CHAPTER-1

INTRODUCTION

1.1 Introduction

Modern power system is a complex network comprising of transmission lines, variety of loads and numerous amount of generators. Today modern power system is facing various challenges due to day by day increasing complexity in their structure and operation. In the recent past years, power system instability got a wide attention due to increased load demand. With the increased loading of long transmission lines, the problem of transient stability after a major fault was becoming a serious issue. With the lack of new generation and over exploitation of existing facilities make these types of problems more severe in modern power systems. Demand for power was rising day by day due to rapid development in industrial sector [2]. Since the last decade, the traditional concepts and practices adopted by power system have changed due to deregulation of electricity market. The changes arises due to lack of adequate funds in setting up the new plants for generation and overall to improve the efficiency of the power system. The deregulated structure is introducing the competition at various levels in trading sectors.

To meet this demand, it becomes essential to enhance the existing generation and transmission facilities. With the increased loading of long transmission lines, the problem of transient stability can become a transmission limiting factor. The design of modern power system should be flexible so that it can adapt itself to variable momentary conditions. While the power flow in some of the transmission lines in their normal limits, other lines get overloaded, which overall deteriorates the system security, stability and voltage profiles. Now it becomes more important to control power flow along transmission lines to meet the need of power transfer [5]. In ac power systems, the electrical generation and load must balance at all times up to some extent i.e. power system must be self regulating. Stability depends upon both initial operating conditions of the system and severity of disturbance. If the generation is less than load, there is drop in voltage and frequency which leads to generation minus transmission losses and there is chance of system collapse. In case of minor faults, generator excitation controller with only excitation control is sufficient but it is not sufficient to maintain the stability of system under major faults occurring near generator terminals. Thus there is great need to improve electric power utilization, simultaneously maintain the system security and stability.

1.2 Power System Constraints

As we can see that the transmission systems are being pushed closer to stability and thermal limits to deliver quality of power to consumers. The limitations of transmission system can take many forms and may involve power transfer within the area or between many areas or may include the following characteristics [13]:

1. Voltage stability limit
2. Dynamic voltage limit
3. Thermal limit
4. Transient stability limit
5. Power system oscillation damping limit
6. Steady state power transfer limit
7. Short circuit current limit

Each transmission system may have one or more of these system level limits. The key solution to these problems is to use the technology in more effective way such as development of FACTS devices. In the late 1980s, the Electric Power Research Institute (EPRI) introduced a new approach to solve the problem of designing and operating power systems; the proposed concept is known as Flexible AC Transmission Systems (FACTS) [6].

1.3 Introduction of FACTS Devices

FACTS are defined by the IEEE as "a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability". Thus the need for more efficient and fast responding electrical systems has given rise to development of new solid-state devices commonly known as FACTS devices. FACTS devices will enhance stability and increase the line loadings closer to thermal limits [4]. FACTS devices can control variables and different parameters of the transmission line i.e. terminal voltages, line impedance and load angle in a fast and effective way. The main purpose of introducing FACTS devices in modern power system is to provide control over the power flow in a network if they are placed at right locations. These aspects are playing a significant role in deregulated electricity market. Flexible AC transmission systems use thyristors which are practically designed to overcome limitations faced by old mechanically controlled power systems. By using high speed electronic controllers, the main objectives of FACTS devices are:

1.2.1 To enhance the transmission capacity

1.2.2 To control power flow in transmission lines over the designated routes.

1.2.3 Secure loading of transmission lines near to their thermal limits.

1.2.4 Greater ability to transfer power between controlled areas.

1.2.5 Prevention of cascading outages.

1.2.6 Damping of power system oscillations.

Two main reasons for use of FACTS devices in a modern power system are: Rapid development in the field of power electronics which made these devices cost effective and increased loading of power systems, along with deregulation of electricity market, motivates the use of power flow in a cost effective manner. Several issues like congestion management, enhancement of security, availability of power and transmission pricing etc are overruled by the use of FACTS devices. The insertion of such devices in power systems seems to be an upcoming strategy to reduce the power flows in heavily loaded lines resulting in increased system loadability, low system loss, improved stability of the network and reduced cost of production. Also, reduces mitigation of power quality problems such as voltage sag, swell & interruption [23]. New generation of FACTS devices are based on pulse width modulation (PWM) voltage source converters. To meet the demand of high power, pulse width modulation (PWM) voltage source converters has improved the characteristics of GTO. An integrating gate commutate thyristor (IGCT) was developed by ABB utilizes the latest thyristor technology. IGCT can be turned off without snubber and can work on high frequencies. The development of IGCT and ETO provides a low cost solution for megawatts PWM applications.

Also, the power flow between the two buses of the lossless transmission lines is given by [5]:

$$P_{ij} = V_i V_j / X_{ij} \, \mathrm{Sin}\delta ij \qquad (1.1)$$

Where

V_i i^{th} bus voltage magnitude

δ_i i^{th} bus voltage angle

V_j j^{th} bus voltage magnitude

δ_j j^{th} bus voltage angle

X_{ij} Line reactance

From the equation (1.1), it is clear that the power flow in a transmission line is a function of transmission line impedance, the magnitude of receiving and sending end voltages and the phase angle between the voltages. Thus by controlling one of the parameter or combination of parameters, we can control the active as well as reactive power of the transmission line. By the development of FACTS technology such as Static synchronous series capacitor (SSSC), Static Var Compensator (SVC), Unified power flow controller (UPFC), Static synchronous compensator (STATCOM), Thyristor controlled series capacitor (TCSC) etc., line impedance, bus voltages and phase angle in the power system can be regulated flexibly. By the use of such controllers, line power flow can be changed in such a way that thermal limits cannot be violated; stability margins increased, losses minimized and the requirement of the modern power system is fulfilled without violating the specified power dispatch. The magnitude of voltage can be controlled by using Static Var compensators (SVC), thereby improving system performance. Thyristor controlled phase angle regulator (TCPAR) controls the phase angle of the voltage. Thyristor controlled series capacitor (TCSC) controls the line impedance which further improves system reliability. FACTS devices are the key to produce electrical power economically and environmental friendly [5].

CHAPTER-2

LITERATURE REVIEW

In this chapter some selected research papers related to two area power system stability enhancement using FACTS controllers are reviewed as:-

D.Murali, et al. presents the new challenges to power system stability and in particular transient stability and small signal stability for two area power system [2]. They investigate the improvement of transient stability for two area power system with effective use of different types of FACTS controllers. The performance of UPFC was compared with different types of FACTS devices like Static Var Compensator, Static Synchronous Series Compensator, Thyristor controlled series compensator etc. The Simulation results show the effectiveness and robustness of UPFC over other FACTS devices.

Anuradha S.Deshpande, et al. proposed a method of evaluating the first swing stability of a large power system in presence of FACTS devices [3]. They considered FACT device and associated transmission line were represented by its equivalent pi circuit model. The model is then interfaced to the power network to obtain the system reduced admittance matrix which was used to generate the machine swing curves. The proposed method of generating dynamic response and evaluating first swing stability of a power system in the presence of FACTS device is tested on the three machine eleven bus sample test system. The results shows that the first swing of the generator gets reduced which further improves first swing stability.

Sthitaprajna rath, et al. presents a comprehensive review on the research and developments in power system stability enhancement using FACTS damping controllers [4]. They discussed about the several technical issues that may create hindrance in FACTS devices installations. They also compared the performance of different FACTS controllers. They conclude that with the use of FACTS controllers, maximum power can be transferred while maintaining dynamic stability and security.

Dr.M.Rajaram, et al. described the real and reactive power flow control through a transmission line by placing a FACT (UPFC) device at sending end of an electrical power transmission system [5]. Matlab/Simulink shows the performance of UPFC. Power flow control performance of UPFC was compared with other FACTS devices like SVC, STATCOM and SSSC.

Arun Kumar, et al. presented a detailed study on power system stability enhancement like frequency stability, rotor angle stability and voltage stability by using different FACTS controllers like SVC, TCSC, SSSC, STATCOM, UPFC and IPFC in an integrated power system networks [6]. They conclude about the essential features of FACTS controllers and their potential to enhance the system stability. They also described about the location and feedback signals that are frequently used to design the FACTS-based damping controllers. Performance comparison of different FACTS controllers were reviewed and discussed.

Sameh Kamel, et al. presents a report on modeling of the standard IEEE 14 bus system by using power system toolbox (PST) package [7]. They described the basic fact about the system which was tested under small and large disturbances to improve the dynamic stability and stability margins. Results show a precise solution of increased stability margins when different FACTS controllers were added. FACTS controllers were modeled and tested to show the effect of these controllers on stability margins under both small and large disturbances.

Salim.Haddad, et al. presents a case study on modeling and interface of different FACTS devices in distributed power system by the use of Matlab [8]. Simulation results investigate about the amount of active and reactive power flowing through transmission system. Results also depict the efficiency of FACTS devices in improving the stability of the power system.

M.A Abido, presented a review on the research and developments in the power system stability enhancement using FACTS controllers [9]. They thoroughly discussed about how FACTS devices were installed in the system to overcome the related issues which may arise during installation. In addition, some of the utility experience and semiconductor technology development have been reviewed. Results show the essential features of FACTS controllers and their potential to enhance the system stability was discussed. Also a brief review of FACTS applications to optimal power flow was presented.

Rahul Somalwar, et al. presented a review of enhancement of transient stability by FACTS devices [10]. They also described about the coordination problem that likely to be occur among different control schemes. They investigate the system under fault conditions by using equal area criterion method. Discussions were carried out on effectiveness of FACTS controllers in enhancing the transient stability of power system.

K. Venkateswarlu, et al. described the analysis and enhancement of transient stability using shunt controlled FACTS controllers [11]. They briefly described that FACTS devices open up new opportunities for controlling power and enhancing the usable capacity in existing system. Results show the basic simulation of STATCOM for enhancing the transient stability of a two machine system using Matlab. The system was simulated under three phase fault condition and transient stability was predicted before and after the use of FACT device i.e. STATCOM.

Thomas J.Overbye, et al. presented the use of FACTS devices for power system stability enhancement [12]. They thoroughly describe the research on the development of new techniques for analysis and control of power systems using flexible AC transmission systems (FACTS) devices for both voltage and transient stability time frames. These methods are widely used to shown the potential for enhancing the system stability margins.

Results indicate that the FACTS devices are widely used to increase system stability margins by permitting control intervention during a system disturbance.

Alok Kumar Mohanty, et al. described the power system stability improvement using FACTS devices [13]. They briefly described about the challenges faced by modern power system under fault conditions and explained the need of FACTS devices to overcome these problems. In addition, they listed out the power system constraints and proposed the solutions to meet the power demand in future. Also, they described various network connections which are used and future directions of FACTS technology were discussed. They summarized about the semiconductor technology used in FACTS devices.

S.Abazari, et al. proposed the transient stability improvement by using advanced static Var Compensator (SVC) [14]. They propose a new method for calculating the current references for an ASVC. The current references calculated are based on Transient energy function (TEF). Simulation was carried out with the help of C++ and Matlab Simulink. Results show a comparison between optimal control and bang-bang control in an ASVC for improving transient stability in a multi-machine system.

Dr. Tarlochan Kaur, et al. proposed transient stability improvement of long transmission line system by using SVC [15]. They briefly described that shunt FACTS devices-SVC is used in a two area power system for improving the transient stability. Matlab Simulation describes the two area power system with various loads connected at different buses in different cases is being studied. Results indicate that after fault clearing, high transients had appeared in rotor angle difference of two machines when SVC was not connected to system. Use of SVC in line has significantly decreased the transient time and enhanced the stability.

Mohammad Mohammadi, presents the voltage stability analysis with static Var Compensator (SVC) for various faults in power system with and without power system stabilizer (PSS) [16]. He thoroughly described that when Shunt FACTS devices were placed at midpoint of transmission line, they play a very important role in controlling the reactive power flow, voltage fluctuations and transient stability of the two machine system. His study mainly deals with the location of FACTS devices to improve the transient stability of power system. A power system computer aided design is used for simulation and results indicate the performance of SVC on voltage stability of the system.

D.K Sharma, et al. described a method of voltage stability in power system using STATCOM [17]. They proposed that placing of FACTS devices at key location is an important aspect. They studied the various FACTS devices that can be installed and FACTS devices model is incorporated into Newton-Raphson algorithm to perform load flow analysis. The proposed algorithm is tested on standard IEEE 30 bus power system for optimal allocation of STATCOM.

S.H Hosseini, et al. proposed the transient stability enhancement of AC transmission system using STATCOM [18]. They briefly described that STATCOM can increase transmission capacity, damping low frequency oscillations and improves transient stability. They proposed a control block diagram of STATCOM for transient stability improvement. Matlab was used for simulating the results of two machine system. Results indicate that the STATCOM not only improves the transient stability but also compensated the reactive power in steady state. They conclude that STATCOM can increase the reliability and capability of AC transmission system.

Aarti Rai, et al. described the enhancement of voltage stability and reactive power control of distribution system using FACTS devices [19]. They thoroughly described the optimal location of FACTS devices, voltage stability analysis and control of reactive power in system. Matlab software was used for simulation and the performance of the whole system such as voltage stability, transient stability and power swings were analyzed and compared with and without FACTS devices. They also showed that transient stability and power oscillation damping can be improved if power system stabilizers were used in combination with FACTS devices.

Y.L Tan, et al. presents the effects of FACTS controller line compensation on power system stability [20]. They described the effects of line compensation of SMIB power system using FC-TCR type TCSC or SVC for transient stability enhancement. They presented a novel method for analysis of line compensation by SVC. The maximum power transfer for a line depends on degree of compensation. The results indicate the effectiveness of SVC for stability enhancement is increased if the degree of compensation is increased.

Sidharta Panda, et al. described the improvement in power system transient stability with an off-center location of shunt FACTS devices [21]. Their study deals with the placement of Shunt FACTS devices to improve the transient stability of a long transmission line with predefined direction of real power flow. They proved the validity of mid-point location of shunt FACTS devices. Results indicate that if shunt FACTS devices were placed slightly off-centre towards sending end, gives better performance in improving transient stability.

Bindeshwar Singh, presents the application of FACTS controllers in power system for enhances the power system stability [22]. They predicted different kind of stabilities with various FACTS devices. He presents the current status of research and developments in the field of the power system stability such as rotor angle stability, frequency stability, and voltage stability enhancement by using different FACTS controllers in an integrated power system networks. He also describes the linkages between power system reliability, security and stability are established.

S.K Srivastava, presents an overview on Advanced power electronic based FACTS controllers [23]. He studied the better utilization of power system capabilities by installing the FACTS devices. He explained the basic concept of FACTS devices and their utilization to enhance the stability and security of modern power system. He critically reviewed the performance of various FACTS devices and their controllers which are under test and

R&D. He concludes that the FACTS devices improve the power system performance both statically and dynamically.

V.Kakkar, et al. explained the recent trends on FACTS and D-FACTS [24]. They briefly explained about the challenges faced by modern power system which includes limited available energy resources, time, capital required and land use restrictions. They studied to analyze the recent trends on FACTS and D-FACTS to improve the performance of modern power system so that the constraints can be overruled. Results indicate that D-FACTS have more reliability and cost saving approach over FACTS devices. Also for the robust, sensitive and optimum operation, D-FACTS controllers are the better choice for improving power system transmission line performance.

Karim Sebaa, et al. presents the power system dynamic stability enhancement via coordinated design of PSS and SVC based controllers using hierarchical real coded NSGA-II [25]. Results indicate the solution of tuning and location of minimum number of PSS and FACTS based controllers were proposed. Also their results show that by use of evolutionary algorithm, one can find the optimal locations and minimum controller's parameters simultaneously.

S.V Ravi Kumar, et al. presents the transient stability using UPFC and SVC [26]. They thoroughly described the damping of power system oscillations after a three phase fault and also analyze the effect of UPFC and SVC on transient stability performance of power system. They developed a general program for transient stability studies using modified portioned approach. The modeling of SVC and UPFC were studied and tested on a 10-generator, 39-bus, New England test generator. Results indicate that the SVC helps in improving the system performance by improving critical clearing time.

Nasimul Islam Maruf, et al. presents a study on thyristor controlled series capacitor as a useful FACT device [27]. They discussed the basic principle and benefits of TCSC during the fault conditions. They conclude that TCSC is a useful FACT device for enhancing the transient stability, steady state stability, dynamic stability and voltage stability of power system under severe conditions. They also briefly discussed about reduction in transmission losses, load sharing between parallel lines and reactive power balance.

Vibhor Gupta described the study and effects of UPFC and its control system for power flow control and voltage injection in power system [28]. He studied the operating modes of UPFC. Simulation is carried out in MATLAB and results indicate the use of power flow controller and voltage injection. He concludes about the benefits of using UPFC in the system.

S.Javed Sajjadi, described the effects of series and shunt FACTS devices in transient stability enhancement of multi-machine system [29]. They described the injection model of unified power flow controller and series quadrature voltage injection. Results indicate that the shunt compensation was used for power oscillation damping and effects of series and shunt compensation on transient stability was discussed. They conclude about the different locations of UPFC installed in system and their effect on stability of system was discussed.

N.K Sharma, et al. described the performance of UPFC in several modes operation using different control mechanism based on proportional plus integral control (PI) and Proportional plus integral plus derivative control (PID) [30]. They also developed ANFIS based controller by using ANFIS editor of Matlab. The MATLAB simulation results indicate the capability of UPFC on power flow control and the effectiveness of controllers on the performance of UPFC in the different operating modes.

T.K. Gangopadhyay, et al. discussed the problem of designing the damping controller for low frequency oscillations in power system under dynamic uncertainty [31]. They applied H mixed sensitivity technique to design robust damping controllers for unified power flow controller in uncertain conditions. A single machine infinite bus system (SMIB) incorporating UPFC is taken into account and results indicate the adequate damping of oscillations over the operating range conditions.

From the review of above literature, different researchers worked on different parameters to improve the transient stability of the system but no one shows the comparison between two machines, 5-bus system with RL load using shunt FACT devices.

