CHAPTER ONE

INTRODUCTION

1.1 Preface

Modern electric power system is facing many challenges due to day by day increasing complexity in their operation and structure. In the recent past, one of the problems that got wide attention is the power system instability. With the lack of new generation and transmission facilities and over exploitation of the existing facilities geared by increase in load demand make these types of problems more imminent in modern power systems. Demand of electrical power is continuously raising at a very high rate due to rapid industrial development [1].To meet this demand, it is essential to raise the transmitted power along with the existing transmission facilities. The need for the power flow control in electrical power systems is thus evident. With the increased loading of transmission lines, the problem of transient stability after a major fault can become a transmission power limiting factor. The power system should adapt to momentary system conditions, in other words, power system should be flexible. In an ac power system, the electrical generation and load must balance at all times up to some extent, the power system is self-regulating .If generation is less than load ,the voltage and frequency drop, and thereby the load goes down to equal the generation minus transmission losses. But there are only a few percent margins for such a self-regulation. Hence there is chance of system collapse. Generator excitation controllerwithonly excitation control can improve transient stability for minor faults but it is not sufficient to maintain stability of system for large faults occur near to generator terminals [2]. Thus, this requires a review of traditional methods and the creation of new concepts that emphasizemore efficient use of already existing power system resources without reduction in system stability and security. 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). The two main objectives of FACTS are to increase the transmission capacity and control power flow over designated transmission routes. 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 [3].

1.2 Why We Need Transmission Interconnections

We need these interconnections because, apart from delivery, the purpose of the transmission network is to pool power plants and load centers in order to minimize the total power generation capacity and fuel cost. Transmission interconnections enable taking advantage of diversity of loads, availability of sources, and fuel price in order to supply electricity to the loads at minimum cost with a required reliability. In general, if a power delivery system was made up of radial lines from individual local generators without being part of a grid system, many more generation resources would be needed to serve the load with the same reliability and the cost of electricity would be much higher. With that perspective, transmission is often an alternative to a new generation resource. Less transmission capability means that more generation resources would be required regardless of whether the system is made up of large or small power plants. In fact small distributed generation becomes more economically viable if there is a backbone of a transmission grid. One cannot be really sure about what the optimum balance is 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. The cost of transmission lines and losses, as well as difficulties encountered in building new transmission lines, would often limit the available transmission capacity. It seems that there are many cases where economic energy or reserve sharing is constrained by transmission capacity, and the situation is not getting any better. In a deregulated electric service environment, an effective electric grid is vital to the competitive environment of reliable electric service.

On the other hand, as power transfers grow, the power system becomes increasingly more complex to operate and the system can become less secure for riding through the major outages. It may lead to large power flows with inadequate control, excessive reactive power in various parts of the system, large dynamic swings between different parts of the system and bottlenecks, and thus the full potential of transmission interconnections cannot be utilized. The power systems of today, by and large, are mechanically controlled. There is a widespread use of microelectronics, computers and high-speed communications for control and protection of present transmission systems; however, when operating signals are sent to the power circuits, where the final power control action is taken, the switching devices are mechanical and there is little high-speed control. Another problem with mechanical devices is that control cannot be initiated frequently, because these mechanical devices tend to wear out very quickly compared to static devices. In effect, from the point of view of both dynamic and steady-state operation, the system is really uncontrolled. Power system planners, operators, and engineers have learned to live with this limitation by using a variety of ingenious techniques to make the system work effectively, but at a price of providing greater operating margins and redundancies. These represent an asset that can be effectively utilized with prudent use of FACTS technology on a selective, as needed basis. In recent years, greater demands have been placed on the transmission network, and these demands will continue to increase because of the increasing number of nonutility generators and heightened competition among utilities themselves. Added to this is the problem that it is very difficult to acquire new rights of way. Increased demands on transmission, absence of long-term planning, and the need to provide open access to generating companies and customers, all together have created tendencies toward less security and reduced quality of supply. The FACTS technology is essential to alleviate some but not all of these difficulties by enabling utilities to get the most service from their transmission facilities and enhance grid reliability. It must be stressed, however, that for many of the capacity expansion needs, building of newlines or upgrading current and voltage capability of existing lines and corridors will be necessary[1].

1.3 Problem Statement

The power system network is becoming more complex now a days and it is very difficult to maintain the stability of the power system. The continuous demand in electrical power system network may cause the system to be heavily loaded which leads to voltage instability. Under heavy loaded condition there may be insufficient reactive power which leads to voltage to drop. The problem in this research concentrated on transient stability which is common occurs in power system networks and it involves major disturbances such as:

- Loss of generation.
- Line-switching operations.
- Faults (three phase fault).
- Sudden load changes.

1.4 Objectives

The objectives of this research are summarized as follows:

1. Transient stability improvement in interconnected systems using STATCOM controller.

2. Study opportunities of FACTS in improvement the stability problems (transient stability).

3. Comparison between STATCOM and SVC.

1.5 Methodology

Firstly we collected all data which can provides us in this research. Secondly we used MATLAB/SIMULINK program to simulate two typical machines (13.8kV) interconnected, after that we applied three phase fault for 0.1 sec at the midpoint of transmition lines. After the fault applied we found out the change which occurs in the network and displayed the results by Simulink scopes. Finally we involved the shunt device STATCOM (phasor model) to improve the transient stability at midpoint of the transmition lines.

1.6 Project Layout

This Project Layout is organized as follows:

- **Chapter one** represents an introduction that include background, problems, objectives, methodology and the layout of research.
- **Chapter two** covers the concept and different types of FACTS devices, also contains classification of stability.
- **Chapter three** represents the contents and the application of static synchronous compensator (STATCOM). Also provides comparison between STATCOM and static var compensator (SVC).

- **Chapter four** represents simulation and discusses the results of simulation that have been done by the MATLAB program.
- **Chapter five** consists of the conclusion of this research and the recommendations presented by the students of this research.

CHAPTER TWO

STABILITY AND FACTS DEVICES

2.1 Power System Stability

Power system stability may be broadly defined as that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance.

Power system stability refers to the ability of synchronous machines to move from one steady-state operating point following a disturbance to another steady-state operating point, without losing synchronism [4,5].

Broadly Stability is classified into three terms:

- Rotor angle Stability.
- Frequency Stability.
- Voltage Stability.

Voltage stability is concerned with the ability of a power system to maintain acceptable voltages at all busses in the system under normal condition causes progressive and uncontrollable decline in voltage the main factor causing instability is the inability of the power system to meet the demand for reactive power .

2.2 Classification of Stability

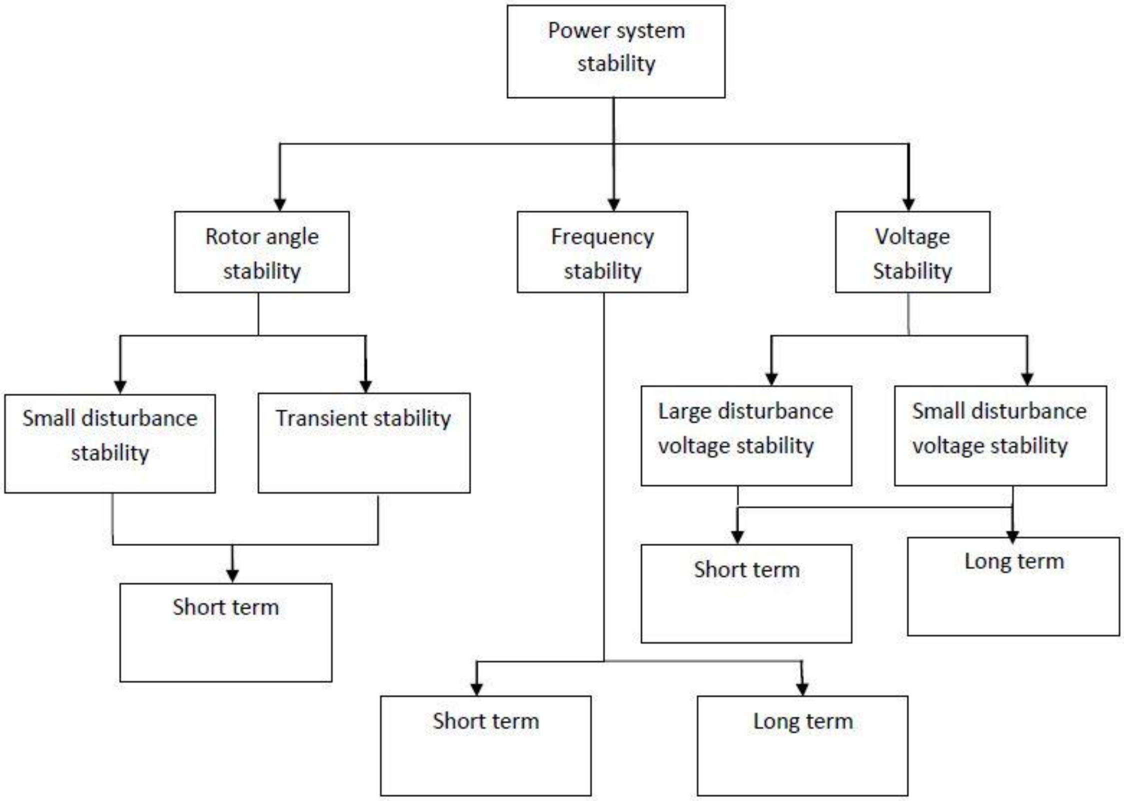

Figure 2.1: Classification of Power System Stability

In this project over emphasis is on Transient stability aspect of power system.

2.3 Transient Stability

Transient stability is mainly concerned with the ability of power system to maintain synchronism when subjected to severe disturbances such as three phase fault on transmission line. It's not only depends upon on the operating state of system but also on the severity of disturbance [4,5].

Transient stability, involves major disturbances such as:

- Loss of generation.
- Line-switching operations.
- Faults.

- Sudden load changes.

2.4 Power –Angle Curve

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

2.5 Power Angle Equation

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

$$P = \frac{EV}{X} sin\delta \tag{2.1}$$

$$X = Xd + X1 \tag{2.2}$$

The maximum steady state power transfer occurs when $\delta = 90^0$. From equation:

$$Pe\, max = \frac{EV}{X} \sin(90) = \frac{EV}{X} \tag{2.3}$$

$$Pe = Pe\, max * \ sin\delta \tag{2.4}$$

2.6 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 the second order.

$$M \frac{d^2\delta}{d^2t} = Pm - Pe = Pa \tag{2.5}$$

$$M = J.w \tag{2.6}$$

2.7 Equal Area Criteria

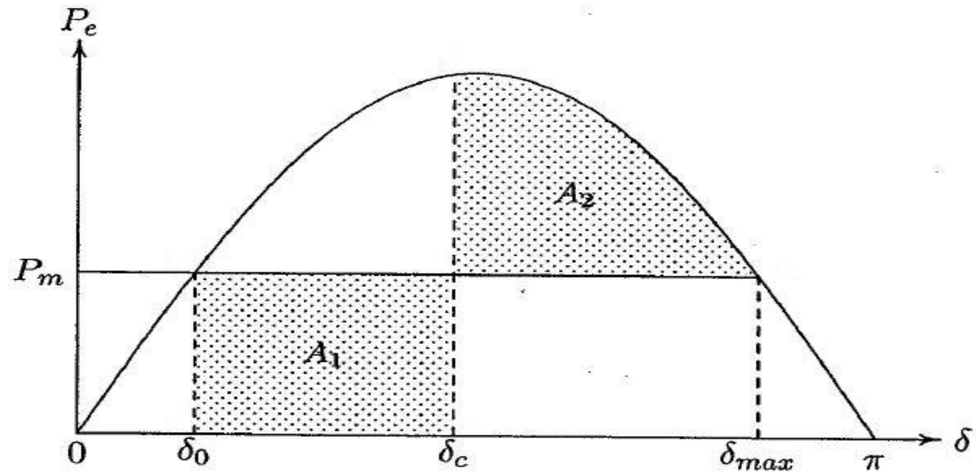

Figure 2.2: Power-Angle curve

Consider the power angle curve as shown in Figure 2.2 above. Suppose the given system is operating at an angle of δ_0 and delivering a power of Pm when fault occurs. During fault transmitted electrical power decreases significantly while mechanical power i.e. Pm remains constant, the accelerating power Pa becomes equal to Pm. The difference in the power develops the rate of change of stored kinetic energy in to rotor masses. As a result the rotor will accelerate due to of accelerating power and hence the load angle will increase. Now at angle δc 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 exceed than the mechanical power and machine will start to decelerate. However, due to stored kinetic energy in machine, the load angle will still keep on increasing. If this increasing angle will not stop than system will loss synchronism and become unstable. The relationship between the rotors
Angle and the accelerating power [4]:

$$\frac{d^2\delta}{d^2t} = \frac{W0}{2H}(Pm - Pe) \tag{2.7}$$

Multiply both sides by2 $\frac{d\delta}{dt}$ then equation [1] becomes:

$$\frac{d}{dt}\left[\frac{d\delta}{dt}\right]^2 = \frac{W0(Pm - Pe)}{H}\frac{d\delta}{dt} \qquad (2.8)$$

Now integrate equation between two arbitrary angles δ_0 andδc becomes:

$$\frac{H}{W0}\left[\frac{d\delta}{dt}\right]^2 = \int_{\delta 0}^{\delta c}(Pm - Pe)\ d\delta \qquad (2.9)$$

Now suppose the generator is at rest atδ_0. We then have$\frac{d\delta}{dt}$= 0. Once a fault occurs, themachine starts accelerating. Once the fault is cleared, the machine keeps on acceleratingbefore it reaches its peak atδ_c, at which point we have again$\frac{d\delta}{dt}$ =0Thus area of accelerating is given as:

$$A1 = \int_{\delta 0}^{\delta c}(Pm - Pe)\ d\delta = 0 \qquad (2.10)$$

Similarly area of deceleration is given as:

$$A2 = \int_{\delta c}^{\delta max}(Pe - Pm)\ d\delta\ = 0 \qquad (2.11)$$

Case 1:

If area of acceleration is greater than area of deceleration i.e.A1 > A2. The generator load angle will then cross the point δ_{max}, beyond which the electrical power will be less than the mechanical power forcing 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 subsequent acceleration and deceleration areas to be smaller than the first ones of 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 [4][5].

2.8 Overview of FACTS

The development of FACTS-devices has started with the growing capabilities of power electronic components. Devices for high power levels have been made available in converters for high and even highest voltage levels. The overall starting points are network elements influencing the reactive power or the impedance of a part of the power system. Figure 2.3 below shows a number of basic devices separated into the conventional ones and the FACTS-devices. For the FACTS side the taxonomy in terms of 'dynamic' and 'static' needs some explanation. The term 'dynamic' is used to express the fast controllability of FACTS-devices provided by the power electronics. This is one of the main differentiation factors from the conventional devices. The term 'static' means that the devices have no moving parts like mechanical switches to perform the dynamic controllability. Therefore most of the FACTS-devices can equally be static and dynamic.

The left column in Figure 2.3 contains the conventional devices build out of fixed or mechanically switchable components like resistance, inductance or capacitance together with transformers. The FACTS-devices contain these elements as well but use additional power electronic valves or converters to switch the elements in smaller steps or with switching patterns within a cycle of the alternating current. The left column of FACTS-devices uses Thyristor valves or converters. These valves or converters are well known since several years. They have low losses because of their low switching frequency of once a cycle in the converters or the usage of the Thyristors to simply bridge impedances in the valves [6].

