

**ANALYSIS OF VOLTAGE STABILITY IMPROVEMENT  
IN TWO MACHINE 3-BUS MODEL WITH STATCOM  
USING MATLAB SIMULATION**

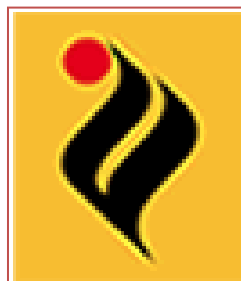
*Thesis submitted in partial fulfillment of the requirements for the award  
of the degree of*

**MASTER OF ENGINEERING  
in  
POWER SYSTEMS & ELECTRIC DRIVES**

Submitted By  
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**JULY-2012**

## CERTIFICATE

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I hereby certify that the work which is being presented in the thesis entitled, “ANALYSIS OF VOLTAGE STABILITY IMPROVEMENT IN TWO MACHINE 3-BUS MODEL WITH STATCOM USING MATLAB SIMULATION”, in partial fulfillment of the requirements for the award of degree of Master of Engineering in *Power Systems and Electric Drives* submitted in Electrical and Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Ms. Manvir Kaur. The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

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This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.



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## **Abstract**

For all the economic activities, electricity is a necessity and access of this to the people bear direct impact on growth of a country. With the expansion in power system along with restructuring in some states the complexity is increasing continuously. From the three components of power system the transmission and distribution systems are the most important one from which the consumers are getting power. Requirement of good power quality along with additional load by consumers, make the compensating device a necessity in modern era power system. As these devices are quite expensive and also add to the complexity of the system, the analysis of compensating device is a prior topic. In this thesis two machine model with three bus system is taken and simulated in MATLAB. Simulation results of transient stability from three phase fault with STATCOM are analyzed for different loading conditions.

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# Chapter 1

## Introduction

### 1.1 Overview

Electricity is backbone for almost all economic activities in present times and it is a proven fact that access of this precious perishable commodity to people bears direct impact on pace of development of the country. India has the fifth largest installed power capacity in the world (the first four are US, Japan, China and Russia), and is one of the top power consumers. With rapid industrialization and increasing population the demand for electricity is increasing day by day. Existing power system is expanding due to increased demand and becoming more complex with different types of loads and generation from varied and distributed resources and with new technology and restructuring of electrical power system adds to the complexity of the modern power system.

### 1.2 Motivation for research

Expansion of power system along with restructuring and deregulation the complexity of system is increasing continuously. Demand for additional load and requirement of good power quality by consumers makes the use of compensation devices a necessity. These compensation devices add to utilities complexity and expenses, so it becomes important to use them at a location which offers a better compensation and proper utilization of these devices.

### 1.3 Power system consists of mainly three parts:

#### 1. Generation

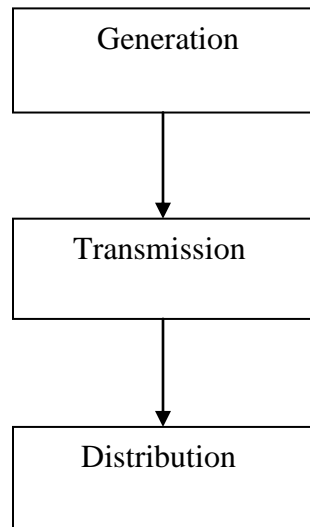
Generation is mainly by synchronous generators driven by prime mover working on various forms of energy e.g. hydro, thermal, nuclear, solar, wind, tidal, geothermal etc.

#### 2. Transmission

Transmission is done to transmit the generated power to load centers using overhead lines.

### 3. **Distribution**

Distribution is process of providing the electrical energy at desired level at consumer premise



**Fig. 1.1 Levels of power system**

## **1.4 Preference of ac over dc**

Reasons of preference of ac over dc are as:

1. It is economical and convenient to generate ac
2. Easy transformation of voltage level possible in ac system

However, HVDC is also used for bulk transfer of power for long distances (usually greater than 500 km). Modern interconnected power system consists of generation from different types of generating plants located in geographically different parts of the country according to their feasibility, connecting different load centers with these generating plants consists of

transmission system and in the end distribution system for distribution of electrical energy at the consumer premise at a within a fixed defined limits of voltage and frequency. Due to complex and large power system the control and transfer of electrical power with optimal performance of various parts of system is becoming more and more difficult.

## **1.5 Interconnection**

We need these interconnections in power system because the transmission network pool power plants and load centers in order to minimize the total power generation capacity and cost. It increase the firm capacity of the entire system .Transmission interconnections taking advantage of diversity of loads, availability of sources and full price in order to supply electricity to the loads at minimum cost with a required reliability .Transmission is often an alternative to the new generation resource. We cannot predict about the optimum balance between generation and transmission unless the system planners use advanced methods of analysis which integrate transmission planning into an integrated value-based transmission/generation planning scenario .Hence, we need to incorporate some control mechanism in order to increase the power transfer capability and enhance the controllability.

Also, as the power system grow in size it becomes more complex to operate and its security against major outages decreases. Other effects arise like; excess reactive power in some parts of the system, large dynamic swings between different parts of the system and power flows between various parts without adequate control.

The power systems of today are largely controlled mechanically. Mechanical control of power system has drawbacks like

1. Slow operation
2. Less frequent control due to wear out of mechanical parts
3. Controls are of on/off nature not regulatory

## **1.6 Fundamental requirements of a designed power system:**

1. It must supply energy at minimum cost and minimum ecological impact.
2. It must be able to meet continuously changing demand of load both active and reactive.

3. Quality of power should meet certain minimum standards in:
  - a. Constant frequency
  - b. Constant voltage

In modern interconnected power system the effect of instability or poor power quality is on both power system and load connected to it. Modern information age increasing use of computers and sophisticated electronic devices requires with a very good power that remains within specified limits of voltage for their proper functioning. This needs great stress on quality of electrical power being supplied to the load. Poor quality power sometimes causes serious economic consequences and cost business millions of rupees each year in revenues loss, process improvements, and scrapped product in industrial assembly lines which are increasingly automated and work on semiconductor equipments control which are sensitive to the quality of power being supplied.

### **1.7 The Costs of Poor Power Quality due to low power factor can be Significant**

1. **Lost production:** Each time production is interrupted, your business loses profit on product that is not manufactured and sold.
2. **Damaged product:** Interruptions can damage a partially complete product, causing the material to be re-run or scrapped.
3. **Energy cost:** Electric utilities may charge penalties on poor power factor or high peak demands.

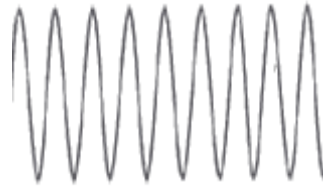
### **1.8 Power Monitoring Equipment**

Basic power monitoring equipment consists of the following components:

1. Computers
2. Internet or intranet
3. A power meter that measures Watts, Amps, power factor, AC power, etc.
4. Data storage facilities

## 1.9 Power quality

It is the set of limits of electrical properties that allows electrical systems to function in their intended manner without significant loss of performance or life. The term is used to describe electric power that drives an electrical load and the load's ability to function properly with that electric power.



**Fig. 1.2 Normal voltage waveform**

The good quality of power can be specified as:

1. The supply voltage should be within guaranteed tolerance of declared value
2. The wave shape should be pure sine wave within allowable limits for distortion.
3. The voltage should be balanced in all three phases.
4. Supply should be reliable i.e. continuous availability without interruption.

## 1.10 Power quality problem

The power quality problem is defined as any problem manifested in voltage, current or frequency deviations which results in mal-operation of customer equipment. The power quality problem causes the deterioration of performance of various sensitive electronic and electric equipments.

Modern industrial machinery and commercial computer networks are prone to many different failure modes. When the assembly line stops, or the computer network crashes for no apparent reason, very often the electric power quality is suspected. Power quality problems may be very difficult to troubleshoot, and often the electric power may not have any relation to the actual problem. For example, in an industrial plant the faults of an automated assembly machine may

ultimately be traced to fluctuations in the compressed air supply or a faulty hydraulic valve. Or in an office building, the problems on a local area network may be find their root cause with coaxial cable tee locations that are too close together, causing reflections and signal loss.

Without the proper power, an electrical device (or load) may malfunction, fail prematurely or not operate at all. There are many causes of such poor quality power.

The electric power industry comprises electricity generation (AC power), electric power transmission and ultimately electricity distribution to an electricity meter located at the premises of the end user of the electric power. The electricity then moves through the wiring system of the end user until it reaches the load/equipment. The complexity of the system to move electric energy from the point of production to the point of consumption combined with variations in weather, generation, demand and other factors provide many opportunities for the quality of supply to be compromised.

While "power quality" is a convenient term for many, it is the quality of the voltage—rather than power or electric current that is actually described by the term. Power is simply the flow of energy and the current demanded by a load is largely uncontrollable.

### **1.11 Causes for poor voltage quality**

These are defined in terms of:

1. Magnitude (amplitude)

Voltage events — appearing in the form of sags, swells, impulses,

2. Duration (length)

Total harmonic distortion — can affect equipment performance in different ways.

Typically, the ultimate impact of such events is determined by the sensitivity of the equipment on the branch circuit.

### **1.12 Effect of poor voltage quality**

Voltage events interrupt sensitive processes, shorten the useful life of equipment, and cause computer and communications problems. Oftentimes, these disturbances trigger needless expenses in the form of implemented solutions to misdiagnosed problems. Unless the source of the problem is correctly identified and its cause found and repaired, the costs and time required to solve the problem add up quickly

## 1.13 Reasons affecting the power quality

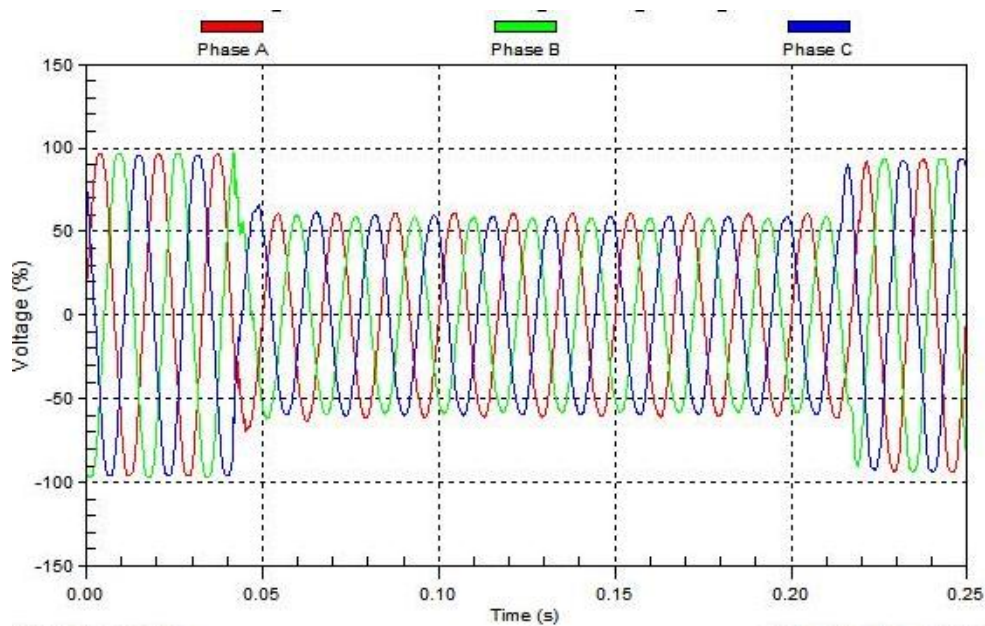
Distribution system consists of many non linear resources that have an negative effect on power quality.

### 1.13.1 Voltage dips

It can be considered as a short time reduction in voltage of a small time of less than 0.5 seconds. They are considered to be one of the most severe disturbances to the electrical equipments.

### 1.13.2 Voltage sags

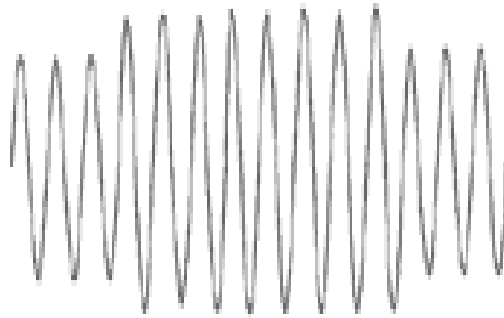
A sag is a period of low voltage with an amplitude ranging from 10%-90% and for a duration of half a cycle to few minutes .It disturbs the equipment performance. Sags occur for many reasons, including voltage drop caused by long runs of wire, switching loads, poor wiring, and overloaded branch circuits.