The work done in this thesis is to show the comparison between two shunt FACT devices i.e. STATCOM and SVC for two machines system for power system stability enhancement.

CHAPTER-3

POWER SYSTEM STABILITY

3.1 Introduction

“Power system stability can be defined as the ability of an electric power system, for a given initial operating condition, to remain in a state of operating equilibrium after being subjected to a physical disturbance”[22]. Power system stability has been the area of study from early days of electrical power generation and transmission. Power system stability has gained more importance in today’s interconnected power system having high capacity generating stations and network of long EHV/HVDC transmission lines. Stability refers to ability of power system machines to run in synchronism. The tendency to lose synchronism is called unstable condition. Thus the subject matter of power system stability refers to maintaining synchronism of synchronous generators, generating stations and regional grids. The generation should match the load to maintain constant frequency. The voltage should be maintained in specified limits. The synchronous machines and synchronous generators should maintain synchronism with grids. Synchronism should be maintained between the regional grids connected together by tie-lines or interconnectors. Two cases must be analyzed while studying stability studies:

1. Single synchronous machine operating against infinite bus.
2. Two synchronous machines connected by a tie-line.

Thus we can say that the term stability has a close relation with synchronism. During the system disturbance such as sudden change of load, sudden switching and power swings etc. the synchronous machine experience oscillations of torque angle about the mean position. Loss of synchronism will result in loss of stability. Ability of synchronous machine or part of system to develop restoring forces equal to more than disturbing forces so as to remain in synchronism is called stability. The disturbance may be sudden or change in load may be gradual. Steady state stability refers to ability of the system or its part to respond to small, gradual change in power at a given point in the system. Steady state stability limit is the maximum possible power that can be transferred at a given point of the system without the loss of synchronism, with very gradual increase in power.

Stability can be broadly classified as:

1) Rotor angle stability
2) Voltage stability
3) Frequency stability

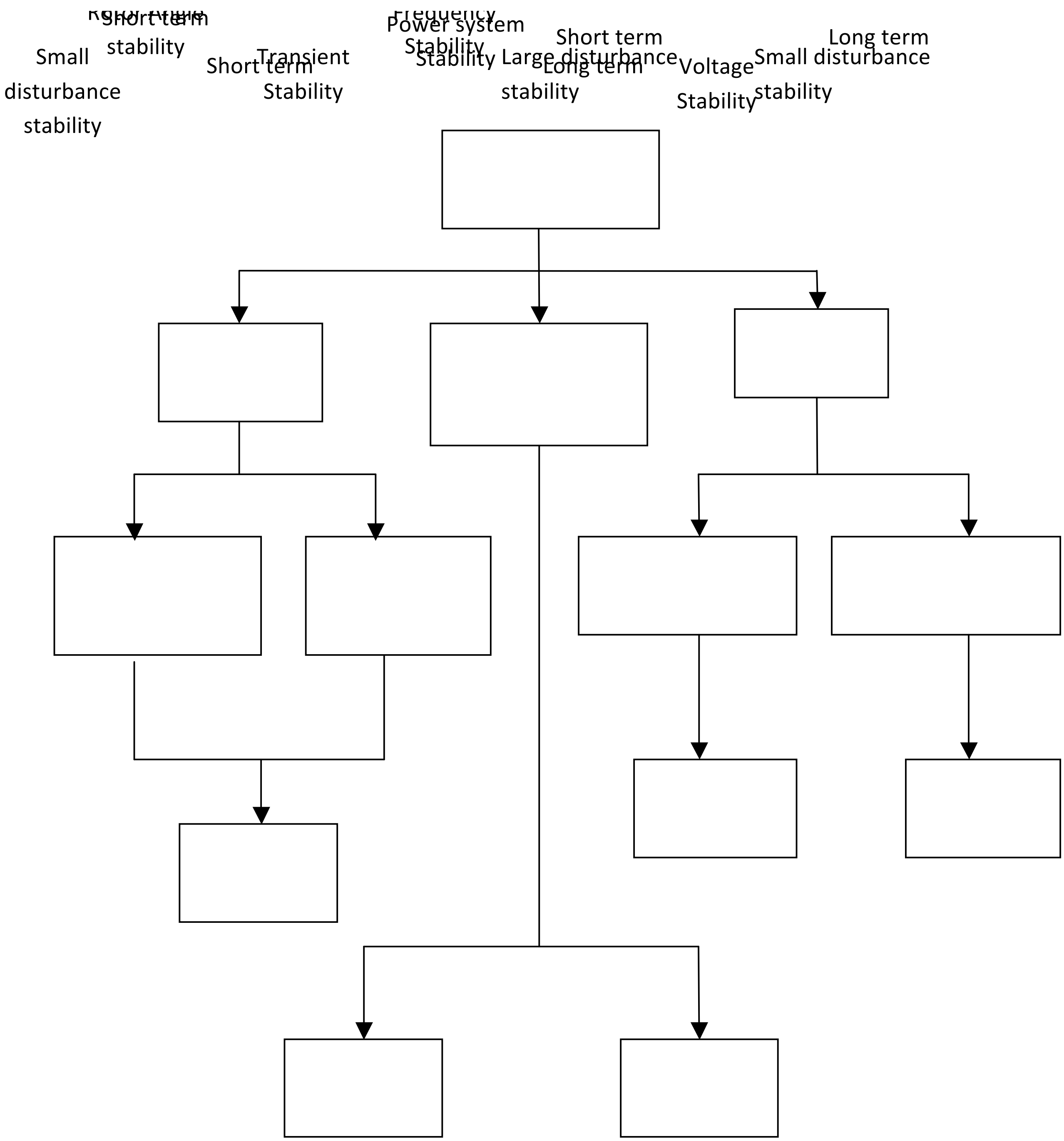

Figure 3.1 Classification of Power System Stability [22]

3.2 Rotor Angle Stability

Rotor angle stability is defined as the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. It depends on the ability to maintain/restore equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system. Instability can be seen in the form of increasing angular swings of some generators leading to their loss of synchronism with other generators. Under the steady-state conditions, equilibrium was maintained between the input mechanical torque and the output electromagnetic torque of each generator and the speed remains constant. When the system feels disturbance, the upset equilibrium results in acceleration or deceleration of rotor's of the machines. If one generator temporarily runs faster than another, the angular position of its rotor relative to that of the slower machine will advance. This tends to reduce the speed difference and hence the angular separation. The power-angle relationship was highly nonlinear. Beyond a certain limit, a further increase in angular separation is accompanied by a decrease in power transfer. Loss of synchronism can occur between one machine and the rest of the system, or between groups of machines. The change in Electromagnetic torque can be resolved into components [22]:

1. Synchronizing torque component, in phase with rotor angle deviation.
2. Damping torque component, in phase with the speed deviation.

The stability of the system will depend on both the components of torque for each of the synchronous machine. The system will show periodic or non-oscillatory behavior if there is a lack of synchronizing torque while system will show oscillatory behavior if there is a lack of damping torque. It is further classified as:

3.2.1 Small-disturbance rotor angle stability: Small disturbance rotor angle stability depends on the initial operating state of the system. In modern power systems, small-disturbance rotor angle stability problem is usually associated with in sufficient damping of oscillations. The problem of periodic instability was eliminated by use of continuously acting generator voltage regulators.

3.2.2 Transient stability: It is defined as the ability of the power system to maintain synchronism after subjected to a severe disturbance, such as a three phase fault occurs on a transmission line [26]. The resulting system response will show large excursions of generator rotor angles and power-angle relationship will show nonlinear response. Transient stability depends on both the initial operating state of the system and the severity of the disturbance. Instability can be seen in the form of a periodic angular separation due to lack of synchronizing torque, resulting in first swing instability. In case of large power systems, transient instability may not occur due to widespread use of fast acting regulators which does not allow the system to lose its synchronism. Some of the general features of transient stability analysis are:

- Load shedding / islanded operation.
- Choice of generator models.
- Transient stability analysis of multiple-islanded systems.
- Standard IEEE excitation system models, turbine and governor models.
- Commercial excitation models and governor models.

- Models for power system stabilizers and different stabilizing signals.
- Modeling load characteristics as function of frequency.
- Under frequency/Under Voltage relay operation.
- Load shedding.
- Loss of generators.
- Multiple transient stability disturbance scenarios for load flow study.

As we know that the power system stability is closely related with switchgear and protection. Today power system is large interconnected grids having high fault levels at station buses. Transient stability limit of a transmission system or the network can be increased by the following:

1. Rapid fault clearing by circuit breakers at both ends of the faulty transmission line.
2. Fast and selective protection, stable during the conditions of power swings.
3. Auto reclosing of circuit breakers for transmission lines. Transient stability can be increased by automatic reclosing of circuit breakers which have opened under temporary fault condition.
4. Single pole tripping for single-line to ground fault. Single pole auto reclosing.
5. Higher transmission voltages and better voltage control.
6. Faster protection by static relays and carrier aided distance protection of transmission lines.
7. Reducing series reactance of the tie-lines by using series capacitors or by adding parallel lines.
8. Asynchronous HVDS links for transmission of bulk power.
9. Using rapid response excitation system for synchronous generators.
10. HVDC transmission with damping control.
11. Increasing steady state voltage stability and transient voltage stability of transmission links and faster voltage control of load buses.

Thus by adopting those methods, we can improve the transient stability of modern power systems.

3.3 Voltage Stability

Voltage stability is defined as the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. The main purpose is to maintain the equilibrium between load demand and load supply from power system. Due to instability, system response will show fall or rise of voltages at some buses. Voltage instability results in loss of load in an area, or tripping of transmission lines and other elements leading to cascading outages which further affect the reliability parameters such as SAIDI and SAIFI. These long duration outages will result in loss of synchronism of some generators. Drop in bus voltages can also be associated with rotor angle instability. Voltage instability is a serious issue which may results to large power cuts for long duration.

3.3.1 Major causes of voltage instability

1. The driving force to voltage instability is usually the loads. The power consumed by loads should always be stored during the major disturbance in power system.
2. The situation of voltage instability occurs when load dynamics attempt to restore the power consumption beyond the capability of transmission network and connected generation.
3. A voltage drop generally occurs when there is a transfer of active and reactive power through transmission network is the major reason of voltage instability. This further limits the capability of transmission network and voltage stability.
4. Voltage stability also affected when reactive power demand increases beyond the sustainable capacity of available reactive power sources.
5. Nonlinear loads also causes voltage instability.
6. Most common form of voltage instability is frequency variation, progressive drop of voltage at bus and overvoltage instability.
7. Over voltages are caused due to capacitive behavior of the network as well as by under excitation limiters which absorb more reactive power.

It is further classified as:

3.3.2 Large-disturbance voltage stability: Large disturbance voltage stability is defined as the system's ability to maintain steady voltages after being subjected to large disturbances such as system faults and loss of generation [22]. System response may be determined by load characteristics and the interactions of both continuous and discrete controls. Determination of large-disturbance voltage stability requires the detailed study of the nonlinear response of the power system over a period of time to capture the performance and interactions of several devices such as motors, under load transformer tap changers, and generator field-current limiters.

3.3.3 Small-disturbance voltage stability: Small disturbance voltage stability is defined as the system's ability to maintain steady voltages when subjected to small disturbances such as incremental changes in system load. The study of small disturbance will be helpful in determining, at any instant, how the system voltages will respond to small system changes. By taking appropriate assumptions, system equations can be linearized and factors can be determined which hamper stability of the system.

3.3.4 Techniques employed to improve voltage instability

1. By the use of reactive power compensation technology, voltage stability can be improved.

2. Implementation of fixed capacitor bank compensation.

3. Back to back phase control of thyristor controlled reactor or thyristor switched capacitor.

4. Using FACTS devices like STATCOM, SSSC, UPFC and MPFC.

3.4 Frequency Stability

Frequency stability refers to the ability of a power system to maintain steady frequency after being subjected to a severe disturbance resulting in a loss of synchronism between generation and load. It depends on the ability to maintain/restore equilibrium between system generation and load, with minimum loss of load. Instability indicate that the system response contain sustained frequency swings which may lead to tripping of generating units and/or loads. Severe system faults generally result in large disturbance of frequency, power flows, voltage, and other system variables, which may cause a huge amount of loss and inconvenience to power industry. The processes which cause frequency instability are very slow, such as boiler dynamics and volts/Hertz protection tripping generators. Generally, frequency stability problems are associated with lack of monitoring the system responses, coordination of control and protection equipment, or insufficient generation reserve.

3.5 Dynamic Stability

One of the most important parts of power system stability is dynamic stability. Controlling devices which improve dynamic stability of power systems are called power systems stabilizers (PSS) and FACTS controllers. The main problem is to analyze the location of power system stabilizers which need to be placed at right location to obtain the optimum results. Changes and expansions of the network may cause movement of stabilizers. One solution of this problem is collecting the stabilizers in one place of network and connecting them to network through a channel which may eliminate the above problem.

3.6 Power-Angle Curve

The graphical representation of Power P_e and the load angle δ is called power angle diagram or power angle curve. Maximum power will be transferred when $\delta=90^0$. δ increased beyond 90^0 as P_e decreases and becomes zero at 180^0.

3.7 Power-Angle Equation

The expression establishing the relationship between the active power transferred (P_e) to the system and the angle δ is known as proper angle equation. The expression for the active power transferred to the system is given by:

$$P = EV/X \sin \delta \qquad (3.1)$$

Where

$$X = X_d + X_1 \qquad (3.2)$$

X Transfer Reactance

X_d Transient Reactance of Machine

X_1 Reactance of Transmission line

E Magnitude of the voltage

V Voltage of infinite bus

δ Angle between the voltage E and V

The maximum steady state power transfers occurs at $\delta = 90^0$. From equation

$$P_{e\,max} = EV/X \sin 90 = EV/X \qquad (3.3)$$

$$P_e = P_{e\,max} \sin \delta \qquad (3.4)$$

3.8 Swing Equation

The equation establishing the relationship between the accelerating power and angular acceleration is called swing equation. It is a non linear differential equation of second order.

$$\mathbf{M\, d^2a/dt^2 = P_s - P_e = P_a} \qquad (3.5)$$

$$M = J\omega \qquad (3.6)$$

Where

M Angular Momentum of Rotor

J Moment of Inertia of rotor

ω Synchronous speed of rotor

P_s Mechanical power input

P_e Electrical power output

P_a Accelerating power

3.9 Equal Area Criteria

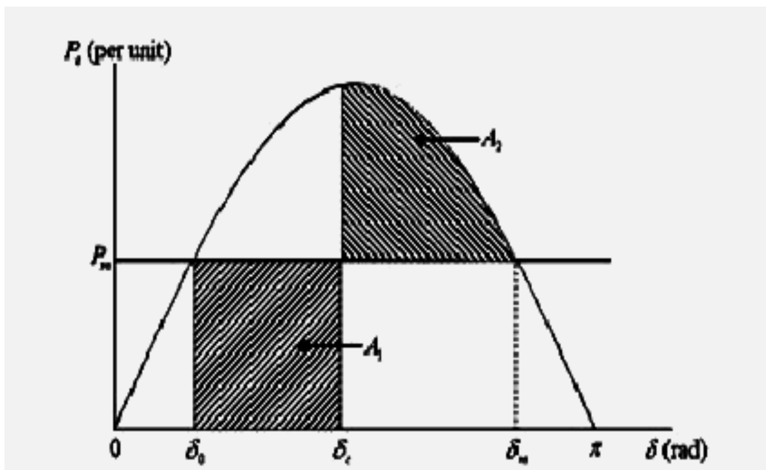

Figure 3.2 Power-Angle Curve

Consider the power angle curve as shown in Figure 3.2. Suppose the given system is operating at an angle of δ_0 and the power delivered by system is equal to P_m when fault occurs. During the fault, transmitted electrical power decreases significantly while mechanical power i.e. P_m remains constant, the accelerating power P_a will becomes equal to P_m. As a result the rotor will accelerate due to affect of accelerating power and hence the load angle will increase. Now at angle δ_c suppose the circuit breaker recloses. Thus power will then revert back to the normal operating curve. At that point the transmitted electrical power will be greater than the mechanical power and machine will start to decelerate but due to stored kinetic energy in machine, the load angle will still keep on increasing. If the angle continues to increase, than system will loss synchronism and become unstable. The relationship between the rotor angle and the accelerating power:

$d^2\delta/dt^2 = \omega_0/2H\ (P_m - P_e)$ (3.7)

Multiplying both sides by 2 dδ/dt, then equation 3.7 becomes

$2 \times d\delta/dt \times d^2\delta/dt^2 = \omega_0\ (P_m - P_e)\ d\delta/Hdt$ (3.8)

After rearranging the equation 3.8, we get

$d/dt\ [d\delta/dt]^2 = \omega_0\ (P_m - P_e)\ d\delta/H\ dt$ (3.9)

Now integrating the above equation between two arbitrary angles δ_0 and δ_c, it becomes

$H/\omega_0\ [d\delta/dt]^2 = \int_{\delta 0}^{\delta c}(Pm - Pe)\ d\delta$ (3.10)

Now assume that generator is at rest at δ_0. Then dδ/dt = 0. Once a fault occurs, the machine starts accelerating. Once the fault is cleared, the machine keeps on accelerating before it reaches its peak at δ_c. Thus the area of acceleration is given by:

$A_1 = \int_{\delta 0}^{\delta c}(Pm - Pe)d\delta = 0$ (3.11)

Similarly area of deceleration is given by:

$A2 = \int_{\delta 0}^{\delta c}(Pe - Pm)d\delta = 0$ (3.12)

Case 1: If area of acceleration is greater than area of deceleration i.e. A1 > A2. The generator load angle will cross the point δ_m, beyond which the electrical power will be less than the mechanical power which forces the acceleration power to be positive. The generator will therefore start accelerating before it slows down completely and will eventually become unstable.

Case 2: If area of acceleration is lesser than area of deceleration i.e. A1 < A2. The machine will decelerate completely before accelerating again. The rotor inertia will force the acceleration and deceleration areas to be smaller than the first ones and the machine will eventually attain the steady state.

Case 3: If the area A1 = A2, then the accelerating area is equal to decelerating area and this defines the boundary of the stability limit.

