PERFORMANCE ANALYSIS OF TWO MACHINE TRANSMISSION NETWORK WITH PI CONTROLLER BASED UPFC

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

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Submitted By
Deepak Makkar
(Reg. No. 801141010)

Under the Supervision of:
Ms. Manvir Kaur
Lecturer, EIED

ELECTRICAL & INSTRUMENTATION ENGINEERING DEPARTMENT
Thapar University
Patiala-147004
JULY-2013

CERTIFICATE

I hereby certify that the work which is being presented in dissertation entitled, **"PERFORMANCE ANALYSIS OF TWO MACHINE TRANSMISSION NETWORK WITH PI CONTROLLER BASED UPFC"**, in partial fulfillment of the requirement for the award of degree of Master of Engineering in Power Systems and Electric Drives at Thapar University, Patiala is an authentic record of my own work carried out under the supervision of **Ms. Manvir Kaur, Lecturer (EIED).** The matter embodies in this dissertation has not been submitted for the award of any other degree to any other university.

Deepak
Deepak Makkar
Reg. No. 801141010

Date: 12 July, 2013

It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

Ms. Manvir Kaur
Lecturer, EIED
Thapar University, Patiala

Countersigned By:

S. Ghosh
Dr. Smarajit Ghosh
Professor & Head, EIED
Thapar University, Patiala

Dr. S.K. Mohapatra
Sr. Professor & Dean (Academic Affairs)
Thapar University, Patiala

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Deepak

DEEPAK MAKKAR

Reg. No.801141010

ABSTRACT

With the rapid development of the power electronics industry, an increasing number of high power semiconductor devices are available for power system applications. These new devices have made it possible to consider new technologies such as Flexible Alternating Current Transmission Systems (FACTS). The Unified Power Flow Controller (UPFC) is versatile FACTS controller that can control three system parameters individually or simultaneously in appropriate combination.

The work presented in this dissertation is concentrated on the two machine power system transmission model based on controlled voltage source. The model has been developed using MATLAB/SIMULINK. In this SIMULINK model consists of two parallel transmission lines, the one transmission line incorporating a UPFC and another is uncompensated. The overall aim is to control power flow by improving reactive power, voltage profile improvement and reduce the THD level in the transmission network. Simulation results of the model are analyzed.

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CHAPTER-1

Introduction

1.1 Overview

In recent years, greater demands have been placed on the transmission network, and these demands will continue to increase. With the increase in electrical power demand, power systems are increasingly becoming complex to operate. Such a stressed system is continuously under threat of losing stability following a disturbance. Therefore, it has become more difficult to construct new generation facilities and transmission lines due to energy and environment problems [20].

On the other hand, as power transfers grow, the power system becomes increasingly more complex to operate and the system can become less secure. It may lead to large power flows with inadequate control, excessive reactive power in various parts of the system, large dynamic swings between different parts of the system and thus the transmission network cannot be fully utilized. Hence, it is advisable to enhance the power transfer capability of the existing transmission lines instead of constructing new one. Therefore, a new technology is essential to overcome all above mentioned problems to get the most services from their transmission facilities and enhance grid reliability.

In recent times, the availability of high power semiconductor devices for power system applications have led to a new technologies such as Flexible AC Transmission Systems (FACTS) for secure loading, power flow control and damping of power system oscillations. FACTS devices are considered one such technology that reduces the transmission congestion and allows better utilization of the existing grid infrastructure, enhance power system stability, along with many other benefits. FACTS were introduced by Hingorani in the late of 1980s to increase the controllability and utilization of existing transmission network by replacing mechanically controlled system. With these devices there is a possibility that current through a line can be controlled at a reasonable cost and enables a large potential of increasing the capacity of existing lines with larger conductors, and also provide control to enable corresponding power to flow through such lines under normal and contingency conditions. The

FACTS technology is not a single high-power controller, but rather a collection of controllers, which can be applied individually or in coordination with others to control one or more of the interrelated system parameters.

Among all the FACTS devices, UPFC has been recognized as one of the best featured FACTS devices, it is capable of providing simultaneous active and reactive power flow control, as well as voltage magnitude control [3]. In the presently used practical implementation, the UPFC consists of two voltage sourced converters (VSC). These VSC's are back-to-back converters, which are connected via a common DC link to allow bi-directional flow of real power between two converters. These two devices are operated from a common DC link provided by a dc storage capacitor [7]. Ratings of this DC link capacitor bank may have a significant impact on the cost and physical size of the UPFC. The capacitor is sized for a specified ripple voltage, typically 10% of the nominal voltage.

An equivalent two machine power network was developed based on sets of equations for a system including the UPFC. It can simultaneously perform the function of transmission line real/reactive power flow control in addition to UPFC bus voltage/shunt reactive power control. The control mechanism and the controller have important effect on the performance of UPFC. The proposed model has been used to demonstrate some of the features of UPFC for power flow control and voltage control application. In the cases where UPFC dynamics are included, the most common approach for controlling the UPFC has been to use PI control. PI control is simple to implement, yet very effective in damping an oscillatory mode when it is properly tuned. The proposed control is the dynamic control required to achieve given active and reactive power flow and voltage set points.

1.2 Scope of Work

It was analyzed from the literature survey that, FACTS technology provides opportunities for controlling power and enhancing the utilization of existing power system. UPFC is one of the FACTS device with attractive features used in transmission system in order to change various parameters of the controlled system and make the system more reliable, flexible and stable. Different type of controller namely PI, PID, fuzzy can be used to control the converter. In this dissertation, the effectiveness of PI controller based UPFC under disturbance conditions such as fault is analyzed.

1.3 Organization of Dissertation

The work carried out in the dissertation has been summarized in six chapters.

Chapter 1 covers the overview and scope of work. It also contains the organization of dissertation.

Chapter 2 discusses the various FACTS Devices in Power System Stability.

Chapter 3 discusses the introduction of STATCOM, SSSC and Unified Power Flow Controller (UPFC).

Chapter 4 presents the literature review.

Chapter 5 covers the results and discussion.

Chapter 6 contains the conclusion and future scope.

CHAPTER-2

FACTS Devices in Power System Stability

2.1 Power Flow Control

Power systems in general are interconnected for economic, security and reliability reasons. Exchange of contracted amounts of real power has been in vogue for a long time for economic and security reasons. In order to control the power flow in the interconnected areas, power flow control equipment such as phase shifters are installed. They direct real power between control areas. The interchange of real power is usually done on an hourly basis. On the other hand, reactive power flow control in the interconnected areas is also very important. Reactive power flow control on transmission lines connecting different areas is necessary to regulate remote end voltages. Though local control actions within an area are the most effective during contingencies, occasions may arise when adjacent control areas may be called upon to provide reactive power to avoid low voltages and improve system security.

Power flow in a network is not easily controlled because line parameters that determine the flow of power in the system are difficult to control. Also, the ability to control power flow at the transmission level has greatly been influenced by the advances made in the field of high power switching devices. Solid state device provides the flexibility for controlling the power flow in the system. A schematic diagram of a simple power transmission line, represented by its inductive reactance, connecting a sending-end voltage source and a receiving end voltage source is depicted in Fig. 2.1.

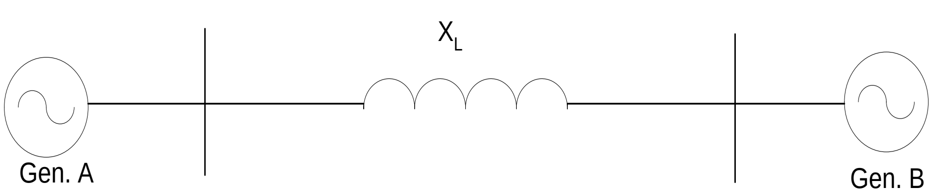

Fig. 2.1 Power Transmission Line

The active and reactive power flow on a line between two ends (which can be in either direction) is a function of the magnitudes of the voltage at both ends, the line impedance and the load angle.

The complex, real and reactive power at receiving end is given below:

$$S_R = P_R + jQ_R = V_R I^* \quad \text{..........................} \; (2.1)$$

$$P_R = \frac{V_s\,V_r}{X_L}\,\mathrm{Sin}(\delta) \quad \text{..........................} \; (2.2)$$

$$Q_R = \frac{1}{X_L}[V_S V_R \cos\delta - V_R^2] \quad \text{..........................} \; (2.3)$$

The sending end real and reactive power is given below:

$$P_S = \frac{V_s\,V_r}{X_L}\,\mathrm{Sin}(\delta) \quad \text{..........................} \; (2.4)$$

$$Q_S = \frac{1}{X_L}[V_S^2 - V_S V_R \cos\delta] \quad \text{..........................} \; (2.5)$$

Where, V_S and V_R are the magnitudes (RMS) of sending and receiving end voltage, respectively, while δ is the phase-shift between sending and receiving end voltage. The equations for sending and receiving active power flows, P_S and P_R are equal because the system is assumed to be a lossless system.

From equations (2.2), (2.4) and equations (2.3), (2.5), it is concluded that real or active power transfer mainly depends on the power angle, while the direction of flows depends on the sign of the angle and reactive power transfer depends mainly on voltage magnitude, which flows from highest voltage magnitude to lowest voltage magnitude respectively.

The derivative dP/dδ decides whether the system is stable or unstable. The steady state limit is reached when the derivative is zero. Typical power transfers correspond to power angles below 30°; to ensure steady state rotor angle stability, the angles across the transmission system are usually kept below 45°.

2.2 Importance of Power Flow Control

In practice, an alternating system supply or consume two types of power i.e. real or active power and reactive power. Real power is necessary to provide the useful work whereas reactive power is necessary to support the voltage in the line. Reactive power has a profound effect on the system operation, security and reliability. In order to improve the system efficiency it is necessary to control the power flow in the electrical power system for proper operation of electrical equipment to prevent damages such as:

- Overheating of generators and motors.
- To reduce transmission losses.
- To maintain the ability of the system to withstand and prevent voltage collapse.
- Unconditional outages.

2.3 Concept of Power System Stability

Power System Stability may be defined as that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance. The various disturbances could be faults, load changes, generator outages, line outages, voltage collapse or some combination of these. The power system stability can be broadly classified into three types are:

(1) Rotor Angle Stability: Rotor angle stability is a stability that is commonly analyzed through the use of time-domain simulations in the electric utility industry. Rotor angle instability occurs when there is a loss of synchronism at one or more synchronous generator. Remaining in synchronism means that all the generator electromagnetic torque is exactly balanced by the mechanical torque. If in some generator the balance between electromagnetic and mechanical torque is disturbed, due to disturbances in the system, then this will lead to oscillations in the rotor angle.

(2) Frequency Stability: When the total generation output matches system load and less demand, then the system is said to be a frequency stable system. Frequency instability may occur due to a significant loss of load or generation within a given system and it is commonly analyzed through the use of time-domain simulations. Frequency instability may lead to sustained frequency swings leading to tripping of generating units or loads.

(3) Voltage Stability: The voltage stability is the ability of the power system to maintain steady acceptable voltages at all buses in the system at normal open conditions and after being subjected to a disturbance [12]. Voltage instability is generally characterized by loss of a stable operating point as well as by the deterioration of voltage levels in and around the electrical center of the region undergoing voltage collapse. Voltage collapse, a form of voltage instability, commonly occurs as a result of reactive power deficiency. Unmitigated rotor angle instability can also result in voltage instability. A voltage collapse at a bus can lead to large excursions in rotor angle and frequency.

The main difference between voltage stability and angle stability is that voltage stability depends on the balance of reactive power demand and generation in the system whereas the angle stability mainly depends on the balance between real power generation and demand. Beside rotor angle stability and frequency stability, power system stability mostly concerns for voltage stability. Voltage control and stability problems are not new to the power industry but in these days receiving more attention. As a result of heavily stressed systems, voltage problems are now also a source of concern in highly developed networks. Voltage instability occurs in a system when a disturbance, increase in load demand, or change in system condition causes a progressive and uncontrollable decline in voltage. Instability is mainly caused by the inability of the power system to meet the demand for reactive power. It is usually the voltage drop that occurs when active power and reactive power flow through inductive reactance associated with the transmission network.

The voltage stability criterion for every bus in the system is that, the bus voltage magnitude increases as the reactive power injection at the same bus is increased. Voltage stability is essentially a local phenomenon, whereas voltage collapse is more complex than simple voltage instability and is usually the result of a sequence of events accompanying voltage instability leading to a low-voltage profile in a significant part of the power system. Voltage collapse may be total or partial blackout. Voltage stability is sometimes also called load stability.

2.4 Elements impact on voltage stability

Various power system elements that have a significant impact on voltage stability are:

1. **Loads:** Load characteristic could be critical in voltage stability analysis. This should include transformer ULTC (under load tap changer) action, reactive power compensation and voltage regulators in the sub transmission system. It is important to account for voltage and frequency dependence of loads.