**Fig. 1.3 Voltage sag**

### 1.13.3 Voltage swells

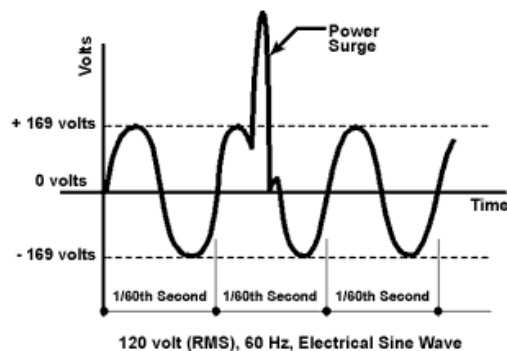
A swell is defined as the period of increase in rms voltage for a duration of 0.5 cycles to one minute. Swells have serious impact on equipment functioning, they are not as common as sags. Both minor and major swells affect equipment performance.



**Fig. 1.4 Voltage swell**

### 1.13.4 Voltage spikes/impulse/surges

An impulse is a short burst of energy that lasts for less than a cycle. Impulses range in magnitude from twice the nominal voltage to several thousand volts. Every impulse does not have an impact on equipment performance. However when impulses occur repeatedly over some time (or when the energy level is very high), an impulse cause equipment degradation or even immediate failure.



**Fig. 1.5 Voltage spike**

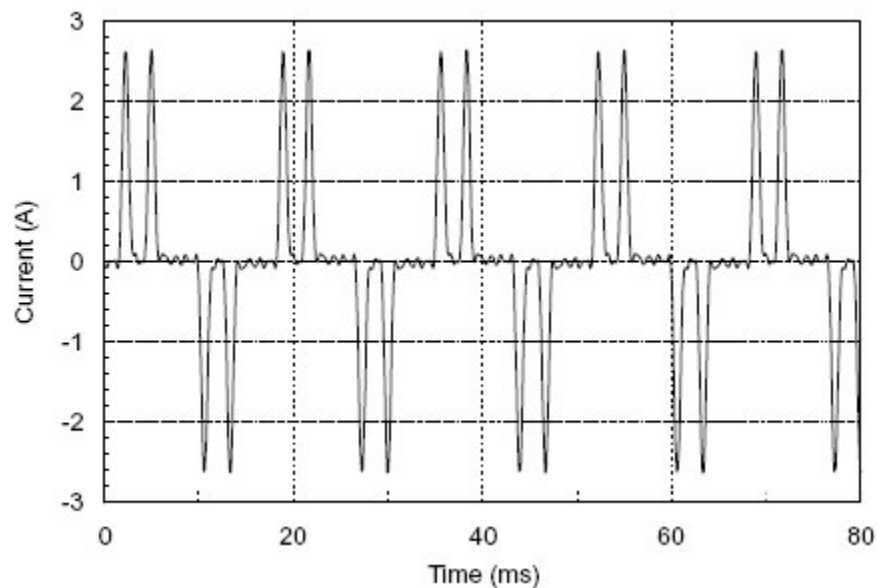
### 1.13.5 Harmonics

AC voltage is a sine wave .In our country fundamental frequency is 50 Hertz. Harmonics are the signals having frequencies with multiples of fundamental frequency that distort the sinusoidal waveform.

Total harmonic distortion (THD) is measured as a percentage of the fundamental frequency. Equipment runs well on voltage that is a pure sine wave. High levels of distortion may cause equipment problems. On single-phase branch circuits, levels of THD greater than 5% to 8% should be investigated.

### 1.13.6 Flickers

Flickers are the visual irritation and introduction of many harmonic components in the supply power and their associated ill effects.



**Fig. 1.6 shows flicker in current output**

### **1.14 Causes of dips, sags and surges:**

1. Rural location remote from power source.
2. Unbalanced load on a three phase system.
3. Switching of heavy loads.
4. Long distance from a distribution transformer with interposed loads.
5. Unreliable grid systems.
6. Equipments not suitable for local supply.

### **1.15 Causes of transients and spikes:**

1. Lightning
2. Arc welding
3. Switching on heavy or reactive equipments such as motors, transformers, motor drives
4. Electric grade switching

### **1.16 Standards Associated with Voltage Sags**

Standards associated with voltage sags are intended to be used as reference documents describing single components and systems in a power system. Both the manufacturers and the buyers use these standards to meet better power quality requirements. Manufacturers develop products meeting the requirements of a standard, and buyers demand from the manufacturers that the product comply with the standard. The most common standards dealing with power quality are the ones issued by IEEE, IEC, CBEMA, and SEMI.

#### **1.16.1 IEEE Standard**

The Technical Committees of the IEEE societies and the Standards Coordinating Committees of IEEE Standards Board develop IEEE standards. The IEEE standards associated with voltage sags are given below [19].

- IEEE 446-1995, “IEEE recommended practice for emergency and standby power systems for industrial and commercial applications range of sensibility loads” The standard discusses the effect of voltage sags on sensitive equipment, motor starting, etc. It shows principles and examples on how systems shall be designed to avoid voltage sags and other power quality problems when backup system operates.
- IEEE 493-1990, “Recommended practice for the design of reliable industrial and commercial power systems”

The standard proposes different techniques to predict voltage sag characteristics, magnitude, duration and frequency. There are mainly three areas of interest for voltage sags. The different areas can be summarized as follows:

- Calculating voltage sag magnitude by calculating voltage drop at critical load with knowledge of the network impedance, fault impedance and location of fault.
- By studying protection equipment and fault clearing time it is possible to estimate the duration of the voltage sag.
- Based on reliable data for the neighborhood and knowledge of the system Parameters an estimation of frequency of occurrence can be made.
- IEEE 1100-1999, “IEEE recommended practice for powering and grounding Electronic equipment”. This standard presents different monitoring criteria for voltage sags and has a chapter explaining the basics of voltage sags. It also explains the background and application of the CBEMA (ITI) curves. It is in some parts very similar to Std. 1159 but not as specific in defining different types of disturbances.
- IEEE 1159-1995, “IEEE recommended practice for monitoring electric power quality”

The purpose of this standard is to describe how to interpret and monitor electromagnetic phenomena properly. It provides unique definitions for each type of disturbance.

IEEE 1250-1995, “IEEE guide for service to equipment sensitive to momentary voltage disturbances”

This standard describes the effect of voltage sags on computers and sensitive equipment using solid-state power conversion. The primary purpose is to help identify potential problems. It also

aims to suggest methods for voltage sag sensitive devices to operate safely during disturbances. It tries to categorize the voltage-related problems that can be fixed by the utility and those which have to be addressed by the user or equipment designer. The second goal is to help designers of equipment to better understand the environment in which their devices will.

## **1.17 ORGANISATION OF THESIS**

The system have been carried out in following manner-

**CHAPTER 1:** In this chapter the introductory concept of power network and its operation is given. Literature survey related to dissertation topic is also given.

**CHAPTER 2:** This chapter presents the concept of voltage stability and reasons for voltage instability.

**CHAPTER 3:** This chapter presents system simulation studies with STATCOM. Simulation results are given and stability analysis has been performed.

**CHAPTER 4:** This chapter presents the problem formulation and results.

**CHAPTER 5:** This chapter presents the conclusion and scope of future work. It describes that how so that system remains in stable region under permissible disturbance.

**REFERENCES:** This section includes books, IEEE journals and IEEE preceding which have been used during work of dissertation.

#### 2.1 Voltage stability

Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the power system under normal operating conditions and after being subjected to a disturbance [3].

#### 2.2 Classification of voltage stability

1. **Large disturbance voltage stability:**

It is concerned with a system's ability to control voltages following large disturbance such as system faults, loss of generation, or circuit contingencies. The ability is determined by system-load characteristics and the interaction of both continuous and discrete control and protections

2. **Small disturbance voltage stability:**

It is concerned with a system's ability to control voltage following small perturbations such as incremental changes in system load. This form of stability is determined by characteristics of load continuous controls, and discrete controls at a given instant of time.

#### 2.3 Improving voltage profile

Voltage support at a load can be achieved by reactive power injection at the load point of common coupling. The common method for voltage support by installing mechanically switched shunt capacitors in the primary terminal of the distribution transformer. The mechanical switching may be done on a schedule, via signals from a SCADA system, with some timing schedule or with no switching at all. The disadvantage with this method is that high speed transients cannot be compensated. Sometimes, particular sag

cannot be corrected due to relatively large timing of mechanical switching devices.  
Transformer taps may be used, but tap changing under load is costly

## 2.4 Power disturbances

Power disturbances are defined in terms of magnitude and duration. Disturbances range from transients that last for microseconds to outages that continue for hours.

Categories	Typical Duration	Typical Voltage Magnitude
2.0 Short Duration Variations		
2.1 Instantaneous		
2.1.1 Sag	0.5 - 30 cycles	0.1 - 0.9 pu
2.1.2 Swell	0.5 - 30 cycles	1.1 - 1.8 pu
2.2 Momentary		
2.2.1 Interruption	0.5 cycles - 3 s	<0.1 pu
2.2.2 Sag	30 cycles - 3 s	0.1 - 0.9 pu
2.2.3 Swell	30 cycles - 3 s	1.1 - 1.4 pu
2.3 Temporary		
2.3.1 Interruption	3 s - 1 min	<0.1 pu
2.3.2 Sag	3 s - 1 min	0.1 - 0.9 pu
2.3.3 Swell	3 s - 1 min	1.1 - 1.2 pu

Table 1 - Categories and Typical Characteristics of Power System Electromagnetic Phenomena

## **2.5 Power flow in ac system**

Due to difficulty in electrical energy storage and very limited storage capacity available the power system generation must meet the demand at all times. This leads to a very difficult and complex control of power system. Electrical power system is self regulating to some extent, if the load increases above the available generation capacity the voltage and frequency goes down.

## **2.6 Voltage instability**

This is a stability phenomenon, where the power system loses its ability to control load bus voltage due to various reasons. This phenomenon can lead to failure of the total or partial power system due to interventions of various control and protection actions.

### **2.6.1 Reasons for voltage instability**

1. Failure to provide necessary power support to the loads as a consequence of power transfer limit. The power transfer limit is determined not only by the bus voltage phase angle, but also by bus voltage magnitude.
2. Failure to meet the reactive power demand of the system.
3. Failure to meet power requirements due to equipments reaching their control and operating limits. Examples are transformer tap limits, generator reactive power supply capabilities.
4. Inconsistency in the load power requirements as function of bus voltage and power supply characteristics.

## **2.7 Methods to improve voltage stability**

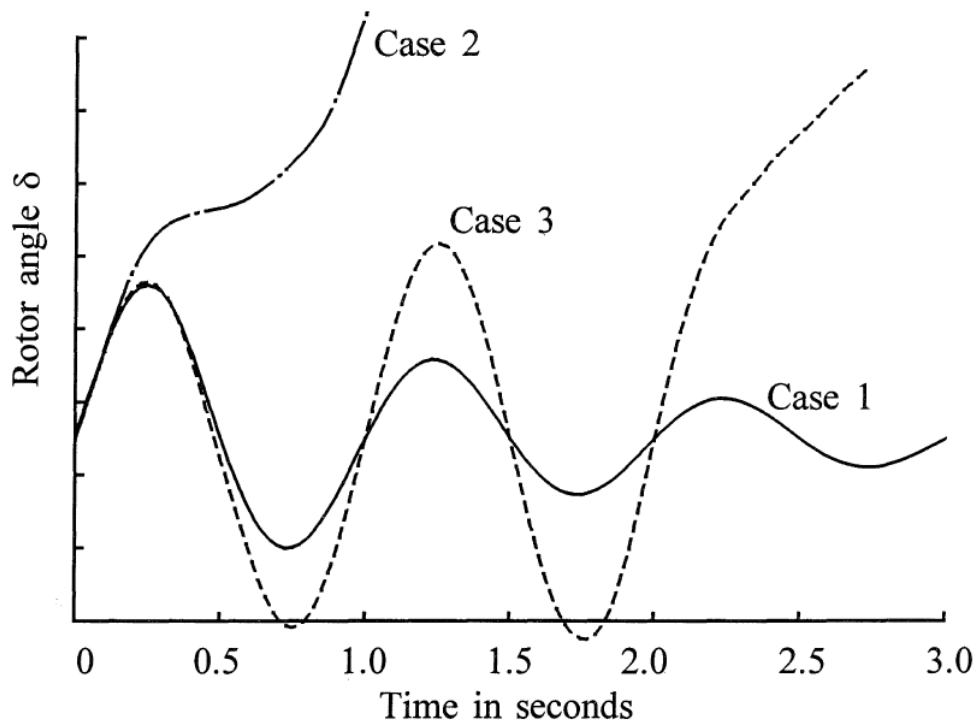
Voltage stability is of two types:

### **1. Steady state stability**

Steady state stability is the ability of the system to maintain synchronism under small disturbances [3]. Such disturbances occur continuously on system because of small variations in load generation. The disturbances are considered sufficiently small for linearization system of equation to be permissible for purpose of analysis.