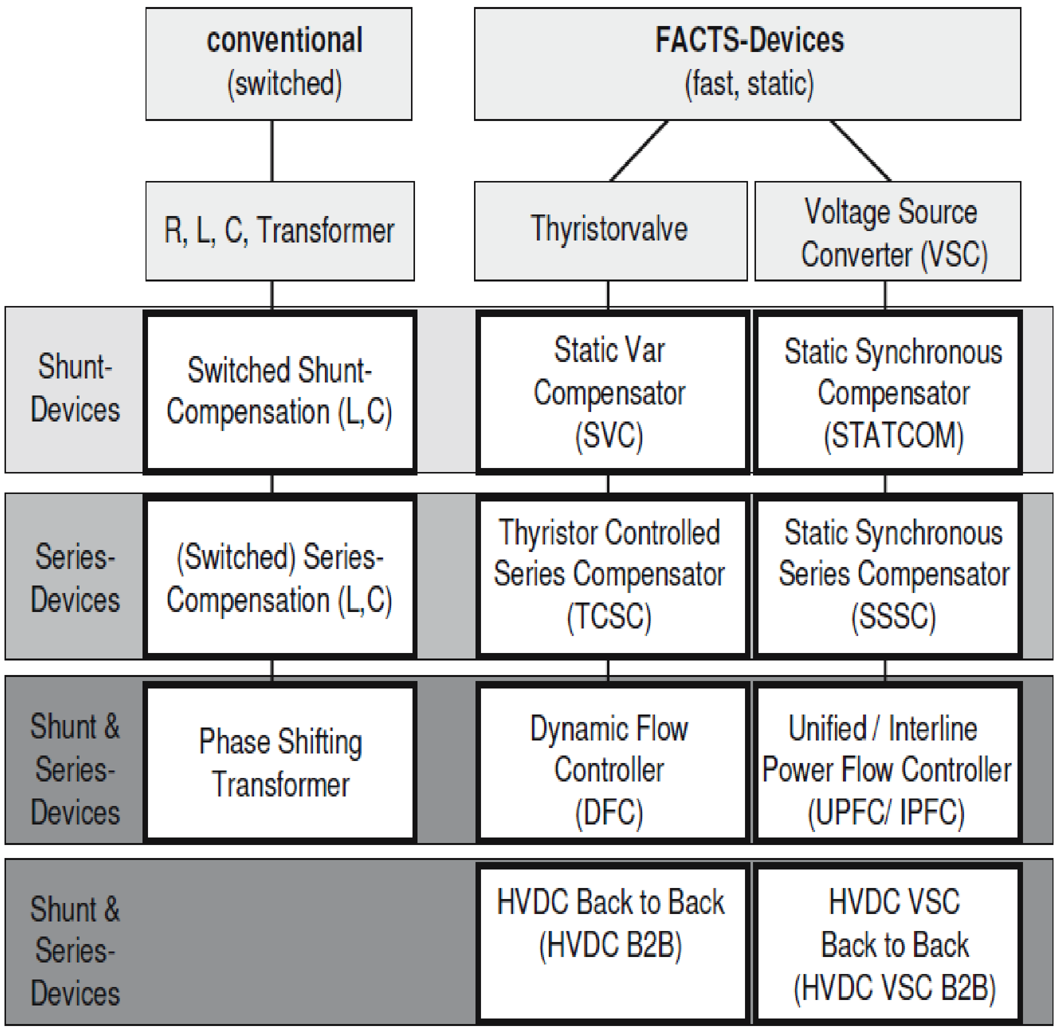

Figure 2.3: Overview of major FACTS devices

2.9FACTS-Devices and Applications

Flexible AC Transmission Systems, called FACTS, got in the recent years a well-known term for higher controllability in power systems by means of power electronic devices. Several FACTS-devices have been introduced for various applications worldwide. A number of new types of devices are in the stage of being introduced in practice. In most of the applications the controllability is used to avoid cost intensive or landscape requiring extensions of power systems, for instance like upgrades or additions of substations and power lines. FACTS-devices provide a better adaptation to varying operational conditions and improve the usage of existing installations.

The basic applications of FACTS-devices are:

- Power flow control.
- Increase of transmission capability.
- Voltage control.
- Reactive power compensation.
- Stability improvement.
- Power quality improvement.
- Power conditioning.
- Flicker mitigation.
- Interconnection of renewable and distributed generation and storages.

In all applications the practical requirements, needs and benefits have to beconsidered carefully to justify the investment into a complex new device. Figure 2.4 below shows the basic idea of FACTS for transmission systems. The usage of lines for active power transmission should be ideally up to the thermal limits. Voltage and stability limits shall be shifted with the means of the several different FACTS devices. It can be seen that with growing line length, the opportunity for FACTS devices gets more and more important. The influence of FACTS-devices is achieved through switched or controlled shunt compensation, series compensation or phase shift control. The devices work electrically as fast current, voltage or impedance controllers. The power electronic allows very short reaction times down to far below one second. In the following a structured overview on FACTS-devices is given. These devices are mapped to their different fields of applications [6][7].

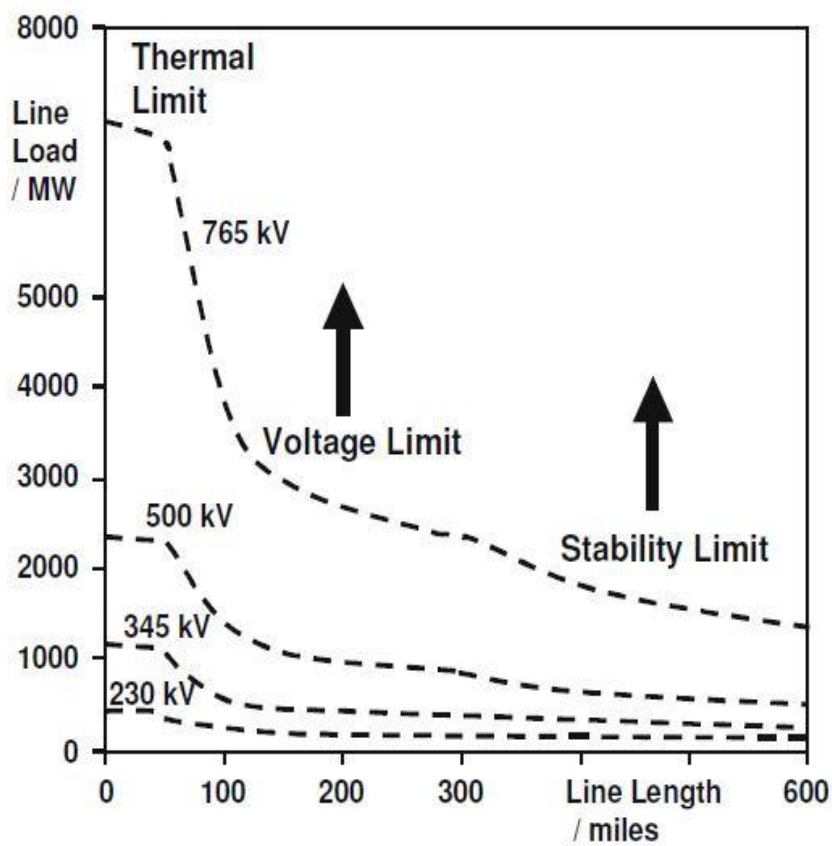

Figure 2.4: operational limits of transmission lines for different voltage levels

2.10Basic Types of FACTS Controllers

In general, FACTS Controllers can be divided into four categories:

- Series Controllers.
- Shunt Controllers.
- Combined series-series Controllers.
- Combined series-shunt Controllers.

2.11 Series Controllers

The series Controller could be variable impedance, such as capacitor, reactor, etc., or power electronics based variable source of main frequency, sub-synchronous and harmonic frequencies (or a combination) to serve the desired need. In principle, all series Controllers inject voltage in series with the line. Even variable impedance multiplied by the current flow through it, represents an injected series voltage in the line. As long as the voltage is in phase quadrature with the line current, the series Controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well. Series devices have been further developed from fixed or mechanically switched compensations to the thyristor Controlled Series Compensation (TCSC) or even Voltage Source Converter based devices [1].

The main applications of Series Controller are:

• Reduction of series voltage decline in magnitude and angle over a power line.

• Reduction of voltage fluctuations within defined limits during changing power transmissions.

• Improvement of system damping respect. Damping of oscillations.

• Limitation of short circuit currents in networks or substations.

• Avoidance of loop flows response. power flow adjustments [6].

2.12 Types of Series Controllers

Some types of series controllers are shown below:

2.12.1 Thyristors-controlled series capacitor (TCSC)

Thyristor Controlled Series Capacitors (TCSC) addresses specific dynamical problems in transmission systems. Firstly it increases damping when large electrical systems are interconnected. Secondly it can overcome the problem of Sub- Synchronous Resonance (SSR), a phenomenon that involves an interaction between large thermal generating units and series compensated transmission systems. The TCSC's high speed switching capability provides a mechanism for controlling line power flow, which permits increased loading of existing transmission lines, and allows for rapid readjustment of line power flow in response to various contingencies. The TCSC also can regulate steady-state power flow within its rating limits. From a principal technology point of view, the TCSC resembles the conventional series capacitor. All the power equipment is located on an isolated steel platform, including the thyristor valve that is used to control the behavior of the main capacitor bank. Likewise the control and protection is located on ground potential together with other auxiliary systems. Figure 2.5 below shows the principle setup of a TCSC and its operational diagram. The firing angle and the thermal limits of the thyristors determine the boundaries of the operational diagram.

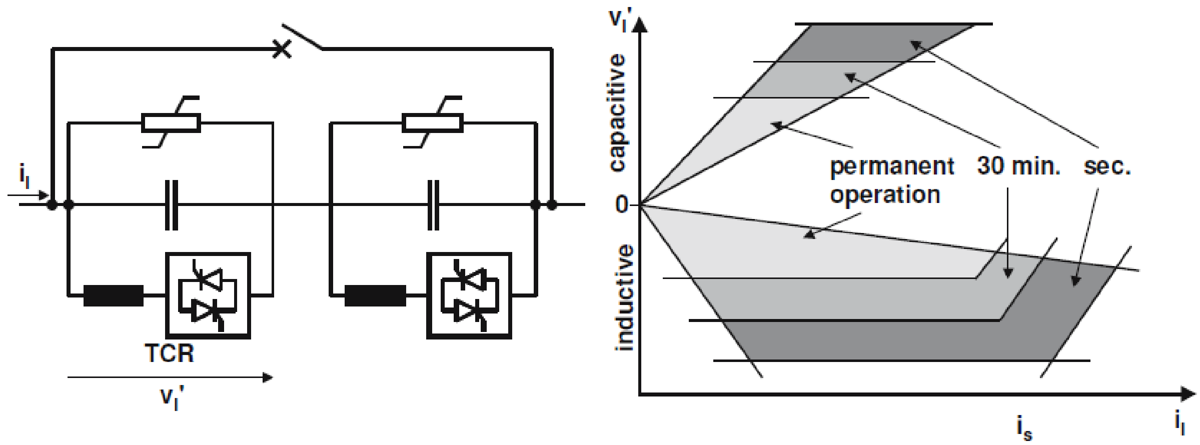

Figure 2.5: principle setup and operational diagram of a thyristor controlled Series compensation (TCSC)

The main principles of the TCSC concept are two; firstly, to provide electromechanical damping between large electrical systems by changing the reactance of a specific interconnecting power line, i.e. the TCSC will provide a variable capacitive reactance. Secondly, the TCSC shall change its apparent impedance (as seen by the line current) for sub-synchronous frequencies, such that a prospective sub synchronous resonance is avoided. Both objectives are achieved with the TCSC, using control algorithms that work concurrently. The controls will function on the Thyristor circuit in parallel to the main capacitor bank such that controlled charges are added to the main capacitor, making it a variable capacitor at fundamental frequency but a “virtual inductor” at sub-synchronous frequencies [6].

2.12.2 SSSC

While the TCSC can be modeled as series impedance, the SSSC is a series voltage source. The principle configuration is shown in Figure 2.6 below which looks basically the same as the STATCOM. But in reality this device is more complicated because of the platform mounting and the protection. A Thyristor protection is absolutely necessary, because of the low overload capacity of the semiconductors, especially when IGBTs are used. The voltage source converter plus the Thyristors protection makes the device much more costly, while the better performance cannot be used on transmission level. The picture is quite different if we look into power quality applications. This device is then called Dynamic Voltage Restorer (DVR). The DVR is used to keep the voltage level constant, for example in a factory in feed. Voltage dips and flicker can be mitigated. The duration of the action is limited by the energy stored in the DC capacitor. With a charging mechanism or battery on the DC side, the device could work as an uninterruptible power supply. A picture of a modularized installation with 22 MVA is shown on the right in Figure 2.6 [6].

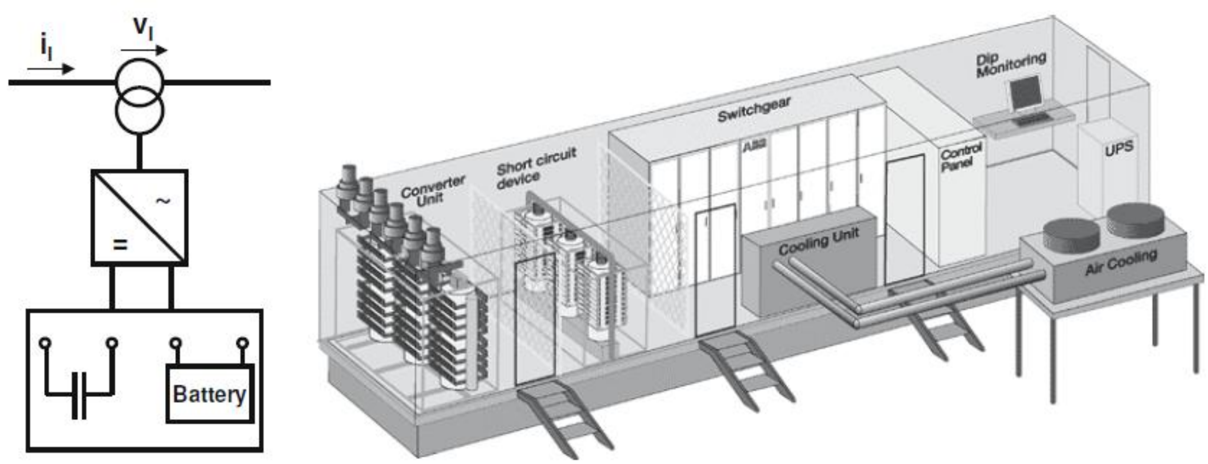

Figure 2.6: principle setup of SSSC and implementation as DVR for power quality applications

2.13 Shunt Controllers

As in the case of series Controllers, the shunt Controllers may be variable impedance, variable source, or a combination of these. In principle, all shunt Controllers inject current into the system at the point of connection. Even variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of current into the line. As long as the injected current is in phase quadrature with the line voltage, the shunt Controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well[1].

2.14 Types of Shunt Controllers

There are common types of shunt controllers which classified as follow:

2.14.1 SVC

Electrical loads both generate and absorb reactive power. Since the transmitted load 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 or even a voltage depression, at the extreme a voltage collapse. A rapidly operating Static Var Compensator (SVC) can continuously provide the reactive power required to control dynamic voltage oscillations under various system conditions and there by improve the power system transmission and distribution stability. Installing an SVC at one or more suitable points in the network can increase transfer capability and reduce losses while maintaining a smooth voltage profile under different network conditions. In addition an SVC can mitigate active power oscillations through voltage amplitude modulation.

SVC installations consist of a number of building blocks. The most important is the thyristor valve, i.e. stack assemblies of series connected anti-parallel thyristors to provide controllability. Air core reactors and high voltage AC capacitors are the reactive power elements used together with the Thyristor valves. The step up connection of this equipment to the transmission voltage is achieved through a power transformer. The Thyristor valves together with auxiliary systems are located indoors in an SVC building, while the air core reactors and capacitors, together with the power transformer are located outdoors. In principle the SVC consists of Thyristor Switched Capacitors (TSC) and Thyristor Switched or Controlled Reactors (TSR / TCR). The coordinated control of a combination of these branches varies the reactive power as shown in Figure 2.7 below. The first commercial SVC was installed in 1972 for an electric arc furnace. On transmission level the first SVC was used in 1979. Since then it is widely used and the most accepted FACTS-device [7].

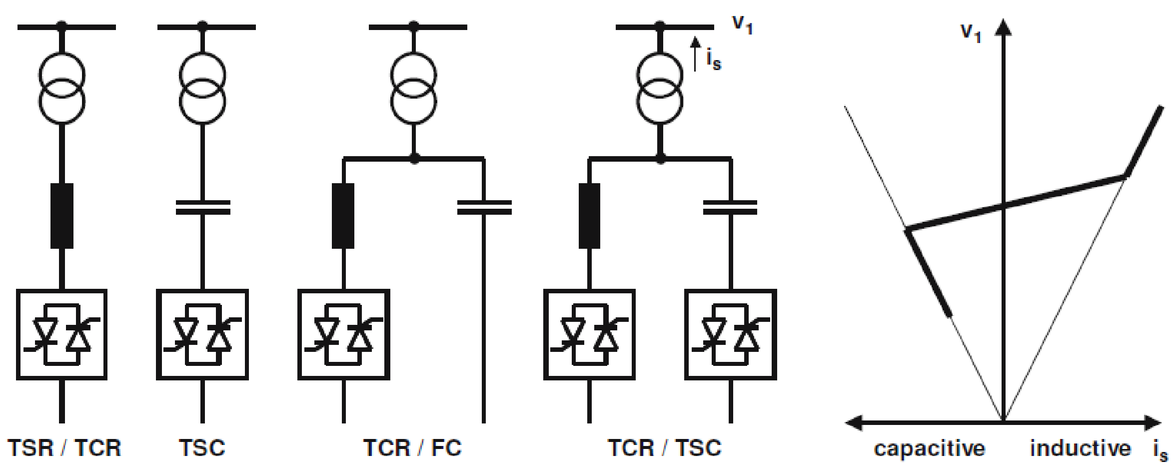

Figure 2.7: SVC building block and voltage/current characteristic

2.14.2 STATCOM

The STATCOM has a characteristic similar to the synchronous condenser, but as an electronic device it has no inertia and is superior to the synchronous condenser in several ways, such as better dynamics, a lower investment cost and lower operating and maintenance costs. A STATCOM is built with thyristors with turn-off capability like GTO or today IGCT or with more and more IGBTs. The structure and operational characteristic is shown in Figure 2.8 below. The static line between the current limitations has a certain steepness determining the control characteristic for the voltage. The advantage of a STATCOM is that the reactive power provision is independent from the actual voltage on the connection point. This can be seen in the diagram for the maximum currents being independent of the voltage in comparison to the SVC in Figure 2.7 above. This means, that even during most severe contingencies, the STATCOM keeps its full capability.

