MODELING OF STATCOM AND SVC FOR POWER SYSTEM STEADY STATE OPERATION AND ENHANCEMENT OF TRANSIENT STABILITY OF A MULTI-MACHINE POWER SYSTEM BY STATCOM

A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Technology

In

Electrical Engineering

(Power Control & Drives)

By

Laxmidhar Sahu

Roll No. 209EE2177

DEPARTMENT OF ELECTRICAL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA
ODISHA, INDIA
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Under the Supervision of

Prof. Prafulla Chandra Panda

DEPARTMENT OF ELECTRICAL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA
ODISHA, INDIA
PIN-769008

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Dedicated

to

My beloved Parents

NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA

CERTIFICATE

This is to certify that the thesis report entitled "**Modeling of STATCOM and SVC for Power System Steady State Operation and Enhancement of Transient Stability of a Multi-Machine Power System by STATCOM**" submitted by **Mr. Laxmidhar Sahu** in partial fulfillment of the requirements for the award of Master of Technology degree in **Electrical Engineering** with specialization in "**Power Control and Drives**" during session 2009-2011 at **National Institute of Technology, Rourkela** (**Deemed University**) and is an authentic work by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other university/institute for the award of any degree or diploma.

Prof. P. C. PANDA
Dept. of Electrical Engineering
NIT Rourkela

Date:
Place: Rourkela

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LAXMIDHAR SAHU

Roll No: 209EE2177

CONTENTS

ABSTRACT

Transmission networks of modern power systems are becoming increasingly stressed because of growing demand and restrictions on building new lines. One of the consequences of such a stressed system is the threat of losing stability following a disturbance. Flexible ac transmission system (FACTS) devices are found to be every effective in stressing a transmission network for better utilization of its existing facilities without sacrificing the desired stability margin. Flexible AC Transmission System (FACTS) controllers, such as Static Synchronous Compensator (STATCOM) and Static VAR Compensator (SVC), employ the latest technology of power electronic switching devices in electric power transmission systems to control voltage and power flow, and play an important role as a stability aid for and transient disturbances in an interconnected power systems.

This report presents the improvement of transient stability of a multi-machine power system with a STATCOM. Transient stability improvement is essential from the view point of maintaining system security that is the incidence of a fault should not lead to tripping of generating unit due to loss of synchronism. Static synchronous compensator is widely used in power system to control power by injecting appropriate reactive power into the system. STATCOM has the capability of improving stability and damping by dynamically controlling it's reactive power output. The STATCOM is modeled by a voltage source connected to the system through a coupling transformer. The transient stability improvement of the multi-machine power system at different fault condition is investigated in this work.

To illustrate the performance of the FACTS controller (STATCOM), a three machine, nine-bus Western System Coordinating Council (WSCC) Multi-Machine Power System has been considered. The proposed system is also analyzed for different fault clearing times.

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CHAPTER 1

INTRODUCTION

1.1 Introduction – The power system today are complicated networks with hundreds of generating stations and load centers being interconnected through power transmission lines. An electric power system can be subdivided into four stages: i) generation, ii) transmission iii) distribution and iv) utilization (load). The basic structure of a power system is as shown in Fig.1.1. It is composed of generating plants, a transmission system and distribution system. These subsystems are interconnected through transformers T1, T2 and T3.

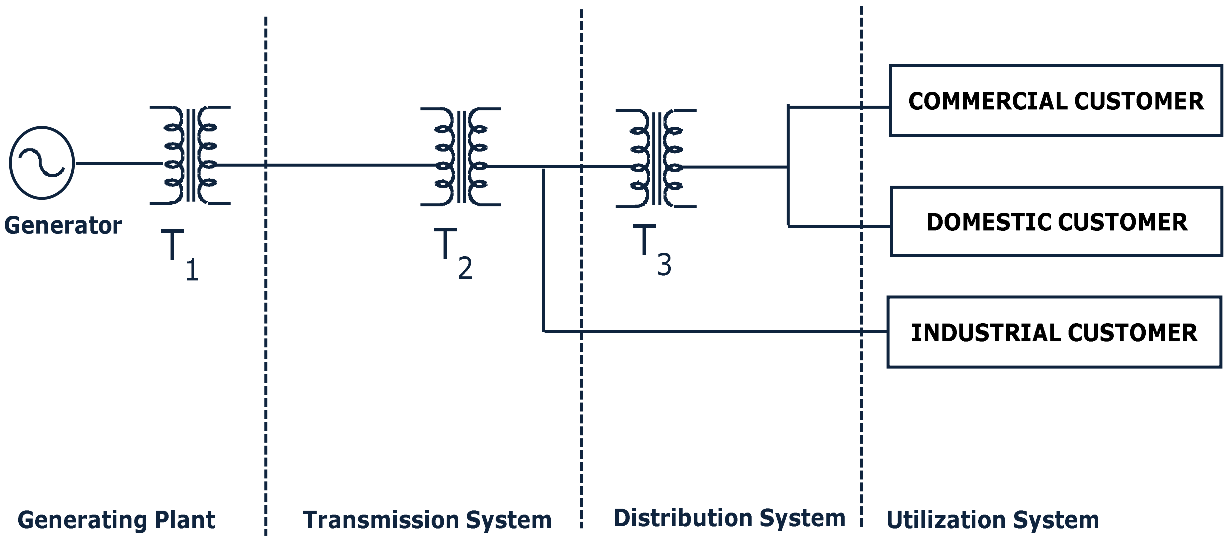

Fig. 1.1 Typical power systems

The power system is a highly nonlinear system that operates in a constantly changing environment; loads, generator outputs, topology, and key operating parameters change continually. When subjected to a transient disturbance, the stability of the system depends on the nature of the disturbance as well as the initial operating condition. The disturbance may be small or large. Small disturbances in the form of load changes occur continually, and the system adjusts to the changing conditions. The system must be able to operate satisfactorily under these conditions and successfully meet the load demand. It must also be able to survive numerous disturbances of a severe nature, such as a short-circuit on a transmission line or loss of a large generator [1].

Now-a-days it is becoming very difficult to fully utilize the existing transmission system assets due to various reasons, such as environmental legislation, capital investment, rights of ways issues, construction cost of new lines, deregulation policies, etc. Electric utilities are now forced to operate their system in such a way that makes better utilization of existing transmission facilities. Flexible AC Transmission System (FACTS) controllers, based on the rapid development of power electronics technology, have been proposed in recent years for better utilization of existing transmission facilities. With the development of FACTS technique, it becomes possible to increase the power flow controllability and enhance power system's stability. Recently, Flexible Alternative Current Transmission System (FACTS) controllers have been proposed to enhance the transient or dynamic stability of power systems [2]-[3].

During the last decade, a number of control devices under the term FACTS technology have been proposed and implemented. Application of FACTS devices in power systems, leads to better performance of system in many aspects. Voltage stability, voltage regulation and power system stability, damping can be improved by using these devices and their proper control [4].There are various forms of FACTS devices, some of which are connected in series with a line and the others are connected in shunt or a combination of series and shunt. 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 other to control one or more of the inter related system parameters like voltage, current, impedance, phase angle and damping of oscillations at various frequencies below the rated frequency. Among all FACTS devices, static synchronous compensators (STATCOM) plays much more important role in reactive power compensation and voltage support because of its attractive steady state performance and operating characteristics. The fundamental principle of a STATCOM installed in a power system is the generation ac voltage source by a voltage source inverter (VSI) connected to a dc capacitor. The active and reactive power transfer between the power system and the STATCOM is caused by the voltage difference across the reactance. The STATCOM can also increase transmission capacity, damping low frequency oscillation, and improving transient stability. The STATCOM is represented by a voltage source, which is connected to the system through a coupling transformer. The voltage of the source is in phase with the ac system voltage at the point of connection, and the magnitude of the voltage is controllable. The current from the source is limited to a maximum value by adjusting the voltage. Mathematical modeling and analysis of static compensator (STATCOM) is presented in [5]-[6]. It explains the use of STATCOM for improvement of transient stability and power transfer.

1.2 Facts controllers

The IEEE Power Engineering Society (PES) Task Force of the FACTS Working Group has defined FACTS and FACTS Controller as given below [3].

Flexible AC Transmission System (FACTS): *Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability.*

FACTS Controller *A power electronic-based system and other static equipment that provide control of one or more AC transmission system parameters.*

It is worthwhile to note the words “other static Controllers” in this definition of FACTS ensure that there can be other static Controllers which are not based on power electronics.

The general symbol for FACTS Controller is shown in Fig. 1.2a. FACTS Controllers are divided into four categories [3]:

i) Series FACTS Controllers
ii) Shunt FACTS Controllers
iii) Combined Series-Series FACTS Controllers
iv) Combined Series-Shunt FACTS Controllers

i) Series FACTS Controllers: - These FACTS Controllers could be variable impedance such as capacitor, reactor or a power electronic based variable source, which in principle injects voltage in series with the line as illustrated in Fig. 1.2b. As long as the voltage is in phase quadrature with the line current, the series Controllers only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

ii) Shunt FACTS Controllers: - The shunt Controllers may be variable impedance such as capacitor, reactor or power electronic based variable source, which is shunt connected to the line in order to inject variable current, as shown in Fig. 1.2c. As long as the injected current is in phase quadrature with the line voltage, the shunt Controllers only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

iii) Combined Series-Series FACTS Controllers: - These Controllers are the combination of separate Series FACTS Controllers, which are controlled in a coordinated manner in a multiline transmission system, as illustrated in Fig. 1.2d. This configuration provides independent series reactive power compensation for each line but also transfers real power among the lines via power link. The presence of power link between series controllers names this configuration as "Unified Series-Series Controller".

iv) Combined Series-Shunt FACTS Controllers: - These are combination of separate shunt and series controller, which are controlled in a co-ordinated manner (Fig. 1.2e) or a Unified Power Flow Controller with series and shunt elements (Fig. 1.2f). When the Shunt and Series FACTS Controllers are unified; there can be a real power exchange between the series and shunt controllers via power link.

Although Series FACTS Controllers for a given MVA size is several times more powerful than Shunt FACTS Controllers, they have to be designed to ride through contingency and dynamic overloads, and ride through or by-pass short circuit currents [3]. Therefore, Shunt FACTS Controllers are more popular in order to control voltage at and around the point of connection through injection of reactive current (lagging or leading) or a combination of active and reactive current for a more effective voltage control and damping of voltage oscillations. Shunt connected FACTS Controllers have also found wide applications in the distribution and transmission systems for many years since they present simple, cost effective solutions in load compensation. The common Shunt connected FACTS Controllers are static shunt compensators: SVC and STATCOM.

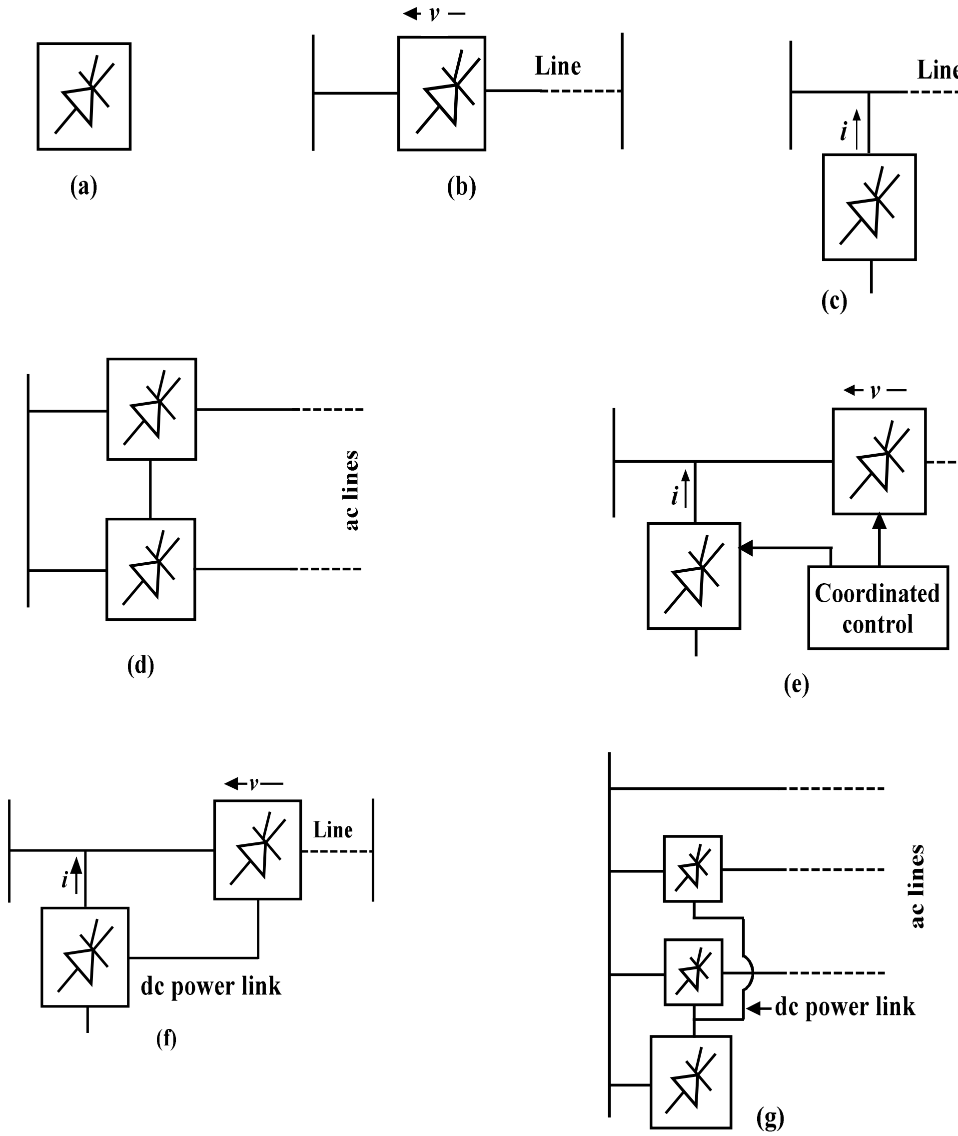

Fig. 1.2 Basic Types of FACTS Controllers [3]: (a) general symbol for FACTS Controller, (b) series FACTS Controller, (c) shunt FACTS Controller, (d) unified series-series FACTS Controller, (e) coordinated series and shunt Controller, (f) unified series-shunt Controller, (g) unified Controller for multiple lines

1.3 Static Shunt Compensators: SVC AND STATCOM

Although static shunt compensators in both transmission systems and distribution systems have the same structure, their objectives are different due to their concerns on the power quality issues.

The primary objectives of a shunt compensator in a distribution system are as follows

- compensation of poor load power factor so that the current drawn from the source will have a nearly unity power factor.
- suppression of harmonics in loads so that the current drawn from source is nearly sinusoidal.
- voltage regulation for the loads that cause fluctuations in the supply voltage.
- cancelation of the effect of unbalance loads so that the current drawn from the source is balanced (load balancing).

All of these objectives are not necessarily met for a typical shunt compensator. The required shunt compensator should be designed in view of the needs of load to be compensated since each of these functions has a certain cost to the compensator.

On the other hand, the objectives of these shunt compensator in a transmission system are as given below in order to increase the transmitted power in the transmission lines.

- Midpoint voltage regulation for Line Segmentation in order to increase transmittable power in the transmission system.
- End of line voltage support to prevent voltage instability requires the compensation of load having poor factor. This increases the maximum power transmission capability of the transmission line while improving the voltage instability limits.
- Improvement of transient stability margin by increasing the maximum transmittable power in the transmission line.
- Power oscillation damping by exchanging active (real) power with power system so that oscillations in the machine angle due to any minor disturbance can be damped out rapidly.

1.3.1 Static Var Compensator (SVC)

According to definition of IEEE PES Task Force of FACTS Working Group:

Static VAr Compensator (SVC): *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).*

This is a general term for a Thyristor Controlled Reactor (TCR) or Thyristor Switched Reactor (TSR) and/or Thyristor Switched Capacitor (TSC) (Fig. 1.3). The term, “SVC” has been used for shunt connected compensators, which are based on thyristors without 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[3],[7].

