages which can be achieved for power system enhancement by utilizing the FACTS devices [1-7]:

- Controlling active and reactive power flows smoothly and rapidly
- Reducing undesired reactive power flows in the system
- Reducing serious voltage drops on the lines
- Increasing the loading capability of the transmission lines to levels closer to their thermal limits without violating any security constraints
- Increased power transmission capability and stability of power corridors

- Limiting the impacts of faults and equipment failure
- Helps in damping out the oscillations and avoid damages in equipments
- Improving steady-state and transient stability
- Controlling voltage and improving power quality
- Quickly shifting the power flow from congested transmission line to any free parallel line
- Dynamic voltage control, to limit over-voltages on lightly loaded lines
- Maintaining power quality in the point of connection.

In addition to all the above said advantages, when compared to the conventional mechanical devices used to control AC power systems, such as tap-changing transformers or shunt capacitor switches, FACTS controllers are not prone to many mechanical wear and tears.

2.3 Classification of FACTS Controllers [1, 2, 8]

A FACTS controller may be any power electronic-based system and other static equipment that provide control of one or more AC Transmission Systems parameters to enhance controllability and increase power transfer capability. Flexible AC Transmission Systems (FACTS) is a technology that responds to the needs of dynamic control of voltage, impedance and phase angle of the high voltage AC lines. It has the ability to accommodate changes in the electric transmission systems or operating conditions while maintaining sufficient steady state and transient margins. FACTS controllers may be divided into two categories based on whether they are controlled by thyristor devices with no gate turn-off, or with power devices with gate turn-off capability. FACTS controllers can be divided into the following two discrete families, based on their technology.

- **Thyristor-controlled FACTS Controllers** which has thyristors with no intrinsic turn-off ability arranged with capacitors/reactors but have much faster response and are operated by sophisticated controls. Static Var Compensator (SVC) and Thyristor Controlled Series Capacitor (TCSC) belong to this family.
- **Converter-based FACTS Controllers** will have self-commutated voltage-sourced switching converters which can rapidly control static, synchronous ac voltage or current sources. Static Synchronous Compensator (STATCOM) and Static Synchronous Series Compensator (SSSC) belong to this family.

Based on their positioning in the transmission network, FACTS devices can also be divided into the following types, such as:

- **Series Controllers** inject voltage in series with the line. Current flowing through the line multiplied by the variable impedance represents injected series voltage in the line. The series controllers supply only reactive power as long as the voltage and current are in phase quadrature. Few series connected controllers are Static Synchronous Series Compensator (SSSC), Thyristor Controlled Series Capacitor (TCSC), Thyristor Switched Series Capacitor (TSSC), Thyristor Controlled Series Reactor (TCSR), GTO Thyristor-Controlled Series Capacitor (GCSC), and Phase Angle Regulator (PAR).

- **Shunt Controllers** inject current into the line at the point of connection. When the current injected is in phase with the line voltage, the shunt controller either supplies or consumes the variable reactive power. Few shunt connected controllers are Static Synchronous Compensator (STATCOM), Thyristor-controlled Reactor (TCR), Thyristor-Switched Reactor (TSR), Thyristor-Switched Capacitor (TSC) and Static Var Compensator (SVC).

- **Combined Series – Shunt Controllers** inject current into the line through shunt part and voltage in series through the series part, as they are combination of both series and shunt controllers with coordinated function. When they function as unified, there can be real power exchange in between. Few combined series – shunt connected controllers are Unified Power Flow Controllers (UPFC), Thyristor Controlled Phase Shifting Transformer (TCPST), Interphase Power Controller (IPC), Dynamic Flow Controller (DMC) and Unified Power Quality Conditioner (UPQC).

2.4 Series FACTS controllers

2.4.1 Thyristor Controlled Series Capacitor (TCSC)

Thyristor Controlled Series Capacitor, proposed in 1986, belongs to the family of Series Controllers. It consists of a series compensating capacitor shunted by a Thyristor Controlled Reactor (TCR). TCSC configurations comprise controlled reactors in parallel with sections of a capacitor bank. This combination allows smooth control of the fundamental frequency capacitive reactance over a wide range. The capacitor bank of each phase is mounted on a platform to enable full insulation to ground. The thyristor valve contains a string of series connected high power thyristors. The inductor is of air-core design. A metal oxide varistor (MOV) is connected across the capacitor to prevent overvoltage. The single line diagram of the TCSC is shown in Figure 2.1.

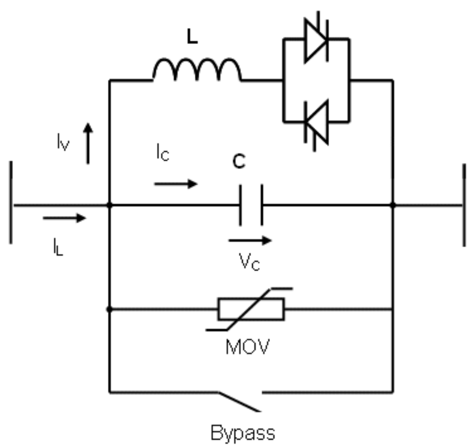

Figure 2.1 Single line diagram of a TCSC [9]

2.4.1.1 Principle of operation, configuration and control of TCSC

TCSC provides a continuously variable capacitance by partially cancelling the effective compensating capacitance by the TCR. TCR behaves as continuously variable reactive impedance, at the fundamental system frequency which can be controlled by a delay angle. TCSC thus presents a tunable parallel LC circuit to the line current that is a constant AC source.

TCSC employs conventional thyristors with no internal turn-off capability. These thyristors are the most rugged power semiconductors, available with the highest current and voltage ratings, and they also have the highest surge current capability. For a short term, they are suitable for providing the bypass operation.

Normally, TCSC's stability fundamental frequency impedance is relative only to the firing angle α. When α is between 145° and 180°, the equivalent reactance is capacitive. When α is between 90° and l40°, the equivalent reactance is inductive. When a fault occurs, TCSC's control system will react to make sure of protection. If short circuit current is large enough, the metal oxide varistor will be fired. TCSC's control system would rapidly send its commands to bypass thyristor and make TCSC become inductive. So TCSC's capacitive reactance would decrease and gradually change into inductive reactance. This characteristic makes it possible for distance relay with memory polarizing voltage and proper setting value to be used in TCSC line. If short circuit current is not large enough, TCSC's control system will not command to bypass the thyristors [3].

The main principle of TCSC is to provide electromechanical damping in the line, by providing variable capacitive reactance. It is achieved by using control algorithm in the controls which function on the thyristor circuit in parallel to the main capacitor bank. Thus the main capacitor functions as a variable capacitor at fundamental frequencies [10].

2.4.1.2 Applications and Installations of TCSC

Application of TCSC has the following benefits by series compensation:

- Elimination of sub synchronous resonance risks
- Damping of active power oscillations
- Post-contingency stability improvement

- Dynamic power flow control
- Increased transfer capacity

A recent project involving TCSCs has been carried out in Brazil, where a TCSC is used in combination with five conventional series capacitors on a 1,017-km-long 500-kV transmission system. In this application (operating since 1999), the TCSC system is utilized for damping and transient stability enhancements. The latest projects have been carried out in India and China [3, 11].

2.4.2 Static Synchronous Series Compensator (SSSC)

The static synchronous series compensator (SSSC) is used in controlling active and/or reactive power-flow through a line. It consists of a series transformer, a voltage source convertor and a DC link capacitor. To compensate as a pure reactance, the voltage Vc should be controlled in quadrature with the current. The command signals 'PWM magnitude' and 'PWM phase angle' are from the SSSC voltage regulator as shown in Figure 2.2 [12].

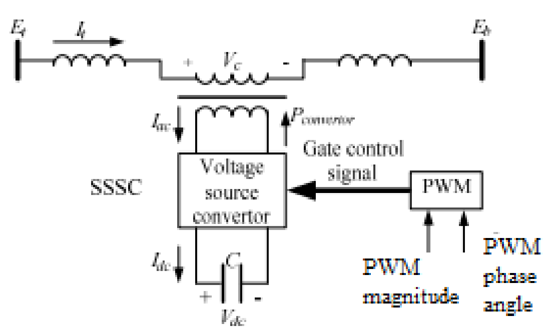

Figure 2.2 Single line diagram of a SSSC [10]

2.4.2.1 Principle of operation, configuration and control of SSSC

In normal conditions, the SSSC operates in stand-by mode. However, during disturbances, nominal system voltage will be compared with the voltage variation to find the differential voltage. This differential voltage is then injected by the SSSC. An SSSC is limited by its voltage and current ratings. It is capable of matching a compensation reactance (both inductive and capacitive), in series with the transmission line inductive reactance. The SSSC device is connected to the power line by means of the injection transformer. The inverter present in SSSC is bidirectional converter. It will act as inverter in capacitive compensation and as rectifier during inductive compensation [13].

In order to increase the power flow in a line the SSSC must provide a capacitive reactance in series with the transmission line. The capacitive compensation increases the line current and the power flow. For regular capacitive compensation, the output voltage must lag the line current by 90°, 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°. Then, the inserted voltage is in phase with the voltage developed by the inductive reactance of line. In case of inductive compensation the inductive reactance is added to the line inductive reactance, which results in the decrease of the line current and the power flow in the line. The energy source connected to the converter will provide the required voltage to increase the power flow during capacitance compensation. The SSSC will absorb the voltage from the line and store it in the energy source during inductive compensation. The commonly used voltage sources are battery and super capacitors [14].

2.4.2.2 Applications and Installations of SSSC

Application of SSSC has the following benefits by series compensation:

- Elimination of voltage sags and swells
- Capability of operating in both inductive and capacitive modes
- Damping of Sub-Synchronous oscillations
- Dynamic power flow control and increased power transfer capacity
- Power factor correction through continuous voltage injection
- Reducing harmonic distortion by active filtering

Recent developments related to SSSCs are the installation and testing of a prototype device in the Spanish 220-kV grid as part of the REEDES2025 project [10, 11, 15, 16].

2.5 Shunt FACTS controllers

2.5.1 Static VAR Compensator (SVC)

The idea behind the working of SVC is to increase the transmitted electrical power by increasing the transmission line voltage via capacitive vars, when the machines accelerate and to decrease it by decreasing the voltage via inductive vars, when the machines decelerate. With proper coordination of the capacitive reactance and inductive reactance, the var output can be varied continuously between the capacitive and inductive ratings of the equipment. The SVC is mainly used for reactive power compensation, voltage regulation and power factor corrections [15].

2.5.1.1 FACTS Devices in SVC

The Static Var Compensator (SVC) is a combination of the Thyristor-Switched Capacitor (TSC) and Thyristor Controlled Reactor (TCR). It has capacitive as well as inductive compensation.

2.5.1.1.1. Thyristor-Controlled Reactor (TCR)

The Thyristor-Controlled Reactor (TCR) is a shunt compensator, which produces an equivalent continuous variable inductive reactance by using phase-angle control. The magnitude of the current is controlled on the basis of the firing angel α. The value of firing angle α may vary from 90° to 180°, measured from the zero crossing of the voltage. At α=90°, the reactor is fully inserted in the circuit and for α=180°, the reactor is completely out of the circuit [15]. Figures 2.3(a) and 2.3(b) show the single line diagram of TCR and TSC respectively.

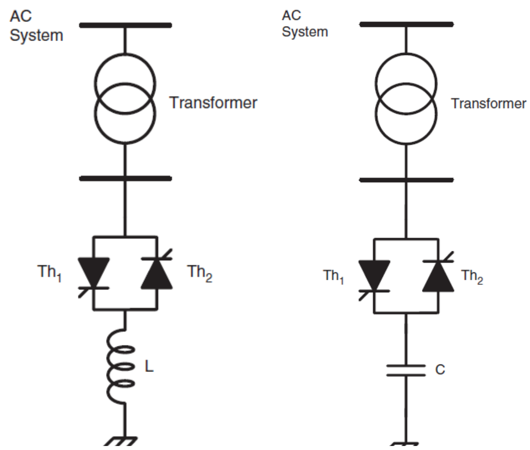

Figure 2.3 a) Single line diagram of TCR, b) Single line diagram of TSC [15]

2.5.1.1.2 Thyristor-Switched Capacitor (TSC)

The Thyristor-Switched Capacitor (TSC) is a shunt compensator, which produces an equivalent continuous variable inductive capacitance. The thyristor is turned-on only when zero-voltage switching is achieved; hence it is called as Thyristor-Switched Capacitor (TSC). This means that the voltage across the thyristor terminals has to be zero at the turn-on instant. In practical cases, it may be slightly positive, since thyristors need positive anode–cathode voltages to be triggered (large anode–cathode voltage during turn-on, however, may produce a large current spike that may damage the thyristors). Therefore, due to this switching characteristic, the thyristors can only connect the capacitor to the grid or disconnect it. Consequently, only step-like control is possible and, therefore, a continuous control is not possible. The capacitor is added to the power system by means of thyristor switching action to increase capacitive reactance to improve the power transfer in the system [15]. The single line diagram of the SVC is shown in Figure 2.4.

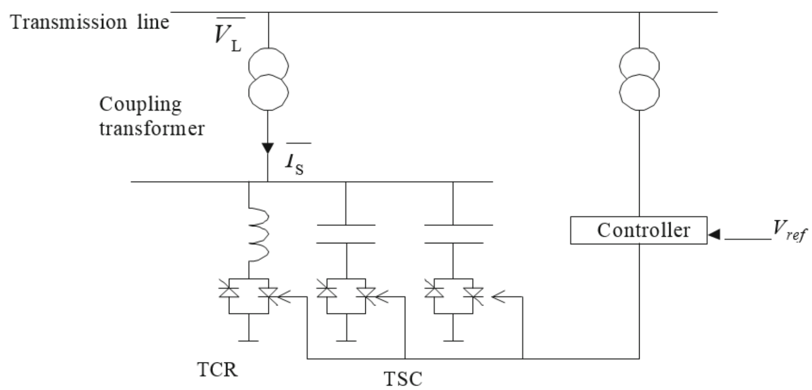

Figure 2.4 Single line diagram of an SVC [5]

2.5.1.2 Principle of operation, configuration and control of SVC

SVC consists of Thyristor Switched Capacitors (TSC) and Thyristor Switched or Controlled Reactors (TSR/TCR). The coordinated control of the combination of these branches varies the reactive power. The SVC operates as a shunt-connected variable reactance. The main task of SVC is to produce or draw reactive power to regulate the voltage level of the power system. SVC installations consist of a number of building blocks. The most important is the thyristor valve, i.e. stack assemblies of series connected anti-parallel thyristors to provide controllability.

Air core reactors and high voltage AC capacitors are the reactive power elements used together with the thyristor valves. The equipment's step-up connection to the transmission voltage is achieved through an SVC power transformer. The thyristor valves, together with auxiliary systems, are located inside an SVC building, while the air core reactors and capacitors, together with a power transformer, are located outdoors.

By means of phase angle modulation switched by the thyristors, the reactor may be variably switched into the circuit, and so provide a continuously variable reactive power injection (or absorption) to the electrical network. In this configuration, coarse voltage control is provided by the capacitors; the thyristor-controlled reactor is to provide smooth control. Smoother control and more flexibility can be provided with thyristor-controlled capacitor switching [3].

2.5.1.3 Applications and Installations of SVC

A rapidly operating Static Var Compensator (SVC) can continuously provide the reactive power required to control dynamic voltage swings under various system conditions and thereby improve the power system transmission and distribution performance.

SVC improves network stability, increases transfer capability and reduce losses, maintains a smooth voltage profile, continuously provides reactive power and mitigates active power oscillations under different network conditions. SVC is normally used for voltage regulation and for improving the transient and dynamic stability. Voltage support capability of the SVC deteriorates with decreasing system voltage [2].

SVCs were first applied in the United States in the 1970s, long before the concept of FACTS was formulated. The first application was the EPRI-Minnesota Power & Light and Westinghouse project commissioned in 1978, in which SVCs enabled a 25% power increase along the line where they were installed [??]. Worldwide, there is a steady increase in the number of installations. Most recently, SVCs have been ordered or installed in Chile, Canada, the USA, Mexico, South Africa and Finland [16-18]. In the particular case of Europe, the largest number of SVCs are to be found in the UK, while one of the latest (providing reactive power support in the range -200/+240 MVAR) installed in the Kangasala substation, Finland, in 2009 [19].

2.5.2 Static synchronous Compensator (STATCOM)

STATCOM controls transmission voltage by reactive power shunt compensation. A typical STATCOM consists of a coupling transformer, an inverter and an energy storage element like battery or DC capacitor. The single line diagram of the SVC with TCR and TSC is shown in Figure 2.5.

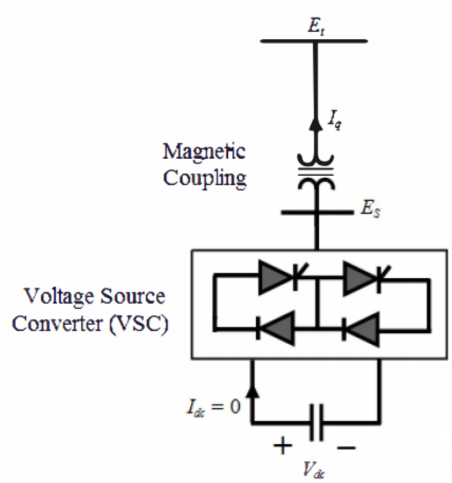

Figure 2.5 Single line diagram of an STATCOM [20]

A STATCOM is built with thyristors with turn-off capability like GTO, IGBT or IGCT. The advantage of a STATCOM is that the reactive power provision is independent of the actual voltage at the connection point. Even during most severe contingencies; the STATCOM keeps its full capability. This is a solid-state synchronous condenser connected in shunt with the AC system. The output current is adjusted to control either the nodal voltage magnitude or the reactive power injected at the bus [3, 4].

2.5.2.1 Principle of operation, configuration and control of STATCOM

The STATCOM consists of one Voltage Sourced Converter and its associated shunt-connected transformer. It is the static counterpart of the rotating synchronous condenser but it generates or absorbs reactive power at a faster rate because no moving parts are involved. In principle, it performs the same voltage regulation function as SVC but in a more robust manner, because, unlike the SVC, its operation is not impaired by the presence of low voltages [4].

The static synchronous compensator is based on a solid-state voltage source, implemented with an inverter and connected in parallel to the power system through a coupling reactor, in analogy with a synchronous machine, generating balanced set of three sinusoidal voltages at the fundamental frequency, with controllable amplitude and phase-shift angle. This equipment, however, has no inertia and no overload capability.

A charged capacitor acts as a source of direct current. In this process, a power converter AC-DC power supply provides a regulated output to produce a controllable three phase voltage. STATCOM can be used for filtering harmonics, improving transient and dynamic stability, dynamic over voltages and under voltages, voltage collapse, steady state voltage, excess reactive power flow and adverse transients. The STATCOM can help wind farms in improving voltage regulations, power factor and stability of power load. STATCOM reactive power flow is determined between the grid voltage and the voltage of the power converter.

The control of reactive power in the STATCOM is done by controlling its terminal voltage.

- If the source voltage is larger than STATCOM voltage then the STATCOM reactive power is inductive
- If the source voltage is smaller than STATCOM voltage then the STATCOM reactive power is capacitive

The reactive power control in a STATCOM is, therefore, a problem of how to control the magnitude of its voltage. There are two basic principles: in the case of multi-pulse converters, the output voltage magnitude can only be controlled by controlling the DC side voltage that is the DC capacitor voltage; in the case of PWM control, the DC capacitor voltage can be kept constant and the voltage can be controlled by the PWM controller itself.

2.5.2.2 Applications and Installations of STATCOM

Application of STATCOM has the following benefits by series compensation:

- Fast reactive power control
- Dynamic real power exchange

- Transient and dynamic stability improvement
- Improved voltage control
- Efficient reactive power compensation

After two experimental installations of converter-based VAR compensators during the 1980s, GTOs with greatly increased ratings have become available, and a ±80 MVAR installation, using 4,500 V, 3,000 A GTOs, has been set up in Japan [??]. In the USA, in 1995, a STATCOM rated for ±100 MVAR was commissioned at the Sullivan substation of the Tennessee Valley Authority (TVA) power system. In this case, the GTOs are rated for 4,500 V and 4,000 A to control a 161-kV bus voltage [??]. The number of STATCOMs installed worldwide is currently estimated at about 20 devices deployed in the USA, Japan, China and the UK (the only application in Europe) for a total installed power of over 1,200 MVA [11, 16-19].