3.10 Swing Curve

The result of swing equation is the expression for power angle as a function of time. A graph obtained from the solution is called swing curve of the machine and inspection of the swing curve of all machine of the system will show whether the machine remain in synchronism after a disturbance or not. Swing curve is very useful in predicting the system stability. From the fig 3.3, we can say that if the value of load angle δ starts decreasing after reaching the maximum value and tends to attain a steady new value, the system will not lose stability. It will come back to its equilibrium position after the damping of oscillations is reached.

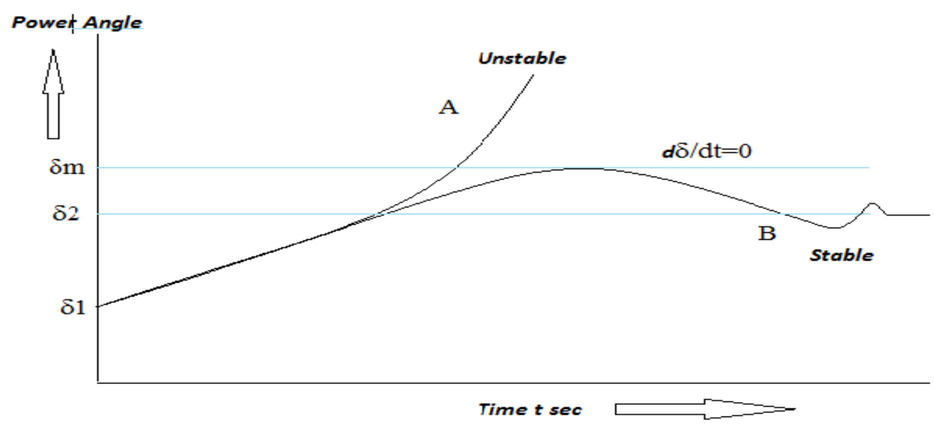

Figure 3.3 Swing Curve

If the swing curve is such that the load angle δ goes on increasing and doesn't come back to its equilibrium position with time, the system will lose its stability. Curve A in the figure depicts the condition of instability. The swing curve indicates that dδ/dt is maximum during initial straight portion of swing curve.

Thus from the swing curve, we can drive the following conclusions:

1. If during the first swing, dδ/dt goes on reducing and reaches a zero value and then reverses, the condition of system will remain stable.
2. If dδ/dt goes on increasing and dδ/dt does not reduce with time, the angle δ goes beyond 90^0 and the power system will synchronism. The stability will be lost.

CHAPTER-4

FACTS CONTROLLERS

4.1 Types of FACTS Controllers

Basically, FACTS controllers are broadly classified into four main categories:

1. Series Controller
2. Shunt Controller
3. Combined Series-Series Controller
4. Combined Series-Shunt Controller

Table 4.1: Comparison among FACTS Controllers

Name	Type	Controller Used	Purpose
STATCOM	Shunt	GTO	Voltage Control
SVC	Shunt	Thyristor	Voltage Control
SSSC	Series	GTO	Power flow Control
TCSC	Series	Thyristor	Power flow Control
UPFC	Shunt and Series	GTO	Voltage and Power flow Control
TCPAR	Series and Series	Thyristor	Power flow Control

4.2 Compensation Techniques used by FACTS Controllers

Consider a case of Lossless transmission line. Active power at any point can be written as [1]:

$$P_s = P_r = P = V^2/X \sin\delta \qquad (4.1)$$

Similarly, reactive power at any point can be written as:

$$Q_s = -Qr = Q = V^2/X\ (1-\cos\delta) \qquad (4.2)$$

Three basic types of compensation used by FACTS Devices:

1. Series compensation
2. Shunt compensation
3. Shunt-series compensation

4.2.1 Series compensation: In series compensation, the FACTS are connected in series with the power system. It works as a controllable voltage source. Series inductance exists in all AC transmission lines. On long lines, when a large current flows, this causes a huge voltage drop. To compensate, series capacitors are connected, decreasing the effect of the inductance. In series compensation, line reactance X is modified i.e. active and reactive powers will become [1]:

$$P = V^2/X\text{-}Xc \sin(\delta) \quad (4.3)$$

$$Q = V^2/X\text{-}Xc\ (1\text{-}\cos\delta) \quad (4.4)$$

Advantages of series compensation:

1. Reduction of series voltage drop.
2. Reduction of voltage fluctuation.
3. Improvement of system damping.
4. Limitation of short circuit current.

4.2.2 Shunt compensation: In shunt compensation, power system is connected in shunt (parallel) with the FACTS. It works as a controllable current source. Shunt compensation is of two types:

Shunt capacitive compensation: This method is used for improving the power factor. Whenever an inductive load is connected to the transmission line, power factor lags because of lagging load current. To compensate its effect, a shunt capacitor is connected which draws current leading the source voltage. The net result is improvement in power factor.

Shunt inductive compensation: This method is used either when charging the transmission line, or, when there is very low load at the receiving end. The receiving end voltage may become double the sending end voltage (generally in case of very long transmission lines).

In shunt compensation, the active and reactive powers will become [1]:

$$P = 2V2/X \sin(\delta/2) \quad (4.5)$$

$$Q = 2V2/X\,[1-\cos(\delta/2)] \tag{4.6}$$

Advantages of shunt compensation:

1. Compensate the reactive power and hence reduce the losses.
2. Improvement in static and transient stability.
3. Improvement in power quality.

4.3 Static Var Compensator

According to the definition of IEEE of FACTS working group: Static Var Compensator: 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) [15]. SVC was widely used for shunt connected compensators, which are based on thyristors without gate turn-off capability. Among the FACTS controllers, static Var compensator provides the fast acting dynamic compensation in case of severe faults. SVC also reduces the system losses by providing optimal control and dampens the power swings. The main objective of SVC is to control the voltage rapidly at weak points in the network.

4.4 Operating Principal of SVC

A simple circuit of SVC consists of fixed capacitor-Thyristor controlled reactor connected to transmission line via coupling transformer. The effective reactance of FC-TCR was varied by firing the angle of thyristors. The firing angle can be controlled by using PI (Proportional + Integral controller) in such a way that the voltage of the bus at which SVC was connected, is maintained at the reference value. SVC also consists of two main components: thyristor-switched reactor for absorbing reactive power and thyristor-switched capacitor for supplying reactive power [16]. A functional model of SVC is shown in fig 4.1.

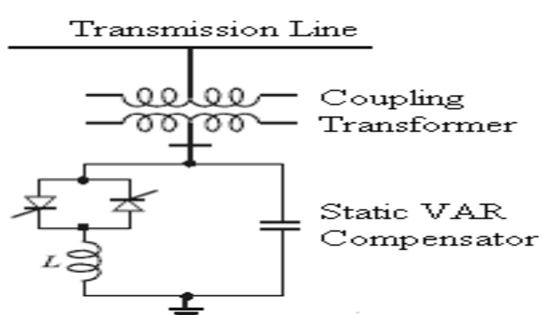

Figure 4.1 Functional model of SVC [16]

The SVC can be seen as the dynamic source of reactive current. Capacitor banks which are installed in SVC can be switched in and out by the use of fast acting thyristors. As we know that the electrical loads generate and absorb reactive power which results in the variation of reactive power equilibrium at grid. The result can be undesirable voltage amplitude variations or condition of voltage collapse or voltage depression. A rapidly opening static voltage compensator (SVC) can supply necessary reactive power in abnormal conditions to avoid voltage swings under different system conditions and thereby improving transmission and distribution performance. Installing more than one unit of SVC at appropriate points in the network will enhance power transmission capacity through improved voltage stability and also maintains the smooth voltage profile under different abnormal conditions.

4.5 Advantages of SVC

1. It can diminish active power oscillations through voltage amplitude modulation.
2. Direct and rapid bus voltage control.
3. Enhance power transfer during low voltage conditions.
4. Decrease the acceleration of local generators.
5. Static and Dynamic voltage control

4.6 Static Synchronous Compensator (STATCOM)

"A Static synchronous compensator is a shunt-connected static Var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage" [17].

The concept of STATCOM was proposed by Gyugyi in 1976. A STATCOM is considered as one of the important shunt connected flexible AC transmission controller to control the power flow and enhance the transient stability. A Statcom is a controlled reactive power source. It normally regulates the voltage by compensating the reactive power in or out from the power system. The basic function of STATCOM is to absorb the reactive power when the system voltage is high and injects the reactive power when the system voltage is low. Voltage source inverter (VSC) will supply the required reactive power which was connected to secondary side of coupling transformer. Thus STATCOM is providing a voltage support by generating or absorbing capacitor banks [17].

4.7 Operating Principle of STATCOM

STATCOM is made up of a coupling transformer, a VSC and a dc energy storage device. Power converter employed in STATCOM is basically of two types: Voltage source converter and current source converter. In voltage source converter dc voltage has always one polarity and power reversal takes place through reversal of dc current polarity but in case of current source converter, direct current has always one polarity and power reversal takes place through reversal of dc voltage polarity. In current source converters, the power semiconductor devices used requires bidirectional voltage blocking while voltage source converters can operate on higher efficiencies in high power applications. Due to this reason, now days the voltage source inverters are preferred over current source inverters. STATCOM is capable of exchanging reactive power with the transmission line because of its small energy storage device i.e. small dc capacitor. If this dc capacitor is replaced with dc storage battery or other dc voltage source, the controller can exchange real and reactive power with the transmission system. The region of operation can be extended from two quadrants to four quadrants. A functional model of a STATCOM is shown in Figure 4.2

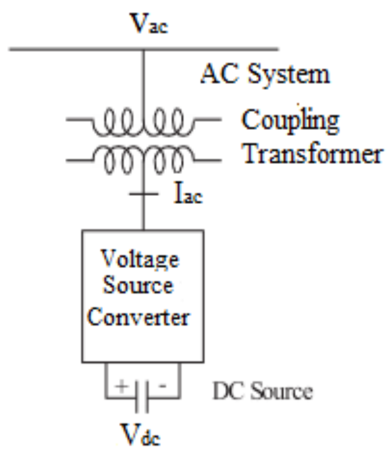

Figure 4.2 Functional model of STATCOM [17]

The relationship between fundamental component of the converter ac output voltage and voltage across dc capacitor is given as:

$$V_{out} = K\,V_{dc} \qquad (4.7)$$

Where

K is coefficient which depends on the converter configuration, number of switching pulses and the converter controls. The fundamental component of the converter output voltage i.e. V_{out} can be controlled by varying the DC voltage across the capacitor. The DC voltage can be varied by varying the angle α of the operation of the converter. The direction of flow of reactive power whether it is from system to coupling transformer or coupling transformer to system depends upon the difference between the converter output voltage and the ac system bus voltage. The capacitor will be charged and discharged during each switching cycle but the average capacitor voltage will remain constant in steady state. If the capacitor voltage will not remain constant, then capacitor will gain or lose charge in each cycle and there would be the flow of real power into or out of converter. The ability of STATCOM to absorb/supply real power will depend on size of this DC capacitor.

If the magnitude of voltage produced by voltage source converter is less than the magnitude of voltage produced by ac system, then the reactive power is flowing from ac system to voltage source converter. If the magnitude of voltage produced by voltage source converter is greater than the magnitude of voltage produced by ac system, then the reactive power is flowing from ac voltage source converter to ac system. For inductive operation, we know that the current lags behind the voltage by an angle of 90^0. Assuming converter losses to be very small and if the amplitudes of converter output voltages and ac system are equal, then there will be no flow of ac current in or out of the converter. The magnitude of ac current can be calculated by using the following equation:

$$I_{ac} = V_{out} - V_{ac}/X \qquad (4.8)$$

Let V_{out} and V_{ac} are the magnitudes of converter output voltage and ac system voltage when there is flow of current from converter to ac system, while X represents the coupling transformer leakage reactance. Te reactive power exchange can be calculated as:

$$Q = V^2_{out}\text{-}V_{out}V_{ac}\cos\alpha/X \qquad (4.9)$$

The real power exchanged between the voltage-sourced converter and ac system can be calculated as:

$$P = V_{ac}V_{out}\sin\alpha/X \qquad (4.10)$$

4.8 V-I Characteristics of STATCOM

When the STATCOM is working in voltage regulation mode, It implements the V-I characteristics as shown. The V-I characteristics are depicted by the following equation:

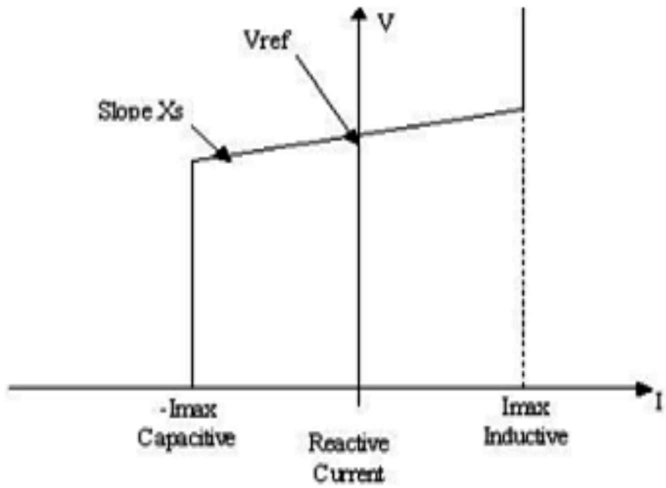

Figure 4.3 V-I characteristics of STATCOM [17]

$$V = V_{ref} + Xs \,.\, I \qquad (4.11)$$

Where

V Positive sequence voltage

I Reactive current (pu/P_{norm})

P_{norm} Converter rating in MVA

X_s Slope

(I>0 indicates inductive current and I<0 indicates capacitive current)

4.9 Operating Modes of STATCOM

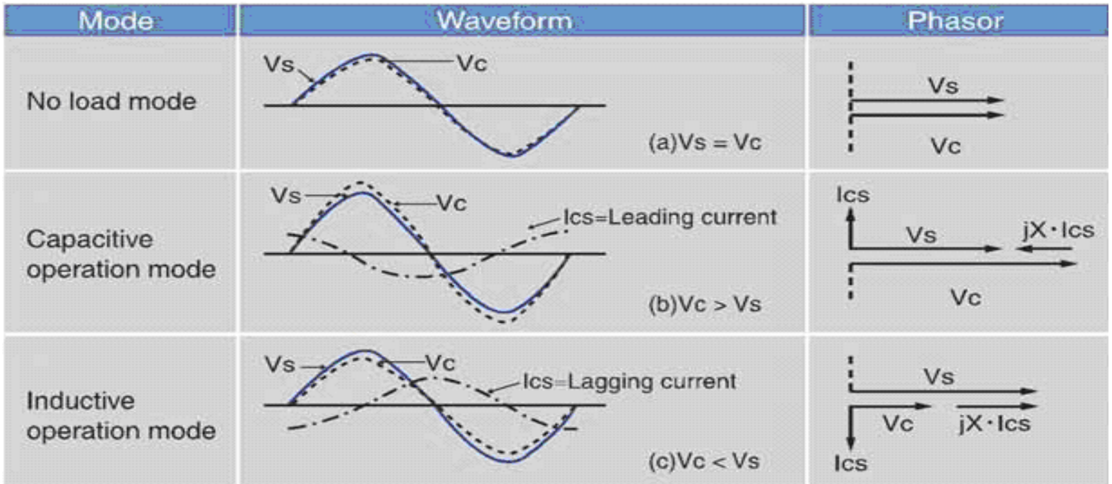

Figure 4.4 Operating Modes of STATCOM

4.10 Advantages of STATCOM over SVC

1. STATCOM has a fast response than SVC.
2. It requires less space as passive elements are eliminated
3. It can be interfaced with real power source i.e. battery.
4. STATCOM is more effective than SVC in improving transient stability of the system because it can generate full capacitive current at time of low voltage and maintain the level of synchronism.
5. Active power control is possible with STATCOM than SVC. [15] [16] [17].

4.11 Static Synchronous Series Capacitor (SSSC)

The SSSC is commonly used for series compensation. The device can be considered as the synchronous voltage source as it can eject sinusoidal voltage of variable magnitude and controllable phase angle, in series with transmission line. The voltage injected by SSSC is in quadrature with line current which further provides the effect of inserting the inductive or capacitive reactance in series with transmission line. This variable reactance will influence the power flow in a transmission line [2].

Thus SSSC is regarded as the solid-state synchronous voltage source employing an appropriate DC to AC inverter with gate turn-off thyristors which are used for series compensation of transmission lines. SSSC will work in same way as STATCOM. SSSC is able to exchange active and reactive power with transmission system.

4.12 Operating Principle of Static Synchronous Series Capacitor (SSSC)

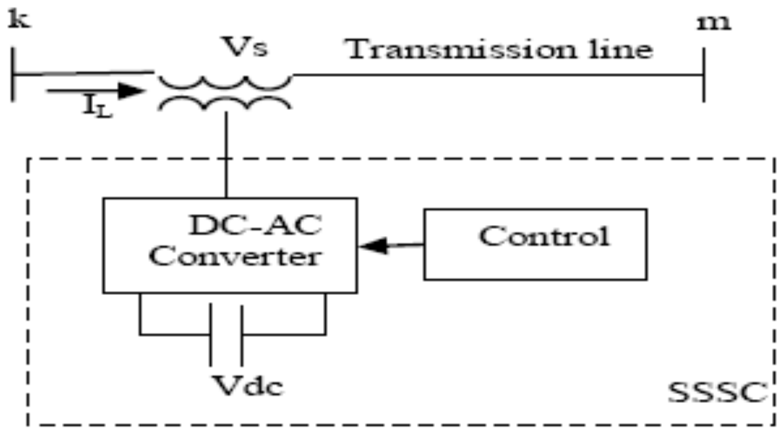

Figure 4.5 Functional Diagram of SSSC [2]

The basic functional diagram of SSSC is shown in fig 4.5. SSSC consists of a voltage source inverter connected to transmission line through coupling transformer. A source of energy is required for providing and maintaining the DC voltage across the DC capacitor and compensation of SSSC losses. SSSC when operated with sufficient amount of DC supply, can inject a component of voltage in anti-phase with the voltage developed across the line resistance. SSSC can exchange both active and reactive powers to enhance the power transmission capacity, maintaining high X/R ratio independently of the degree of compensation. SSSC can also be operated as controllable serial condenser and a serial reactance. Due to this important feature, SSSC yield excellent results with high and low loads.