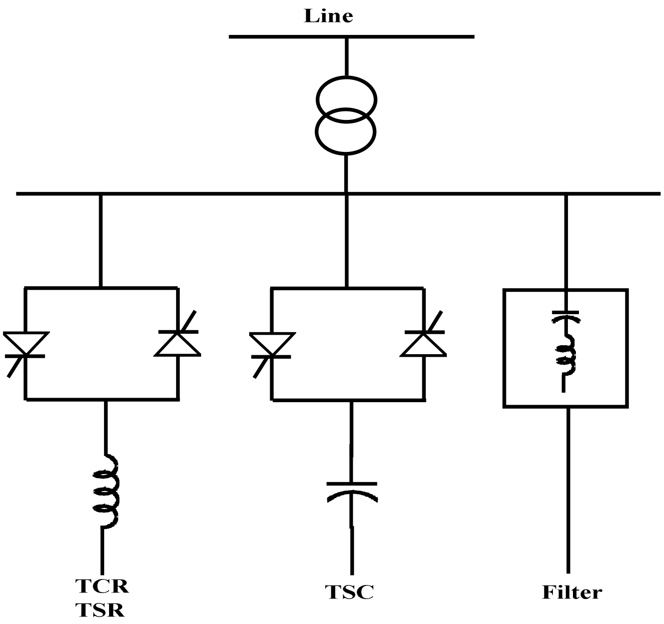

Fig. 1.3 Static Var Compensators: Thyristor Controlled Reactor (TCR) or Thyristor Switched Reactor (TSR), Thyristor Switched Capacitor (TSC), Passive Filter

1.3.2 Static Synchronous Compensator (STATCOM)

According to definition of IEEE PES Task Force of FACTS Working Group:

Static Synchronous Compensator (STATCOM): *A Static synchronous generator operates as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage.*

The STATCOM is the static counterpart of the rotating synchronous condenser but it generates/absorbs reactive power at a faster rate because no moving parts are involved. In principle, it performs the same voltage regulation functions as the SVC but in robust manner because unlike the SVC, its operation is not impaired by the presence of low voltage. The STATCOM has superior performance during low voltage condition as the reactive current can be maintained constant. (In a SVC , the capacitive reactive current drops linearly with the voltage at the limit of capacitive susceptance). It is even possible to increase the reactive current in a STATCOM under transient conditions if the devices are rated for the transient overload.

The possibility of generating controllable reactive power directly, without the use of ac capacitors or reactors by various switching power converters was disclosed by Gyugi in 1976 [3]. Functionality, from the standpoint of reactive power generation, their operation is similar to that of an ideal synchronous machine whose reactive power output is varied by excitation control. Like the mechanically powered machine these converters can also exchange real power with the ac system if supplied from an appropriate, usually dc energy source. Because of these similarities with a rotating synchronous generator, they are termed Static Synchronous Generator (SSG). When SSG is operated without an energy source and with appropriate controls to function as shunt-connected reactive compensator, it is termed, analogously to the rotating synchronous compensator (condenser) a Static Synchronous Compensator (STATCOM) or Static Synchronous Condenser (STATCON).

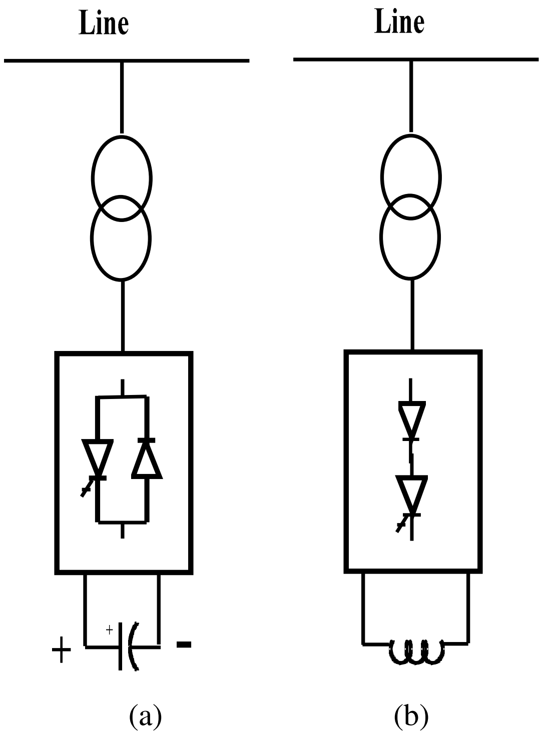

Fig. 1.4 Static Synchronous Compensator (STATCOM) based on (a)voltage-sourced and (b) current-sourced converter.

1.4 Power System Stability

Transmission networks of modern power systems are becoming increasingly stressed because of growing demand and restrictions on building new lines. One of the consequences of such a stressed system is the threat of losing stability following a disturbance. FACTS devices are found to be every effective in stressing a transmission network for better utilization of its existing facilities without sacrificing the desired stability margin.

Power system stability is a complex subject that has challenged power system engineers for many years. 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 tendency of a power system to develop restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium is known as stability. If the forces tending to hold machines in synchronism with one another are sufficient to overcome the disturbing forces, the system is said to remain stable. Conversely, instability means a condition denoting loss of synchronism or falling out of step. Stability considerations have been recognized as an essential part of power system planning for a long time. With interconnected systems continually growing in size and extending over vast geographical regions, it is becoming increasingly more difficult to maintain synchronism between various parts of a power system. For convenience of analysis, stability problems are classified into three basic types – steady state stability, dynamic stability and transient stability. Steady- state stability refers to the ability of the power system to regain synchronism after small and slow disturbances, such as gradual power changes. The dynamic stability is concerned with small disturbances lasting for a long time with the inclusion of automatic control devices. Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance. Transient stability studies deals with the effects of large, sudden disturbances such as the occurrence of a fault, the sudden outage of a line or the sudden application or removal of loads. Stability depends on both the initial operating state of the system and the severity of the disturbance [1],[8].

1.4.1 Transient Stability ─ Equal- Area Criterion

The transient stability studies involve the determination of whether or not synchronism is maintained after the machine has been subjected to severe disturbances. This may be sudden application of load, loss of generation, loss of large load, or a fault on the system. In most disturbances, oscillations are of such magnitude that linearization is not permissible and the nonlinear swing equation must be solved. For a quick prediction of stability *equal-area criterion* method can be used [8]. This method is based on the graphical interpretation of the energy stored in the rotating mass as an aid to determine if the machine maintains its stability after a disturbance.

The method is only applicable to a one - machine system connected to an infinite bus or a two-machine system.

Consider a synchronous machine connected to an infinite bus. The swing equation with damping neglected is given by

$$\frac{H}{\pi f_0}\frac{d^2\delta}{dt^2} = (P_m - P_e) = P_a \quad (1.1)$$

where P_a is the accelerating power. From the above equation

$$\frac{d^2\delta}{dt^2} = \frac{\pi f_0}{H}(P_m - P_e) \quad (1.2)$$

Multiplying both sides of the equation by $2d\delta/dt$, we get

$$2\frac{d\delta}{dt}\frac{d^2\delta}{dt^2} = \frac{2\pi f_0}{H}(P_m - P_e)\frac{d\delta}{dt} \quad (1.3)$$

This may be written as

$$\frac{d}{dt}\left[\left(\frac{d\delta}{dt}\right)^2\right] = \frac{2\pi f_0}{H}(P_m - P_e)\frac{d\delta}{dt} \quad (1.4)$$

or

$$d\left[\left(\frac{d\delta}{dt}\right)^2\right] = \frac{2\pi f_0}{H}(P_m - P_e)d\delta \quad (1.5)$$

Integrating both sides

$$\left(\frac{d\delta}{dt}\right)^2 = \frac{2\pi f}{H}\int_{\delta_0}^{\delta}(P_m - P_e)d\delta \quad (1. 6)$$

or

$$\frac{d\delta}{dt} = \sqrt{\frac{2\pi f_0}{H} \int_{\delta_0}^{\delta} (P_m - P_e) d\delta} \tag{1.7}$$

Equation (1.7) gives the relative speed of the machine with respect to the synchronously revolving reference frame. For stability , this speed must become zero at some time after the disturbance. Therefore , from (1.7) , we have for the stability criterion

$$\int_{\delta_0}^{\delta} (P_m - P_e) d\delta = 0 \tag{1.8}$$

Consider the machine operating at the equilibrium point δ_0, corresponding to the mechanical power input $P_{m0} = P_{e0}$ as shown in Fig. 1.5. Consider a sudden step increase in input power represented by the horizontal line P_{m1}. Since $P_{m1} > P_{eo}$, the accelerating power on the rotor is positive and the power angle δ increases. The excess energy stored in the rotor during the initial acceleration is

$$\int_{\delta_0}^{\delta_1} (P_{m1} - P_e) d\delta = \text{area abc} = \text{area } A_1 \tag{1.9}$$

With increase in δ, the electrical power increases, and when $\delta = \delta_0$, the electrical power matches the new input power P_{m1}. Even though the accelerating power is zero at this point, the rotor is running above synchronous speed; hence δ and electrical power P_e will continue to increase. Now $P_m < P_e$, causing the rotor to decelerate synchronous speed until $\delta = \delta_{max}$. according to (1.8), the rotor must swing past point b until an equal amount of energy is given up by the rotating masses. The energy given up by the rotor as it decelerates back to synchronous speed is

$$\int_{\delta 1}^{\delta_{max}} (P_{m1} - P_e) d\delta = \text{area bde} = \text{area } A_2 \tag{1.10}$$

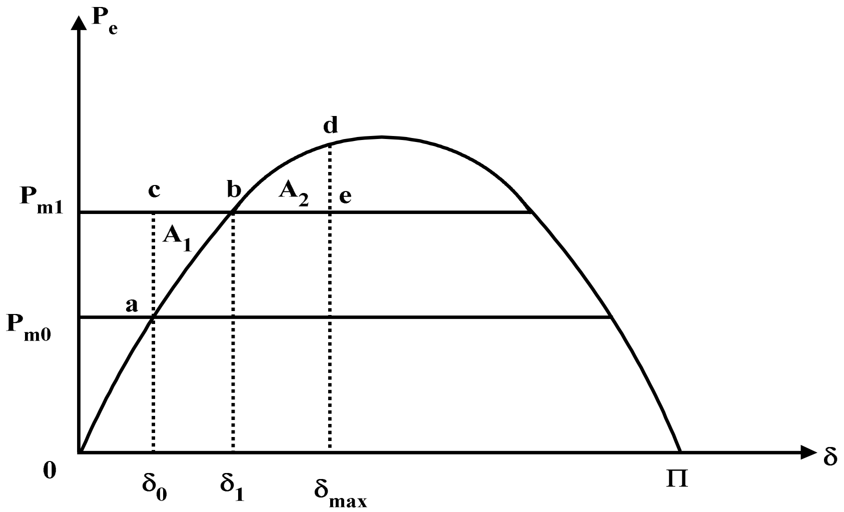

Fig. 1.5 Equal-area criterion – sudden change of load

The result is that the rotor swings to point b and the angle δ_{max}, at which point

$$|\text{area } A_1| = |\text{area } A_2| \tag{1.11}$$

This is known as the *equal-area criterion*. The rotor angle would then oscillate back and forth between δ_0 and δ_{max} at its natural frequency. The damping present in the machine will cause oscillations to subside and the new steady state operation would be established at point *b*.

1.4.2 Factors Influencing Transient Stability

Many factors affect the transient stability of a generator in a practical power system. From the small system analyzed above, the following factors can be identified:

- The post-disturbance system reactance as seen from the generator. The weaker the post-disturbance system, the lower the Pmax will be.
- The duration of the fault-clearing time. The longer the fault is applied, the longer the rotor will be accelerated and the more kinetic energy will be gained. The more energy that is gained during acceleration, the more difficult it is to dissipate it during deceleration.
- The inertia of the generator. The higher the inertia, the slower the rate of change of angle and the lesser the kinetic energy gained during the fault.

- The generator internal voltage (determined by excitation system) and infinite bus voltage (system voltage). The lower these voltages, the lower the Pmax will be.
- The generator loading before the disturbance. The higher the loading, the closer the unit will be to Pmax, which means that during acceleration, it is more likely to become unstable.
- The generator internal reactance. The lower the reactance, the higher the peak power and the lower the initial rotor angle.
- The generator output during the fault. This is a function of faults location and type of fault.

1.5 Literature Review

In recent years, power demand has increased substantially while the expansion of power generation and transmission has been severely limited due to limited resources and environmental restrictions. As a consequence, some transmission lines are heavily loaded and the system stability becomes a power transfer-limiting factor. Flexible AC transmission systems (FACTS) controllers have been mainly used for solving various power system steady state control problems. However, recent studies reveal that FACTS controllers could be employed to enhance power system stability in addition to their main function of power flow control. The literature shows an increasing interest in this subject for the last two decades, where the enhancement of system stability using FACTS controllers has been extensively investigated. This work presents a comprehensive review on the research and developments in the power system stability enhancement using FACTS damping controllers. The static synchronous compensator (STATCOM) is one type of FACTS devices which resembles in many respects a rotating synchronous condenser used for voltage control and reactive power compensation. The STATCOM can increase transmission capacity, damping low frequency oscillation, and improving transient stability. This paper [9] presents a control block diagram of STATCOM for the transient stability improvement. The SIMULINK/MATLAB software package is used for simulation of test system. In this paper the STATCOM is connected to the 230KV line for a typical two machine transmission system. The study demonstrates that STATCOM not only considerably improves transient, stability but also compensates the reactive power in steady state.

In large power systems the generators are of generally synchronous type, so it is necessary to maintain synchronism with the grid in order to provide standard service to consumer. The disturbance in power system is mainly due to sudden change of heavy load, faults, and loss of excitation. In this paper, the rate of change of transient energy of the system is taken into account i.e. the dissipation of kinetic energy (K.E.) of the power system due to disturbances as a measure of system damping. To provide additional damping in the power system without additional cost, the output power of the FACTS devices like STATCOM and SSSC already connected in the power system for compensation is used. They modulate the system output, so as to reduce the system oscillation and hence stability improves[10]. Static Synchronous Compensator (STATCOM) is a power electronic based device that has capability of controlling the power flow through the line by injecting appropriate reactive power to power system. This work investigates the effect of STATATCOM on inter-area power system stability. The STATCOM is modeled as the variable susceptance and is incorporated into the model of power system. The simulation results are tested on the Kundur's Inter area power system[11].

A comparative study of variation of transient stability condition on application of TCSC and STATCOM individually vis-á-vis the effect of their simultaneous application has been made in [12]. The best possible locations of the FACTS devices are found to vary with the location of the fault and the operating criteria of the devices. TS (Trajectory sensitivity) and η can be used to identify these locations. In some cases, the FACTS device may have some adverse effect on system stability. Also an increase in compensation by the FACTS devices does not ensure an enhanced stability margin. Therefore, evaluation of the system stability condition is required for better and safer system operation. This evaluation can be done using TS. The best possible location for stability improvement for simultaneous placement of the devices may differ from the best locations for individual placement. Therefore, separate stability assessment is needed for the simultaneous operation of the compensators. Also the best possible locations of the devices change in a stressed system. All these underline the importance of a tool for transient stability assessment like trajectory sensitivity.

The PSS is a device that improves the damping of generator electromechanical oscillations. Stabilizers have been employed on large generators for several decades, permitting utilities to improve stability-constrained operating limits. In order to describe the application of the PSS, it is necessary to introduce general concepts of power-system stability and synchronous generator operation. This paper [13] discusses power-system instability and the importance of fast fault-clearing performance to aid in reliable production of power. An explanation regarding small-signal stability, high-impedance transmission lines, line loading, and high-gain fast-acting excitation systems is provided. Transient stability is discussed, including synchronizing and damping torques. The power-angle curve is used to illustrate how fault-clearing time and high initial response excitation systems can affect transient stability. The term “power-system stability” has become increasingly popular in generation and transmission. The sudden requirement for power-system stabilizers (PSSs) has created confusion about their applicability, purpose, and benefit to the system. This work discusses the fundamentals of the PSS and its effectiveness. In this paper, it has been made clear that STATCOM with the proposed nonlinear control system can improve damping of oscillation, however, that in a larger power system, the control performance of STATCOM with the proposed nonlinear control system depends on fault location and installation bus of STATCOM.