2.6 Combined Series-Shunt Controllers

2.6.1 Unified Power Flow Controller (UPFC)

A combination of STATCOM and SSSC, which are coupled using a common dc link, to allow bidirectional flow of active power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM, are controlled to provide concurrent active and reactive series line compensation without an external electric energy source. The UPFC, by means of angularly unconstrained series voltage injection, is able to control concurrently or selectively the transmission line voltage, impedance, and angle or, alternatively, the active and reactive power flow in the line.

The energy storing capacity of the DC capacitor is generally small, and so the shunt converter has to draw active power from the grid in the exactly same amount as the active power being generated by the series converter. The single line diagram of the UPFC is shown in Figure 2.6 below.

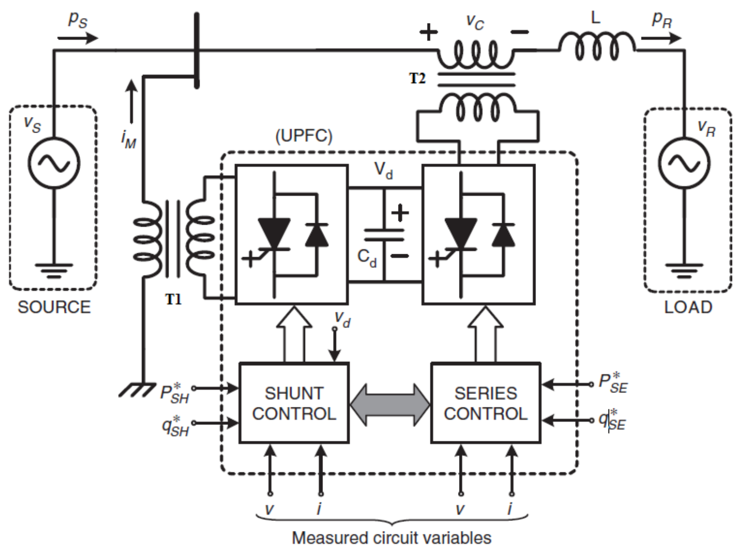

Figure 2.6 Single line diagram of an UPFC [15]

2.6.1.1 Principle of operation, configuration and control of UPFC

UPFC regulates voltage by continuously variable in-phase voltage injection. Functionally, this is similar to that obtainable with a transformer tap changer having infinitely small steps. Series reactive compensation is similar, but more general than, controlled series capacitive and inductive series compensation. This is because the UPFC injected series compensating voltage can be kept constant, if desired, independent of line current variation, whereas the voltage across the series compensating (capacitive and inductive) impedance varies with the line current. The UPFC can function as a perfect phase shifter. From the practical viewpoint, in contrast to conventional phase shifters, the AC system does not have to supply the reactive power that the phase-shifting process demands. Since, it is actually generated by the UPFC converter, multifunction power flow control, is executed by simultaneous terminal voltage regulation, series capacitive line compensation and phase shifting, enhancement of transmission capacity, transient stability, power oscillation damping, and voltage stability. For its speed and control characteristics, the UPFC is the most complete and powerful FACTS device in performing those steady-state and dynamic functions [21].

The power converter connected to the insertion transformer is used to generate voltage at the fundamental frequency with variable amplitude and phase angle, 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 with the line will be applied for direct voltage control, series compensation, and phase-shift.

The power converter connected to the shunt coupling transformer provides the active power from the AC power grid to the power converter connected to the series coupling transformer via the common DC link. Since this converter can also supply or draw reactive power at its AC terminal, independently of the active power it transfers to (or from) the DC terminal, it follows that, with proper controls, it can also achieve the task of an independent static capacitor developing compensation for reactive power at the transmission line. Thus, executing a regulation of indirect voltage where the input port of the unified power flow controller is achieved [22].

2.6.1.2 Applications and Installations of UPFC

Application of UPFC has the following benefits by series compensation:

- Accurate control of line active and reactive power
- Improves transmission capacity
- Series and Shunt compensation
- Phase shifting regulation
- Damping of system oscillation

Currently there are three UPFC solutions implemented worldwide, two are in the USA and one is in South Korea. The first installation of this device was in 1998 at the Inez station by American Electric Power (AEP) in eastern Kentucky, in a joint effort with the EPRI and Westinghouse. In this application, the UPFC employs two GTO-based converters, each rated ±160 MVA, connected by a common DC link. The second UPFC installation was deployed in 2001, at the Marcy substation operated by the New York Power Authority (NYPA) with the support of EPRI. The third UPFC, rated 80 MVA, was installed in 2002, by the Korea Electric Power Corporation (KEPCO) at its 154 kV Kangjin substation [11, 23, and 24].

2.7 Advantages of FACTS devices

In situations where local reactive power supply is insufficient, the transmission grid is used to transport reactive power from other sources. This reactive power transmission reduces the available capacity for active power transmission on affected lines. By providing local reactive power compensation, less reactive power needs to be transported through the grid, leading to a slight increase in available transmission capacity. FACTS devices such as SVC and STATCOM provide such local reactive power compensation.

Shunt devices such as static VAR compensator (SVC) and static synchronous compensator (STATCOM), have been most widely applied, and typically used for reactive VAR compensation and voltage support. Series devices such as the Thyristor controlled series capacitor (TCSC) and the static synchronous series compensator (SSSC) can be used for controlling active power flow on transmission lines. Series-shunt devices such as the universal power flow controller (UPFC) can be used for accomplishing both functions with maximum flexibility, and higher cost [4]. Application of FACTS devices for some of the common issues in a power system is given in Table 2.1.

Table 2.1 Application of FACTS devices

ISSUE	DEVICE
Steady state voltage control	SVC
Dynamic and post contingency voltage control	SVC, STATCOM
Transient Stability Improvement	SVC
Power Oscillation Damping	SVC, TCSC
Power Quality Improvement	SVC, STATCOM
Sub-synchronous resonance mitigation	TCSC

2.8 Summary

This chapter discussed the terms and definitions of the Flexible Alternating Current Transmission Systems (FACTS) devices. The principles of operation, configuration and control methodology of devices such as TCSC, SSSC, SVC, STATCOM, and UPFC had been discussed. The performance of the transmission lines of power system has been increased by the implementation of FACTS devices. Prior to their era, the capacity of transmission lines was increased by traditional compensation technique. Based on the controllers or converters employed, the FACTS devices can regulate voltage, impedance and phase angle or to control the real and reactive power flow. FACTS devices are capable of enhancing the operation of the power system and thus the power system can withstand any unexpected faults or contingencies and future expansion or modifications in the power system.

Chapter 3
Midpoint Reactive Power Compensation

3.1 Introduction

Very large majority of the transmission line in any power network are AC lines. The power transferred by these lines may vary due to many physical constraints such as the line itself or the load or the source. The type of load connected to a power system can alter the power quality. Depending upon whether the load is resistive or inductive or capacitive, it will absorb either real power or reactive power or both. Typically, most of the loads used are inductive loads which need reactive power in addition to the real power. Due to this, it is very important to plan for the reactive power supply, and also the transmission network to operate within the desired voltage limits. One of the many techniques to make it possible is by making up or taking away the reactive power in the power system, called reactive-power control. This chapter presents an overview of the reactive power in power systems, how it affects the power system and provides the methods of reactive power compensation.

3.2 Reactive power in power systems

The energy which flows across the transmission lines in the power system is called 'Power'. Power is usually measured in the units called 'watts'. The term power normally denotes 'Real Power'. In ac transmission, when the voltage and current are not in phase, there is another component called 'reactive power' or 'imaginary power' in power systems [6]. Reactive power refers to the power in the power system which does no useful work but needed to maintain the voltage to deliver the real power. The reactive power appears when the voltage and the current waveforms are not in phase. The reactive power is measured in terms of 'volt-ampere reactive'. The angle between the voltage and current waveforms is termed as phase angle δ. This gives rise to another phenomenon called "Power Factor". The power factor is the ratio of real power to the apparent power. Apparent power is the combination of real power and reactive power which is measured in terms of 'volt-amperes'. The phase angle is positive, when the current lags voltage, which is called the lagging power factor. This mainly occurs due to the inductive loads. The phase angle is negative when the current leads voltage, which is called the leading power factor. This mainly occurs due to capacitive loads. Since reactive power doesn't travel far, it becomes necessary to produce the reactive power wherever it is needed. This is one of the reasons for the compensation devices connected at the load or where it is most needed [25].

3.3 Basics of power transmission

The basics of power transmission in a simple system are shown below:

Figure 3.1 Model of a simple transmission system

Figure 3.1 shows a simplified power transmission system with two buses which are connected to each other by a transmission line, which is assumed lossless and has only a reactance X. V1∟δ and V2∟0 represent the sending end and receiving end voltages with phase angle δ. P2 and Q2 represent the active and reactive power at the receiving end.

The current in the transmission line can be written as:

$$I = \frac{V_1(\cos\delta + j\sin\delta) - V_2}{jX} \tag{3.1}$$

The complex power at the receiving end is:

$$S_2 = P_2 + jQ_2 = V_2.I^* = V_2\left(\frac{V_1(\cos\delta + j\sin\delta) - V_2}{jX}\right)^* = \frac{V_1 V_2}{X}\sin\delta + j\left(\frac{V_1 V_2\cos\delta - V_2^2}{X}\right) \tag{3.2}$$

The active power and reactive power at the load are:

$$P_2 = \frac{V_1 V_2}{X}\sin\delta = P_{max}\sin\delta;\ Q_2 = \frac{V_1 V_2\cos\delta - V_2^2}{X} \tag{3.3}$$

The complex power at the sending is:

$$S_1 = P_1 + jQ_1 = V_1.I^* = V_1.\left(\frac{V_1(\cos\delta + j\sin\delta) - V_2}{jX}\right)^* = \frac{V_1 V_2}{X}\sin\delta + j\left(\frac{V_1{}^2 - V_1 V_2 \cos\delta}{X}\right) \tag{3.4}$$

The active power and reactive power at the sending end are:

$$P_1 = \frac{V_1 V_2}{X}\sin\delta = P_{max}\sin\delta;\ Q_1 = \frac{V_1{}^2 - V_1 V_2 \cos\delta}{X} \tag{3.5}$$

From Equations (3.3) and (3.5), active power at both the ends is same, since the line is considered lossless. Active power can reach its maximum when δ = 90̊. Reactive power mainly depends on the voltage magnitudes and it always flows from the highest to lowest voltage bus.

3.3.1 Case study: Simple 2-bus system

To know more about the reactive power transmission, the following case study is analyzed. Case 1 analyzes a lossless two bus system with base values (100 MVA and 230 kV). The load is 265 MW + j80 MVAR.

It is assumed that the source voltage is 1.0 per unit at zero degree phase angle (230 kV line-line). The reactance (X) and shunt charging (B) of the transmission lines are given in the values of 0.15 and 2.5 p.u. respectively. This is illustrated as PI-model of a transmission line in Figure 3.2. The PI model represents the impedance parameters of the transmission line under study. As the line discussed here is lossless, the line resistance (R) and shunt conductance (G) values are zero.

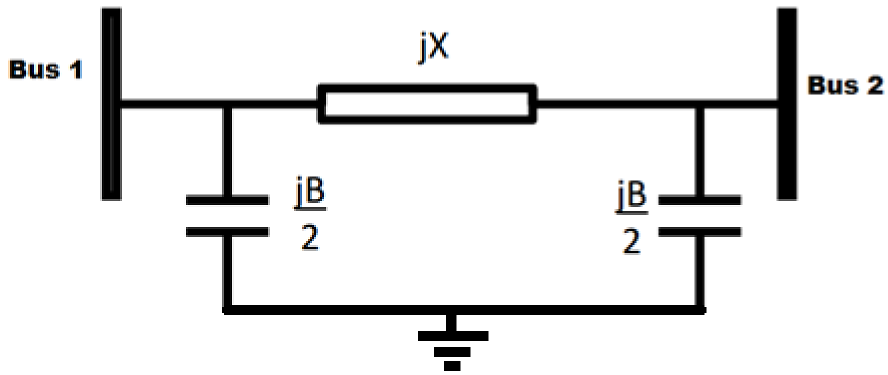

Figure 3.2 PI model of a transmission line

PowerWorld simulator [26] is used for analyzing all the case studies in this chapter.

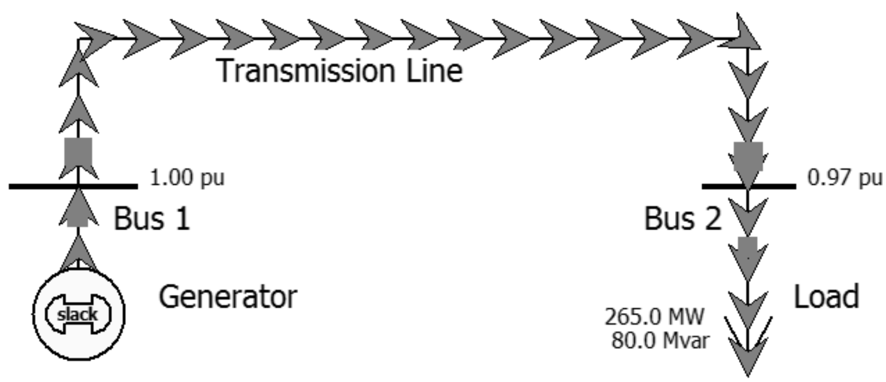

Figure 3.3 One line diagram of a simple 2-bus power system

When analyzing this case, for the given transmission line parameters and the load, the voltage at the receiving end drops to 0.97p.u. In this particular case (load), it doesn't make any huge impact in the power system, as 0.95 to 1.05 p.u voltage is usually considered normal. But if the load voltage magnitude is to be maintained at 0.99 p.u, alternate compensation methods need to be considered. The load in the system (265 MW + j 80 MVar) is varied gradually from no load to full load in equal intervals from 0 to 1 (1 corresponds to 80 MVar). The variation in the voltage magnitude in the receiving end is given in Table 3.1 below.

Table 3.1 Load vs Load Voltage

Steps	Real Power (MW)	Reactive Power (Mvar)	Load Voltage (p.u)
0	0	0	1.23
0.1	26.5	8	1.22
0.2	53	16	1.2
0.3	79.5	24	1.19
0.4	106	32	1.17
0.5	132.5	40	1.15
0.6	159	48	1.12
0.7	185.5	56	1.1
0.8	212	64	1.06
0.9	238.5	72	1.02
1	265	80	0.97

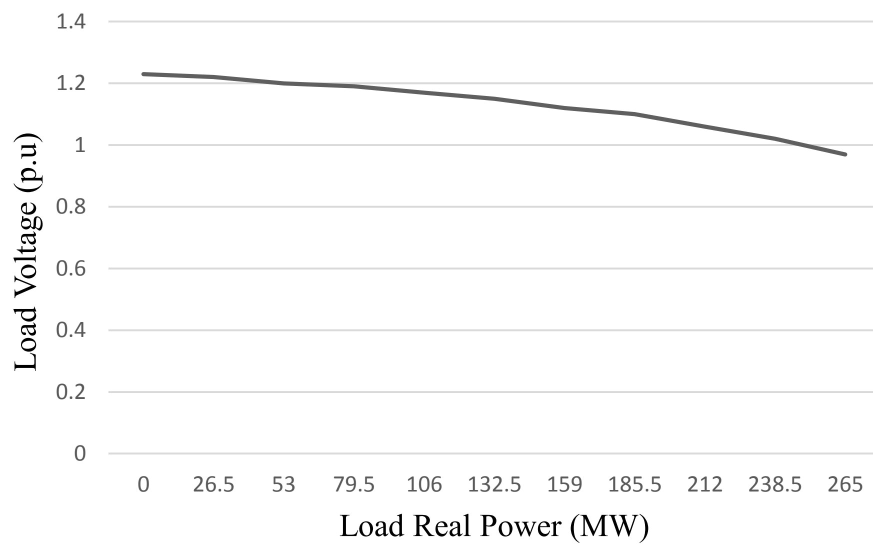

Figure 3.4 Load real power vs. Receiving end load voltage

When load increases, the voltage magnitude decreases gradually in the receiving end as shown in Figure 3.4. Also when the load increases, the reactive power generated from the sending end is not adequate to meet the reactive power need at the load end due to the reactive power absorbed by the transmission line. From the PowerWorld simulation, it is identified that for this case, at 251.75 MW + j 84 MVar, the voltage magnitude at the receiving end is maintained at 1.0 p.u.

3.4 Compensation of reactive power in the power system

Reactive power compensation is the technique or practice used to control the reactive power circulation in the power system. It can be done by either absorbing or injecting the reactive power where needed. This thesis inspects various compensation methods which can be used to supply the reactive power at the load or wherever it is needed the most. As shown in Section 3.2, the increase in reactive power at the load end deteriorates the power transmission and voltage magnitude at the load end. In this chapter, shunt compensation technique is analyzed, although there are various other methods being used for reactive power compensation. If the reactive power is not properly controlled, it can lead to many issues in the voltage magnitude, efficiency and quality of the power system.

The reactive power compensation is most sought after to utilize the existing transmission networks to their full potential by minimizing the reactive power losses in the transmission line. The main objective of reactive power compensation is to maintain the voltage within acceptable working limits.

3.4.1 Case study: Shunt reactive power compensation in 2-bus system

Case study 2 proposes the shunt compensation at the load bus. As shown in the case study 1, to operate the power system in the desired voltage magnitude of 1.0 p.u, it should be operated in the 251.75 MW + j 76 Mvar load. But it is not possible for any power system to operate in the same load condition always. Thus when load increases or decreases, there should be a compensating source at the load. It can be either a simple shunt capacitor, synchronous condenser or any sophisticated FACTS device.

For example, in the previous case study 1, when the load is increased to 278.3 MW + j 84 MVar the receiving end voltage drops to 0.94 p.u . In this case study 2, as shown in Figure 3.5, a generator which is assumed to supply only the reactive power is added at the load end. The transmission line has an equivalent reactance of 0.15 p.u. and a shunt charging of 2.5 p.u. This generator arrangement can supply the reactive power 20 Mvar to compensate and so the load voltage magnitude to 1.0 p.u.

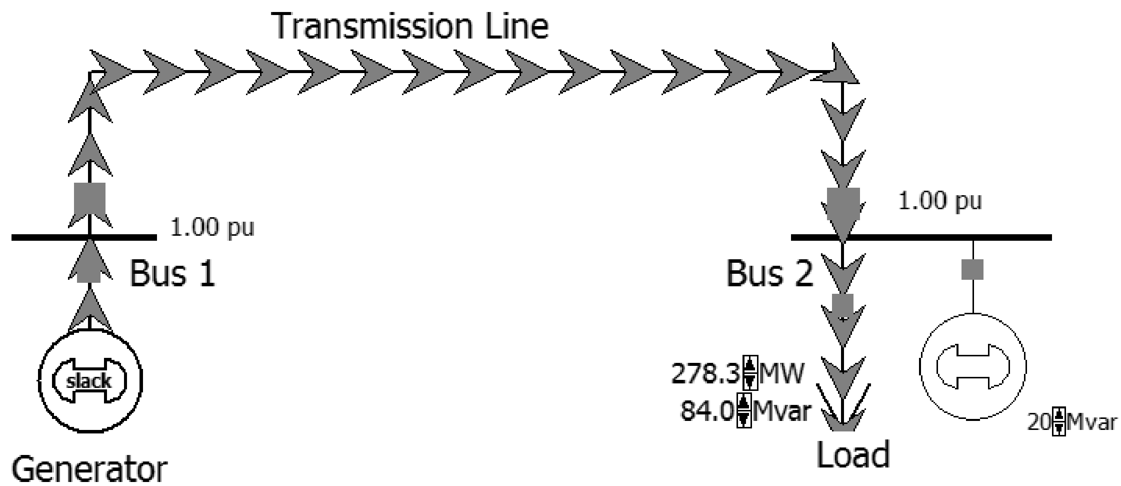

Figure 3.5 One line diagram of simple power system with VAR compensation

The load condition is varied in steps of 0 to 1.0. The var generator arrangement injected reactive power in the system to maintain the magnitudes of sending end voltage (V_S) and receiving end voltage (V_R) at 1.0 p.u. ($|V_s| = |V_R| = 1.0$ p.u.). The result is analyzed and tabulated in Table 3.2. Load voltage is maintained at 1.0 p.u for all cases.