4.13 Operating Modes of SSSC

SSSC can be operated in 2 modes:

12. Capacitive mode
13. Inductive mode

In inductive mode of operation, the inductive level compensation reactance level increases from 0% to 100%, while at the same time line current decreases. In capacitive mode of operation, the capacitive reactance compensation level increases from 0% to 33%, while at the same time the line current also increases. When the emulated reactance is capacitive, the active and reactive power flow increases and the effective reactance decreases as the reactance compensation increases in positive direction. Similarly, when the emulated reactance is inductive, the active and reactive power flow decreases and the effective reactance increases as the reactance compensation increases in negative direction.

4.14 Advantages of Static Synchronous Series Capacitor (SSSC)

1. It balances the load in interconnected distribution networks.

2. It reduces harmonics as it filtered the injected voltage by converter installed at load side.

3. It helps in covering the reactive power demand.

4.15 Thyristor Controlled Series Capacitor (TCSC)

TCSC is known as one of the best FACT device which was used over the past few years to increase the power transfer as well as to enhance the power system stability. TCSC uses silicon controlled rectifiers to manage a capacitor bank connected in series with the transmission line. TCSC allows a utility to transfer more amount of power on a particular line by controlling reactive power. TCSC is a combination of thyristor controlled reactor (TCR) and a capacitor which controls the capacitive reactance of a particular line over a wide range and simultaneously inserting the inductive reactance into the line. TCSC provides an effective way of solving the problems of transient stability, steady state stability, dynamic stability and voltage stability in a long transmission lines. TCSC introduces a thyristor controlled capacitor in series with transmission line which provides control over line impedance [13].

4.16 Operating Principle TCSC

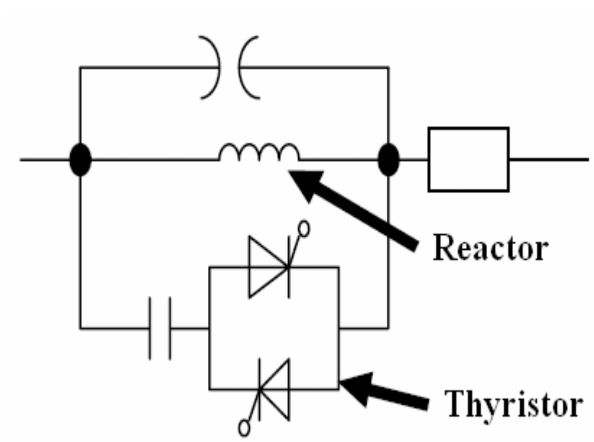

Figure 4.6 Functional Diagram of TCSC [27]

Figure 4.6 shows the basic diagram of TCSC. TCSC comprised of a series capacitor bank, shunted by a Thyristor Controlled Reactor (TCR), to provide a smoothly variable series capacitive reactance. It is a one-port circuit in series with transmission line and it uses natural commutation. Its switching frequency is low and has no DC port. Insertion of a capacitive reactance in series with the line's inherent inductive reactance lowers the total, effective impedance of the line and thus virtually reduces its length. As a result, both angular and voltage stability gets improved [27].

4.17 Advantages of Thyristor Controlled Series Capacitor (TCSC)

1. Balancing of Load flows: TCSC enables the load flow on the parallel circuits and optimize the different voltage levels, thereby minimizing the overall system losses.

2. Power system interconnection: TCSC allows interconnection of power systems of different areas to transfer power with minimum losses.

3. Mitigation of Sub synchronous resonance risk (SSR): SSR is phenomenon which is associated with series compensation at the time of adverse conditions. TCSC ensures the elimination risk of SSR.

4. Power oscillation damping and voltage stability: More amount of power can be transmitted over fewer lines with increased transmission capacity and a stable voltage response will be obtained.

5. Increasing of first swing stability: A stable operation will be obtained under severe fault conditions which prevent the condition of system collapse.

4.18 Unified Power Flow Controller (UPFC)

UPFC is considered as the last generation of FACTS devices. UPFC has the capability to overcome the various issues and provide an appropriate solution to various problems faced by modern power systems like line outage, congestion, cascading line tripping and power system stability loss. The UPFC is a device which can control simultaneously all three parameters of line power flow (line impedance, voltage and phase angle). UPFC is FACT device which combines the features of two FACTS devices: the Static Synchronous Compensator (STATCOM) and the Static Synchronous Series Compensator (SSSC). The two FACT devices i.e. SSSC and STATCOM are basically two Voltage Source Inverters (VSI's) connected respectively in shunt with the transmission line through a shunt transformer and in series with the transmission line through a series transformer, further which are connected to each other by a common dc link storage capacitor. The shunt inverter is used for voltage regulation to insert reactive power flow into the line and to balance the real power flow exchanged between the series inverter and the transmission line. The series inverter can be used to control the real and reactive line power flow and used to insert voltage of controllable magnitude and phase in series with the transmission line. Thus UPFC combines the function of active and reactive series compensation of transmission line, phase shifting and reactive power shunt compensation. UPFC is useful in suppressing power system oscillations after fault clearing, thereby improving the transient stability of power system. Due to rapid growth in industrial sector and electrical markets, there is need of flexible and fast power flow controllers such as UPFC to improve system stability and provide the reliable supply to emerging sector.

4.19 Operating Principle of Unified Power Floe Controller (UPFC)

The basic components of the UPFC are two voltage source inverters (VSIs) sharing a common dc storage capacitor and connected to the power system through coupling transformers. One VSI is connected to in shunt to the transmission system via a shunt transformer, while the other one is connected in series through a series transformer. A basic UPFC model is shown in fig 4.7 [31].

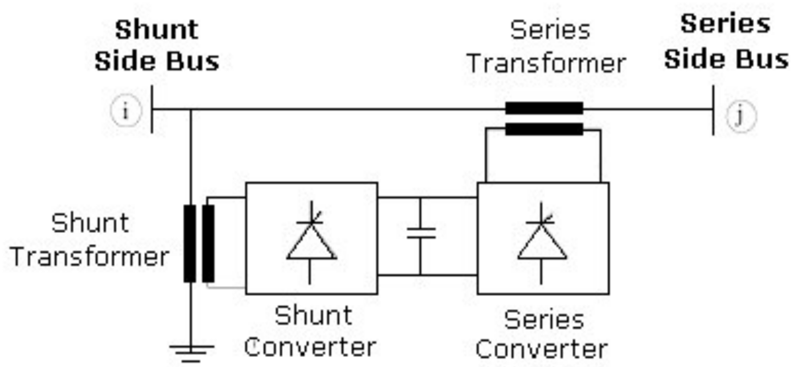

Figure 4.7 Functional Diagram of UPFC [31]

The series inverter will be used to inject a symmetrical three phase system voltage (V_c) of controllable magnitude and phase angle in series with the line to control active and reactive power flows on the transmission line. Series inverter will exchange active and reactive power with the line. The reactive power was provided by the series inverter and the active power is transmitted to the dc terminals. The shunt inverter is operated in such a way so as to keep the voltage across the storage capacitor V_{dc} constant. So, the net real power absorbed from the line by the UPFC is equal only to the losses of the inverters and their transformers. The remaining capacity of the shunt inverter can be used to exchange reactive power with the line so to provide a voltage regulation at the connection point.

The two VSI's can work independently of each other by separating the dc side. So in that case, the shunt inverter is operating as a STATCOM (Static Synchronous Compensators) that generates or absorbs reactive power to regulate the voltage magnitude at the connection point. Instead, the series inverter is operating as SSSC (Static Synchronous series compensators) that generates or absorbs reactive power to regulate the current flow, and hence the power flows on the transmission line [31].

4.20 Operating Modes of UPFC

The UPFC can be operated in various modes. In particular, the shunt inverter is operating in such a way to inject a controllable current into the transmission line. This current consists of two components with respect to the line voltage: the real or direct component, which is in phase or in opposite phase with the line voltage and the reactive or quadrature component, which is in quadrature. The direct component is automatically determined by the requirement to balance the real power of the series inverter. The shunt inverter can be controlled in two different modes [23]:

VAR Control Mode: The reference input is an inductive or capacitive VAR request. The shunt inverter control translates the Var reference into a corresponding shunt current request and adjusts gating of the inverter to establish the desired current.

Automatic Voltage Control Mode: The shunt inverter reactive current is automatically regulated to maintain the transmission line voltage at the point of connection to a reference value. For this mode of control, voltage feedback signals are obtained from the sending end bus which is feeding the shunt coupling transformer. The series inverter controls the magnitude and angle of the voltage injected in series with the line to ensure the power flow on the line.

Direct Voltage Injection Mode: The reference inputs are directly the magnitude and phase angle of the series injected voltage. When the injected voltage is kept in phase with the system voltage or in quadrature with the line current, provides series reactive compensation.

Phase angle shifter emulation mode: The reference input signal is phase displacement between the two end bus voltages. The injected voltage is controlled by input bus voltage so that the output bus voltage is phase shifted by an angle.

Automatic Power Flow Control Mode: In this control mode, the series injected voltage is determined automatically and continuously by a closed loop control system to ensure that the values of P and Q are maintained irrespective of the system changes.

4.21 Advantages of UPFC

1. Power transmission capacity of transmission line is enhanced with the use of UPFC.

2. UPFC provides a significant damping to power system oscillations when used in power flow control mode.

3. Improvement in transient stability of the system by the use of UPFC.

4. After fault clearing, post settling time of the system with UPFC is very less as compared to other systems installed with different FACTS controllers.

4.22 Interline Power Flow Controller (IPFC)

IPFC is a multi-functional FACT controller. Basic functional diagram of IPFC is shown in fig 4.8 [23].

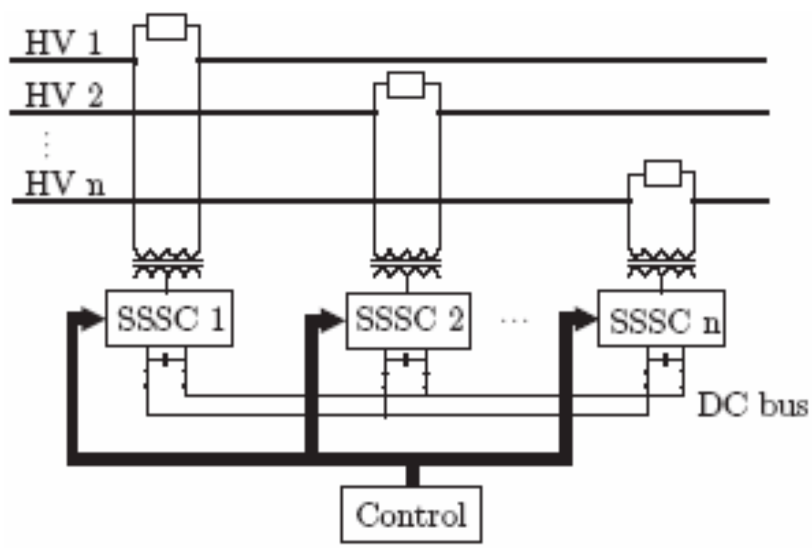

Figure 4.8 Functional Diagram of IPFC [23]

The IPFC consist of a number of voltage-sourced converters (VSCs), which are connected back-to-back at their dc terminals. Each VSC is coupled to a different transmission line via series coupling transformer and is able to provide independent series reactive compensation, as an SSSC. However, the converters can transfer active power among them via their common dc terminal. A multi-converter IPFC configuration allows the IPFC to provide reactive power series compensation in one series branch and active and reactive compensation both for remaining series branch.

Also, IPFC helps in addressing the problems of compensating a number of transmission lines at a given substation. Series capacitive compensators are used to increase the active power transmission between the lines but they are unable to control the reactive power of the line at the same time. Thus we conclude that with IPFC, active power can be transmitted over the lines. Therefore, it is possible to:

1. Equalize active and reactive power flow between the lines.
2. Reduce the burden of lines by active power transmission.
3. Increase the effectiveness of overall compensating systems for major disturbances.
4. Reduce the reactive power demand and compensate against the low voltage drops.

4.23 Under Developed FACTS Device

Today in modern power systems, technology used in developing the FACTS devices to provide a general solution to power system stability problems is revolutionarized. Some of the under developed FACT devices are listed below which will provide solutions to more complex problems and enhance power system stability to great extent.

4.24 Generalized Unified Power Flow Controller (GUPFC): Generalized unified power flow controller is considered as one of the latest generation of FACTS devices which are useful in controlling bus voltage and power flow of more than one line or even a sub network. The basic functional diagram of GUPFC is shown in fig 4.9 [23].

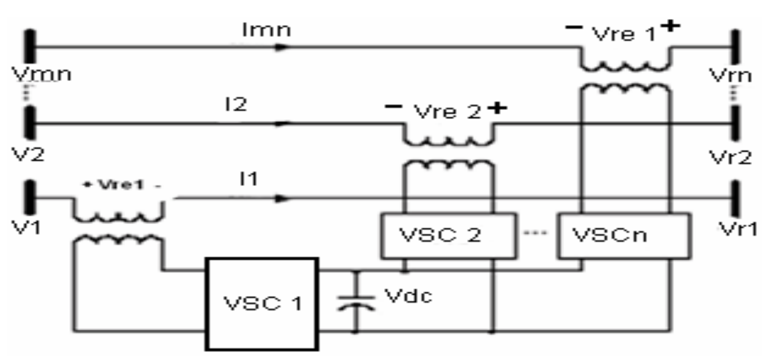

Figure 4.9 Functional Diagram of GUPFC [23]

From the figure, we can see that the GUPFC consist of three converters. One is shunt connected and other two are in series with transmission line, which are capable of controlling bus voltage at substation, real and reactive power flow on two existing lines of the substation. The GUPFC and IPFC have very similar structures except that *VSC1* is shunt-connected at bus-1. The *VSC1* is responsible for balancing the active power required by the series converters and also provides shunt reactive compensations to regulate the voltage magnitude at bus-1 [23]. The active and reactive power of the series connected transmission line is controlled by *VSC2*- *VSCn*, which provide the active and reactive compensation.

4.25 Advantages of GUPFC

1. It is widely used in modeling other members of the CSC family in power flow and OPF analysis.

2. The strong controlling capability of GUPFC in controlling bus voltage and multi-line power flow offers a great solution in solving the various power system stability problems.

4.26 Convertible Static Compensator (CSC)

It also belongs to latest generation of FACTS controller family which provides flexibility in adapting the latest power system control needs and enable unique control capabilities of power system. It was first installed in Utica, New York. When it was fully implemented, it will provide the long term solution for power transfer, voltage stability, power flow control, improving reliability and enhance power system stability. Basic functional diagram is shown in fig 4.10 [23]

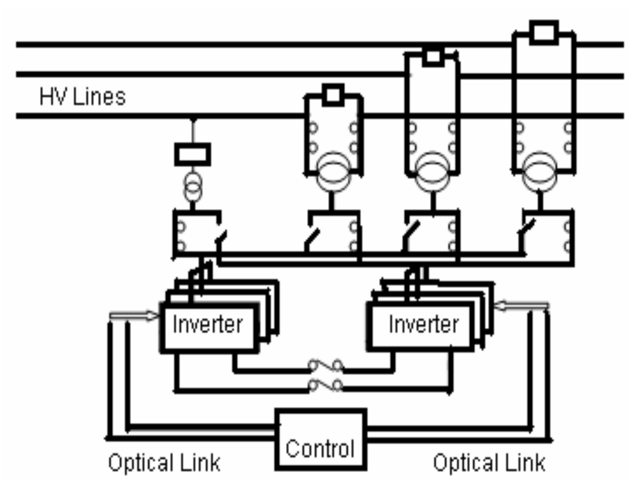

Figure 4.10 Functional Diagram of CSC [23]

From the above figure, the CSC can utilize the two inverters at different configurations such as STATCOM, SVC, UPFC, SSSC and IPFC. The CSC can be implemented in 11 different configurations. The control mode will determine the type of configuration used for CSC. Interlock and sequence control logic is to be implemented for automatic changes from one configuration to other. It basically consists of inner and outer loops. The inner loop is so well designed to provide the magnitude and angle controlled synchronous voltage source, which is utilized for voltage and power utilization. The outer loop is designed specially to damp the power system oscillations. The purpose of using damping controller at outer loop is to increase the reliability of transmission system for more stability. The CSC is yet to be examined for relieving the transmission line congestion at low frequencies.

4.27 Capabilities of Different FACT Controllers

Capabilities of different FACT controllers were depicted in table 4.2 [33].

Table 4.2: Capabilities of Different FACTS Controllers

Controller	Voltage control	Transient Stability	Damping oscillations	Reactive power compensation	Power flow control	SSR Mitigation
SSSC	X	X	X	X	X	X
STATCOM	X	X	X	X		
SVC	X	X	X	X		
TCSC	X	X	X		X	X
TSSC	X	X	X		X	
UPFC	X	X	X	X	X	X
SMES		X	X			

4.28 Benefits of FACTS Devices

Benefits of FACTS devices in electrical transmission system can be summarized as [4] [13]:

1. Better utilization of existing transmission assets.
2. Increase transmission system capacity and reliability.
3. Increase dynamic and transient grid stability.
4. Mitigate sub-synchronous resonance (SSR).
5. Limit short circuit currents.
6. Power quality improvement to industrial users.
7. Load compensation.
8. Improves system transient stability limit.
9. Increase loadability of the system.
10. Improves system security.