Transient stability is important from the view point of maintaining system security that is the incidence of a fault should not lead to tripping of generating unit due to loss of synchronism and the possibility of a cascaded outage leading to system black out. TCSC allows the fundamental capacitive reactance to be smoothly controlled over a wide range. The TCSC controller can be designed to control the power flow, to increase the transfer limits or to improve the transient stability. The TCSC controller can provide a very fast action to increase the synchronization power through quick changing of the equivalent capacitive reactance to the full compensation in the first few cycles after a fault, hence subsequent oscillations are damped. In the present work [14] TCSC controller for single machine infinite bus (SMIB) and multi-machine power system is designed using SIMULINK (a software tool associated with MATLAB). Multi-machine power system with turbine and governing system is modeled. Modeling is done for system with TCSC controller. Effect of TCSC controller parameter variation on rotor angle is also studied. A detailed analysis is conducted for the proposed controller for different fault clearing time. It has been observed that TCSC controller can improve the stability margin significantly. TCSC controller provides variable impedance, which is required for the compensation. The presented controller is suitable only in capacitive zone. For the transition from a capacitive vernier mode to bypass mode the TCSC controller can be modeled with detailed dynamics.

1.6 Objectives and Scope of the Project

The objectives of the project are

- To study the steady state operating condition of the electrical network. The steady state may be determined by finding out the flow of active and reactive power throughout the network and the voltage magnitudes and phase angles at all nodes of network (5-bus system) with and without FACTS devices.
- To investigate the effect of STATCOM for improving transient stability of the multi-machine power system. The simulation results of the nine-bus system are performed at different fault conditions with different fault clearing time. To illustrate the performance of the FACTS controller (STATCOM), a three machine, nine-bus WSCC Multi-Machine Power System has been considered.

1.7 Organization of the Thesis

Chapter 1

This chapter discusses introduction about FACTS, different FACTS Controllers, power system stability, transient stability, literature review, objective of the work and chapter wise contribution of the thesis.

Chapter 2

This chapter presents load flow analysis, the sample five – bus network, power flow model of STATCOM and SVC, and power flow study with STATCOM and SVC.

Chapter 3

This chapter presents modeling of STATCOM and generator and the WSCC nine – bus system, STATCOM control strategies.

Chapter 4

This chapter presents simulation results of the nine – bus system with different fault conditions with and without STATCOM and discusses in details.

Chapter 5

This chapter presents conclusion and suggestion for future work.

CHAPTER 2

LOAD FLOW ANALYSIS

2.1 Introduction

Load flow study in power system is the steady state solution of the power system network. The power system is modeled by an electric network and solved for the steady-state powers and voltages at various buses. The direct analysis of the circuit is not possible, as the load are given in terms of complex powers rather than impedances, and generators behave more like power sources than voltage sources. The main information obtained from the load flow study comprises of magnitudes and phase angles of load bus voltages, reactive powers and voltage phase angles at generator buses, real and reactive power flow on transmission lines together with power at the reference bus, other variables being specified. This information is essential for the continuous monitoring of the current state of the system and for the analyzing the effectiveness of the alternative plans for the future, such as adding new generator sites, meeting increased load demand and locating new transmission sites. In load flow analysis, we are mainly interested in voltages at various buses and power injection into the transmission system. In addition, power flow analysis is required for many other analyses such as transient stability and contingency studies. The main objective of a power flow study is to determine the steady state operating condition of the electrical network. The steady state may be determined by finding out the flow of active and reactive power throughout the network and the voltage magnitudes and phase angles at all nodes of network. Such information is used to carry out security assessment analysis, where the nodal voltage magnitudes and active and reactive power flows in transmission lines and transformers are carefully observed to assess whether or not they are within prescribed operating limits. [15]-[17].

In solving a power flow problem, the system is assumed to be operating under balanced conditions and a single-phase model is used. In a power system each bus or node is associated with four quantities i.e. voltage magnitude $|V|$, phase angle δ, real power P, and reactive power Q. In a load flow solution two out of the four quantities are specified and the remaining two are required to be obtained through the solution of the equations. Based on the difference between power flow in the sending and receiving ends, the losses in a particular line can also be computed.

2.2 Newton-Raphson Approach

The Newton-Raphson (NR) method is a powerful method of solving non-linear algebraic equations. Because of its quadratic convergence, Newton's method is mathematically superior to the Gauss-Seidel method and is less prone to divergence with ill-conditioned problems. It works faster, and is sure to converge in most cases as compared to the Gauss-Siedel (GS) method. It is indeed the practical method of load flow solution of large power networks. Its only drawback is the large requirement of computer memory, which can be overcome through a compact storage scheme. One of the main strengths of the Newton-Raphson method is its reliability towards convergence. Contrary to non Newton-Raphson solutions, convergence is independent of the size of the network being solved and the number and kinds of control equipment present in the system. Hence in the proposed work Newton-Raphson method is preferred [18]-[19].

2.3 The Sample Five Bus Network

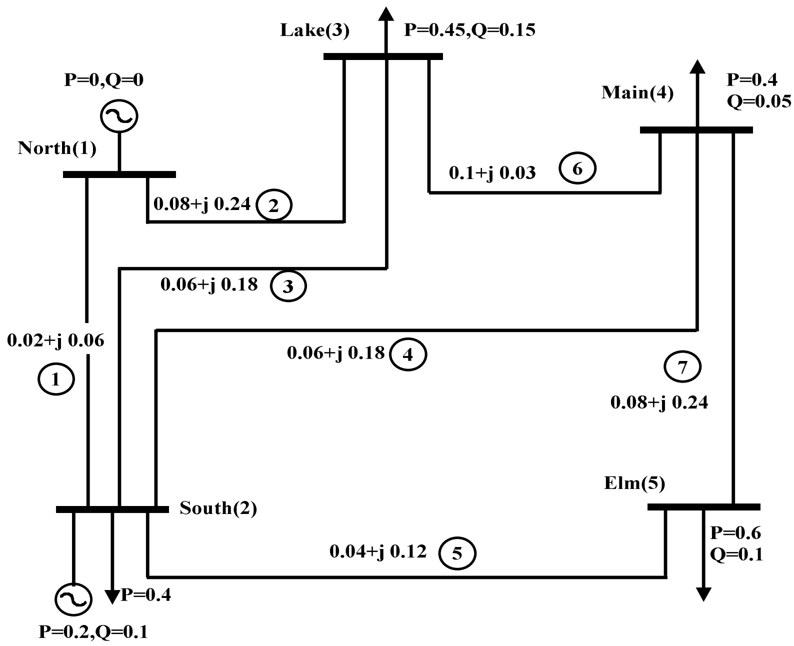

Fig 2.1 The 5 bus network

For study we have considered the five bus system as shown in Fig. 2.1, which is a seven line, two generator and three load bus. The input data for the considered system are given in Table 2.1 for the bus and Table 2.2 for transmission line [20]. The transmission line impedances and line charging admittances are in per unit.

Table 2.1 Input bus data(p.u.)

Bus No.	Type	Generation		Load		Voltage	
		P	Q	P	Q	|V|	θ
1	Slack	0	0	-	-	1.06	0
2	P-V	0.4	0	0.2	0.1	1	0
3	P-Q	-	-	0.45	0.15	1	0
4	P-Q	-	-	0.4	0.05	1	0
5	P-Q	-	-	0.6	0.1	1	0

Assuming Base Quantity of 100MVA and 100KV

Table 2.2 Input transmission line data (p.u)

Line no	Line Code	Impedance (R+jX)	Line charging admittance
1	1-2	0.02+j0.06	0+j0.06
2	1-3	0.08+j0.24	0+j0.05
3	2-3	0.06+j0.18	0+j0.04
4	2-4	0.06+j0.18	0+j0.04
5	2-5	0.04+j0.12	0+j0.03
6	3-4	0.01+j0.03	0+j0.02
7	4-5	0.08+j0.24	0+j0.05

The load flow result and Power flow diagram for the 5-bus system is shown in Table 2.3 and Fig. 2.2 respectively.

Table 2.3 Power flow result without FACTS devices(p.u.)

Parameter	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
VM(p.u.)	1.06	1	0.985	0.986	0.9717
VA(deg)	0	-2.05	-4.62	-4.95	-5.78

It is observed from the above table that all the nodal voltages are within acceptable voltage magnitude limits. From the power flow diagram it is clear that the largest power flow takes place in the transmission line connecting the generator buses: 89.42 MW, and 73.93 MVAR leave north and 86.63 MW and 72.73 MVAR arrive at South. This is also the transmission line that incurs higher active power loss (i.e. 2.79 MW). The operating conditions demand a large amount of reactive power generation by the generator connected at North (i.e. 90.61 MVAR). This amount is well in excess of the reactive power drawn by the system loads (i.e. 40MVAR). The generator at South draws the excess of reactive power in the network (i.e. 61.4 MVAR). This amount includes the net reactive power produced by several of the transmission lines.

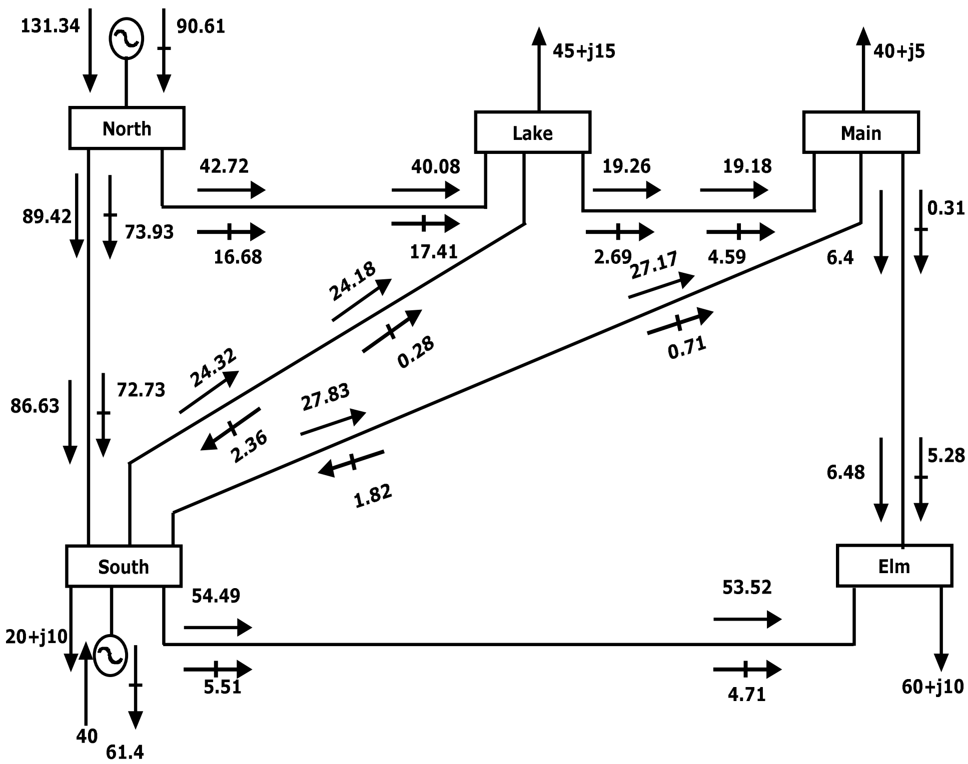

Fig 2.2 The five bus network and power flow result

2.4 Power Flow Model of STATCOM

The STATCOM 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. It is even possible to increase the reactive current in a STATCOM under transient conditions if the devices are rated for the transient overload. The bus at which STATCOM is connected is represented as a PV bus, which may change to a PQ bus in the events of limits being violated. The power flow equations for the STATCOM are derived below from the first principles and assuming the following voltage source representation [15]-[16].

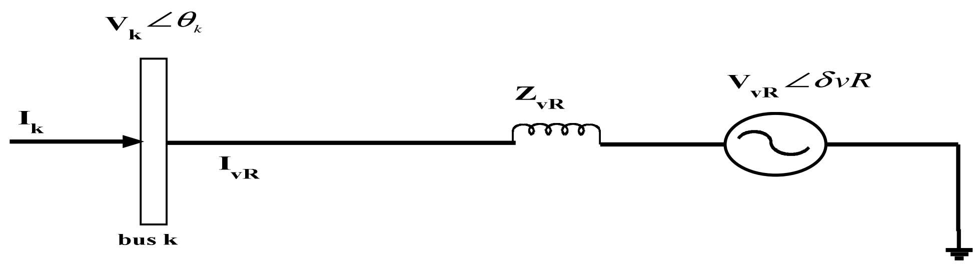

Fig 2.3 STATCOM-equivalent circuit

Based on the shunt connection shown in Fig 2.3, the following may be written as

$$E_{vR} = V_{vR}(\cos\delta_{vR} + j\sin\delta_{vR}) \tag{2.1}$$

$$S_{vR} = V_{vR} I_{vR}^{*} = V_{vR} Y_{vR}^{*} (V_{vR}^{*} - V_{k}^{*}) \tag{2.2}$$

Where V_{vR} and δ_{vR} are the controllable magnitude ($V_{vRmin} \leq V_{vR} \leq V_{vRmax}$) and phase angle ($0 \leq \delta_{vR} \leq 2\pi$) of the voltage source representing the shunt converter. The following are the active and reactive power equations for the converter at bus k,

$$P_{vR} = V_{vR}^{2} G_{vR} + V_{vR} V_{k} [G_{vR} \cos(\delta_{vR} - \theta_{k}) + B_{vR} \sin(\delta_{vR} - \theta_{k})] \tag{2.3}$$

$$Q_{vR} = -V_{vR}^{2} B_{vR} + V_{vR} V_{k} [G_{vR} \sin(\delta_{vR} - \theta_{k}) - B_{vR} \cos(\delta_{vR} - \theta_{k})] \tag{2.4}$$

$$P_{k} = V_{k}^{2} G_{vR} + V_{k} V_{kR} [G_{vR} \cos(\theta_{k} - \delta_{vR}) + B_{vR} \sin(\theta_{k} - \delta_{vR})] \tag{2.5}$$

$$Q_{k} = -V_{k}^{2} B_{vR} + V_{k} V_{vR} [G_{vR} \sin(\theta_{k} - \delta_{vR}) - B_{vR} \cos(\theta_{k} - \delta_{vR})] \tag{2.6}$$

2.5 Power Flow Model of SVC

In power flow studies the SVC is normally modeled as a synchronous generator with zero active power generation, upper and lower limits are given for reactive power generation. SVC is used extensively to provide fast reactive power and voltage regulation support. It also increases system stability margin and to damp power system oscillations. From the operational point of view, the SVC behaves like a shunt-connected variable reactance, which either generates or absorbs reactive power in order to regulate the voltage magnitude at the point of connection to the AC network. It is easy for practical implementation [16].

The equivalent circuit shown in Fig 2.4 is used to derive the SVC non-linear power equations and the linearised equations required by Newton's method.

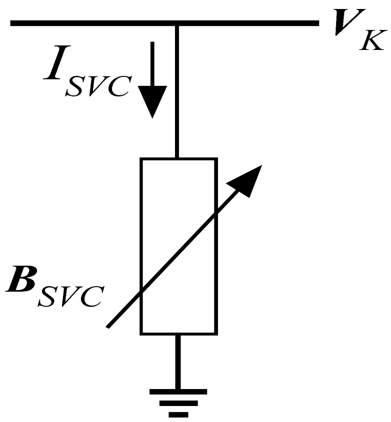

Fig 2.4 Variable shunt susceptance model of SVC

With reference to Fig 2.4 the current drawn by the SVC is

$$I_{SVC} = jB_{SVC}V_K \tag{2.7}$$

And the reactive power drawn by the SVC, which is also the reactive power injected at bus K

$$Q_{SVC} = Q_K = -V_K^2 B_{SVC} \tag{2.8}$$

Then the linearised equation is given by

$$\begin{bmatrix} \Delta P_K \\ \Delta Q_K \end{bmatrix}^{(i)} = \begin{bmatrix} 0 & 0 \\ 0 & Q_K \end{bmatrix}^{(i)} \begin{bmatrix} \Delta\theta_K \\ \Delta B_{SVC} / B_{SVC} \end{bmatrix}^{(i)} \tag{2.9}$$

Where the equivalent susceptance B_{SVC} is taken to be the state variable.