In the distributed energy sector the usage of Voltage Source Converters for gridInterconnection is common practice today. The next step in STATCOM development is the combination with energy storages on the DC-side. The performance for power quality and balanced network operation can be improved much more with the combination of active and reactive power [1].

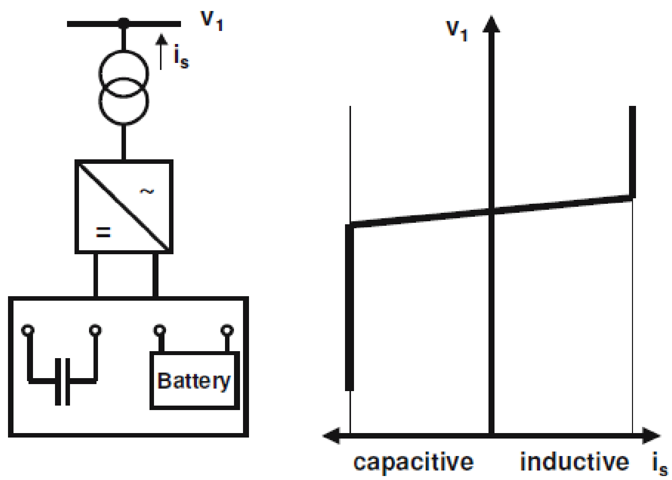

Figure 2.8: STATCOM structure and voltage /current characteristic [8]

2.15 Combined Series-Series Controllers

This could be a combination of separate series controllers, which are controlled in a coordinated manner, in a multiline transmission system. Or it could be a unified Controller, Figure 2.9 bellow in which series Controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power tint. The real power transfer capability of the unified series-series Controller, referred to as Interline Power Flow Controller, makes it possible to balance both the real and reactive power flow in the lines and thereby maximize the utilization of the transmission system. Note that the term "unified" here means that the dc terminals of all Controller converters are all connected together for real power transfer [1].

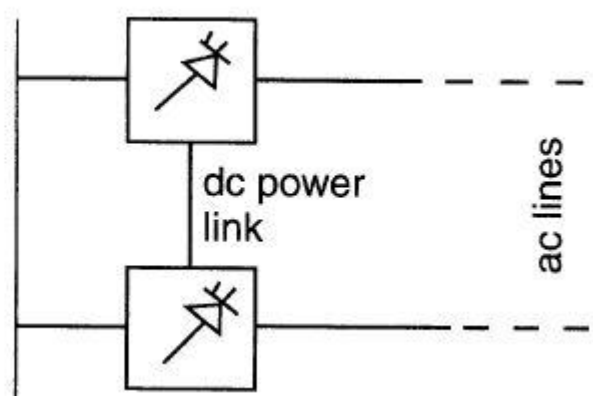

Figure 2.9: unified series- series Controller

2.16 Combined Series-Shunt Controllers

This could be a combination of separate shunt and series Controllers, which are controlled in a coordinated manner or Unified Power Flow Controller with series and shunt elements. In principle, combined shunt and series Controllers inject current into the system with the shunt part of the Controller and voltage in series in the line with the series part of the Controller. However, when the shunt and series Controllers are unified, there can be a real power exchange between the series and shunt Controllers via the power link [1].

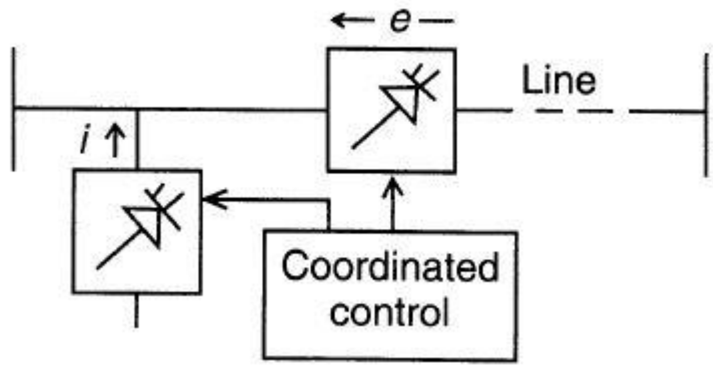

Figure 2.10: coordinated series and shunt Controller

2.17 Types of Combined Series-Shunt Controllers

- Unified Power Flow Controller.
- Interline Power Flow Controller.
- Generalized Unified Power Flow Controller.

2.17.1 Unified power flow controller

The UPFC is a combination of a static compensator and static series compensation. It acts as a shunt compensating and a phase shifting device simultaneously. The UPFC consists of a shunt and a series transformer, which are connected via two voltage source converters with a common DC-capacitor. The DC-circuit allows the active power exchange between shunt and series transformer to control the phase shift of the series voltage. This setup, as shown in Figure 2.11 below provides the full controllability for voltage and power flow. The series converter needs to be protected with a Thyristor bridge. Due to the high efforts for the Voltage Source Converters and the protection, an UPFC is getting quite expensive, which limits the practical applications where the voltage and power flow control is required simultaneously.

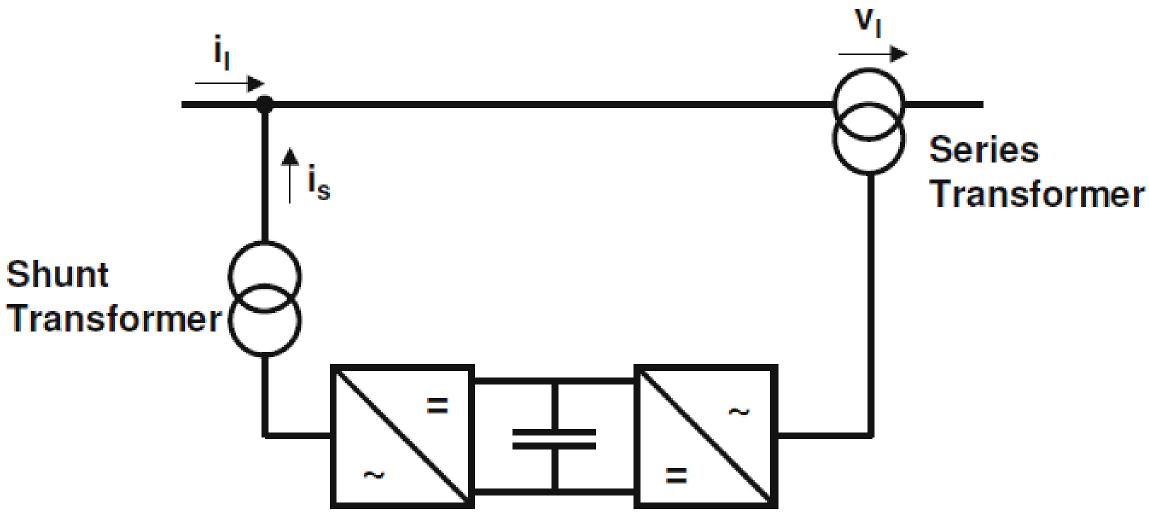

Figure 2.11: Principle Configuration of an UPFC

2.17.2Interline power flow controller

One of the latest FACTS-devices is named convertible static compensator (CSC) and was recently installed as a pilot by the New York Power Authority (NYPA). The CSC-project shall increase power transfer capability and maximize the use of the existing transmission network. Within the general conceptual framework of the CSC, two multi-converter FACTS-devices, the Interline Power Flow Controller (IPFC) and the Generalized Unified Power Flow Controller (GUPFC), are among many possible configurations. The target is to control power flows of multi-lines or a sub network rather than control the power flow of a single line by for instance DFC or UPFC. The IPFC combines two or more series converters and the GUPFC combines one shunt converter and two or more series converters. When the power flows of two lines starting in one substation need to be controlled, an Interline Power Flow Controller (IPFC) can be used. The IPFC consists of two series VSCs whose DC capacitors are coupled. This allows active power to circulate between the VSCs. Figure 2.12 below shows the principle configuration of an IPFC. With this configuration two lines can be controlled simultaneously to optimize the network utilization. In general, due to its complex setup, specific application cases need to be identified justifying the investment [8-11].

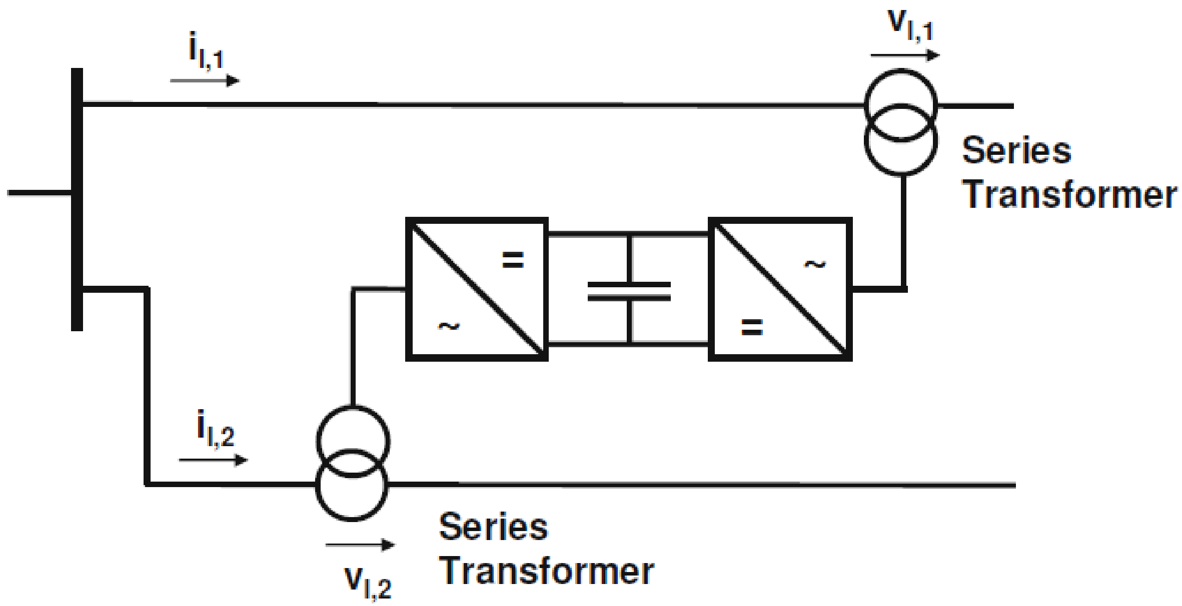

Figure 2.12: Principle Configuration of an IPFC

2.17.3Generalized unified power flow controller

The GUPFC combines three or more shunt and series converters. It extends the concept of voltage and power flow control beyond what is achievable with the known two-converter UPFC. The simplest GUPFC consists of three converters, one connected in shunt and the other two in series with two transmission lines in a substation. Figure 2.13 below shows the principle configuration. The basic GUPFC can control total five power system quantities such as a bus voltage and independent active and reactive power flows of two lines. The concept of GUPFC can be extended for more lines if necessary. The device may be installed in some central substations to manage power flows of multi-lines or a group of lines and provide voltage support as well. By using GUPFC-devices, the transfer capability of transmission lines can be increased significantly. Furthermore, by using the multi-line management capability of the GUPFC, active power flows on lines can not only be increased, but also be decreased with respect to operating and market transaction requirements. In general the GUPFC can be used to increase transfer capability and relieve congestions in a flexible way. The complexity of its configuration and control scheme needs specific applications cases [11].

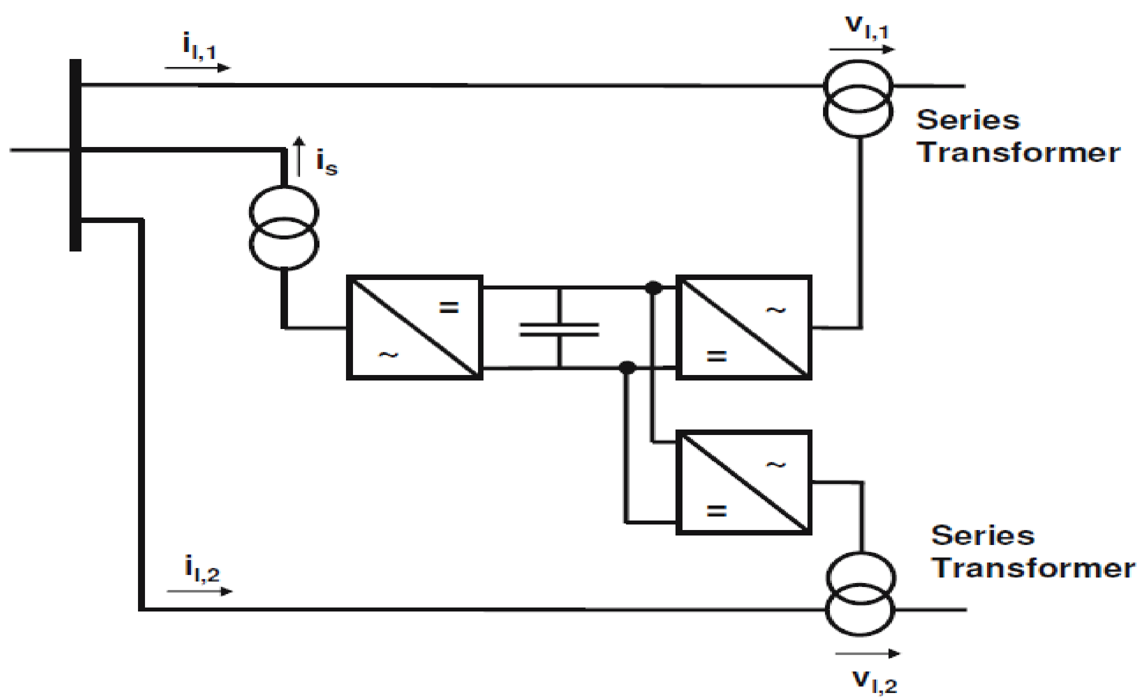

Figure 2.13: Principle Configuration of a GUPFC

2.18 Back-To-Back Device

The Back-to-Back devices provide in general a full power flow controllability and power flow limitation. An overload of these devices is therefore impossible. They can resist cascading outages, which might occur due to line outages when one line after the other is overloaded. This gives a great benefit even if the frequency decoupling characteristic is not needed.

Conventional HVDC Back-to-Back systems with Thyristor converters need space consuming filters to reduce the harmonic distortion. The reactive power is not controllable. These devices are mainly used when two asynchronous networks need to be coupled or in the usual application as power transmission line over long distances.

The HVDC with Voltage Source Converters instead provides benefits as well within synchronous operated networks. It has a much smaller footprint and provides the full voltage controllability to the network on both ends. Therefore it can be operated in addition to the power flow control as two STATCOMS. On both ends a full four quadrant circular operational diagram is provided. This reactive power provision can be used to increase the transmission capability of surrounding transmission lines in addition to balancing the power flow. Figure 2.14belowshows the principle configuration of a HVDC Back-to-Back with Voltage Source Converters [11].

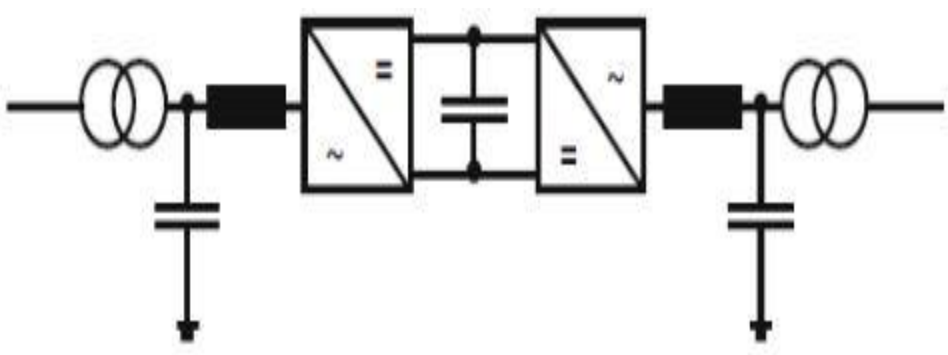

Figure 2.14: Schematic configuration of a HVDC Back to Back with voltage source converter

CHAPTER THREE

STATCOM OPERATION AND CONTROL

3.1 Overview

In 1999 the first SVC with Voltage Source Converter called STATCOM (static compensator) went into operation. The STATCOM has a characteristic similar to the synchronous condenser, but as an electronic device it has no inertia and is superior to the synchronous condenser in several ways, such as better dynamics, a lower investment cost and lower operating and maintenance costs. A STATCOM is built with thyristors with turn-off capability like GTO or today IGCT or with more and more IGBTs.