2. **Generators and their Excitation Control:** For voltage stability analysis it may be necessary to account for the droop characteristic of the AVR rather than to assume zero droop. If load compensation provided, its effect should be represented. Field currents and armature current limits should be represented specifically rather than as a fixed value of the maximum reactive power limit.

3. **Static Var Systems (SVSs):** When an SVS is operating within the normal voltage control range, it maintains bus voltage with a slight droop characteristic. When operating at the reactive power limits, the SVS becomes a simple capacitor or reactor; this could have a very significant effect on voltage stability.

4. **Automatic Generation Control (AGC):** For contingencies resulting in a significant mismatch between generation and load, the action of primary speed control and supplementary tie line bias frequency control can change system generation significantly, sometime to detriment of voltage stability.

5. **Protection Control:** These include generating unit and transmission network protection and controls. Examples are generators excitation protection, armature over current protection, transmission line over current protection, capacitor bank controls, phase shifting regulators, and under voltage load shedding [12].

2.5 Analysis of Voltage Stability

2.5.1 Single Load, Infinite Bus System

The characteristics of voltage stability are illustrated by an infinite-bus system. In Fig.2.2, infinite bus has constant voltage, E. The load is assumed to have constant power factor $\cos\phi$.

The line impedance is Z=R+jX.

The purpose is to calculate the load voltage V with different values of load. The voltage is calculated by solving the load flow equation:

$$\frac{V^*.(E-V)}{Z} = S^* \qquad \text{……………………… (2.6)}$$

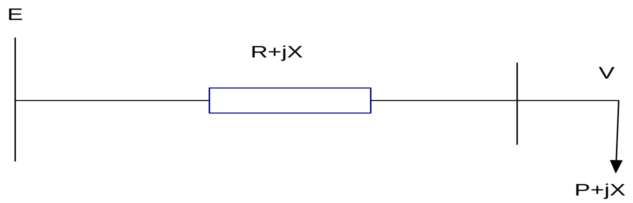

Fig 2.2 Infinite Bus System

Where,

E is the voltage at infinite bus

V is the voltage load, V=$V\angle\delta$

S is the load power demand S=P+jQ

Z is the line impedance Z= R+jX

The solution of load voltages is often presented as PV curve as shown in Fig. 2.3.

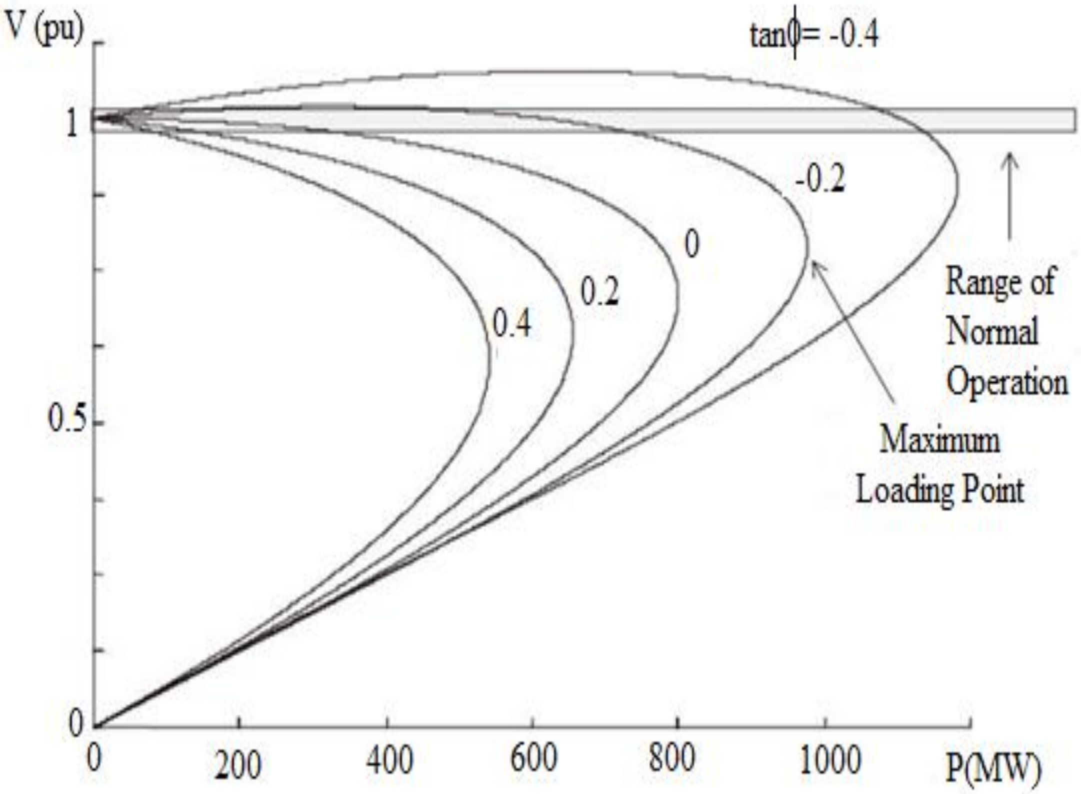

Fig. 2.3 PV Curve

$$\sqrt{\frac{E^2}{2}-QX\pm\sqrt{\frac{E^2}{4}-X^2P^2-XE^2Q}} \qquad \text{……………………….. (2.7)}$$

This figure illustrates PV- curves for different load power factors. For each curve, it presents both solutions of the power system. The higher voltage solution, which is corresponding to "+ve" sign in eqn. 2.7 is stable, while the lower voltage, corresponding to "-ve" sign, is unstable. In normal operation, power systems are operated in the upper part of the PV-curve. The head of the curve is called the maximum power point where solutions unite The maximum power and the voltage of the point are obtained when the impedance of the load is equal with the impedance of the transmission line [13]. They are calculated as follows:

$$P_{\max} = \frac{\cos\phi}{1+\sin\phi}\frac{E^2}{2X} \qquad \text{………………………. (2.8)}$$

$$V_{\max} = \frac{E}{\sqrt{2}\sqrt{1+\sin\phi}} \qquad \text{……………………… (2.9)}$$

$$\cos\phi = \frac{P}{\sqrt{P^2+Q^2}} \qquad \text{…………………… (2.10)}$$

PV-curves play a major role in understanding and explaining voltage stability. From a PV curve, the variation of bus voltages with load, distance to instability (VS margin) and critical voltage at which instability occurs may be determined.

2.5.2 Voltage stability of a simple 2-bus system

The basic concept of voltage stability can be explained with a simple two-bus system shown in Fig. 2.4.The load is of constant power type. Real power transfer from bus 1 to 2 is given by [10].

$$P = \frac{EV}{X}\sin\delta \qquad \text{..…………………… (2.11)}$$

Reactive power transfer from bus 1 to bus 2

$$Q = -\frac{V^2}{X} + \frac{EV}{X}\cos\delta \qquad \text{..…………………… (2.12)}$$

Where, $E = E\angle\delta$ is the voltage at bus 1.

$V = V\angle 0$ is the voltage at bus 2.

X = impedance of the line.

δ = power angle

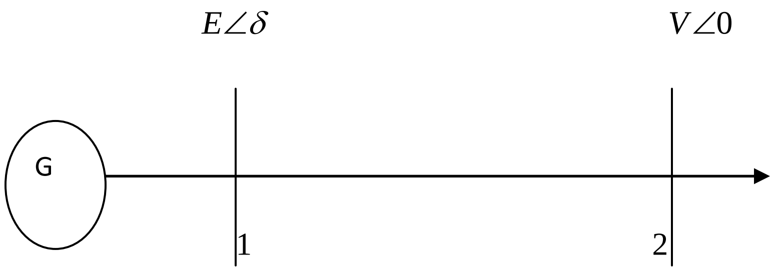

Fig. 2.4 Simple Two-Bus System

Normalizing the term in eqn. (2.11) and eqn. (2.12) , $v = \frac{V}{E}$, $p = \frac{P.X}{E^2}$ we obtain $q = \frac{Q.X}{E^2}$, one obtains

$p = v\sin\delta$ …………………….. (2.13)

$q = -v^2 + \cos\delta$ ……………………. (2.14)

$v^2(\sin^2\delta + \cos^2\delta) = p^2 + (q + v^2)$

or

$v^4 + v^2(2q+1) + (p^2 + q^2) = 0$ .....…………………. (2.15)

Positive real solution of v from (5.10) are given by

$v = \sqrt{\frac{1}{2} - q \pm \sqrt{\frac{1}{4} - p^2 - q^2}}$ ..…………………… (2.16)

2.6 Reasons of Voltage Instability

- Failure to provide desired voltage magnitude and voltage phase angle that is necessary to achieve power support to the loads.
- Increase in loading.
- Unable to provide systems reactive power demand.
- Due to generator reactive power supply capabilities and transformer tap limits.
- Inconsistency in the load power requirements as a function of bus voltage and power supply characteristics.
- Line tripping or generator outages.

Most of these changes have a significant impact on the reactive power production, consumption and transmission in the system.

2.7 Prevention of Voltage Instability

Some of the preventions to avoid voltage stability are:

- Placement of Series and Shunt Capacitors.
- Generation Redispatch.
- Placement of FACTS Controllers.
- Load Shedding.
- Blocking of Tap-Changer Transformers.
- Installation of Synchronous Condensers.
- Temporary reactive power overloading of generators

2.8 Voltage Profile Improvement

Voltage profile plays a major role to provide information regarding system stability, line outage and reactive power compensation**.** Voltage stability and system stability are interrelated, and is defined as the difference between load ability limit and current operating load level. Modern power system is becoming more and more complex due to increase in power demand and large interconnected power system, so the power system becomes less reliable and secure. Planning and operation of such a large interconnected system lead to instability. Voltage instability is one of the instability which results in a major blackout. A good voltage profile can be achieved by providing voltage support. The voltage and reactive power are linked with each other. So voltage profile can be improved by reactive power compensation at the point of coupling. Mechanically switched capacitor is one of the reactive power compensation methods. Switching may be done via signals from a SCADA system on the timing schedule basis, or no switching at all. But this method also suffers from a disadvantage of the slow speed of operation or operation with some time delay. Voltage stability can be achieved by tap changing transformer, but this is an expensive method of stability improvement.

The real and reactive power flow in a transmission line depends on the various parameters such as sending end and receiving end voltages, phase difference between voltages and line reactance. The FACTS technology has the ability to control such parameters in real time, and vary the transmitted power according to the system requirement. By controlling the power flow rapidly within the prescribed limits, it could become possible to increase transient and dynamic stability, as well as damping of power oscillations.

2.9 Introduction to FACTS Devices

Flexible AC Transmission System (FACTS) is defined by IEEE as "Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability."

With the rapid development in the power electronics industry, Flexible Alternating Current Transmission System (FACTS) devices are being used in power systems. FACTS controllers are capable of controlling the network condition in a very fast manner and afford unique control flexibility and versatility. This feature of FACTS can be exploited to improve the voltage stability, and steady state and transient stabilities of a complex power system. This allows increased utilization of existing network closer to its thermal loading capacity, and thus FACTS technology is being promoted as a means to extend the capacity of existing power transmission networks to their limits without the necessity of adding new transmission lines. Other potential advantages of FACTS lie in their ability to improve damping and to control the flow of power through selected corridors in a network. This extra flexibility permits the independent adjustment of certain system variables (such as power flows) which are normally not controllable. FACTS devices can be differentiated by their controllable parameters and by the manner in which they are realized electronically. Thus, devices exist which can control line series or shunt reactance**,** phase-shifting transformer angle or combinations of these**.** Other devices inject controllable voltages in series or in parallel with the line being compensated [2].

2.10 Basic Types of FACTS Controller

2.10.1 Shunt Connected Controllers

The shunt Controllers may be variable impedance, variable source, or a combination of these. In principle, all shunt Controllers inject current into the system at the point of connection. Even variable shunt impedance connected to the line voltage causes a variable current flow and hence represents an injection of current into the line. As long as the injected current is in phase quadrature with the line voltage, the shunt Controller only supplies or consumes variable reactive power. Any other phase relationship will involve the handling of real power as well. Fig.2.5.1 shows the shunt connected controller.