At the end of iteration (i), the variable shunt susceptance B_{SVC} is updated according to

$$B_{SVC}^{(i)} = B_{SVC}^{(i-1)} + \left(\frac{\Delta B_{SVC}}{B_{SVC}}\right)^{(i)} B_{SVC}^{(i-1)} \tag{2.10}$$

The changing susceptance represents the total SVC susceptance necessary to maintain the nodal voltage magnitude at the specified value.

2.6 Power Flow Study With STATCOM

The STATCOM is included in the bus 3 of the sample system to maintain the nodal voltage at 1 p.u.. Here the STATCOM data are: the initial source voltage magnitude is 1 p.u, Phase angle is 0 degrees and the converter reactance is 10 p.u.

The load flow result and power flow diagram result for the 5-bus system with STATCOM at bus 3 is shown in Table 2.4 and Fig 2.5 respectively.

Table 2.4 Result with STATCOM included at bus 3

Parameter	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
VM(p.u.)	1.06	1	1	0.9953	0.9754
VA(deg)	0	-2.06	-4.752	-4.823	-5.783

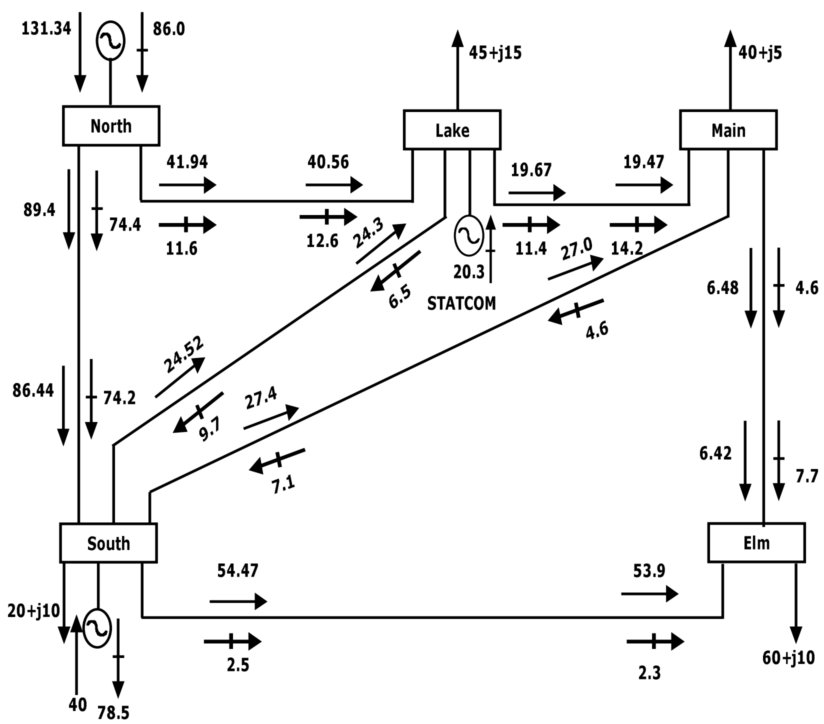

Fig. 2.5 STATCOM-upgraded test network and power flow result

Here the power flow result indicates that the STATCOM generates 20.3 MVAR in order to keep the voltage magnitude at 1 p.u. at bus 3. The largest reactive power flow takes place in the transmission line connecting North and South, where 74.4 MVAR leaves North and 74.2 MVAR arrives at South. In general, more reactive power is available in the network than in the base case, and the generator connected at South increases its share of reactive power absorption compared with the base case. Active power flows are only marginally affected by the STATCOM installation.

2.7 Power Flow Study With SVC

The SVC is included in the bus 3 of the sample system to maintain the nodal voltage at 1 p.u.. Here the SVC data are: the initial source voltage magnitude is 1 p.u , Phase angle is 0 degrees and the converter reactance: 10 p.u.

The power flow diagram and load flow result for the 5-bus system with SVC at bus 3 is shown in Table 2.5 and Fig 2.6 respectively.

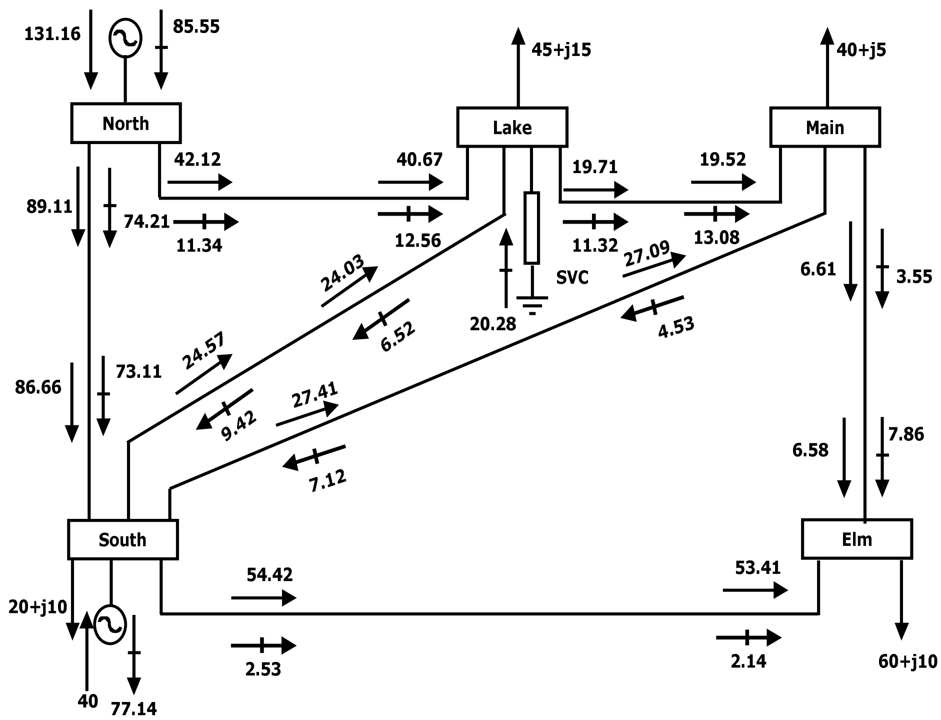

Fig. 2.6 SVC-upgraded test network and power flow result

Table 2.5 Result with SVC included at bus 3

Parameter	**Bus 1**	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**
VM(p.u.)	1.06	1	1	0.9944	0.9752
VA(deg)	0	-2.053	-4.78	-4.832	-5.797

2.8 Discussion

In this chapter the power flow of the five bus system has been studied without and with FACTS devices performing the Newton-Rapson method. Power flow without FACTS devices shows that the operating conditions demand a large amount of reactive power generation by the generator connected at bus 1 (i.e. 90.61 MVAR). This amount is well in excess of the reactive power drawn by the system loads (i.e. 40 MVAR). The generator at bus 2 draws the excess of reactive power in the network (i.e. 61.4 MVAR).

Use of STATCOM results in an improved network voltage profile, except at bus 5, which is too far away from bus 3 to benefit from the influence of STATCOM. The power flow result indicates that the STATCOM generates 20.3 MVAR in order to keep the voltage magnitude at 1 p.u at bus 3. The SVC injects 20.28 MVAR into bus 3 and keeps the nodal voltage magnitude at 1 p.u. The action of the SVC results in an overall improved voltage profile. The STATCOM is superior to the SVC in providing voltage support under large system disturbances during which the voltage excursions would be well outside of the linear operating range of the compensator.

CHAPTER 3

MODELING OF STATCOM AND GENERATOR FOR TRANSIENT STABILITY STUDIES

3.1 Introduction And Basic Circuit Configuration of STATCOM

The Static Synchronous Compensator (STATCOM) is a shunt connected reactive compensation equipment which is capable of generating and/or absorbing reactive power whose output can be varied so as to maintain control of specific parameters of the electric power system. The STATCOM provides operating characteristics similar to a rotating synchronous compensator without the mechanical inertia, due to the STATCOM employ solid state power switching devices it provides rapid controllability of the three phase voltages, both in magnitude and phase angle. The STATCOM basically consists of a step-down transformer with a leakage reactance, a three-phase GTO or IGBT voltage source inverter (VSI), and a DC capacitor. The AC voltage difference across the leakage reactance produces reactive power exchange between the STATCOM and the power system, such that the AC voltage at the bus bar can be regulated to improve the voltage profile of the power system, which is the primary duty of the STATCOM. However, for instance, a secondary damping function can be added into the STATCOM for enhancing power system oscillation stability . A STATCOM can be used for voltage regulation in a power system, having as an ultimate goal the increase in transmittable power, and improvements of steady-state transmission characteristics and of the overall stability of the system. Under light load conditions, the controller is used to minimize or completely diminish line over voltage; on the other hand, it can be also used to maintain certain voltage levels under heavy loading conditions.

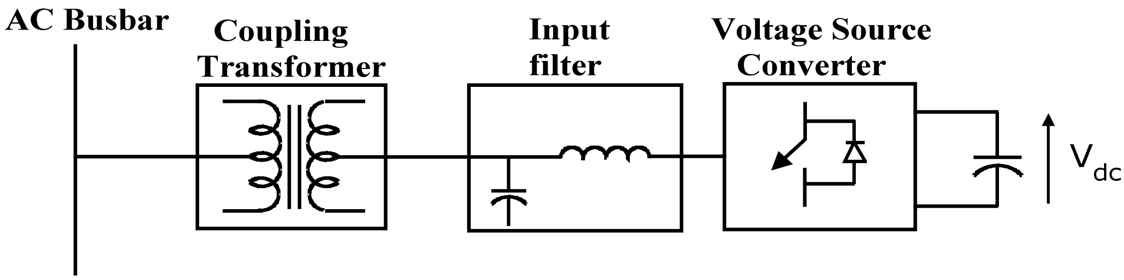

Fig 3.1 Connection of STATCOM to AC Bus bar

STATCOM consists of the coupling transformer, input filter, Voltage Source Converter and a controller. The connection of STATCOM to AC bus is shown in Fig. 3.1. When two AC sources of same frequency are connected through a series inductance, active power flows from leading source to lagging source and reactive power flows from higher voltage magnitude AC source to lower voltage magnitude AC source. Active power flow is determined by the phase angle difference between the sources and the reactive power flow is determined by the voltage magnitude difference between the sources. Hence, STATCOM can control reactive power flow by changing the fundamental component of the converter voltage with respect to the AC bus bar voltage both phase wise and magnitude wise.

Typical applications of STATCOM are:

- Effective voltage regulation and control.
- Reduction of temporary over voltages.
- Improvement of steady-state power transfer capacity.
- Improvement of transient stability margin.
- Damping of power system oscillations.
- Damping of sub synchronous power system oscillations.
- Flicker control.
- Power quality improvement.
- Distribution system applications

3.2 Basic Operating Principles of STATCOM

The basic electronic block of a STATCOM is a voltage-sourced converter that converts a dc voltage at its input terminals into a three-phase set of ac voltages at fundamental frequency with controllable magnitude and phase angle [3]. The basic principle of reactive power generation by a voltage-sourced converter is similar to that of the conventional rotating synchronous machine shown schematically in Fig 3.2.

For purely reactive power flow, the three-phase induced electromotive forces (EMFs), e_a, e_b, and e_c, of the synchronous rotating machine are in phase with the system voltages v_a, v_b, and v_c. The reactive current *I* drawn by the synchronous compensator is determined by the magnitude of the system voltage *V*, that of the internal voltage *E*, and the total circuit reactance (synchronous machine reactance plus transformer leakage reactance plus system short circuit reactance) X,

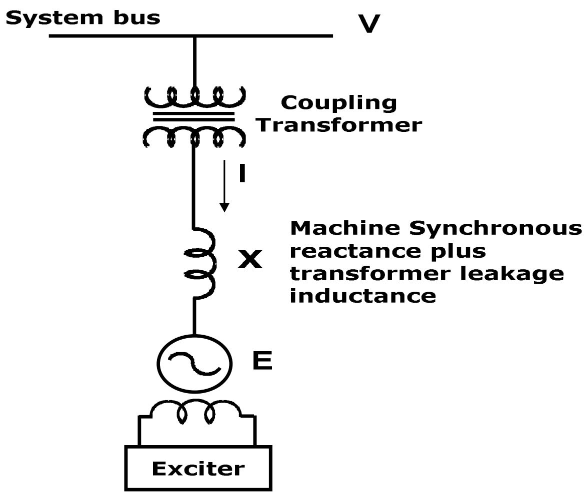

Fig. 3.2 Reactive power generation by a synchronous compensator

$$I = \frac{V - E}{X} \tag{3.1}$$

The corresponding reactive power Q exchanged can be expressed as follows

$$Q = \frac{1 - \frac{E}{V}}{X} V^2 \tag{3.2}$$

By controlling the excitation of the machine, and hence the amplitude E of its internal voltage relative to the amplitude V of the system voltage, the reactive power flow can be controlled. Increasing E above V (i.e. operating over-excited) results in a leading current as a result machine acts as capacitor. Decreasing E below V (i.e. operating under-excited) produces a lagging current as a result machine acts as a inductor. Under either operating condition a small amount of real power of course flows from the ac system to the machine to supply its mechanical and electrical losses. Note that if the excitation of the machine is controlled so that the corresponding reactive output maintains or varies a specific parameter of the ac system (e,g., bus voltage), then the machine (rotating var generator) functions as a rotating synchronous compensator.

The basic voltage-sourced converter scheme for reactive power generation is shown schematically, in the form of a single-line diagram in Fig 3.3.

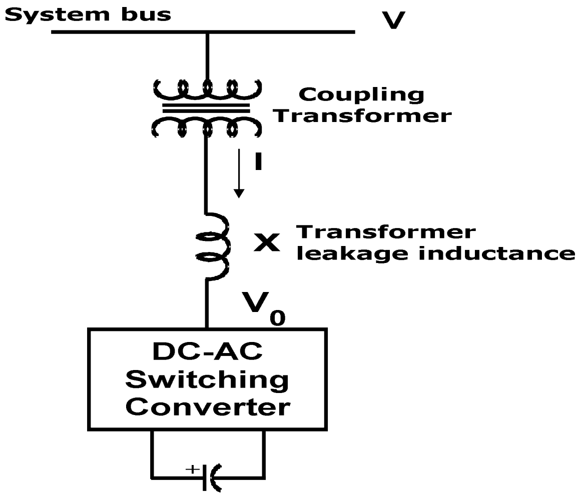

Fig 3.3 Reactive power generation by controlled voltage-sourced switching converter

From a dc input voltage-sourced , provided by the charged capacitor C_s, the convertor produces a set of controllable three-phase output voltages with the frequency of the ac power system. Each output voltage is in phase with, and coupled to the corresponding ac system voltage via a relatively small (0.1 – 0.15 p.u.) tie reactance (which in practice is provided by the per phase leakage inductance of the coupling transformer). By varying the amplitude of the output voltage produced, the reactive power exchange between the converter and the ac system can be controlled in a manner similar to that of the rotating synchronous machine. That is, if the amplitude of the output voltage is increased above that of ac system voltage, then the current flows through the tie reactance from the converter to the ac system, and the converter generates reactive (capacitive) power for the ac system. If the amplitude of the output voltage is decreased below that of the ac system, then reactive current flows from the ac system to the converter, and the converter absorbs reactive (inductive) power. If the amplitude of the output voltage is equal to that of the ac system voltage, the reactive power exchange is zero.