Table 3.2 Compensated reactive power and change in phase angle

Steps	Load real power (MW)	Load reactive power (Mvar)	Reactive power compensated by the reactive power source at Load (Mvar)	Phase Angle δ (degrees)
1	265	80	10	23.42
1.1	291.5	88	30	25.93
1.2	318	96	52	28.49
1.3	344.5	104	75	31.11
1.4	371	112	100	33.81
1.5	397.5	120	126	36.6
1.6	424	128	155	39.49
1.7	450.5	136	186	42.51
1.8	477	144	220	45.68
1.9	503.5	152	257	49.05
2	530	160	297	52.66

From Table 3.2, it can be observed that the compensated reactive power had increased drastically to meet the increase in the reactive power demand (due to increased load) and maintains the load voltage magnitude to 1.0 p.u. The plot between real power increase and the required reactive power for compensation is as shown in Figure 3.6 below.

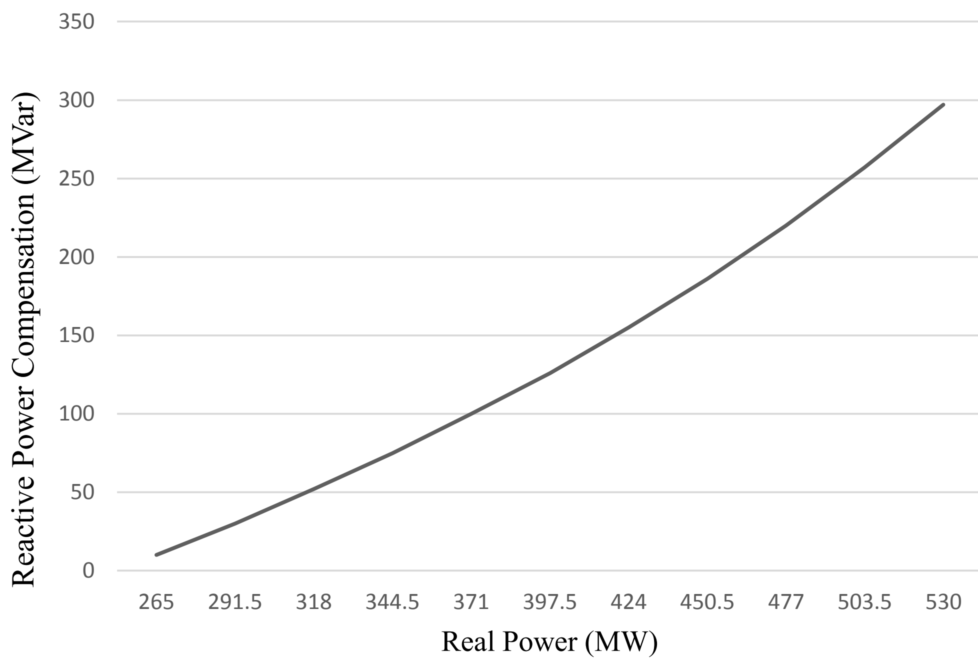

Figure 3.6 Load increase vs. compensation needed

When a large power of 530 MW is needed, a huge amount of reactive power (297 MVar) is needed to compensate at the load end. For this case, 274.5 MVar is supplied into the system for the reactive power requirements of the transmission line. Thus this external supply of reactive power helps the power system to work in acceptable voltage limits and additional load demands can be met without depending on the generator alone for the reactive power supply. Thus, the reactive power compensation directly benefits the power system. From the PowerWorld simulation, it was observed that at 90˚ the power transfer is maximum, which is around 689 MW of real power.

3.5 Midpoint Compensation

The magnitude of the midpoint voltage depends on power transfer. Usually voltage at the midpoint will be comparatively higher than the sending and receiving end of the lines. For increase in the power transfer, midpoint voltage level increases too. This voltage influences the insulation of the transmission line. A symmetrical line is said to be the one in which the end voltages (sending and receiving end) are held at nominal values. In this symmetrical line, the midpoint voltage shows the highest magnitude variation [7].

The voltage at the receiving end of the line is given as,

$$V_r = V_m \cos\frac{\beta a}{2} - jZ_0 I_m \sin\frac{\beta a}{2} \qquad (3.6)$$

where

V_r = voltage at the receiving end;

V_m = voltage at the midpoint of the line;

I_m = current at the midpoint of the line;

Z_0 = surge impedance or characteristic impedance

$\beta = \omega\sqrt{(lc)}$ rad/km = the wave number;

$\beta * a = \omega\sqrt{(lc)}a$ rad = electrical length for a line of ‘a’ kms

l = line inductance (H/km)

c = line capacitance (F/km)

When the line is symmetrical and lossless, real power at the sending end, receiving end and the midpoint are equal, which is P, and the reactive power will be zero.

$$P_s = -P_r = P_m = P; \; Q_m = 0 \quad (3.7)$$

Current at the midpoint will be, $I_m = P / V_m$

From the above equations, the receiving end voltage is

$$V_r = V_m \cos\frac{\beta a}{2} - jZ_0 \frac{P}{V_m} \sin\frac{\beta a}{2} \quad (3.8)$$

$$V_r^2 = V_m^2 \cos^2\frac{\beta a}{2} + Z_0^2 \frac{P^2}{V_m^2} \sin^2\frac{\beta a}{2} \quad (3.9)$$

Setting $V_r = V_{nom}$ (nominal voltage) and $\frac{V_{nom}^2}{Z_0} = P_0$ (Surge Impedance Loading), we get

$$\frac{V_r^2}{V_{nom}^2} = \left(\frac{V_m}{V_{nom}}\right)^2 \cos^2\frac{\beta a}{2} + \left(\frac{Z_0}{V_{nom}^2}\right)^2 P^2 \left(\frac{V_{nom}}{V_m}\right)^2 \sin^2\frac{\beta a}{2} \quad (3.10)$$

If $V_m = V_{nom}$, (per unit voltage at mid-point), then considering that $(V_r/V_{nom}) = 1$,

$$V_m^4 - \frac{V_m^2}{\cos^2\frac{\beta a}{2}} + \left(\frac{P}{P_0}\right)^2 \tan^2\frac{\beta a}{2} = 0 \quad (3.11)$$

Therefore,

$$V = \left[\frac{1}{2\cos^2\frac{\beta a}{2}} \pm \sqrt{\left(\frac{1}{4\cos^2\frac{\beta a}{2}} - \left(\frac{P}{P_0}\right)^2 \tan^2\frac{\beta a}{2}\right)}\right]^{1/2} \quad (3.12)$$

Equation (3.12) determines the midpoint voltage of a symmetrical line as function of the power flow P on it. The values of line parameters ‘l’ and ‘c’ remain independent of the transmission voltage.

The line inductance values range from 0.78 to 0.98 mH/km and that of the line capacitance ranges from 12.1 to 15.3 nF/km. Based on these parameters, the surge impedance, $Z_0 = \sqrt{\frac{l}{c}}$, lies anywhere between 225 Ω to 285 Ω.

3.5.1 Case Study 3: Reactive power compensation of Hydro-Quebec system

In order to understand the effect of the reactive compensation on the voltage profile and in turn on the total power system, a 500 km 735 kV long transmission system is taken into consideration. The data of the power system is similar to the 735 kV Hydro-Quebec transmission system from James Bay to a substation close to Montreal. The line inductance is 0.932 mH/km and the line capacitance is 12.2 nF/km. An equivalent circuit modeled using PowerWorld software is shown in Figure 3.7. Bus-3 is inserted at the midpoint to show the position of midpoint in the transmission line.

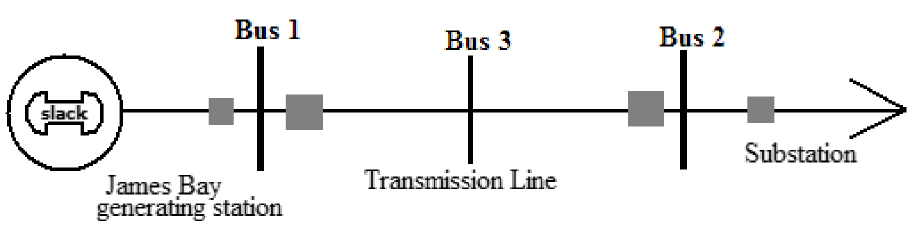

Figure 3.7 Hydro-Quebec model transmission system

A 1230 MW load at 0.95 power factor lag is taken as base load which is P + jQ = S (cos θ + j sin θ) = 1230 MW + j 404.28 MVAR

Line inductance, l = 0.932 mH/km; line capacitance, c = 12.2nF/km

Line impedance, z = jωL = 0.3514 Ω/km

Line admittance, y = jωC = 4.6 x 10^{-6} S/km

Characteristic impedance, Z_0 = 276.39 Ω

Wave number, β = 1.2714 x 10^{-3} radians/km

Electrical length of the line, βa = 0.509 radians

Surge impedance loading of the line, SIL = $(735k)^2$ / 276.39 = 1954.58 MW

Assuming there is no reactive power support in the system, mentioned in Figure 3.7, the receiving end voltage for various loads ranging from no load to SIL, with the sending end voltage in 1.0 per unit, is calculated and presented in Table 3.3 below.

Table 3.3 Power transfer vs receiving end voltage

k	Real Power (MW)	Reactive Power (MVAR)	V_r (pu)
0	0	0.00	1.24
0.1	123	40.43	1.23
0.2	246	80.86	1.22
0.3	369	121.28	1.2
0.4	492	161.71	1.18
0.5	615	202.14	1.16
0.6	738	242.57	1.14
0.7	861	283.00	1.11
0.8	984	323.42	1.08
0.9	1107	363.85	1.05
1	1230	404.28	1
1.1	1353	444.71	0.94

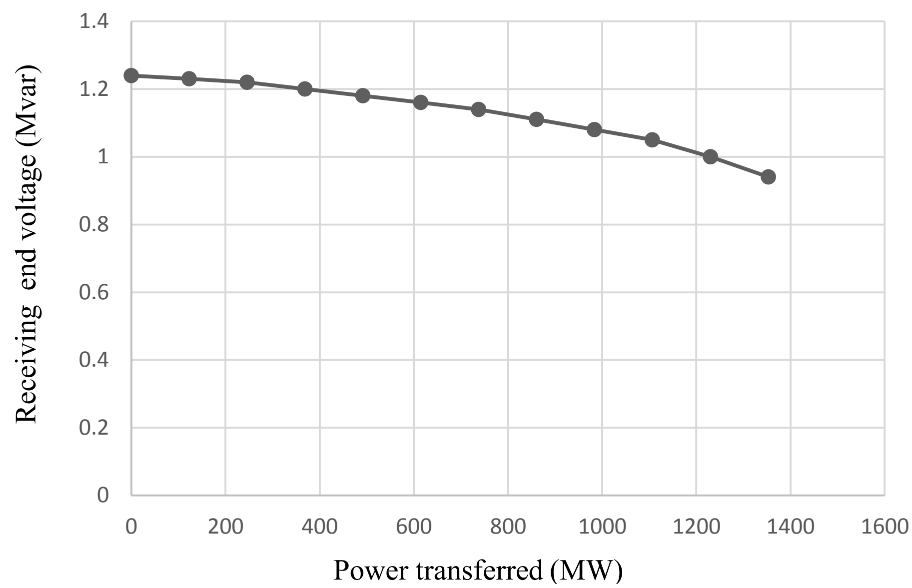

Figure 3.8 Power transferred vs receiving end voltage

The voltage characteristic at the load bus looks like the graph in Figure 3.8 for the increase in the load demand. From the PowerWorld simulation, when load increases the voltage at the load bus decreases. This is due to the fact that the generating station needs to satisfy the reactive power demands of the transmission line and the increasing demand of the load. Even though the current system can transmit around 1955 MW, the receiving end voltage drops below the desired 0.95 per unit value, immediately after 1350 MW. Effective reactive power compensation is needed to bring the load bus to 0.95 per unit. It is assumed that the load connected at the receiving end is of fixed power factor 0.95 lagging.

Figure 3.9 shows the difference in the reactive power absorbed by the system to the reactive power generated from the generating station. It is clear from the data that the difference grows larger for the increase in load demand. It will be difficult to maintain the receiving end voltage to the desired 1.0 per unit level without satisfying the reactive power requirement. It is important to bring the required additional reactive power to hold the receiving end voltage to 1 per unit (735 kV).

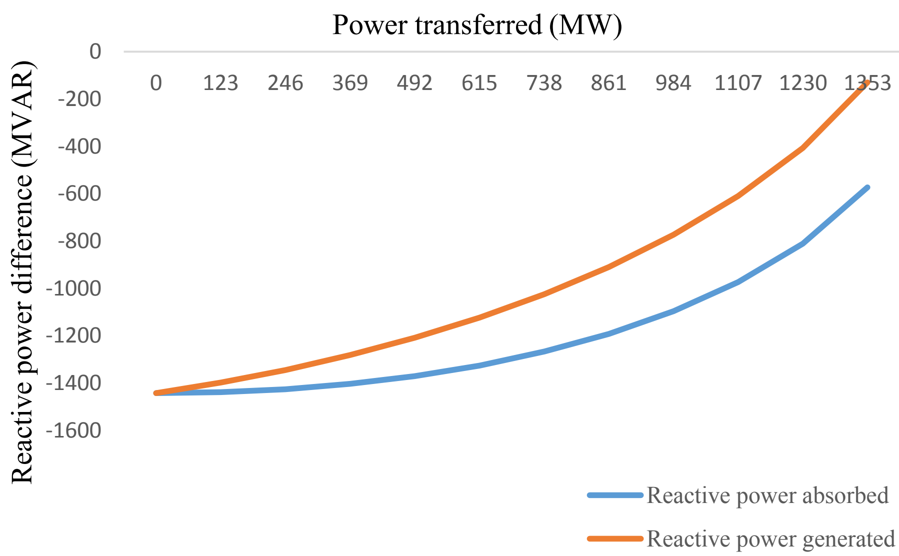

Figure 3.9 Lack of generated reactive power

For any load condition, the reactive power balance at the receiving end is,

$$Q_c = Q_r + Q_l \qquad (3.13)$$

Where Q_r = the reactive power flow from the receiving end into the line; Q_l = the reactive power of the load, and Q_c is the reactive power needed from the system to hold the receiving end voltage (V_r) in the rated value of 1.0 per unit. In this case, it is observed that at no load (P=0), approximately 1400 MVAR reactive power is needed in order to maintain the receiving end voltage at the rated value of 1.0 per unit. The receiving end of the power system is assumed to have a fixed power factor of 0.95.

3.5.1.1 Reactive power support using a VAR compensator

In real world scenario, there will be MVAR support to keep the power system stable. A *var compensator* is added to the load bus to provide the needed reactive power. A synchronous generator which supplies only reactive power is assumed to be the *var compensator* as shown in Figure 3.10 below.

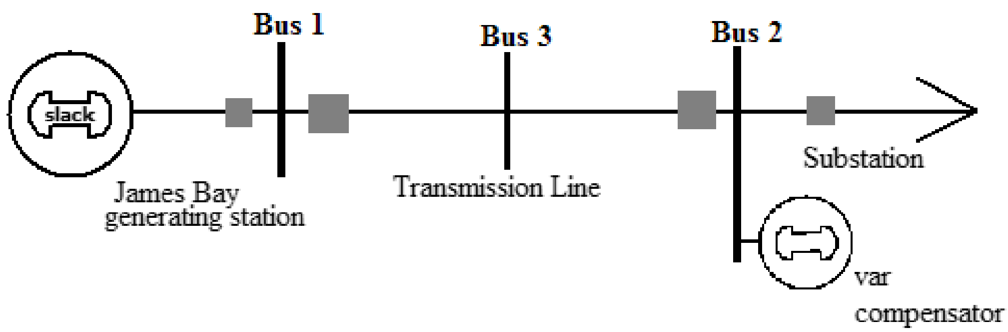

Figure 3.10 Synchronous generator as 'var' compensator

The load demand is increased gradually by small steps from the full load value of 1230 MW to 3321 MW. Using the PowerWorld simulator, the reactive power required to compensate the load demand and maintain the receiving end voltage at 1.0 per unit is determined. The phase angle difference (δ) between the generator bus and the load bus is also calculated. All the results achieved are tabulated in Table 3.4.

Table 3.4 Load demand increase vs Reactive power compensation

k	Real Power (MW)	Reactive Power (MVAR)	Compensated Reactive Power (MVAR)	Phase angle difference (degrees)
1	1230	404.28	0	21.94
1.1	1353	444.71	92.55	24.27
1.2	1476	485.14	191.52	26.64
1.3	1599	525.56	296.93	29.06
1.4	1722	565.99	409.24	31.54
1.5	1845	606.42	528.98	34.09
1.6	1968	646.85	656.82	36.71
1.7	2091	687.28	793.6	39.43
1.8	2214	727.70	940.38	42.26
1.9	2337	768.13	1098.54	45.23
2	2460	808.56	1269.91	48.35
2.1	2583	848.99	1457.04	51.69
2.2	2706	889.42	1663.61	55.29
2.3	2829	929.84	1895.39	59.25
2.4	2952	970.27	2162.27	63.73
2.5	3075	1010.70	2484.44	69.08
2.6	3198	1051.13	2919.16	76.28
2.7	3321	1091.56	3787.41	90

There is a steep increase in the external reactive power supply to compensate the gradual increase in load, in order to maintain the voltage magnitude at 1.0 per unit. The graph of compensated reactive power versus the power transfer is plotted and is as shown in Figure 3.11 below.

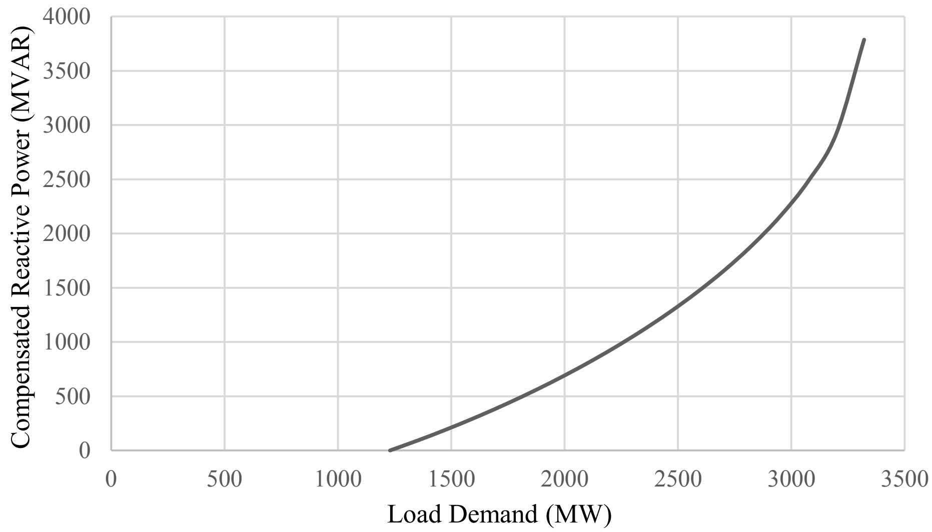

Figure 3.11 Load demand vs. Compensated reactive power

From Figure 3.11, it can be noticed that initially at the full load 1230 MW there is no reactive power compensation. In order to achieve a stable voltage magnitude at load bus, during the steady increase in load demand, reactive power compensation is required. For a maximum of 3321 MW power transfer, 3787 MVAR reactive power is required, while the reactive power generated by the sending end is utilized to satisfy the reactive power requirements of the transmission line. Because of this 'var' compensation, the system was able to perform the power transfer without any need to change the generator or transmission line configurations. So, it is understood that the reactive power compensation has a direct impact on the voltage stability and efficient power transfer of the power system. Also, the increase in reactive power requirement is linear with respect to increase in the load demand only until certain load level, after which the reactive power requirement increases exponentially.

The graph of the phase angle difference between the sending end and receiving end versus the real power transferred is provided in Figure 3.12 below.