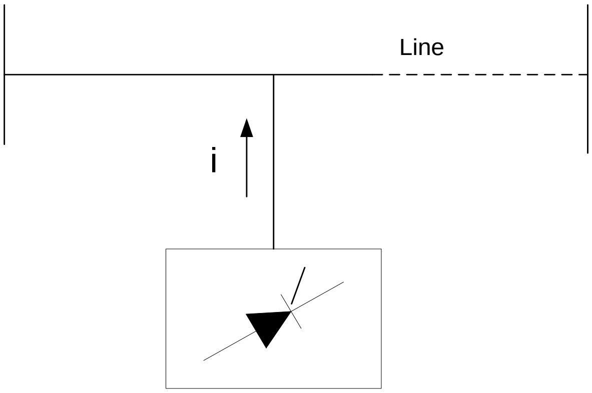

Fig.2.5.1 Shunt Connected Controller

Static VAR Compensator (SVC) is a shunt connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage). It is a first generation FACTS device that can control voltage at the required bus thereby improving the voltage profile of the system. This is a general term for a thyristor-controlled or thyristor-switched reactor, and/or thyristor-switched capacitor or combination. SVC is based on thyristors without the gate turn-off capability. It includes separate equipment for leading and lagging vars; the thyristor-controlled or thyristor-switched reactor for absorbing reactive power and thyristor-switched capacitor for supplying the reactive power. SVC is considered by some as a lower cost alternative to STATCOM, although this may not be the case if the comparison is made based on the required performance and not just the MVA size. The primary task of an SVC is to maintain the voltage at a particular bus by means of reactive power compensation (obtained by varying the firing angle of the thyristors). SVCs have been used for high performance steady state and transient voltage control compared with classical shunt compensation. SVCs are also used to damping power swings, improve transient stability, and reduce system losses by optimized reactive power control [15].

Thyristor Controlled Reactor (TCR): A shunt-connected, thyristor-controlled inductor whose effective reactance is varied in a continuous manner by partial-conduction control of the thyristor valve. TCR is a subset of SVC in which conduction time and hence, current in a shunt reactor is controlled by a thyristor-based ac switch with firing angle control.

Thyristor Switched Reactor (TSR): A shunt-connected, thyristor-switched inductor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve. TSR is another subset of SVC. TSR is made up of several shunt connected inductors which are switched in and out by thyristor switches without any firing angle controls in order to achieve the required step changes in the reactive power consumed by the system. Use of thyristor switches without firing angle control results in lower cost and losses, but without a continuous control.

Thyristor Switched Capacitor (TSC): A shunt-connected, thyristor-switched capacitor whose effective reactance is varied in a stepwise manner by full or zero conduction operation of the thyristor valve. TSC is also a subset of SVC in which thyristor based ac switches are used to switch in and out (without firing angle control) shunt capacitors units, in order to achieve the required step change in the reactive power supplied to the system. Unlike shunt reactors, shunt capacitors cannot be switched continuously with variable firing angle control.

Static Synchronous Compensator (STATCOM) is a static synchronous generator operated as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independently of the ac system voltage [7].

STATCOM is one of the key FACTS Controllers. It can be based on a voltage sourced or current-sourced converter. As mentioned before, from an overall cost point of view, the voltage-sourced converters seem to be preferred, and will be the basis for presentations of most converter-based FACTS Controllers.

For the voltage-source converter, its ac output voltage is controlled such that it is just right for the required reactive current flow for any ac bus voltage dc capacitor voltage is automatically adjusted as required to serve as a voltage source for the converter. STATCOM can be designed to also act as an active filter to absorb system harmonics.

STATCOM as defined above by IEEE is a subset of the broad based shunt connected Controller which includes the possibility of an active power source or storage on the dc side so that the injected current may include active power.

2.10.2 Series Connected Controllers

The series Controller could be variable impedance, such as capacitor, reactor, etc., or power electronics based variable source of main frequency, sub-synchronous and harmonic frequencies (or a combination) to serve the desired need, is shown in Fig. 2.5.2. In principle, all series Controllers inject a voltage in series with the line. Even variable impedance multiplied by the current flow through it, represents an injected series voltage in the line. As long as the voltage is in phase quadrature with the line current, the series Controller only supplies or consumes variable reactive power. Any other phase relationship will involve the handling of real power as well.

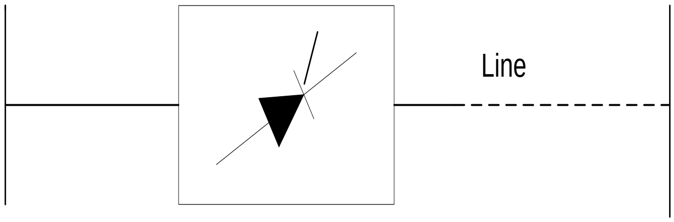

Fig. 2.5.2 Series Connected Controller

Thyristor Controlled Series Capacitor (TCSC) is a capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance. It is an alternative to SSSC above and like an SSSC; it is a very important FACTS Controller. A variable reactor such as a Thyristor-Controlled Reactor (TCR) is connected across a series capacitor. When the TCR firing angle is 180 degrees, the reactor becomes non-conducting and the series capacitor has its normal impedance. As the firing angle is advanced from 180 degrees to less than 180 degrees, the capacitive impedance increases. At the other end, when the TCR firing angle is 90 degrees, the reactor becomes fully conducting, and the total impedance becomes inductive, because the reactor impedance is designed to be much lower than the series capacitor impedance. With 90 degrees firing angle, the TCSC helps in limiting fault current. The TCSC may be a single, large unit, or may consist of several equal or different-sized smaller capacitors in order to achieve a superior performance. It is one of the important members of FACTS family that is increasingly applied with long transmission lines by the utilities in modern power systems. It can have various roles in the operation and control of power systems, such as scheduling power flow, decreasing unsymmetrical components, reducing net loss, providing voltage support, limiting short-circuit currents, mitigating sub-synchronous resonance (SSR), damping the power oscillation, and enhancing transient stability [15].

Thyristor-Switched Series Capacitor (TSSC): A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-switched reactor to provide a stepwise control of series capacitive reactance, instead of continuous control of capacitive impedance. This approach of switching inductors at firing angle of 90 degrees or 180 degrees but without firing angle control could reduce cost and losses of the Controller. It is reasonable to arrange one of the modules to have thyristor control, while others could be thyristor switched.

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

Thyristor-Switched Series Reactor (TSSR): An inductive reactance compensator which consists of a series reactor shunted by a thyristor-controlled switched reactor in order to provide a stepwise control of series inductive reactance. This is a complement of TCSR, but with thyristor switches fully on or off (without firing angle control) to achieve a combination of stepped series inductance.

Static Synchronous Series Compensator (SSSC) is a member of FACTS family which is connected in series with a power system. It consists of a solid state voltage source converter which generates a controllable alternating current voltage at the fundamental frequency. When the injected voltage is kept in quadrature with the line current, it can emulate as inductive or capacitive reactance so as to influence the power flow through the transmission line. While the primary purpose of a SSSC is to control power flow in steady state, it can also improve transient stability of a power system [7].

2.10.3 Combined Series and Shunt Controllers

This could be a combination of separate shunt and series Controllers, which are controlled in a coordinated manner, shown in Fig.2.5.3 (a), or a Unified Power Flow Controller with the series and shunt elements Fig.2.5.3 (b). In principle, combined shunt and series Controllers inject current into the system with the shunt part of the Controller and voltage in series in the line with the series part of the Controller. However, when the shunt and series Controllers are unified, there can be a real power exchange between the series and shunt Controllers via the power link.

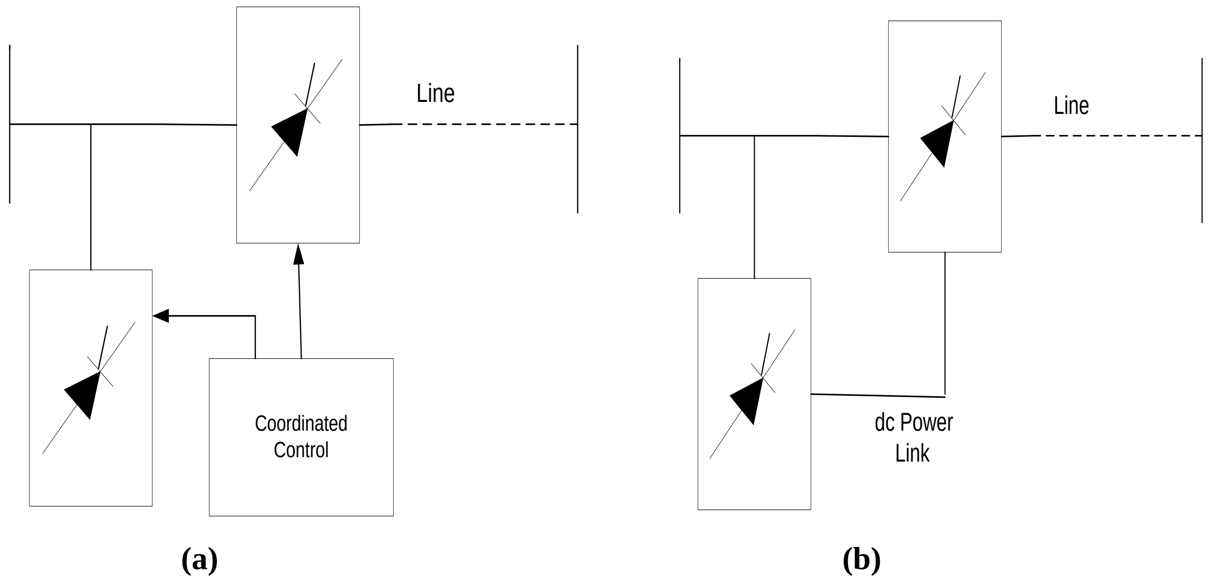

Fig. 2.5.3 Series and Shunt Controller

Unified power Flow controller (UPFC) among the available FACTS devices, is the most versatile one that can be used to improve steady state stability, dynamic stability and transient stability. The UPFC can independently control many parameters since it is the combination of Static Synchronous Compensator (STATCOM) and SSSC. These devices offer an alternative mean to mitigate power system oscillations. It has been reported in many papers that UPFC can improve stability of single machine infinite bus (SMIB) system and multi-machine system. The inter-area power system has special characteristics of stability behavior. This paper investigates the improvement of transient stability of a two-area power system with a UPFC. A Matlab/Simulink model is developed for a two-area power system with a UPFC. The performance of UPFC is compared with other FACTS devices such as SVC, TCSC, and SSSC respectively. From the simulation results, it is inferred that UPFC is an effective FACTS device for the transient stability improvement [23].

2.10.4 Combined Series-Series Controllers

This could be a combination of separate series controllers, which are controlled in a coordinated manner, in a multiline transmission system, shown in Fig. 2.5.4. Or it could be a unified

Controller, Fig. 2.5.4, in which series Controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link. The real power transfer capability of the unified series-series Controller, referred to as Interline Power Flow Controller, makes it possible to balance both the real and reactive power flow in the lines and thereby maximize the utilization of the transmission system.

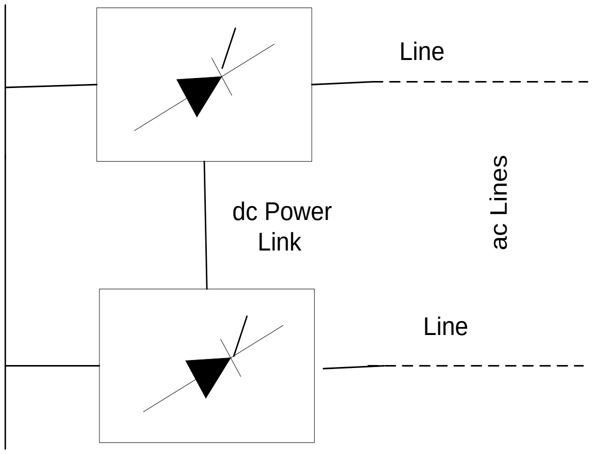

Fig.2.5.4 Series-Series Controller

Note that the term "unified" here means that the terminals of all Controller converters are connected together for real power transfer.

FACTS technology opens up new opportunities for controlling power and enhancing the usable capacity of the present, as well as new and upgraded lines and it consists of devices which depend on the reliable and high speed power electronic devices instead of mechanical controllers. Thus, the utilization of the existing power system comes into optimal condition and the increased controllability of the system make the power system more reliable, secure and reduce the cost of electricity. These opportunities arise through the ability of FACTS controllers to control the interrelated parameters that govern the operation of transmission systems including series impedance, shunt impedance, current, voltage, phase angle, and the damping of oscillations at various frequencies below the rated frequency. It is not possible to overcome these constraints by mechanical means without lowering the useable transmission capacity.

Control of any of the above parameters can help to control the power flow and the process is known as compensation. FACTS devices could be placed either in series or in shunt with the transmission line with the intention of controlling the power flow in it. If the transmission line impedance is modified by the addition of FACTS, it is termed as series compensation. If the phase angle difference is modified, it is termed as phase angle compensation. Shunt compensation, in which the FACTS device is placed in parallel, is mainly used to improve the system voltage characteristics. Static VAR compensator (SVC) belongs to this family of FACTS devices.

By providing added flexibility, FACTS controllers can enable a line to carry power closer to its thermal rating. The latest generation of FACTS controllers is based on the concept of the solid state synchronous voltage source (SVS). The SVS behaves as an ideal synchronous machine because it can generate fundamental three phase balanced sinusoidal voltage of controllable amplitude and the phase angle. It can generate the reactive power and with the approximate storage device it also can exchange the real power with the ac system. The SVS can be implemented by using the voltage sourced converter (SVC). The SVS can be used as a shunt or series compensator. If it operates as a shunt compensator it is called a static compensator (STATCOM) and if as a series compensator it is called a static synchronous series compensator (SSSC). But the most versatile controller in the FACTS family is unified power flow controller (UPFC) because it can operate as a shunt and series compensator. The UPFC is a combination of STATCOM and SSSC.