The three-phase output voltage is generated by a voltage-sourced dc to ac converter operated from an energy storage capacitor. All of the practical converters so far employed in actual transmission applications are composed of a number of elementary converters, that is, of single-phase H-bridges, or three-phase, two-level, six-pulse bridges, or three-phase, three-level, 12-pulse bridges shown in Fig 3.4

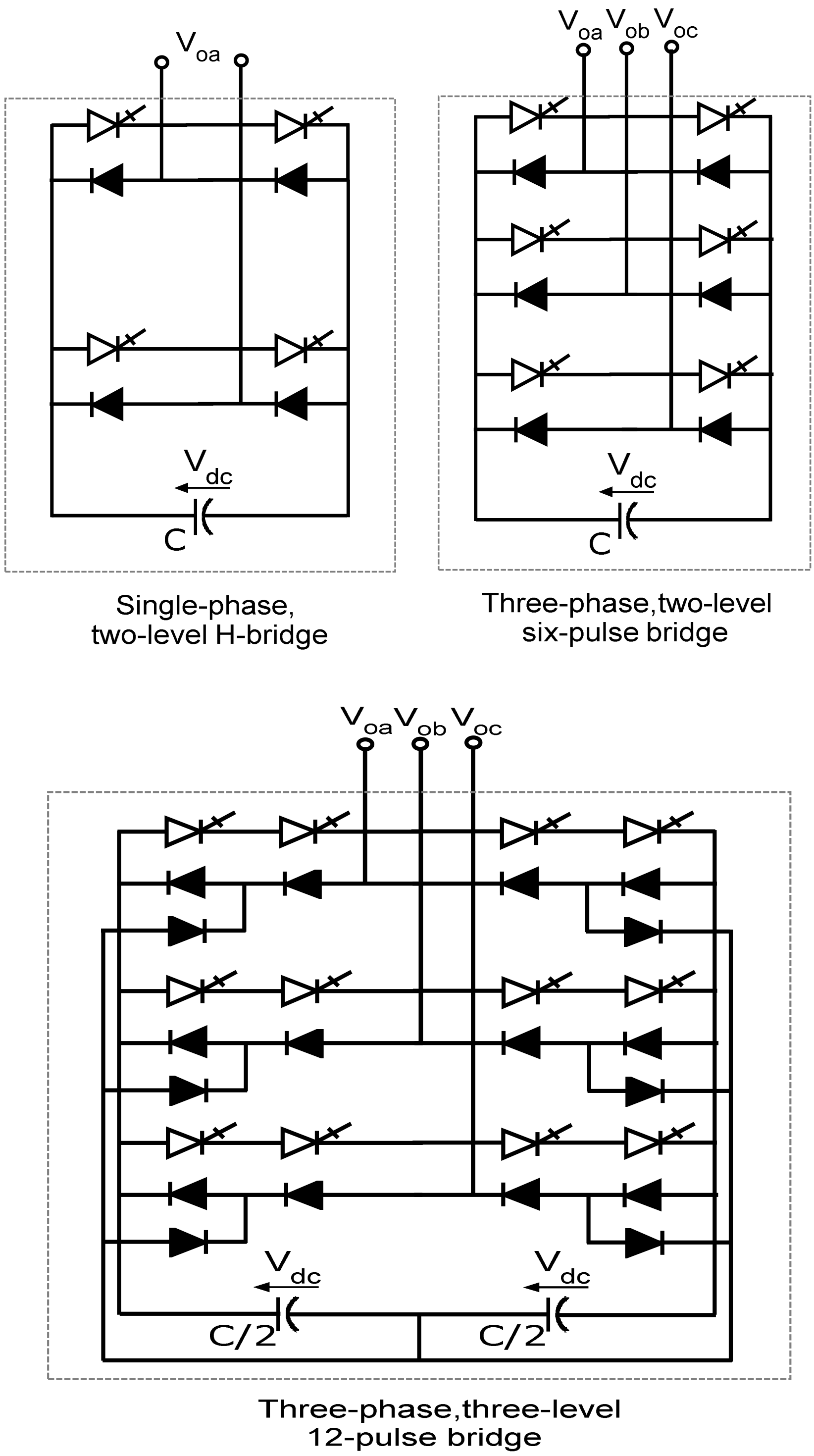

Fig 3.4 Basic converter schemes used for reactive power generation

The valves used in the elementary converter usually comprise a number (3 to 10) of series connected power semiconductors, e.g., GTO thyristors with reverse-parallel diodes. Each elementary converter produces a square or a quasi-square or a pulse-width modulated output voltage waveform. These component voltage waveforms are phase-shifted from each other (or otherwise made complementary to each other) and then combined, usually with the use of appropriate magnetic components, to produce the final output voltage of the total converter. With sufficient design, this final output voltage can be made to approximate a sine wave closely enough so that no filtering is required.

The operation of the voltage-sourced converter, used as a controllable static var generator, can be explained without considering the detailed operation of the converter valves by basic physical laws governing the relationship between the output and input powers. The key to this explanation in the physical fact that, like in all switching power converters, the net instantaneous power at the ac output terminals must always be equal to the net instantaneous power at the dc input terminal (neglecting the losses in the semiconductor switches). Since the converter supplies only reactive output power (its output voltages are controlled to be in phase with the ac system voltages), the real power provided by the dc source (charged capacitor) must be zero (as the total instantaneous power on the ac side is also zero). Furthermore, since reactive power at zero frequency (at the dc capacitor) by the definition is zero, the dc capacitor plays no part in the reactive power generation. In other words the converter simply interconnects the three ac terminals in such a way that the reactive output currents can flow freely between them. Viewing this from terminals of the ac system, one could say that the converter establishes a circulating current flow among the phase with zero net instantaneous power exchange. The presence of the input ripple current components is thus entirely due to the ripple components of the output voltage, which are a function of the output waveform fabrication method used. In a practical var generator, as explained above, the elementary two or three-level converters would not meet practical harmonic requirements either for the output voltage or for the input (dc capacitor) current. However by combining a number of these basic converters into a multi-pulse structure (and / or using appropriate pulse-width modulation – PWM – or other wave shaping techniques), the output voltage distortion and capacitor ripple can be theoretically reduced to any desired degree. Thus, a static (var) generator, employing a perfect voltage-sourced converter, would produce sinusoidal output voltages, would draw sinusoidal reactive currents from the ac system and zero input current from the dc capacitor. In practice due to system unbalance and other imperfections (which could increase the ac power fluctuation considerably), as well as economic restrictions, these ideal conditions are not achieved, but can be approximated quite satisfactory by appropriate converter structures and wave shaping techniques so that the size of the dc capacitor in normal transmission applications remains relatively small.

In a practical converter, the semi converter switches are not lossless, and therefore the energy stored in the dc capacitor would be used up by the internal losses. However these losses can be supplied from the ac system by making the output voltages of the converter lag the ac system voltages by a small angle. In this way the converter absorbs a small amount of real power from the ac system to replenish its internal losses and keep the capacitor voltage at the desired level. The mechanism of phase angle adjustment can also be used to control the var generation or absorption by increasing or decreasing the capacitor voltage, and thereby the amplitude of the output voltage produced by the converter. The capacitor also has a vital function even in the case of a converter, in establishing the necessary energy balance between the input and output during the dynamic changes of the var output.

It is, of course, also possible to equip the converter with the dc source (e,g., a battery) or with an energy storage device of significant capacity (e.g., a large dc capacitor, or a superconducting magnet). In this case the converter can control both reactive and real power exchange with the ac system, and thus it can function as a static synchronous generator. The capability of controlling real as well as reactive power exchange is a significant feature which can be used effectively in applications requiring power oscillation damping, leveling peak power demand, and providing uninterrupted power for critical loads. This capability is unique to the switching converter type var generator and it fundamentally distinguishes it from its conventional thyristor-controlled counterpart.

3.3 Modeling of STATCOM

The STATCOM is modeled by a voltage source connected to the power system through a coupling transformer. The source voltage is the output of a voltage-sourced converter (VSC) realizing the STATCOM. From the Fig. 3.5 STATCOM is assumed at the midpoint of the transmission line. The phase angle of the source voltage is equal as that of the midpoint voltage.

Therefore, there is exchange of only reactive power and no real power between the STATCOM and the ac system [3],[20].

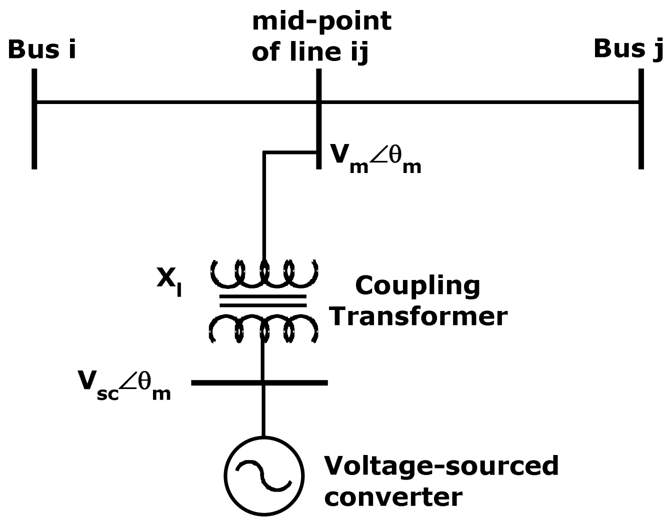

Fig. 3.5 Representation of STATCOM

The expressions for the current flowing from the STATCOM to the system and the reactive power injection are given as

$$I = \frac{(V_{sc} - V_m)\angle\theta_m}{jX_l} \quad (3.3)$$

$$Q = V_m^2 . \frac{(V_{SC} / V_m - 1)}{X_l} \quad (3.4)$$

Where Vm is the magnitude of the voltage at the midpoint of the line and Vsc is the magnitude of the voltage of the voltage-sourced converter, θm is the phase angle of the mid-point voltage, and X_l is the coupling transformer leakage reactance. The magnitude of the voltage of the voltage-sourced converter determines the direction and nature of the reactive power flow. If it is greater than the magnitude of the line midpoint voltage , then reactive power is injected to the ac system, whereas if the line midpoint voltage magnitude is greater, then reactive power will be drawn from the ac system. Here only the reactive power injection mode of operation is considered. The leakage reactance of the coupling transformer is taken as 0.1 p.u.

During fault conditions a constant value of source voltage magnitude may cause a very high value of current drawn from the STATCOM (Isc). For this, a maximum limit, denoted by Imax , is set for the STATCOM current. For a practical system, this current limit is decided by the rating of the STATCOM. When the current reaches the limit Imax, STATCOM behaves like a constant current source. To include this feature in the simulation, Vsc is kept constant at the pre-specified value (denoted by Vsco) when Isc ≤ Imax . But, whenever the value of Isc exceeds Imax , the value of Vsc is adjusted such that Isc becomes equal to Imax . The STATCOM is used to control power flow of power system by injecting appropriate reactive power during dynamic state.

The STATCOM is a voltage-sourced-converter (VSC)-based shunt-connected device. By injecting a current of variable magnitude in quadrature with the line voltage, the STATCOM can inject reactive power into the power system.The STATCOM does not employ capacitor or reactor banks to produce reactive power as does the SVC, but instead uses a capacitor to maintain a constant dc voltage for the inverter operation.An equivalent circuit for the STATCOM is shown in Fig. 3.6.

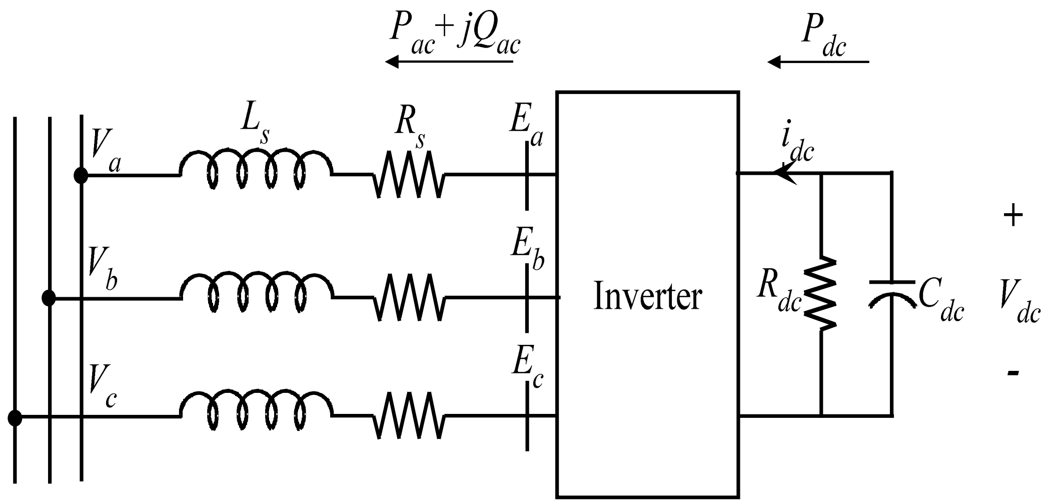

Fig 3.6 Equivalent circuit of the STATCOM

The loop equations for the circuit may be written in vector form as

$$\frac{d}{dt}i_{abc} = -\frac{R_s}{L_s}i_{abc} + \frac{1}{L_s}\left(E_{abc} - V_{abc}\right) \tag{3.5}$$

where R_s and L_s represent the STATCOM transformer losses, E_{abc} are the inverter ac side phase voltages, V_{abc} are the system-side phase voltages, and i_{abc} are the phase currents. The output of the STATCOM is given by

$$E_a = kV_{dc}\cos(\omega t + \alpha) \tag{3.6}$$

Where V_{dc} is the voltage across the dc capacitor, k is the modulation gain, and α is the injected voltage phase angle. By defining a proper synchronous reference frame, the dynamic model can be simplified. The reference frame coordinate is defined in which the d-axis is always coincident with the instantaneous system voltage vector and the q-axis is in quadrature with it. By transforming the system model to this reference frame, the STATCOM equations at bus i can be written as [21],[22]

$$\frac{1}{\omega_s}\frac{d}{dt}i_d = -\frac{R_s}{L_s}i_d + \frac{\omega}{\omega_s}i_q + \frac{k}{L_s}\cos(\alpha+\theta_i)V_{dc} - \frac{V_i}{L_s}\cos\theta_i \tag{3.7}$$

$$\frac{1}{\omega_s}\frac{d}{dt}i_q = -\frac{R_s}{L_s}i_q + \frac{\omega}{\omega_s}i_d + \frac{k}{L_s}\cos(\alpha+\theta_i)V_{dc} - \frac{V_i}{L_s}\sin\theta_i \tag{3.8}$$

$$\frac{C_{dc}}{\omega_s}\frac{d}{dt}V_{dc} = -k\cos(\alpha+\theta_i)i_d - k\sin(\alpha+\theta_i)i_q\frac{V_{dc}}{R_{dc}} \tag{3.9}$$

Where i_d and i_q are the injected dq STATCOM currents, V_{dc} is the voltage across the dc capacitor, R_{dc} represents the switching losses, R_s and L_s are the coupling transformer resistance and inductance, respectively.

