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ENHANCEMENT OF POWER STABILITY AND DAMPING OSCILLATION IN MULTI MACHINE SYSTEM USING (SSSC) WITH POD CONTROLLER

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Enhancement of Power Stability and Damping Oscillation In Multi Machine System Using (SSSC) With POD Controller

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Rizan Ahmed ALI

ABSTRACT

ENHANCEMENT OF POWER STABILITY AND DAMPING OSCILLATION IN MULTI MACHINE SYSTEM USING SSSC WITH POD CONTROLLER

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When power system is heavily loaded due to the continuous demand in this case causes active and reactive power to be instable and insufficient. In this thesis, a proper approach has been presented to compensate active and reactive power and also damping oscillations in a multi-machine system consisting of four machines, six buses using Static Synchronous Series Compensator (SSSC). SSSC can be considered one of the most significant series compensation of flexible alternating current transmission system (FACTS) family used in power transmission systems. Both single phase and three phase faults have been considered in the study. Simulation studies of the presented approach have done with SSSC, without SSSC, and finally with SSSC and Power System Damper (POD). Simulation results showed that the system became unstable with oscillations when SSSC has been not used. It can be concluded from simulation results that When SSSC is inserted in the power network, the power transfer is increased and oscillations are reduced. When SSSC is used with POD controller, the system becomes stable in faster way than without controller. In a result, the system performance has been greatly improved and power system oscillations have been reduced and damped out very quickly by using SSSC and POD.

Keywords— Flexible AC Transmission System Controller, Static Synchronous Series Compensator, Power Oscillation Damper.

ÖZET

POD KONTROLÜ SSSC İLE ÇOKLU MAKİNE SİSTEMİNDE SÖNÜMLEME SALINIMLARININ VE GÜÇ İSTİKRARININ IYILEŞTİRİLMESİ

ALI, Rizan Ahmed
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Güç sistemi sürekli ağır talep nedeniyle yüklendiğinde bu durum aktif ve reaktif gücün kararsız ve yetersiz olmasına neden olur. Tezde, dört makine, altı bara içeren çoklu makine sisteminde aktif ve reaktif güç ve aynı zamanda sönümleme salınımlarını telafi etmek için Statik Senkron Seri kompanzasyon (SSSC) kullanarak uygun bir yaklaşım sunulmuştur. SSSC güç iletim sistemlerinde kullanılan esnek alternatif akım iletim sistemi (FACTS) ailesinin en önemli seri kompanzasyonu olarak kabul edilebilir. Önerilen yaklaşımın benzetim çalışmaları SSSC ile, SSSC olmaksızın ve son olarak SSSC ve güç sistem söndürücü (POD) ile yapılmıştır. Benzetim çalışmaları SSSC kullanılmadığında sistemin salınımlarla kararsız olmaya başladığını gösterdi. Benzetim sonuçlarından SSSC'nin güç şebekesine dahil edildiğinde güç transferinin artığı ve salınımların azaldığı sonucu çıkartılabilir. SSSC, POD kontrol cihazı ile kullanıldığında sistem kontrol cihazı kullanılmadığı durumdan daha hızlı kararlı hale gelmektedir. Sonuç olarak, POD ve SSSC kullanımı ile sistem performansı büyük ölçüde iyileştirmiştir ve güç sistemi salınımları azaltılmıştır ve çok hızlı bir şekilde sönümlenmiştir.

Anahtar kelimeler: Esnek AC İletim Sistemi Kontrolörü, Statik Seri Senkron Kompansatör, Güç Salınım söndürücü.

Dedicated to

“All My Family”

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LIST OF SYMBOLS /ABBREVIATIONS

FACTS	Flexible AC transmission systems
SSSC	Static Synchronous Series Compensator
STATCOM	Synchronous Static Compensator
POD	power oscillations damping
PSC	Power System Controller
p.u	Per unit
TCSC	Thyristors- controlled Series Capacitor
TSR	Thyristor-Switched Inductor
TSC	Thyristor-Switched Capacitor
TCSR	Thyristor-Controlled Series Reactor
IPFC	Interline Power Flow Controller
UPFC	Unified Power Flow Controller
TCPAR	Thyristor Controlled Phase Angle Regulator
SVC	Static Var Compensator
DPFC	Dynamic Power Flow Controller
VSC	Voltage Source Converter
Vs	Sending end voltages
Vr	Receiving end voltage
δ	Phase angle
P	Active Power
Q	Reactive Power
MW	Megawatt
MVA	Mega volt amper
Mvar	Mega volt amper reactive
B	Bus
FC-TCR	Fixed Capacitor Thyristor-Controlled Reactor
GTO	Gate turn-off thyristor
IGCT	Integrated Gate-Commutated Thyristor
IGBT	Insulated-gate bipolar transistor

PWM	Pulse-Width Modulation
Tw	Time constant
PLL	Phase-locked loop
AVR	Automatic voltage regulator
GCC	Gulf Cooperation Council
HVDC	High-voltage direct current
PI	Proportional-Integral Controller
PID	Proportional–integral–derivative controller
IGCT	Integrated Gate-Commutated Thyristor

CHAPTER 1

INTRODUCTION

1.1 General

The stability of a power system can be defined as the capability of an electric power system to regain a condition of operating equilibrium, for any given initial operating condition, after being to physical disturbances where most of the system variables are bounded so that the whole system remains intact. This form of power stability can be achieved through the use of flexible AC transmission systems (FACTS), which are considered to be the prominent ones when desiring to power system operations as well as increasing the power transfer capacity. The flexible AC transmission systems are noted to exploit switching devices that are power electronic based to improve stability and to control the flow of power in the lines [1].

After widespread research and development, the flexible AC transmission system devices are considered now to be a mature and proven technology. The controllability and the flexibility that the devices are observed to provide the most efficient and reliable solutions when it comes to power systems. The flexible AC transmission systems can then be defined as the transmission systems of alternating current that incorporate in them electronics based on power and other controllers that are static to improve the capability of power transfer and controllability. Tentatively, their main aim is to supply reactive power that is either capacitive or inductive, while improving the quality of transmission and power system stability.

One member of the flexible AC transmission systems (FACTS) device is the Static Synchronous Series Compensator (SSSC) that connects to the transmission line in series [2]. The Static Synchronous Series Compensator (SSSC) device injects a voltage that is both sinusoidal and controllable that remains in series with the network transmission. The voltage source that has been injected imposes reactance that is virtual in the power line, which then regulates the flow of power in the transmission lines [3].

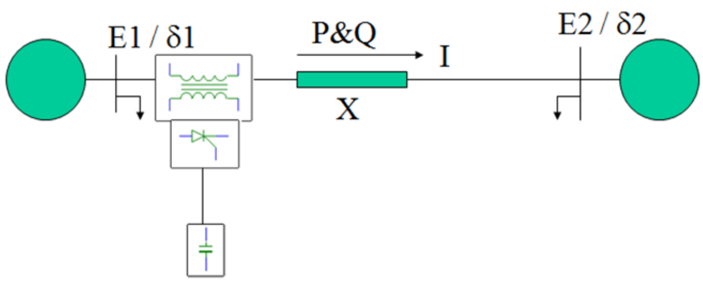


Figure1.1 FACTS Implementation-SSSC

Nonetheless, the ability of the static synchronous series compensator (SSSC) device to function both in the modes that are capacitive and inductive makes it efficient in regulating the flow of power in the system. In either inductive or capacitive modes, the voltage that is injected remains to be in a state of quadrature with the current in the line and therefore acts as inductive or capacitive reactance that is in series with the lines of transmission. Besides regulating the flow of power in the transmission lines, the static synchronous series compensator (SSSC) device offers better time of response with smooth transmission that is perfect from positive (+ve) to negative (-ve) power through the injection of zero voltage.

Unlike other devices of the flexible AC transmission systems that are also series compensating, the static synchronous series compensator devices do not run the risk of getting into issues of classical resonance at the operations of fundamental frequencies [4]. This is because for all the practical scenarios, the line of inductance (L) is regulated basically by the injection of compensating voltage that has been produced. Additionally, the static synchronous series compensator (SSSC) based Power Oscillation Damping (POD) device modulate a series of reactive power compensation [5].

Tentatively, the effectiveness, as well as the features that are attractive of the static synchronous series compensator devices, has increased its use in a very short period. The design of the devices is based on the damping controller and has also been noted to be handled differently. According to [6], a theory of time optimal control has been used to design a static synchronous series compensator (SSSC) based damping controller.