The advantages of the SVS compensators over the mechanical and thyristor compensators are:

- Better performance and the operating characteristic.
- Reduced equipment size and installation cost.
- Uniform use of same power electronic device in different compensation and control applications.

Various possible benefits from FACTS technology:

- Provide greater flexibility and reliability
- Power flows Control
- Increase the loading capability of lines
- Increase the system security
- Expansion of lines
- Mitigate voltage sags

CHAPTER-3

Unified Power Flow Controller (UPFC)

3.1 Introduction to UPFC

The UPFC is one of the most effective FACTS controllers. It provides multi-functional flexibility required to solve many of the problems faced by the power industry and able to control, simultaneously or selectively, all the parameters i.e. voltage, impedance, and phase angle, affecting power flow in the transmission line [7]. It consists of two VSC's connected back-to-back through a DC link capacitor. One of the VSC perform the function of STATCOM by injecting current in the transmission line through transformer and other VSC performs the function of SSSC by injecting voltage of controllable magnitude and angle in series through a series insertion transformer.

3.2 Introduction to STATCOM

Static Synchronous Compensator (STATCOM) is a voltage source converter connected in shunt with the power system, capable of controlling the transmission line voltage by internally generating reactive power (either inductive or capacitive). It is based on voltage source converter device and it acts both as a sink and source of reactive power depending on the system requirements. Electrical loads both generate and absorb reactive power. Since the transmitted load often varies considerably from one hour to another, the reactive power balance in a grid varies as well. The result can be unacceptable voltage amplitude variations, a voltage depression, or even a voltage collapse.

STATCOM can provide instantaneous and continuously variable reactive power in response to grid voltage transients, enhancing the grid voltage stability. The STATCOM operates according to voltage source principles and PWM switching of IGBTs (Insulated Gate Bipolar Transistors) rating and response speed. The STATCOM has a characteristic similar to the synchronous condenser, but as an electronic device it has no inertia and is superior to the synchronous condenser in several ways, such as better dynamics, a lower investment cost and lower operating and maintenance costs. The main applications in transmission, distribution and industrial networks are:

- Reduction of unwanted reactive power flows and therefore reduced network losses.
- Keeping of contractual power exchanges with balanced reactive power.
- Compensation of consumers and improvement of power quality especially with huge demand fluctuations like industrial machines, metal melting plants, railway or underground train systems.
- Compensation of Thyristor converters e.g. in conventional HVDC lines.
- Improvement of static or transient stability.

3.2.1 STATCOM Installation

Static synchronous compensator/static synchronous condenser is a regulating device used in power system for ac transmission. Installing a STATCOM at one or more suitable points in the network will increase the grid transfer capability through enhanced voltage stability, while maintaining a smooth voltage profile under different network conditions. The STATCOM provides additional versatility in terms of power quality improvement capabilities.

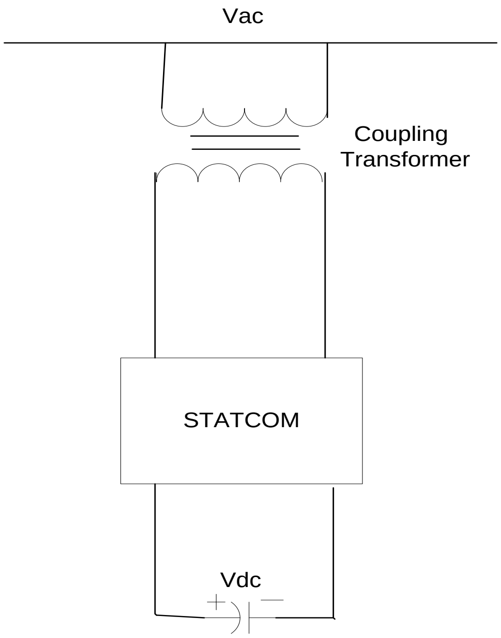

Fig. 3.1 STATCOM Structure

A STATCOM is build with Thyristors with turn-off capability like IGBTs. The structure of STATCOM is shown in Fig. 3.1. In the distributed energy sector the usage of Voltage Source Converters for grid interconnection is common practice today. The next step in STATCOM development is the combination with energy storages on the DC-side. The performance for power quality and balanced network operation can be improved much more with the combination of active and reactive power.

3.2.2 Features of STATCOM

1. Compact size.
2. System voltage support and stabilization by smooth control over a wide range of operating conditions.
3. Dynamic response following system contingencies.
4. High reliability with redundant converter design and modular construction.
5. Flexibility of future reconfiguration to back to back power transmission or UPFC (unified power flow controller) and other configurations.

3.3 Introduction to SSSC

Static Synchronous Series Compensator (SSSC) is a series connected voltage source converter which can modify the effective line impedance, and an alternative to series line compensation. This compensator is, in general, a solid-state switching converter which is able to exchange active and reactive power at its output terminals with an ac power system, when operated with an appropriate dc power supply at its input terminals. When coupled to an energy storage capacitor, an SSSC can only generate or absorb reactive power to and from the system. The SSSC is operated as a series compensator without an external electric energy source, whose output voltage is controllable and is in quadrature with the line current. It is employed for increasing or decreasing the overall reactive voltage drop across the line, thus modeling an inductive or a capacitive reactance in series with the transmission line. This variable reactance influences the electric power flow in the transmission line. A small component of the voltage which is in phase with the line current provides for the losses in the inverter.

The transmitted real power therefore becomes a parametric function of the injected voltage *(Vs)* and can be expressed as follows:

$$P = \frac{V^2}{X_L - X_q} \operatorname{Sin}\delta \qquad \text{.......................... (3.1)}$$

$$X_q = \frac{V_q}{I} \qquad \text{.......................... (3.2)}$$

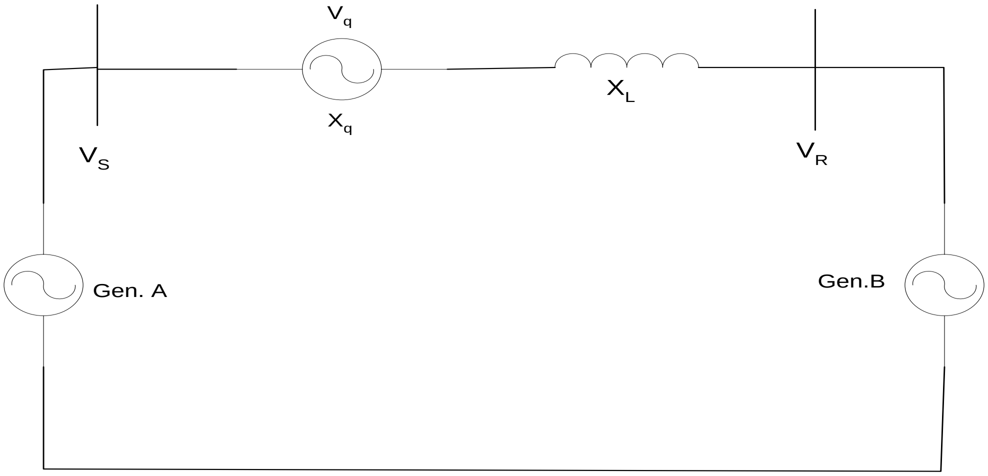

Fig. 3.2 Basic two machine system with a SSSC

The compensating reactance (Xq) illustrated in Fig. 3.2 is defined to be negative when the SSSC is operated in an inductive mode; the compensating reactance has a positive value when the SSSC is operating in the capacitive mode. The effects of the compensating reactance on the normalized power flow in the transmission line are as follows: when the emulated reactance is inductive, the real and reactive power flow decrease and the effective reactance increases as the reactance compensation increases in the negative direction, and when the emulated reactance is capacitive the real and reactive power flow increase and the effective reactance decreases as the reactance compensation increases in the positive direction.

While the TCSC can be modeled as series impedance, the SSSC is a series voltage source. The idea of SSSC is to inject voltage in series with the transmission line. The magnitude of inserted voltage is fully controlled while the phase angle is maintained in quadrature with the line current. Unlike the TCSC, the SSSC is able to maintain a constant compensating voltage in face of variable line current or control the amplitude of the injected compensating voltage independent of the amplitude of the line current. However, the angle of the injected voltage can lead or lag the line current which corresponds to adding a series capacitance or inductance with the transmission line.

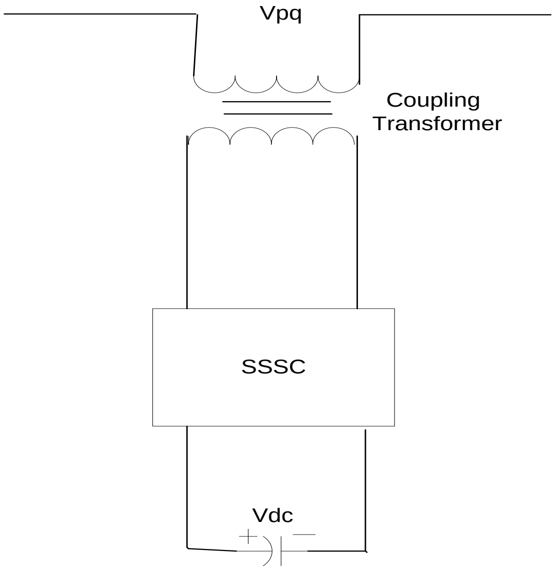

Fig. 3.3 SSSC Structure

As the SSSC is based on the principle of voltage source inverter, it is self sufficient in generating or absorbing reactive power. The SSSC structure is shown in Fig. 3.3. The TCSC can only increase the transmitted power by a fixed percentage of the uncompensated power at a given transmission angle. However, the SSSC can increase or decrease the transmitted power by a fixed fraction of the maximum power transmitted by the uncompensated line.

The SSSC can exchange both reactive and real power with the ac system, simply by controlling the phase angle of the injected voltage with respect to the line current. The exchange of real power requires that the dc terminal of the SSSC should be connected to an energy source/sink.

3.4 Unified Power Flow Controller (UPFC)

The Unified Power Flow Controller (UPFC) concept was proposed by Gyugyi in 1991. UPFC is the member of FACTS device that has emerged for the control and optimization of power flow in electrical power transmission systems. A UPFC is a power electronics-based system which can provide control of the transmission line impedance, phase angle and reactive power. It provides multifunctional flexibility required to solve many of the problems being faced by power industry. The UPFC is able to control simultaneously or selectively, all the parameters affecting power flow in the transmission line (i.e. voltage, impedance, and phase angle) and this unique capability is due to both series and shunt compensation to a transmission line simultaneously [7].

As it consists of a series converter namely Static Synchronous Series Compensator (SSSC), injects a voltage in series with the system voltage provides the most cost effective solution to mitigate voltage sags by improving power quality level that is required by customer and a shunt converter namely Static Synchronous Compensator (STATCOM) connected by a DC link capacitor, to allow bi-directional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source. 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 real and reactive power flow in the line. The transmission line voltage can be controlled by the Static Synchronous Compensator (STATCOM) which is shunt-connected; the line impedance can be effectively controlled by the series-connected Static Synchronous Series Compensator (SSSC). The UPFC may also provide independently controllable shunt reactive compensation. Viewing the operation of the UPFC from the standpoint of conventional power transmission based on reactive shunt compensation, series compensation and phase shifting, the UPFC can fulfill all these functions and thereby meet multiple control objectives by injection of voltage. It can simultaneously perform the function of transmission line real/reactive power flow control in addition to UPFC bus voltage/shunt reactive power control. The control of real power is associated with similar change in reactive power, i.e. increased real power flow also resulted in increased reactive power.

3.4.1 Basic Operating Principle

In the presently used practical implementation, the UPFC consists of two voltage sourced converters, as illustrated in Fig.2.4, these back to back converters, labeled “converter 1” and “converter 2” in the figure, are operated from a common dc link provided by a dc storage capacitor. This arrangement functions as an ideal ac-to-ac power converter in which the real power can freely flow in either direction between the ac terminals of the two converters, and each converter can independently generate or absorb reactive power at its own ac output terminal.

Converter 2 provides the main function of UPFC by injecting a voltage V_{pq} with controllable magnitude V_{pq} and phase angle in series with the line via an insertion transformer. This injected voltage acts essentially as a synchronous ac voltage source. The transmission line current flows through this voltage source resulting in reactive and real power exchange between it and the ac system. The reactive power exchanged at the ac terminal is generated internally by the converter. The real power exchanged at the ac terminal is converted into dc power which appears at the dc link as a positive or negative real power demanded.