The advantage of a STATCOM is that the reactive power provision is independent from the actual voltage on the connection point. This can be seen in the diagram for the maximum currents being independent of the voltage in comparison to the SVC in Figure 3.1below. This means, that even during most severe contingencies, the STATCOM keeps its full capability.

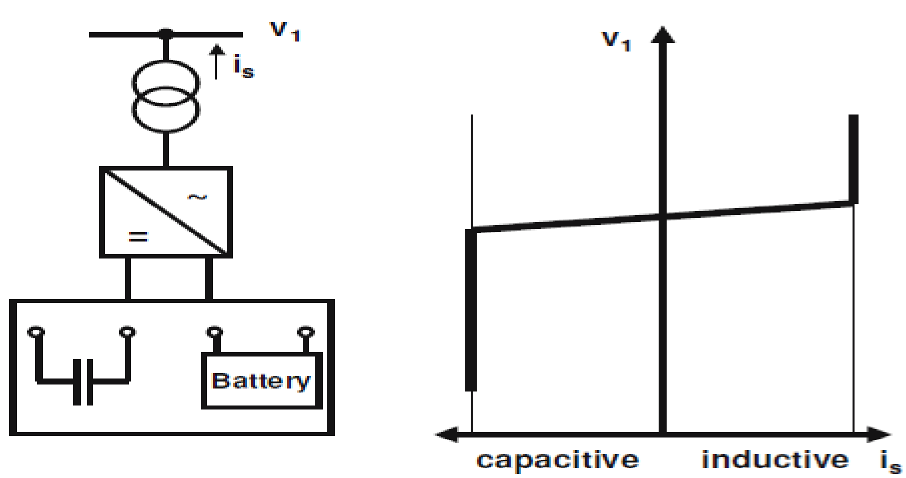

Figure 3.1: The maximum currents being independent of the Voltage

In the distributed energy sector the usage of Voltage Source Converters for grid interconnection is common practice today. The next step in STATCOM development is the combination with energy storages on the DC-side. The performance for power quality and balanced network operation can be improved much more with the combination of active and reactive power [8].

3.2 Need for Reactive Power Compensation

The main reason for reactive power compensation in a system is:

1. The voltage regulation.
2. Increased system stability.
3. Better utilization of machines connected to the system.
4. Reducing losses associated with the system.
5. To prevent voltage collapse as well as voltage sag.

The impedance of transmission lines and the need for lagging VAR by most machines in a generating system results in the consumption of reactive power, thus affecting the stability limits of the system as well as transmission lines. Unnecessary voltage drops lead to increased losses which needs to be supplied by the source and in turn leading to outages in the line due to increased stress on the system to carry this imaginary power. Thus we can infer that the compensation of reactive power not only mitigates all these effects but also helps in better transient response to faults and disturbances.

In recent times there has been an increased focus on the techniques used for the compensation and with better devices included in the technology, the compensation is made more effective. It is very much required that the lines be relieved of the obligation to carry the reactive power, which is better provided near the generators or the loads. Shunt compensation can be installed near the load, in a distribution substation or transmission substation. The amount of reactive power supplied by any compensating device depends on the voltage drop at the bus and its capabilities. For example, a STATCOM can supply its maximum rated compensating current even at lower voltages. The rating of the STATCOM also decides the maximum reactive power that can be supplied, but usually they have some extra capability called the transient capability which is available to the system for a short period of time. The reactive power supplied is also dependent on the immediate reactive power sources in the system [1].

3.3 Static Synchronous Compensator (STATCOM)

STATCOM or Static Synchronous Compensator is a shunt device, which uses force-commutated power electronics (i.e. GTO, IGBT) to control power flow and improve transient stability on electrical power networks. It is also a member of the so-called Flexible AC Transmission System (FACTS) devices. The STATCOM basically performs the same function as the (static var compensators) but with some advantages.

One of the many devices under the FACTS family, a STATCOM is a regulating device which can be used to regulate the flow of reactive power in the system independent of other system parameters. STATCOM has no long term energy support on the dc side and it cannot exchange real power with the ac system. In the transmission systems, STATCOMs primarily handle only fundamental reactive power exchange and provide voltage support to buses by modulating bus voltages during dynamic disturbances in order to provide better transient characteristics, improve the transient stability margins and to damp out the system oscillations due to these disturbances.

A STATCOM consists of a three phase inverter (generally a PWM inverter) using SCRs, MOSFETs or IGBTs, a D.C capacitor which provides the D.C voltage for the inverter, a link reactor which links the inverter output to the AC supply side, filter components to filter out the high frequency components due to the PWM inverter. From the DC Side capacitor, a three phase voltage is generated by the inverter. This is synchronized with the AC supply. The link inductor links this voltage to the AC supply side. This is the basic principle of operation of STATCOM.

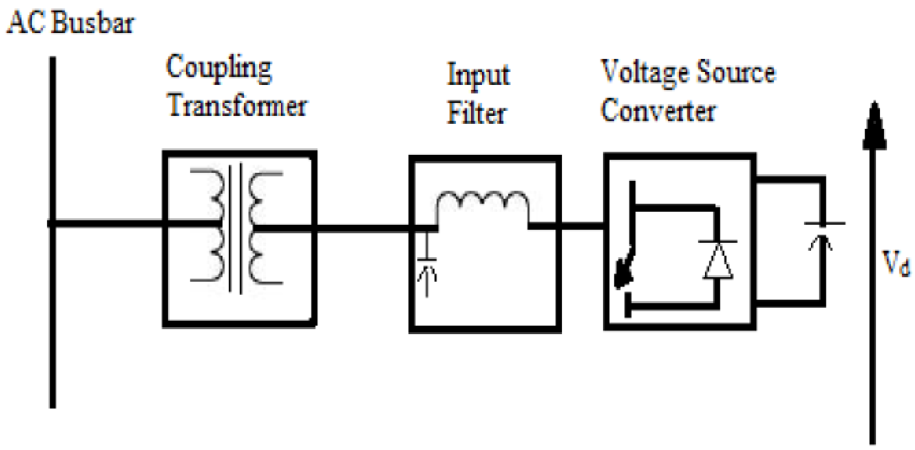

Figure 3.2: principle of operation of STATCOM

For two AC sources which have the same frequency and are connected through a series inductance, the active power flows from the leading source to the lagging source and the reactive power flows from the higher voltage magnitude source to the lower voltage magnitude source. The phase angle difference between the sources determines the active power flow and the voltage magnitude difference between the sources determines the reactive power flow. Thus, a STATCOM can be used to regulate the reactive power flow by changing the magnitude of the VSC voltage with respect to source bus voltage.

3.4 Components of STATCOM

1. Voltage-Source Converter (VSC).
2. DC Capacitor.
3. Inductive Reactance (X).
4. Harmonic Filters.

3.4.1 Voltage-source converter (VSC)

The voltage-source converter transforms the DC input voltage to an AC output voltage. Two of the most common VSC types are described below.

3.4.1.1 Square-wave inverters using gate turn-off thyristors

Generally, four three-level inverters are utilized to make a 48-step voltage waveform. Subsequently, it controls reactive power flow by changing the DC capacitor input voltage, simply because the fundamental component of the converter output voltage is proportional to the DC voltage.

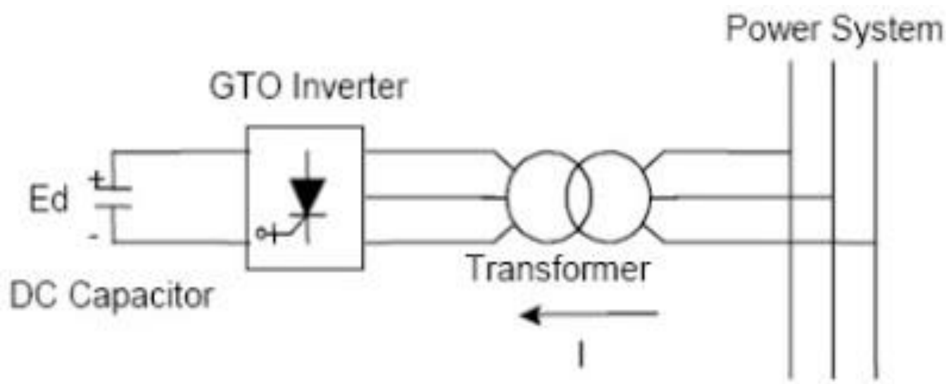

Figure 3.3: GTO-based STATCOM Simple Diagram

In addition, special interconnection transformers are employed to neutralize harmonics contained in the square waves produced by individual inverters.

3.4.1.2 PWM Inverters using insulated gate bipolar transistors (IGBT)

It uses Pulse-Width Modulation (PWM) technique to create a sinusoidal waveform from a DC voltage source with a typical chopping frequency of a few kHz. In contrast to the GTO-based type, the IGBT-based VSC utilizes a fixed DC voltage and varies its output AC voltage by changing the modulation index of the PWM modulator.

Moreover, harmonic voltages are mitigated by installing shunt filters at the AC side of the VSC.

3.4.2 DC Capacitor

This component provides the DC voltage for the inverter.

3.4.3 Inductive reactance (X)

It connects the inverter output to the power system. This is usually the leakage inductance of a coupling transformer.

3.4.4 Harmonic filters

Mitigate harmonics and other high frequency components due to the inverters.

3.5 Applications of STATCOM

STATCOMs are typically applied in long distance transmission systems, power substations and heavy industries where voltage stability is the primary concern. In addition; static synchronous compensators are installed in select points in the power system to perform the following:

- Voltage support and control.
- Voltage fluctuation and flicker mitigation.
- Unsymmetrical load balancing.
- Power factor correction.
- Active harmonics cancellation.
- Improve transient stability of the power system.

3.6 Operating Principle of STATCOM

STATCOM is made up of a coupling transformer, a VSC and a DC energy storage device. 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, extending its region of operation from two to four quadrants. A functional model of a STATCOM is shown in Figure 3.4below.

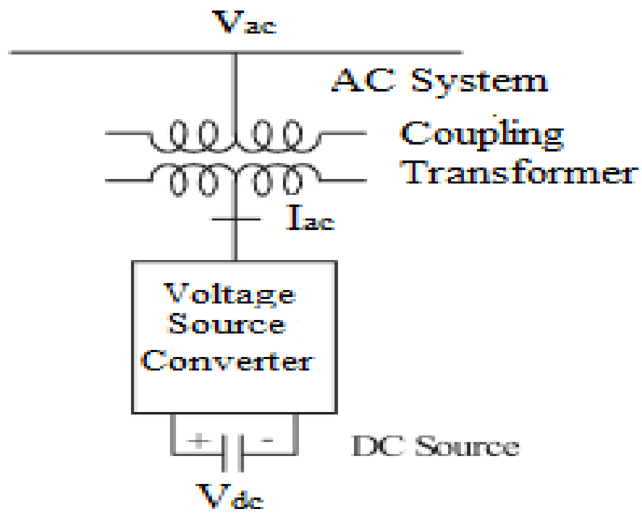

Figure 3.4: Functional model of STATCOM [1]

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

$$Vout = k * Vdc \tag{3.1}$$

Where k is coefficient which depends upon on the converter configuration, number of switching pulses and the converter controls. The fundamental component of the converter output voltage i.e. Vout can be controlled by varying the DC voltage across capacitor which can be done by changing the phase angle α of the operation of the converter switches relative to the phase of the AC system bus voltage. The direction of flow of reactive power whether it is from coupling transformer to the system or from system to the coupling transformer depends upon the difference between the converter output voltage and the AC system bus voltage. The real power flowing into the converter supplies the converter losses due to switching and charges the DC capacitor to a satisfactory

DC voltage level. The capacitor is charged and discharged during the course of each switching cycle but in steady state, the average capacitor voltage remains constant. If that were not the case, there would be real power flowing into or out of the converter, and the capacitor would gain or lose charge each cycle. In steady state, al1 of the power from the AC system is used to replenish the losses due to switching. The STATCOM's ability to absorb/supply real power depends on the size of DC capacitor and the real power losses due to switching. Whenever the DC capacitor and the losses are relatively small. The amount of real power transfer is also relatively small. This implies that the STATCOM’s output AC current Iac, has to be approximately + 90^0 with respect to AC system voltage at its line terminals. Varying the amplitude of the converter three-phase output voltage Vout controls the reactive power generation/absorption of the STATCOM. If the amplitude of the converter output voltage Vout is increased above the amplitude of the AC system bus voltage Vac then the AC current Iac, flows through the transformer reactance from the converter to the AC system generating reactive power. In this case, the ac system draws capacitive current that leads by an angle of 90^0 the AC system voltage, assuming that the converter losses are equal to zero. The AC current flows from the AC system to the voltage-sourced converter if the amplitude of the converter output voltage is decreased below that of the AC system, and consequently the converter absorbs reactive power. For an inductive operation, the current lags the AC voltage by an angle of 90^0. Assuming again that the converter losses are neglected. If the amplitudes of the AC system and converter output voltages are equal, there will be no AC current flow in/out of the converter and hence there will be no reactive power generation/absorption the AC current Magnitude can be calculated using the following equation:

$$Iac = \frac{Vout - Vac}{X} \tag{3.2}$$

Assuming that the AC current flows from the converter to the AC system. Vout and Vac are the magnitudes of the converter output voltage and AC system voltage respectively, while X represents the coupling transformer leakage reactance. The corresponding reactive power exchanged can be expressed as follows:

$$Q = \frac{Vout^2 - Vout * Vac * \cos \propto}{X} \tag{3.3}$$

The real power exchange between the voltage-sourced converter and the AC system can be calculated using:

$$P = \frac{Vac * Vout * \sin \propto}{X} \tag{3.4}$$

3.7 Operating Modes

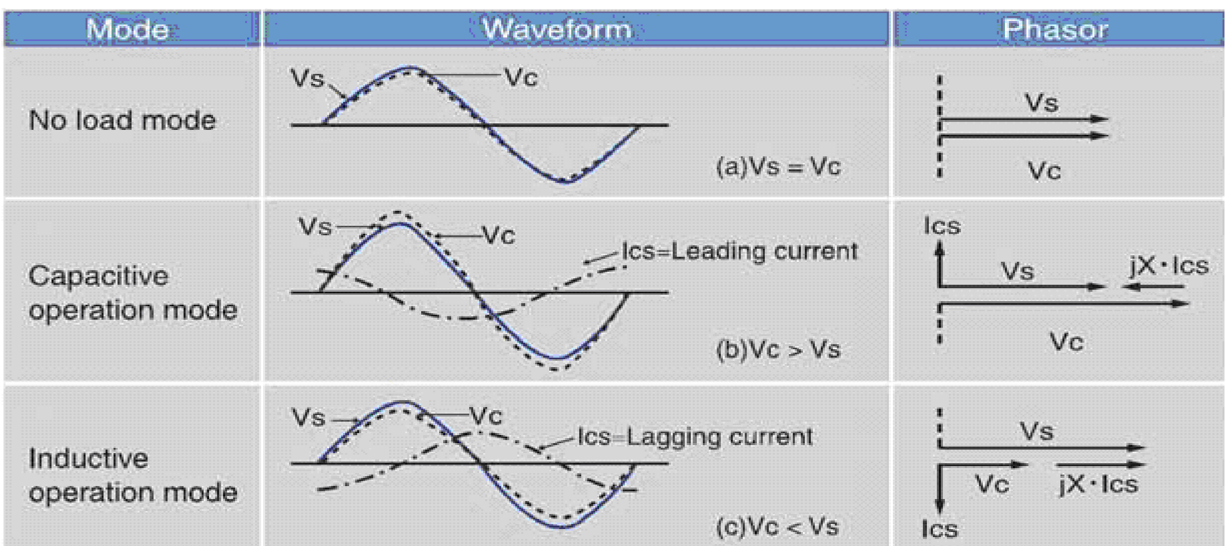

Figure 3.5 Operating modes of STATCOM

3.7.1 Voltage regulation

When a STATCOM is used for compensating the voltage across an AC power System (typically AC transmission lines), the voltage across the STATCOM is regulated using a voltage control loop implemented in the STATCOM controller (see Figure 3.6below). This controller monitors the voltage across the STATCOM side of the step-down transformer, the current flowing through the STATCOM side of the step-down transformer, and the voltage across the DC side of the STATCOM. Using these measured values, the STATCOM controller determines the switching signals to be applied to the three-phase bridge in order to ensure that the line voltages measured across the STATCOM side of the step down transformer are equal to the AC bus line voltage command (the value of this command being set so that the resulting voltage across the STATCOM is at the required value), and that the voltage measured across the DC side of the STATCOM is equal to the DC bus voltage command. The block diagram of a STATCOM designed for voltage compensation (i.e., automatic voltage control) is shown in Figure 3.6.