Tentatively, with respect to the current in the transmission line, the control of the angular position of the voltage by the static synchronous series compensator (SSSC) can correct the changes that happen to active and reactive power with the current system that is alternating. This capability of exchanging power is another characteristic of the SSSC that has significant application potential. When the SSSC has a direct supply of current that can be simply powered, it will be able to inject a voltage in the phase. Thus, the static synchronous series (SSSC) compensator will resolve the issues of transfer of reactive and active power in both the direct and alternating current system.

The model structure of the static synchronous series compensator (SSSC) consists of a voltage source converter, a transformer that is connected to shunt, a controller, a capacitor of direct current and a magnetic circuit. In the circuit, the capacitor is connected since if there is no device of energy storage, the converter will not absorb or generate power making the operation limited. In the system, the exchange of power that is reactive is controlled by the voltage source converter's voltage amplitude. In the case that the voltage source converter's amplitude is increased, then the power will flow from the SSSC to the current system that is alternating making the system generate reactive power. On the other hand, if the amplitude is decreased, the current flows from the alternating current system to the SSSC and power absorption takes place.

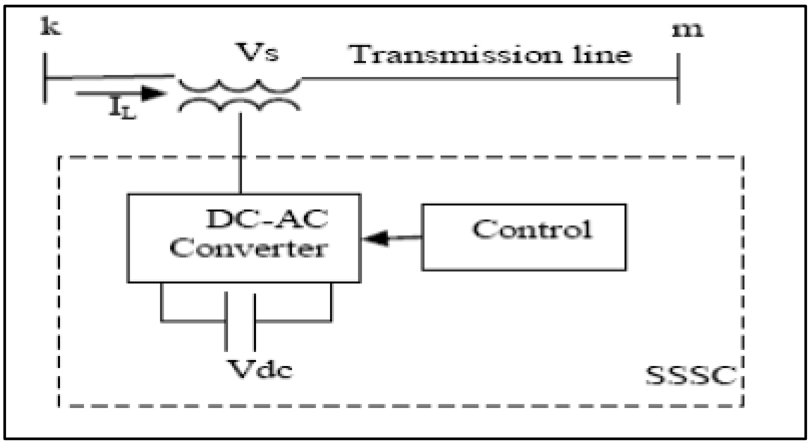


Figure1.2 Simplified diagram of a SSSC

During the operation modes for the static synchronous series (SSSC) compensator, there are several control strategies. One of them is the constant voltage mode of injection. In this operation mode, the static synchronous series compensator (SSSC) generates a voltage of three phase with respect to an input that is a reference. This strategy of injection of direct voltage is used to provide reactive series compensation whereby the voltage that is being injected is placed in quadrature with the transmission line current [7].

Constant impedance mode of emulation is another operation mode for the static synchronous series compensator. The mode offers an opportunity for the operator to regulate the total impedance of the line that can be specified by the referenced input. Thus, through the series transformer, the series of voltage being injected will create an impedance that is virtual that is observed by the transmission line. Tentatively, a constant power mode of control is considered to be an operating mode of the SSSC. The voltages being injected can vary in phase angle and magnitude so that the power flow control remains constant. This mode is used by the static synchronous series compensator (SSSC) to improve system stability. In conclusion, the paper aims to improve the stability of power through the static synchronous series compensator (SSSC) with and without the power oscillation damping.

1.2 Objectives of Thesis

1- To understanding the static synchronous series compensator (SSSC) based power oscillation damping controller concepts through the transmission system.

2- Improve Stability &Damping of power system using the static synchronous series compensator (SSSC) with POD.

3- Analysis of the system behavior against disturbance condition.

1.3 Overview of the Chapters

A brief review of the contents of this thesis is given as follows that is organized in five chapters:

Chapter 1: This chapter gives a simple detail of the work, and an introduction of the study that is including objective of the thesis and the organization of the project.

Chapter 2: This chapter explains the literature related to the work and the place of this work in the literature.

Chapter 3: This chapter mentions about Flexible Ac Transmission System (FACTS) device and a basic description of each type.

Chapter 4: This chapter shows general information about SSSC and discusses the role of SSSC based Power system controller (POD) to improve power stability & damping oscillation

Chapter 5: This chapter represents the simulation studies and the discussion of the results.

Chapter 6: This chapter contains the conclusion and suggestions for future work.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

This chapter covers numerous critical analyses of different researchers and scholars regarding the power system stability improvement using SSSC with POD controller. The process involved the use of detailed inquiries and analyses on the thesis' subject matter by examining relevant published engineering reports, as well as scholarly written materials. The research design can be cited as appropriate for this thesis as it provides reliable and equally quantifiable information that addresses the power system stability improvement using SSSC with POD. The articles were thus evaluated and extensively probed to yield reasonable information to ensure that the objectives of the study were achieved. The experimentations of researchers in this chapter involve several models of Static Series Synchronous Compensator (SSSC) that is controlled externally through the use of newly designed PSC (Power System Controller). The PSC used in different scenarios as expressed by different researchers are meant for improvements of power system stability, as well as damping effect in the case of an on line power system.

2.2 Related Work in the Literature

According to Rahman *et al.,* (2012) analyze the simulation of power system with different platforms. As per the author, a power system network can preferable simulated with the phasor simulation method while, on the other hand, the network is simulated in three different steps, which are; without SSSC, with SSSC that is not externally controlled, and finally SSSC with PSC (Power System Controller). The simulation results from experimentation b showed that without SSSC, the parameters of the power system become unstable during faults. Furthermore, when SSSC is imposed on the power system network, the parameters of the system firmly become stable. Also, simulation results show when SSSC is controlled by PSC controllers, the parameters of the system became more stable in a relatively faster way than without a controller.

As per Rahman *et al.*, (2012) it was observed that the ratings for SSSC are only 15 MVA with controllers and 100 MV without the controllers. Therefore, SSSC with the PSC controllers was found to be more effective in enhancing the voltage stability and equally increase the transmission capacity of the power system. Also, the power system oscillations are significantly reduced with controllers in comparison with scenarios that controllers were not used in the power system. As a result, with the use of PSC controllers, the performance of the system is greatly enhanced.

According to Rahman et al., (2012) analyzes the importance of stability improvements in a power system and equally focuses on different variation possible in any power system. Stability improvement is critically essential for large scale power system. In this regard, the SSSC is among the key members of FACTS family that can be installed in a wide range of transmission lines. Also traditionally, either mechanically or fixed switched shunt and series capacitors, synchronous generators and reactors were typically being used to damped out oscillation. Nonetheless, there are several restrictions with regard to the use of the various conventional devices. Technically, for numerous reasons, the desired performance was not able to achieve effectively. In such a scenario, a SSSC is regarded as an electrical device that provides fast-acting reactive power compensation typically on the high voltage transmission networks. It has the ability to improve the specific voltage profiles in the transient state. A SSSC can be externally controlled through the use of designing power system controller that significantly improves both the dynamic and steady state performance in large scale power system. It is the dynamic nature of the SSSC that is associated with the use of thyristor devices, such as IGCT and GTO [8].

Jowder (2005) examines the control concept of SSSC with the aim of determining the specific modes of operation that influence SSSC on small disturbances, as well as transient stability of a radial power system. The SSSC does not utilize any active source of power, and thus the injected voltage is forced to stay in quadrature with the line current. The findings of the Jowder (2005) show that by varying the magnitude Vq of the voltage that is injected in the quadrature with the current, and then the SSSC performs a variable reactance compensator function, which are either inductive or capacitive. The variations in the injective voltage are thus performed through VSC (Voltage-Sourced Converter) that is connected to the secondary section of the coupling transformer. Also, the VSC utilizes forced commutates power electronic devices to synthesize a voltage from a source of DC voltage.

As per Jowder (2005), the control system involves various elements that are crucial in the process of synthesizing voltage from the DC source. Firstly, there is the PLL (phase-locked loop), which ensures that the synchronization takes place on the positive sequence component of the current in the power system. Therefore, the PLL's output is useful in computing the direct axis, as well as quadrature axis components of AC three-phase currents and voltages. Also, there are systems for measurement, which are useful in measuring the AC positive sequence of voltages and DC voltage regulators. These elements are important in the computation of the two critical components of the converter voltage, which are required in obtaining the needed DC voltage and the injected voltage [9].

Dua and Prakash (2013) critically analyze and make projective findings regarding voltage level improvement of power system using SSSC with POD. And present analyses about a SSSC device with an aim of determining its effect on a power system with and without POD controller. According to their study, the power system can be explained as a highly nonlinear system, which operates in a dynamic environment. This means that generator outputs, loads, topology, and other essential operating parameters often change continually. As a result, the subjection of a power system to a transient disturbance means that the system's stability will depend on initial operating condition, as well as the nature of the disturbance.