## 2. Transient state stability

Transient stability is the ability of the power system to maintain synchronism when subjected to severe transient disturbances [3]. The resulting system response involves large excursion of generator rotor angles and is influenced by non linear power angle relationship. Stability depends on both initial operating state of the system and severity of the disturbance. Usually the system is altered so that the post disturbance steady state operation from that prior to the system. Behavior of a synchronous machine for stable and unstable operation is illustrated in the Fig. 2.1.



**Fig. 2.1 Rotor angle response to transient disturbances**

- In case 1, the rotor angle increases to a maximum and then decreases and oscillates with decreasing amplitude until it reaches a steady state.

- In case 2 the rotor continues to increase steadily until synchronism is lost. This type of instability is referred to as first swing instability and is caused by insufficient synchronizing torque.
- In case 3 the system is stable in the first swing but becomes unstable as a result of growing oscillations as the end is approached. This form of instability generally occurs when post fault steady state condition itself is small signal unstable, and this is not necessarily as a result of the transient disturbance.

## **2.8 Factors influencing transient stability**

1. Generator loading.
2. Generator output during fault. This depends on the fault location and type.
3. The fault clearing time.
4. The generator inertia.

## **2.9 Transient stability enhancement**

Methods of improving transient stability are:

1. Reduction in disturbing influence by minimizing the fault severity and duration
2. Increase in restoring synchronizing forces.
3. Reduction of accelerating torque through control of prime mover and mechanical power.
4. Reduction of accelerating torque by applying artificial load.

## **2.10 Power quality improvement approach**

Power quality improvement from the consumer side and from the power utility side:

### **1. Load conditioning**

Consumer side power quality improvement is called load conditioning which ensures that the equipment is less sensitive to power disturbances allowing operation even under significant voltage distortion. In this approach equipment design is done for performing under poor power quality with optimum performance and life.

## 2. Line conditioning

System that suppress or counteracts the power system disturbances, they are connected to low and medium voltage distribution system in series or in shunt these systems are based on PWM converters.

Series active power filters must operate in conjunction with shunt passive filters in order to compensate load current harmonics. Shunt active power filters operate as a controllable current source and series active power filters operates as a controllable voltage source. Both schemes are implemented preferable with voltage source PWM inverters, with a dc bus having a reactive element such as a capacitor. However, with the restructuring of power sector and with shifting trend towards distributed and dispersed generation, the line conditioning systems or utility side solutions will play a major role in improving the inherent supply quality; some of the effective and economic measures can be identified as following:

### 2.10.1 Lightning and Surge Arresters:

Arresters are designed for lightning protection of transformers, but are not sufficiently voltage limiting for protecting sensitive electronic control circuits from voltage surges.

### 2.10.2 Thyristor Based Static Switches:

The static switch is a versatile device for switching a new element into the circuit when the voltage support is needed. It has a dynamic response time of about one cycle. To correct quickly for voltage spikes, sags or interruptions, the static switch can be used to switch one or more devices such as capacitors, filters. Static switches are fast acting and can be used for switching at precise instances due to their inherent fast action due to absence of moving parts

### 2.11 Comparison of various facts devices:

FACTS DEVICE	TYPE OF CONNECTION	FUNCTION
SVC	Shunt	Var compensation, steady

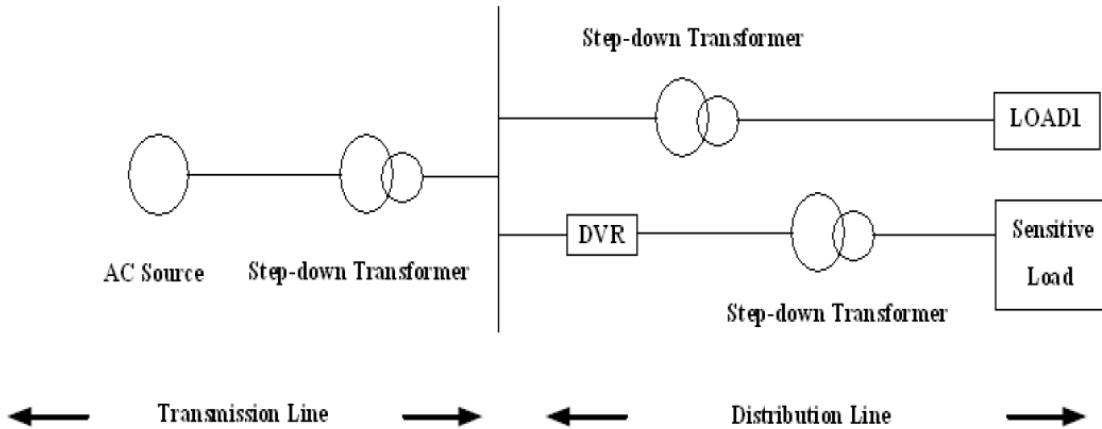
		state and dynamic stability
STATCOM	Shunt	Generating or absorbing the reactive power
SSSC(Static Synchronous Series Compensator)	Series	Controlling transmitted electric power by increasing or decreasing reactive voltage drop
TCSC	Series	Capacitive reactance compensator in continuous manner
UPFC	Two port	Terminal voltage control, phase angle regulation, series line compensation

**TABLE 2 Comparison of fact devices**

## **2.12 Custom Power Devices For Regulating Load side Voltage**

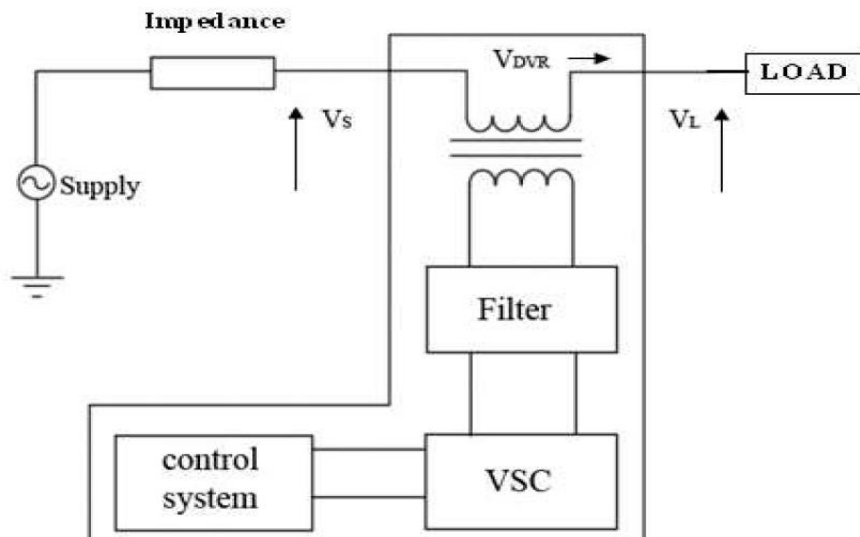
### **2.12.1 Dynamic Voltage Restorer (DVR):**

DVR is a recently proposed series connected solid state device that injects voltage into the system in order to regulate the load side voltage. It is normally installed in a distribution system between the supply and the critical load feeder at the point of common coupling (PCC) [10]. Other than voltage sags and swells compensation, DVR can also added other features like: line voltage harmonics compensation, reduction of transients in voltage and fault current limitations.



**FIG. 2.2 Location of DVR**

The VSC generates a three-phase ac output voltage, which is controllable in phase and magnitude. These voltages are injected into the ac distribution system in order to maintain the load voltage at the desired voltage reference. By injecting voltages of controllable amplitude, phase angle and frequency (harmonic) into the distribution feeder in instantaneous real time via a series injection transformer, the DVR can restore the quality of voltage at its load side terminals when the quality of the source side terminal voltage is significantly out of specification for sensitive load equipment [10]. The reactive power exchanged between the DVR and distribution system is internally generated by the DVR without any ac passive reactive components, i.e. reactors and capacitors. For large variations in the source voltage, the DVR supplies partial power to the load from a rechargeable energy source attached to the DVR dc terminal. The DVR, with its three single phase independent control and inverter design is able to restore line voltage to critical loads during sags caused by unsymmetrical L-G, LL, L-L-G, as well as symmetrical three phase faults on adjacent feeders or disturbances that may originate many miles away on the higher voltage interconnected transmission system. Connection to the distribution network is via three single-phase series transformers thereby allowing the DVR to be applied to all classes of distribution voltages. At the point of connection the DVR, within the limits of its inverter, provide a highly regulated clean output voltage.



**FIG. 2.3 Block diagram of DVR**

### 2.12.1.1 Type of load characteristics

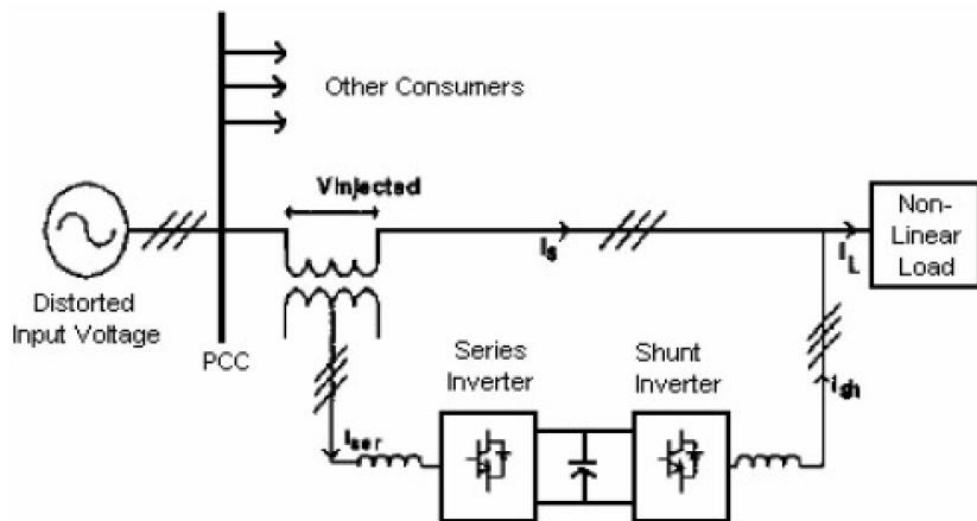
There are four different methods of DVR voltage injection which are:

1. Pre-sag compensation method.
2. In-phase compensation method.
3. In-phase advanced compensation method.
4. Voltage tolerance method with minimum energy injection.

### 2.12.2 Unified Power Quality Conditioner (UPQC):

The Universal Power Quality Conditioner (UPQC) is a more complete solution for the power quality problem. The basic structure of this equipment is shown in shown in Fig 2.4. In this figure, the UPQC is an association of a series and shunt active filter based on two converters with common dc link. The series converter has the function to compensate for the harmonic components present in the source voltages in such a way that the voltage on the load is sinusoidal and balanced [10]. The shunt active filter has the function of eliminating the harmonic components of nonlinear loads in such a way that the source current is sinusoidal and balanced.

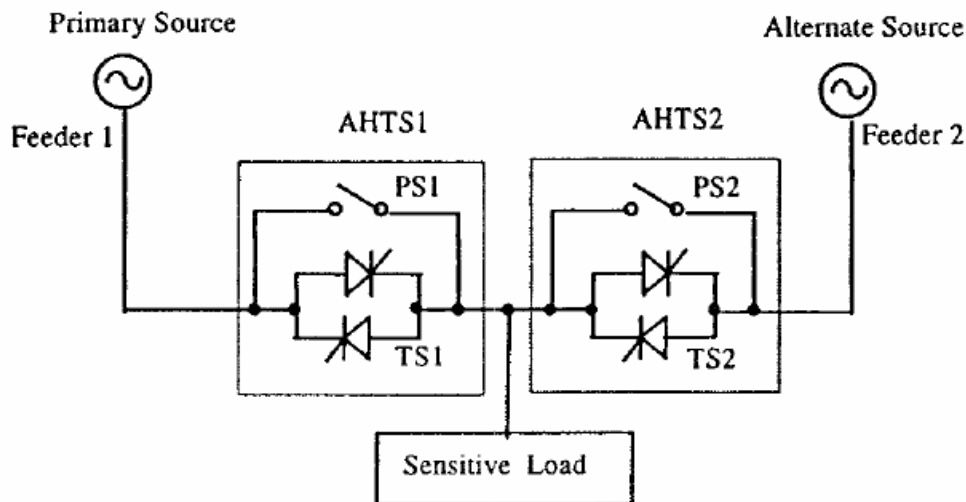
This equipment is a good solution for the case when the voltage source presents distortion and a harmonic sensitive load is close to a nonlinear load.



**FIG. 2.4 Block diagram of UPQC**

### 2.12.3 Solid State Transfer Switch (SSTS):

The SSTS consists of two three-phase static switches, each constituted in turn by two anti - parallel thyristors per phase. Normally, the static switch on the primary source is fired regularly, while the other one is off. In the event of a voltage disturbance, the SSTS [1] is used to transfer the load from the preferred source to an alternative healthy source. This results in a very effective way of mitigating the effects of both interruptions and voltage dips by limiting their duration as seen from load.