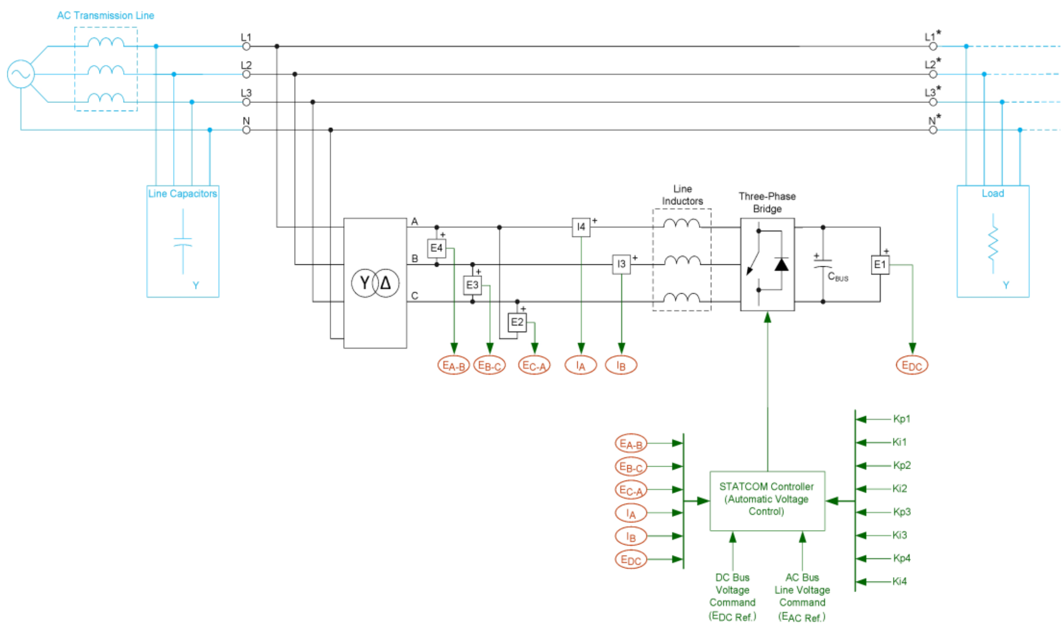

Figure 3.6: Diagram of STATCOM designed for voltage compensation

As Figure 3.6 above shows, three voltage sensors measure line voltages E_{A_B} ,E_{B_C}, and E_{C_A} across the STATCOM side of the step-down transformer, two current sensors measure the currents I_A and I_B flowing through the STATCOM side of the step-down transformer, and a voltage sensor measures DC voltage

E_{DC} across the DC side of the STATCOM. These voltage and current values are sent to the STATCOM controller.

The STATCOM controller compares the measured line voltages to the AC bus line voltage command E_{DCref}., and determines the error in the measured line voltages across the STATCOM side of the step-down transformer. The STATCOM controller also compares the measured DC voltage E_{DC} to the DC bus voltage command $E_{DC\ ref}$., and determines the error in the measured voltage across the DC side of the STATCOM. Using these calculated error values and the measured voltage and current values, the STATCOM controller determines the switching signals to be applied to the three-phase bridge so that the amount of reactive power the STATCOM exchanges with the AC power system to which it is connected ensures that the line voltages measured across the STATCOM side of the step-down transformer are equal to the AC bus line voltage command, and that the amount of active power flowing through the STATCOM makes the voltage measured across the DC side of the STATCOM equal to the DC bus voltage command. Note that line voltage E_{A_B} is also used to provide the phase angle (θ) information required to perform mathematical calculations in the controller [3].

3.7.2 Phase angle control

In this case the quantity controlled is the phase angle δ. The modulation index "m" is kept constant and the fundamental voltage component of the STATCOM is controlled by changing the DC link voltage. By further charging of the DC link capacitor, the DC voltage will be increased, which in turn increases the reactive power delivered or the reactive power absorbed by the STATCOM. On the other hand, by discharging the DC link capacitor, the reactive power delivered is decreased in capacitive operation mode or the reactive power absorbed by the STATCOM in an inductive power mode increases. For both capacitive and inductive operations in steady-state, the STATCOM voltage lags behind AC line voltage ($\delta > 0$).

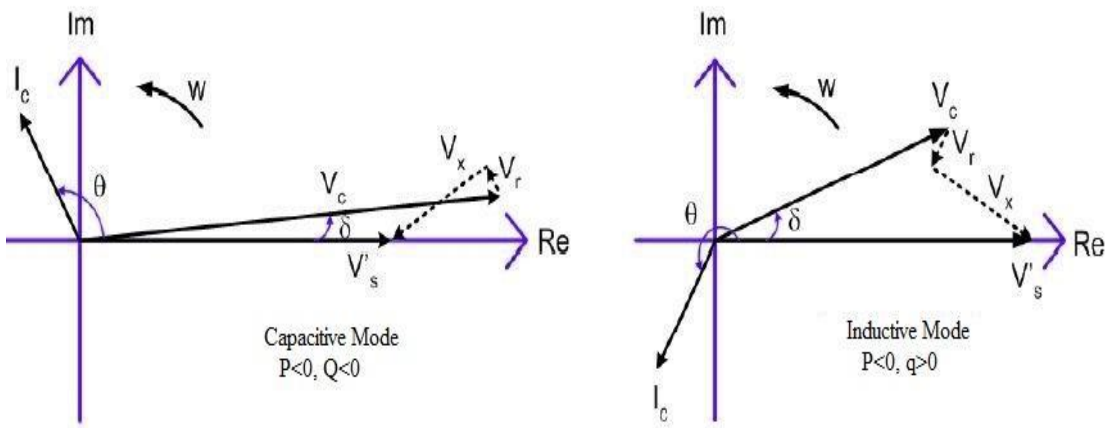

Figure 3.7: The pharos diagrams of capacitive and inductive mode

By making phase angle δ negative, power can be extracted from DC link. If the STATCOM becomes lesser than the extracted power, Pc in becomes negative and STATCOM starts to deliver active power to the source. During this transient state operation, Vd gradually decreases. The phasor diagrams which illustrating power flow between the DC link in transient state and the ac supply is shown in above Figure 3.7. For a phase angle control system, the open loop response time is determined by the DC link capacitor and the input filter inductance. The inductance is applied to filter out converter harmonics and by using higher values of inductance; the STATCOM current harmonics is minimized.

The reference reactive power (Qref) is compared with the measured reactive power (Q). The reactive power error is sent as the input to the PI controller and the output of the PI controller determines the phase angle of the STATCOM fundamental voltage with respect to the source voltage [12].

3.8 PWM Techniques Used In STATCOM

We use sinusoidal PWM technique to control the fundamental line to-line converter voltage. By comparing the three sinusoidal voltage waveforms with the triangular voltage waveform, the three phase converter voltages can be obtained. The fundamental frequency of the converter voltage i.e. f1, modulation frequency, is determined by the frequency of the control voltages, whereas the converter switching frequency is determined by the frequency of the triangular voltage i.e. fs, carrier frequency. Thus, the modulating frequency f1 is equal to the supply frequency in STATCOM.

The Amplitude modulation ratio, ma is defined as:

$$ma = \frac{Vcontrol}{Vtri} \qquad (3.5)$$

Where V control is the peak amplitude of the control voltage waveform and V tri is the peak amplitude of the triangular voltage waveform. The magnitude of triangular voltage is maintained constant and the V control is allowed to vary. The range of SPWM is defined for $0 \leq ma \leq 1$ and over modulation is defied for $(ma>1)$.

The frequency modulation ratio mf is defined as:

$$mf = \frac{fs}{fi} \qquad (3.6)$$

The frequency modulation ratio, mf, should have odd integer values for the formation of odd and half wave symmetric converter line-to-neutral voltage (VA_0). Thus, even harmonics are eliminated from the VA_0 waveform. Also, to eliminate the harmonics we choose odd multiples of 3 for mf.

The converter output harmonic frequencies can be given as:

$$fh = (jmf \pm k)f1 \quad (3.7)$$

The relation between the fundamental component of the line-to-line voltage (VA_0) and the amplitude modulation ratio ma can be gives as:

$$VA0 = ma * \frac{Vd}{2} \quad ; ma \leq 1 \quad (3.8)$$

From which, we can see that VA_0 varies linearly with respect to ma, irrespective of mf. The fundamental component converter line-to-line voltage can be expressed as:

$$Vll = \frac{\sqrt{3}}{2\sqrt{2}} * ma * Vd \quad ; ma \leq 1 (3.9)$$

In this type of PWM technique, we observe switching harmonics in the high frequency range around the switching frequency and its multiples in the linear range. From above equation, we can see that the amplitude of the fundamental component of the converter line-to-line voltage is 0.612maVd. But for square wave operation, we know the amplitude to be 0.78Vd. Thus, in the linear range the maximum amplitude of fundamental frequency component is reduced. This can be solved by over modulation of the converter voltage waveform, which can increase the harmonics in the sidebands of the converter voltage waveform. Also, the amplitude of VLL1 varies nonlinearly with ma and also varies with mf in over modulation as given In a Constant DC Link Voltage Scheme the STATCOM regulates the DC link voltage value to a fixed one in all modes of operation. This fixed value is determined by the peak STATCOM fundamental voltage from the full inductive mode of operation to full capacitive mode at minimum and maximum voltage supply. Therefore, for $0 \leq ma \leq 1$. The fundamental voltage is varied by varying ma in the linear range [13].

3.9 STATCOM Model

Figure 3.8 shows the basic model of a STATCOM which is connected to the AC system bus through a coupling transformer. In a STATCOM, the maximum compensating current is independent of system voltage, so it operates at full capacity even at low voltages. A STATCOM's advantages include flexible voltage control for power quality improvement, fast response, and applicability for use with high fluctuating loads.

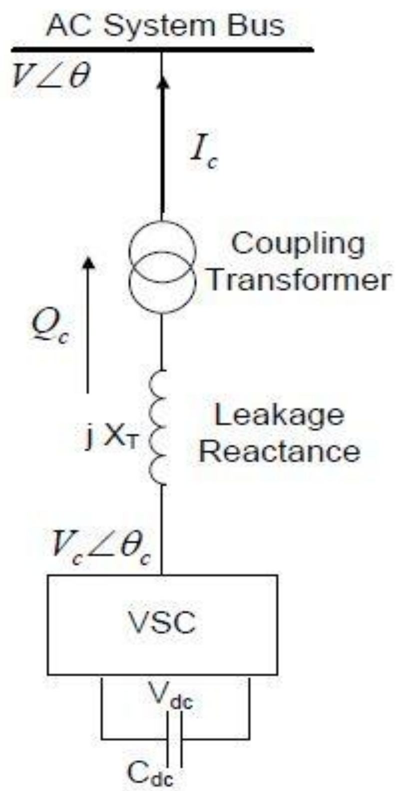

Figure 3.8: Basic model of a STATCOM

The output of the controller *Qc* is controllable which is proportional to the voltage magnitude difference（*Vc*- *V)* and is given by (3.10).

$$Qc = \frac{V(Vc - V)}{X} \quad (3.10)$$

The shunt inverter, transformer and connection filter are the major components of a STATCOM. The control system employed in this system maintains the magnitude of the bus voltage constant by controlling the magnitude and/or phase shift of the voltage source converter's output voltage. By properly controlling iq, reactive power exchange is achieved. The DC capacitor voltage is maintained at a constant value and this voltage error is used to determine the reference for the active power to be exchanged by the inverter.

The STATCOM is a static var generator whose output can be varied so as to maintain or control certain specific parameters of the electric power system. The STATCOM is a power electronic component that can be applied to the dynamic control of the reactive power and the grid voltage. The reactive output power of the compensator is varied to control the voltage at given transmission network terminals, thus maintaining the desired power flows during possible system disturbances and contingencies.

STATCOMs have the ability to address transient events at a faster rate and with better performance at lower voltages than a Static Voltage Compensator (SVC). The maximum compensation current in a STATCOM is independent of the system voltage. Overall, a STATCOM provides dynamic voltage control and power oscillation damping, and improves the system's transient stability. By controlling the phase angle, the flow of current between the converter and the ac system are controlled. A STATCOM was chosen as a source for reactive power support because it has the ability to continuously vary its susceptance while reacting fast and providing voltage support at a local node. Figure 3.9 below show the block diagram of the STATCOM controller.

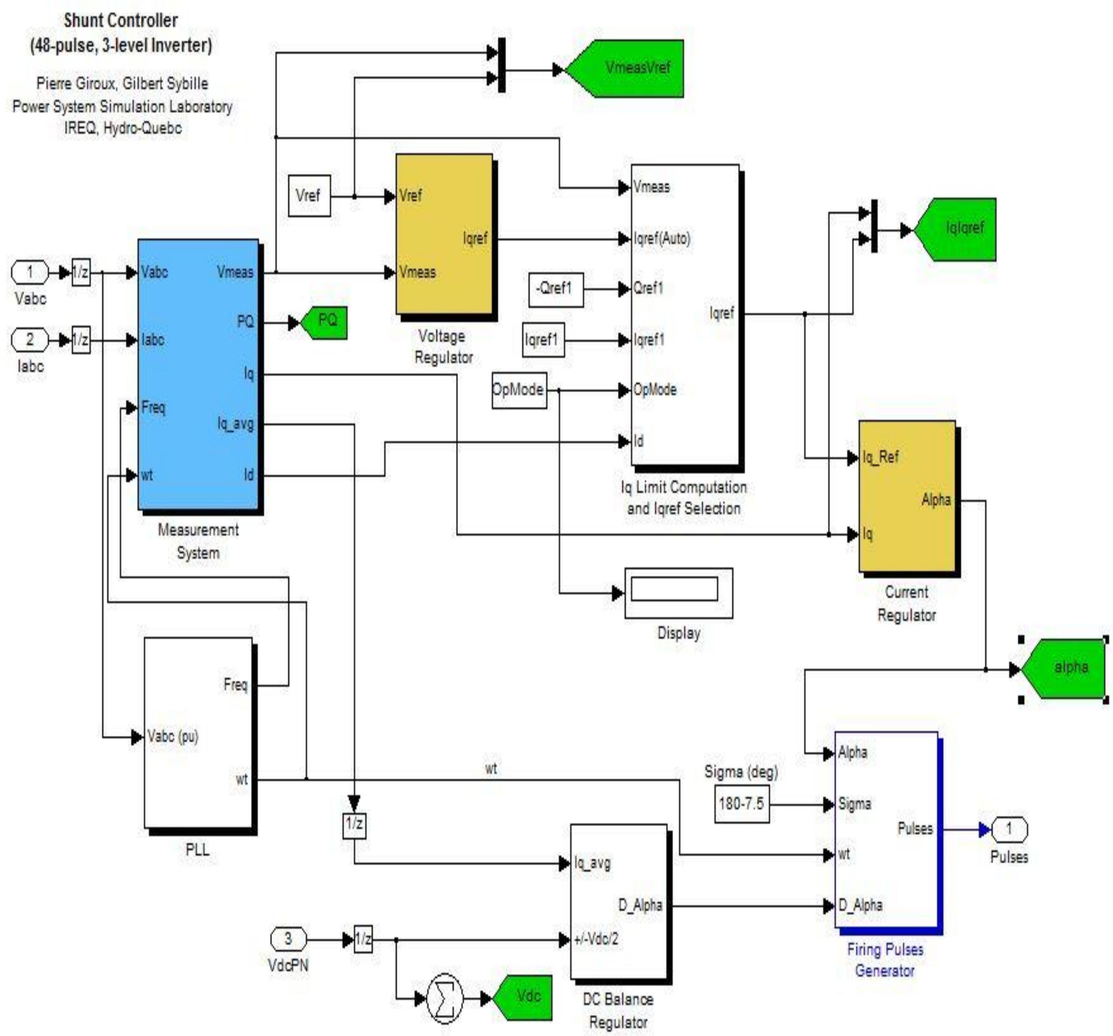

Figure 3.9 Control scheme of the STATCOM

By controlling the phase and magnitude of the STATCOM output voltage, the power exchange between the AC system and the STATCOM can be controlled effectively. The outputs of the controller are id_ ref and iq _ref which are the reference currents in the dq coordinates which are needed to calculate the power injections by the STATCOM as in (3.11) and (3.12).

$$Pinj = Vi(idcos\theta i + iqsin\theta i) = vdid + vqiq \tag{3.11}$$

$$Qinj = Vi(idsin\theta i - iqcos\theta i) = -vdid + vqiq \tag{3.12}$$

The STATCOM ratings are based on many parameters which are mostly governed by the amount of reactive power the system needs to recover and ride through typical faults on the power system and to reduce the interaction of other system equipment that can become out of synchronism with the grid. Although the final rating of the STATCOM is determined based on system economics, the capacity chosen will be at least adequate for the system to stabilize after temporary system disturbances. The type of faults that the system is expected to recover from also determines the size of the STATCOM. For example, a three phase impedance fault of low impedance requires a very high rating STATCOM while a high impedance short circuit fault needs a lower rating device to support the system during the fault and help recover after the fault. The converter current ratings and the size of the capacitor also decide the capability of the STATCOM [13].