As per Dua and Prakash (2013), small disturbance is usually common in the form of load changes in most power systems, whereby they occur continually. Hence, the system should be able to adjust to these changing conditions, as well as meet the load demand. However, it is essential to quickly damp these oscillations as soon as possible, since they cause power quality problems and mechanical wear in the power plants. To ensure that voltage stability and damping oscillation is improved, the supplementary control laws are applicable to the existing devices. The supplementary actions referred to in this context is POD (power oscillation damping) and voltage stability.

According to the analysis provided by Dua and Prakash (2013), voltage stability and POD control were applied to the SSSC. The SSSC uses the voltage source converter to ensure a controllable voltage was injected; quadrature with line current of the power network is useful in providing both inductive and capacitive impedance compensation at the power line current. It is these features that make the SSSC a relatively attractive FACTS device useful in power oscillation damping, power flow control, as well as improving transient stability. The analysis of power system conducted by Dua and Prakash (2013), compared the performance of a two-machine power system in cases of with and without damping controllers in scenarios of 3 phase short circuit faults. The findings showed that in damping power system oscillations, the static synchronous series compensator (SSSC) with POD was recommended as more effective when compared to the SSSC without POD controller [10].

Sunil and Ghosh (1999), provide an exclusive analysis for the modeling and control design of a static synchronous series compensator (SSSC). They focused on the different designs of controls in the SSSC with an aim of establishing its functionality when POD controller is or not used. In the analysis, the rating of SSSC is practically essential. Based on the explanations provided by them, the SSSC primarily supplies inductive or capacitive compensating voltage independent of the line current in a power system. In this case, the VA rating of the static synchronous series compensator (SSSC) is usually the product of maximum line current and maximum series compensating voltage. Its equation representation is as follows: $VA = V_{max}. I_{max}$. More importantly, the VA rating of the SSSC entails the solid state inverter and the coupling transformer. An SSSC of a VA rating of 1 p.u covers control ranges corresponding to 2 p.u compensating VARs. This means that the control range, in this case, is continuous from +1 p.u VARs capacitive and -1 p.u VARs inductive[11] .

According to explanations provided by Sen (1999), in capacitive mode, the voltage that is injected into the SSSC is usually made to lag the current in the transmission line by 90^o. In such a case, the operation of SSSC is compared to the operation of a series capacitor, which presents a variable capacitance kX_c, that is; $V_{pq} = -j\ KX_c l_{line}$, where K is the variable [12].

Righy and Harley (1998), analyze the control scheme for SSSC in a power system and focuses on the functionality of voltage source inverter. In the analysis, the SSSC is stated as the main element in the provision of inductive or capacitive compensating voltage that is independent of the line current. In this case, the VA rating of the SSSC, which entails coupling transformer and solid-state inverter, is the product of the maximum line current, as well as the maximum series compensating voltage. Therefore, $VA = V_{max}.\ I_{max}$. For an SSSC of 1 p.u VA rating, it will cover a control range that is corresponding to 2 p.u compensating VARs, which is the control range that is continuous from -1 p.u VARs on the inductive side, and +1 p.u VARs on the capacitive side. In summation, the various articles used on this literature survey illustrate the different techniques utilized by different researchers regarding stabilizing a power system using SSSC either with or without POD. The results yielded in the numerous experimentation clearly demonstrate how power system can be stabilized using diverse means. These results are useful in determining the necessary parameter that influence the stability of current or voltage in either a two or three phase power system [13].

Ravi Kant Yadav*, V. K. Giri (2014), display a systematic procedure for modeling, Simulation SSSC controller in a multimachine system to improve power system stability. For the SSSC controller propose problem the controller has been experienced in example power system subjected to different types of disturbances such as asymmetrical fault and small disturbance conditions. The simulation results show that, the hereditarily tuned SSSC controller enhanced the stability performance of the power system and power system oscillations are successfully damped out under strict disturbance situation [14].

Dhoble, P.,& Bhandakkar, (2013), showed a detailed analysis of SSSC series and STATCOM shunt FACTS devices and donated a brief idea and focusing on the preferable device for voltage control, active and reactive power flow in the power system. A methodical process of SSSC and STATCOM device for modeling and Simulink was utilized and investigated for enhancement of active & reactive power flow control in a two-area four-machine 11-bus. Results of SSSC series FACTs device compare with the one of shunt FACTs device STATCOM. A simulation results were acquired from the environment of MATLAB/SIMULINK model.

According to their study, it is revealed from the simulation results that the SSSC device based power oscillation damping (POD) controller are more effective to improve the active, reactive power flow and voltage control in a power system as compared to STATCOM [15].

Mihalic and Papic (1998), studied and tested simple transmission system that involves 2 hydraulic power plants. They list some interesting findings of the power system model with SSSC. They explained that the first power substation indicated as the G_1 was rated at 2100 MVA, and thus represented six machines of 350 MVA. On the other hand, the second power substation G_2 was rated at 1400 MVA subsequently representing 4 machines of 350 MVA. The system modeled by a dynamic load. Also, the generation substation G_1 was connected to the load using two transmission lines, which were L_1 and L_2. It is essential to acknowledge that the first transmission line is 280 km in length while the second transmission line, L_2, is split into two segments of a length of 150 km. The difference in lengths in the first and second transmission line is meant for purposes of simulating a three phase fault, particularly at the midsection or the midpoint of the line. According to their study if the SSSC is rated at 100 MVA, then it can be explained to have a capability of injecting up to about 10 percent of the nominal voltage in the power transmission system [16].

Shankar, C. U., Thottungal, R., & Mythili, S. (2015), investigated the power flow control problem in a transmission line by using Static Synchronous Series Compensator (SSSC) with a PI controller under fault conditions and presented analyses of the static synchronous series compensator (SSSC) which has a capability of delivering a compensating voltage with a capacitive and inductive range. According their study PI Controller is used to tune the circuit and also to provide zero steady state error. The results confirm by installing the SSSC in the system the voltage stability has been improved and power oscillations are damped properly when compared to the two machine system without SSSC [17].

CHAPTER 3

FACTS DEVICE

3.1 Introduction

Increasing in demands for power systems in the lives of individuals, its transmission and distribution that is effective is an area of study of great importance. However, there have been certain limitations such as on the construction of new power lines of transmission and such have persuaded the designers of power systems to seek out some alternative solutions to transmit power efficiency over the lines of transmission and improve its stability. Moreover, the construction of new power lines of transmission has been observed to be both time consuming and expensive. Because of this, the solution to this issue has been found in the use of flexible AC transmission system devices [18].

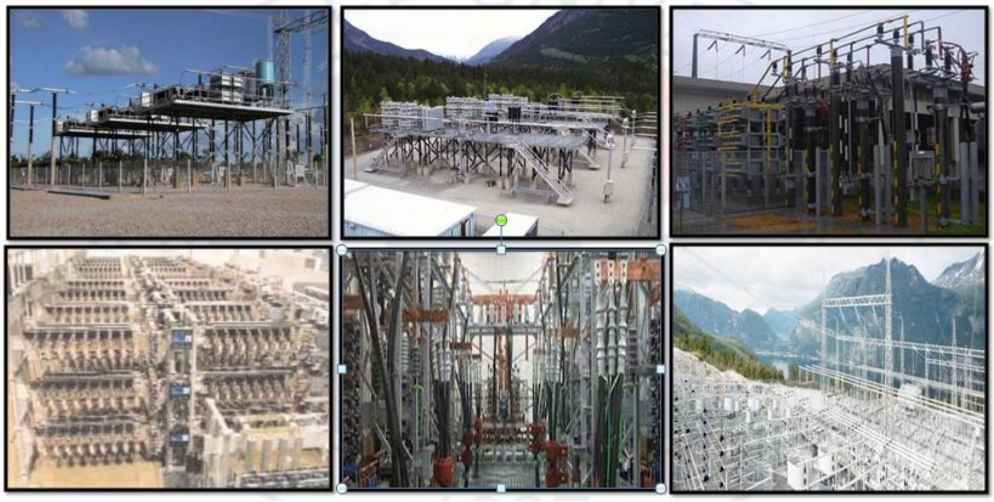
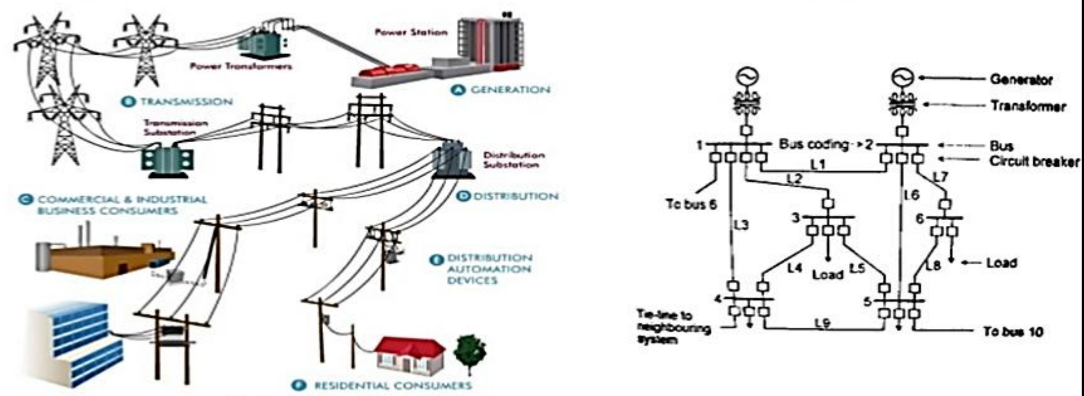