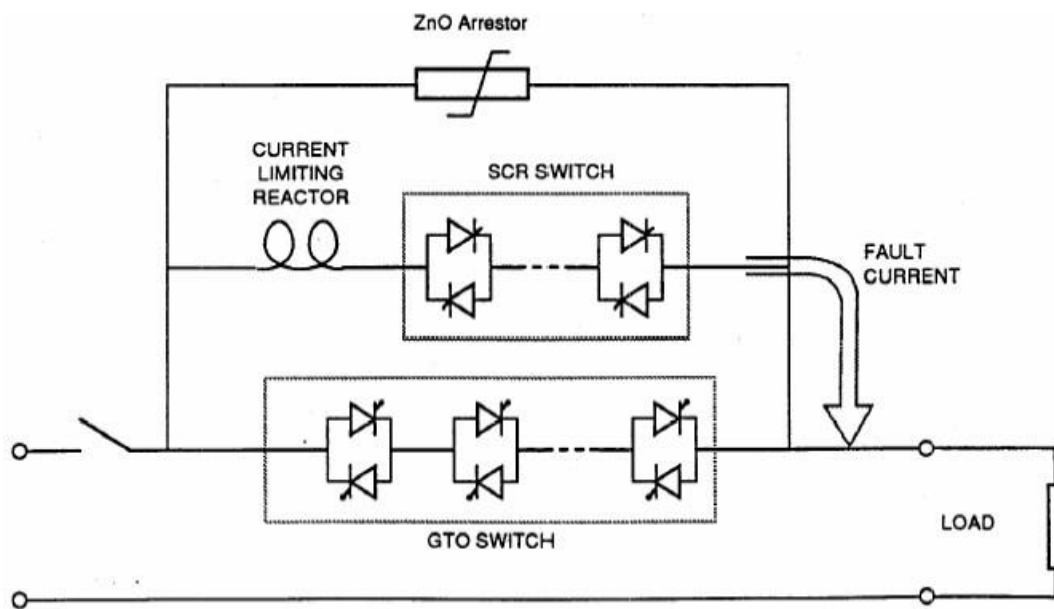
**FIG. 2.5 Block diagram of SSTS**

The SSTS can be used very effectively to protect sensitive loads against voltage sags, swells and other electrical disturbances. The SSTS ensures continuous high-quality power supply to sensitive loads by transferring, within a time scale of milliseconds, the load from a faulted bus to a healthy one. The basic configuration of this device consists of two three-phase solid-state switches, one for the main feeder and one for the backup feeder. These switches have an arrangement of back-to-back connected thyristors, as illustrated in the schematic diagram of Fig 2.5. Each time a fault condition is detected in the main feeder, the control system swaps the firing signals to the thyristors in both switches, i.e., Switch 1 in the main feeder is deactivated and Switch 2 in the backup feeder is activated. The control system measures the peak value of the voltage waveform at every half cycle and checks whether or not it is within a prespecified range. If it is outside limits, an abnormal condition is detected and the firing signals to the thyristors are changed to transfer the load to the healthy feeder.

#### **2.12.4 Solid State Breaker (SSB):**

It offers a solution to several problems originated in distribution systems since it can act as [1]:

1. Transfer switch by transferring sensitive loads from the normal supply that experiences a disturbance to an alternate supply unaffected by the disturbance
2. A substation bus-tie switch that is normally open; a fault on one feeder leads to opening its circuit breaker, the bus-tie switch will close to serve the loads from other feeder as soon as the faulty feeder is separated from loads
3. A current limiter that conducts inrush and fault currents for several cycles.

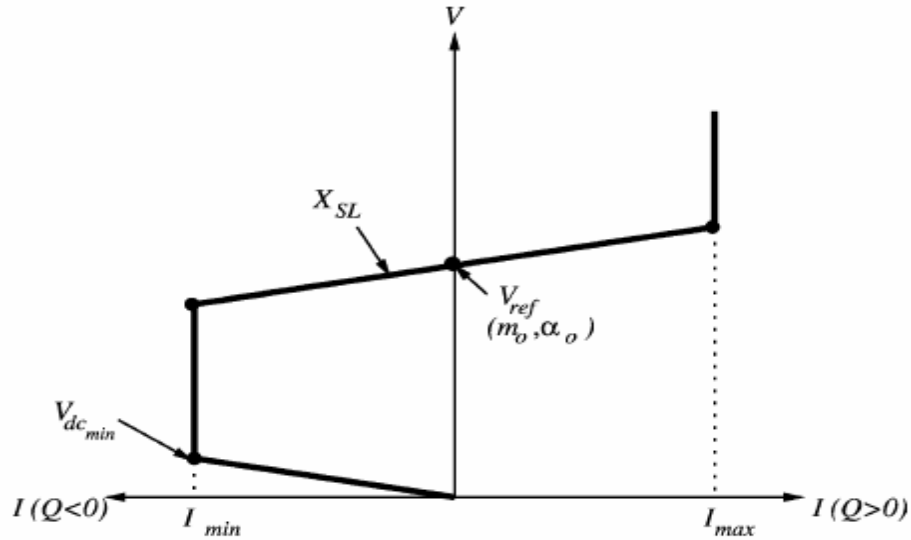


**FIG. 2.6 Block diagram of SSB**

Fig. 2.6 Shows a schematic diagram of a SSB acting as a fault current limiter (FCL), constructed from a number of antiparallel GTO modules; in normal operation GTO elements are closed, under abnormal condition the breaker detects the rise of both the steady state current and the rate of current change,  $di/dt$ , and opens rapidly. The SSB in its present form is not likely to replace the conventional circuit breaker. However it has a number of applications where, used in place of a circuit breaker could provide uninterrupted power by providing rapid transfer to a secondary feeder or limit reactive inrush currents by pulse width modulating the current

## 2.13 STATCOM

Static synchronous compensator/static synchronous condenser is a regulating device used in power system for ac transmission. It is based on voltage source converter based device it acts both as a sink and source of reactive power depending on the requirement of the system requirements.



**Fig. 2.7 V-I Characteristics of STATCOM**

Electrical loads both generate and absorb reactive power. Since the transmitted load often varies considerably from one hour to another, the reactive power balance in a grid varies as well. The result can be unacceptable voltage amplitude variations, a voltage depression, or even a voltage collapse.

STATCOM can provide instantaneous and continuously variable reactive power in response to grid voltage transients, enhancing the grid voltage stability. The STATCOM operates according to voltage source principles and PWM switching of IGBTs (Insulated Gate Bipolar Transistors) rating and response speed. Active harmonic filtering and voltage flicker mitigation.

### 2.13.1 STATCOM Installation

Installing a STATCOM at one or more suitable points in the network will increase the grid transfer capability through enhanced voltage stability, while maintaining a smooth voltage profile under different network conditions. The STATCOM provides additional versatility in terms of power quality improvement capabilities

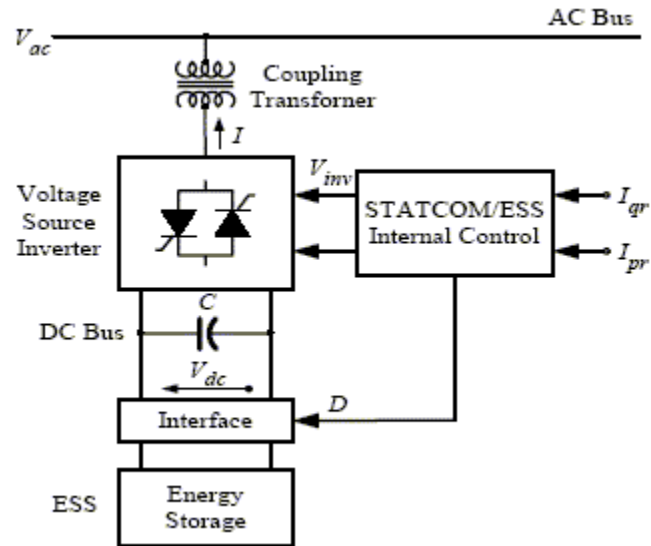


Fig. 2.8

### 2.13.2 STATCOM features

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

### 2.13.3 STATCOM different modes of operation

Fig 2.9 is showing different modes of operation of STATCOM

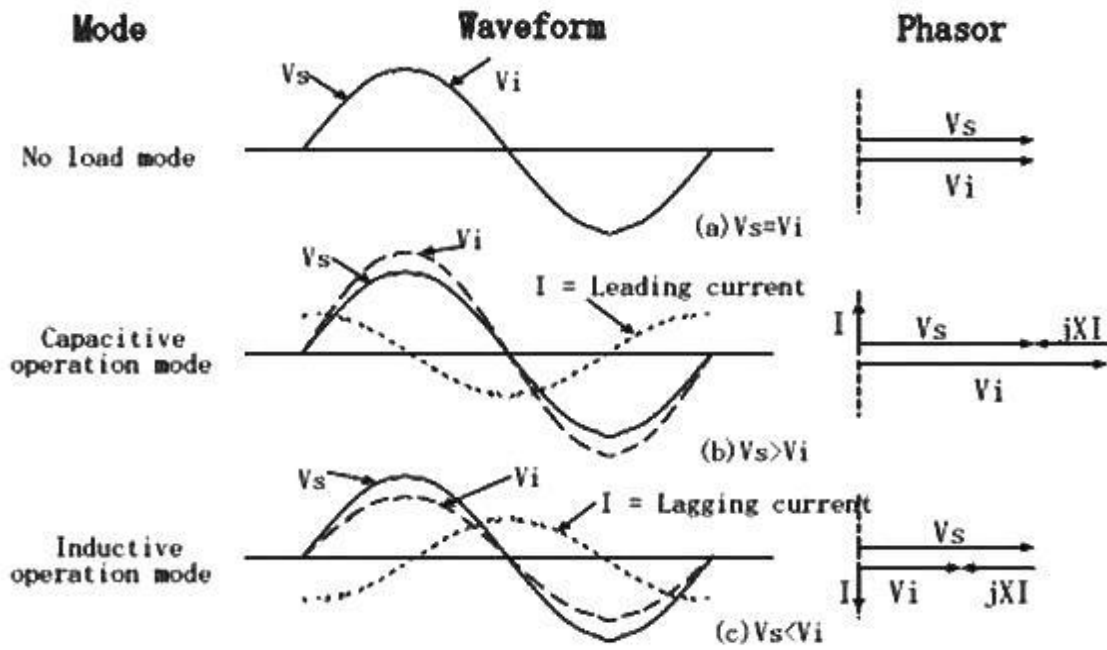


Fig. 2.9 Showing different operating modes of STATCOM

## Chapter 3

### Literature review

Fouad, A.A., *et al.*, [4] discussed direct methods of transient stability analysis of a multi machine power system, using a function describing the system's transient energy. Fouad examined the trajectory of the disturbed system and dealt with the following questions: concept of a controlling unstable equilibrium point, the manner in which some generators tend to lose synchronism, and identifying- the energy directly responsible for system separation. Fouad stated that by resolving these issues the transient stability analysis by a direct method will substantially improve.

Kannan, P., *et al.*, [5] dealt with voltage sag compensation of 30 bus system using UPFC. The UPFC is a pair of back to back power electronic inverters which control the real and reactive power flow in a transmission line. Modeling and simulation of IEEE 30 bus system was done with and without UPFC. Digital simulation using MATLAB/SIMULINK was done with these models and the results were presented. The effect of UPFC on the profile of real power, reactive power and the voltage was presented.

Kazemi, et al., [6] discussed that one of the major causes of voltage instability is the reactive power limit of the system. Improving the system's reactive power handling capacity via Flexible AC transmission System (FACTS) devices is a remedy for prevention of voltage instability and hence voltage collapse. In this paper, the effects of two FACTS controllers, STATCOM and UPFC, on voltage stability are studied. Continuation Power Flow (CPF), with accurate model of these controllers, is used for this study. Applying saddle node bifurcation theory with the use of Power System Analysis Toolbox (PSAT), the optimal location of these controllers is determined. The study has been carried out on the 6-bus and IEEE 14-Bus Test Systems and results are presented

Abido, M.A. [7] discussed about the substantial rise in power demand in recent years, 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. This paper presents a comprehensive review on the research and developments in the power system stability

enhancement using FACTS damping controllers. Several technical issues related to FACTS installations have been highlighted and performance comparison of different FACTS controllers has been discussed. In addition, some of the utility experience, real-world installations, and semiconductor technology development have been reviewed and summarized. Applications of FACTS to other power system studies have also been discussed.