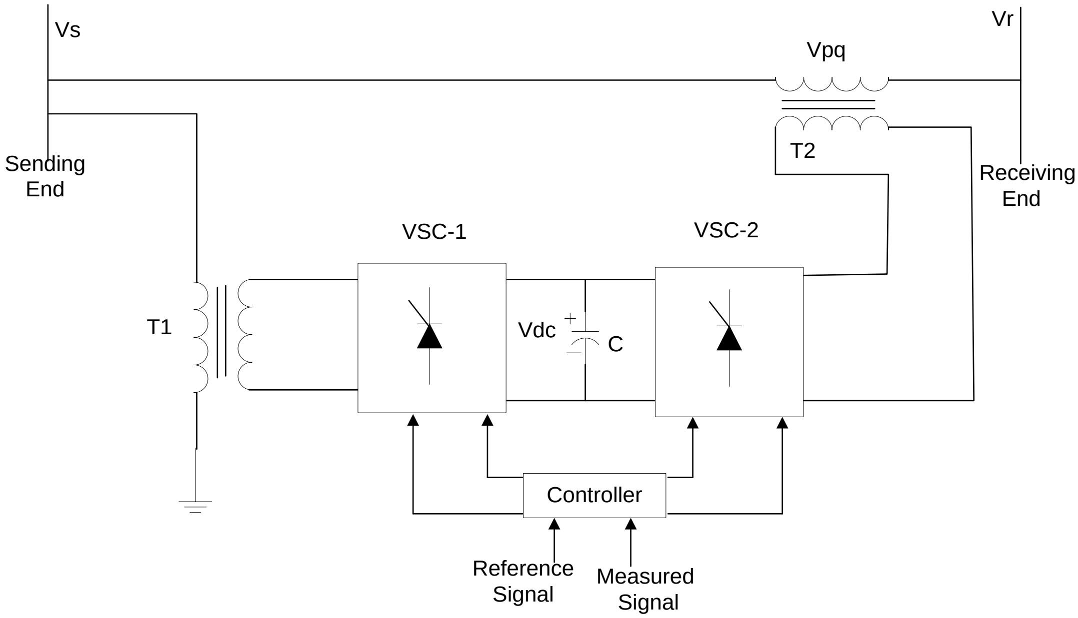

Fig. 3.4 UPFC Structure

The basic function of converter 1 is to supply or absorb the real power demanded by converter 2 at the common dc link to support the real power exchange resulting from the series voltage injection. This dc link power demanded by converter 2 is converted back to ac by converter 1 and coupled to the transmission line bus via a shunt connected transformer. In addition to real power demand of converter 2, converter 1 can also generate or absorb controllable reactive power, if it is desired, and thereby provide independent shunt reactive compensation for the line. It is important to note that whereas there is a closed direct path for the real power negotiated by the action of series voltage injection through converter 1 and 2 back to the line, the corresponding reactive power exchanged is supplied or absorbed locally by converter 2 and therefore does not have to be transmitted by the line. Thus, converter 1 can be operated at a unity power factor or to be controlled to have a reactive power exchange with the line independent of the reactive power exchanged by converter 2. Obviously, there can be no reactive power flow through the UPFC dc link.

3.4.2 Transmission Control Capabilities

Viewing the operation of the Unified Power Flow Controller from the standpoint of traditional power transmission based on reactive shunt compensation, series compensation, and phase angle regulation, the UPFC can fulfill all these functions and thereby meet multiple control objectives by adding the injected voltage V_{pq} with appropriate amplitude and phase angle, to the (sending-end) terminal voltage Vs. Using phasor representation, the basic UPFC power flow control functions are illustrated in Figure 3.5 [7].

Voltage regulation with continuously variable in-phase/anti-phase voltage injection, is shown in Figure 3.5(a) for voltage increments Vpq = ±ΔV ($\rho = 0$). This is functionally similar to that obtainable with a transformer tap changer having infinitely small steps.

Series reactive compensation is shown in Figure 3.5(b) where Vpq = Vq is injected in quadrature with the line current I. Functionally this is similar to series capacitive and inductive line compensation attained by the SSSC. The injected series compensating voltage can be kept constant, if desired, independent of line current variation, or can be varied in proportion with the line current to imitate the compensation obtained with a series capacitor or reactor.

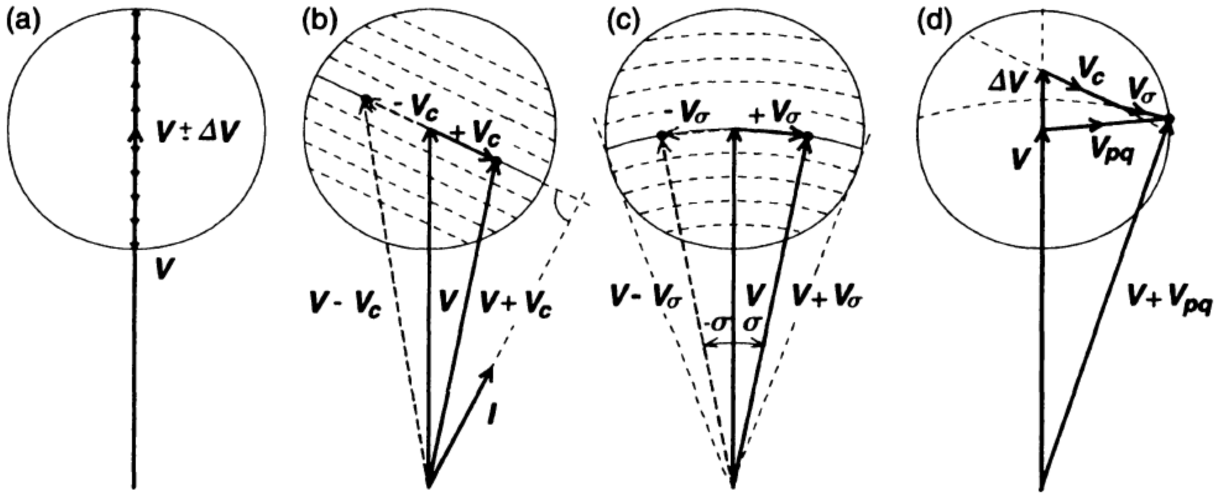

Fig. 3.5 Phasor Diagrams

Phase angle regulation (phase shift) is shown in Figure 3.5(c) where Vpq = Vσ is injected with an angular relationship with respect to V_s, that achieves the desired σ phase shift (advance or retard) without any change in magnitude. Thus the UPFC can function as a perfect Phase Angle Regulator which can also supply the reactive power involved with the transmission angle control by internal Var generation.

Multifunction power flow control, executed by simultaneous terminal voltage regulation, series capacitive line compensation, and phase shifting, is shown in Figure 3.5(d) where,

$$Vpq = \Delta V + Vq + V\sigma$$

This functional capability is unique to the UPFC. No single conventional equipment has similar multifunctional capability. The general power flow control capability of the UPFC, from the viewpoint of transmission control, can be illustrated best by the real and reactive power in the transmission line. The real and reactive power characterizing the power transmission of the uncompensated system at a given angle δ. Since angle ρ is freely variable between 0 and 2π at any given transmission angle $\delta(0 \leq \delta \leq \pi)$, it follows that Ppq($\rho$) and Qpq($\rho$) are controllable between –V*Vpq/X and +V*Vpq/X independent of angle δ.

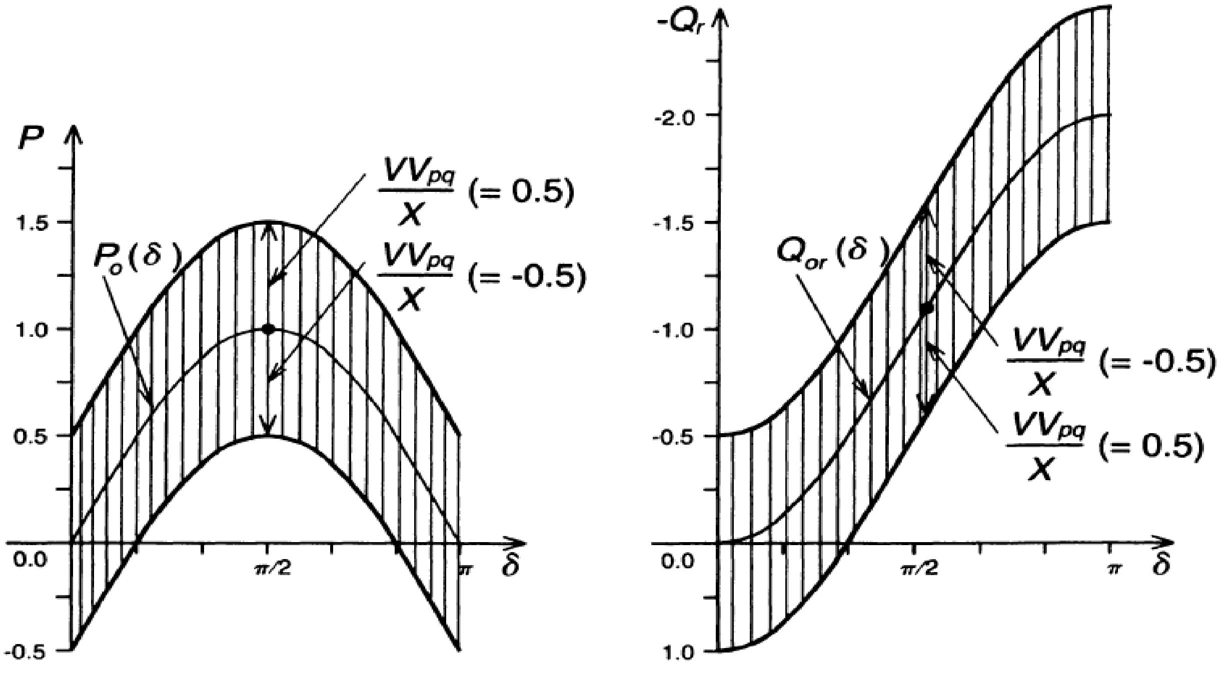

Fig. 3.6 Range of transmittable real power P and receiving-end reactive power demand Q vs transmission angle δ of a UPFC controlled transmission line.

Therefore, the transmittable real power P is controllable between

$$P_o(\delta) - \frac{V*Vpqmax}{X} \leq P_o(\delta) \leq P_o(\delta) + \frac{V*Vpqmax}{X} \qquad \text{………………………} (3.3)$$

And reactive power Q, is controllable between at any transmission angleδ, as shown in Fig. 3.6.

$$Q_o(\delta) - \frac{V*Vpqmax}{X} \leq Q_o(\delta) \leq Q_o(\delta) + \frac{V*Vpqmax}{X} \qquad \text{………………………} (3.4)$$

The wide range of control for the transmitted power that is independent of the transmission angle δ, observable in the figure, indicates not only superior capability of the UPFC in power flow applications, but it also suggests powerful capacity for transient stability improvement and power oscillation damping.

3.5 abc to dq0 Transformation

The abc to dq0 transformation is also known as Park's Transformation. It is a space vector transformation used to simplify the analysis of three-phase circuits. Basically, this transformation is a mathematical transformation of three-phase signals (i.e. abc) to dq0 signals. In the case of balanced three-phase circuits, application of the dqo transform reduces the three AC quantities to two DC quantities. Simplified calculations can then be carried out on these two DC quantities before performing the inverse transform to recover the actual three-phase AC results. It is often used in order to simplify the analysis of three-phase synchronous machines or to simplify calculations for the control of three-phase inverters.

The dq0 transformation applied to three-phase current is shown below:

$$[I_{dq0}] = \begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} = K[I_{abc}] = K\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

Similarly, the dq0 transformation for three-phase voltage is given as:

$$[V_{dq0}] = \begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = K[V_{abc}] = K\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

Where,

$$K = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

3.5.1 Instantaneous Power in dq0 Frame

The instantaneous active and reactive power from a set of two-phase (dq) voltages and currents are:

$$P = V_d I_d + V_q I_q \qquad \text{……………………….. (3.5)}$$

$$Q = V_q I_d - V_d I_q \qquad \text{……………………….. (3.6)}$$

When the synchronous frame is aligned to voltage, we saw earlier that the quadrature component : $V_q = 0$. Therefore, the power eqns. (3.5) and (3.6) reduce to:

$$P = V_d I_d \qquad \text{……………………… (3.7)}$$

$$Q = -V_d I_q \qquad \text{……………………… (3.8)}$$

The above eqns. (3.7) and (3.8) shows that independent control of active and reactive power is possible by means of controlling the dq current components (I_d and I_q).

3.5.2 Advantages of dq0 Transform:

1) The dq0 transform reduces three-phase AC quantities (e.g. V_a, V_b and V_c) into two DC quantities (e.g. V_d, V_q). For balanced systems, the 0-component is zero. The DC quantities facilitate easier filtering and control.

2) Active and reactive power can be controlled independently by controlling the dq components.