Figure 3.1 FACTS Device

Flexible AC transmission system devices are considered now to be a mature and verified technology. The controllability and the flexibility that the devices are observed to provide the most efficient and reliable solutions when it comes to power systems. The flexible AC transmission systems (FACTS) can then be defined as the transmission systems of alternating current that integrates in them electronics based on power and other controllers that are static to improve the capability of power transfer and controllability. Tentatively, their main aim is to supply reactive power, that is either capacitive or inductive, while improving the quality of transmission and power system stability both dynamic & voltage stability, less active and reactive power loss, voltage regulation. Figure 3.2 demonstrates the distribution system that consists of organized transmission lines, generating plants, transformers and a variety of loads [19, 20].



$$S = P + jQ$$

$$\sum Pi = P_{Generator} + P_{Load} + P_{Compensation}$$

$$\sum Qi = Q_{Generator} + Q_{Load} + Q_{Compensation}$$

Figure 3.2 Distrbution System

FACTS controllers In general can be classified into four categories such as:

1-Series connected -FACTS Devices:

This type, injects voltage in series with the transmission line and in quadrature with the current. It's Including Static Synchronous Series Compensator (SSSC), Thyristors-Switched Series Capacitor (TCSC), and Thyristor-Controlled Series Reactor (TCSR) after disturbances they can successfully control, power flow and damp oscillations in the system. The most prevalent device of this type is SSSC because of its multi employment ability [20].

2- Shunt connected -FACTS Devices: Is a control which is controlled both active and reactive power. They inject current into the system instead of voltage at the point of mutual connection which is the only difference with series controllers. Including static synchronous compensator (STATCOM), Thyristor-Switched Inductor (TSR), Thyristor Controlled Inductor (TCR), Thyristor-Switched Capacitor (TSC), and Thyristor-Switched Resistor (TCBR) [21, 22, 23].

3-Combined Series-Series Connected:

This type is a collection of separate series FACTS devices, which are controlled in a coordinated technical. An example of this controller is the Interline Power Flow Controller (IPFC). It uses to balance the real and reactive power flows on transmission lines [20, 23].

4-Combined Series -Shunt Connected:

This type is a collection of separate series and shunt devices, which are controlled coordinated technical. Including Unified Power Flow Controller (UPFC), Thyristor Controlled Phase Angle Regulator (TCPAR), and Phase-Shifting Transformer adjusted by Thyristor Switches (TCPST) [20, 23].

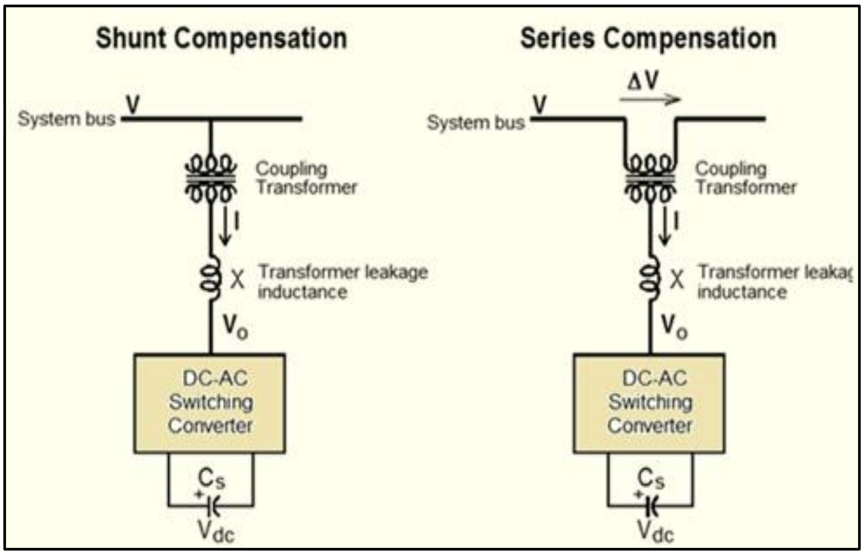


Figure 3.3 Series and shunt compensation

Depending on the power electronic devices used in power system the FACTS controllers can be classified as [24]:

1. Thyristor valve. This type of controller includes:

- Static Var Compensator (SVC).
- Thyristor Controlled Series Compensator or Capacitor (TCSC).
- Thyristor Controlled Phase Shifting Transformer (TCPS).
- Dynamic Power Flow Controller (DPFC)

2. Voltage Source Converter (VSC). This type of controller includes:

- Synchronous Static Series Compensator (SSSC)
- Interline Power Flow Controller (IPFC).
- Unified Power Flow Controller (UPFC)
- Synchronous Static Compensator (STATCOM) [20, 25]

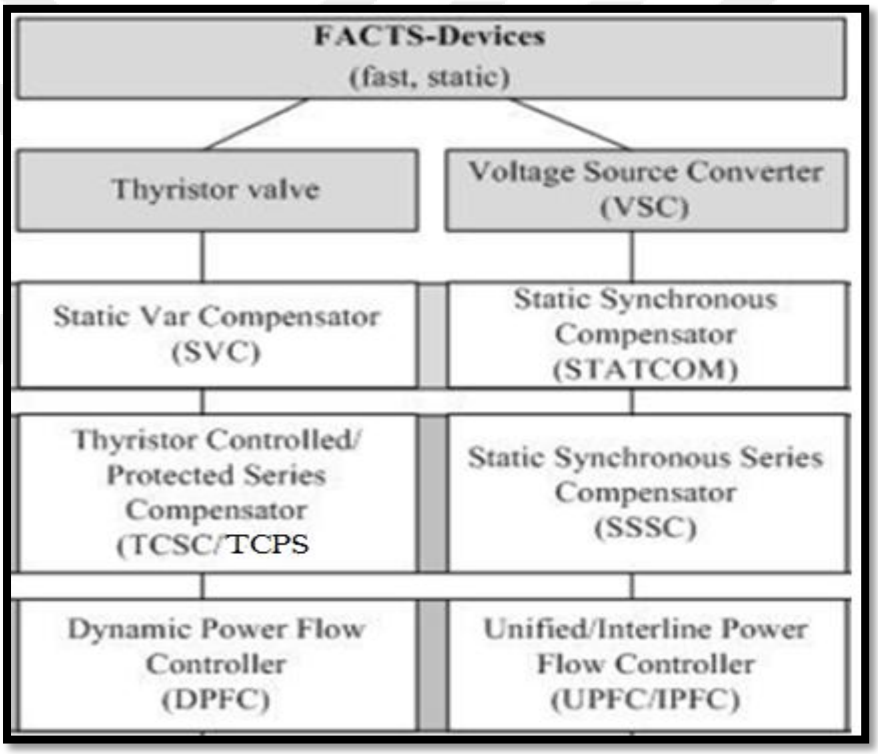


Figure 3.4 Major FACTS-Devices [25]

3.2 Basic description of the FACTS devices

3.2.1 Static Var Compensator (SVC):

The systems of static var have been utilized in the lines of transmission for control the voltage that is rapid as the weak points in the network of the power system. The static var compensators (SVC) are described to be shunt connected static absorbers or generators whereby their outputs are occasionally varied to control and regulate the voltage of the power system. The utilization of the static var compensator in the power lines of transmission is to provide performance that is higher in the steady state as well as in transient stability of voltage, to reduce the loss of the system, to dampen the power swing and also to control the flow of reactive and real power [26].