3.10 Location of STATCOM

Simulation results show that STATCOM provides effective voltage support at the bus to which it is connected to. The STATCOM is placed as close as possible to the load bus for various reasons. The first reason is that the location of the reactive power support should be as close as possible to the point at which the support is needed. Secondly, in the studied test system the location of the STATCOM at the load bus is more appropriate because the effect of voltage change is the highest at this point. The location of the STATCOM is based on quantitative benefits evaluation. The main benefits of using a STATCOM in the system are reduced losses and increased maximum transfer capability. The location of STATCOM is generally chosen to be the location in the system which needs reactive power. To place a STATCOM at any load bus reduces the reactive power flow through the lines thus reducing line current and also the I^2R losses. Shipping of reactive power at low voltages in a system running close to its stability limit is not very efficient. Also, the total amount of reactive power transfer available will be influenced by the transmission line power factor limiting factors. Hence, sources and compensation devices are always kept as close as possible to the load [14].

3.11 STATCOM versus SVC

- V-I and V-Q characteristics: STATCOM can be operated over its full output current range even at very low system voltage levels. In other words, the maximum capacitive or inductive output current of the STATCOM can be maintained independently of the AC system voltage, and the maximum Var generation or absorption changes linearly with the AC system voltage. Reversely, the maximum attainable compensating current of SVC decreases linearly with AC system voltage, and the maximum var output decreases with the square of this voltage. The STATCOM is superior to the SVC in providing voltage support under large system disturbances during which the voltage excursions would be well outside of the linear operating range of the compensator. The capability of providing maximum compensating current at reduced system voltage enables the STATCOM to perform in a variety of applications the same dynamic compensation as an SVC of considerably higher rating.
- Transient stability: The ability of the STATCOM to maintain full capacitive output current at low system voltage makes it more effective than the SVC in improving the transient stability. The transmittable power can be increased if the shunt compensation is provided by a STATCOM rather than by an SVC.
- Response time: SVC includes TCR (thyristor controlled reactor), which per-phase can be controlled per half cycle through changing the firing angle, and TSC (thyristor switched capacitor), which needs a full cycle to

upgrade for a transient-free switching. With the semiconductor device having turn-off capability and VSC technology, STATCOM can update its control at least within half-cycle with line switching frequency.

- Capability to exchange real power: STATCOM, in contrast to SVC, has the unique capability to interface with an energy storage system, exchange real power with the power network in bi-directions, and independently control both reactive power and real power.
- Harmonics: With the innovation of VSC topologies and fast switching semiconductor devices and modulation methods, the harmonics emission of STATCOM is very low and a filter is not required.
- Loss vs. Var output characteristic: Both STATCOM and SVC have relatively low loss nearby zero Var output. The loss contribution of power semiconductors and related components to the total compensator losses are higher for the STATCOM than for the SVC. However, the rapid semiconductor developments will reduce the device losses, and the technological advances probably will have help to reduce the overall losses of the STATCOM more than those of the SVC.
- Physical size and installation: With high power density of semiconductor devices and VSC capability to circulate reactive power, STATCOM does not need large capacitor and reactor banks, which are used in conventional SVCs. Thus, overall size is significantly reduced (about 30～40%) for STATCOM.
- Lifetime: Compared to a typical life of thousands operation times for mechanical breakers or switches, a semiconductor device has almost infinite switching cycles. With less passive components, STATCOM has an even longer lifetime than SVC. With fast development and

improvement of semiconductor devices, the lifetime of STATCOM is expected to be improved further [1].

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

The relatively recent development and use of FACTS controllers in power transmission systems has led to many applications of these controllers to improvement the stability of power networks [15,16]. Several FACTS equipment is readily available or still under development, based on the solid state switch with conventional thyristors and on the voltage source inverter with GTO switches. All these equipment provide controllability to the AC transmission system by adjusting the reactive power in shunt, the series impedance of transmission line, or the active and reactive power in series [17].The STATCOM was proposed by several researchers to compensate the reactive current from or to the power system. This function is identical to the synchronous condenser with rotating mass, but its response time is extremely faster than of the synchronous condenser. This rapidity is very effective to increase transient stability, to enhance voltage support, and to damp low frequency oscillation for the transmission system [18].In this project a controller design and a simulation model development with the SIMULINK/MATLAB program are performed to verify the transient stability and compensation of reactive power of AC transmission system.

Figure 4.1below shows single line diagram of two area system (area 1 & area 2). Area1 (1000 MW hydraulic generation plant) connected to area 2 (5000 MW hydraulic generation Plant) through 500 kV, 700 km transmission line.

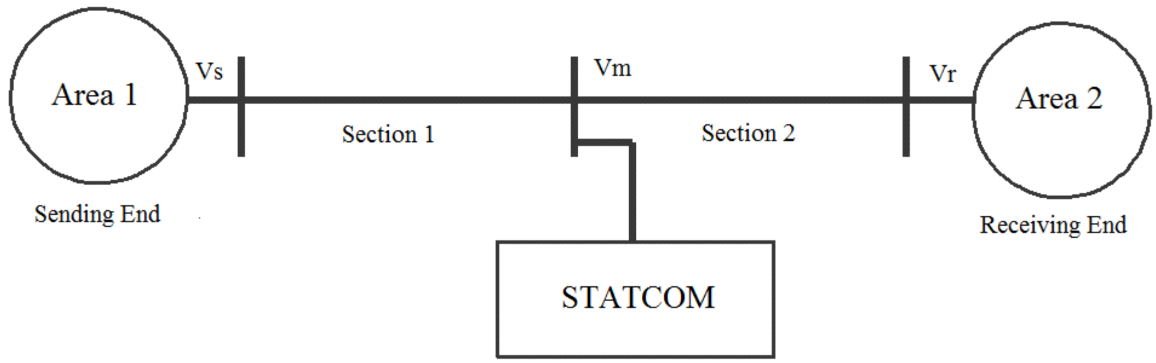

Figure 4.1: Single Line Diagram of Two Area Interconnected System

Both plants fed to a load center, modeled by a 5000 MW resistive load. System is initialized so that line carries 950 MW which is close to its surge impedance loading. In order to maintain system stability Static synchronous compensator of 200 MVA is connected at midpoint of transmission line. By connecting it at midpoint the power transfers capability of system increases significantly [19,20].

4.2 Simulation Model of Two Machine System

Simulink Model of two machines (M1 & M2) system installed with STATCOM controller is shown in Figure 4.2.Machine M1 referred to a 1000 MW hydraulic generation plant while Machine M2 referred to 5000 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, 700km transmission line. Resistive load of 5000MW connected on Machine M2 side. GTO based STATCOM having rating of 200 MVA connected at midpoint of transmission line.

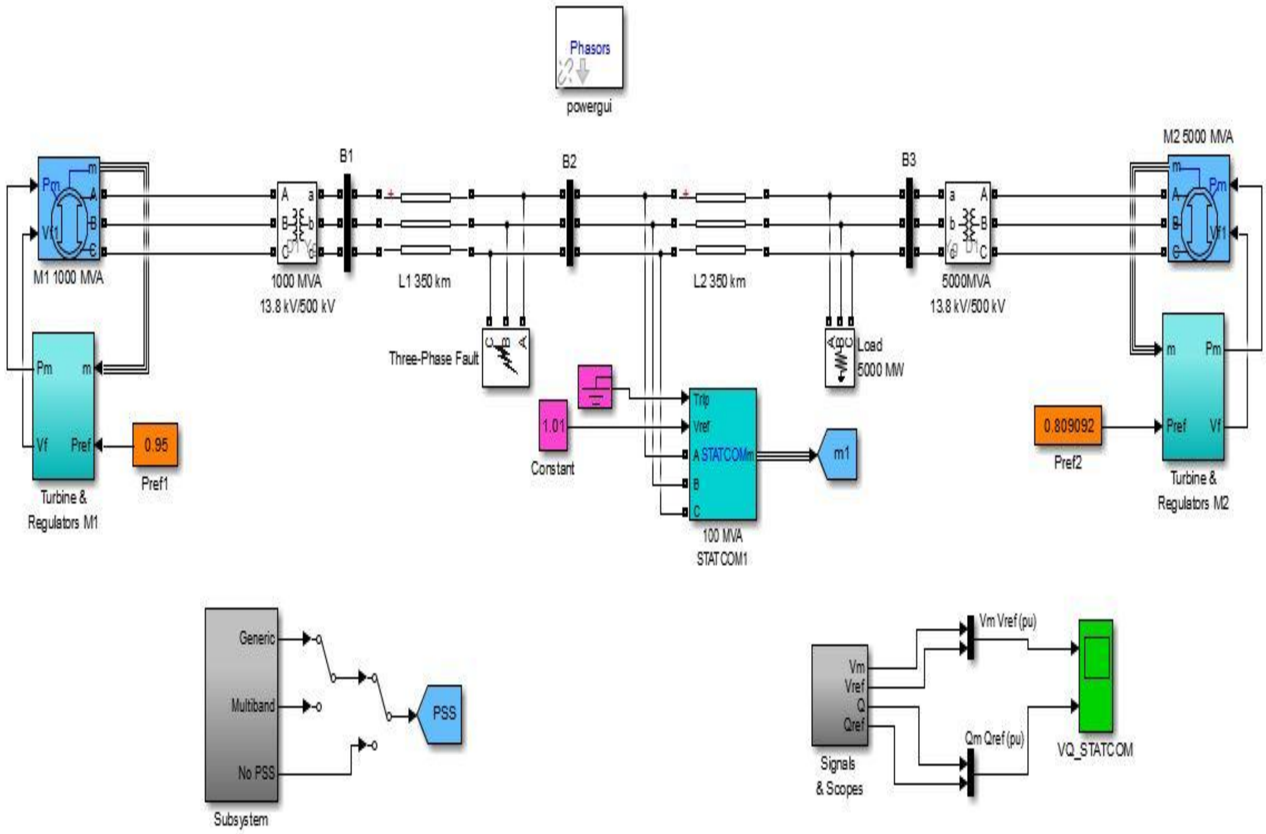

Figure 4.2: Two machine system installed with STATCOM Controller

4.3 Simulation Results

The simulation result shows the system response during fault and after STATCOM installed and show comparison between STATCOM and SVC.

4.3.1 System results without and with STATCOM controller

A three phase fault applied for (0.1 sec) during time period from (1.0 sec to1.1 sec).Figure 4.3 to Figure 4.16below shown the System results before and after STATCOM installed under three phase fault.

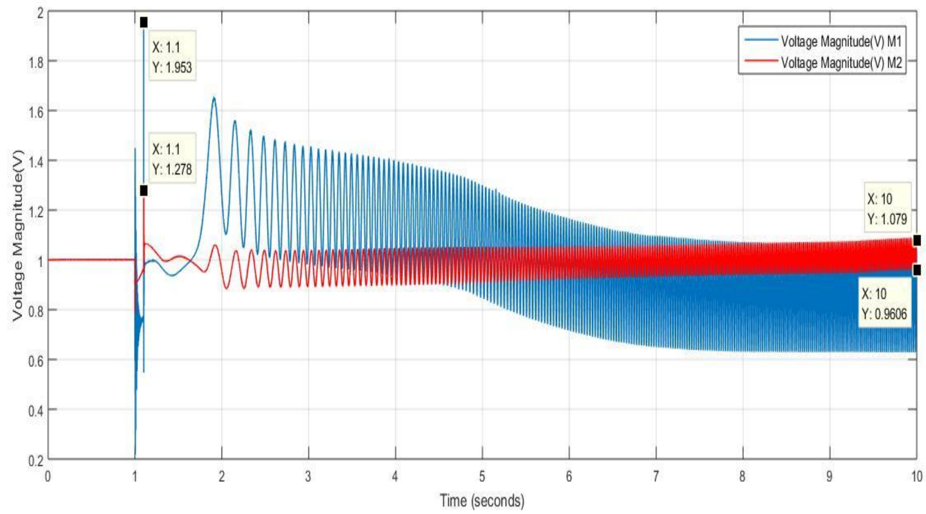

Figure 4.3: Voltage magnitude (V) without STATCOM controller

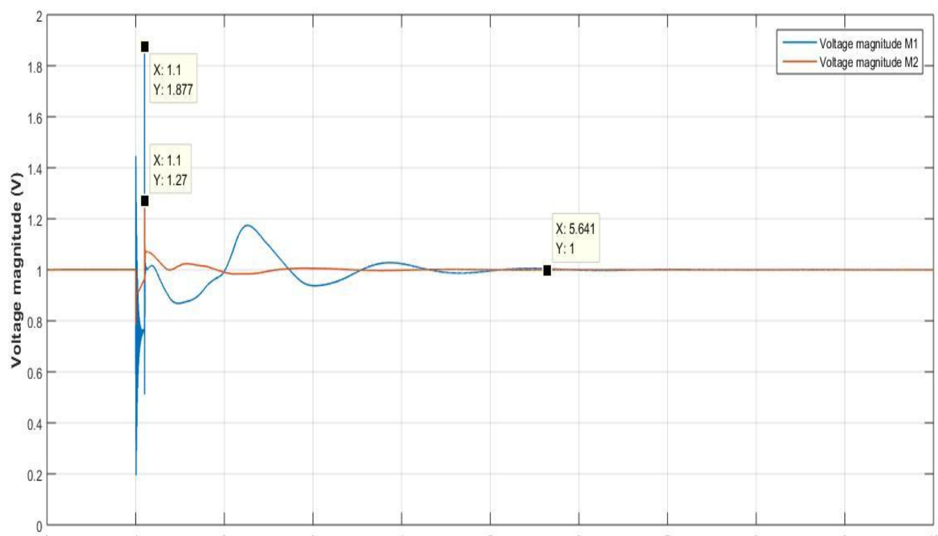

Figure 4.4: Voltage magnitude (V) with STATCOM controller

Before three phase fault the magnitude voltage was (1pu) even 1.0sec.After three phase faults at 1.1sec, the voltage of system became unstable shown in Figure 4.3 above after 10sec magnitude voltage became (1.079 for M1 and 0.9606 for M2). When STATCOM controller installed the system voltage became stable after 5.641sec and magnitude voltage referred to (1pu) as shown in Figure 4.4 above and maximum over shoot decrease (from 1.953 to 1.877 for M1& from 1.278 to 1.27for M2).

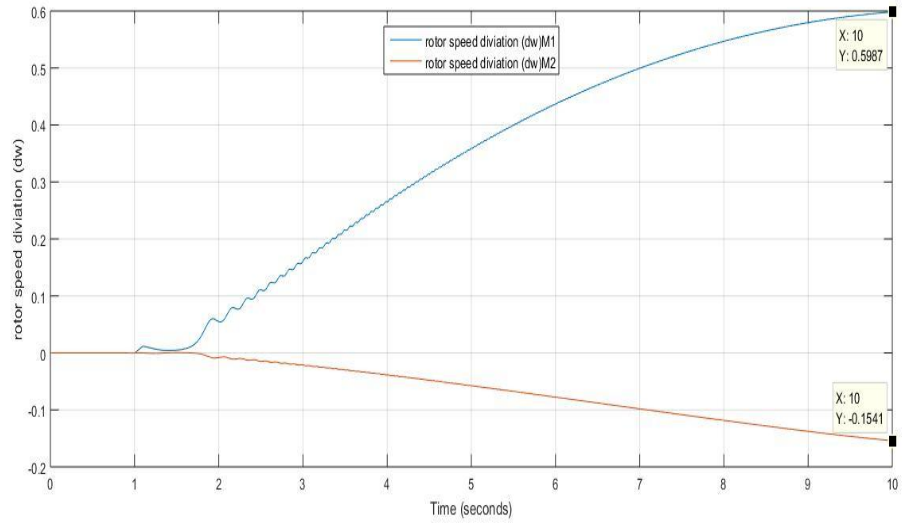

Figure 4.5: Rotor speed deviation (dw) without STATCOM controller

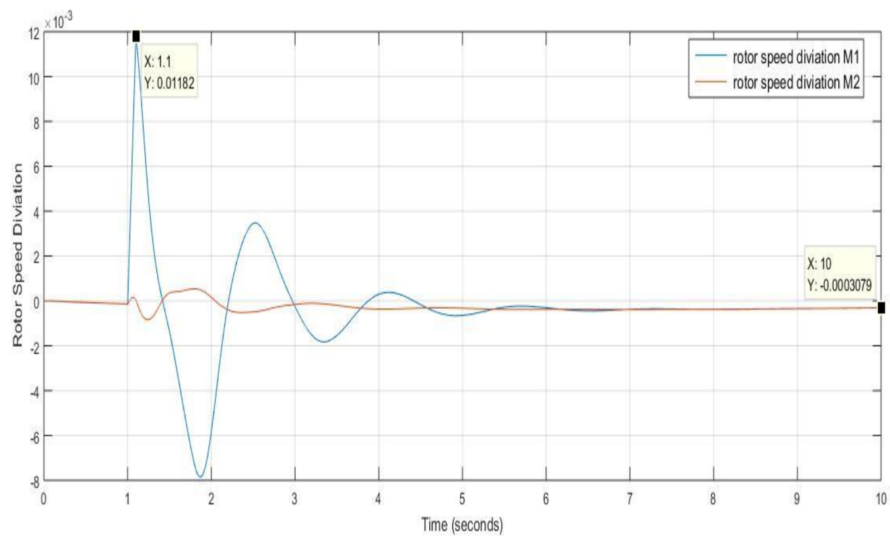

Figure 4.6: Rotor speed deviation (dw) with STATCOM controller

Before three phase fault the rotor speed deviation was zero even1.0 sec. After three phase faults at1.1sec, the rotor speed deviation of two machine shown in Figure 4.5 above became (0.5987 for M1 and -0.1541 for M2).When STATCOM controller installed the rotor speed deviation becomes (-0.000379) after 10sec as shown in Figure 4.6 above and maximum over shoot decrease to (0.001182 for M1 and .000523 for M2) and the number of cycle decrease to three cycles.