4.29 Application of FACTS Devices

FACTS devices employ a variety of applications to enhance the power system stability. One of the great advantages of the FACT devices is that they are flexible to use in all three states of power system. Various applications of FACTS devices are [4]:

1. **Steady state application:** Various steady state applications of FACTS controllers include voltage control (low and high), increase of thermal loading, loop flows control, reduction in short circuit level and power flow control. SVC and STATCOM can be used for voltage control while TCSC is widely used for loop flow control and power flow control.
2. **Dynamic voltage control:** Various shunt FACT devices like UPFC, STATCOM and SVC are used for dynamic control of voltage under severe disturbances and prevents the power system losses and blackouts.
3. **Transient stability enhancement:** Large disturbances like tripping of transmission line or a generator are the major causes of transient instability. FACT devices resolve the above problems by providing the fast and rapid response during the first swing to control voltage and power in a transmission line.
4. **Dynamic Application:** Dynamic applications of FACT controllers include oscillation damping, voltage stability and transient stability enhancement. One of the most important capabilities of FACT applications is to reduce the impact of primary disturbance. FACT devices provide a solution through dynamic voltage support (STATCOM), dynamic flow control (TCSC), or both can be achieved by the use of UPFC.

CHAPTER-5

SIMULATION AND RESULTS

5.1 Two machine system

Figure 5.1 shows the general diagram of two area system (area 1 & area 2). Area1 (1000 MW hydraulic generation plant) connected to Area 2 (1000 MW hydraulic generation Plant.) through 500 kV, 720 km transmission line.

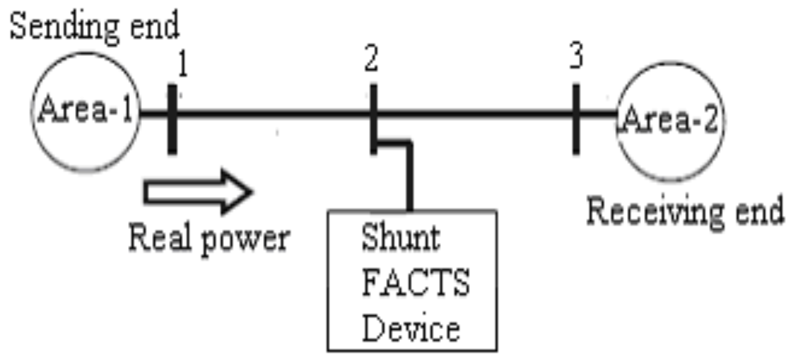

Figure 5.1 Two Area Interconnected System

5.2 Single line diagram of two machine system

Single line diagram of two machines (M1 & M2) system installed with shunt FACT device is shown in fig 5.2. Both plants fed to a load centre, modeled by a 500 MW and 1000MW RL load. System is initialized so that line carries 950 MW which is close to its surge impedance loading (SIL=977 MW). In order to maintain system stability, the transmission line is shunt compensated with FACT device (SVC and STATCOM) of 200Mvar at the midpoint of line. By connecting the FACT device at the midpoint, the power transfer capability of the system increases significantly. The direction of real power flow is from area-1 to area-2. Two machine systems are equipped with hydraulic turbine and governor (HTG), excitation system and power system stabilizer (PSS). The FACT devices do not have power oscillation damping unit (POD) [2].

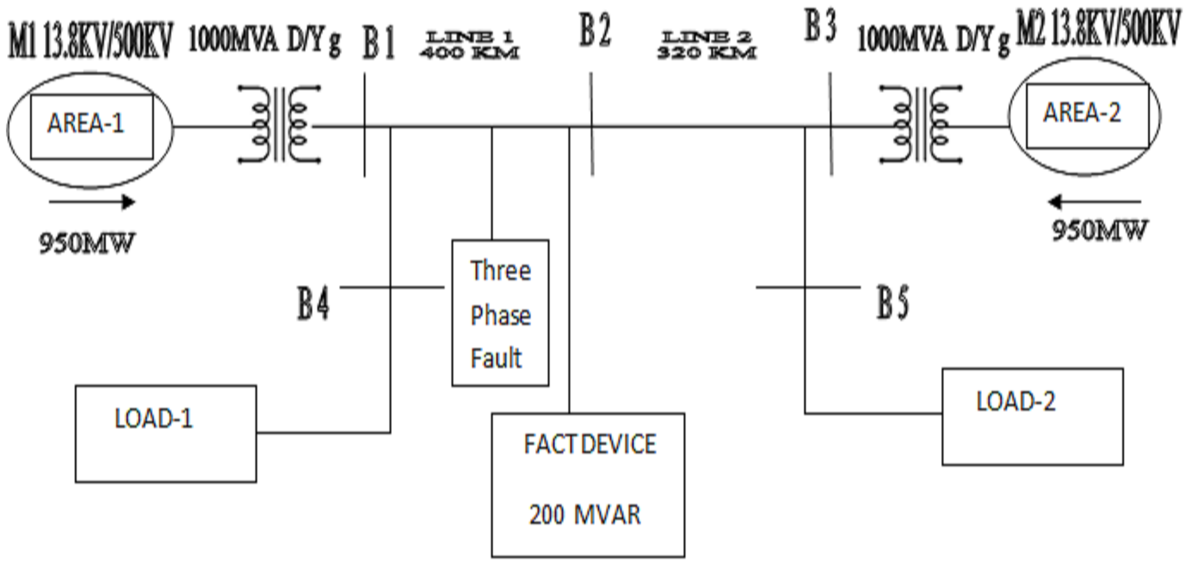

Figure 5.2 Single line diagram of two machine system

5.3 Simulink model of two machine system

Simulink model of two machines (M1 & M2) system consist three subsystems: first subsystem is installed with three phase fault. Second subsystem is installed with PSS and SVC of 200Mvar capacity at midpoint of transmission line. Third subsystem is installed with PSS and STATCOM of 200Mvar capacity at midpoint of transmission line. Simulink model of all three subsystems are shown in fig 5.3, fig 5.4 and fig 5.5. The detailed model of Turbine and regulator is shown in fig 5.6 while the model of PSS is depicted in fig 5.7.

Machine M1 referred to a 1000 MW hydraulic generation plant while Machine M2 referred to 1000 MW generating plant. Each machine equipped with a Governor, excitation system and Power system stabilizer. These components are included in Turbine & Regulator1 and Turbine & Regulator 2. Both machine connected through a 500 kV, 720km transmission line. RL load of 500MW connected on Machine M1 side and RL load of 1000MW connected to machine M2 side.