CHAPTER- 4

Literature Review

Noroozian *et al.* (1997) demonstrated the capability of UPFC in power flow application. A steady state mathematical model for the UPFC was proposed. It was shown that UPFC can be controlled in a power system to satisfy the several objectives such as regulating power flow through a transmission line and minimization of power loss without generation reschedule.

Sen *et al.* (1998) modeled a UPFC using Simulation that consists of two voltage source inverters-one injected the almost sinusoidal voltage in series with the transmission line at any angle with the line current and other injected the almost sinusoidal current at the point of connection which has real and reactive part. The real part was in phase with the line voltage and the reactive part was in quadrature with the line voltage.

Sanbao *et al.* (2000) studied the dynamic characteristics of UPFC based on a detailed Simulink model. Analysis of the simple power system with the UPFC has shown that the UPFC can control the voltage and the power flow control of the system effectively. The used control strategy was based on the need to maintain a desired power flow.

Kim *et al.* (2000) presented a UPFC operation algorithm .The proposed algorithm controls real powers of multiple UPFCs with their reactive powers maintained as constants. The proposed algorithm was tested with 3 UPFCs on the normal operating system and on the same system with a line fault. The study had shown two results. The first was: UPFCs operated by the proposed algorithm could provide the normal operating system with the relief of the power flow congestion in the system and enhanced the system security level. Second was by applying the algorithm, the UPFCs with a proper capacity could enlarge the security margin to prevent the overload problem of the system in an increased load or faulted condition.

Takeshita *et al*.(2002) focused on controlling the output voltage of SSSC to zero for sufficiently stabilizing the fluctuation of UPFC's. The UPFC controlling the output voltage of SSSC to zero operated as a fault current limiter. It reduced instantaneous voltage drops in the entire power system. To improve fault current limiting, a series reactor, which compensates completely for SSSC in normal conditions, was inserted between power systems.

Dong-Jun *et al.* (2003) constructed UPFC voltage-source model with equivalent voltage-sources and impedances using MATLAB. The dynamic responses of UPFC switching-level model were shown and the dynamic characteristics were analyzed. At first, detailed switching-level simulation had been performed. The results had shown that UPFC can control the bus voltage and power flow of transmission line. The appropriate equivalent impedances of UPFC model had been determined by optimization routine. This routine automatically determined the equivalent impedances. These impedances can be used efficiently in large power system simulation including UPFC.

Kannan *et al.* (2004) presented a new real and reactive power coordination controller for UPFC. The basic control strategy was such that the shunt converter of the UPFC controlled the UPFC bus voltage/shunt reactive power and the dc link capacitor voltage. The series converter controlled the transmission line real and reactive power flow. This real power coordinator avoided the two coordination problems, such as the problem of real power coordination between the series and the shunt converter control system and the other the problem of excessive UPFC bus voltage excursions during reactive power transfers requiring reactive power coordination.

Eskandar *et al. (2005)* presented an approach to improve transient stability of power system using UPFC and compared this method with other existing approaches, it was concluded that in this new method the active power oscillation was damped more rapidly and gave better stability performance than in the others.

Zhu *et al.* (2005) analyzed the real power, reactive power and voltage balance of UPFC. It provided the two important results related to UPFC. First, shunt converter provided all the required reactive power during power flow changes. Second, the UPFC bus voltage could be controlled both from the sending end and from the receiving end side. There would be two control schemes for the UPFC, conventional one and proposed one. The experiment results indicated that the proposed control scheme had a better reactive power flow control, however their real power flow control performance was same.

Xiaoyao *et al.* (2006) evaluated the performance of a distance relay as applied to a transmission system with UPFC. A detailed model of the UPFC and its control was proposed for the purpose of accurately simulating the fault transients and then an apparent impedance calculation procedure for a transmission line with UPFC based on the power frequency sequence component is investigated. The results highlighted the fundamental problems of protecting a transmission system employing a UPFC using distance protection.

Kalyani *et al.* (2008) presented control and performance of UPFC, intended for installation on a transmission line. A control system was simulated with shunt inverter in AC and DC voltage control mode and series inverter in open loop phase angle control mode. Simulation results had shown the effectiveness of UPFC in controlling real and reactive power through the line. Due to the AC voltage controller, AC voltage regulation was improved. The DC voltage controller maintains the DC link voltage to the DC voltage set point.

Guo *et al.* (2009) proposed a new control for UPFC. The proposed control exhibited very good performance in damping active power oscillations and maintaining the UPFC shunt bus voltage. The proposed control worked well in both large and small systems with rapid dynamic response and independent control. The primary advantages of the proposed control were (1) it worked over a wide range of operating conditions, (2) required only three parameters, and (3) the parameters were easily chosen and did not require considerable tuning effort.

Hu *et al.* (2010) proposed a new reliability model for UPFC. This model divided the UPFC operation into four states: UPFC up state, STATCOM state, SSSC state and UPFC down state, in order to improve the accuracy of model. Various operating schemes such as different placement locations of UPFC and different capacities of UPFC were used to illustrate the advantages of developed model and to examine the impact of UPFC on system reliability.

Muthukrishnan *et al.* (2010) presented the control and performance of the UPFC for power quality improvement using MATLAB simulink environment. Simulation results had shown the effectiveness of UPFC to control the real and reactive power. The real and reactive power was increased with the increase in angle of injection. UPFC system had advantage of reduced maintenance.

Shu-jun *et al.* (2011) researched on dynamic characteristics of Unified Power Flow Controller (UPFC). A detailed simulation model of UPFC considering the charging dynamics of its DC link capacitor was provided. The UPFC device in the dynamic simulation system, can adjust the distribution system power flow among the transmission line quickly and smoothly, and had no significant impact to other operating parameters of the system. At the same time, the UPFC can improve system stability and inhibit the line power flow oscillation.

Ahsaee *et al.* (2012) proposed a fault location algorithm of transmission line including UPFC. In this method, synchronized data of two sides of transmission line was used and the distributed parameter line model in the time domain was taken into account. Two quadratic equations were obtained assuming that the fault was located on the left-hand and right-hand side of UPFC. These two equations were used to derive an optimization problem. The location of fault was calculated by solving this problem.

CHAPTER-5
Results and Discussion

5.1. Simulation Model of Two Machine System

Simulink model of two machines two parallel transmission line systems with UPFC installed on one line is shown in Fig. 5.1

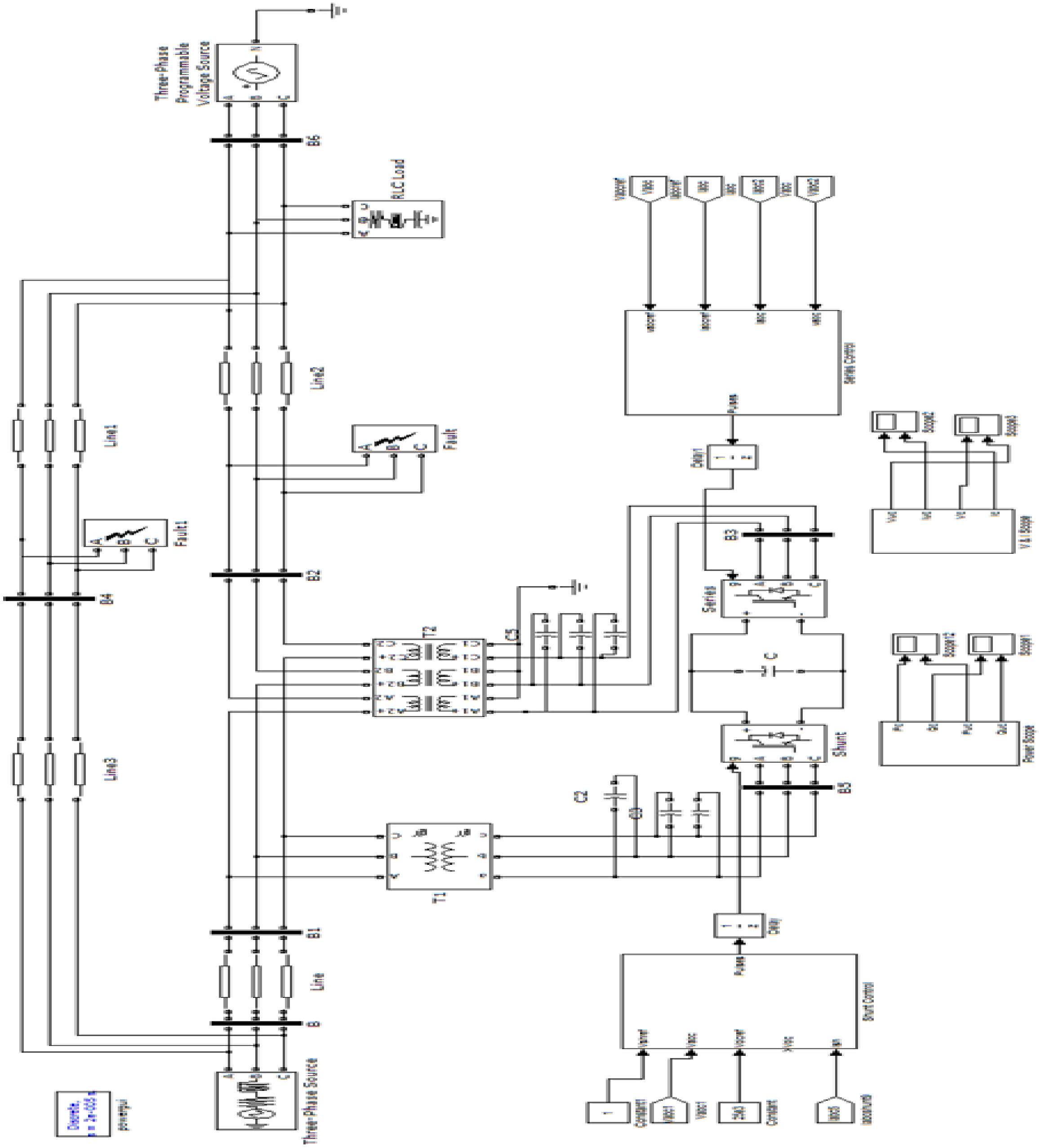

Fig. 5.1.Two Machine Simulink Model Installed with UPFC

Both machines are connected through two parallel 132KV, 200km transmission line. IGBT based UPFC is installed at midpoint of one transmission line.

5.2 Control Strategies of UPFC

Control part of UPFC includes series converter control and shunt converter control. For each part, of which the series converter controller controls the transmission line power (real and reactive power), impedance compensation, damp oscillations, whereas the shunt converter controller controls the bus voltage and DC link voltage, to achieve the bus voltage stability and control the power of the line under dynamic conditions.

5.2.1 Series Control Part

The series control part strategy shown in Fig. 5.2, is based on automatic power flow control mode. The voltage injected by series converter is determined by a closed-loop control system to ensure that the desired active and reactive powers flowing in the transmission line are maintained under disturbances. The reference real (P_{ref}) and reactive (Q_{ref}) power are compared with the measured positive real (P_m) and reactive (Q_m) power flowing in the transmission line, and the error of line power is applied to PI controller to derive the desired direct (V_d) and quadrature (V_q) component of the series inverter voltage.

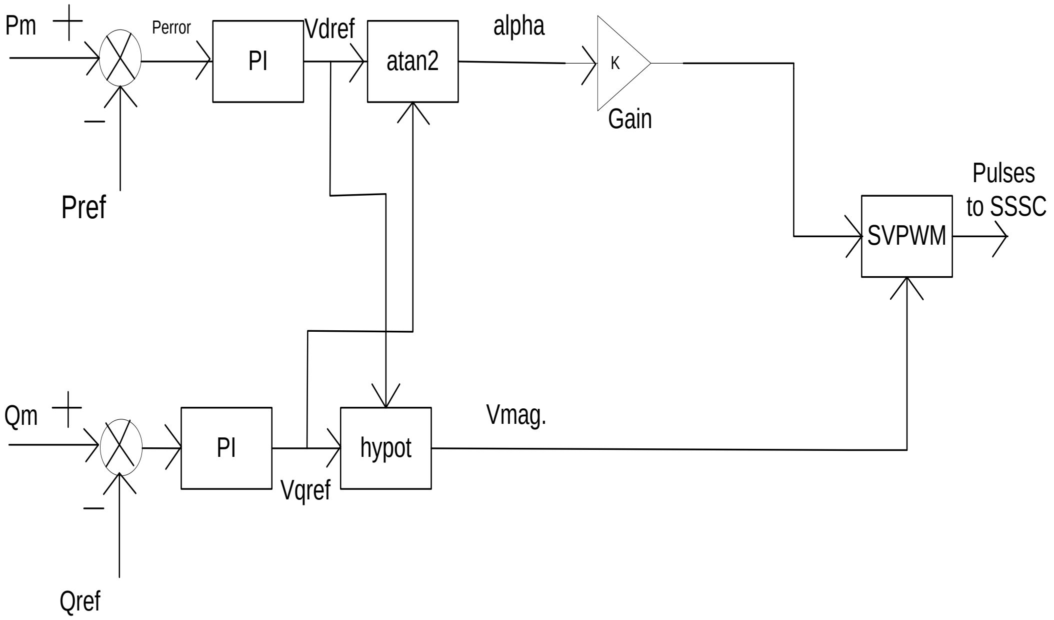

Fig. 5.2 Series control Strategy

$V_{pq} = \sqrt{(V_d^2 + V_q^2)}$ ……………………… (5.1)

$\alpha = \tan^{-1}\frac{Vq}{Vd}$ ……………………… (5.2)

By using V_d and V_q, the magnitude (V_{pq}) and angle (α) of series injected voltage can be calculated as using equation (5.1) and (5.2). Hence, the magnitude (V_{pq}) and angle (α) together are used by the SV-PWM firing pulse generator to generate the desired pulses for the SSSC voltage source converter.