Masood, T. [8] discussed about investigating the behavior of STATCOM against SVC controller by setting up new control parameters. STATCOM and SVC linear operating ranges of the V-I and V-Q as well as their functional compensation capabilities have been addressed to meet operational requirement with certain degree of sustainability and reliability. The other operating parameters like transient stability, response time, capability to exchange real Power and Power losses have also been addressed in STATCOM against SVC control models. In addition to that, STATCOM-Controller's pragmatic response had been identified and determined reliability level to maintain full capacitive output current at low system voltage. Masood stated that STATCOM device has more effectiveness than the SVC in improving transient stability.

Shayanfar, H.A., et al., [9] in this paper Shayanfar proposed application of STATCOM to extend steady-state voltage stability margin in electric power systems. A systematic analytical methodology based on the concept of modal analysis of modified load flow was used to determine the most effective locations for placement of STATCOM. Influence of STATCOM is illustrated using an optimal power flow based on Quadratic Programming with OPF to improve voltage stability. A computer program was developed and applied to the 14-bus to demonstrate the effect of STATCOM and OPF on voltage stability. Shayanfar stated that the incorporation both of STATCOM and OPF improved static voltage stability and loadability of the system.

GYUGYI, L [11] discussed dynamic var compensation of electric power systems, applying power electronics for reactive power generation and control. Gyugyi explained the emergence and status of modern, solid-state var compensators in utility and industrial applications, and explained how dynamic var compensation increases transmittable power by providing voltage support, transient stability improvement, and power oscillation damping in electric power transmission systems. Subsequent he described the methods of reactive power generation and

control using thyristor-controlled reactors, with fixed and thyristor-switched capacitors, or modern gate turn-off (GTO) power converters that can function without ac capacitors or reactors.

Haque, M.H. [12] discussed a simple method of evaluating the first swing stability of a large power system in the presence of various flexible ac transmission system (FACTS) devices. First a UPFC and the associated transmission line were considered and represented by an equivalent circuit model. The above model was then carefully interfaced to the power network to obtain the system reduced admittance matrix which was needed to generate the machine swing curves. The complex voltage at two end buses of the circuit model was also evaluated during simulation to implement various existing control strategies of FACTS devices and to update the reduced admittance matrix. He tested the effectiveness of the proposed method of generating dynamic response and hence evaluated first swing stability of a power system in the presence of various FACTS devices on the ten-machine New England system and the 20-machine IEEE test system.

Haque, M.H. [13] discussed that the FACTS devices are now recognized as a viable solution for controlling transmission voltage, power flow, dynamic response, etc. and represent a new era for transmission systems. Haque proved that the centre 01- midpoint of a transmission line is the optimal location for shunt FACTS devices or reactive power support and the proof is based on the simplified line model. The validity of the above optimal location of shunt FACTS devices was investigated. It was found that the FACTS device needs to be placed slightly off-centre to get the highest possible benefit. He stated that both the power transfer capability and stability of the system can further be improved if the shunt FACTS device is placed at the new optimal point instead of at the midpoint of a line having some resistance.

Wolanski, Z., et al., [14] discussed many controllers of FACTS, such as the STATCOM, the UPFC, the PWM asynchronous dc link, the Thyristor-Controlled Series Capacitor (TCSC) and the PWM Series Static VAR compensator have stabilized ac voltage support. Thus, they can be sited at the mid-point of the transmission line, which has been proven by the late E.W. Kimbark, as the optimum location for shunt capacitor compensation. This paper points out that the ability to double the power transfer of the uncompensated line applies also to the aforementioned FACTS devices. The mid-point siting also facilitates the independent control of reactive power at both ends of the transmission line.

Kamarposhti et al [15] discussed about determining maximum loading margins. It is an important issue in power system operation, as system operators must take proper preventive actions to avoid stability problem. A study of parallel FACTS devices and series FACTS devices on steady-state voltage and power stability is presented. Their steady state modeling and effects on power system performance have been studied. It also studies static stability improvement of the power system and hence power flow improvement in the network. Effects of FACTS on system loadability have been discussed and presented. A method based on the concept of maximum loading point index has been used to compare FACTS devices. The study has been carried out on the IEEE 14 bus test system. The line power transfer capability and loadability of the system and therefore, the stability of the system is increased. It has also been observed that for the improvement of these parameters, the parallel FACTS devices are more adequate than the series FACTS devices.

Buch et al., [16] discussed that one of the major aims of system operator is to maintain system parameters within feasible operational margin. During certain period of time in a day-load changes very rapidly, especially when it tends to increase, a generalized voltage decrement and stressed conditions for reactive power sources occurs. Maintaining Voltage profile under varying load conditions is need of today under unpredictable load scenario. The work embedded highlights expediency of STATCOM for improving voltage profile of power system under perturbations while providing necessary reactive power support.

Mithulananthan, Nadarajah et al., [17] in this paper compared the shunt capacitor, SVC and STATCOM in static voltage stability improvement. Various performance measures were compared under different operating system conditions for the IEEE 14 bus test system. Important issues related to shunt compensation, namely sizing and installation location, for exclusive load margin improvement were addressed. A methodology to alleviate voltage control problems due to shunt capacitor compensation during lightly and heavily loaded conditions was also proposed.

Sode-Yome et al., [18] In this paper, voltage stability assessment with appropriate representations of STATCOM, TCSC and SSSC is investigated and compared in the modified IEEE 14-bus test system. AC and DC representations of STATCOM, TCSC and SSSC are used in the continuation power flow process in static voltage stability study. The appropriate

representation provides more practical solutions in the dc parts of these devices. Static voltage stability margin enhancement using STATCOM, TCSC and SSSC is compared in the modified IEEE 14-bus test system.

Alves, M.F., et al., discussed that the establishment of standards and guidelines to cope with power quality issues has become evident. Among these, voltage sags are the most important cause of interruption of industrial processes. Sag is heavily dependent on the supply systems configuration, process equipment design, systems switching and protection practices, among others. In this environment the development and the proper use of standards to regulate costumers, equipment manufacturers and utilities relations regarding sags issues is a most important question. Alves discussed on the IEEE and IEC Power Quality related Standards, and their applicability to voltage sag evaluation in a industrial or commercial system, utility system, and to equipment.

### Problem formulation and results

#### 4.1 Two machine model

In power system the generation is mostly done by synchronous machines and such systems work in synchronism for power flow from one area to another, so a two machine model is taken with different power ratings and different loads connected with them. Both machines are connected with a long transmission line.

#### 4.2 Power transfer characteristics of two machine system

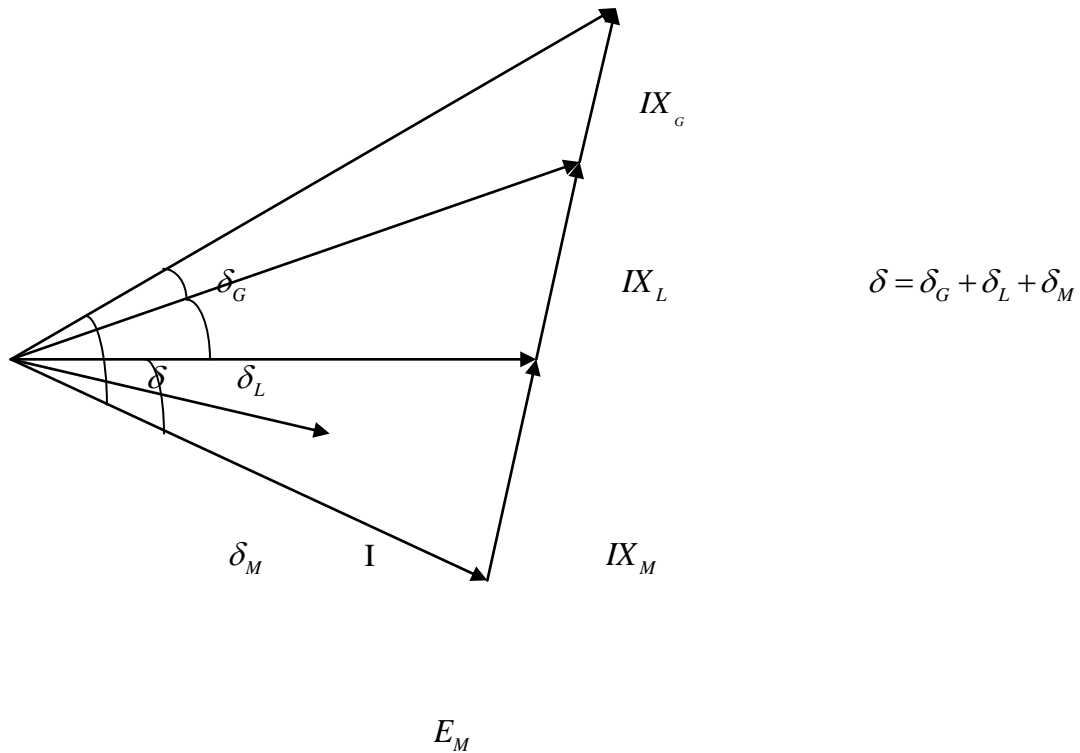
Consider a two machine system with one motor and other generator. Power transfer from generator to motor is a function of angular separation ( $\delta$ ) between the rotor of two machines. This angular separation is due to three components generator internal angle ( $\delta_G$ ), angular difference between terminals of generator and motor and the internal angle of motor.

Power transfer from generator to motor is given by

$$P = \frac{E_g E_m}{X_t} \dots\dots\dots \text{Eq. no. 1}$$

Where,

$$X_t = X_G + X_L + X_M \dots\dots\dots \text{Eq. no. 2}$$



**Fig. 4.1 Phasor diagram**

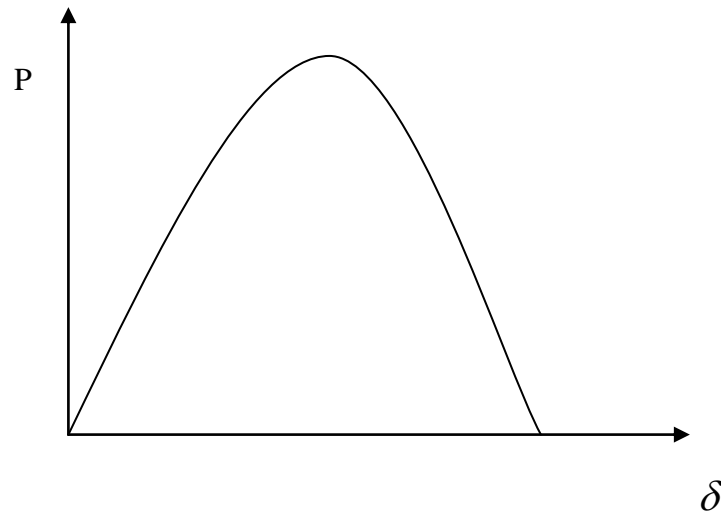
### 4.3 Rotor angle stability

Rotor angle stability is the stability of interconnected machines of a power system to remain in synchronism. The stability problem involves the study of electromechanical oscillations inherited in power systems. A fundamental factor is the manner in which the power outputs of synchronous machines vary as their rotors oscillate.

When two or more synchronous machines are interconnected, the stator voltages and currents of all voltages of all machines must have the same frequency and the rotor mechanical speed of each is synchronized to this frequency. Therefore, the rotors of all synchronous interconnected machines must be in synchronism [3].

#### 4.4 Power versus angle relationship

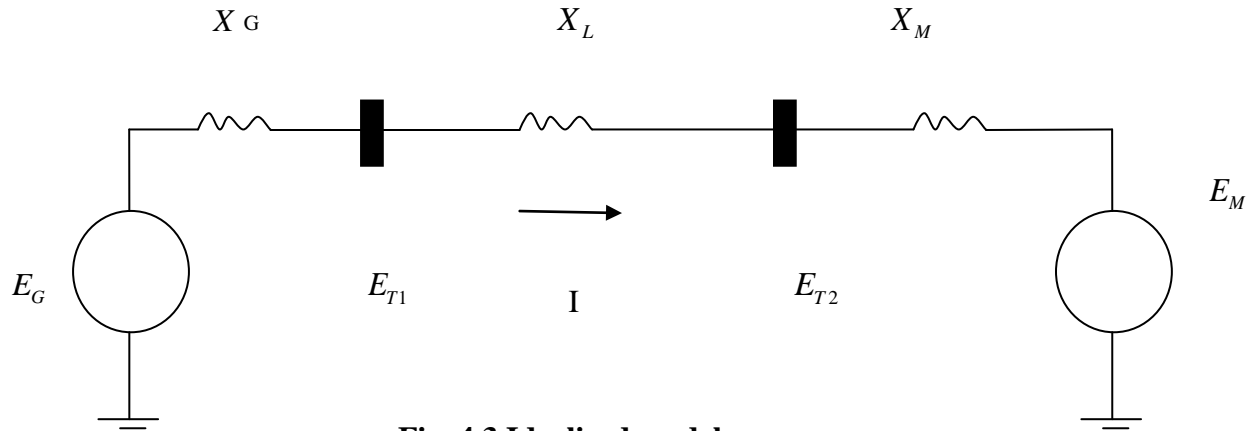
Power versus angle relationship is very important it is the relationship between interchange power and angular positions of rotor of synchronous machine. This relationship is highly non linear. The power transfer from generator to motor is a function of angular separation between rotors of two machines [3].