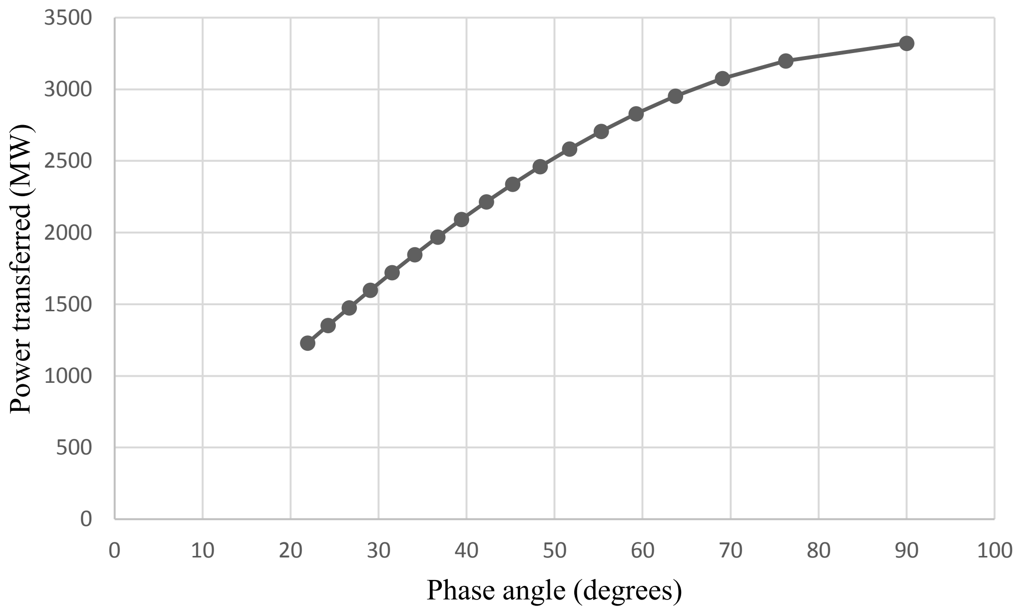

Figure 3.12 Phase angle vs. Load real power

This figure shows that the power transfer increases with the increase in load angle and the maximum power transfer occurs at 90° of the power angle. It is also observed that power transfer is comparatively easier when the phase angle is small and increasingly difficult when it is high. The aim of the reactive power compensation is to maintain the voltage stability at the load end of the power system while increasing the real power transfer.

3.5.1.2 Midpoint voltage magnitude

Voltage profile along the transmission line will be flat only when the load connected at the load bus is equal to surge impedance. Because, under that circumstance, there is no reactive power demand in the system. Usually in a real world scenario, loads are often varying and are barely predictable. So, attaining a flat voltage profile is not possible at all times. When the voltage magnitude at both ends are maintained at 1.0 per unit, the midpoint voltage increases or decreases based on the power. If power transfer is more than SIL, midpoint voltage decreases, as the line absorbs reactive power, and if it is less than SIL, midpoint voltage increases, as the line generates reactive power.

To observe the midpoint voltage variation, the voltage magnitudes at both the ends are maintained at 1.0 per unit, for the Hydro-Quebec system, and then analyzed using the PowerWorld simulator. (The voltage at the receiving end is maintained at 735 kV by using a synchronous generator as a var compensator). The observations are given in Table 3.5.

Table 3.5 Midpoint voltage variation

k	Real Power (MW)	Reactive Power (MVAR)	Midpoint Voltage, Vm (p.u.)
0	0	0.00	1.05
0.1	123	40.43	1.05
0.2	246	80.86	1.05
0.3	369	121.28	1.05
0.4	492	161.71	1.05
0.5	615	202.14	1.05
0.6	738	242.57	1.05
0.7	861	283.00	1.04
0.8	984	323.42	1.04
0.9	1107	363.85	1.04
1	1230	404.28	1.03
1.1	1353	444.71	1.03
1.2	1476	485.14	1.02
1.3	1599	525.56	1.02
1.4	1722	565.99	1.01
1.5	1845	606.42	1.01
1.6	1968	646.85	1
1.7	2091	687.28	0.99
1.8	2214	727.70	0.98
1.9	2337	768.13	0.97
2	2460	808.56	0.96
2.1	2583	848.99	0.95
2.2	2706	889.42	0.93
2.3	2829	929.84	0.92
2.4	2952	970.27	0.89
2.5	3075	1010.70	0.87
2.6	3198	1051.13	0.83
2.7	3321	1091.56	0.75

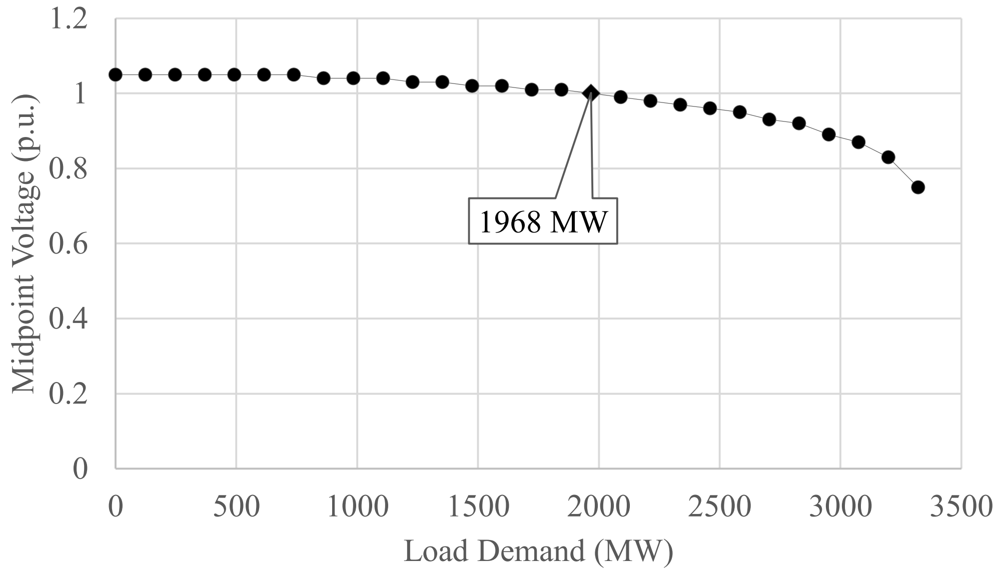

Figure 3.13 Variation of midpoint voltage

From Table 3.11 and Figure 3.13, it is observed that the voltage magnitude of the midpoint is always more than 1.0 per unit from no load to SIL. After SIL, which is 1954 MW in this case, the voltage profile drops below 1.0 per unit steeply, particularly more than 3000MW. The reactive power flow from the load end, Qr, and the reactive power needed by the system for compensation, Qc, for various load demands are presented in Table 3.6 below.

Table 3.6 Reactive power demand vs supply

Real Power (P/P_0)	Load Reactive Power (Ql/P_0)	Reactive power flow from load end (Qr/P_0)	Reactive power needed for compensation (Qc/P_0)
0.000	0.000	-0.329	-0.329
0.063	0.021	-0.328	-0.307
0.126	0.041	-0.324	-0.283
0.189	0.062	-0.318	-0.256
0.252	0.083	-0.310	-0.227
0.315	0.103	-0.299	-0.196
0.378	0.124	-0.286	-0.162
0.441	0.145	-0.270	-0.126
0.503	0.165	-0.252	-0.087
0.566	0.186	-0.231	-0.045
0.629	0.207	-0.207	0.000
0.692	0.228	-0.180	0.047
0.755	0.248	-0.150	0.098
0.818	0.269	-0.117	0.152
0.881	0.290	-0.080	0.209
0.944	0.310	-0.040	0.271
1.007	0.331	0.005	0.336
1.070	0.352	0.054	0.406
1.133	0.372	0.109	0.481
1.196	0.393	0.169	0.562
1.259	0.414	0.236	0.650
1.322	0.434	0.311	0.745
1.384	0.455	0.396	0.851
1.447	0.476	0.494	0.970
1.510	0.496	0.610	1.106
1.573	0.517	0.754	1.271
1.636	0.538	0.956	1.493
1.699	0.558	1.379	1.938

Figure 3.14 shows Q_r/P_0, Q_l/P_0 and Q_c/P_0 as functions of P/P0. It is observed that at no load, 0.329 per unit reactive power must be absorbed to maintain the load voltage at 1.0 per unit. It can be seen from Figure 3.14 that, for more load demand, more Q_c needs to be supplied. MATLAB simulator [27] is used to plot the following figures.

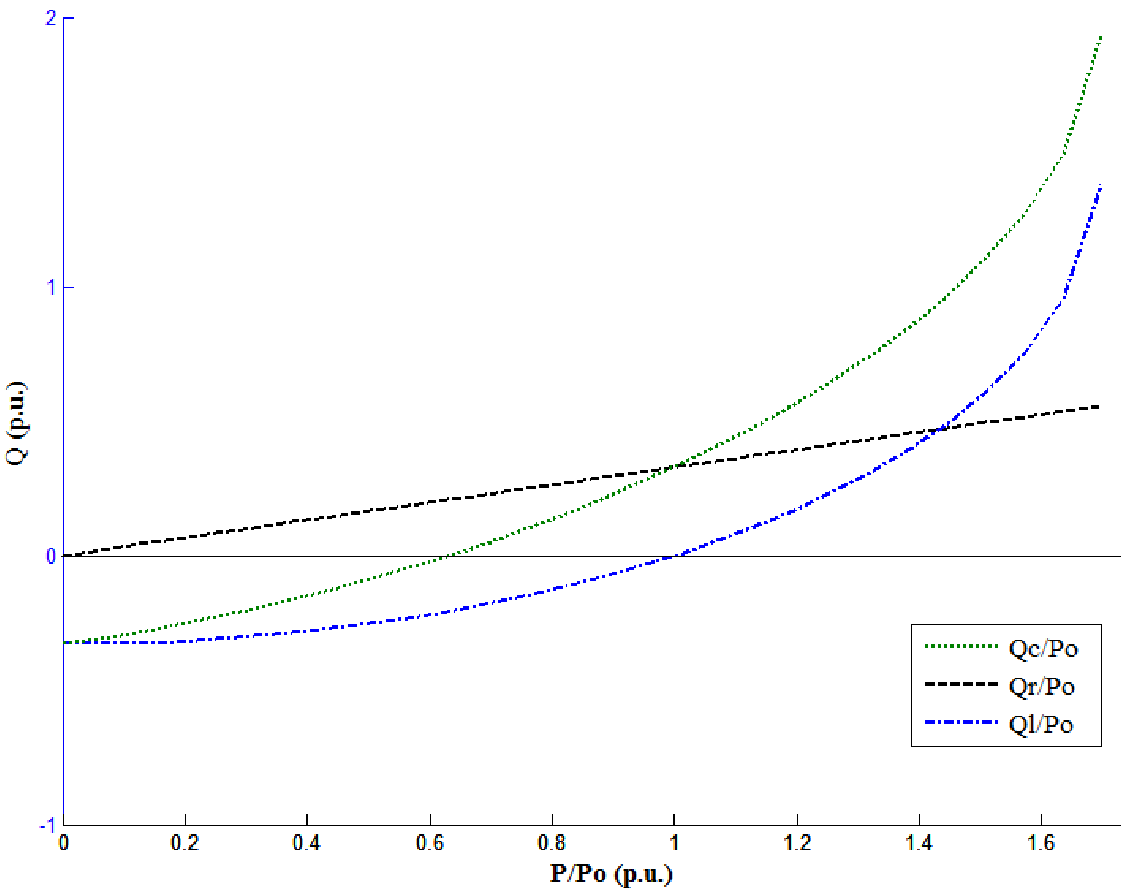

Figure 3.14 Reactive power flows at the receiving end

Figure 3.15 shows the midpoint voltage (V_m) and the load angle (δ) as functions of the power transfer per unit (P/P_0). During light load conditions, that is below the surge impedance loading, midpoint voltage is more than the nominal voltage and it is highest at no load.

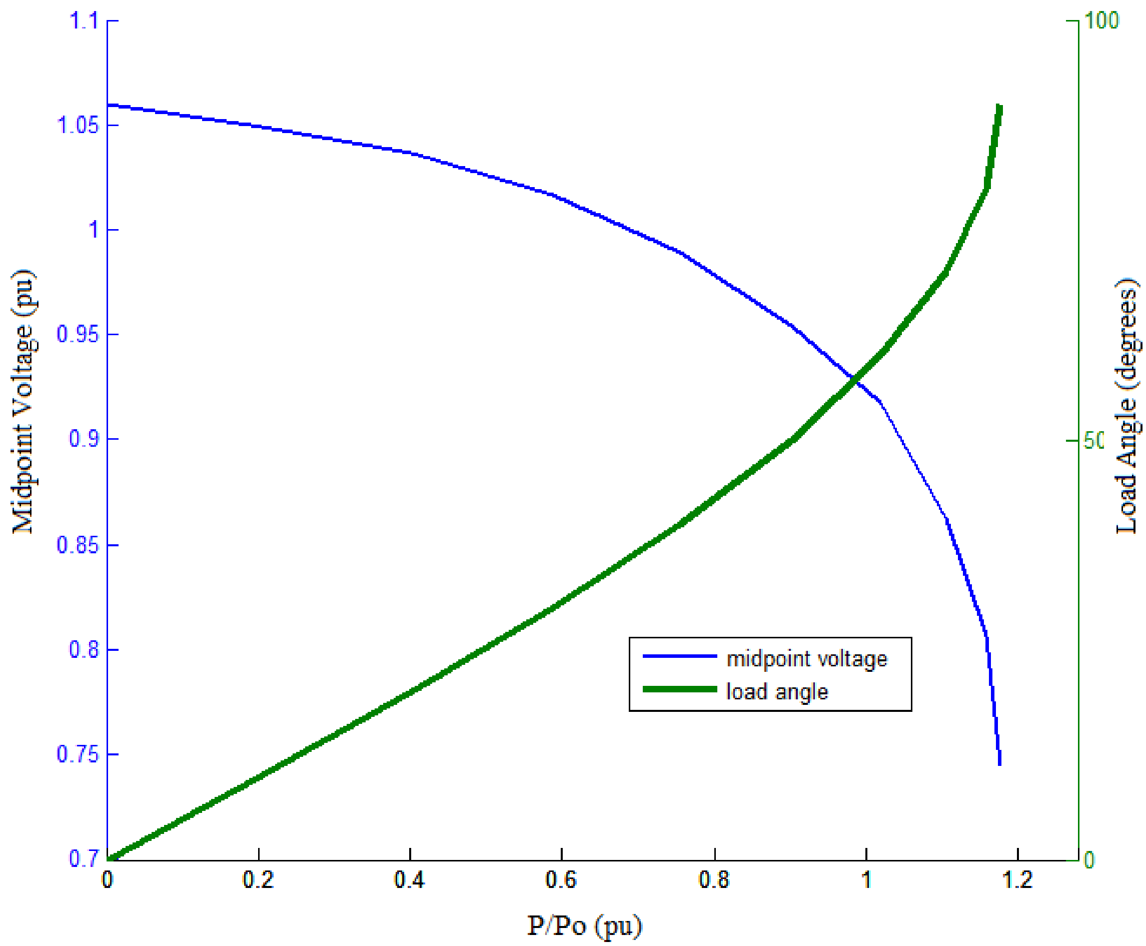

Figure 3.15 Midpoint voltage and load angle as functions of P/Po

If the system is operating at a load angle of say 30° during the full load rating (0.588 P_0), the midpoint voltage of the line will be at 1.0169 per unit. Though, from no load to full load the midpoint voltages are not within the desired limits, it is possible to control the overvoltage, by connecting a controllable reactive power source as a var compensator at the midpoint voltage bus.

Figure 3.16 shows the var compensator added at the midpoint of the line to control the voltage profile.

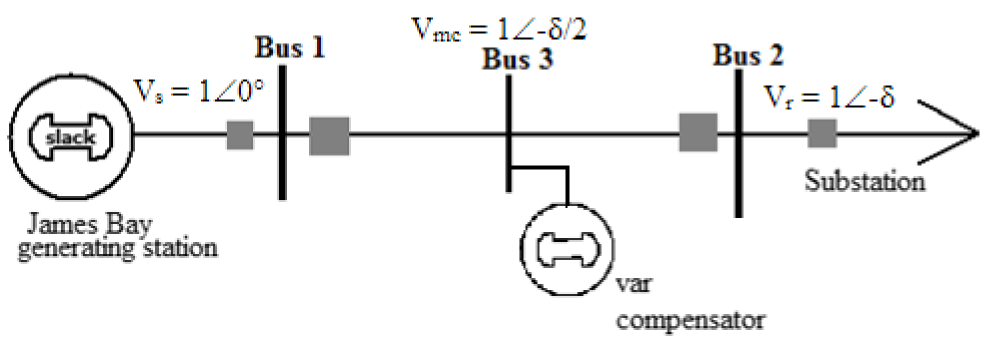

Figure 3.16 Midpoint control

Considering the high voltage magnitude at the midpoint, in order to observe the difference in power transfer and the voltage stability of the system, it is assumed that there is unlimited reactive power compensation, at the midpoint of the system, instead of the load end. Practically it is not always possible to install var compensators in the domestic customers' premises.

3.5.1.3 Midpoint 'var' compensator design

In this case study, it is desired to hold the midpoint voltage at V_{mc} at any load condition using the var compensator of unlimited capacity. From Equation (3.4),

$$Q_m = \left(\frac{V_{mc}{}^2 \cos\frac{\beta a}{2} - V_s V_{mc} \cos\frac{\delta}{2}}{Z_0 \sin\frac{\beta a}{2}} \right) \tag{3.14}$$

where Q_m = reactive power at midpoint;

V_s = voltage at sending end;

V_{mc} = voltage at the midpoint;

Z_0 = surge impedance;

βa = electrical length of an a-km line;

δ = phase angle difference

So the reactive power required at midpoint will be

$$Q_v = 2Q_m \tag{3.15}$$

Then the power transfer of the line will be

$$P_{comp} = \left(\frac{V_s V_{mc} \sin\frac{\delta}{2}}{Z_0 \sin\frac{\beta a}{2}} \right) \tag{3.16}$$

For the 735kV, 500 km line with $\beta = 1.2714 \times 10^{-3}$ radians/km, the sending end and receiving end voltages are assumed to be 1.0 per unit; and then the midpoint voltage at 1.03 per unit, Then βa =1.017 radians; $\beta a/2$ =0.5085 radians and P_{comp}= 3.296 $P_0 \sin(\delta/2)$ and;

$Q_v = 2Q_m = (\ 6.45 - 6.59 \cos(\delta/2)\ ) P_0$

From these data, P_s, P_{comp}, Q_v, for different load angles are observed and their relation is as show in Figure 3.17 below.

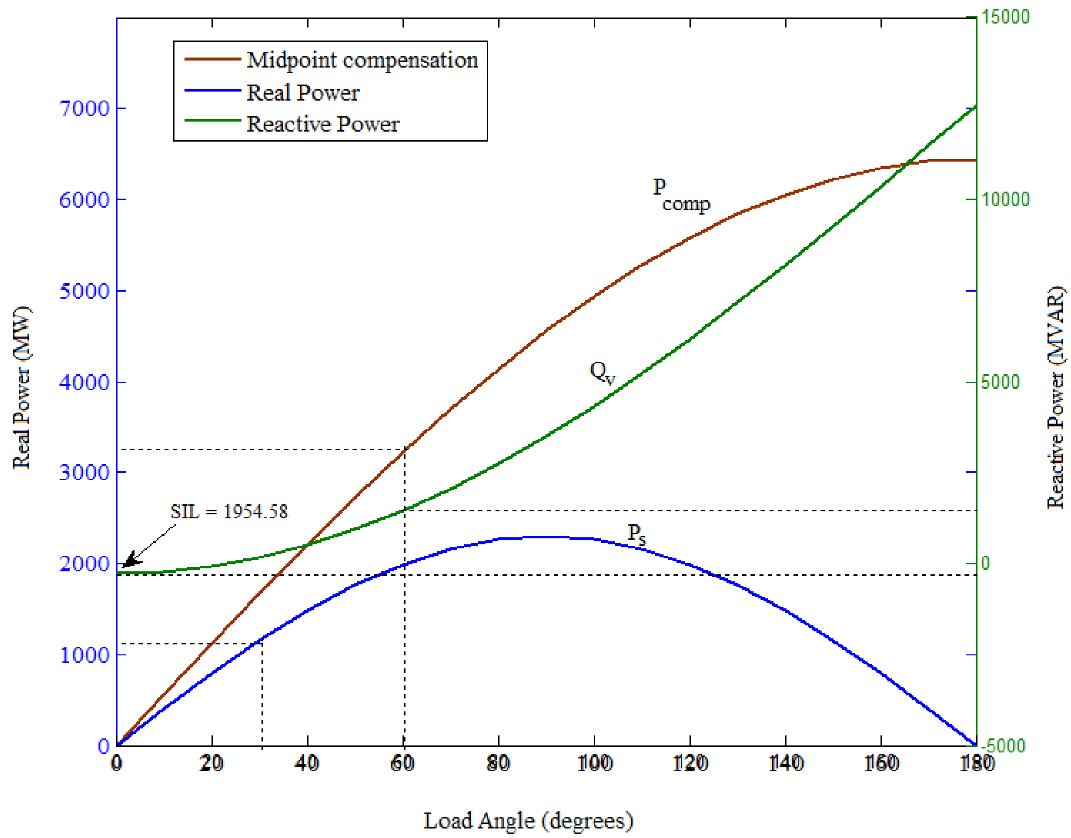

Figure 3.17 Relationship between active power, reactive power and load angle

From this figure, the results interpreted are: If the 735kV line is provided with unlimited reactive power compensation at the midpoint to maintain the midpoint voltage at 1.03 per unit, the maximum power transfer increases from 2297.97 MW to 6441.76MW. The nominal rating for this line could be 2203.41 MW (or 112% of SIL) for $\delta = 40°$. To maintain the midpoint voltage at 1.03 per unit, the var supply ranges from -278.2 MVAR to 12605.33 MVAR, which is very large for a line of SIL = 1954.58 MW.