The damping controller used to damp the oscillations incorporate with STATCOM is shown below

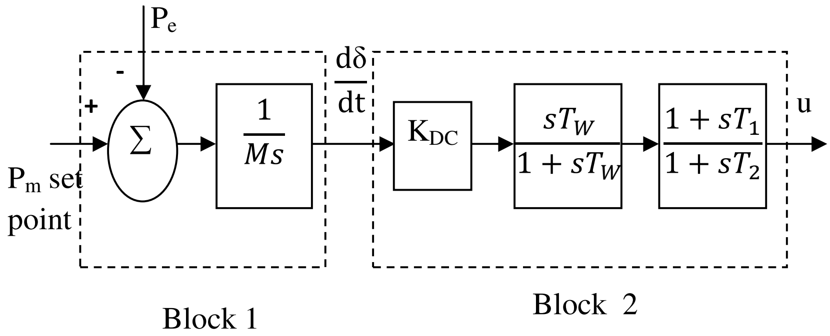

Fig. 3.7. The damping controller incorporate with STATCOM

3.4 The Sample Nine Bus System

For the proposed work we have considered the three- machine, nine- bus WSCC (Western System Coordinating Counsel) system as shown in Figure 3.8,

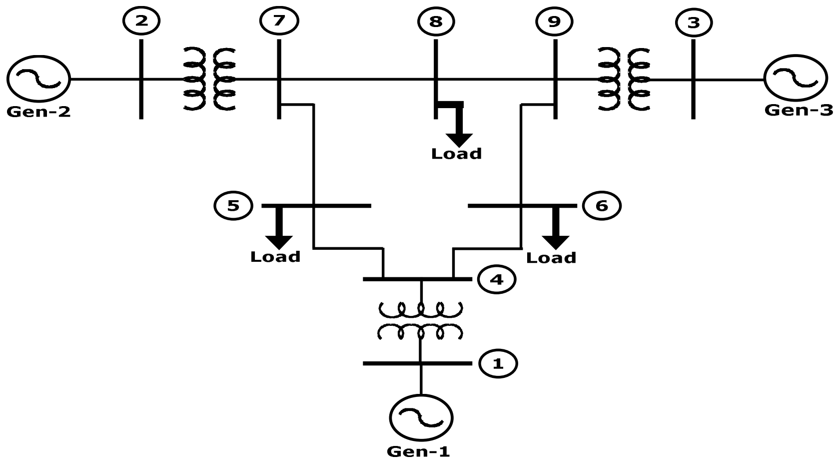

Fig. 3.8 WSCC, Three-Machine, nine-bus system

The input data for the considered system are given in Table 3.1 for the bus and Table 3.2 for transmission line [23]. The transmission line impedances and line charging admittances are in per unit.

Table 3.1 Input bus data (p.u.)

Bus no	**Type**	**Generation**		**Load**		**Voltage**	
		P	**Q**	**P**	**Q**	**|V|**	**θ**
1	Slack	0	0	0	0	1.04	0
2	P-V	1.63	0	0	0	1.025	0
3	P-V	.85	0	0	0	1.025	0
4	P-Q	0	0	0	0	1	0
5	P-Q	0	0	1.25	.50	1	0
6	P-Q	0	0	.90	.30	1	0
7	P-Q	0	0	0	0	1	0
8	P-Q	0	0	1.0	.35	1	0
9	P-Q	0	0	0	0	1	0

Assuming base quantity of 100MVA and 100KV

Table 3.2 Input transmission line data (p.u)

Bus No	**Line Code**	**Impedance (R+jX)**	**Line Charging Admittance**
1	1-4	0+j.0576	0+j0
2	2-7	0+j.0625	0+j0
3	3-9	0+j.0586	0+j0
4	4-5	0.01+j.0850	0+j.088
4	4-6	.017+j.0920	0+j.079
5	5-7	.0320+j.161	0+j.153
6	6-9	.0390+j.17	0+j.179
7	7-8	.0085+j.072	0+j.0745
8	8-9	.0119+j.1008	0+j.1045

The disturbances for the sample system are 3-phase faults at each end of each line (3-phase to earth), followed by clearing the fault via removing one of the lines connected to the faulted bus, followed by a successful three phase reclosure of the faulted line.

3.4.1 Modeling of Multi – Machine Power System

A nonlinear dynamic model can describe a multi – machine power system (Fig 3.8) with three – machines, in which the first machine is chosen as the reference machine. The algebraic equation of the system

$$[I]=[V][Y] \qquad (3.10)$$

i.e.

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix} \qquad (3.11)$$

The dynamics of the machine, in detailed model, can be represented by the following differential equations [24]-[26],

$$\dot{\delta}_1 = \omega_1 \tag{3.12}$$

$$\dot{\omega}_1 = \frac{1}{M_1}(P_{m1} - P_{e1} - D_1\omega_1) \tag{3.13}$$

$$\dot{E}'_{q1} = \frac{1}{T'_{01}}(-E_{q1} + E_{fd1}) \tag{3.14}$$

$$\dot{\delta}_2 = \omega_2 \tag{3.15}$$

$$\dot{\omega}_2 = \frac{1}{M_2}(P_{m2} - P_{e2} - D_2\omega_2) \tag{3.16}$$

$$\dot{E}'_{q2} = \frac{1}{T'_{02}}(-E_{q2} + E_{fd2}) \tag{3.17}$$

$$\dot{\delta}_3 = \omega_3 \tag{3.18}$$

$$\dot{\omega}_3 = \frac{1}{M_3}(P_{m3} - P_{e3} - D_3\omega_3) \tag{3.19}$$

$$\dot{E}'_{q3} = \frac{1}{T'_{03}}(-E_{q3} + E_{fd3}) \tag{3.20}$$

Here δ, ω, M ,P_m , $P_{e,}, E_q$, E'_q and E_{fd} are the angle, speed, moment of inertia, damping coefficient, input mechanical power , output electrical power, voltage back of quadrature-axis synchronous reactance, voltage proportional to the field flux linkage resulting from the combined effect of the field and armature currents and the field voltage acting along the quadrature-axis, respectively , of the machine. Here the subscript 1,2 and 3 represent the respective machines.

CHAPTER 4

SIMULATION RESULTS AND DISCUSSION

4.1 Simulation Results

A three-phase fault is simulated in one of the lines of the nine-bus system i.e. three phase to earth fault. The simulation is done in three phases. To start with, the pre-fault system is run for a small time. Then a symmetrical fault is applied at one end of a line (Fig. 3.8). Simulation of the faulted condition continues until the line is disconnected from the buses at both of the ends of the faulted line after a fault clearing time t_{cl} s. Then the post-fault system is simulated for a longer time (say, 10 s) to observe the nature of the transients. We start with $t_{cl} = 0.1$ s (which is six cycles for a 60-Hz system) and then t_{cl} =.15s. Now the STATCOM is connected to the midpoint of one of the lines. To ensure the reactive power injection mode of operation, the magnitude of the voltage of the STATCOM is set at a value higher than the magnitudes of the pre-fault line midpoint voltage.

Plots of relative machine angles delta-(1-2) and (1-3) are shown in Fig. 4.1 and Fig. 4.2 with fault clearing time t_{cl} = .1 (s) in line 5-7 respectively.

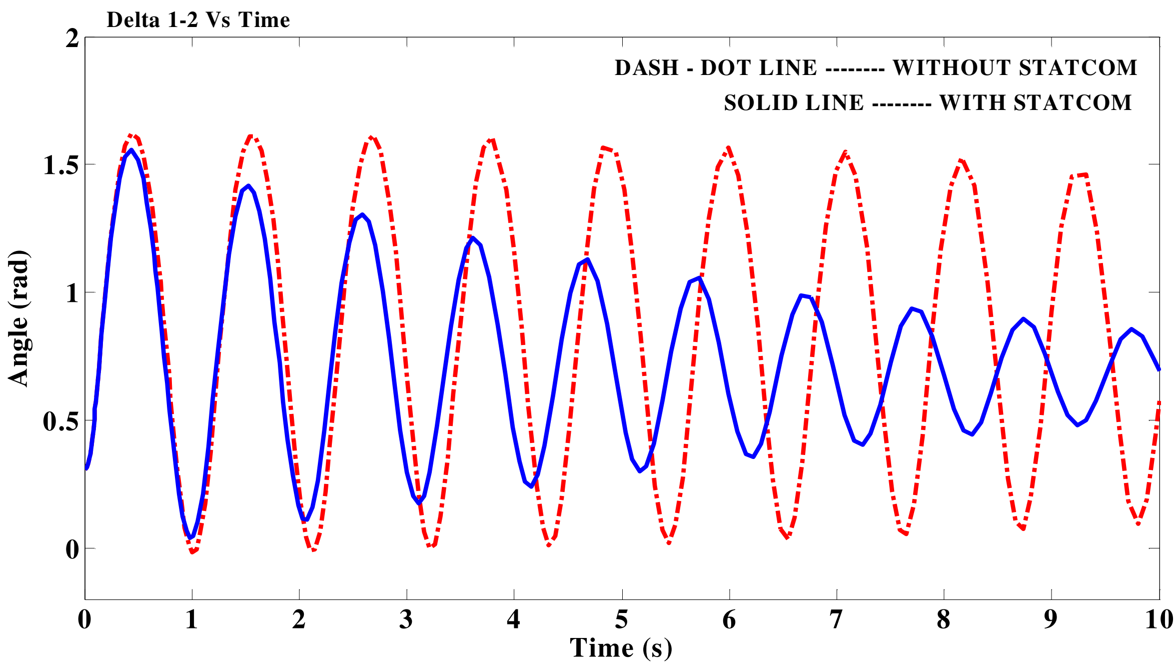

Fig. 4.1. Response of relative machine angles delta 1-2 for fault at bus 7, line removed at 5-7 without STATCOM and with STATCOM

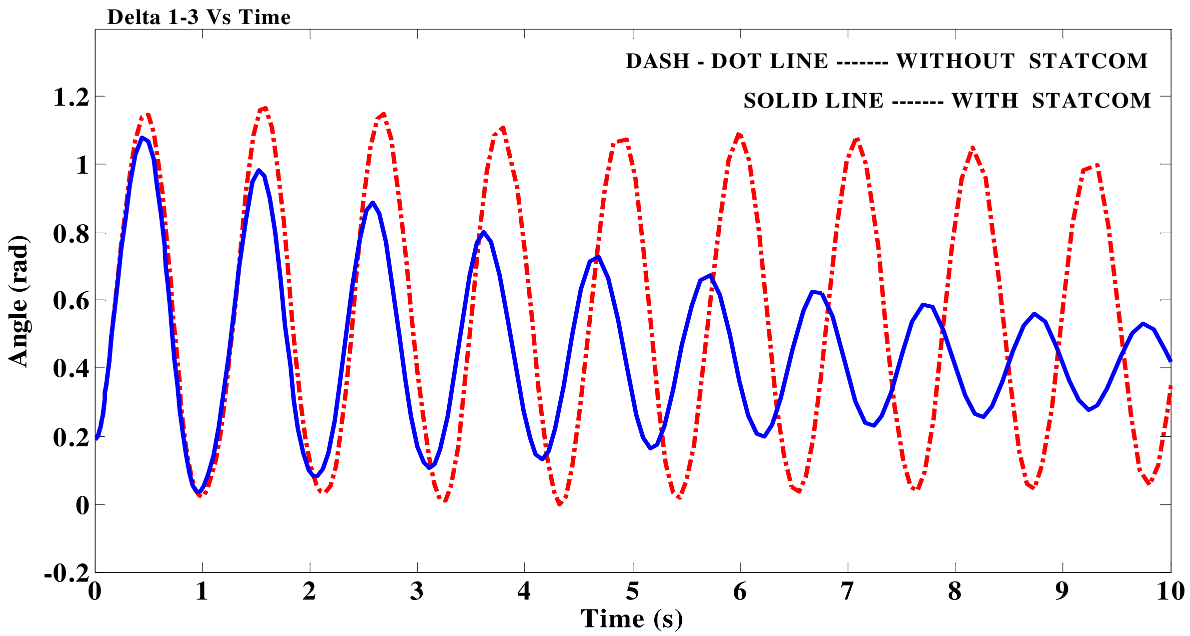

Fig. 4.2. Response of relative machine angles delta 1-3 for fault at bus 7, line removed at 5-7 without STATCOM and with STATCOM

Plots of relative machine angles delta-(1-2) and (1-3) are shown in Fig. 4.3 and Fig. 4.4 with fault clearing time t_{cl} = .15 (s) in line 5-7 respectively.

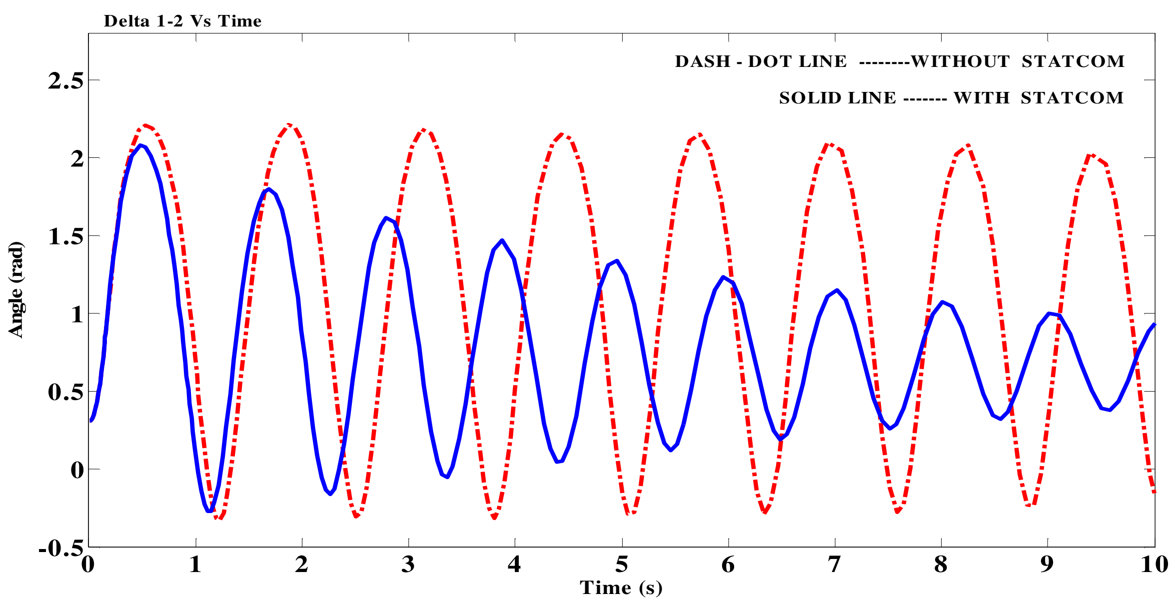

Fig. 4.3. Response of relative machine angles delta 1-2 for fault at bus 7, line removed at 5-7 without STATCOM and with STATCOM

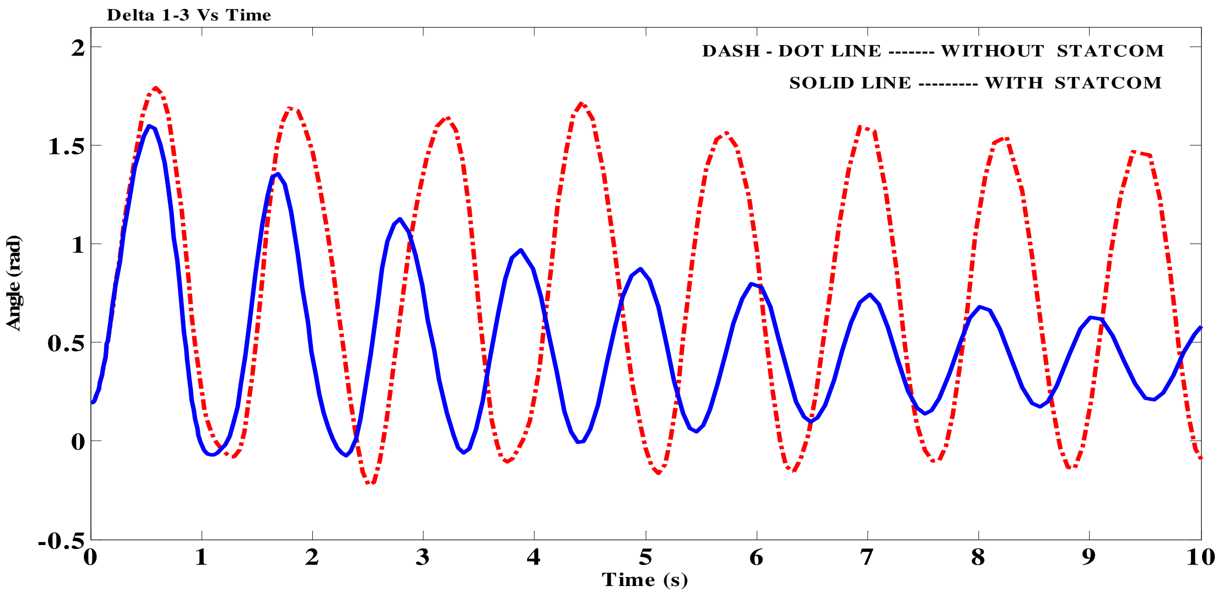

Fig. 4.4. Response of relative machine angles delta 1-3 for fault at bus 7, line removed at 5-7 without STATCOM and with STATCOM

Plots of relative machine angles delta-(1-2) and (1-3) are shown in Fig. 4.5 and Fig. 4.6 with fault clearing time t_{cl} = .1 (s) in line 4-5 respectively.