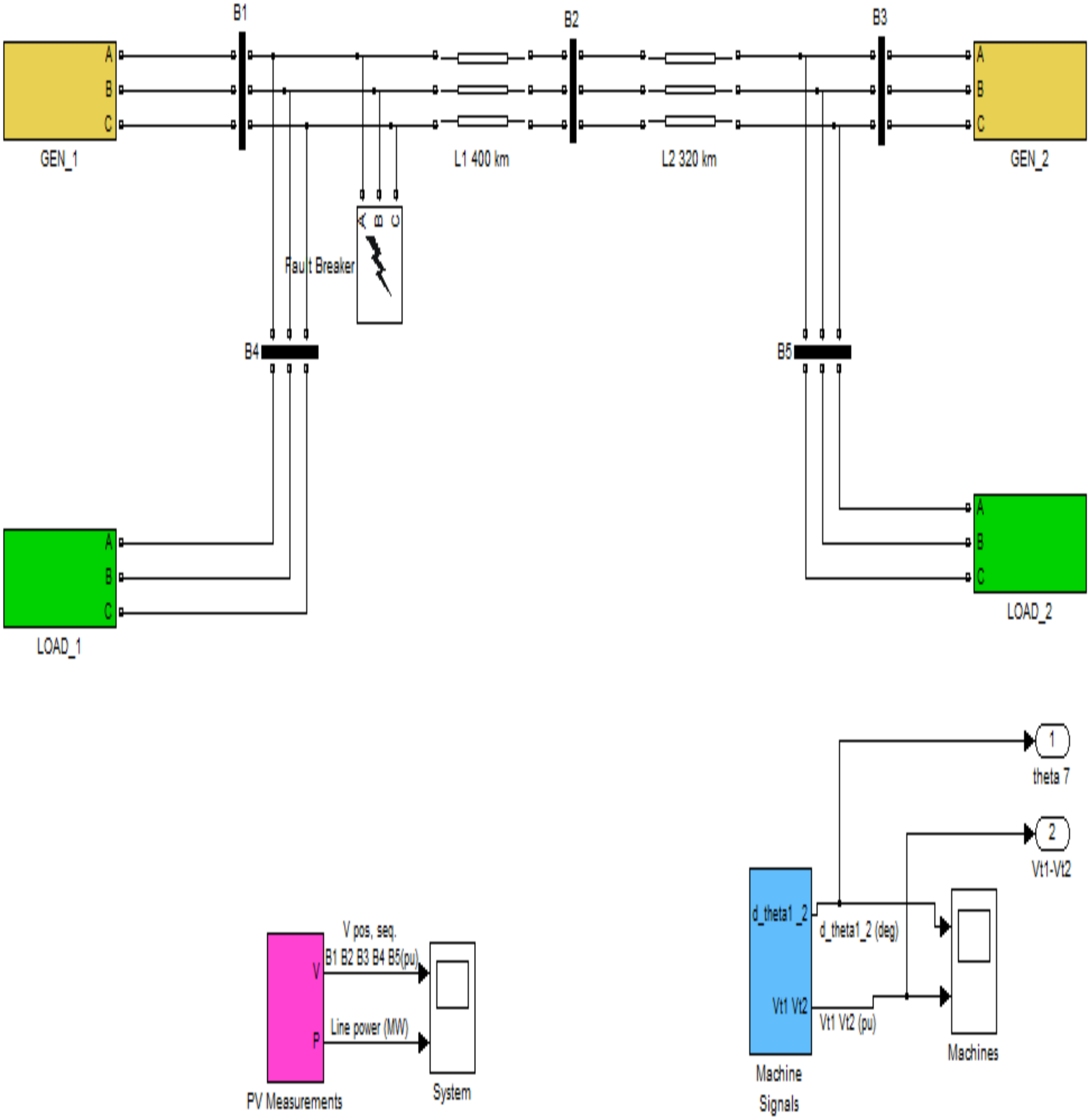

Figure 5.3 Two machine system installed with three phase fault

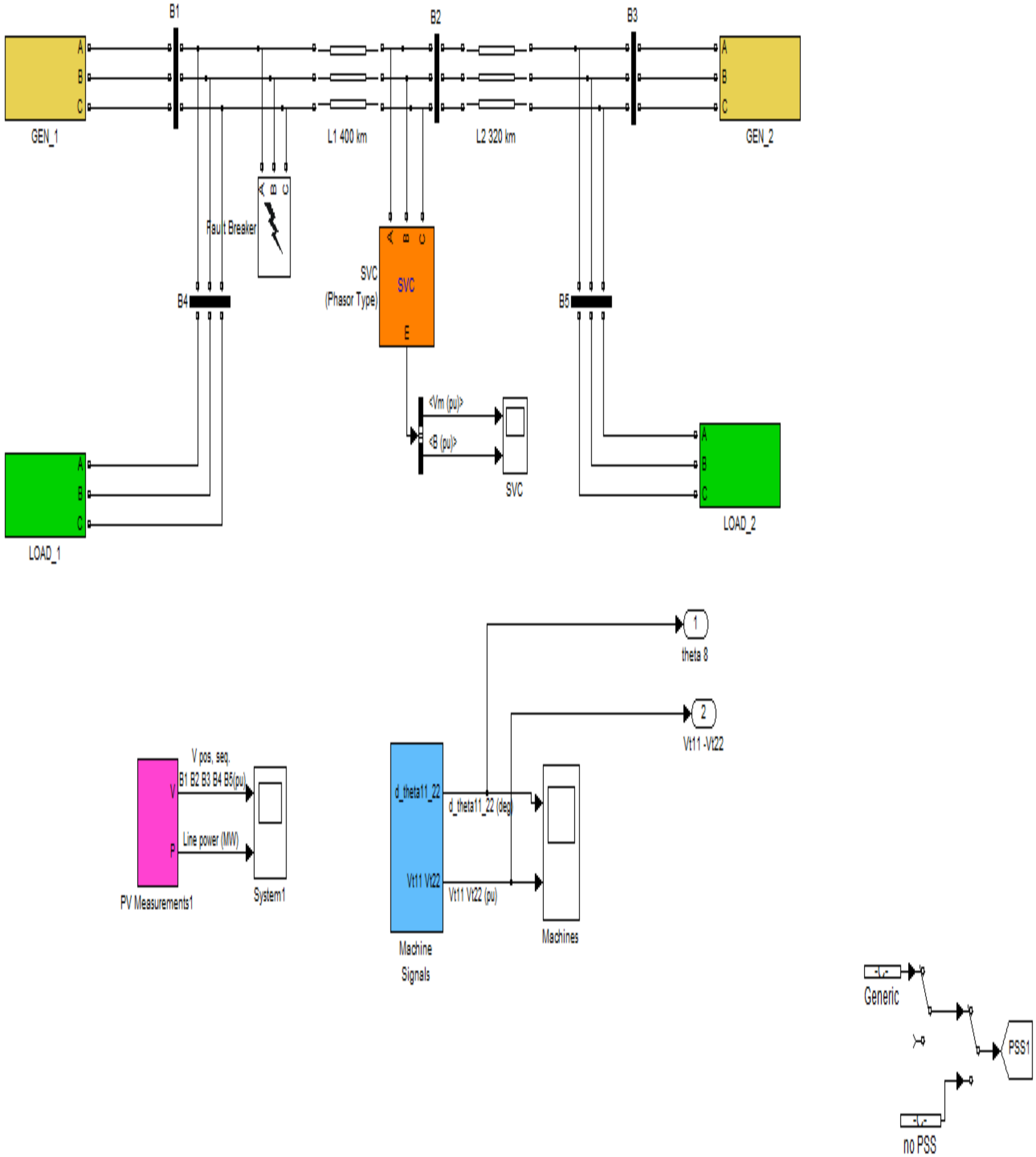

Figure 5.4 Two machine system installed with SVC and PSS

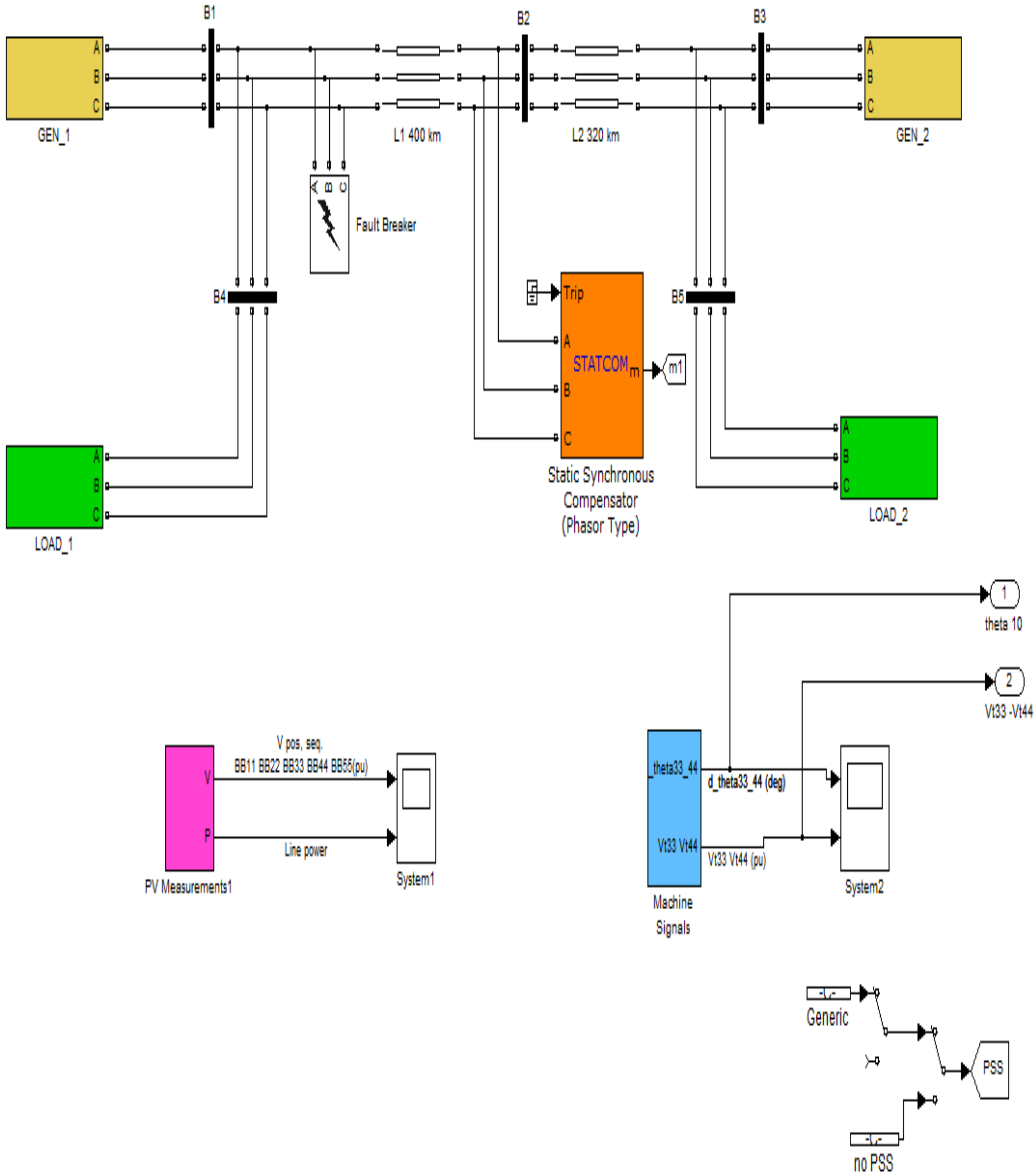

Figure 5.5 Two machine system installed with STATCOM and PSS

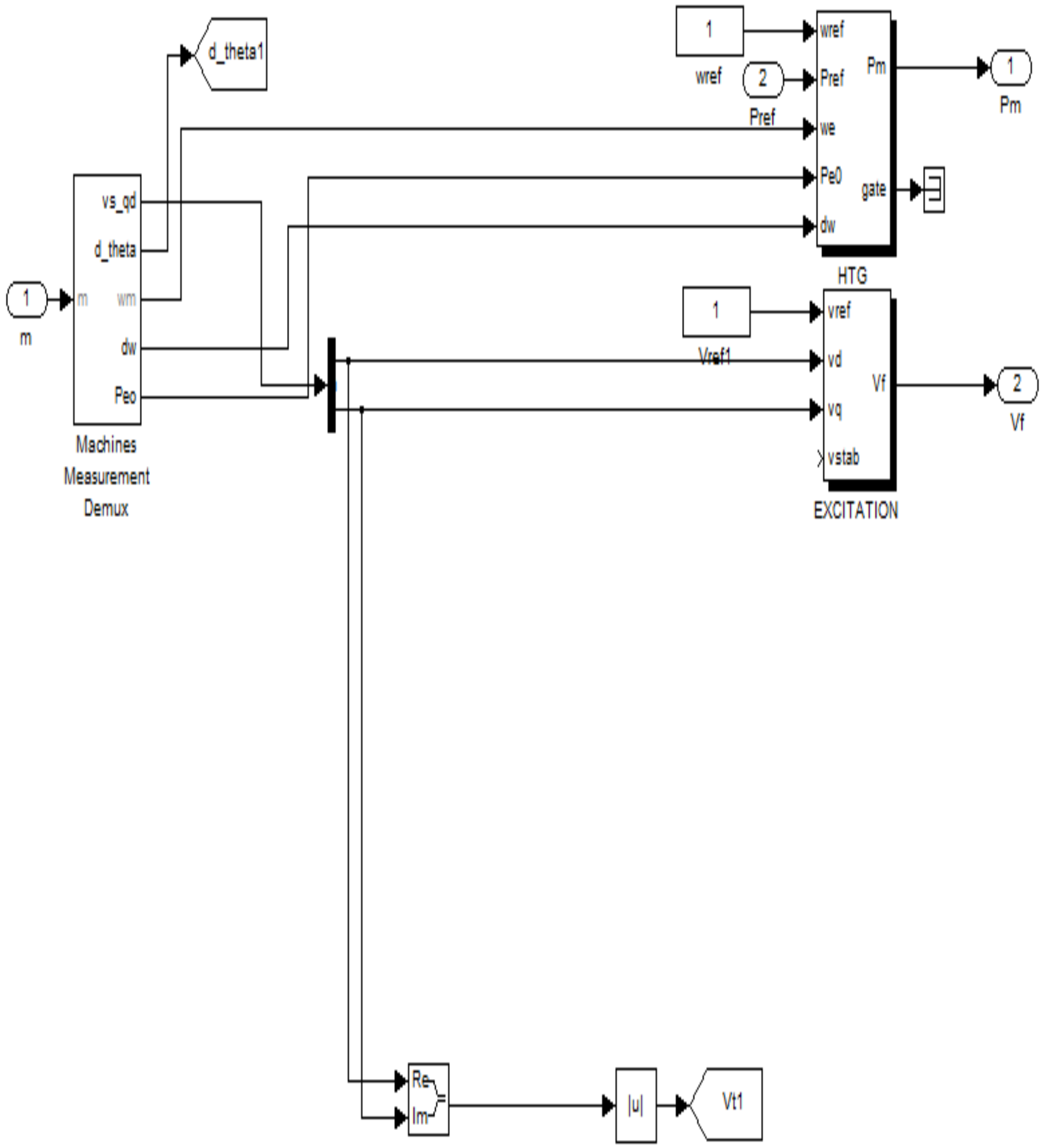

Figure 5.6 Simulink Model of Turbine and Regulator

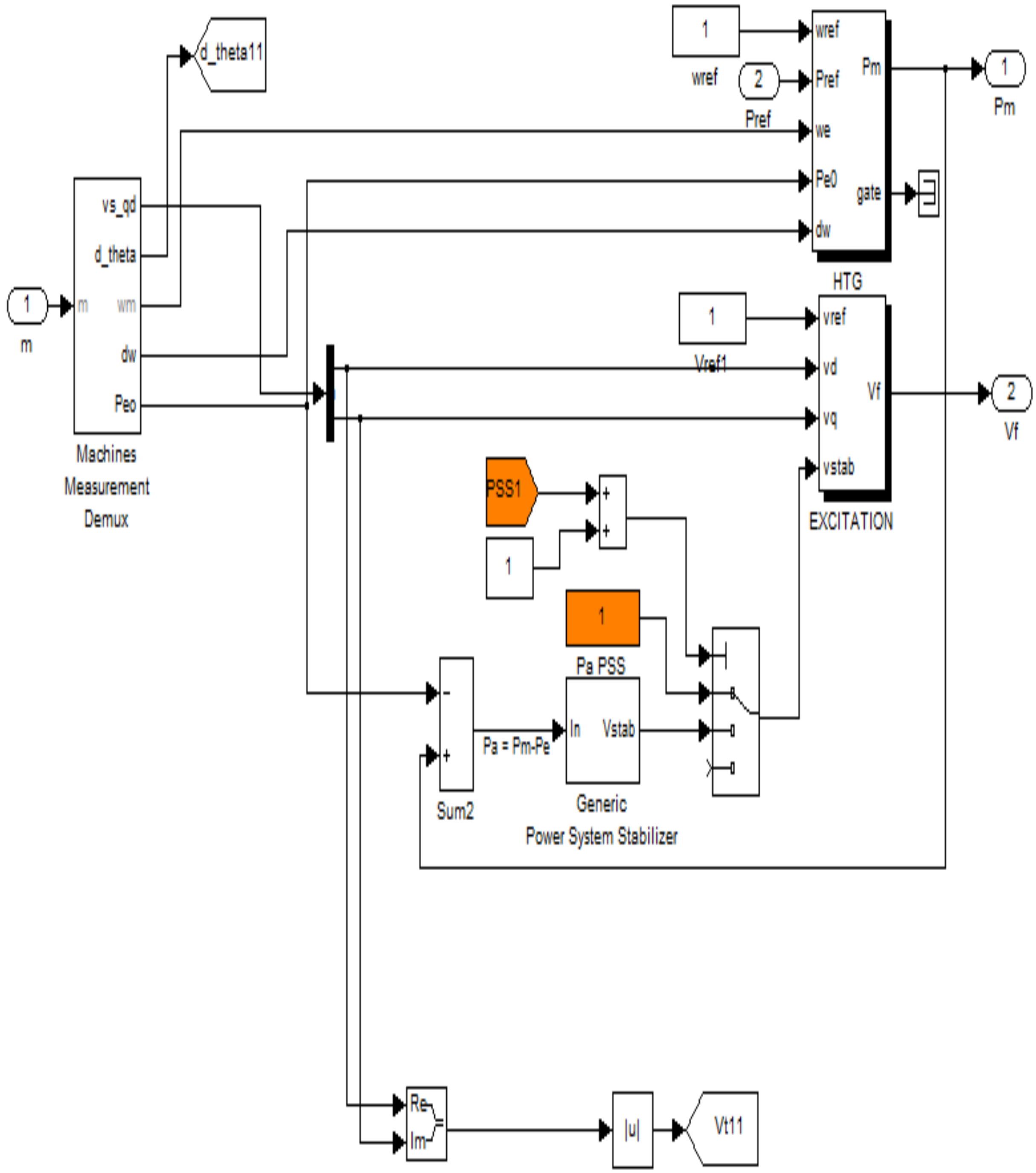

Figure 5.7 Simulink Model of PSS installed with excitation system

5.4 Simulation Results

5.4.1 System without FACT device (under fault)

A three phase fault having clearing time of 0.1 sec is given during the time period of 0.5sec to 0.6sec. System installed without FACT device and PSS becomes unstable and oscillations tend to increase to infinity as shown in fig 5.8 and 5.9. Variation of bus voltages and line power is shown in fig 5.10 and 5.11.

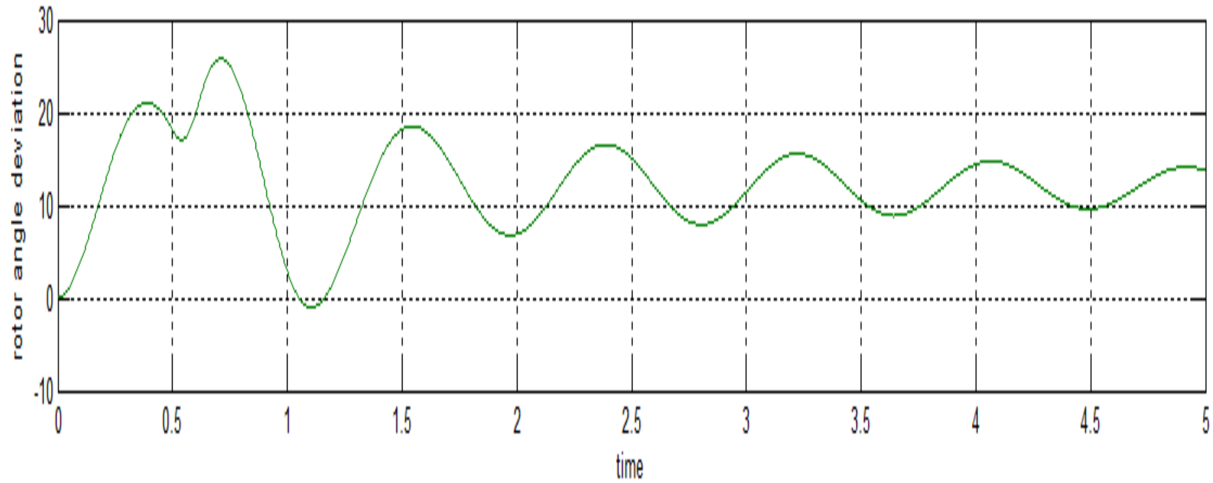

Figure 5.8 Deviation of rotor angle with time

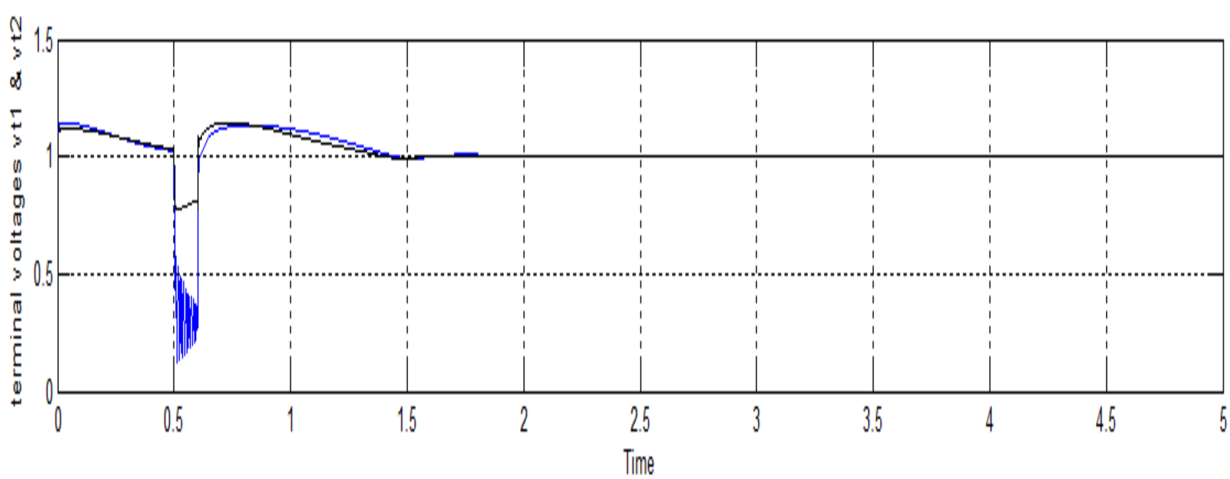

Figure 5.9 Deviation of terminal voltages with time

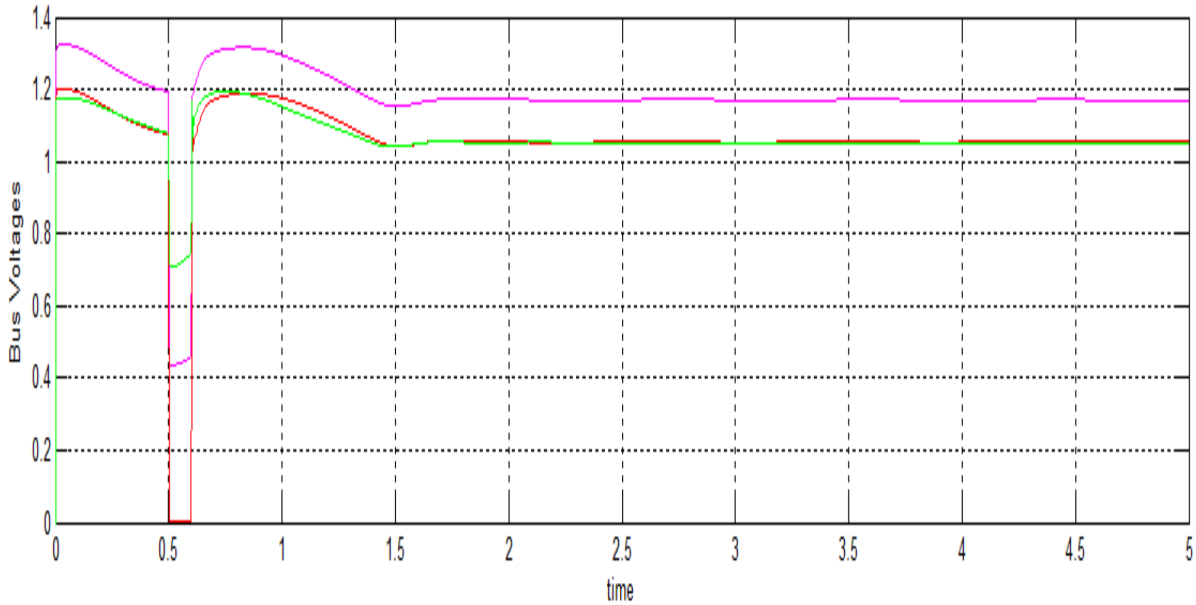

Figure 5.10 Variation of bus voltages with time

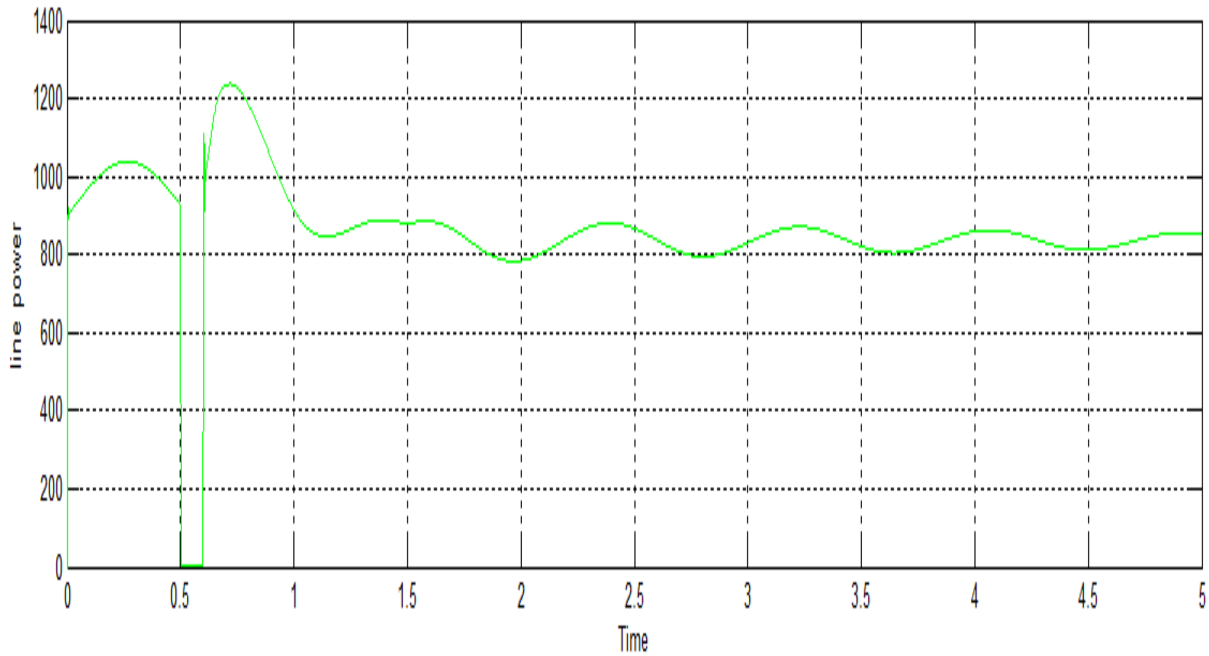

Figure 5.11 Variation of Line power with time

5.4.2 System installed with FACT device (SVC) and PSS.

Now the system is installed with a FACT device commonly known as Static Var compensator. SVC is put in service by selecting the mode to voltage regulation. Generic type PSS will be put in service by setting the command Pa=1 in PSS block. A three phase fault having clearing time of 0.1sec is given to system. System becomes stable after fault is shown in fig 5.12 and 5.13. Response of voltage at SVC bus is shown in fig 5.14. Variation of bus voltages and line power is shown in fig 5.15 and 5.16.