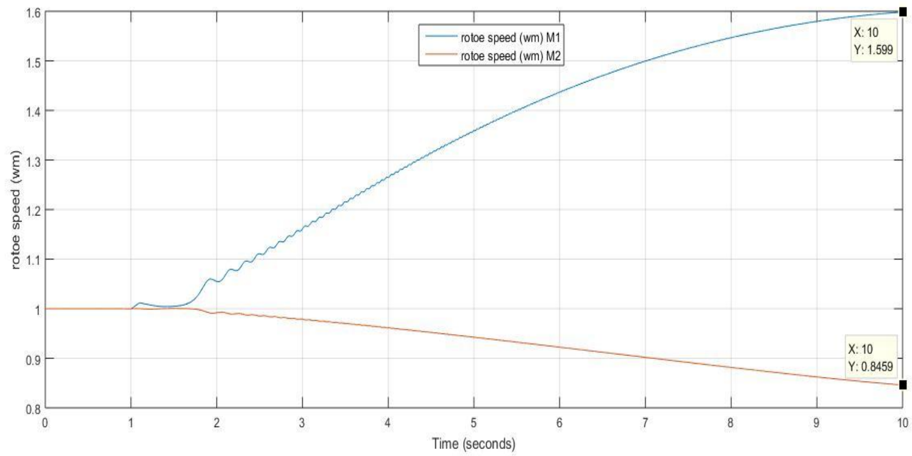

Figure 4.7: Rotor speed (wm) without STATCOM controller

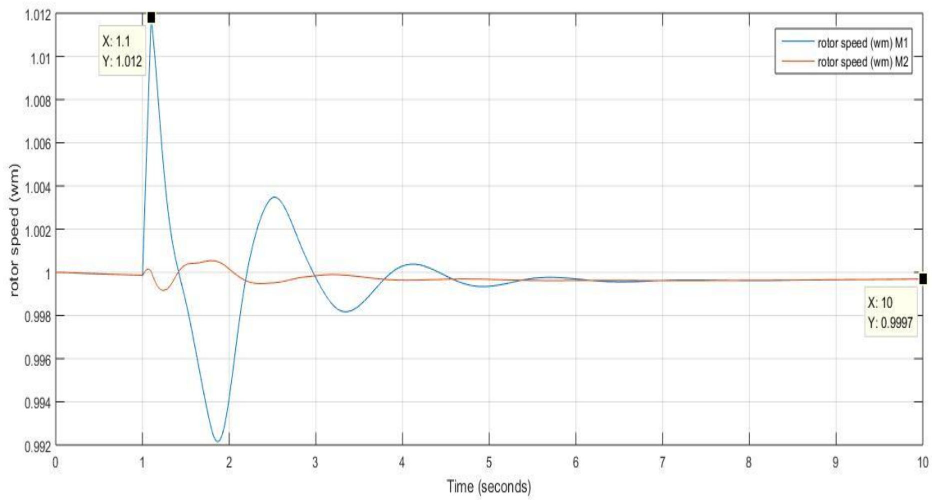

Figure 4.8: Rotor speed (wm) with STATCOM controller

Before three phase fault the rotor speed was (1pu) even1.0 sec. After three phase faults at 1.1sec, the rotor speed of two machine as shown in Figure 4.7above it is became (1.599 for M1 and 0.8459 for M2).When STATCOM controller installed the rotor speed became (0.9997) after 10sec as shown in Figure 4.8above and maximum over shoot decrease to (1.1012 for M1 and 0.523 for M2) and the number of cycle decrease to three cycles.

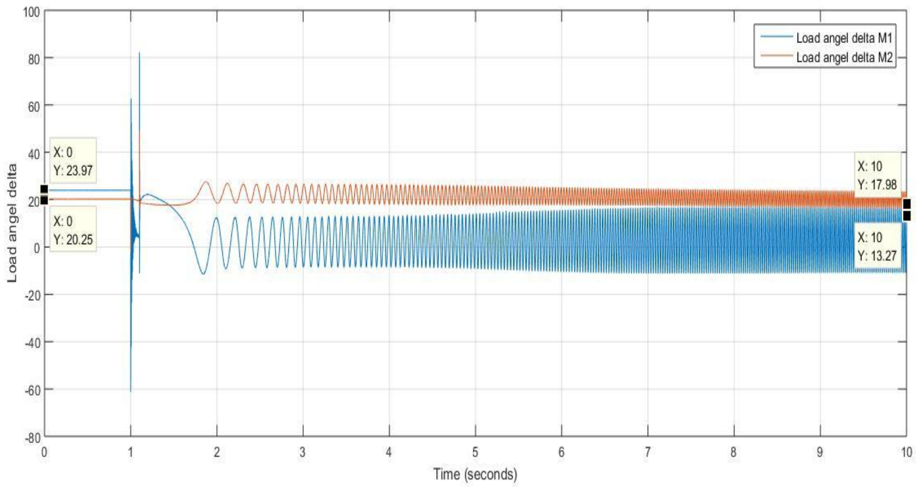

Figure 4.9: Load angle without STATCOM controller

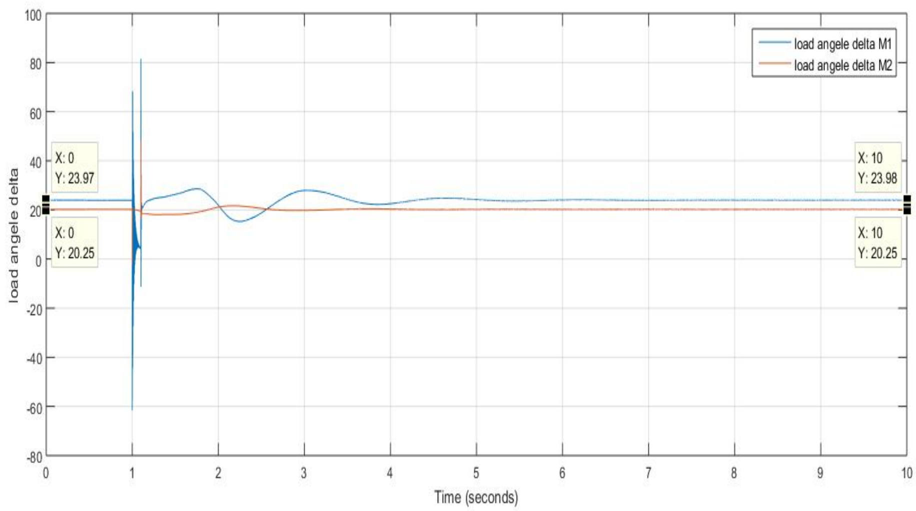

Figure 4.10: Load angle with STATCOM controller

Before three phase fault the load angle was (23.97for M1 and 20.25for M2) even1.0 sec. After Three phase faults at1.1secthe load angle of two machine becomes (17.98 for M1 and 13.27 for M2) after 10sec shown in Figure 4.9 above. When STATCOM controller installed the load angle became (23.98 for M1 and 20.25 for M2) as shown in Figure 4.10above with no change in maximum over shoot before and after STATCOM installed and the number of cycle decrease to three cycles.

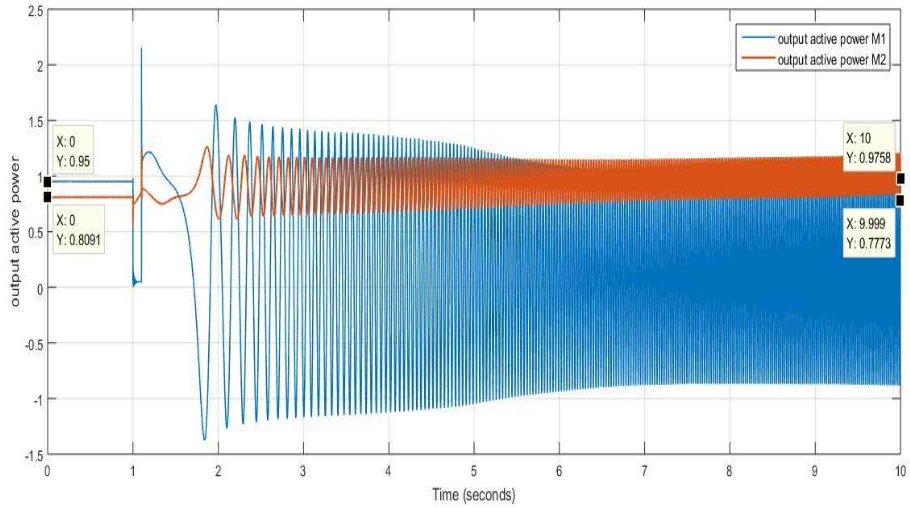

Figure 4.11: Output active power without STATCOM controller

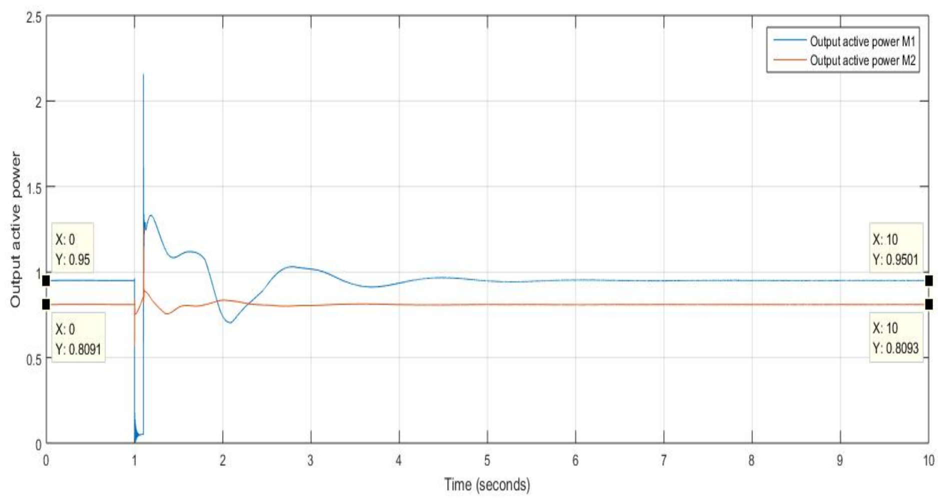

Figure 4.12: Output active power with STATCOM controller

Before three phase fault the output active was (0.95 for M1and 0.8091 for M2) even1.0 sec. After three phase faults at 1.1 sec, the output active power became (zero for M1 and 0.48 for M2) after 10sec output active power became (0.9758 for M1 and 0.7773 for M2) as shown in Figure 4.11above.When STATCOM controller installed output active power after 10sec became (0.9501 for M1 and 0.8093 for M2) as shown in Figure 4.12above with no change in maximum over shoot before and after STATCOM installed and the number of cycle decrease to three cycles.

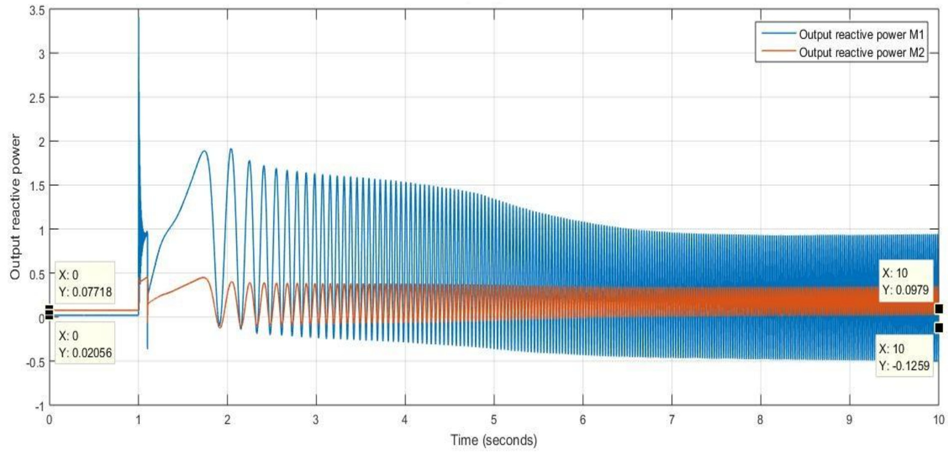

Figure 4.13: Output reactive power without STATCOM controller

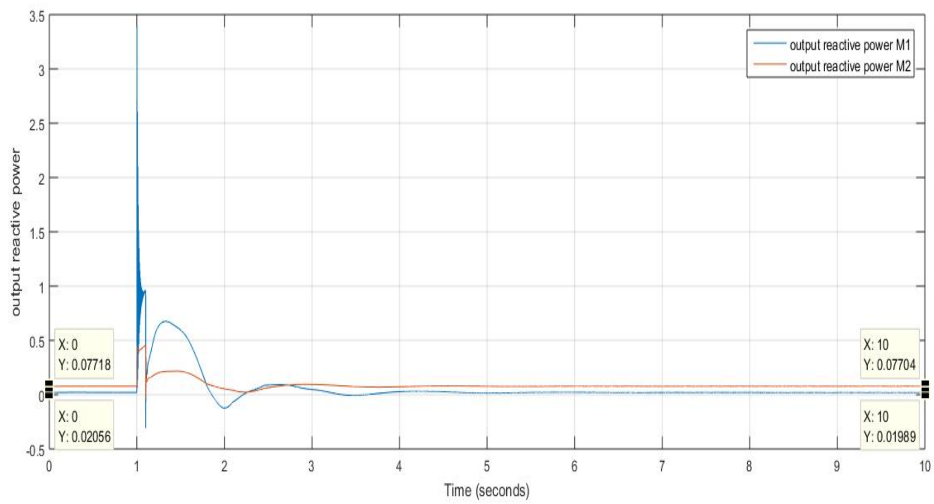

Figure 4.14: Output reactive power with STATCOM controller

Before three phase fault the output reactive was (0.07718 for M1and 0.02056 forM2) even 1.0 sec. After Three phase faults at1.1sec, output reactive power decrease to (-.45 and M1 and -0.1 for M2) after 10sec output reactive power became (0.0979 for M1 and -0.1259 for M2) shown in Figure 4.13.When STATCOM controller installed output reactive power after 10sec became (0.07704 for M1 and 0.01989 for M2) as shown in Figure 4.14 and with no change in maximum over shoot before and after STATCOM installed and the number of cycle decrease to two cycles.

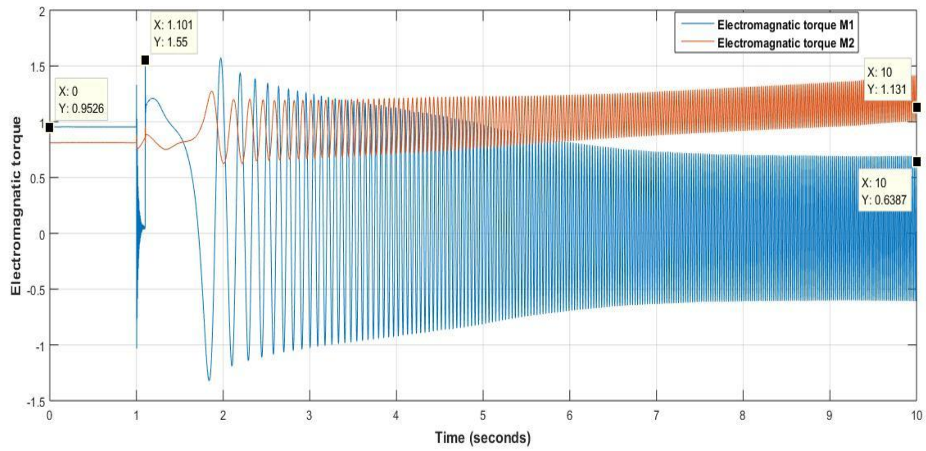

Figure 4.15: Electromagnetic torque without STATCOM controller

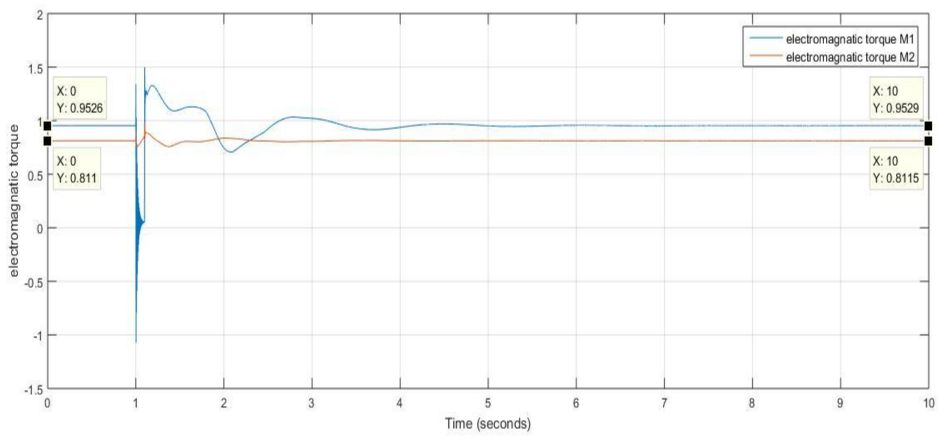

Figure 4.16: Electromagnetic torque with STATCOM controller

Before three phase fault the electromagnetic torque was (0.9526for M1and 0.811for M2) even 1.0 sec. After three phase faults at 1.1sec, electromagnetic torque decrease to (-1.0 and M1 and 0.2 for M2) after 10sec electromagnetic torque became (0.6387 for M1 and 1.31 for M2) shown in Figure 4.15above. When STATCOM controller installed electromagnetic torque after 10secbecomes (0.9529 for M1 and 0.8115 for M2) as shown in Figure 4.16above and with no change in maximum over shoot before and after STATCOM installed and the number of cycle decrease to two cycles.