**Fig. 4.2 Power transfer characteristics of a two machine model**

#### 4.5 Idealized model of two machine system

Idealized model of two machine system transmission line is represented by reactance's of generator, line, and motor.



**Fig. 4.3 Idealized model**

### 4.6 Two area system with shunt FACTS device

A two area system is considered with (area 1 & area 2). These two areas are connected by a single circuit long transmission line as shown in Fig 3. The direction of real power flow is from area 1 to area 2 as the load taken on area 2 is large compared to area one and also the power generation of area two is less than that of area one. For placing the STATCOM in the system to improve the system performance the transmission line is divided in two sections (section 1 and section 2) and 's' is taken as the fraction of line length at which the STATCOM is placed.

For a long transmission line of length \$l\$, having a series impedance of \$z\$ ohm/km and shunt admittance of \$y\$ mho/km, the relationship between the sending-end and receiving-end quantities with A, B, C, D constants of the line can be written as:

$$V_S = AV_R + BI_R \quad \dots\dots\dots \text{Eq. no. 3}$$

$$I_S = CV_R + DI_R \quad \dots\dots\dots \text{Eq. no. 4}$$

Where

$$A = |A| \angle \theta_A$$

$$B = |B| \angle \theta_B$$

$$V_R = |V_R| \angle 0$$

$$V_S = |V_S| \angle \delta$$

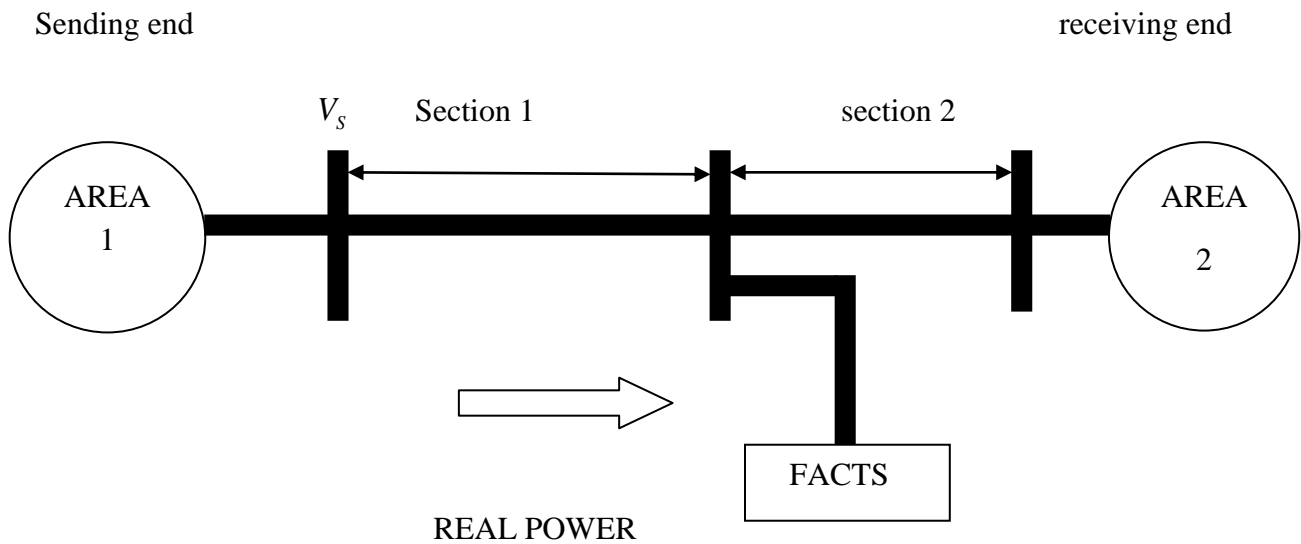
For the simplified model where line resistance and capacitance are neglected, both sending end power ( $V_S$ ) and receiving end power ( $V_R$ ) becomes maximum at power angle  $\delta = 90$ . When a shunt FACTS device is connected to a long line to increase the power transfer capability, the above simplification may provide erroneous results.

The active power flow at the sending end and receiving end for a long transmission line with distributed parameters can be written as

$$P_S = K_1 \cos(\theta_B - \theta_A) - K_2 \cos(\theta_B + \delta) \dots\dots\dots 5$$

$$P_R = K_2 \cos(\theta_B - \delta) - K_3 \cos(\theta_B - \theta_A) \dots\dots\dots 6$$

The shape of the power angle curve depends on the line length or fraction 's'. s is the ratio of section 1 and with section 2 of the transmission line. For lower values of s, the maximum receiving end power of section 1 increases, while the maximum sending end power of section 2 decreases.



**Fig. 4.4 Two area system with shunt FACTS devices**

## **4.7 Location of FACT devices**

Due to recent development of power electronics introduces the use of FACTS devices in power systems. The network conditions can be controlled in a very fast manner using FACTS devices and this unique feature of FACTS devices can be exploited to improve the transient stability of a system. Reactive power compensation is an important issue in electrical power systems and shunt FACTS devices play an important role in controlling the reactive power flow to the power network and hence the system voltage fluctuations and transient stability [10]. SVC and STATCOM are members of FACTS family that are connected in shunt with the system. Even though the primary purpose of shunt FACTS devices is to support bus voltage by injecting or absorbing reactive power, they are also capable of improving the transient stability by increasing or decreasing the power transfer capability when the machine angle increases or decreases, which is achieved by operating the shunt FACTS devices in capacitive (inductive) mode [11].

Previous works on the topic prove that shunt FACTS devices give maximum benefit from their stabilized voltage support when sited at the mid-point of the transmission line [14]. The proof of maximum increase in power transfer capability is based on the simplified model of the line neglecting line resistance and capacitance. However, for long transmission lines, when the actual model of the line is considered, the results may deviate significantly from those found for the simplified model [12].

## **4.8 Problem formulation**

Due to increase in load demand caused by rapid industries growth, power utilities are facing many challenges. One of the problems in power system is voltage instability. Power system does not have ability to meet reactive power demand. Shunt devices are connected in power system for improving transient stability performance of the system. This thesis will present the two machine model which is used to simulate the performance of STATCOM installed at a location and then the performance of STATCOM is observed in two machine model at different locations with different loading conditions.

## **4.9 Simulation study**

Simulation study of a two machine system is performed with a three phase fault and STATCOM for improving transient stability. The direction of real power flow is known and STATCOM control the reactive power flow to the power network and hence control both the system voltage fluctuations and transient stability of the system. The two machines are synchronous generators with hydraulic generation. In the system excitation system and hydraulic turbine and governor are present for simulating hydraulic generation. Power system stabilizer is also used.

### 4.10 Simulink model

This simulink model is formed by blocks from Simpower systems of simulink library in MATLAB.

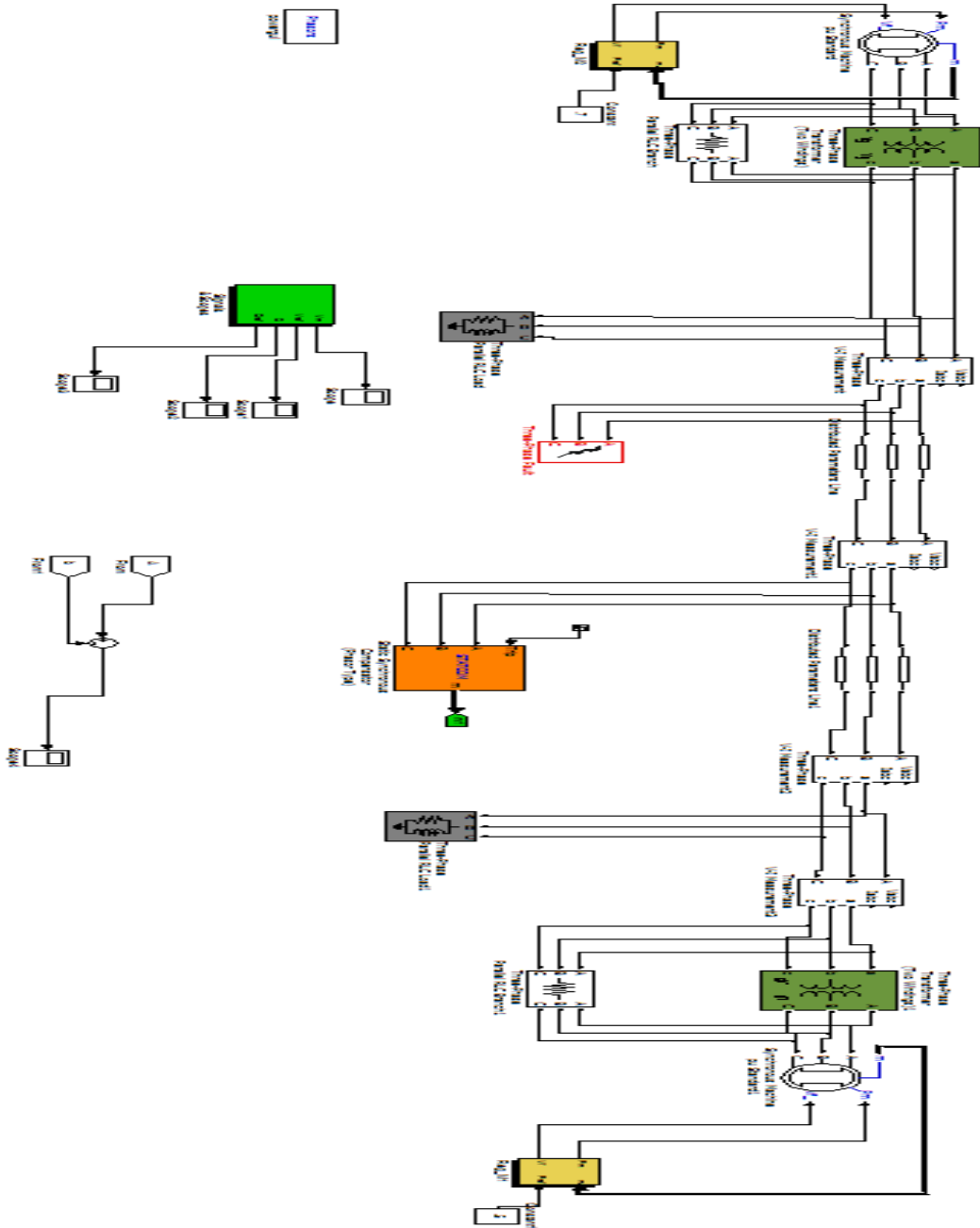


Fig. 4.5 Simulink model of two machine system

## 4.11 Results

### 4.11.1 Case 1

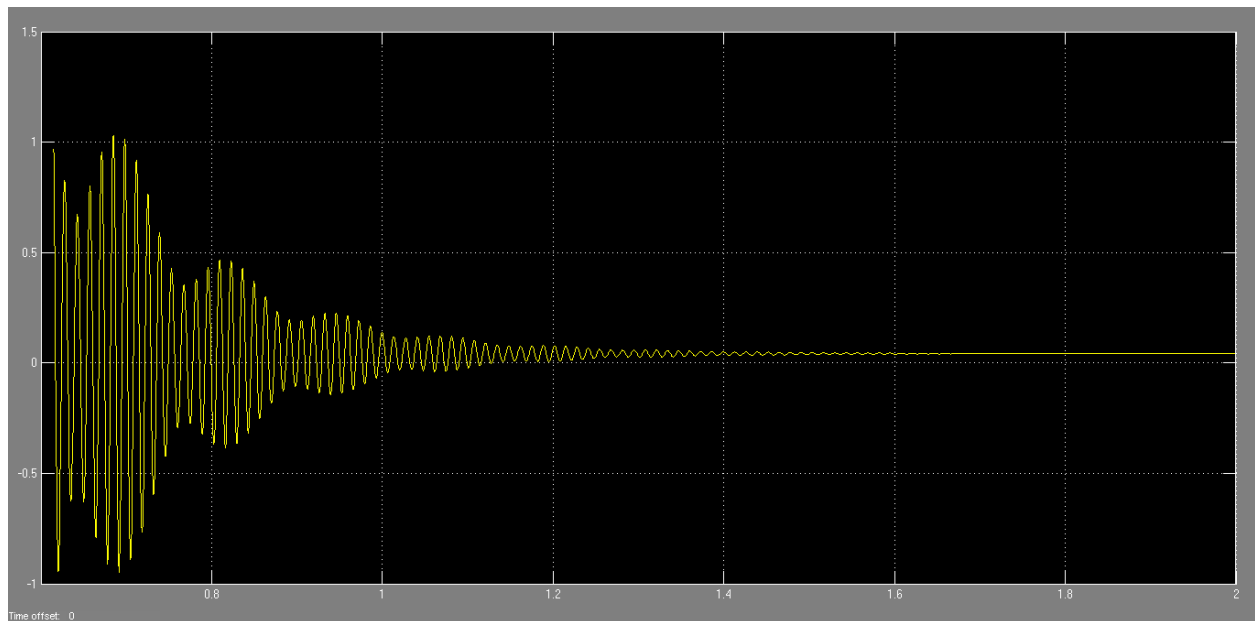
For load values of:

100MW and 200 MVAR at sending end and

1400 MW and 500 MVAR at receiving end

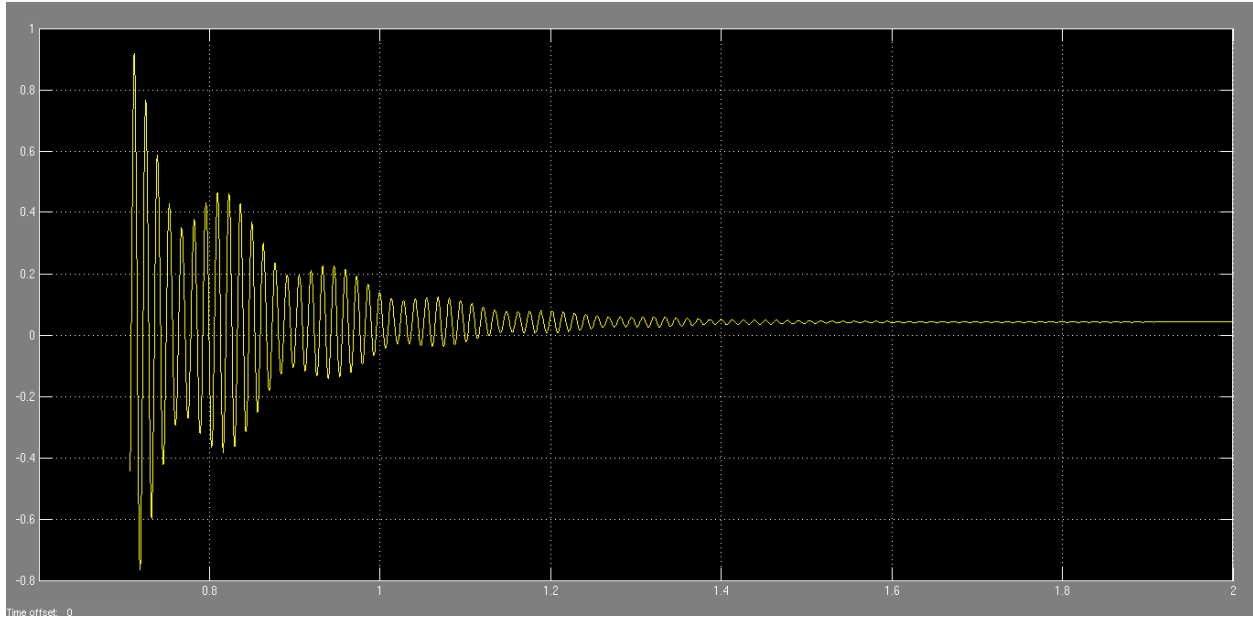
Output graph plot of load angle difference of two machines is given as:

#### 1. At $s=0.428$



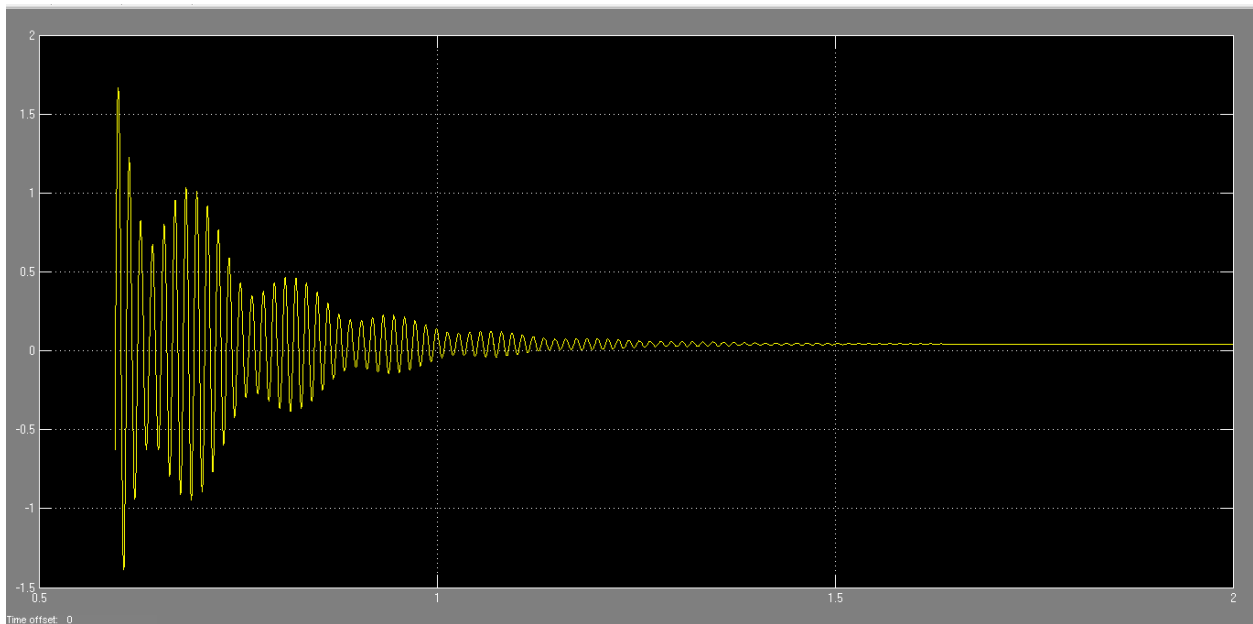
**Fig. 4.6 Plot of load angle difference of two machines**

## 2. At $s=1$



**Fig. 4.7 Plot of load angle difference of two machines**

## 3. At $s= 2.33$



**Fig. 4.8 Plot of load angle difference of two machines**

### 4.11.2 Case 2

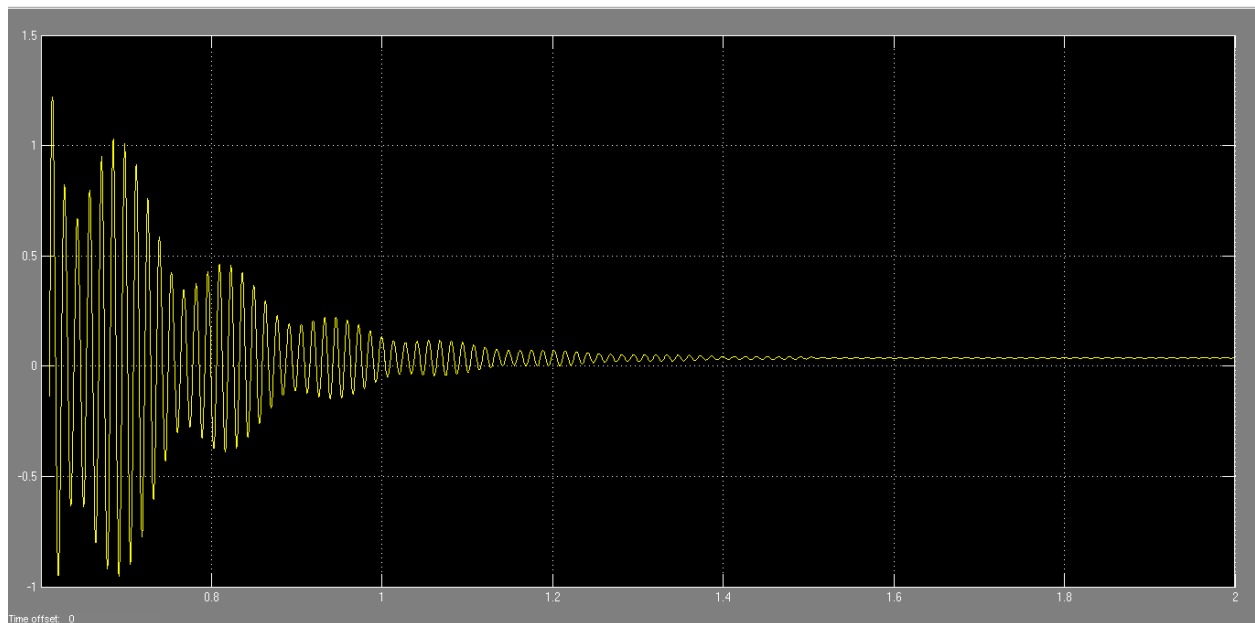
For load values of:

175MW and 200 MVAR at sending end and

1300 MW and 500 MVAR at receiving end

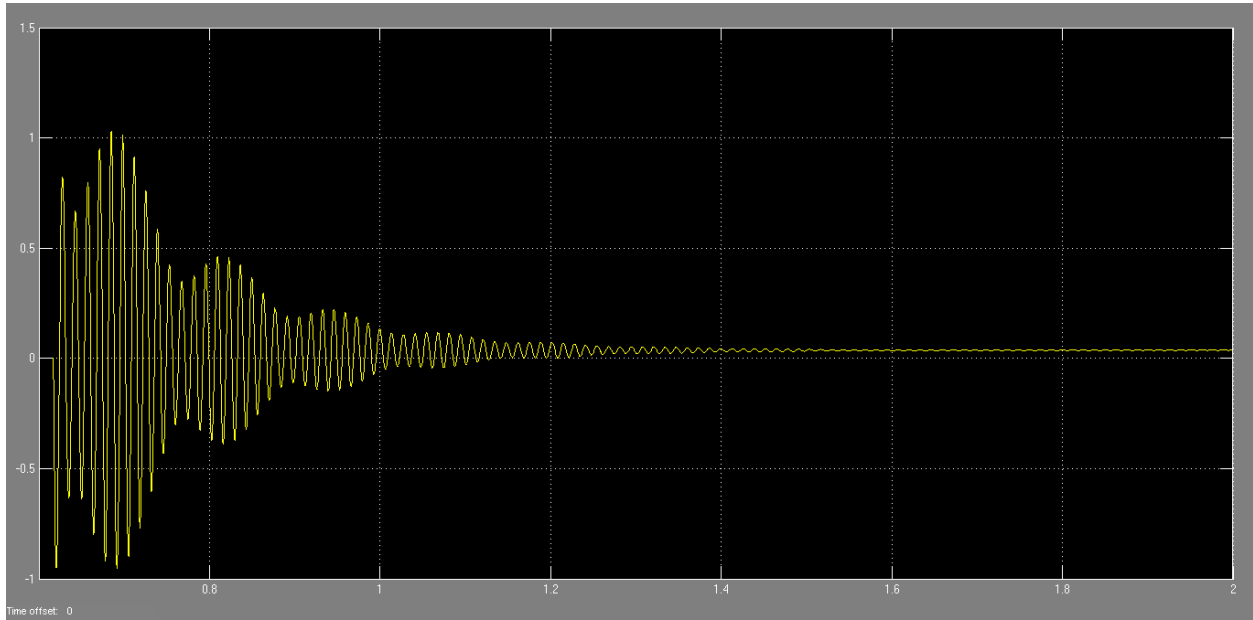
Output graph plot of load angle difference of two machines is given as