To get a reasonable solution, the line was assumed to have a $\delta = 40°$ to provide a stable operation. P_{comp} at that rating is 2203.21 MW with a nominal rating of 1.12 P_0. The reactive power supplied at the midpoint is Q_v = 498.77 MVAR for $\delta = 40°$. From this it will be realistic to operate the var compensator from -250 MVAR to 500 MVAR.

The performance of the line when the midpoint compensator is operated in a controllable range is analysed. After the limit 500MVAR, the compensator behaves like a fixed capacitor of reactance $X_c = 1146.25\Omega$. In the uncontrolled range, the midpoint voltage V_m=805.717 cos $\delta/2$ or 1.09 V_{nom} cos $\delta/2$. From this value of the midpoint voltage, the power flow in the line is calculated as P = 6855.87 sin δ. The var compensator reaches its capacitive limit after the 500 MVAR rating, which is Q_v = 12605.33-12883.53 cos ($\delta/2$) = 500 or $\delta = 40.03°$.

In the same way, below the limit -250 MVAR, the compensator behaves like a fixed inductor $X_l = 2292.5\Omega$. In the uncontrolled range, the midpoint voltage V_m=758.71 cos $\delta/2$ or 1.03 V_{nom} cos $\delta/2$. From this value of the midpoint voltage, the power flow in the line is calculated as P = 3227.94 sin δ. After that, the inductive limit of the var compensator will be reached, which is Q_v = 12605.33-12883.53 cos ($\delta/2$) = -250 or $\delta = 7.58°$.

3.6 Summary

In this chapter, the basic difficulties incurred due to the reactive power transmission across the system have been discussed. The adverse effects of reactive power in a power system are explained through studies presented. A simple 2-bus system is used to show the issues in the power system, related to reactive power. Various compensation techniques were analyzed and presented. Shunt compensation technique which is widely used for reactive power compensation is inspected for the case study and the results are presented.

It is important to compensate the reactive power demand in the system as it adversely affects the power system. If not there is danger of blackouts or voltage instability. In this chapter, the usage of 'var' compensators at the load bus and midpoint for compensation of reactive power is discussed. The Hydro-Quebec case is presented to show the effects of reactive power in large systems.

It is understood that midpoint of a long transmission line has high voltage magnitude and increases steadily with the increase in load demand. As this may adversely affect the insulation of the line and the stability of the system, midpoint compensation technique is studied. This technique is identified to be an effective solution to curb reactive power demands locally and maintain a steady voltage profile throughout the system.

Chapter 4

Application of Thyristor Controlled Reactor (TCR) and Thyristor Controlled Series Capacitor (TCSC) in Reactive Power Compensation

4.1 Introduction

The power transfer in large power system networks is more complex. Any problems arising in those systems are equally complex. Power system engineers constantly devise many new technologies to solve the problems. Before implementing a solution to a power system problem or a new modification to enhance the power system, various factors, devices or techniques need to be considered. This chapter presents the Thyristor Controlled Reactor (TCR) and the Thyristor Controlled Series Capacitor (TCSC) and their applications in solving such a problem. A power system case is modeled in PSCAD software to test the system.

4.2 Thyristor Controlled Reactor

A Thyristor Controlled Reactor (TCR) belongs to the category of FACTS devices. When connected across a series capacitor in the power system, the capacitor can be varied for different conditions. Before studying the Thyristor Controlled Series Capacitor (TCSC), it is important to analyze the functions of a TCR. A TCR can function like a variable shunt reactance, where current is injected into the system at the point of connection with a transmission line. To control the reactive power, current is injected in phase quadrature to the line voltage. The triggering delay angle is adjusted to control the conduction of the thyristor valve. For different values of the delay angle the effective reactance of a TCR is varied continuously. Thyristors are power electronic devices, which operate as bi-stable switches, operating from non-conducting state to conducting state. By varying the delay or firing angle of the thyristors, the output voltages of the thyristor can be controlled. TCRs can be used to limit voltages under lightly loaded conditions [28, 29].

In this chapter, a single-phase TCR is constructed using Power Systems Computer Aided Design (PSCAD) [30] software. PSCAD is a graphical Unix-based user interface, which consists of the software which enables the user to create a circuit graphically.

4.2.1 The Single Phase TCR

A TCR is a shunt-connected, thyristor controlled inductor whose effective reactance is varied in a continuous manner by partial-conduction control of the thyristor valve. In TCR, the conduction time, and hence the current in a shunt reactor is controlled by a thyristor-based ac switch with firing angle control.

A basic single-phase TCR is shown in Figure 4.1. It consists of a fixed reactor of inductance L, and a bi-directional thyristor valve. Usually large thyristors can block voltage levels of 4kV to 9kV and conduct current from 3kA to 6kA. Many thyristors can be connected in series to block the voltage levels at high power ratings [31]. The controllable range of the TCR firing angle, α, extends from 90° to 180°. A firing angle of 90° results in full thyristor conduction with a continuous sinusoidal current flow in the TCR [1].

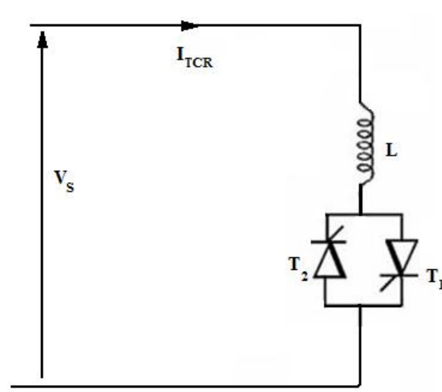

Figure 4.1The basic TCR model

Let the source voltage be,

$$\upsilon_s(t) = V \sin \omega t \tag{4.1}$$

Where V is the peak applied voltage and ω is the angular frequency of the supply voltage.

The TCR current when a thyristor conducts is given by

$$L\frac{di}{dt} - \upsilon_s(t) = 0 \tag{4.2}$$

Where L is the inductance of the TCR reactor

By integration,

$$i(t) = \frac{1}{L}\int \upsilon_s(t)\, dt + C \tag{4.3}$$

where C is the constant.

By substituting (4.1) in (4.3),

$$i(t) = -\frac{V}{\omega L}\cos \omega t + C \tag{4.4}$$

For the boundary value, $\omega t = \alpha$ (where α is the firing angle), i(t) = 0, $C = \frac{V}{\omega L}\cos \alpha$, and therefore,

$$i(t) = \frac{V}{\omega L}(\cos \alpha - \cos \omega t) \tag{4.5}$$

Using Fourier analysis, the fundamental component of the TCR current is obtained as,

$$I_1(\alpha) = \frac{V}{\omega L}\left(1 - \frac{2\alpha}{\pi} - \frac{1}{\pi}\sin 2\alpha\right) = V.B_{TCR}(\alpha) \tag{4.6}$$

where

$$B_{TCR}(\alpha) = B_{max}\left(1 - \frac{2\alpha}{\pi} - \frac{\sin 2\alpha}{\pi}\right) \tag{4.7}$$

and $B_{max} = 1/L\omega$

The variation of $B_{TCR}(\alpha)$ for the firing angle α, as per Equation (4.7), is given in Figure 4.2 below.

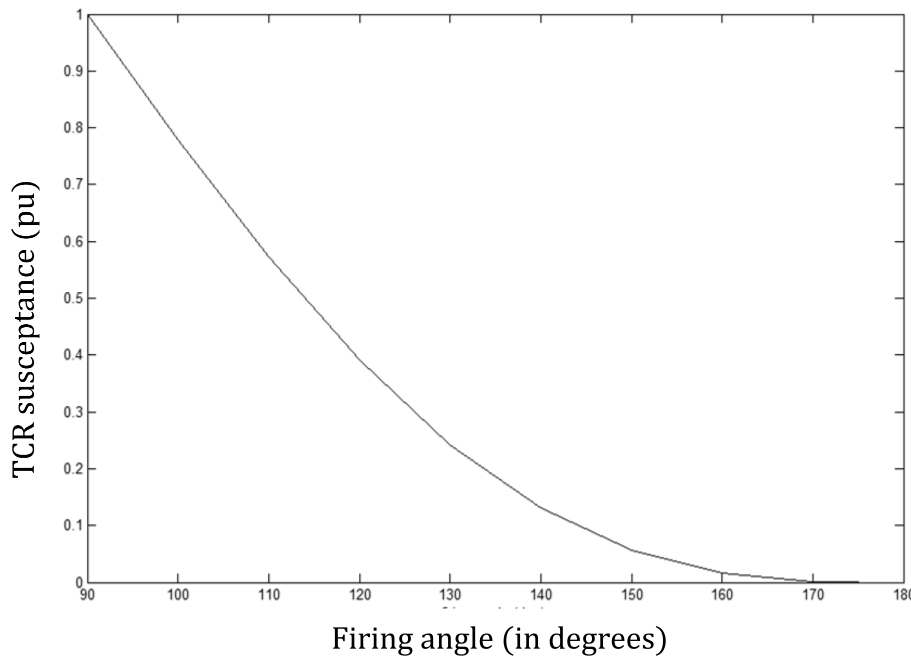

Figure 4.2 Control characteristics of TCR susceptance

The relation between the firing angle (α) and conduction angle (σ) is,

$$\alpha + \frac{\sigma}{2} = \pi \tag{4.8}$$

Thus, the fundamental component of the TCR with respect to (σ) is,

$$I_1(\sigma) = V.B_{max}\left(\frac{\sigma - \sin\sigma}{\pi}\right) = V.B_{TCR}(\sigma) \tag{4.9}$$

where $B_{TCR}(\sigma) = B_{max}\left(\frac{\sigma - \sin\sigma}{\pi}\right)$

By using fourier analysis, the rms values of the nth harmonic is obtained as,

$$I_n = \frac{4}{\pi} \frac{V}{\omega L} \left(\frac{\sin\alpha \cos(n\alpha) - n \cos\alpha \sin(n\alpha)}{n\,(n^2-1)} \right) \qquad (4.10)$$

Where n = 2k+1, k = 1, 2, 3….

The TCR acts like a variable susceptance. Variation of the firing angle changes the susceptance and consequently, the fundamental-current component, which leads to a variation of reactive power absorbed by the reactor [32].

The amplitude of the TCR current can be changed continuously by changing the thyristor firing angle, which can be varied anywhere between 90° and 180° [33]. By increasing the firing angle of the TCR gate pulses, the power losses in the thyristor controller and reactor decreases; however, it leads to the generation of harmonic currents [34].

4.2.2 TCR circuit modeled in PSCAD

The single phase TCR circuit was modeled in PSCAD. The circuit consists of a back-to-back thyristor with a series reactor connected to the equivalent voltage source. V_{as} is the source voltage, I_a, the line current, FP1 and FP2 are the firing pulses for thyristors T1 and T2 respectively. The circuit is as shown in Figure 4.3.

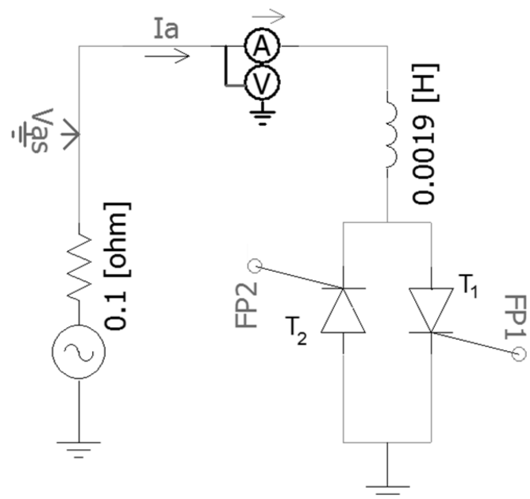

Figure 4.3 Thyristor controlled reactor

Another circuit was created to generate the thyristor firing pulse, as shown in Figure 4.4. For this circuit, comparators were used to detect the positive and negative half cycles of the voltage waveform. By using the multiplier, the positive and negative half cycles were converted to the saw-tooth waveform to obtain the respective positive and negative triangular pulse. The circuit shown in Figure 4.4 produces the firing pulse for various firing angles. The slider tool in the PSCAD is used to vary the firing angle for every simulation to see the difference in the waveform for different firing angles.

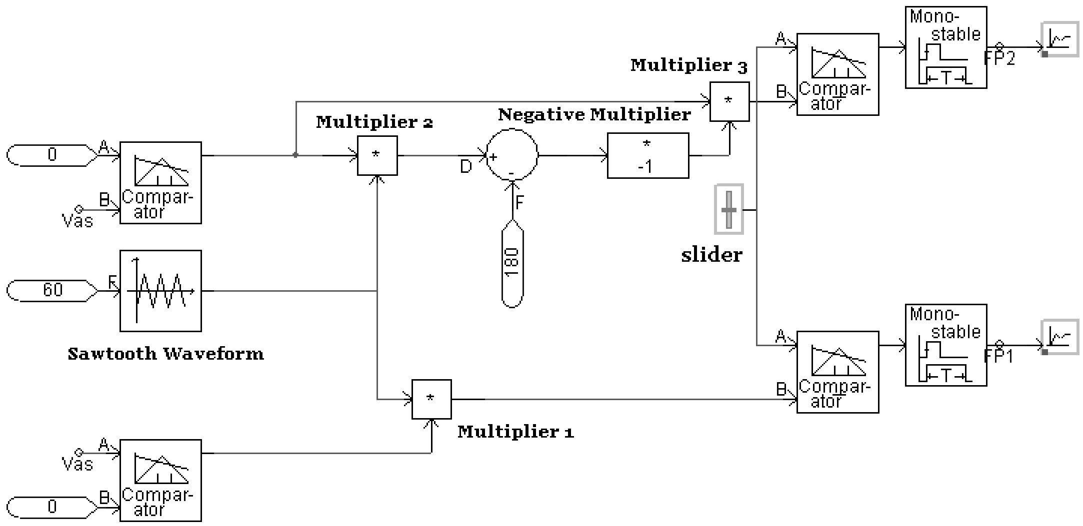

Figure 4.4 Circuit to generate thyristor pulses

4.2.3 Simulation

The thyristor valves can be brought to conduction by applying the gate pulse. The valve will block automatically, when the current crosses zero, unless the gate pulse is reapplied. The current in the reactor can be controlled by the method of firing delay angle control [5]. Since the controllable range of a TCR firing angle is between 90° and 180°, the simulation is carried out for three different angles within this range. The circuit parameters are as given in Table 4.1 below

Table 4.1 TCR Parameters

Parameters	Values
RMS voltage (kV)	132.79(L-G); 230 (L-L)
TCR reactor (mH)	1.9
Resistance (Ω)	0.01

Figure 4.5 shows the simulation for firing angles 100°, 120° and 140° in red, green and blue respectively.

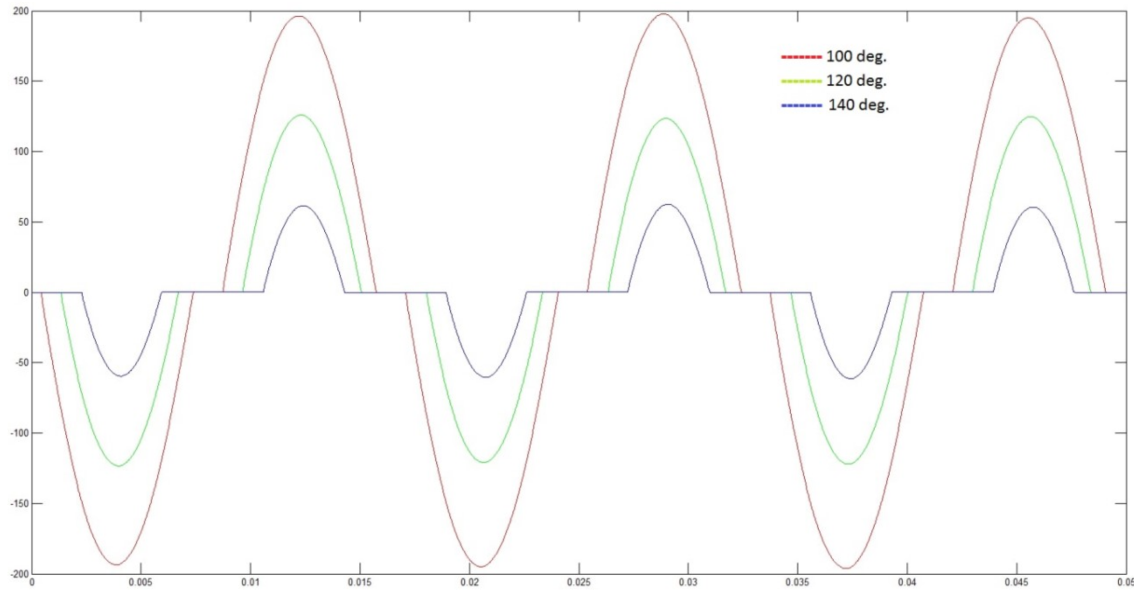

Figure 4.5 Current waveforms for various firing angles

In the current waveform, the continuous waveform is interrupted at the zero crossing automatically when the current reaches the natural zero. When the next thyristor is fed with gate pulse, it starts to conduct in the other half-cycle. From Figure 4.5, it is evident that when the firing angle is close to 90°, the waveform is almost sinusoidal.

Also in Figure 4.5, it can be noticed that there is a considerable time period to regain the waveform and this is due to the delay in the firing angle. Since the TCR acts like a variable susceptance, the variation of the firing angle changes the susceptance and, by that the reactive power Q absorbed by the reactor because the applied ac voltage is constant. The variation of the TCR susceptance with respect to the firing angle is shown in Figure 4.6.

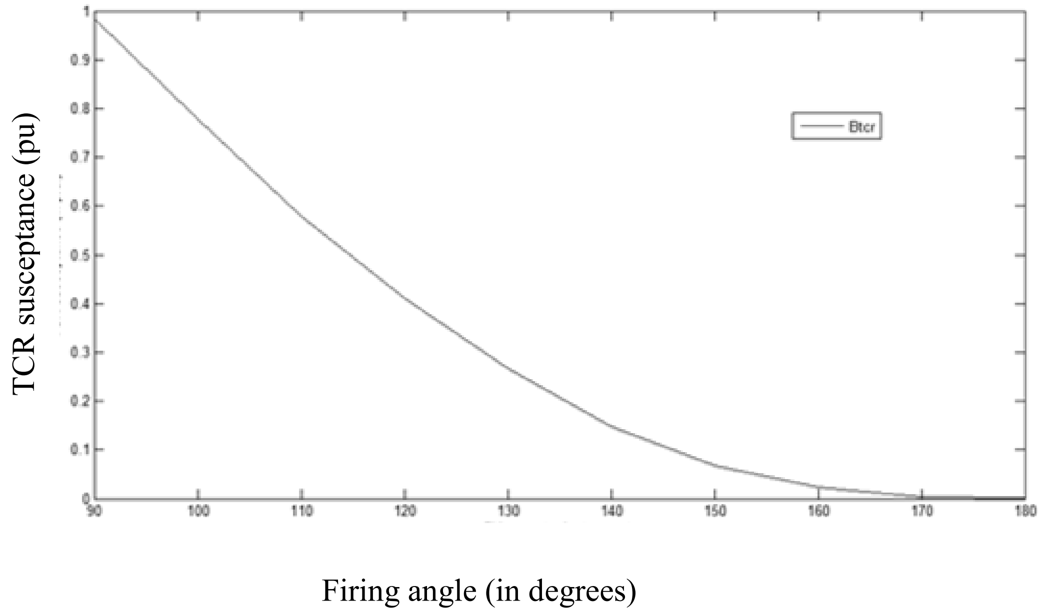

Figure 4.6 Susceptance of TCR as a function of firing angle

The reactive power Q and the TCR susceptance are directly proportional. The change in the reactive power with respect to the variation in firing angle is shown in Figure 4.7 which shows that the reactive power Q decreases as the firing angle varies from 90° to 180°. Thus by controlling the thyristor firing angle of the TCR, the reactive power flow in the power system can be controlled.