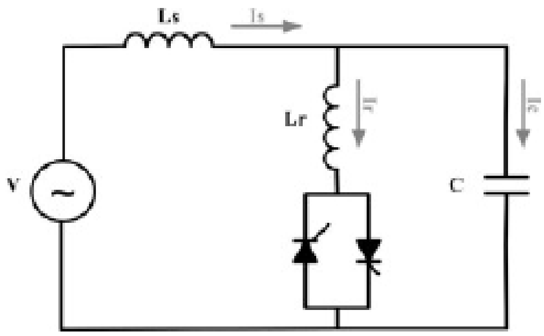


Figure 3.5 Static Var Compensator (SVC)

The Fig 3.5 demonstrates a type of the static var compensator known as FC-TCR. In this type of a static var compensator, the capacitor is parallel connected to the thyristor control reactor. Additionally, the capacitor is fixed whereby it is also partially or fully substituted by a network filter that has an impedance that is capacitive at the frequency that is fundamental to generate power that is reactive. In this static var compensator type, the var generator comprises of a reactor that is variable. The current of the reactor is varied by a manner of firing delay angle control. The current of the reactor is increased when the delay angle αis decreased to decrease the output that is capacitive. On the occasion that both the inductive and capacitive currents become equal, both vars are observed to cancel out and produce an output that is zero var [18]. When the angle αis decreased further, the current that is inductive, then becomes larger than the current that is capacitive, thus producing an output that is inductive [23].

3.2.2 Static Synchronous Compensator (STATCOM)

The static synchronous compensator can be described as a static var compensator that is shuntly connected. This type of flexible A.C transmission controller device has an output current that is either inductive or capacitive and can be independently controlled from the alternating current system voltage. The figure below demonstrates a simple diagram of the static synchronous compensator based on a source converter of voltage [23].

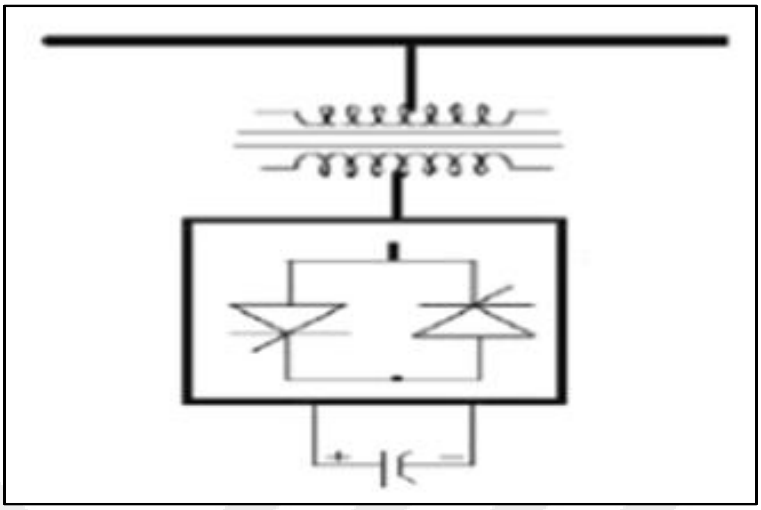


Figure 3.6 Static Synchronous Compensator STATCOM

The converter of source voltage converts the direct current voltage into alternating current, voltage through the use of the GTO and in turn the alternating current voltage is inserted into the power transmission line through the transformer. In the occasion the output of the voltage source converter becomes more than the voltage on the transmission line, the voltage source converter supplies the var that is lacking in the line of transmission. On the other hand, if the voltage in the line of transmission is more than the output from the voltage source converter, then the converter absorbs the var that is lacking from the power system [26].

3.2.3 Thyristor controlled series capacitor (TCSC)

The thyristor controlled series capacitor is a series compensated flexible AC transmission system device. It comprises of a series capacitor bank that is shunted by a capacitor that is controlled by the thyristor so as to provide a series capacitance reactance that is variable in a smooth manner. The following figure demonstrated a simple line diagram of the thyristor controlled series capacitor controller device.

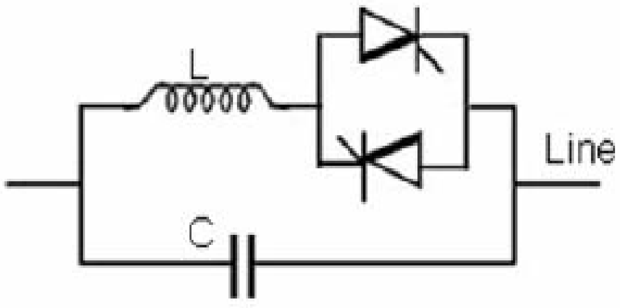


Figure 3.7 Thyristor controlled series capacitor (TCSC)

The thyristor controlled series capacitor is based on the thyristor but without the capability of the gate turn off. In this controller, a variable thyristor that is controlled by the reactor is connected across a capacitor that is in series. On the occasion that the angle of firing of the thyristor controlled reactor is one hundred and eighty degrees, the reactor then turns into a state of not conducting and the series capacitor gains impedance that are normal. Moreover, as the angle of firing decreases, the reactive capacitance increases as well. Additionally, when the angle of firing is ninety degrees, the reactor attains a state of being a full conductor and the impedance that is total becomes inductive.

3.2.4 Static synchronous series compensator (SSSC)

The static synchronous series compensator can be considered to be the most important of the flexible AC transmission system controller that is used for series compensation in power system. The capacitor, in series compensation, is connected in series and is observed to compensate the reactance that is inductive of the power line of transmission. The output voltage of the static synchronous series compensator (Vc) is in a state of quadrature with the current in the transmission line (I). Therefore, the voltage that is across the series capacitor becomes -jXcI, whereby Xc is the reactance that is capacitive of the series capacitor. Tentatively, the voltage drop that is across the inductance line (XL) becomes +jXLI. In turn, they all cancel to each other hence reducing the inductance line effect and also increasing the capability of power transfer.

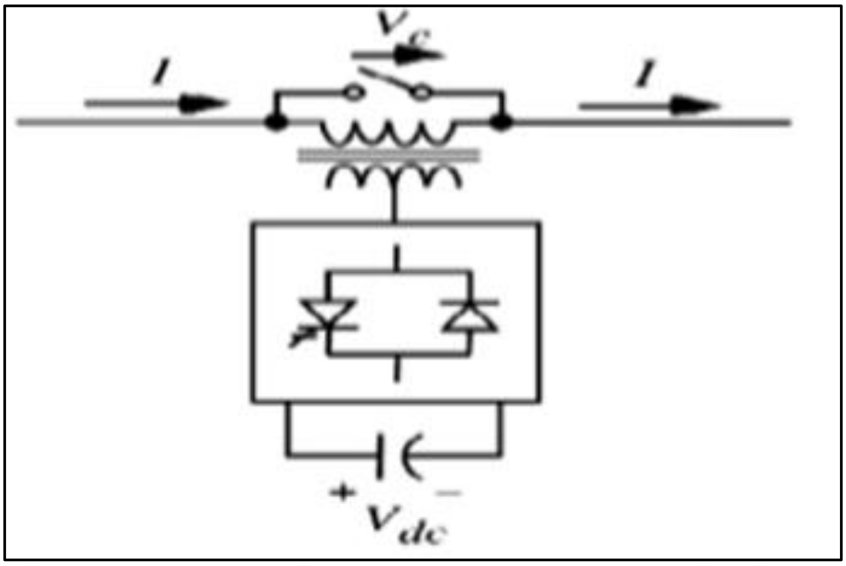


Figure 3.8 Static synchronous series compensator (SSSC)

The figure above is a symbolic representation of the static synchronous series compensator device that uses a voltage source converter [23]. The supply of voltage occurs from a direct current source that is then converted into alternating current voltage using the voltage source converter. Nonetheless, the voltage that is in a state of quadrature is injected into the line of transmission through a coupling transformer [27]. This voltage that has been injected (VC) is noted to lag the current in the transmission line (I) by ninety degrees, and series compensation is then executed. The static synchronous series compensator device controls both the flow of reactive and real power through the system.

3.2.5 Unified Power Flow Controller (UPFC)

The unified power flow controller is a multifunctional flexible AC transmission system device that has the capability of multi-usage compensation. The unified power flow controller focuses in an arrangement on the back to back source converter of voltage. This arrangement is whereby one converter of the controller is in series while the other converter is in shunt with the power line of transmission and both converters are handled from a common direct current link that is provided by a direct current storage capacitor. This form of arrangement works is as ideal alternating current power converter whereby the power that is real can freely flow in either direction between the alternating current terminals of the two converters [26].

Additionally, each converter can either absorb or generate reactive power independently and also at its alternating current output terminal.