4.3.2STATCOM Scopes

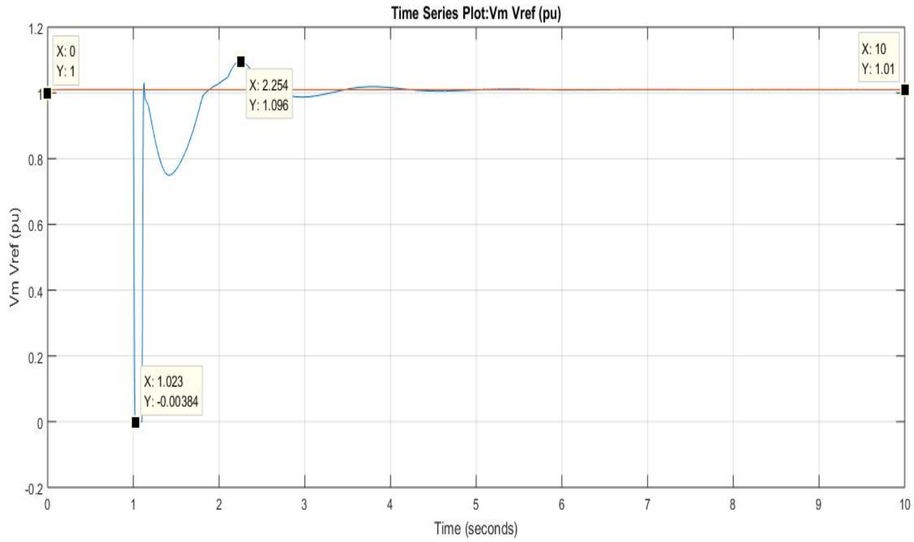

Figure 4.17: reference voltage (Vref) VS maximum rate of voltage change of STATCOM controller (Vm)

Before fault reference voltage set to (1.01pu) of STATCOM .After three fault occurs the STATCOM operate as voltage regulate mode ,the reference voltage Decrease to (-0.00384) minimum over shoot and increase to (1.096pu) maximum over shoot and after 10sec the system become stable and the voltage referred to set value (1.01pu) as shown in Figure 4.17 above.

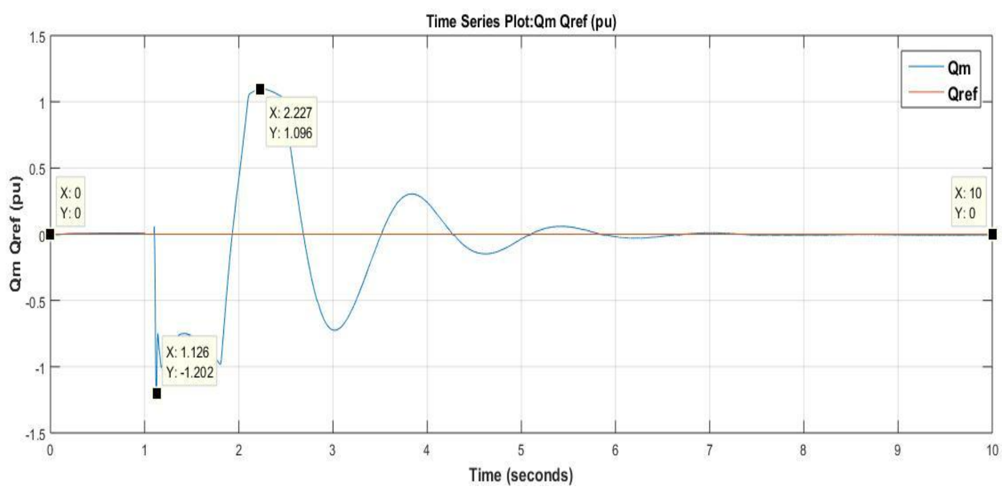

Figure 4.18: reference reactive power (Qref) and maximum rate of change of reactive power STATCOM controller (Qm)

Before fault no reactive power injected or absorbed by STATCOM because the system is stable. After three fault occurs the STATCOM operate as voltage regulate mode, the STATCOM absorb reactive power from system by minimum over shoot (-1.226) at 1.1sec and injected reactive power to system by maximum over shoot (1.096) at 2.5sec .Then the STATCOM absorb and injected reactive power even the system become stable .After10sec the system become stable and the reactive power referred to zero again as shown in Figure 4.18 above.

4.3.3 SVC Scopes compared with STATCOM

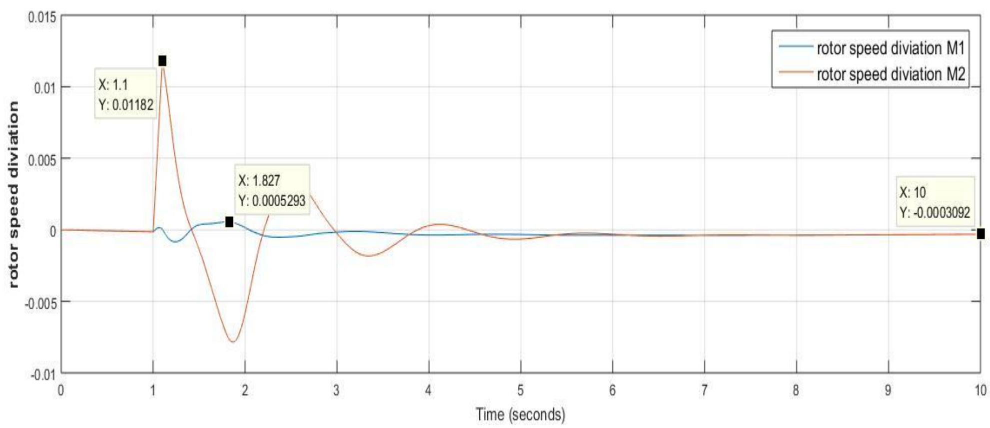

Figure 4.19: Rotor speed deviation (dw) with STATCOM controller

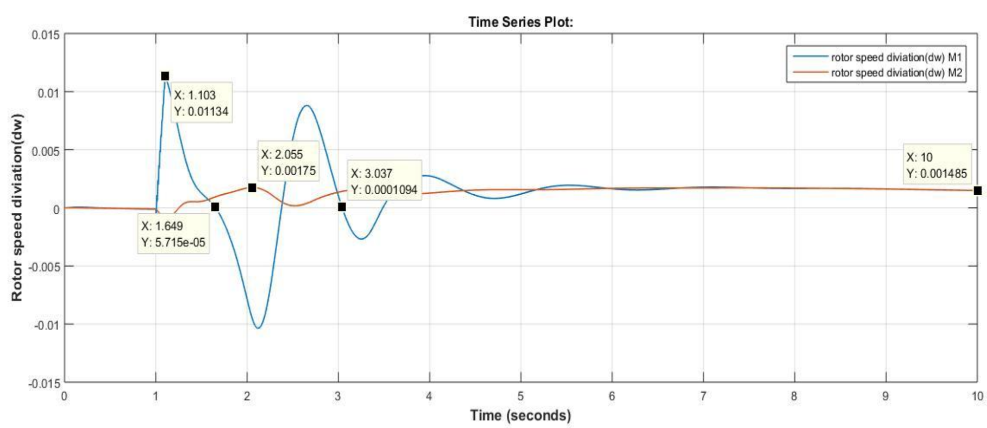

Figure 4.20: Rotor speed deviation (dw) with SVC controller

Figure 4.19 and Figure 4.20 above showed the rotor speed deviation with STATCOM and SVC. Figure 4.19 show the maximum over shoot of rotor speed deviation with STATCOM is (0.01182 for M1).Figure 4.20 show the maximum over shoot of rotor speed deviation with SVC is (0.01134 for M1) and it is less than STATCOM, but after stability rotor speed deviation became (-0.0003079) with STATCOM and became (0.001485) with SVC.

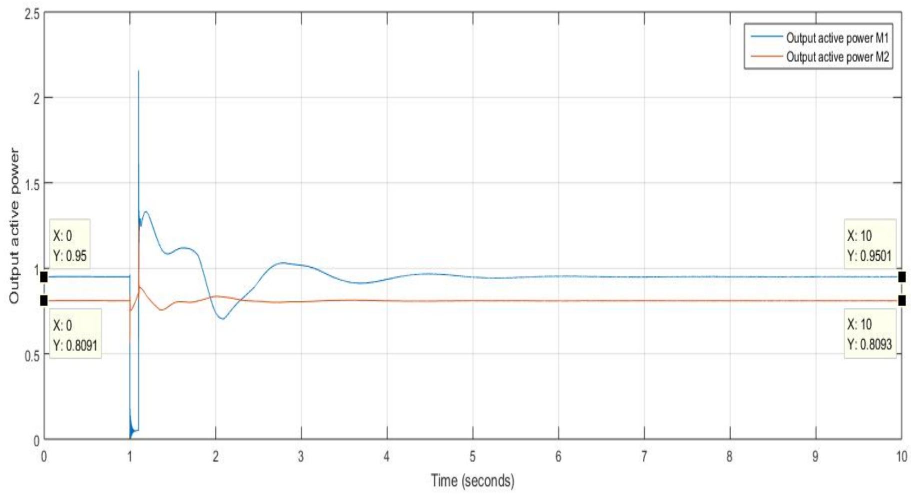

Figure 4.21: Output active power with STATCOM controller

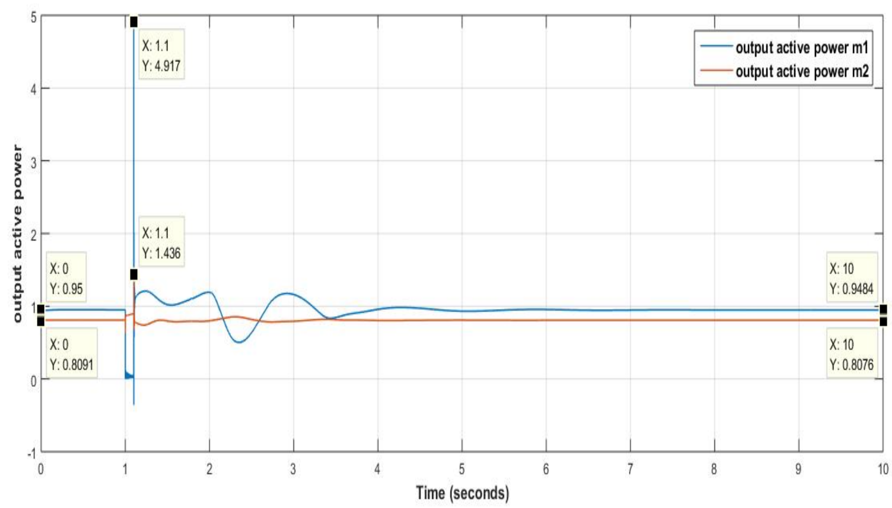

Figure 4.22: Output active power with SVC controller

Figure 4.21 and Figure 4.22 above showed the Output active power with STATCOM and SVC. Figure 4.21 showed the maximum over shoot of Output active power of STATCOM is (2.2) and figure 4.22 shows the maximum over shoot of Output active power of SVC is (4.917) and it is more than with

STATCOM. After stability Output active power became (0.95) with STATCOM and became (0.9484) with SVC for M1.

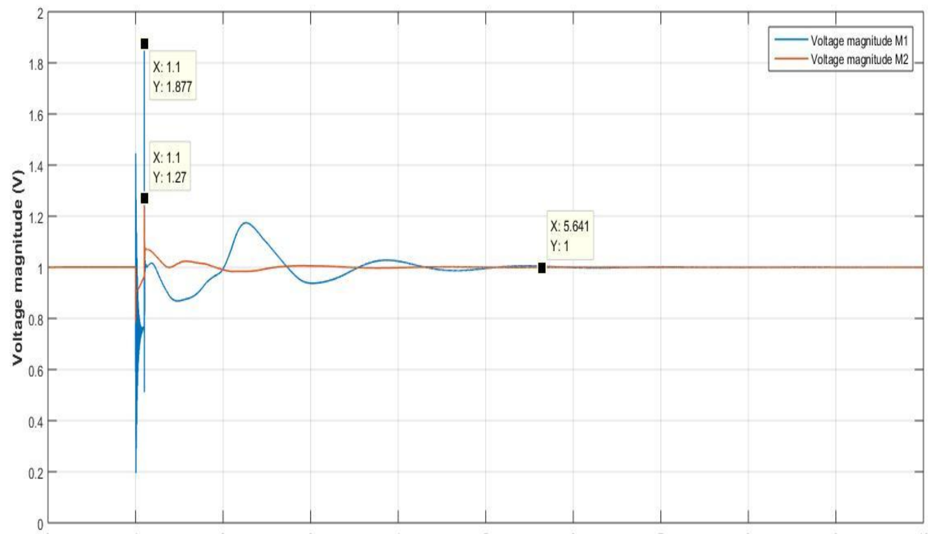

Figure 4.23: Voltage magnitude (V) with STATCOM controller

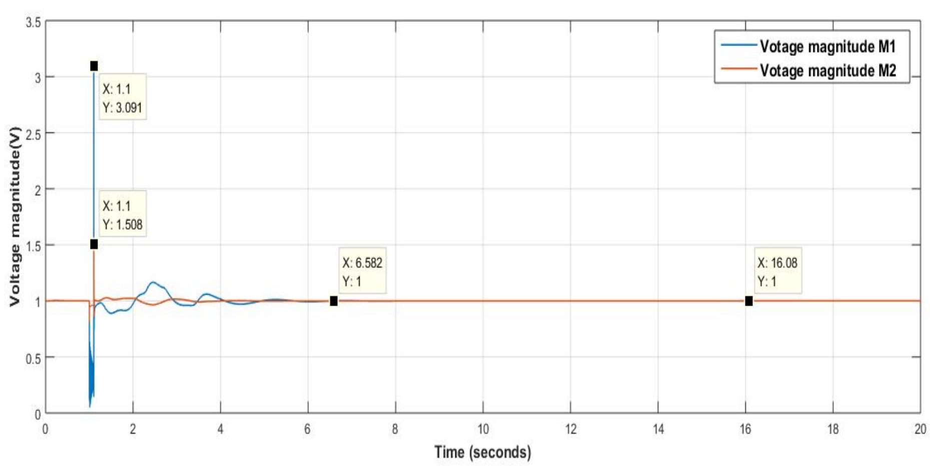

Figure 4.24: Voltage magnitude (V) with SVC controller

Figure 4.23 and Figure 4.24 above showed the Voltage magnitude with STATCOM and SVC. Figure 4.23 showed the maximum over shoot of Voltage magnitude with STATCOM is (1.87) and Figure 4.24 showed the maximum over shoot of Voltage magnitude with SVC is (3.091) more than STATCOM. After system gone to stability Voltage magnitude became same as reference voltage with STATCOM and similar that with SVC for M1.

All above results demonstrated that STATCOM controller improved transient stability and increased damping oscillation ratio and with compared it with SVC controller the above Figures and after calculation the damping ratio for STATCOM (98%) and SVC (33.6%) all this result show the STATCOM controller is better than SVC controller in improving transient stability and in damping the oscillation.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In this project a control system of the STATCOM was presented for the transient stability improvement. The test system was a two machine 500kV AC transmission system. And a simulation model with the MATLAB/SIMULINK was developed to verify the interaction between the STATCOM and AC transmission system. Simulation results in chapter four show that using STATCOM can improve the transient stability of AC transmission system and it is able to compensating the reactive power. Therefore STATCOM can increase reliability and capability of AC transmission system.

5.2 Recommendations

We are recommended for the future studies:

- To use detailed model of STATCOM controller to improve transient stability.
- To use FUZZY controller with STATCOM.
- To use another device of FACTS controllers.

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