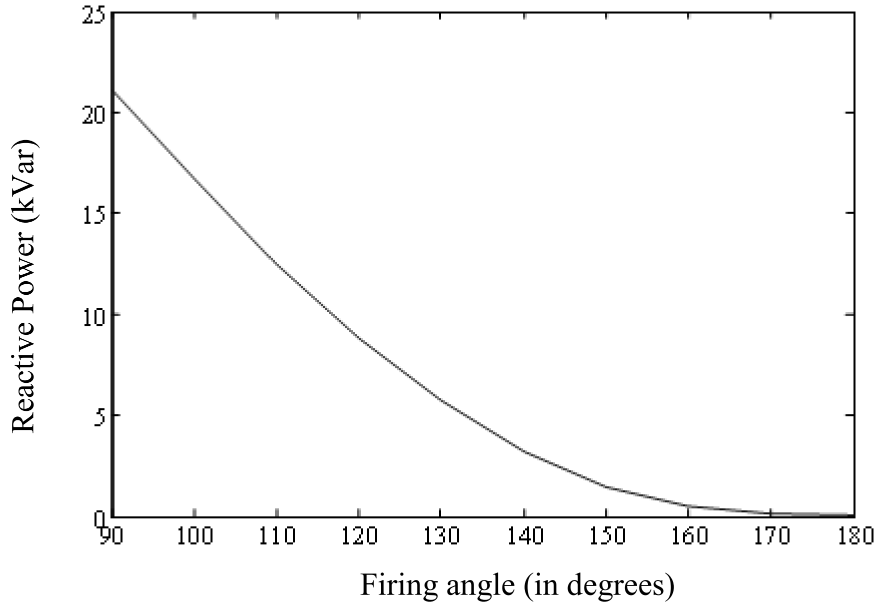

Figure 4.7 Reactive power as a function of firing angle

4.3 Thyristor Controlled Series Capacitor (TCSC)

TCSC is an example of series compensation. TCSC (Thyristor Controlled Series Capacitor) is a device consisting of series compensating capacitor and TCR (Thyristor Controlled Reactor) connected in parallel, used mainly for the control of the active power flow in a power system, which in turn increases the capacity of the transmission lines [10]. The impedance of the TCSC is changed by the thyristor switched reactor connected in parallel to the capacitor. The reactance of the inductor L is defined by the firing angle α of the thyristors. Basically the TCSC provides a continuous variable capacitance by partially cancelling the effective compensating capacitance using the TCR. The basic scheme and the equivalent circuit of a TCSC are shown in Figures 4.8 and 4.9 respectively.

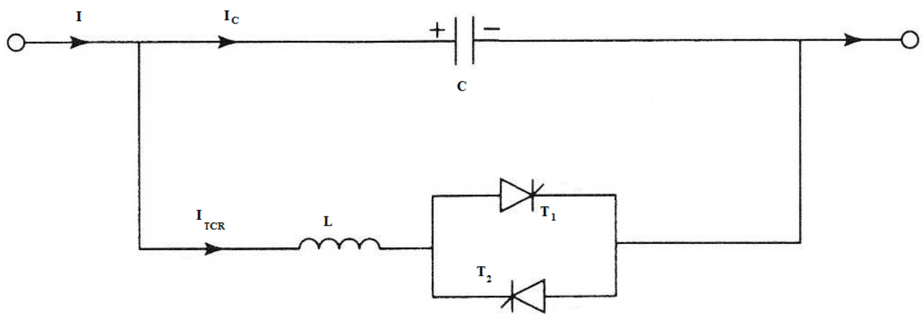

Figure 4.8 Schematic representation of TCSC

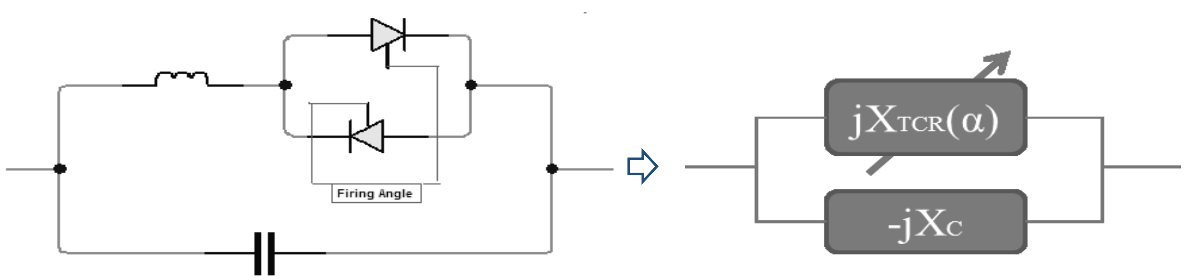

Figure 4.9 Equivalent circuit of TCSC

The TCSC operates in 3 different modes. The equivalent circuit of the TCSC is as shown in Figure 4.9 where the entire TCR circuit is shown as a variable reactor. Reactance of the TCSC can be either capacitive or inductive depending on the TCR reactance. The effective reactance of TCSC is capacitive for $X_C < X_{TCR}$ and inductive for $X_C > X_{TCR}$ [13].

In the Bypassed-Thyristor mode, the thyristors of the TCR are made to fully conduct in both direction and conduction angle is 180º, current flow will be continuous and sinusoidal in the reactor. The net reactance of the TCSC is inductive, as the susceptance of the reactor is larger than that of the capacitor. Most of the line current will be flowing through the thyristor.

In the Blocked-Thyristor mode, the firing pulse to thyristor valves is blocked and hence no current flows through the valves. The net reactance is same as that of the capacitor.

In the Vernier mode or partially conducting mode, the thyristor valves are fired with pulses between 90° and 180° so that the valves conduct for part of a cycle.

4.3.1 Principle of operation of the TCSC

The impedance of the TCSC can be modified by modifying the TCR inductance. By controlling the firing angle the reactor current can be controlled from maximum to zero. From Equation (4.6), the magnitude of the current at the fundamental frequency, with respect to the firing angle, is as given by the following equation:

$$I_{L1}(\alpha) = \frac{V_m}{L.\omega}\left(1 - \frac{2}{\pi}\cdot\alpha - \frac{1}{\pi}\cdot\sin 2.\alpha\right) \tag{4.11}$$

The inductive susceptance of the TCR can be described as

$$B_{TCR}(\alpha) = \frac{1}{L.\omega}\left(1 - \frac{2}{\pi}\cdot\alpha - \frac{1}{\pi}\cdot\sin 2\,\alpha\right) = B_L\cdot\frac{\pi - 2\,\alpha - \sin 2\,\alpha}{\pi} \tag{4.12}$$

by using the formulae $B_L = \frac{1}{\omega L}$ and $I_{L1} = B_{TCR}$.

As reactance is the inverse of susceptance, inductive reactance X_{TCR} is as given below:

$$X_{TCR}(\alpha) = \frac{1}{B_{TCR}(\alpha)} = X_L \cdot \frac{\pi}{\pi - 2\alpha - \sin 2\alpha}, X_L \leq X_{TCR}(\alpha) \leq \infty, X_L = \omega L \tag{4.13}$$

The total reactance of the compensator can be given as

$$X_{TCSC}(\alpha) = \frac{X_{TCR}(\alpha) \cdot X_C}{X_{TCR}(\alpha) - X_C}, \quad X_C = \frac{1}{\omega.C} \tag{4.14}$$

If the inductive reactance of the reactor is smaller than the capacitive reactance, that is $X_L < X_C$, the operating diagram of the TCSC will be as presented in Figure 4.10.

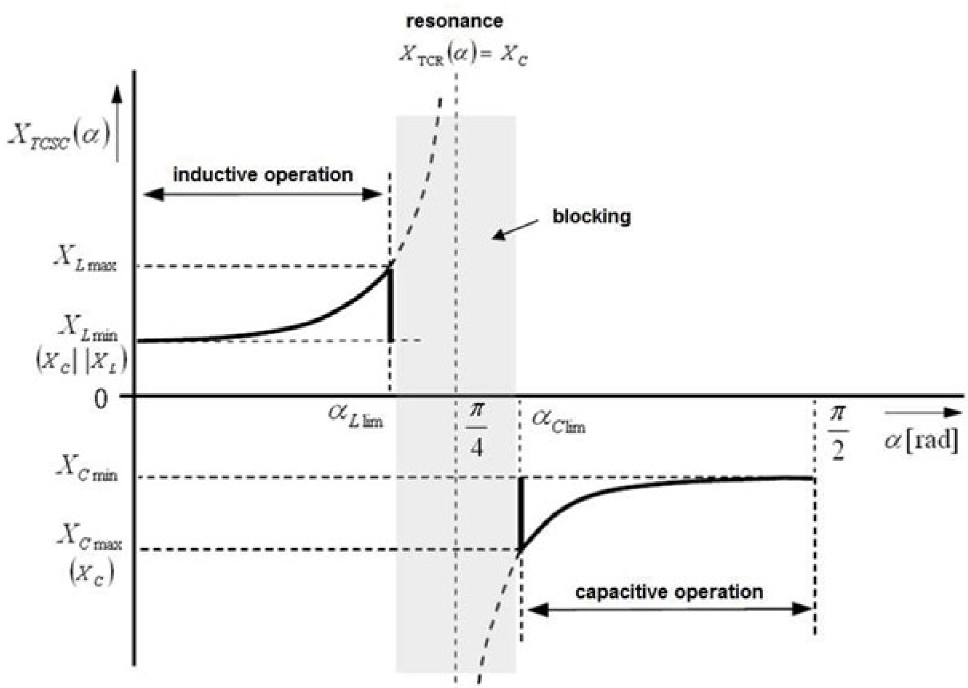

Figure 4.10 Variation of TCSC reactance with firing angle [13]

- If $\alpha = 0$, X_{TCR} is very small, TCSC impedance is inductive and minimum
- For α in between $(0, \boldsymbol{\alpha}_{Llim})$ range, X_{TCR} is smaller than X_C, and X_{TCSC} is inductive
- For α around $\pi/4$, X_{TCR} is equal to X_C, and so resonance occurs causing X_{TCSC} to be indefinite
- For α in between $(\boldsymbol{\alpha}_{Clim}, \pi/2)$ range, X_{TCR} is greater than X_C, and X_{TCSC} is capacitive
- If $\alpha = \pi/2$, X_{TCR} is indefinite, and so X_{TCSC} is capacitive and equal to X_C

Effective reactance of TCSC (X_{TCSC}) with respect to the firing angle (α) is given in Equation (4.15) below [14-17].

$$X_{TCSC}(\alpha) = -(X_C) + C_1(2\pi - 2\alpha + \sin(2\pi - 2\alpha)) - C_2\left(\cos^2(\pi - \alpha)(\omega.\tan(\pi - \alpha)) - \tan(\pi - \alpha)\right) \tag{4.15}$$

where

$$C_1 = \frac{X_L + X_{LC}}{\pi}\ ;\ C_2 = \frac{4}{\pi}\frac{X_{LC}^2}{X_L}$$

$$X_{LC} = \frac{X_c.X_L}{X_c - X_L}$$

$$\omega = \sqrt{\frac{X_C}{X_L}}$$

4.3.2 TCSC circuit modeled in PSCAD

A single phase TCSC circuit is created in the PSCAD as shown in Figure 4.11. The circuit is basically a series capacitor shunted across a thyristor controlled reactor circuit (Section 4.2).

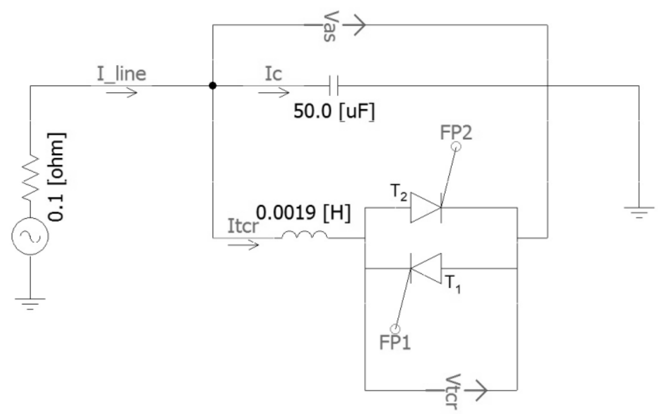

Figure 4.11 Single-phase TCSC - PSCAD model

The circuit parameters are as given in Table 4.2 below. In this circuit, the reactor is 1.9 mH and the capacitor is 50 μF. The circuit was tested for two different firing angles 120° and 160° respectively.

Table 4.2 TCSC parameters

Parameters	Values
RMS voltage (kV)	132.79(L-G); 230 (L-L)
TCR reactor (mH)	1.9
Series Capacitance (μF)	50
Resistance (ohm)	0.01

In Figures 4.12 and 4.13 below, the TCSC voltage (kV), Line current (kA), Capacitor current (kA), TCR current (kA), Valve Voltage (kV) for the firing angles 150° and 120° are plotted respectively below.

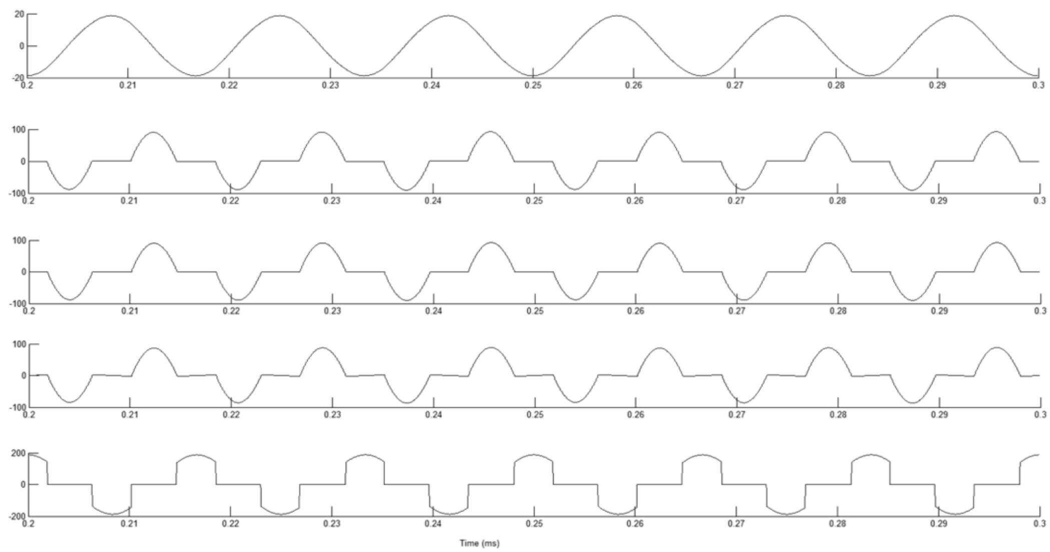

Figure 4.12 TCSC waveforms in capacitive mode of operation (α = 150°)

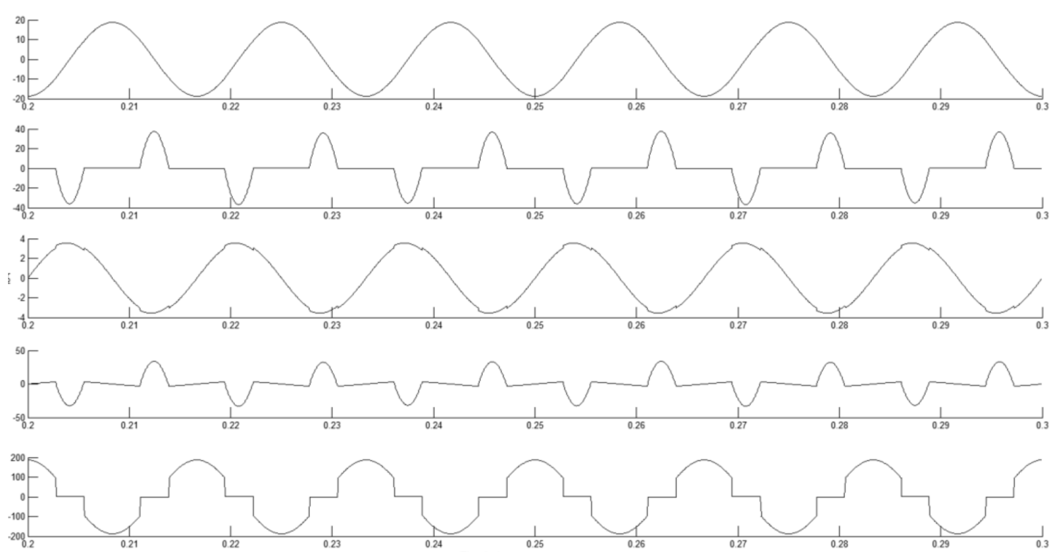

Figure 4.13 TCSC waveforms in inductive mode of operation (α = 120°)

From the plots for different firing angles, it is evident that the current flow through the circuit can be controlled. The current flow in the TCSC valves for the firing angles 150º and 120° are given in Figure 4.14 below.

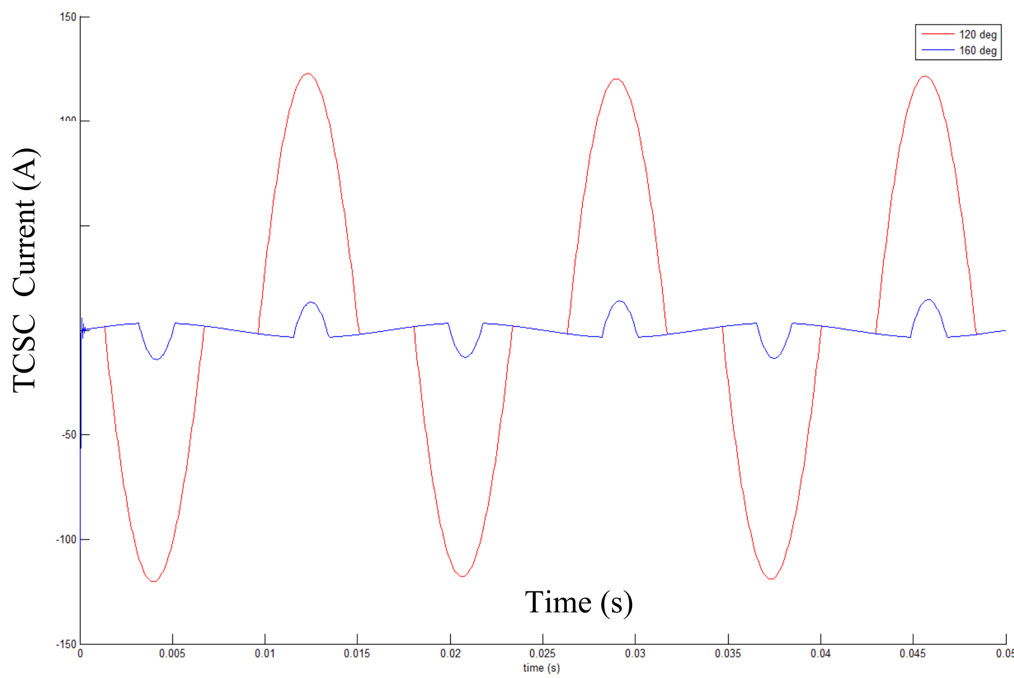

Figure 4.14 Current waveforms for various firing angles

From the plots for various firing angles, it is evident that the current flow through the circuit can be controlled. The capacitive and inductive operation of the TCSC circuit produces a considerable change in the total reactive power Q of the circuit. The change in the reactive power, with respect to the change in firing angle is given below in Figure 4.15. The reactive power Q decreases drastically when the firing angle of the Thyristor is increased from 90° to 180°. Thus by controlling the Thyristor firing angle, the reactive power flow in the power system can be controlled.