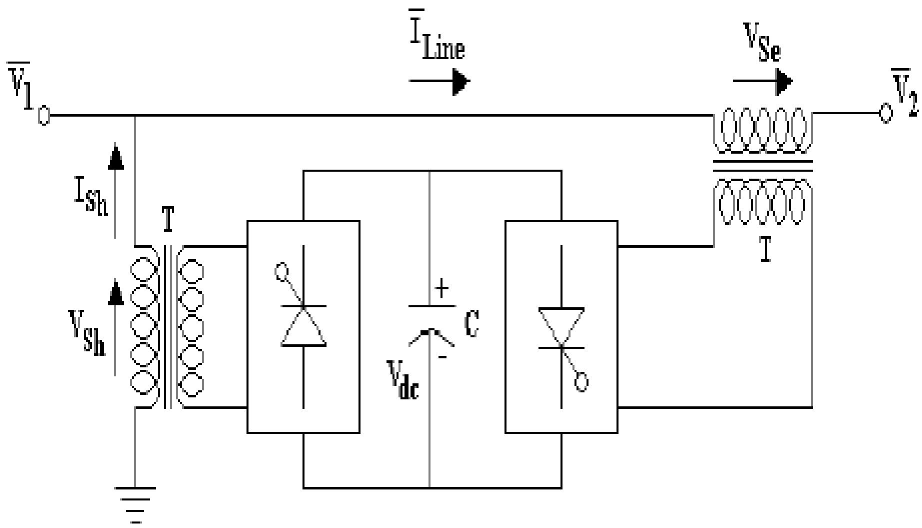


Figure 3.9 Unified power flow controller

The figure above demonstrates the schematic diagram of the unified power flow controller [28]. The first converter has a function of supplying or absorbing the power that is real demanded by the second converter as the common direct current link to support the exchange of real power that results from the injection of series voltage. The direct current link power demand of the second converter is converted back to alternating current by the first converter and is then coupled to the line of transmission through the transformer that is shunt connected [29].

Nonetheless, the first converter can also absorb or generate reactive power that is controllable to provide shunt reactive compensation that is independent of the line of transmission. The unified power flow controller can also be operated for shunt compensation that is reactive, series compensation as well as the regulation of the phase angle to the objectives of multiple controls. The unified power flow controller mainly injects a voltage that is in series with the transmission line whose angle of phase is noted to vary with respect to the voltage in the terminal, and also whose magnitude is observed to vary from zero to a maximum value that has been defined [27].

CHAPTER 4

STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC) AND POWER SYSTEM CONTROLLER (POD)

4.1 Introduction

Static Synchronous Series Compensator (SSSC) is one of the most modern FACTS devices for series compensation in power transmission through a transformer that is used to power flow control and damp oscillations on the power grid. It proposed by Gyugyi in 1989. The SSSC operates as a synchronous voltage source as it can inject an approximately sinusoidal voltage of variable and controllable amplitude and phase angle, in series with a line of transmission also nearly in quadrature with the line current [5]. The injected voltage by SSSC are changing depending on the conditions of the system and the loads that entering into the system or getting out so SSSC is similar to the variable reactance [30].

4.2 The structure of static synchronous series compensator

The static synchronous series compensator structure consists mainly of the source voltage converter. This converter employs control strategies of the modulation of pulse width to control the voltage magnitude. In turn, the voltage source converter assists by controlling the voltage magnitude as well as the reactive power that is generated. This helps to deal with the problems of voltage and stability issues of power quality. Fig (4.1) shows the connection of SSSC with transmission line [31].

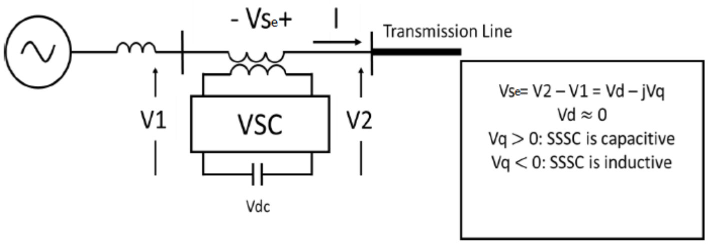


Figure 4.1 Connection diagram of SSSC with transmission Line

The diagram illustrates how a capacitor that is connected on the side of the DC acts as the source of DC voltage. Also, a small active power should be drawn from the transmission line to ensure that the capacitor is kept charged, as well as to provide VSC and transformer losses such that the injected voltage (Vse) remains 90 degrees out of phase with current I. Also, the block diagram presented in the figure designate the converter voltage components, which, are in quadrature and in phase [32]. To represent the power flow through the transmission line basic equations is given by:

$$P = \frac{Vs\ Vr}{XL} \sin(\delta s - \delta r) = \frac{V2}{XL} \sin\delta \quad (4.1)$$

$$Q = \frac{Vs\ Vr}{XL}\left(1 - \cos\left(\delta s - \delta r\right)\right) = \frac{V2}{XL} * (1 - \cos\delta) \quad (4.2)$$

where,

Vs , Vr are sending and receiving end voltages

δs , δr are the phase angles of the voltage sources Vs and Vr respectively. For simplicity, the voltage magnitudes are chosen such those Vs = Vr = V and the difference between the phase angles is:

$$\delta = \delta s - \delta r \quad (4.3)$$

SSSC is capable of emulating a compensating reactance Xq (both inductive and capacitive) in series with the transmission line inductive reactance XL, Therefore, the expressions for power flow given in equation (4.1&4.2) becomes:

$$P_q = \frac{V^2}{X_{eff}} \sin\delta = \frac{V^2}{XL(1-\frac{X_q}{X_L})} sin\delta \quad (4.4)$$

$$Q_q = \frac{V^2}{X_{eff}}(1 - \cos\delta) = \frac{V^2}{XL(1-\frac{X_q}{X_L})}(1 - \cos\delta) \quad (4.5)$$

Where, Xeff is the effective reactance of the transmission line between its two ends, including the emulated variable reactance Xq inserted by the injected voltage source of the Static Synchronous Series Compensator (SSSC). When the SSSC is operating in an inductive mode compensating reactance Xq is defined to be negative and positive when the SSSC is operating in a capacitive mode [33, 34]

The SSSC has a special advantage that is the ability to resemble both capacitive and inductive compensation. Alternating the value of the imaginary (Vq) part of Vse forms capacitive or inductive as follows:

Vq> 0: SSSC is $Capacitive$

Vq< 0: SSSC is $Inductive$

Alternation of Vq is achieved by Voltage Sourced Converter (VSC) located on low voltage side of potential transformer in Figure (4.1). GTOs, IGBTs or IGCTs of VSC employ forced-commutation to create Vd_conv from DC source [31].

4.3 Basic operating principles of the SSSC

Figure 4.1 demonstrates the functional model of the static synchronous series compensator (SSSC) that includes a device for energy storage as a direct current capacitor so as to allow the exchange of power, both reactive and real power, with the network of power system. The voltage that is injected is in quadrature with the current in the transmission line because the source of power that is real is not utilized by the static synchronous series compensator. The operation of the static synchronous series compensator (SSSC) as a reactance that is either inductive or capacitive is noted to depend upon the magnitude of the voltage that has been injected [35].

The coupling transformer is observed to couple the static synchronous series compensator (SSSC) to the network of transmission. The transformer is then connected to a voltage source converter that has an amplitude that can be varied. After that, the voltage denoted as (Vse) is then produced from a direct current, voltage source when the voltage source converter utilizes the power electronic devices. In the case that there is an increase in the amplitude of the voltage source converter, the power then flows from the flexible AC transmission system controller to the power system by generating power that is reactive [36].

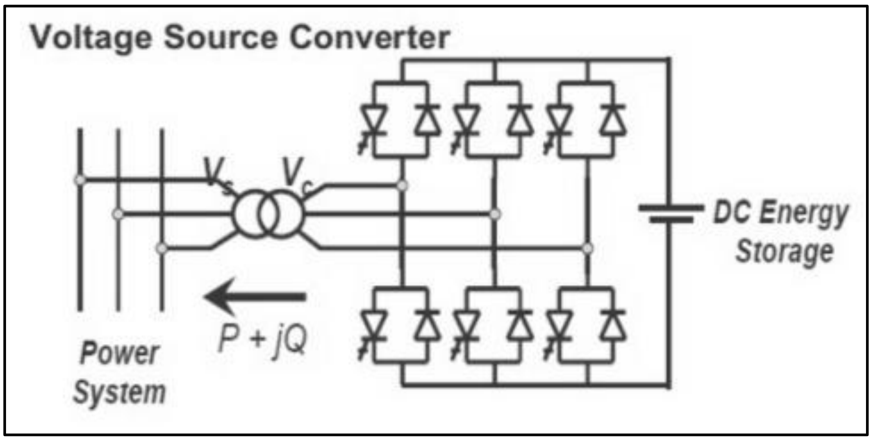


Figure 4.2 Voltage Source Inverter

On the other hand, if the amplitude of the voltage source converter is reduced, the current then begins flowing from the system that is alternating to the static synchronous series compensator (SSSC) and power absorption occurs. The magnitude of the voltage source converter and the phase angle can be changed to control the flow of power in the lines of transmission. Tentatively, the phase displacement together with the voltage that is injected plays a significant role whereby they permit the power exchanges that are reactive and real with the power system [37].