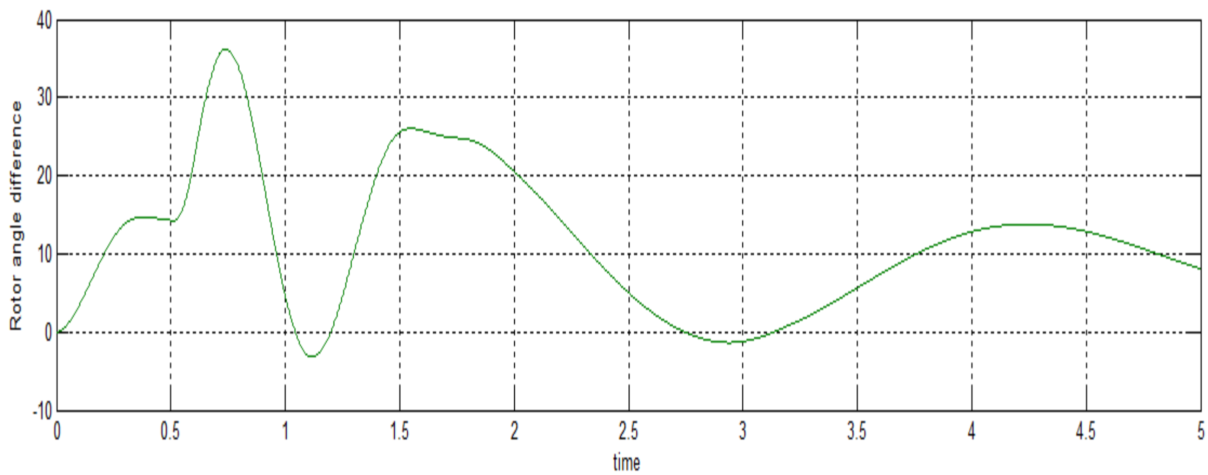

Figure 5.12 Deviation of rotor angle with time (SVC)

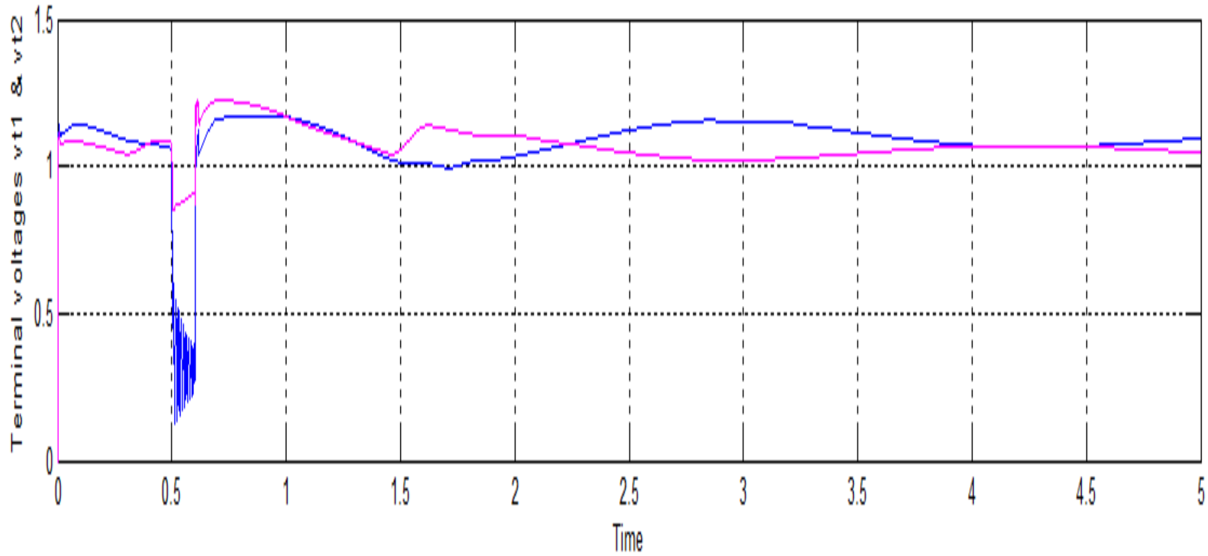

Figure 5.13 Deviation of terminal voltages with time

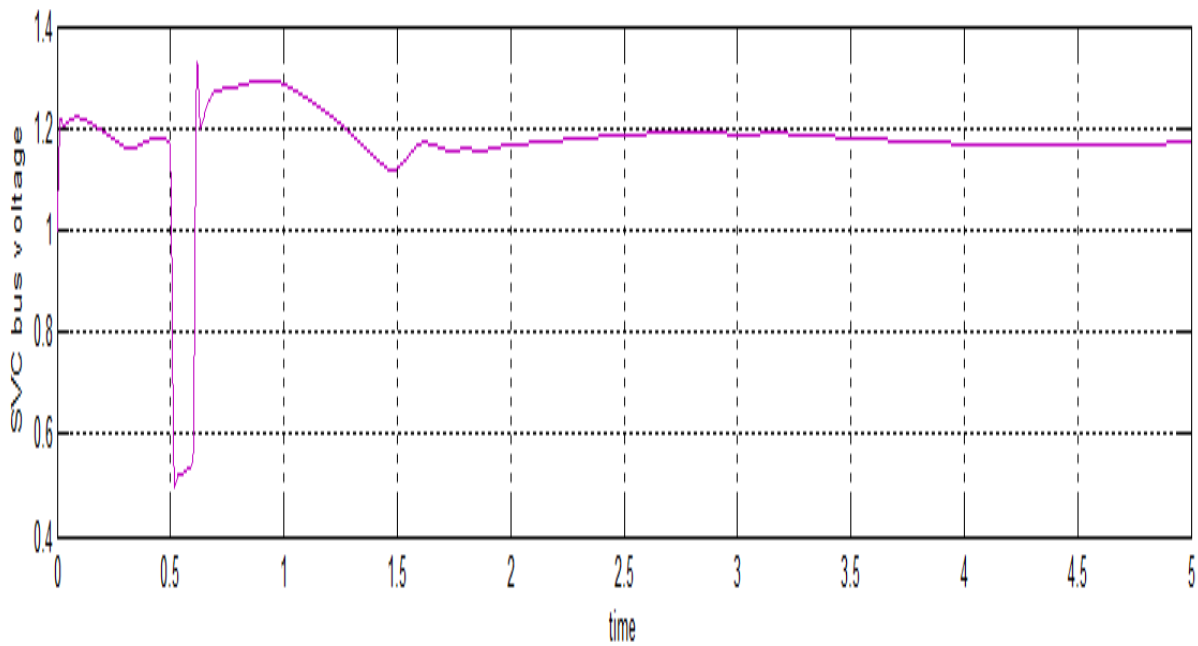

Figure 5.14 Variation of Voltage at SVC bus with time

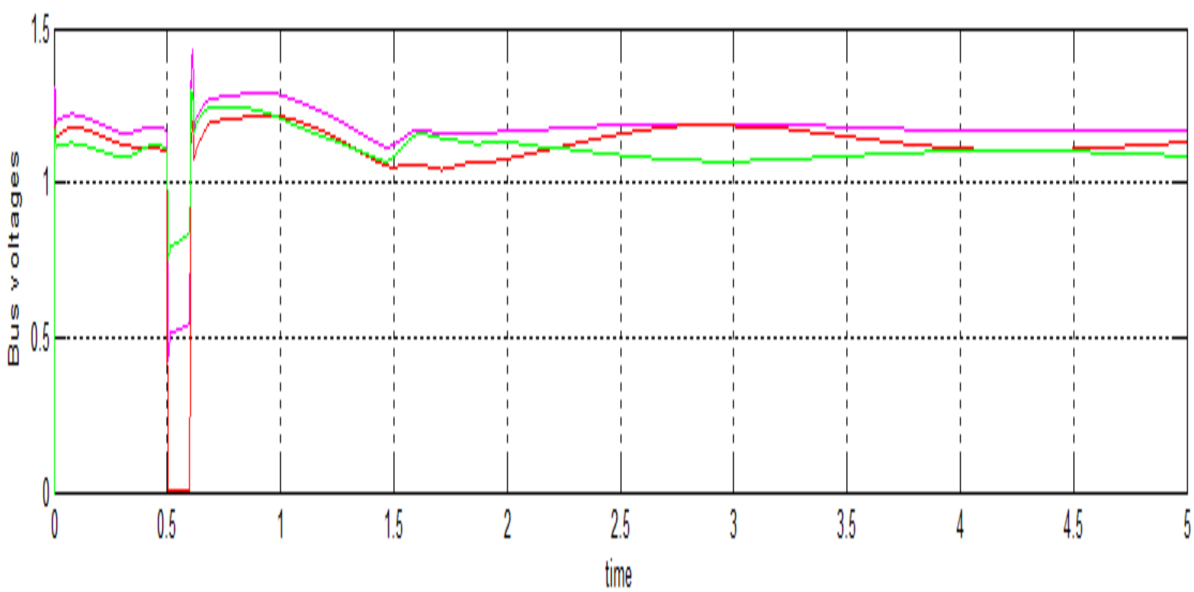

Figure 5.15 Variation of bus voltages with time

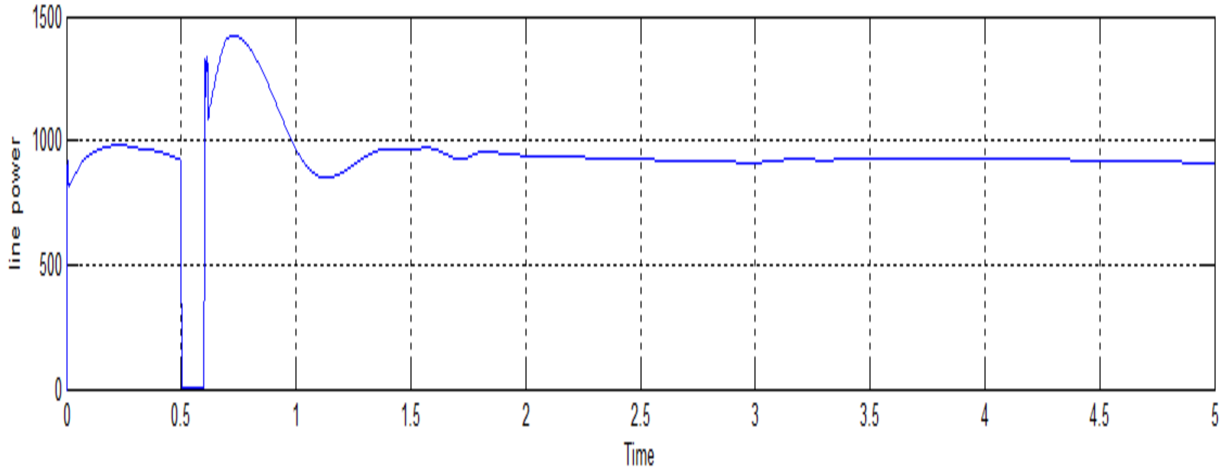

Figure 5.16 Variation of Line power with time

5.4.3 System installed with FACT device (STATCOM) and PSS.

Now the system is installed with a FACT device commonly known as Static Synchronous compensator. STATCOM is put in service by selecting the mode to voltage regulation. Generic type PSS will be put in service by setting the command Pa=1 in PSS block. A three phase fault having clearing time of 0.1sec is given to system. System becomes stable after fault is shown in fig 5.17 and 5.18. Variation of bus voltages and line power is shown in fig 5.19 and 5.20.

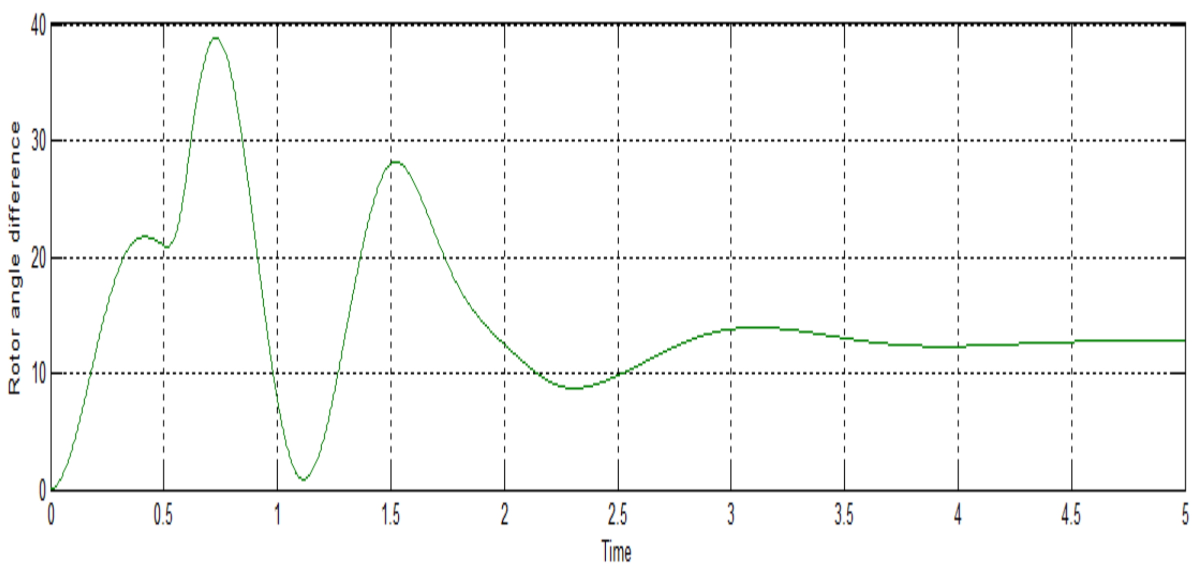

Figure 5.17 Deviation of rotor angle with time (STATCOM)

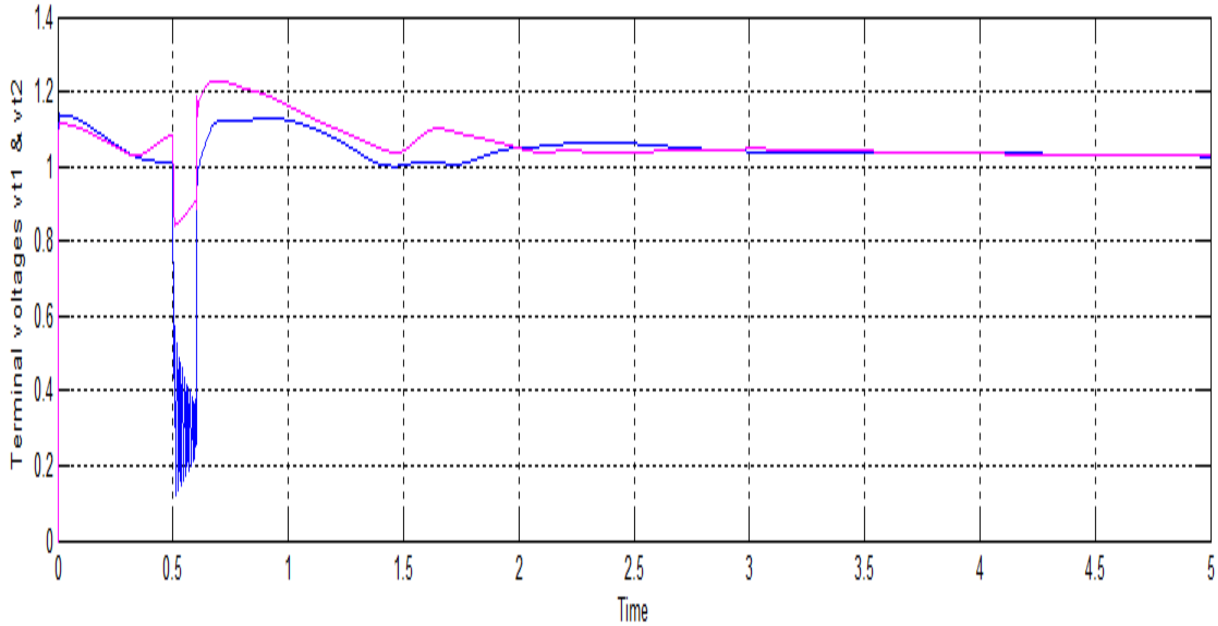

Figure 5.18 Deviation of terminal voltages with time

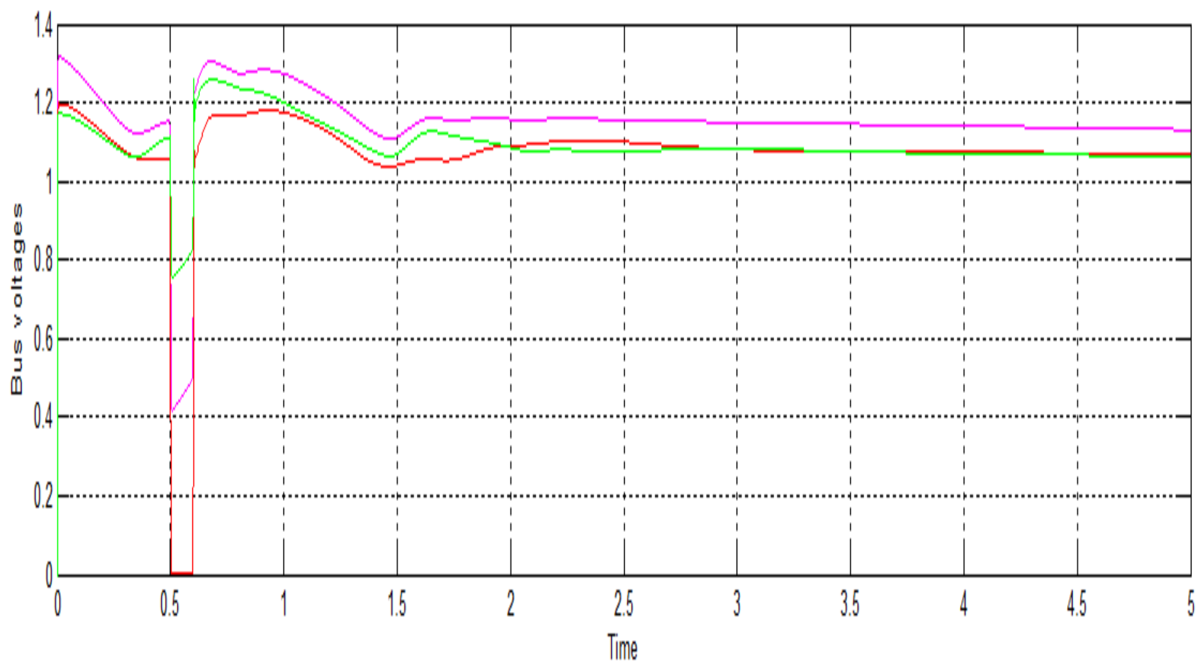

Figure 5.19 Variation of bus voltages with time

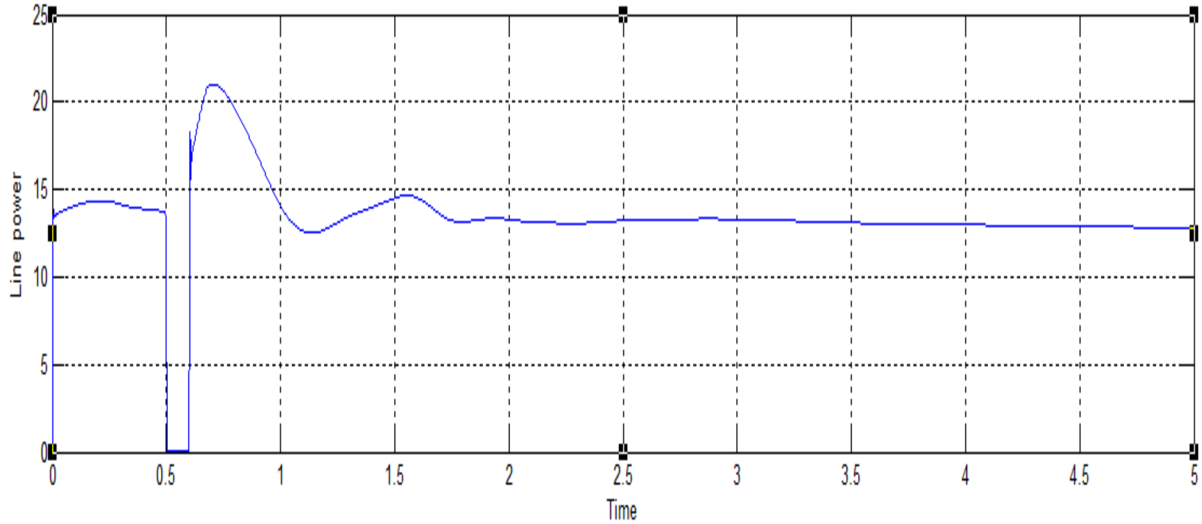

Figure 5.20 Variation of Line power with time

5.5 Comparison between FACT Devices

5.5.1 Comparison between normal system and SVC installed system (under fault).

Responses of the system with three phase fault and system installed with SVC under fault is shown in fig 5.21 and 5.22.