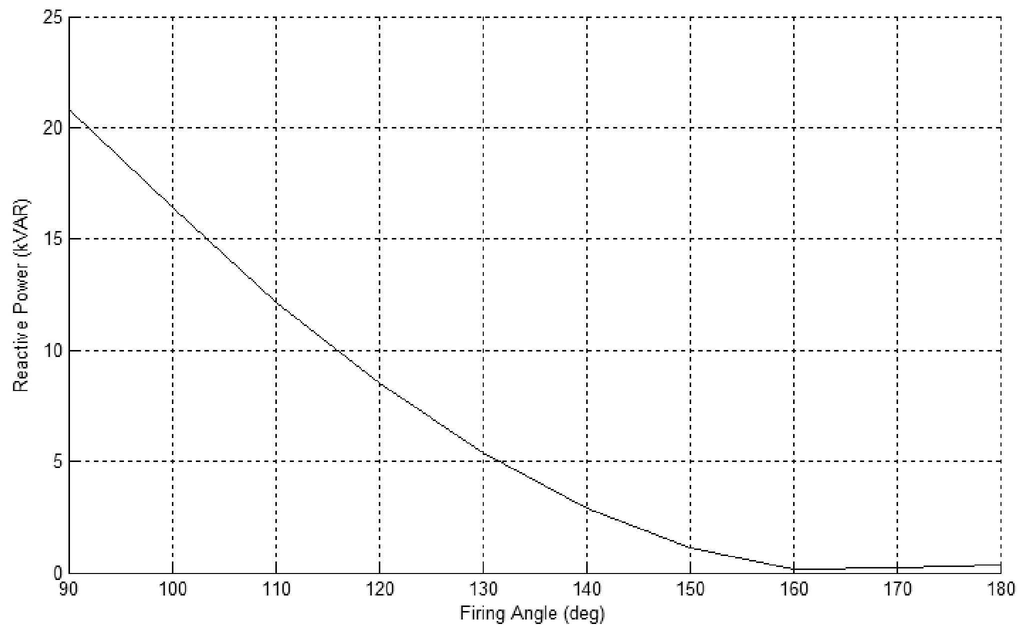

Figure 4.15 Variation of Reactive Power in terms of firing angle

4.3.3 Case Study: 2-bus system

The concept of TCSC improving the power transfer by adjusting the series reactance can be explained using a simple 2-bus system as shown in Figure 4.16 below.

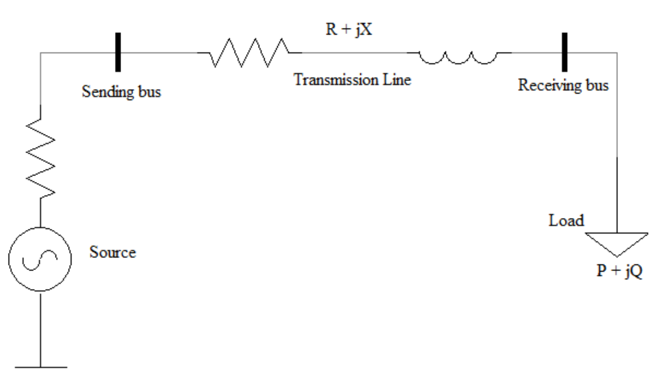

Figure 4.16 One-line diagram of 2-bus system

The 2-bus system shown here is single phase voltage source delivering a load of (100MW +j10MVar) through a transmission line of impedance (6.89 +j 78.72) ohms. The system is modeled using PSCAD and simulated. Results show that there is power loss in the line due to its resistance. In this particular example, due to the impedance in the transmission line, only (75.82MW+j6.95Mvar) power is received at the load end. It is understood that the resistance in the transmission line absorbs real power and the inductance absorbs reactive power. The power difference from the source to the load is given in Figure 4.17 below. P1 & Q1 are the real power and reactive power delivered, whereas P2 & Q2 are the real power and reactive power received.

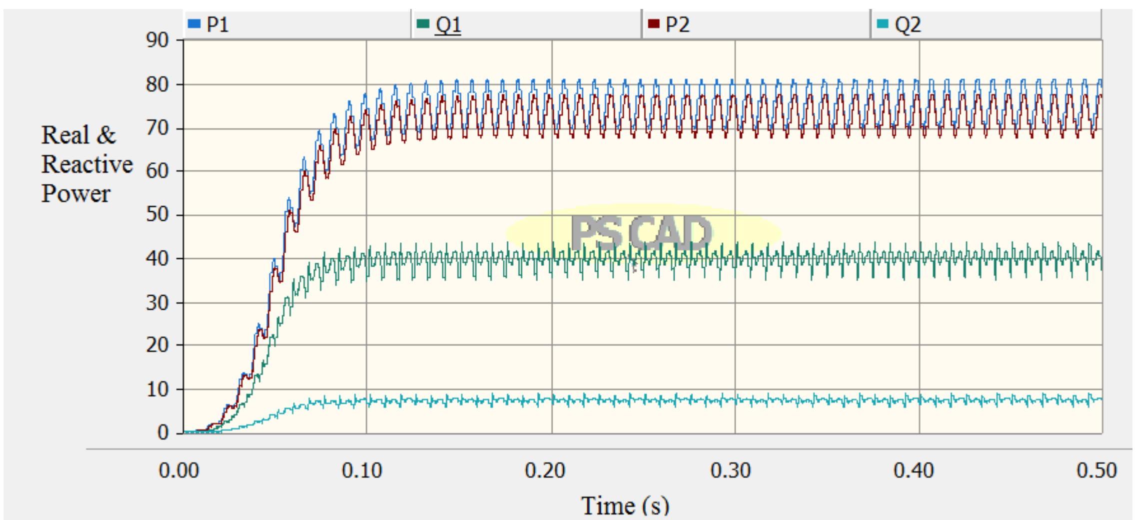

Figure 4.17 Power delivered vs power received

Since the line absorbs a considerable amount of reactive power, it is necessary to compensate that in order to provide the load with the power required. To explain the series compensation, the 2-bus power system is modified with a 100 MVA load with 0.9 pf. There is significant loss in the power at the receiving end. In order to improve power delivery, and say, improved voltage to 0.95pf, around 15.5Mvar reactive power is needed in the system. This can be provided by a capacitor in series with the line. Different capacitance values were added in series and the results were tabulated. These results are presented in Table 4.3 below.

Table 4.3 Power values for various series capacitances

Capacitance (μF)	Real Power at Load (MW)	Reactive Power at Load (MVar)
5	16.24	7.96
10	65.21	32.94
15	94.14	50.13
20	97.21	48.98
25	93.08	42.61
30	88.32	37.71
35	84.24	34.86
40	80.94	33.47

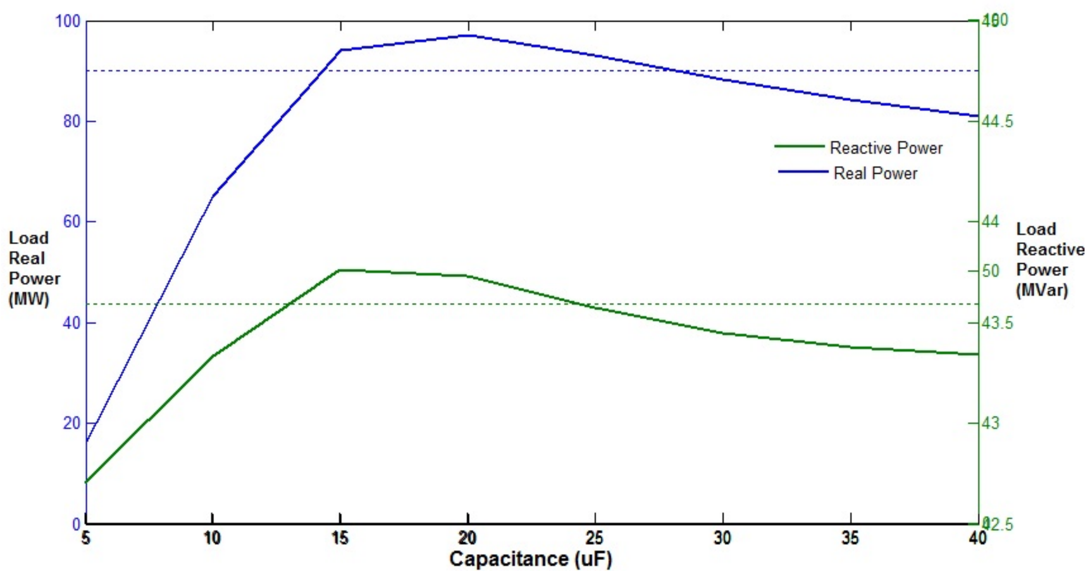

Figure 4.18 Power change for various capacitance values

In this case, from Figure 4.18 above, it can be understood that for capacitance values in the range of 15-25μF, the power rating of the load is improved. 20μF capacitance is adjudged to be used for improving the power transfer in the system.

Fixed series compensation solves the problems in this system, for varying loads the capacitor value has to be changed often. Since it will be a more demanding work considering the time and the labor involved in the process, it will be better if the reactance power can be changed with respect to load changes. This is where the Thyristor Controlled Series Capacitance (TCSC) can be used. As discussed in (4.3.2), the reactance of the system can be varied by the TCR firing angle to control the power transfer in the system. For various firing angles, the reactance changes accordingly and the whole TCSC acts as a variable capacitance as pointed out earlier.

4.4 Summary

In this chapter, the basic function of the TCR and TCSC as a FACTS device, and the advantages of the devices are discussed. The relation between the thyristor firing angle and the reactive power is demonstrated analytically and by simulation using PSCAD. It is shown that the reactive power can be varied continuously by varying the firing angle. It is evident that the TCR can be used as a FACTS device in a power system where reactive power control is needed. The relation between the Thyristor firing angle and the reactive power is shown, and effect of the change in firing angle in the total reactive power of the circuit is shown. Application of FACTS device TCSC in the control of reactive power of a single phase circuit is demonstrated.

Chapter 5

Power Flow Control using Distributed Flexible AC Transmission Systems (D-FACTS)

5.1 Introduction

Distributed Flexible AC Transmission Systems (D-FACTS) devices offer many potential benefits to power system operations. This chapter illustrates the benefits of applying D-FACTS devices in controlling the power system. By studying the power system quantities such as voltage magnitude, voltage angle, bus power injections, line power flows, and real power losses with respect to line impedance, the impact of D-FACTS devices is tested. Independently controllable lines are selected for power flow control, to install D-FACTS devices, for which line flow control are determined. Then, D-FACTS device settings are selected to achieve desired line flow objectives.

5.2 Distributed FACTS devices

Flexible AC Transmission Systems incorporate power electronics and controllers to enhance controllability and increase transfer capability [35]. FACTS devices can improve power system operation by providing a means to control power flow, to improve stability, and to better utilize the existing transmission infrastructure. Transfer of power between two areas will impact flows on other lines in the system, potentially even lines which are far away. Installing FACTS devices in all the anticipated areas is not an economically feasible solution. If the controllers can be installed on the lines which can be affected, it will have direct impact on the system. Such devices which are comparatively much smaller and cheaper, named Distributed Flexible AC Transmission Systems (D-FACTS) were introduced recently [36-39].

D-FACTS or Distributed FACTS devices, (named so due to their distributed placement on overhead lines), are series power flow control devices which are small and light weight. A power system with D-FACTS devices installed on the line is shown in Figure 5.1. These devices are very small compared to the size and length of the high voltage overhead transmission lines. They can be easily installed on the transmission lines without causing major physical changes to the line.

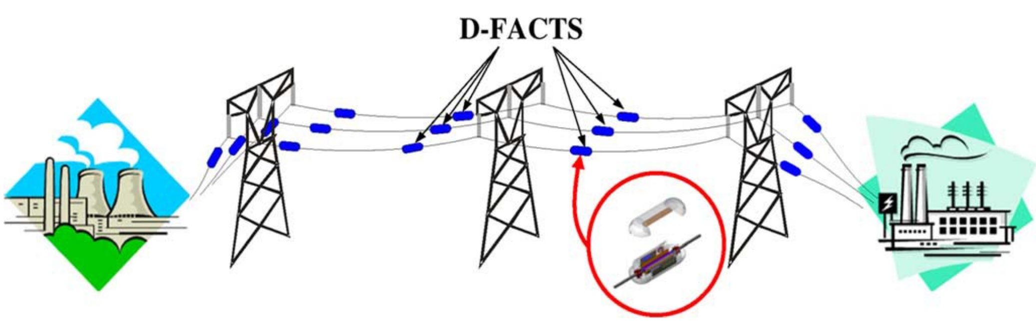

Figure 5.1 Model Transmission Line with D-FACTS [33]

These devices change the effective impedance of transmission lines through the use of a synchronous voltage source. A D-FACTS device changes the effective line impedance by producing a voltage drop across the line which is in quadrature with the line current. The voltage compensated (V_{comp}) to the line is 90° out of phase with the line current (I_{line}).

$$V_{comp} = I_{line}\ Z = j\ I_{line}\ X_L \text{ or } -j\ I_{line}\ X_C \tag{5.1}$$

where Z is the line impedance, X_L the inductive reactance and X_C the capacitive reactance.

A D-FACTS device provides either purely reactive or purely capacitive compensation [38, 39]. By effectively placing the D-FACTS devices, flexible line flow control can be achieved in the power system. Figure 5.2 below, shows the cross section diagram of a typical D-FACTS device, in which it is seen that the devices are clamped or clipped on to the transmission lines and their sizes are comparatively small for a high voltage line.

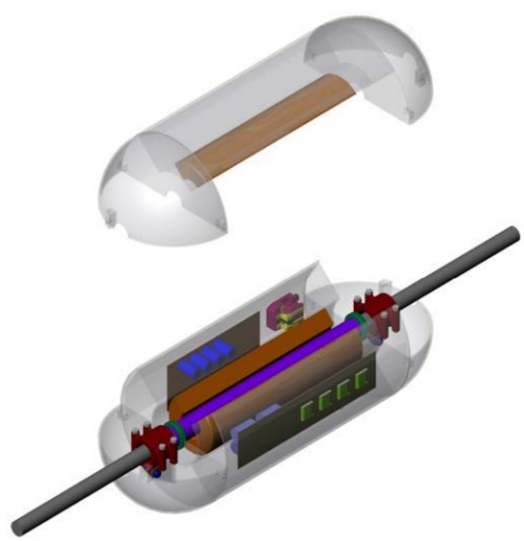

Figure 5.2 Cross section of a typical D-FACTS device [33]

The schematic diagram of a distributed static series compensator (DSSC) in Figure 5.3 below, is used here to illustrate the operation of D-FACTS devices.

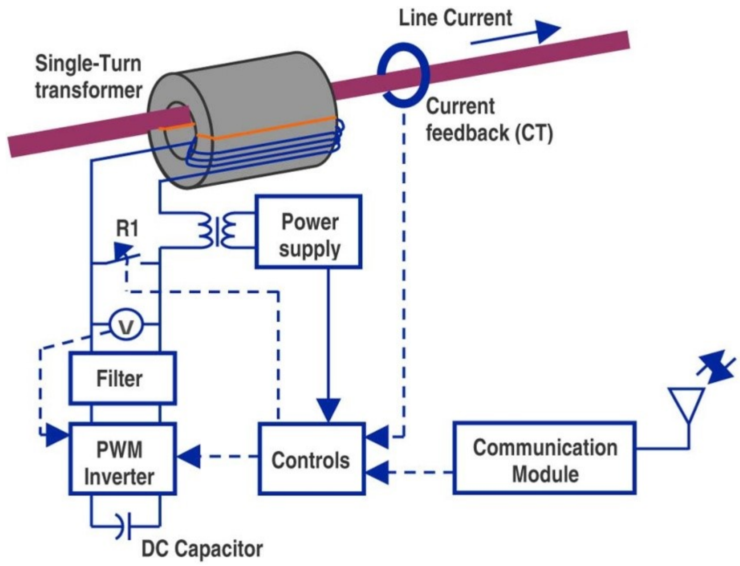

Figure 5.3 Schematic diagram of a D-FACTS device [33]

The DSSC modules consist of a small rated single phase inverter, around 10 kVA and a single turn transformer, equipped with necessary controls, power supply circuits and built-in communications module. The module consists of two parts that can be physically clamped around a transmission line. The transformer and mechanical parts of the module form a complete magnetic circuit only after the module is clamped around the conductor. The weight and size of the DSSC module is low allowing the unit to be suspended mechanically from the power line. [37]

The module gets self-excited from the power line. When the inverter is activated, the module injects reactive impedance in series to the line, which stays idle otherwise. The line inductance can be increased or decreased based on the impedance delivered.

By installing more similar modules, the overall system control function is achieved. These modules contain sensors to monitor the condition of the line on a distributed basis so that it can be fully utilized. By having a large number of D-FACTS modules deployed on the existing transmission lines, distributed along the power system, desired levels of loading are achieved, and helps to effectively utilize the existing grid.

The main aim of implementing D-FACTS over its predecessor FACTS is to exploit the fact that not all locations have equal impact. So the best location for the applications of interest has to be analyzed and then D-FACTS settings to achieve the desired purpose are determined. Potential applications for D-FACTS are to reduce flow through overloaded lines, minimize losses and to minimize cost. D-FACTS devices control of one line affects the flows on all lines. The impact that the control of one line flow has on other line flows is specific to the system. If a system has only one loop, the flows are completely coupled and cannot be controlled independently.

D-FACTS devices can be operated basically in three modes, based on the injected reactance X_{inj}, such as:

1) Limit mode, where X_{inj} responds based on the line current
2) Fixed mode, in which the X_{inj} value is fixed, and can be controlled manually too.
3) Regulation mode, where X_{inj} is controlled to achieve line flow in a particular range.

5.3 D-FACTS case study 1: 7-bus system

The operation of D-FACTS devices can be analyzed using the PowerWorld software, which provides an option to simulate them. These devices are represented in modules where each module will be typically 47 μH. The maximum compensation and the total number of modules can be specified as well as the minimum and maximum line activation currents, I_0 and I_{lim}. The D-FACTS devices will be operated in between range of line current, I_0 and I_{lim}. The devices in a particular line will be inactive until the line current reaches I_0, and after I_{lim}, the cumulative injection of the FACTS devices are at their maximum value.

An example 138kV, 7-bus system is taken for analysis. Table 5.1 provides the details for the system.

Table 5.1 Details for the 7-bus test system

Bus	Voltage (pu)	Voltage (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar
1	1.05	144.9	5.31	0	0	112.41	6.57
2	1.04	143.52	3.71	40	20	156.78	30.17
3	0.99789	137.709	-1	150	40	--	--
4	1	138	-0.1	80	30	103.34	2.1
5	1.01704	140.351	-1.7	150	40	--	--
6	1.04	143.52	3.54	200	0	250	-10.55
7	1.04	143.52	0	200	0	200.16	34.71

The single line diagram of the 7-bus power system is show in Figure 5.4. The goal of the base case study for the 7-bus power system is to show the improvement in the performance of the system and the effectiveness of the D-FACTS device by comparing the performance of the power system without D-FACTS.

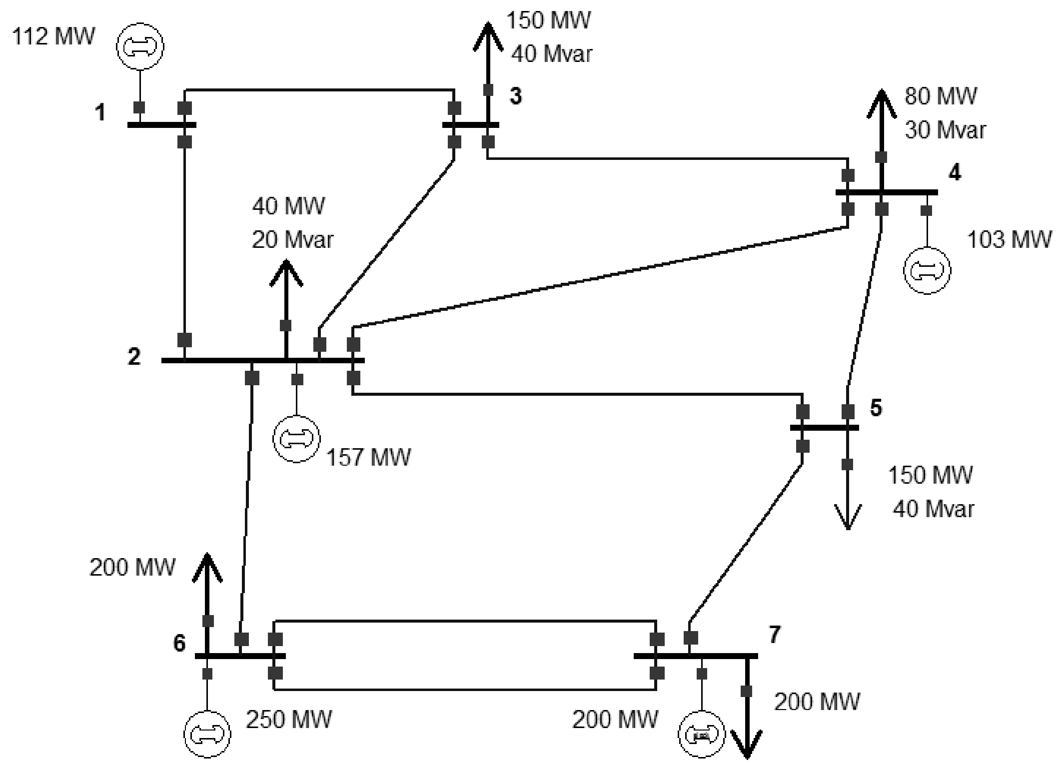

Figure 5.4 7-bus test system

The base case of the 7-bus test system is analyzed for line contingencies, a single line fault at line 7-5 created overloading in the line 2-5. An increase in the load demand at Bus 5 also caused line overloading. Line 2-5 is identified as the most vulnerable in the power system, and it is very important to save the line 2-5 from any overloading to protect the system against any further faults.