In this kind of VSC, the essential component of voltage V_conv is proportional to the voltage Vdc. Therefore Vdc has to vary for controlling the injected voltage. VSC uses IGBT-based PWM inverters. This type of inverter uses Pulse-Width Modulation (PWM) technique to synthesize a sinusoidal waveform from a DC voltage with a typical chopping frequency of a few kilohertz. Harmonics are cancelled by connecting filters on the AC side of the VSC. This type of VSC utilizes a fixed DC voltage Vdc. Voltage V_conv is diversified by changing the modulation index of the PWM modulator. The SSSC (Phasor Type) block models an IGBT-based SSSC (fixed DC voltage). However, as details of the inverter and the harmonics are not performed, it can be also used to model a GTO-based SSSC in transient stability studies [38].

The Dc input may be a battery, a fuel cell, a solar cell or other DC sources such as a rectifier. We can define inverters, which is converting Dc-to-Ac, because in most of the times the power flows from the DC side to the Ac side. DC-to-Ac converters are used in a very wide application area ranging from residential to utility applications where the objective is to generate a sinusoidal Ac output from a DC input source, in which the magnitude, the phase angle, and the frequency can be controlled [39].

Also, the phase displacement of the voltage Vpq that is inserted with respect to the current line I_{line} at the transmission line to help in determining the exchange of active, as well as the reactive power with the AC system. The following is the phasor diagram useful in illustrating the phase displacement as shown in Figure 4.3[40].

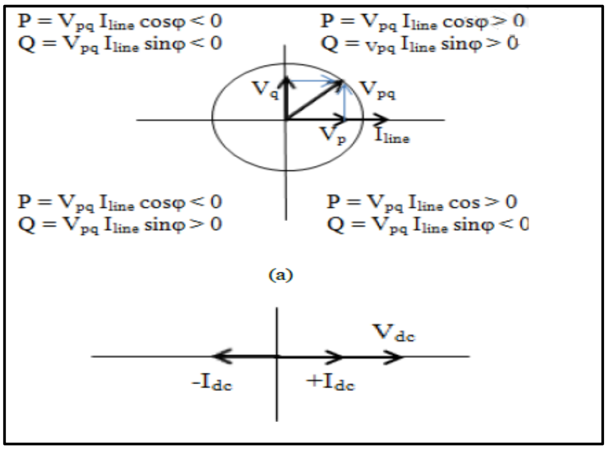


Figure 4.3 SSSC Phsor Diagram

According to theoretical explanations, operation of SSSC in each of the four quadrants illustrated in the above diagram is possible. However, there are several limitations regarding the voltage that is injected into SSSC mainly due to the operating constraints in the practical power system.

In capacitive mode, the injected SSSC voltage is made to lag the transmission line current by 90°; in this case, the SSSC operation is similar to the operation of a series capacitor with variable capacitance kXc, i.e.,Vpq= − jKXcI_{line}, where k is a variable [40]. By this action, the resistance of the total transmission line is reduced while the voltage across the impedance is increased, leading to increase line currents and transmitted power. In verity, this is not true; the inserted voltage magnitude is set by the SSSC control and is independent of the network impedance and, therefore, line current changes. It is assumed that the SSSC losses are zero and, consequently, the series injected voltage is in perfect quadrature with the line current, leading or lagging. It is also possible to reverse the injected SSSC voltage by 180°, i.e., −Vpq = $jKX_L I_{line}$ causing an increase in the transmission line reactance, which results in a decrease of the line current and transmitted power. While this equation for Vpq appears changes in the phase magnitude and phase angle, it can be a bit misleading; since it shows that the series injected voltage magnitude is directly proportional to the line current magnitude [41].

4.4 Control structures of the SSSC

In the control structure of the static synchronous series compensator (SSSC), the operations are analogous to the series compensation. This happens because of the conditions of the system and also how the loads determine the changes in the current and in the voltage that is injected. Tentatively, the changes that are transient that are created in the power system, the flexible AC transmission system controller can then be utilized. A voltage source converter that has a direct current capacitor is connected to the transformer, whereby the direct current capacitor is assumed to be the device for storing energy. The static synchronous series compensator (SSSC) functions along with the change that is transient depending upon the control circuit [36].

Moreover, the direct current capacitor produces a voltage that is provided as input to the voltage source converter and then finally coverts the direct current form to an alternating current form. After that, through the insertion transformer, it injects the alternating current, voltage from the static synchronous series compensator (SSSC) to the transmission line [42]. For controlling the flow of power, the reactive powers, the voltage and the current in the references denoted as d-q are then calculated then compared to one another to provide the error signal. The main purpose of the controller denoted PI is to reduce or remove the error of steady state. PI maintains the charge on the capacitor of direct current whereby it injects voltage that is close to being in quadrature with the current in the transmission line.

Herein, the power exchange that is real between the static synchronous series compensator (SSSC) device and the alternating current system occurs if the voltage that is being injected, does not happen in quadrature with the current in the transmission line. This is noted to either discharge or charge the direct current capacitor [43]. The controller denoted as PI can then retard or advance the injected voltage phase that is about the current in the transmission line. The controller does this so as to regulate the power at the alternating current terminals as well as to keep the voltage at the direct current constant.

The control system involves various elements that are crucial in the process of synthesizing voltage from the DC source. Firstly, there is the PLL (phase-locked loop), which ensures that the synchronization takes place on the positive sequence component of the current in the power system [9]. The major idea behind phaselocking is the ability to generate a sinusoidal signal whose phase is coherently following that of the main parts of the input signal. In various engineering applications, Phase-locked loops are widely used to extract the phase and frequency data for signals [39]. Therefore, the PLL's output is useful in computing the direct axis, as well as quadrature axis components of AC three-phase currents and voltages. Also, there are systems for measurement, which are useful in measuring the AC positive sequence of voltages and DC voltage regulators.

These elements are important in the computation of the two critical components of the converter voltage, which are required in obtaining the needed DC voltage and the injected voltage. The control concept can be presented as shown in the Figure (4.4). Based on this Figure, the Vq voltage regulator requires the assistance of a feed forward type regulator that is useful in predicting the V_conv Voltage from the Id current measurement [44].

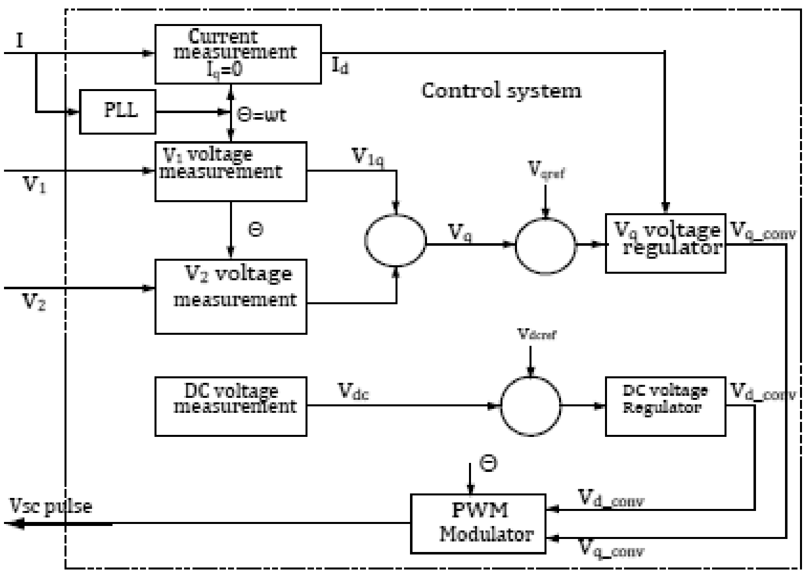


Figure 4.4 SSSC Based Control System

4.5 PWM Technique of SSSC

PWM is one of the most utilized techniques. By this control technique of SSSC the angle and magnitude of the injected voltage can be controlled. The simple closed loop block diagram is presented in Figure 4.5