5.2.2 Shunt Part Control

The shunt part control strategy is shown in Fig. 5.3, is used to operate the voltage source converter to inject or absorb reactive power to regulate the connecting point voltage to the desired value. The PLL gives the reference angle which is synchronized to the phase A voltage and this reference angle is used to decompose the three phase voltage of STATCOM into their real (V_d) and reactive part (V_q), via abc to dq0 transformation.

Similarly, the real (I_d) and reactive part (I_q) of currents can be calculated. This V_d is compared with the desired voltage (V_{shref}) and error is applied to PI controller to produce the reference reactive current (I_{qref}).

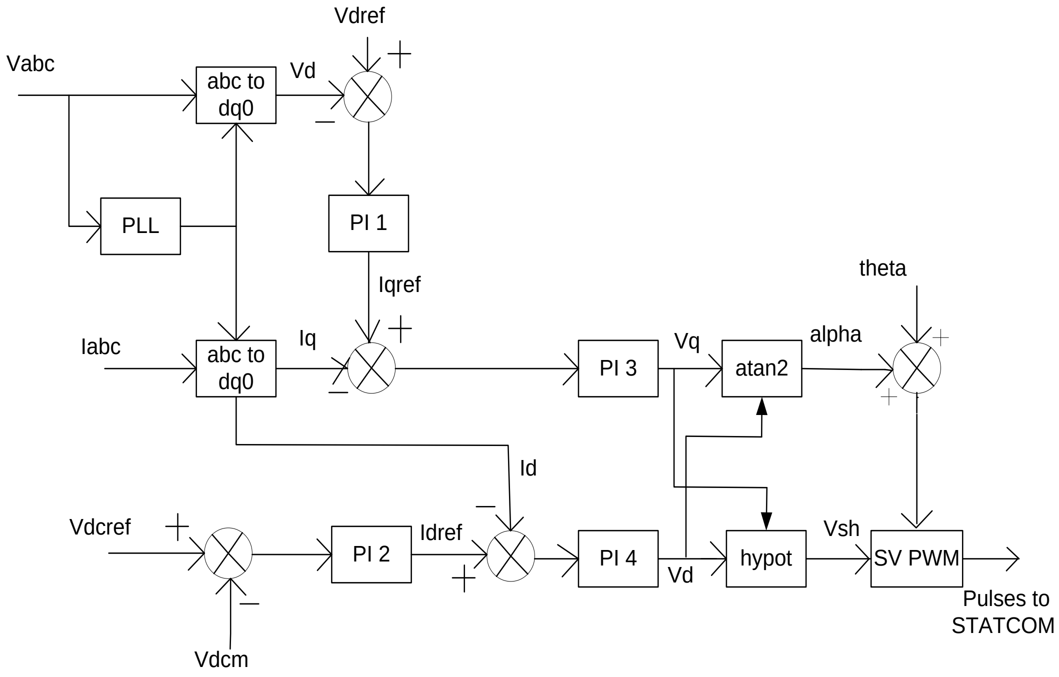

Fig.5.3 Shunt Control Strategy

The reference real current (I_{dref}) can be calculated by comparing reference DC voltage (V_{dcref}) with measured DC capacitor voltage (V_{dcm}) and the error is passed through a PI controller. After comparing the reference and measured values of real (I_{dref}) and reactive current (I_{qref}), the error is passed through a PI controller to obtain real (V_d) and reactive (V_q) voltage magnitude. These voltages are used to calculate V_{sh} and angle ($\theta 1$). This voltage magnitude (V_{sh}) and angle ($\theta 1$) are fed to SV-PWM firing pulse generator to generate the desired pulses for the STATCOM.

PI controller will eliminate forced oscillations and steady state error resulting in operation of on -off controller and P controller respectively. PI controllers are very often used in industry, especially when speed of the response is not an issue. A PI controller is used when:

- large disturbances and noise are present during operation of the process.
- there are large transport delays in the system.

5.3 Simulation Results

The two machine test system, which is simulated by MATLAB/SIMULINK with parameters as given in Table 1.The inverters consist of IGBT based three phase voltage source converters. As discussed earlier, the UPFC can control line voltage, real and reactive power of transmission line in steady state and dynamic conditions. The disturbance used is a single-phase fault near bus 2 and bus 4 of compensated and uncompensated line respectively, at time t = 0.3 second, and cleared in 0.10 second (i.e. at t=0.4). The receiving and sending end voltages are 1p.u. The simulation results for real, reactive power, voltage, current and THD level are discussed below:

Result 1 Real Power:

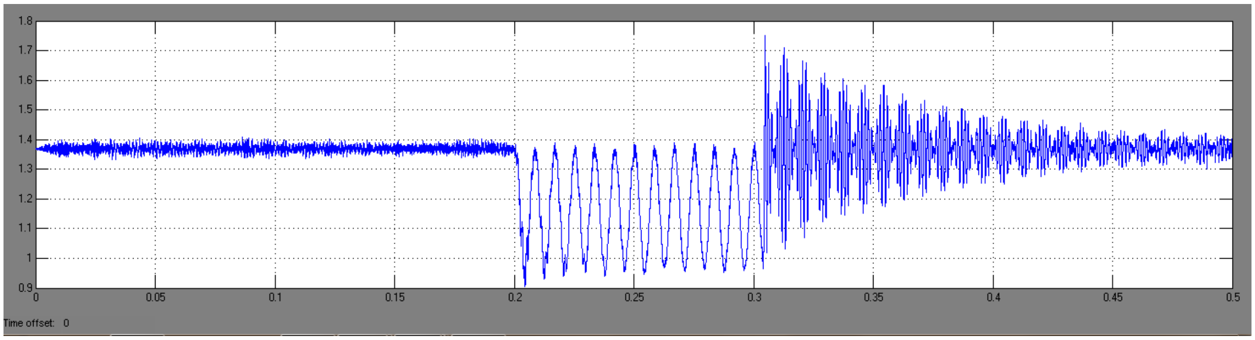

Fig. 5.4.1 Real Power without UPFC

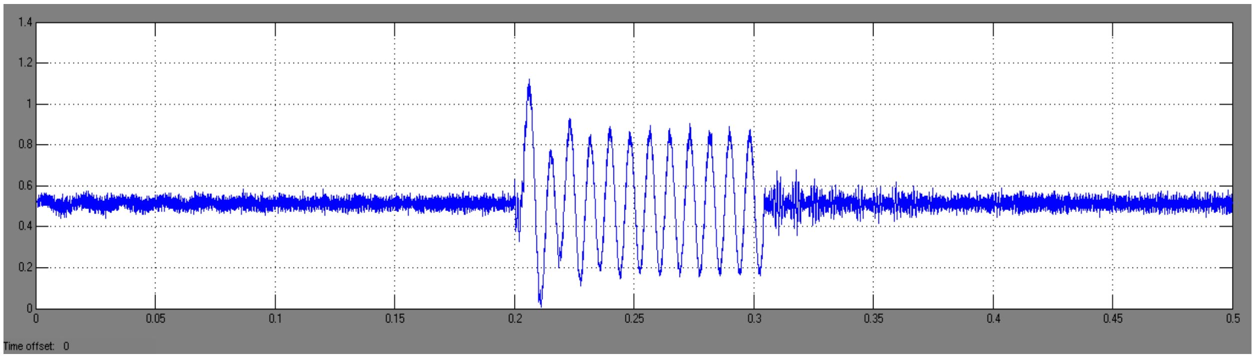

Fig. 5.4.2 Real Power with UPFC

Fig. 5.4.1 and Fig. 5.4.2 shows the real power flow in uncompensated and compensated transmission line respectively. Transmission of real power in existing transmission line is highly improved with the presence of UPFC under dynamic condition, whereas real power flow in line without UPFC is decreased. This is also clear that after clearing of fault the oscillations in real power is also damped with the UPFC and system recover its pre-fault conditions faster.

Result 2 Reactive Power: The reactive power flow through the transmission line without and with UPFC is shown in Fig. 5.5.1 and Fig. 5.5.2 respectively.

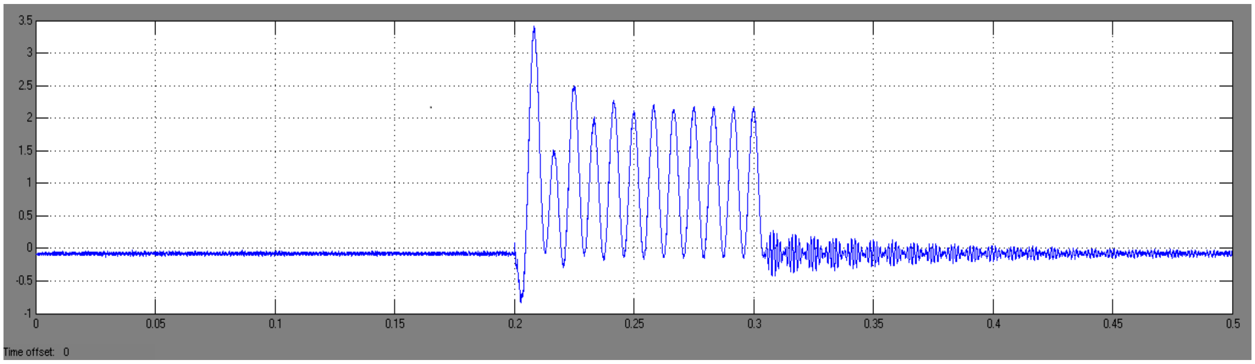

Fig. 5.5.1 Reactive Power without UPFC

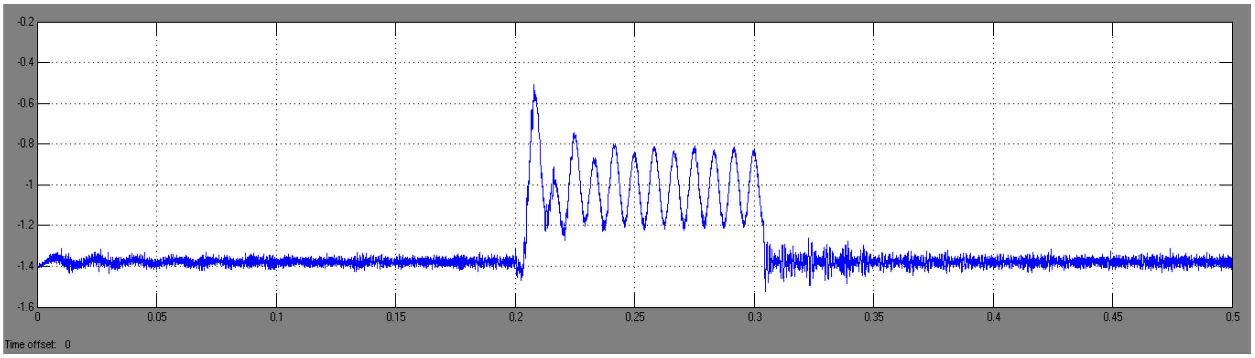

Fig. 5.5.2 Reactive Power with UPFC

It is cleared from figures that the UPFC employed line can be easily control the rise in reactive power by absorbing this excess power and improve the efficiency of transmission line. Similarly, as in real power flow control, the oscillations are also damped for reactive power.

Result 3 Line Voltage:

Fig. 5.6.1 and Fig. 5.6.2 shows the line voltage without and with UPFC installed respectively.