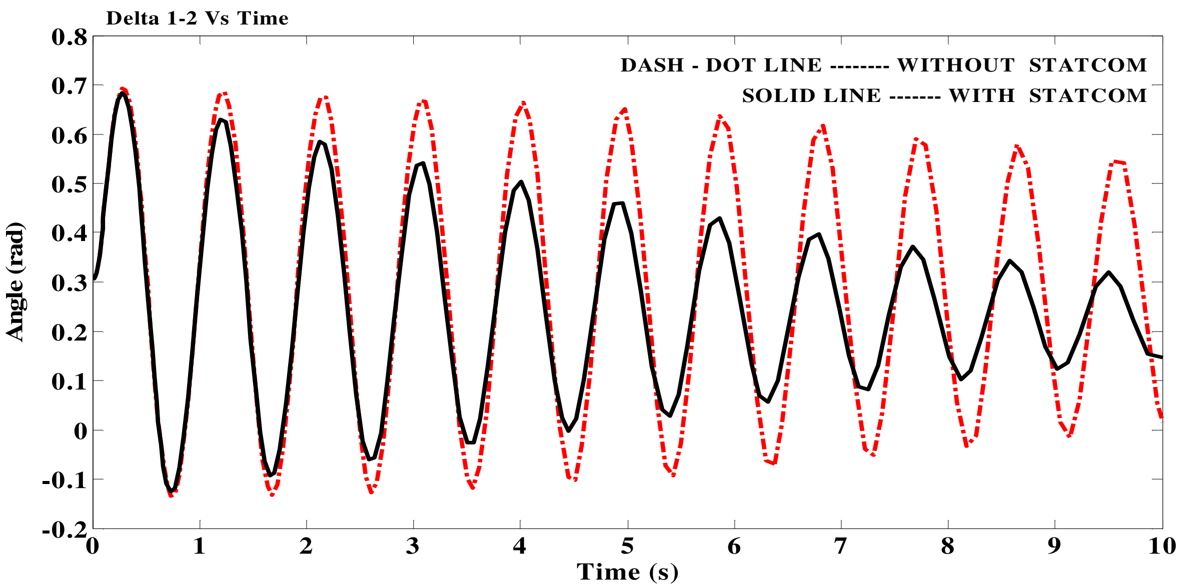

Fig. 4.5. Response of relative machine angles delta 1-2 for fault at bus 5, line removed at 4-5 without STATCOM and with STATCOM

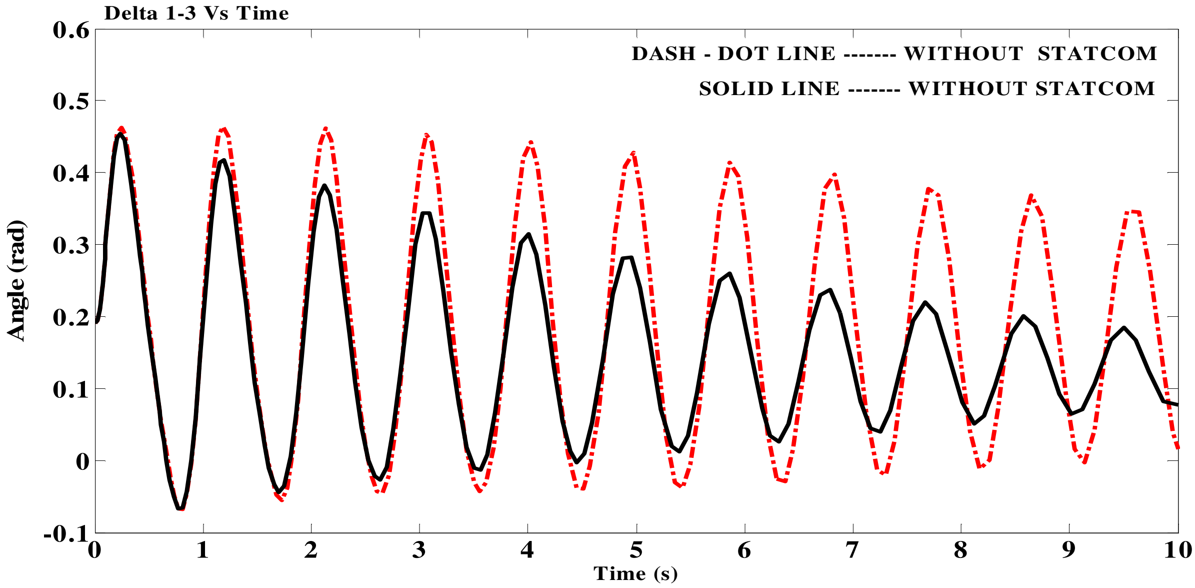

Fig. 4.6. Response of relative machine angles delta 1-3 for fault at bus 5, line removed at 4-5 without STATCOM and with STATCOM

Plots of relative machine angles delta-(1-2) and (1-3) are shown in Fig. 4.7 and Fig. 4.8 with fault clearing time t_{cl} = .15 (s) in line 4-5 respectively.

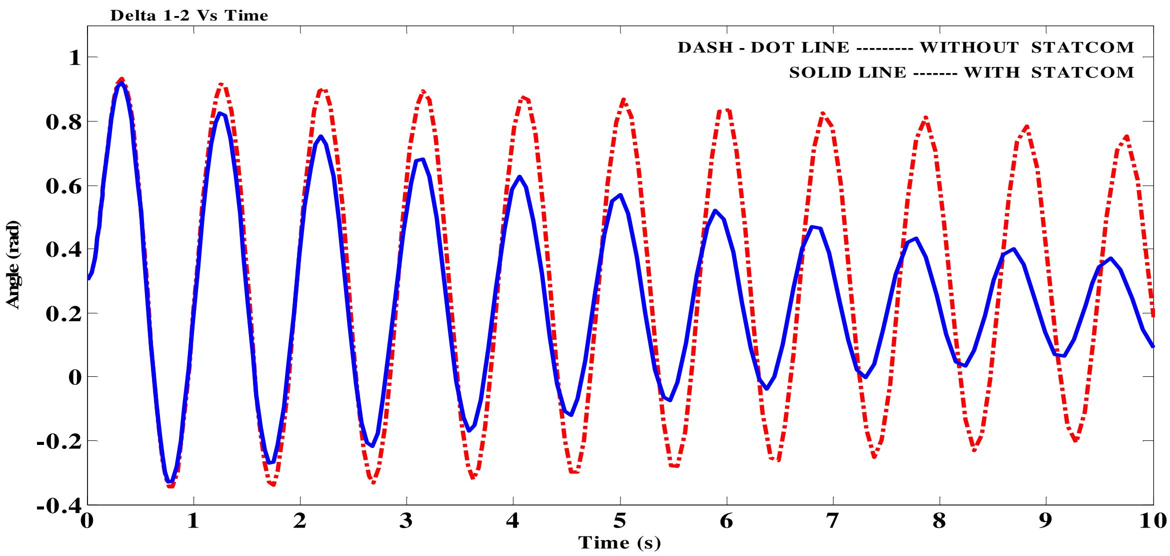

Fig. 4.7. Response of relative machine angles delta 1-2 for fault at bus 5, line removed at 4-5 without STATCOM and with STATCOM.

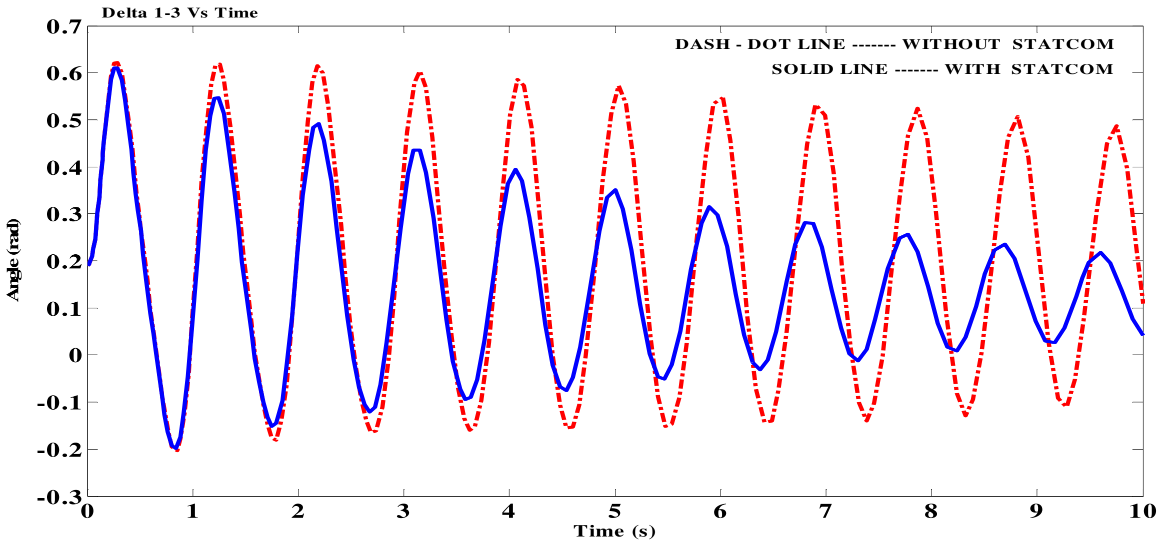

Fig. 4.8. Response of relative machine angles delta 1-3 for fault at bus 5, line removed at 4-5 without STATCOM and with STATCOM.

Plots of relative machine angles delta-(1-2) and (1-3) are shown in Fig. 4.9 and Fig. 4.10 with fault clearing time t_{cl} = .1(s) in line 6-9 respectively.

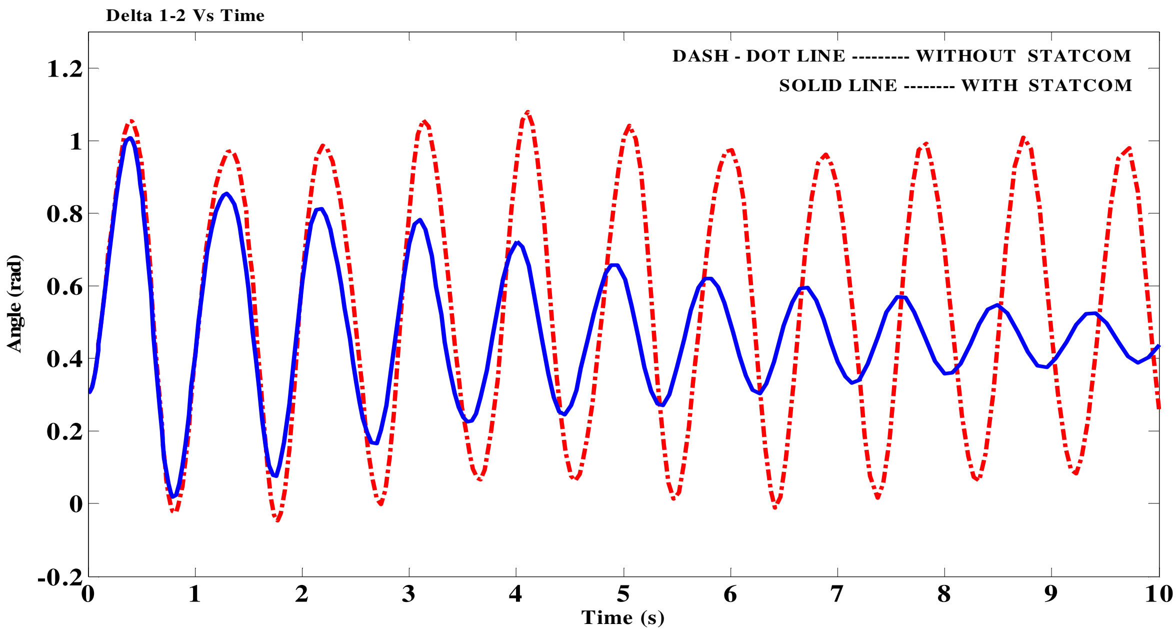

Fig. 4.9. Response of relative machine angles delta 1-2 for fault at bus 9, line removed at 6-9 without STATCOM and with STATCOM.

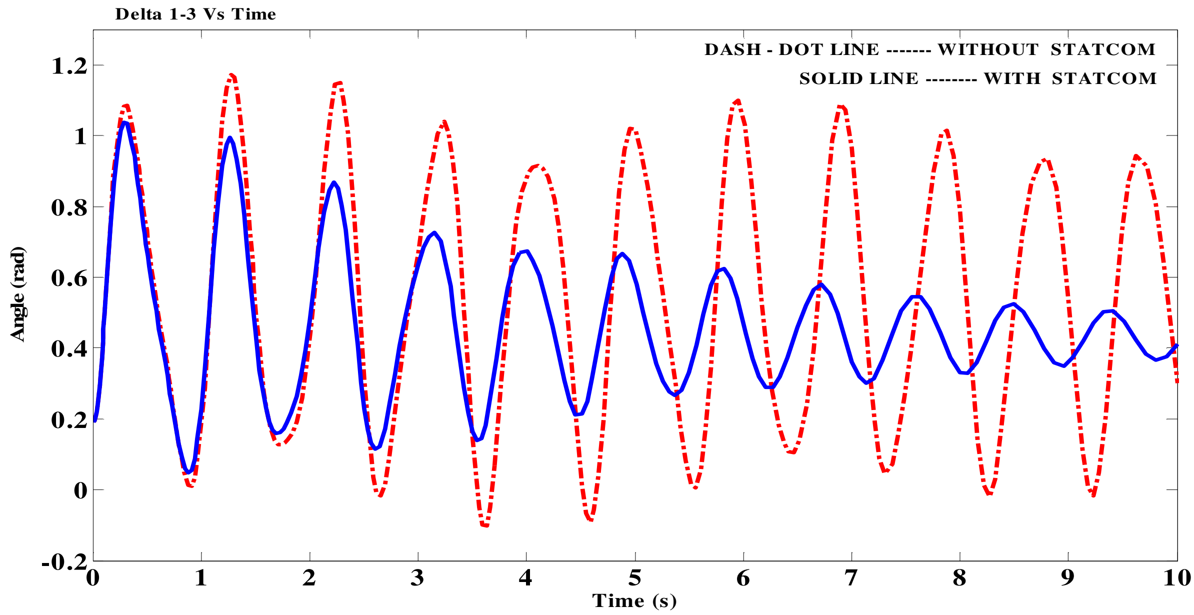

Fig. 4.10. Response of relative machine angles delta 1-3 for fault at bus 9, line removed at 6-9 without STATCOM and with STATCOM.

Plots of relative machine angles delta-(1-2) and (1-3) are shown in Fig. 4.11 and Fig. 4.12 with fault clearing time t_{cl} = .15 (s) in line 6-9 respectively.