#### 1. At $s=0.428$



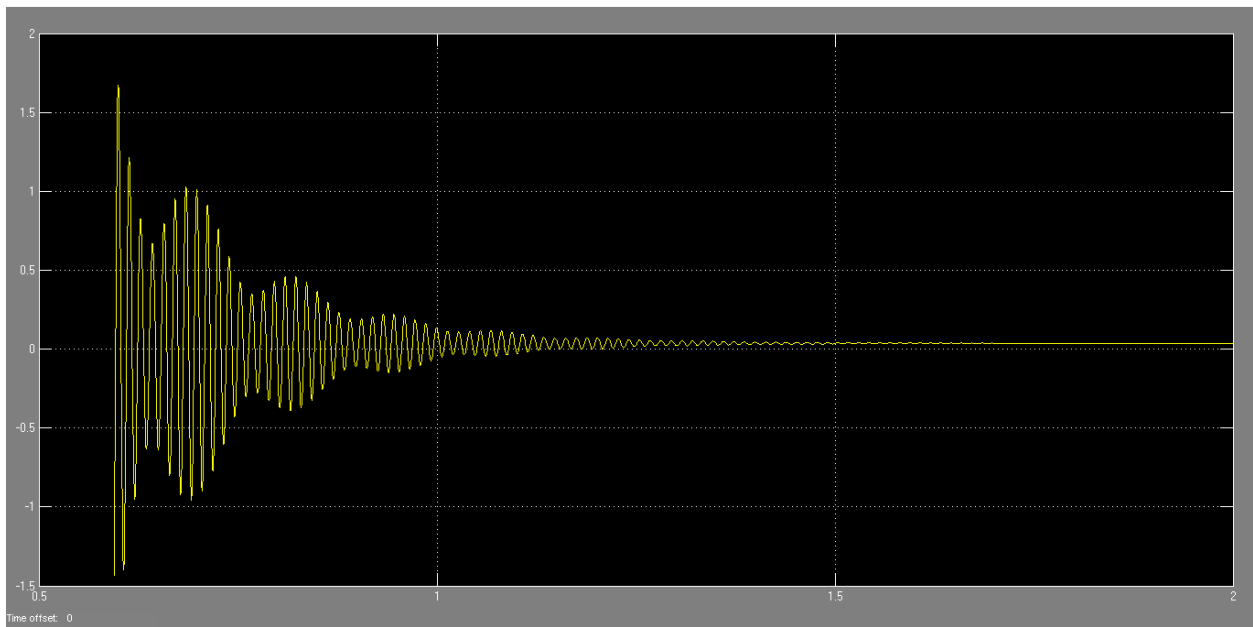
**Fig 4.9 Plot of load angle difference of two machines**

**2. At  $s=1$**



**Fig. 4.10 Plot of load angle difference of two machines**

**3. At  $s=2.33$**



**Fig. 4.11 Plot of load angle difference of two machines**

### 4.11.3 Case 3

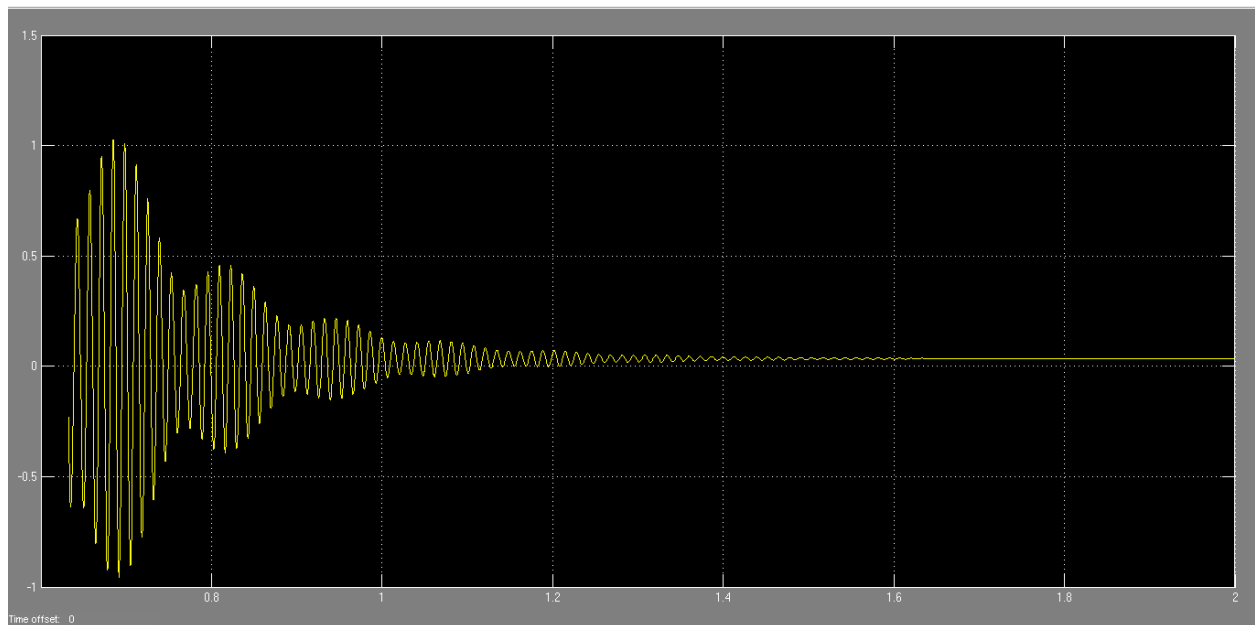
For load values of:

250MW and 200 MVAR at sending end and

1200 MW and 500 MVAR at receiving end

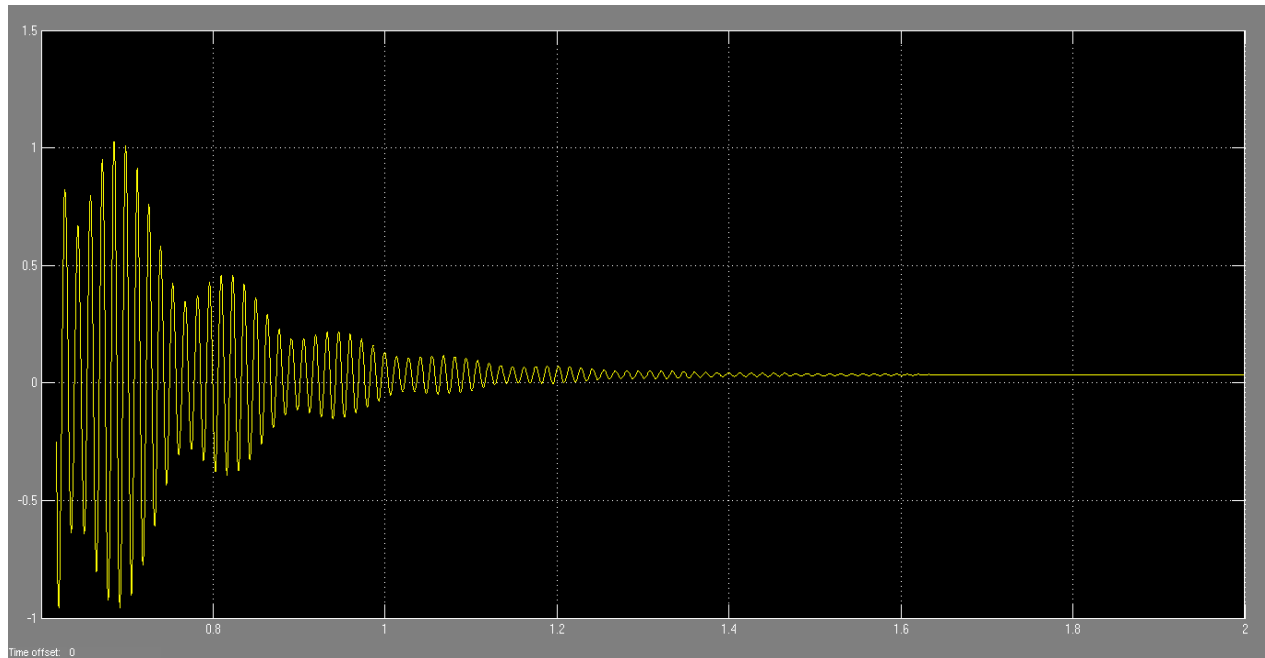
Output graph plot of load angle difference of two machines is given as

#### 1. At $s=.428$



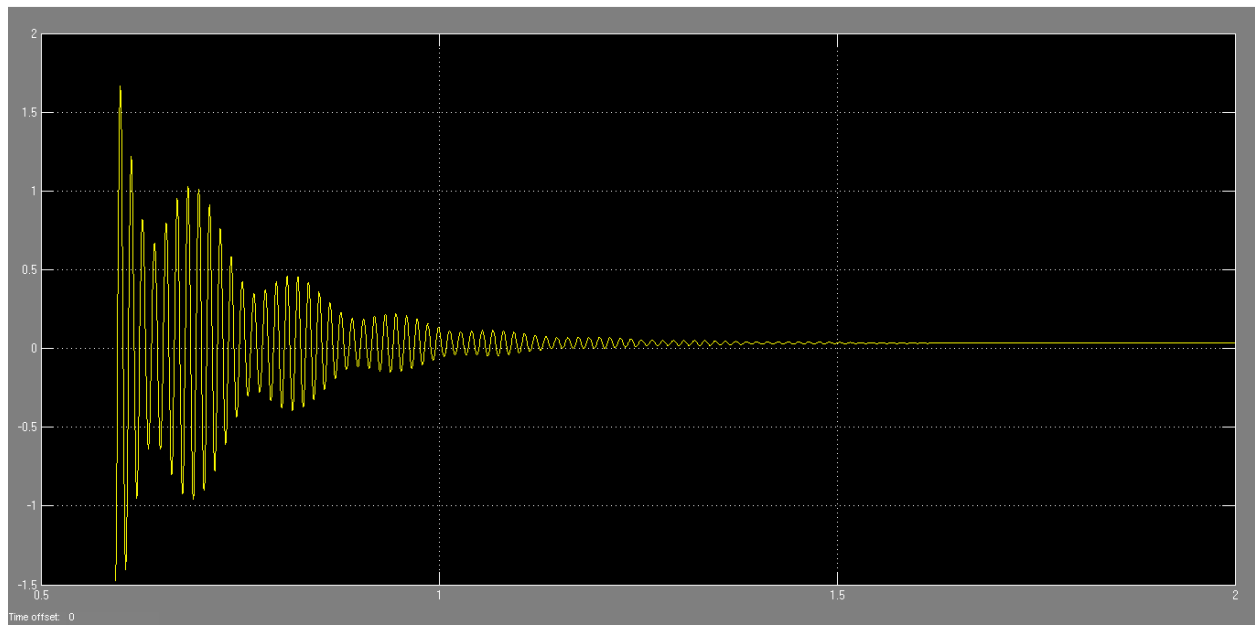
**Fig. 4.12 Plot of load angle difference of two machines**

**2. At  $s=1$**



**Fig. 4.13 Plot of load angle difference of two machines**

**3. At  $s=2.33$**



**Fig. 4.14 Plot of load angle difference of two machines**

On through analysis of the graph plot of load angle difference of two generators the optimal location of STATCOM is known and it can be concluded that the performance of STATCOM depends on the amount of loads connected at two ends and when the direction of power transfer is known. The optimal location for placing STATCOM is near the sending end of the power system and also STATCOM connected at mid point does not necessarily provide optimal performance for transients stability of the system. For different values of  $s$ , it is concluded that the positioning of STATCOM near to the sending end is giving better stability. From the analysis of graph plots for various cases for simulating the two machine model of power system with hydraulic turbine it can be said that the optimal location of STATCOM in a power system change with variation in sending and receiving end loads.

### Conclusion and future scope

#### 5.1 Conclusion

With the expansion of power system, along with restructuring on some countries the complexity of system is increasing continuously. Requirement of good power quality and additional load by consumers makes the compensation devices a necessity in modern power system. These device add to the complexity and expenses of power system. Due to this analysis of power system with these devices has become a priority topic for discussion. In this thesis, a two machine model has been used to simulate power system transient stability behavior. Two machines used are synchronous generators with hydraulic turbine and loads connected at both ends for simulating the system transient stability for three phase fault with STATCOM connected. We were able to simulate the system with different load values at both ends and the system is simulated with STATCOM at different location. Optimal location for placing STATCOM for different set of loads is found by simulating the system for different set of loads. The simulation results analysis has been done from the plot of load angle difference of synchronous generators and from this analysis it has been concluded that the optimal location for placing STATCOM vary according to loads connected at both ends. The effectiveness of the STATCOM in mitigating the transients for a set of loads connected at two ends of the system depends on its location in the system as well as on the load changes.

#### 5.2 Scope of Future Work

The scope of future work after simulating this system is identified as

1. Different FACTS devices such as UPFC, SVC, SSC can be simulated for the given system.
2. The problem could be extended with complex system having multiple machines connected.
3. Application of STATCOM could be applied to a deregulated system facing congestion on a distributed network.

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## Appendix

**Table 1**

Synchronous Generator 1 data

Generators	Values
$M_1$	1400MVA
$X_d$	1.305pu
$X_d'$	0.296pu
$X_d''$	0.255pu
$X_q$	0.474pu
$X_q''$	0.243pu
$X_1$	0.18pu

**Table 2**

Synchronous generator 2 data

Generators	Values
$M_2$	700MVA
$X_d$	1.305pu
$X_d'$	0.296pu
$X_d''$	0.255pu
$X_q$	0.474pu
$X_q''$	0.243pu
$X_1$	0.18pu

**Table 3**

Trans mission line per km	Values
$R_1$	0.1755 ohm
$R_0$	0.2758 ohm
$L_1$	0.8737mH
$L_0$	3.22mH
$C_1$	13.33nF
$C_0$	8.297nF

**Table 4**

STATCOM parameters	Values
$V$	500Kv,+/-100MVAR
R	0.0.71 ohm
L	0.22
$V_{ref}$	1.0
$C_{dc}$	0.03
$K_p$	50
$K_i$	1000