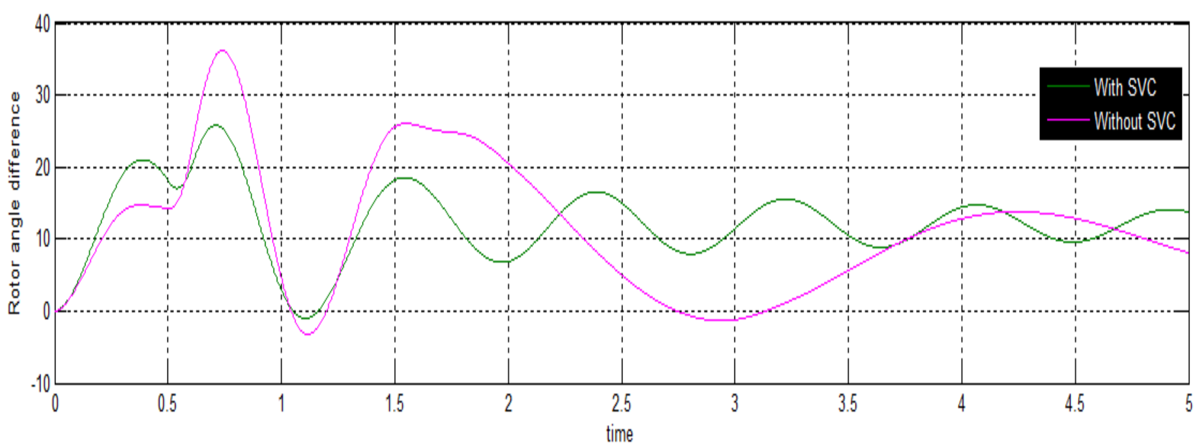

Figure 5.21 Deviation of rotor angle with time.

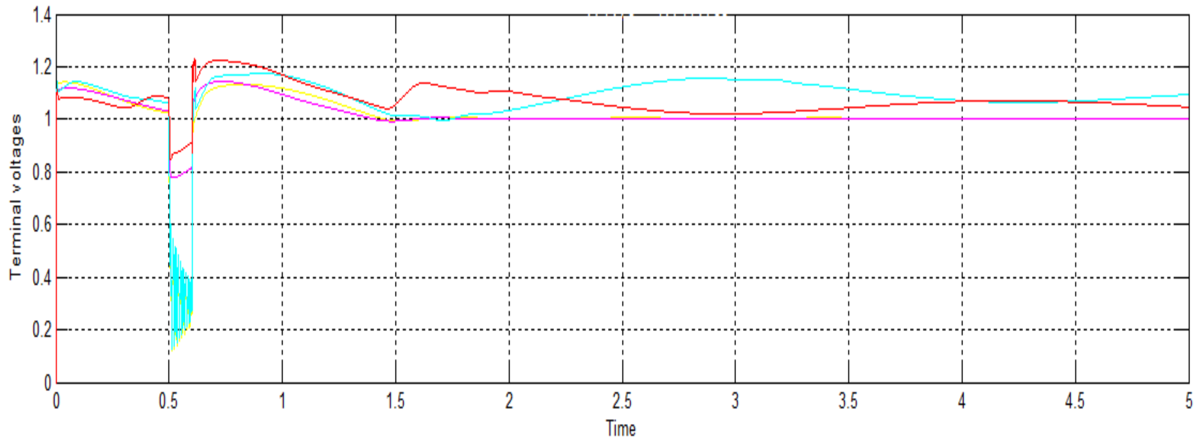

Figure 5.22 Deviation of terminal voltages with time

From the fig 5.21 and 5.22, it's clear that the system installed with SVC will provide necessary damping and improves the transient stability after time t= 4sec. The deviation of terminal voltages will remain close to 1.

5.5.2 Comparison between normal system and STATCOM installed system (under fault).

Responses of the system with three phase fault and system installed with STATCOM under fault is shown in fig 5.23 and 5.24.

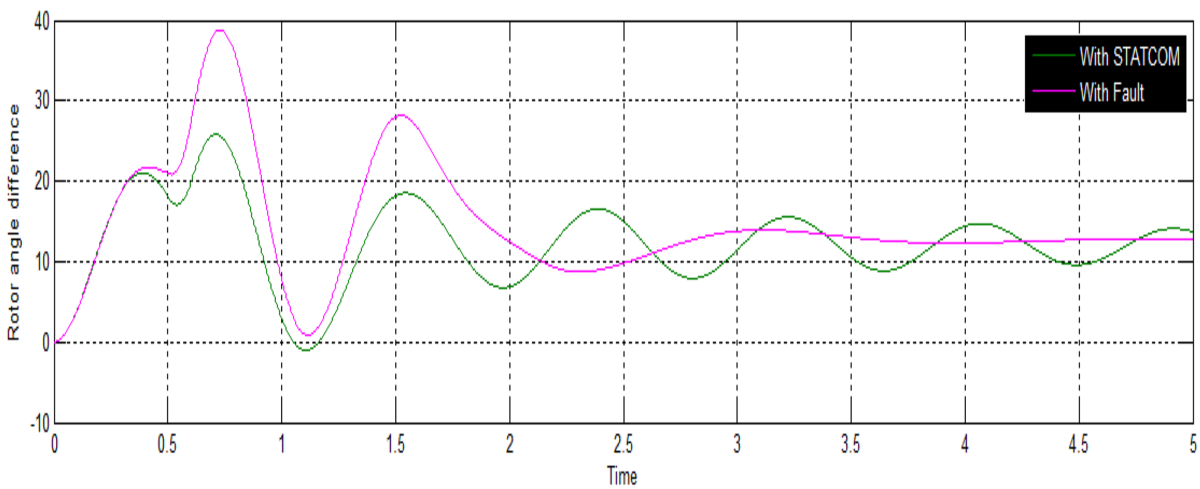

Figure 5.23 Deviation of rotor angle with time.

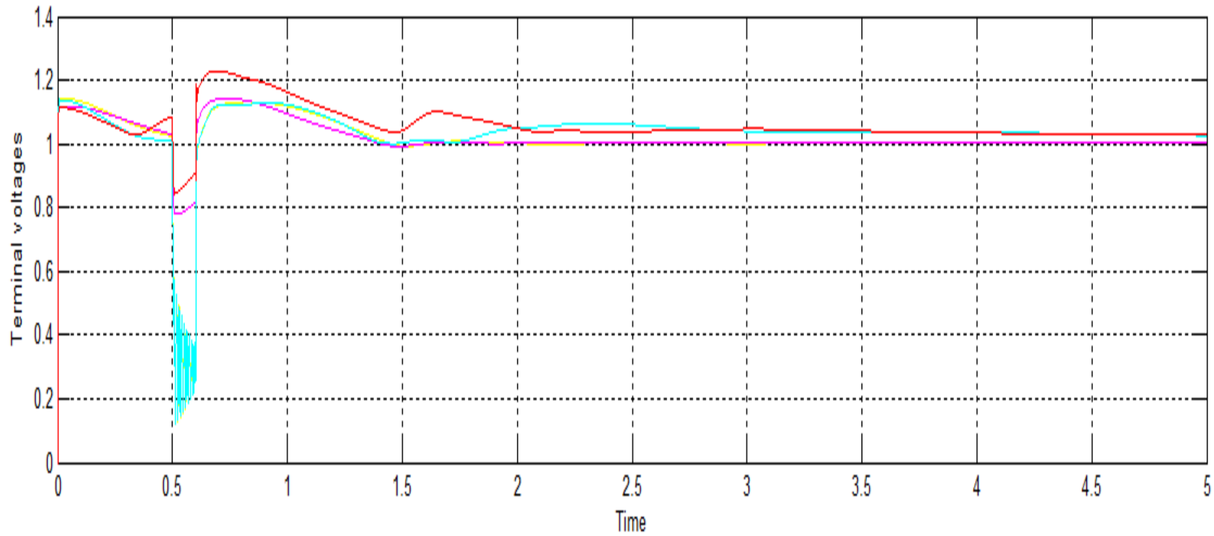

Figure 5.24 Deviation of terminal voltages with time

From the fig 5.23 and 5.24, it's clear that the system installed with STATCOM will provide necessary damping and improves the transient stability after time t= 2.8sec. The deviation of terminal voltages will remain close to 1.

5.5.3 Comparison between SVC and STATCOM installed system (under fault).

Responses of the system with three phase fault and system installed with SVC and STATCOM under fault is shown in fig 5.25 and fig 5.26.

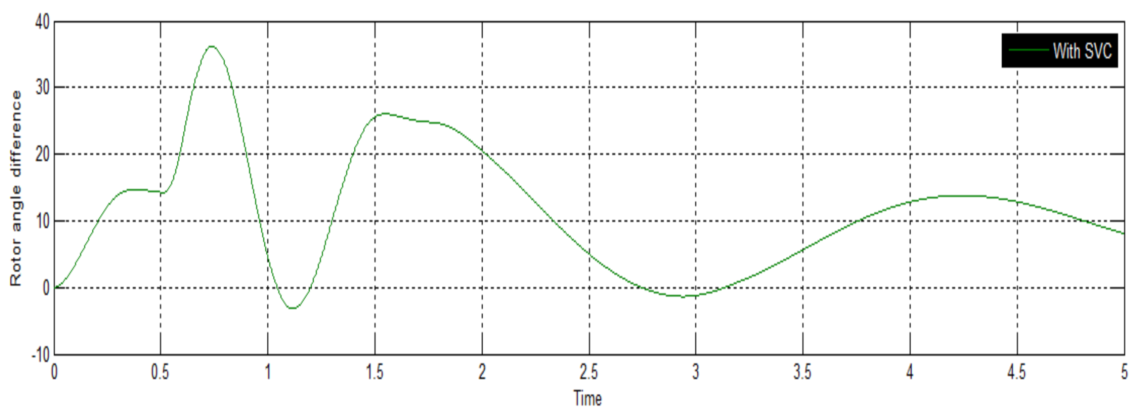

Figure 5.25 Deviation of rotor angle with time (SVC)

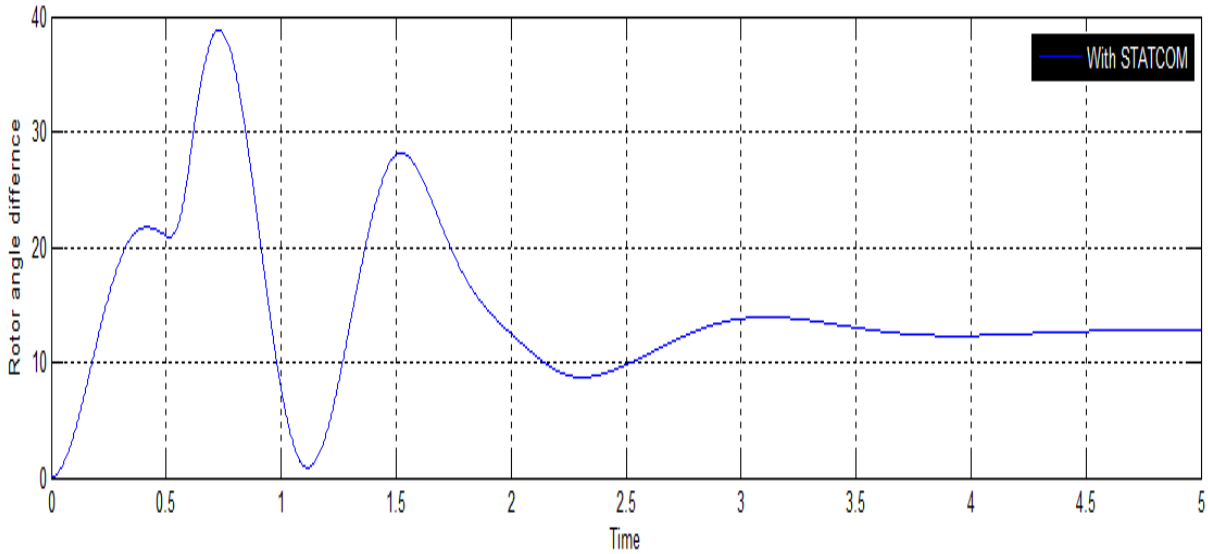

Figure 5.26 Deviation of rotor angle with time (STATCOM)

From the fig 5.25 and fig 5.26, it's clear that STATCOM will provide better stability than SVC after fault clearance. The post settling time of the system after clearing of fault by STATCOM is less than SVC. Table 5.1 shows the desired comparison between SVC and STATCOM.

Table 5.1: Comparison between SVC and STATCOM

Two area power system with	Transient stability enhancement	Post settling period after fault(seconds)
SVC	YES	4.0
STATCOM	YES	2.8

CHAPTER-6

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

In this thesis, various constraints of the modern power system were discussed and on the basis of these constraints, need of FACTS devices were presented. Also, various compensation techniques employed by FACTS devices were discussed. Different types of stability which exist in modern power system were presented in detail. Power system stability enhancement of two machine system along with different types of FACTS devices was discussed. The dynamics of the power system is compared with and without the presence of FACTS devices and Power system stabilizers in the event of major disturbances. The performance of one of the FACT device i.e. STATCOM for transient stability enhancement is compared with the performance of other FACT device i.e. SVC. Controller's inputs are chosen carefully to provide necessary damping in rotor angle and results are taken through simulation. Proposed FACTS controllers were implemented in MATLAB/SIMULINK. Simulation results indicate that the STATCOM controller installed with two machine systems provides better damping characteristics in rotor angle as compared to two machine system installed with SVC. Also, the post settling time of the two machine system installed with STATCOM is found to be less i.e. near to 2.8sec than the system with SVC. Thus, transient stability enhancement of the two machine system installed with STATCOM is better than that installed with SVC.

6.2 Future Scope

In the following, some recommendations are given for future research in this area:

1. To study the performance of different FACTS devices for transient stability enhancement in a multi-machine system.
2. To study the effect of location of FACTS devices for transient stability enhancement in a hybrid system.

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APPENDIX A

(Specification)

Data for Two machines five bus systems

Table A1:- Synchronous Machine Data

Synchronous Machine	MVA	P_n(VA)	V_n(V_{rms})	F_n(Hz)	T_d	R_s(pu)	H(s)	F(PU)	p
M1	1000	1000	13800	60	1.01	2.8544	3.7	0	32
M2	1000	1000	13800	60	1.01	2.8544	3.7	0	32
M3	1000	1000	13800	60	1.01	2.8544	3.7	0	32
M4	1000	1000	13800	60	1.01	2.8544	3.7	0	32
M5	1000	1000	13800	60	1.01	2.8544	3.7	0	32
M6	1000	1000	13800	60	1.01	2.8544	3.7	0	32

Table A2:- Excitation System Data

Excitation System	T_r(s)	Ka	T_a(sec)	Ke	Te(sec)	T_b(s)	T_c(s)	K_f
M1	20	200	0.001	1	0	0	0	0.001
M2	20	200	0.001	1	0	0	0	0.001
M3	20	200	0.001	1	0	0	0	0.001
M4	20	200	0.001	1	0	0	0	0.001
M5	20	200	0.001	1	0	0	0	0.001
M6	20	200	0.001	1	0	0	0	0.001

Table A3:- Transformer Data

Transformer	MVA	P_n(VA)	F_n(Hz)	V_1(ph to ph)	V_2(ph to ph)	R_1(pu)	R_2(pu)	L_1(pu)	L_2(pu)
Tr1	1000	1000	60	13.8	500	0.002	0.002	0.0	0.12
Tr2	1000	1000	60	13.8	500	0.002	0.002	0.0	0.12
Tr3	1000	1000	60	13.8	500	0.002	0.002	0.0	0.12
Tr4	1000	1000	60	13.8	500	0.002	0.002	0.0	0.12
Tr5	1000	1000	60	13.8	500	0.002	0.002	0.0	0.12
Tr6	1000	1000	60	13.8	500	0.002	0.002	0.0	0.12

Table A3:- Load Data

Load	MW	$V_n(V_{rms})$	F_n(Hz)	P(w)	Ql	Qc
L1	500	500	60	500	100	0
L2	1000	500	60	1000	200	0