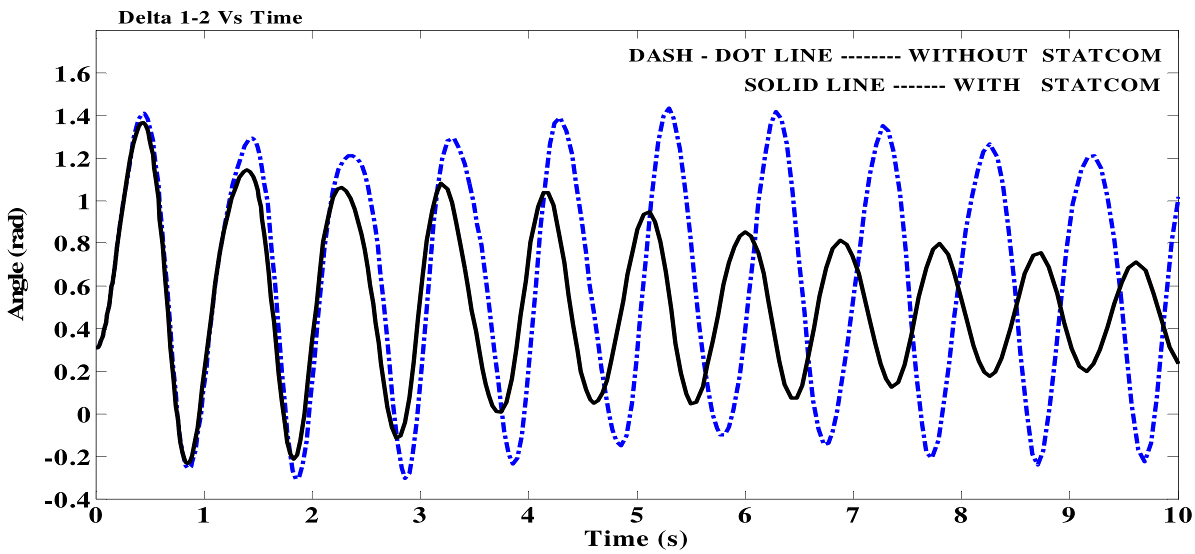

Fig. 4.11. Response of relative machine angles delta 1-2 for fault at bus 9, line removed at 6-9 without STATCOM and with STATCOM.

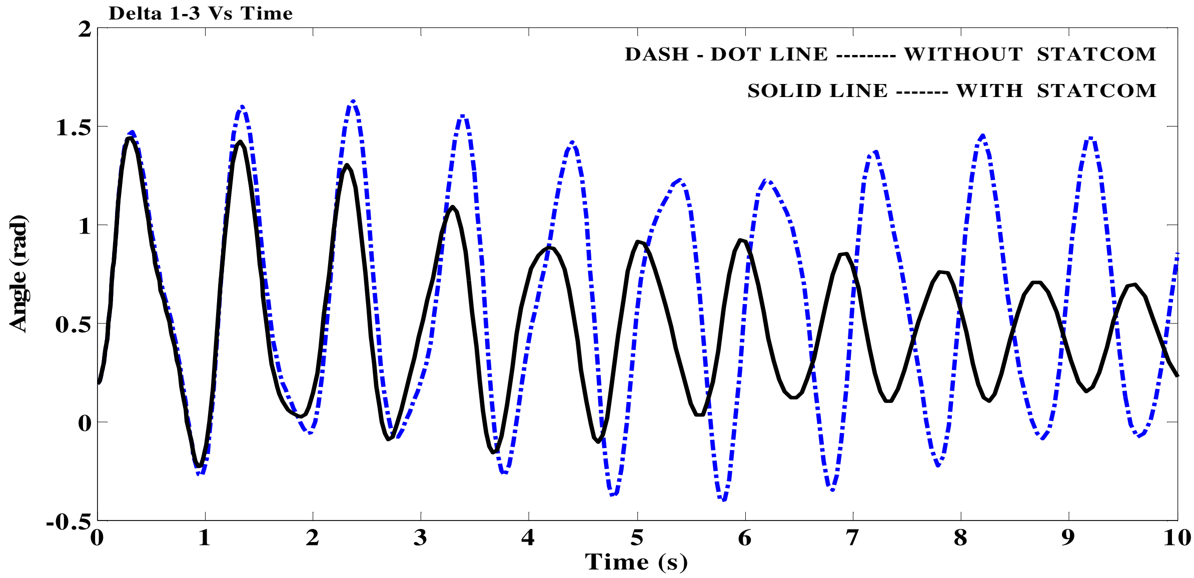

Fig. 4.12. Response of relative machine angles delta 1-3 for fault at bus 9, line removed at 6-9 without STATCOM and with STATCOM.

Plots of relative machine angles delta-(1-2) and (1-3) are shown in Fig. 4.13 and Fig. 4.14 with fault clearing time t_{cl} = .1(s) in line 7-8 respectively.

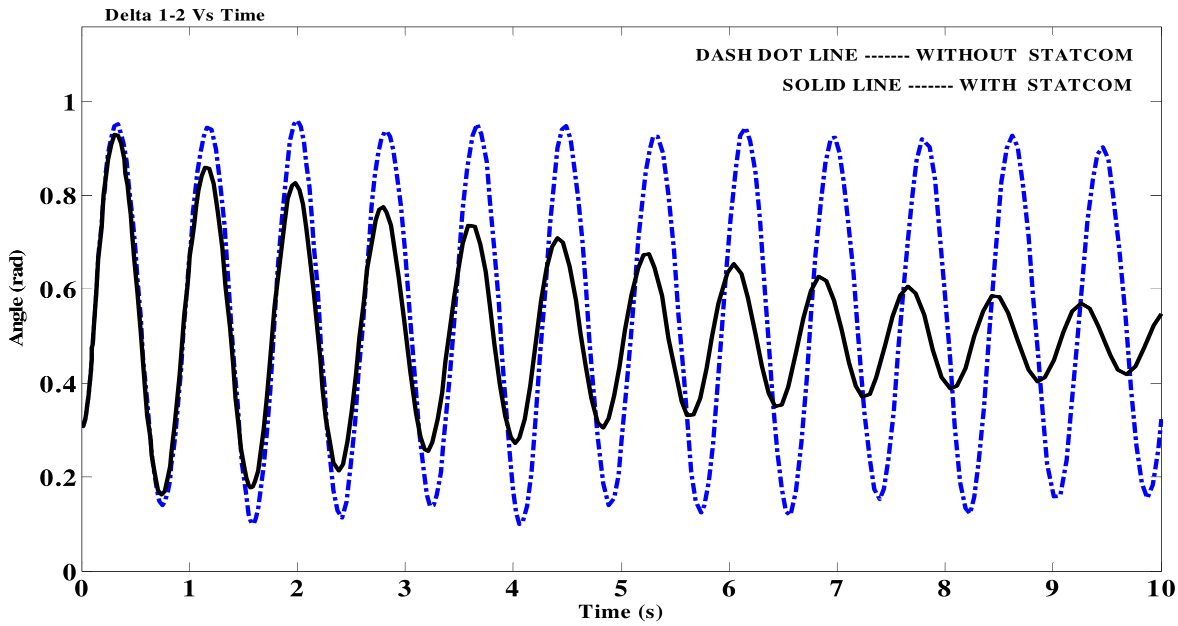

Fig. 4.13. Response of relative machine angles delta 1-2 for fault at bus 8, line removed at 7-8 without STATCOM and with STATCOM.

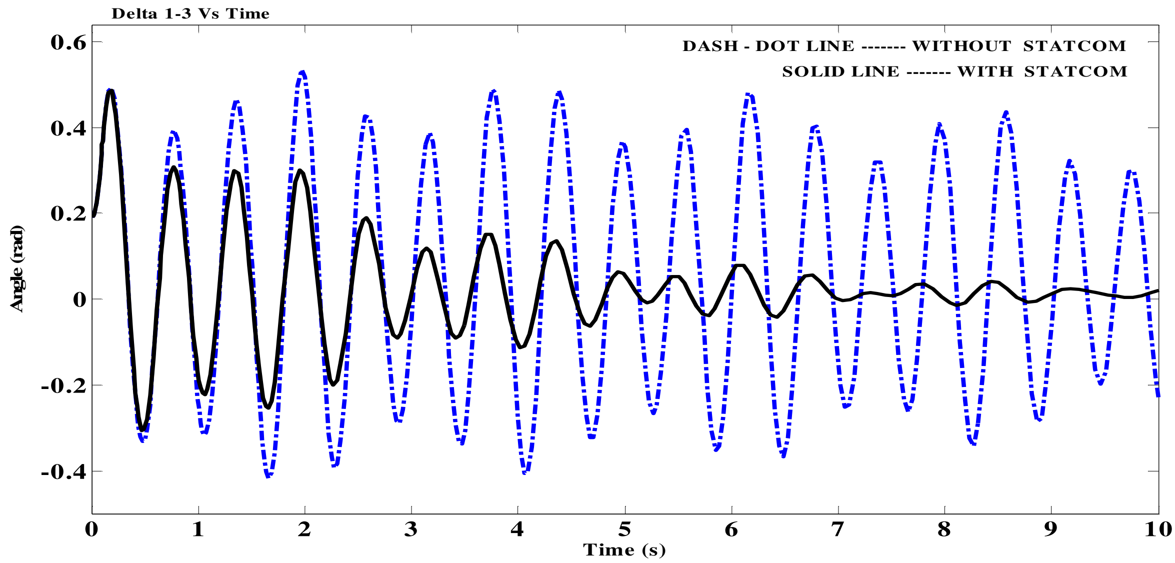

Fig. 4.14. Response of relative machine angles delta 1-3 for fault at bus 8, line removed at 7-8 without STATCOM and with STATCOM.

Plots of relative machine angles delta-(1-2) and (1-3) are shown in Fig. 4.15 and Fig. 4.16 with fault clearing time t_{cl} = .15(s) in line 7-8 respectively.

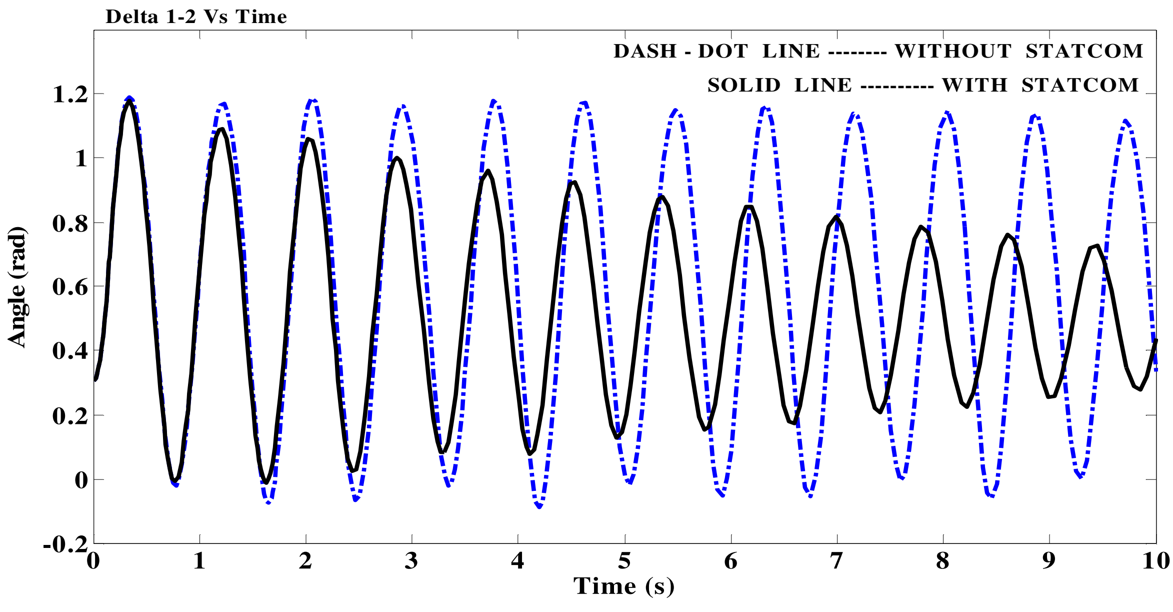

Fig. 4.15. Response of relative machine angles delta 1-2 for fault at bus 8, line removed at 7-8 without STATCOM and with STATCOM.

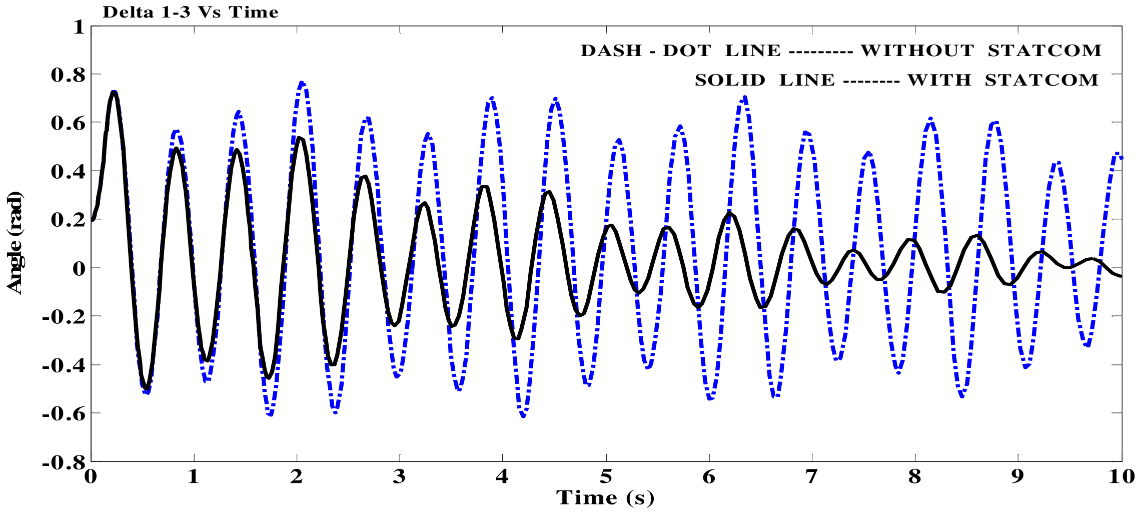

Fig. 4.16. Response of relative machine angles delta 1-3 for fault at bus 8, line removed at 7-8 without STATCOM and with STATCOM.

4.2 Discussion

From the above simulation results we conclude that STATCOM not only considerably improves transient stability but also compensates the reactive power in steady state. The STATCOM is used to control power flow of power system by injecting appropriate reactive power during dynamic state. The best possible location of the FACTS device (STATCOM) is found to vary with the location of the fault and the operating criteria of the device. We also conclude that if the fault clearing time is less, more stability improvement. On the other hand less transient stability improvement occurs if fault clearing time is more.

CHAPTER 5
CONCLUSION AND SCOPE FOR FUTURE WORK

5.1 Conclusion

In this thesis, the effect of STATCOM for improving transient stability of the multi-machine power system is investigated in terms of the Fault Clearing Time. The STATCOM is used to control power flow of power system by injecting appropriate reactive power during dynamic state. Computer simulation results show that STATCOM not only considerably improves transient stability but also compensates the reactive power in steady state. Therefore STATCOM can increase reliability and capability of AC transmission system .It is also found that the best possible location of the STATCOM for transient stability improvement is not fixed for the nine-bus system; rather it varies depending on the fault location.

It is quite clear that before compensating a power system with FACTS device to improve transient stability, we need to assess the system stability conditions for different locations of the fault and the compensator and also with different amounts of compensation. The transient stability improvement of the multi-machine power system at different fault condition is investigated in this work. The proposed work is also analyzed for different fault clearing times.

5.2 Scope for Future Work

The following are the scope for the further research work

(a) Improvement of transient stability can be studied by the use of Thyristor Controlled Series capacitor (TCSC) for the proposed system at different fault conditions.
(b) By the use of both STATCOM and TCSC simultaneously we can improve transient stability of the proposed system at different fault conditions.

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[1] Laxmidhar Sahu, Jose. P. Therattil, P.C. Panda, "Study of Shunt FACTS-Based Controllers Effectiveness on Multi Machine Power System Steady State Operation", IEEE Conference, ICCRC New Delhi, March 2011 (To be published).

[2] Laxmidhar Sahu, Jose. P. Therattil, P.C. Panda, "The Effect of STATCOM on Multi-machine Power System Transient Stability Improvement", IEEE Conference, PACC Coimbatore, July 2011 (Accepted).

[3] Jose. P. Therattil, Laxmidhar Sahu, Rajendra Prasad, P.C. Panda, "Dynamic Stability Enhancement Using Self-Tuning Static Synchronous Compensator", IEEE Conference, PACC Coimbatore , July 2011 (Accepted).