Apart from that, the line 1-2, line 2-3 and line 1-3 closely trail behind line 2-5 in line current flow. If fault occurs at the line 2-5 and any outage happens, the lines 1-2, 2-3 and 1-3 may fail in quick succession. Before any further damages in the line or power outages in the system, it is necessary to take preventive measures. In order to identify the effectiveness of D-FACTS, PowerWorld software is used to simulate them on these lines and the outcomes were analyzed. The results of the analysis are as follows:

To start with, the line 2-5 was equipped with D-FACTS devices. The operating profile of the D-FACTS current is shown in Figure 5.5. The D-FACTS devices are set to operate on limit mode, which will start operating when the line current exceeds 90% of its nominal value and will continue to increase the number of modules until 100% of the line current. Once 100% of the line current is reached, the D-FACTS devices will operate at their maximum reactance value.

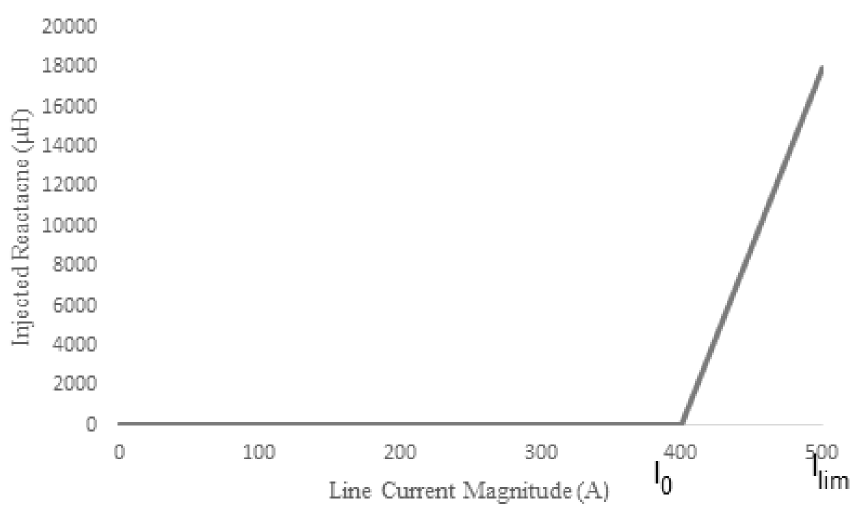

Figure 5.5 D-FACTS profile for current operating point

Each D-FACTS module is set as 47 μH, total number of modules per phase are calculated accordingly. And for the line 2-5, there are 386 modules needed. At its maximum the D-FACTS device is set to inject 30% of the line current value. Figure 5.6 shows the difference in the line current magnitude for the same system with D-FACTS and without D-FACTS. The load demand at bus 5 is increased from 150 MW to 250MW. There is no change in the line current magnitude until 449A. But when the line current increases more than 449A which is 90% of the overall line magnitude, the D-FACTS devices starts operating.

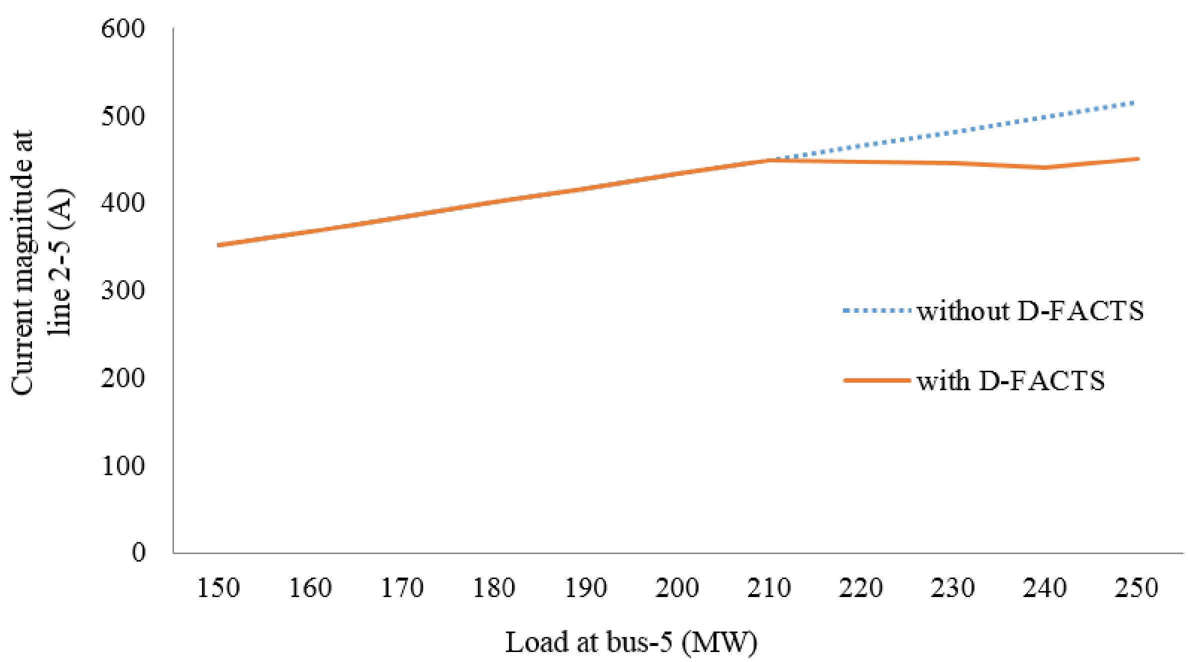

Figure 5.6 Change in the line current magnitude for bus 5 load variation

When load demand at the receiving end increases from 210MW to 250MW, the line current increases from 449 to 515A. By employing the D-FACTS modules, it increases from 449A to 451A only.

The 7-bus test system is operated with the D-FACTS devices and without them, to compare the performance. Table 5.2 shows that in the system without D-FACTS, current in the line 2-5 increases linearly. In the system with D-FACTS, the line current stays nearly the same from 210 MW (where control is applied in D-FACTS modules) to 250MW for the load increase at bus 5.

Table 5.2 Increase in the Line current magnitude vs. Load demand

Load demand (MW)	Line current magnitude (A)		Difference in line current magnitude (A)		No. of D-FACTS in operation
	without D-FACTS	with D-FACTS	without D-FACTS	with D-FACTS	
150	352	352	70.12	70.12	0
160	368	368	73.31	73.31	0
170	384	384	76.49	76.49	0
180	401	401	79.88	79.88	0
190	417	417	83.07	83.07	0
200	433	433	86.25	86.25	0
210	449	449	89.44	89.44	0
220	466	448	92.83	89.24	106
230	482	445	96.02	88.65	232
240	498	441	99.20	87.85	357
250	515	451	102.59	89.84	386

5.4 D-FACTS case study 2: 5-bus system

In the case study 2, a 5-bus test system is employed to analyze the “Regulate” mode of the D-FACTS devices. In the regulate mode, the settings for the D-FACTS device will be automatically determined to achieve a certain range of power flow. The device uses coordinated sensitivities to achieve the desired control range. The single line diagram of the 5-bus power system as shown in Figure 5.7 is taken for study. This study is to analyze the mode of operation of the D-FACTS devices

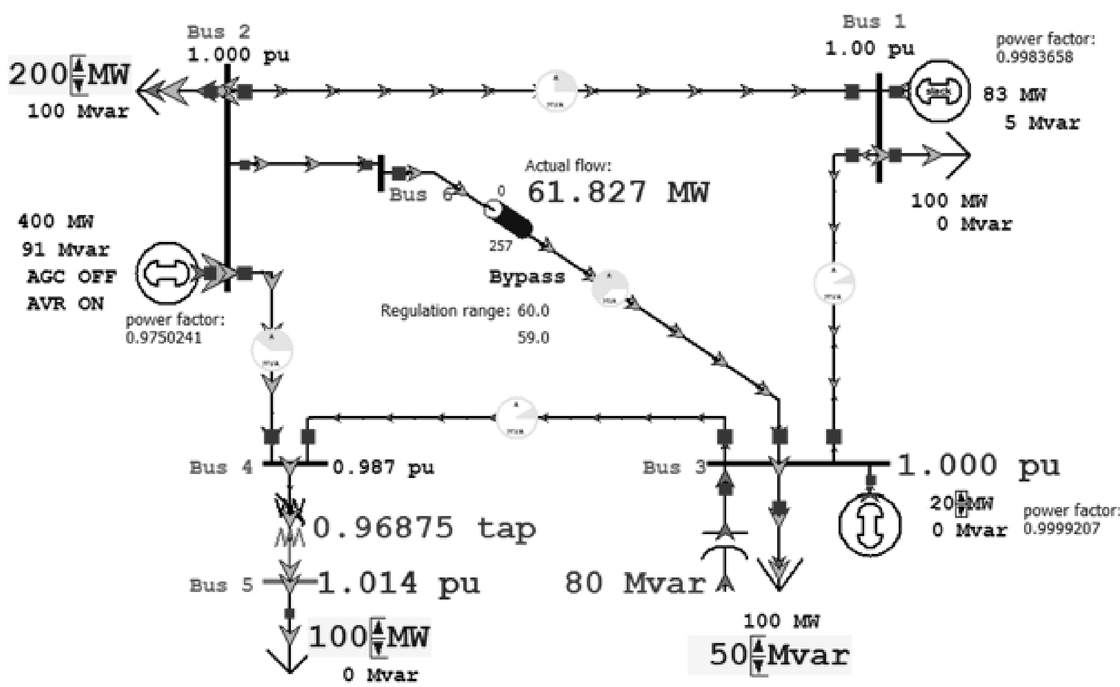

Figure 5.7 5-bus test system

The initial state of operation of the test system is given in Table 5.3 below.

Table 5.3 Details of the 5-bus test system

Bus	Voltage (kV)	Angle δ (Deg)	Load real power (MW)	Load reactive power (MVar)	Generator real power (MW)	Generator reactive power (MVar)	Switched shunts (Mvar)
1	138	0	100	0	82.64	4.73	--
2	137.997	3.66	200	100	400	91.12	--
3	138	-0.99	100	50	20	-30	80
4	136.186	-0.95	--	--	--	--	--
5	34.983	-6.51	100	0	--	--	--
6	138.381	1.89	--	--	--	--	--

The power flow in the line 6-3 is initially out of range at 61.8 MW which is supposed to be maintained around 60 MW. As initially the D-FACTS device is not in operation, that is $X_{inj} = 0$, it will not have any impact on the system. During the operation, the D-FACTS device is set in Regulation mode, to automatically control the power flow across the line 6-2 between 59 MW and 60 MW. In regulate mode, 97 modules of D-FACTS devices were activated to bring the power flow from 61.8 MW to an acceptable 59.32 MW as shown in Figure 5.8 below.

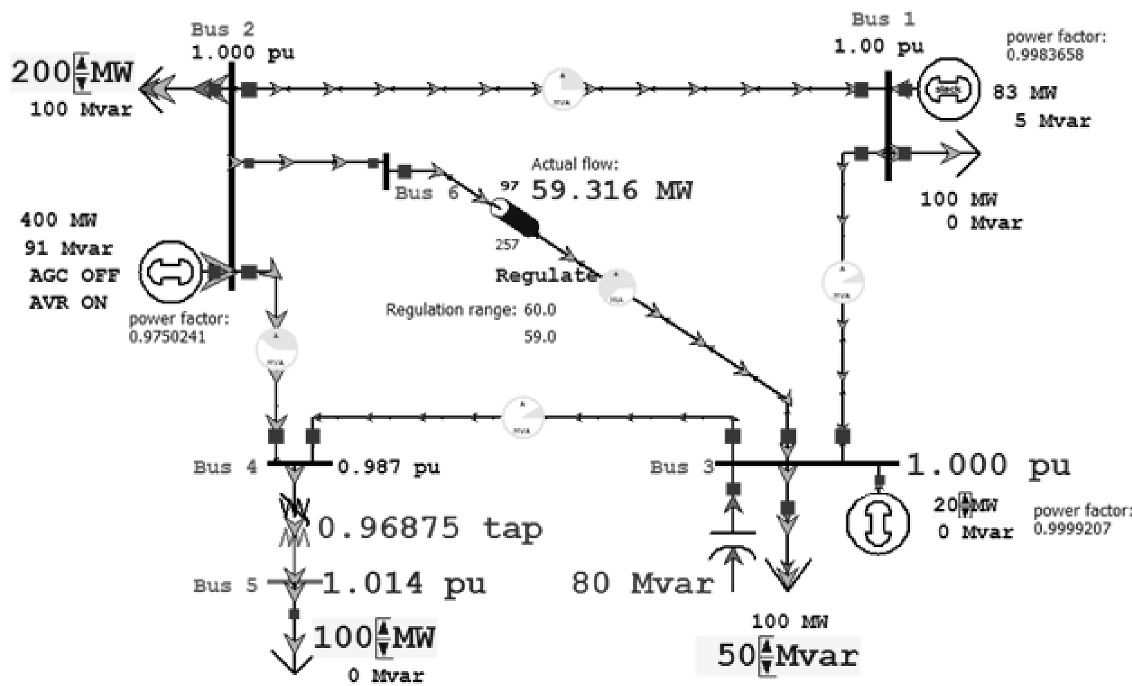

Figure 5.8 5-bus test system with D-FACTS in regulate mode

5.5 Improving the D-FACTS through positioning

From the above case studies, it is established that the flow of current through the transmission line decreases considerably, where D-FACTS devices are installed. By placing the devices at the line which has the worst contingency overload will improve the result significantly. It is possible to improve the performance even better by installing the D-FACTS devices on more than one line based on the factors such as contingency overload, thermal limit and sensitivity. To analyze the improvement of the power flow in the line with respect to change in impedance in another line, the 4-bus system shown in Figure 5.9 is tested. This example is taken from [40]. Table 5.4 provides the generation and load data at each bus in the 4- bus system in Figure 5.9, and Table 5.5 provides the line resistance and reactance in the transmission lines.

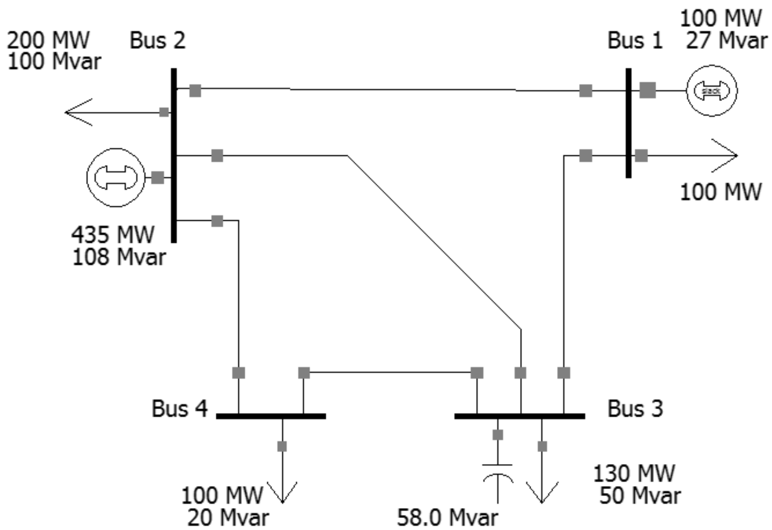

Figure 5.9 4-bus test system

Table 5.4 Details for the 4-bus test system

BusName	**Load (MW)**	**Load(Mvar)**	**Gen(MW)**	**Gen(Mvar)**	**Shunt Mvar**
Bus 1	100	0	100	27	--
Bus 2	200	100	435	108	--
Bus 3	130	50	--	--	58
Bus 4	100	20	--	--	--

Table 5.5 Line details for 4-bus test system

From Bus	**To Bus**	**Resistance (p.u.)**	**Reactance (p.u.)**
Bus 2	Bus 1	0.03	0.16
Bus 3	Bus 1	0.015	0.08
Bus 3	Bus 2	0.03	0.12
Bus 4	Bus 2	0.015	0.08
Bus 3	Bus 4	0.015	0.04

D-FACTS devices are placed on each of the lines independently and their impact on the line current magnitude is measured. In the whole system the line (2, 4) carries more current than other lines with line (2, 3) closely trailing. In order to bring the power system under the limits, D-FACTS devices should be installed on one or more lines. When the line current flow of all the five lines are compared, the D-FACTS installed in (1, 2), (1, 3) and (2, 4) are reasonable while the devices in line (2, 3) gives a huge variation and the line (3, 4) shows very less changes. All the results achieved from this case study are presented in Table 5.6 below.

Table 5.6 Power flow in the lines due to D-FACTS application in other lines

Lines	Power flow in MW								
	Actual power flow (MW)	Lines with D-FACTS control							
		Line 1-2	Line 1-3	Line 2-3	Line 2-4	Line 3-4	Line 1-3 & 2-4	Line 1-2 & 1-3	Line 1-2 & 2-4
1-2	174.59	150.85	161.13	191.75	191.79	175.3	177.31	141.33	166.22
1-3	186.21	168.85	171.37	200.25	203.37	185.68	187.15	155.56	182.76
2-3	335.78	347.11	342.54	286.25	369.1	337.14	377	354.36	382.56
2-4	478.97	490.02	486.45	510.52	430.24	477.5	438.24	493.77	441.59
4-3	82.86	91.91	83.69	111.51	60.59	77.68	53.65	86.32	60.16

To bring other possible combinations into consideration, the system attains a very feasible solution when they are installed in two lines. Although all the combinations more or less provide the same results, when D-FACTS devices are placed on line (1, 3) and line (2, 4), the power system looks more stable. It is assumed that D-FACTS devices can change the line impedance by +/-20% of the uncompensated value [37] .

5.6 Summary

D-FACTS devices have the unique ability to be incrementally installed on multiple lines throughout a system to provide power flow control wherever needed. After D-FACTS devices are installed in certain fixed locations, their control objective can easily be changed to target other lines flows. So D-FACTS devices can provide versatile control for power systems. In this chapter, the successful control of line flows with D-FACTS devices is presented for three different types of systems. The first system is tested for contingency analysis, and overloading, while the second case study dealt with the automatic regulation of a particular line. The third case provided the view of a combination of D-FACTS devices installed in different lines [40].

Chapter 6

Conclusion and Future Work

6.1 Overview of the thesis

Due to the ever growing power demand, power transmission is always close to its limits. But the power systems should be operated in such a way that it's thermal and voltage limits are in control. Otherwise the system may encounter a total blackout. To manage with this situation, the existing power transmission system cannot be relied on and new ways of operating the system are required. Building more new power lines can be a solution but it is not always affordable or acceptable. It has economic or environmental constraints.

By the modern advancements in the power electronics, there are many devices produced to control the existing power system. One such group of devices is the Flexible AC Transmission Systems (FACTS), which were discussed in detail in this thesis. This thesis is aimed at emphasizing the application of FACTS devices in various scenarios where a power system can be maintained effectively and to avoid building new lines.

This thesis proves the point that utilization of the existing power system can be improved through the application of advanced FACTS power electronics devices. TCR, TCSC, SVC and D-FACTS devices were considered for case studies and their outcomes proved to be satisfactory.

6.2 Summary of the research and contribution of the thesis

The main contributions of the thesis can be summarized here. Most commonly used FACTS devices have been categorized and their technology and operation were explained in detail. Comparative study has been made to analyze the improvement in the power system over traditional control measures. A detailed study had been made on the Thyristor Controlled Reactor, Thyristor Switched Series Capacitor on their application of voltage control. Static var compensator is applied for testing its effectiveness in the reactive power compensation and voltage regulation. A new generation of FACTS devices called the Distributed FACTS devices were analyzed for power flow control. PowerWorld, PSCAD, and MATLAB tools were used widely throughout the thesis to simulate the case studies.

6.3 Recommendations for future work

This thesis has effectively discussed the application of SVC, TCR, TCSC and D-FACTS devices in the operation of a power system. Three software tools were used for the case studies presented in the thesis. Improvement in the power system due to the FACTS devices has been studied. Application of D-FACTS devices has been discussed as well.

However a comparative study has not been made. A comparative study to find the optimal FACTS device for a particular scenario will be useful. Case studies for a more complex power system can be considered in future. Detailed studies will be required for the FACTS installation considering the cost and availability of the location.

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