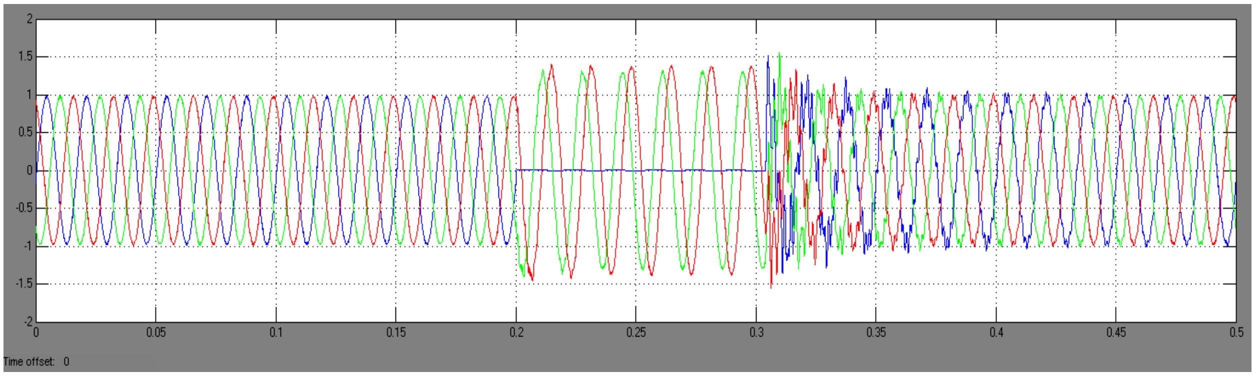

Fig. 5.6.1 Line Voltage without UPFC

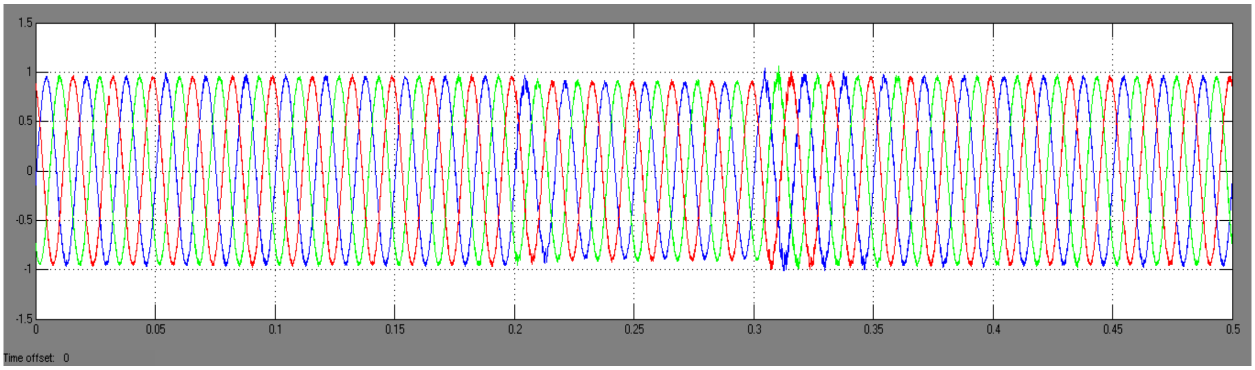

Fig. 5.6.2 Line Voltage with UPFC

During fault, the phase A (or faulted phase) voltage of bus is same as before fault due to UPFC, whereas voltage is reduced to zero of uncompensated line. It is clear that UPFC increase the reliability of line by maintaining the bus voltage.

Result 4 Line Current:

Fig. 5.7.1 and Fig. 5.7.2 shows the current in the line without UPFC and with UPFC respectively.

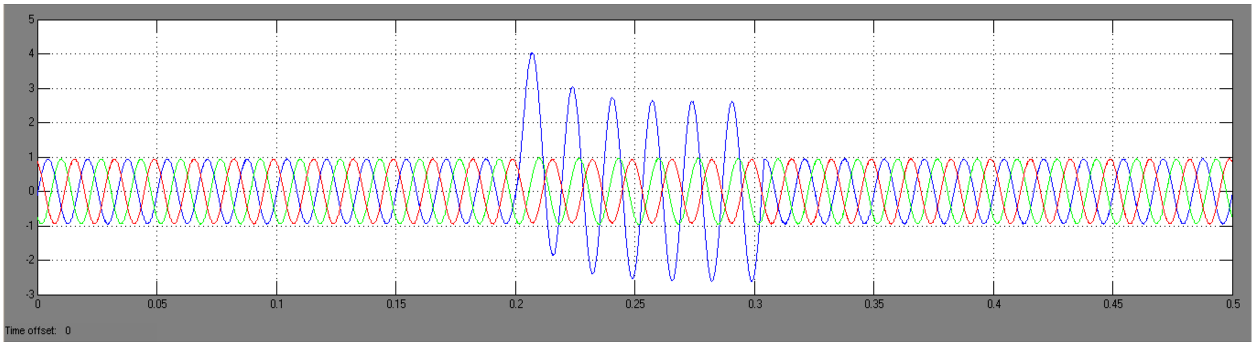

Fig. 5.7.1 Line Current without UPFC

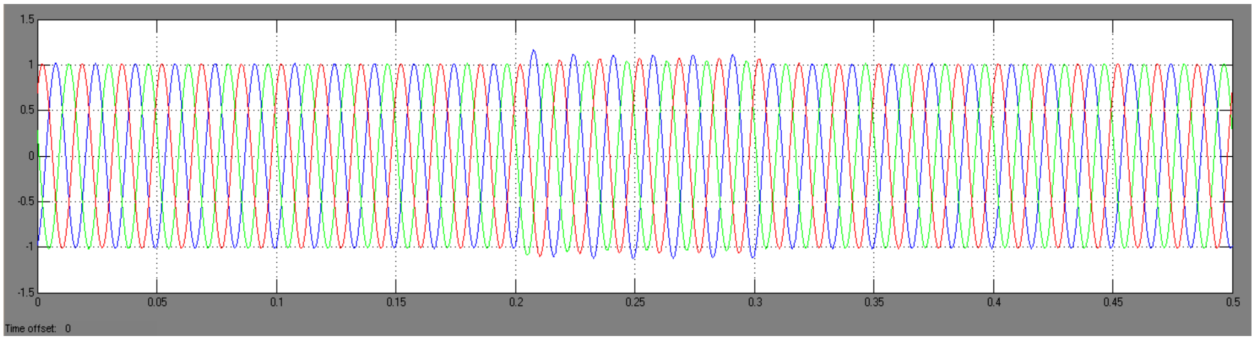

Fig. 5.7.2 Line Current with UPFC

Due to the occurrence of fault, the current in the line is raised to dangerous level. The results show that with the use of UPFC the rise in current is suppressed to safe value. This increase the system security and safety under steady state and dynamic conditions.

Result 5 THD Level:

Fig. 5.8.1 and Fig. 5.8.2 shows the THD level of uncompensated line voltage and compensated line voltage respectively. It is cleared from figures that UPFC is also helpful in reducing THD level in line voltage. THD level is used to quantify the level of harmonics in voltage or current waveform. Total harmonic distortion, or THD, is the summation of all harmonic components of the voltage or current waveform compared against the fundamental component of the voltage or current wave:

$$THD = \frac{\sqrt{V_2^2+V_3^2+V_4^2+ \ldots\ldots\ldots\ldots+V_n^2}}{V_1} \text{ *100 \%}$$

These harmonics can cause problems ranging from telephone transmission interference to degradation of conductors and insulating material in motors and transformers.

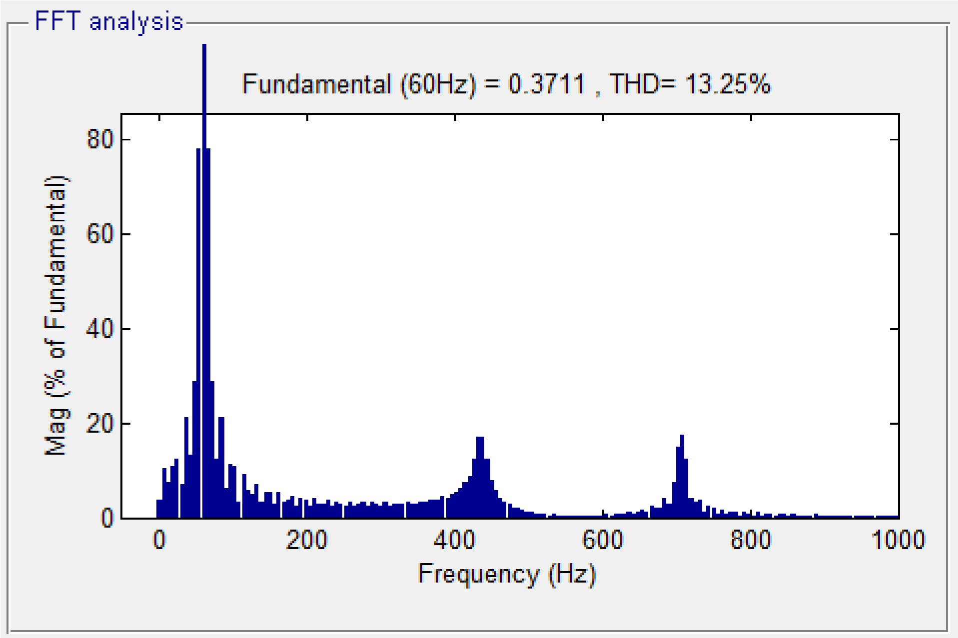

Fig. 5.8.1 THD Level of Line Voltage without UPFC

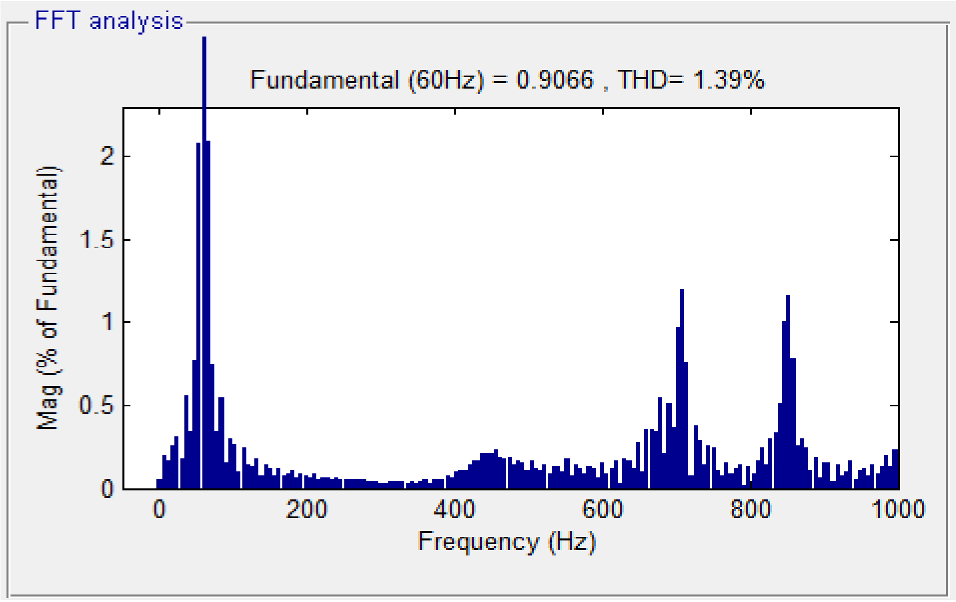

Fig. 5.8.2 THD Level of Line Voltage with UPFC

CHAPTER-6

Conclusion and Future Scope

6.1 Conclusion

In this study, the MATLAB/SIMULINK environment is used to simulate the model of UPFC to a three phase-three wire transmission system. In the thesis, the 132KV transmission system having two 3phase, 132 KV parallel lines, with UPFC installed in the middle of one transmission line and other line is uncompensated. This dissertation presents the control and performance of UPFC on a transmission line under dynamic conditions. A separate control scheme is simulated for both shunt and series converter using PI controller with abc-to-dq0 transformation and space vector PWM technique based scheme is carried to design UPFC controller. IGBT based UPFC controller is controlled by the gate pulses provided by its control scheme. The shunt converter is used in voltage control mode and series converter in power flow control mode. Simulation results has shown the response of UPFC in controlling real, reactive power through the line together with power oscillations damping and, also control voltage and current in the line. By the use of UPFC, bus voltage regulation and THD level is reduced to 1.39% to 13.255. The simulation results has shown the fast response and effectiveness of the presented control scheme. This dissertation presents a fast recovery in the real and reactive power of the system to pre-fault condition by oscillations damping following disturbances through transmission line with UPFC when compared to the system without UPFC.

6.2 Future Scope

With the rapid development in the power transmission system, it suffers from a number of serious disturbances. This would make the system less reliable, secure and stable. For making the system stable and flexible, we need to add various power electronics based devices which can improve the system sytability. In the present work, a PI controller based UPFC is installed to enhance the system stability and performance. In future the work can be extended by applying Fuzzy and Hybrid controller based UPFC to enhance the system flexibility. Also, the UPFC impact can be analyzed for congestion management of a transmission network.

APPENDIX

Table 1 Parameters

Sr. No.	Simulation System Parameters	Set Values
1	**Three-Phase Source**	
	Rated Voltage	132KV
	Frequency	60Hz
	X/R	8
	Short Circuit Capacity	10,000MW
2	**Three-Phase Programmable source**	
	Rated Voltage	132*0.98KV
	Phase Angle(degrees)	20
	Frequency	60Hz
3	DC Link Capacitor	2000µF
4	**Shunt & Series Converter side IGBT**	
	Snubber Resistance	1e5(ohm)
	Snubber Capacitance/resistance	Inf/1e-3 (ohm)

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