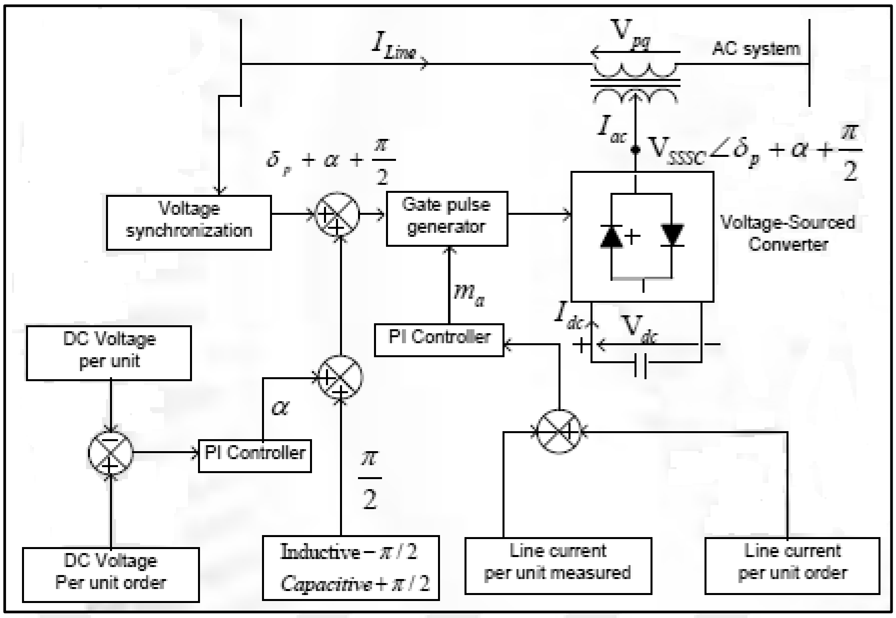


Figure4.5 Functional Control diagram for PWM Controlled SSSC

As shown in figure 4.5 it consists of two control loops [45]. The first one is a voltage control loop and another is a current control loop. The current control loop maintains the magnitude of the injected voltage and voltage control loop maintain the angle of the injected voltage. In the voltage control loop the difference of the measured line voltage and reference line voltage passes through the PI controller. In current control loop the difference of the measured line current and reference line current passes through the PI controller. The gate pulse generator gives the pulses to voltage source converter [45].

4.6 SSSC -Based Damping Controller

Power system oscillations are a major problem and for many years they have been offering a challenge to electric and control engineers. In some cases, these oscillations are very insufficiently damped, and its effect causes a mechanical exhausting of the generation units and unwanted power differences through the transmission lines and increasing the load over of the transmission lines. This case will allow the supplementary control laws to supply a best damp for these bother oscillations. Supplementary control action applied to FACTS devices to increase the system damping is called Power Oscillation Damping (POD) [46]. SSSC with POD controller is a very effective device to damp power oscillations [47]. POD is a new designed controller very efficient for voltage stability under transient conditions.

Depend on the characteristics of the power system, after a severe fault the oscillations may last for 3-20 seconds. Drawn out oscillations that last for a few seconds or more is usually the result of very light damping in the system. During such angular oscillation period, significant cycle variations in currents, voltages, and flows in transmission line will take place. Oscillation effects, mechanical wear in power plants and many power quality problems so it is vital to damp these oscillations as quickly as possible. If further disturbances occur the system is also vulnerable. To improve the voltage stability and the damping of oscillations in power systems, supplementary control laws can be utilized in existing devices. These supplementary actions are pointed to as voltage stability and power oscillation damping (POD) controller [40, 48].

To modulate the SSSC injected voltage the structure used in this thesis is the lead-lag structure as shown in Figure (4.6). This structure consists of a gain block, washout block and two stage lead-lag blocks. The gain block is used to dampen the oscillations. The two stage lead-lag blocks (time constants T1S, T2S, T3S and T4S) provide suitable phase-lead characteristics to compensate for the phase lag between input and the output signals. The washout block acts as a high pass filter with the time constant (Tw) to allow signals related to oscillations to pass as it is. If no faults has happened, then switch will remains open. But the switch is closed when the fault has happened. After filtering or damp out oscillation, it also gives an error signal and finally two error signals has been added, this is Vqref [4, 8]. In the Fig (4.6), Vqref represents the reference injected voltage as desired by the steady state power flow control loop. The steady state power flow loop acts quite slowly in practice and hence, in the present study Vqref is assumed to be constant during large disturbance transient period. The desired value of compensation is obtained according to the change in the SSSC injected voltage ΔVq which is added to Vqref [49].

$$Vq = Vqref + \Delta Vq \quad (4.6)$$

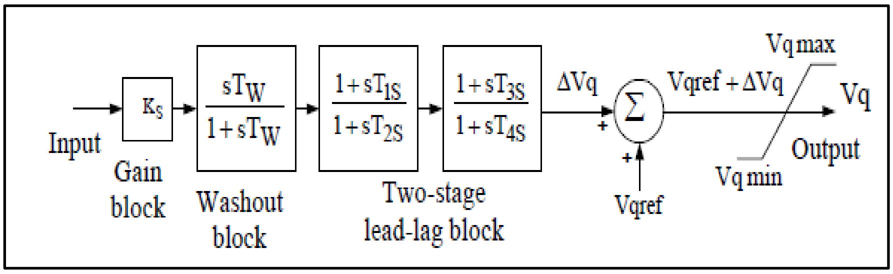


Figure 4.6 POD controller design structure

The transfer function of the SSSC-based controller is:

$$U_{SSSC} = Ks\left(\frac{sTw}{1+sTw}\right)\left(\frac{1+sT1S}{1+sT2S}\right)\left(\frac{1+sT3S}{1+sT4S}\right)y, \quad (4.7)$$

Where, U_{SSSC} is the output and y is the input signals of the SSSC-based controller [49].

4.7 SSSC Rating

SSSC injects compensation voltage in quadrature with feeder current. The voltage magnitude can be either positive or negative. Therefore, SSSC rating can be expressed in VA as follows:

$S_{SSSC}=\sqrt{3} * I_{Line}Max * V_{SSSC}Max\ (VA)$

That is, maximum line current multiplied by maximum voltage that SSSC capable of injected it . For an SSSC of 1 p.u VA rating, it will cover a control range that is corresponding to 2 p.u compensating VARs, which is the control range that is continuous from -1 p.u VARs on the inductive side, and +1 p.u VARs on the capacitive side [31,13].

4.8 Application of SSSC in Power System Grid

The static synchronous series compensator (SSSC) has been utilized in damping the oscillation of power in the Gulf Cooperation Council (GCC) power grid. Through the review, the essential features of the SSSC have proven its potential to improve the power system stability and also to become an important tool for the operational controllability and flexibility of the power system.

4.8.1 Background information of the GCC power system

The power system facilities of the Gulf Cooperation Council (GCC) can be noted to have been configured as well as implemented into different strategic ways that have the mission of meeting sustainable and reliable domestic and industrial power system requirements. First and foremost, a double circuit of 400 KV and the 50 Hz line stretches from Kuwait to Saudi Arabia, whereby and an intermediate connection exists in the Kingdom of Saudi Arabia, and its related facilities of power systems are also installed. Tentatively, a HVDC link that is back-to-back is introduced as an interconnection of 380 kV and 60 Hz at the Kingdom of Saudi Arabia so as to maintain synchronization that is proper and communication with the other power systems that have been installed.

Thirdly, a double circuit of 400 kV overhead line stretches and is connected partially with a submarine link between the KSA and Bahrain alongside the associated facilities of power systems. Nonetheless, there is a double circuit of 400 KV that stretches from the KSA to Qatar into Saudi Arabia whereby the associated substations are also installed. Fifthly, another double circuit of 400 kV stretches from Qatar to the south of Doha and its associated power facilities are installed. Tentatively, a double circuit of 400 KV and the 50 Hz line stretches from Qatar to the United Arab Emirates while another single circuit of 220 KV and the 50 Hz line stretches from the United Arab Emirates to Oman alongside its substations. Finally, there exists a centralized control room that was developed at KSA. This was established to control the operations of the power system within the GCC power grid [50].

4.8.2 Power system plan between the UAE and Oman

In order to establish a power system plan that is proper, there have been multiple studies at the different voltage levels that have been finished in order to establish the operational requirements of the power system on both sides of Oman and the United Arab Emirates. The United Arab Emirates and the Oman substation sites have been chosen for installation of the static synchronous series compensator (SSSC) devices for a number of reasons. One of them is that both the United Arab Emirates and the Oman have an interconnection with domestic and industrial consumers. This was based on an investigation report of the power authorities that noted that there existed some stability issues on both the industrial and consumer power system. The static synchronous series compensator (SSSC) device would be utilized to improve all the existing types and issues of stability between the UAE and the Oman power system facilities. [50, 51]

4.8.3 Mathematical Model for the SSSC

At the midpoint of the GCC power grid, the power line of transmission has been modeled with impedances that are lumped. The voltages v1<∂1 and v2<∂2 are the voltages that are midpoint on both sides of the static synchronous series compensator (SSSC) device. Additionally, the vinj<∂inj of the SSSC device represents the voltage that is injected by the controller. The mathematical model of the static synchronous series compensator (SSSC) device is as follows;

The static synchronous series compensator (SSSC) consists of a source converter of voltage, a direct current storage capacitor as well as a transformer of series injection. The SSSC device is observed to inject V̑Bt into the line of transmission that can then be modulated for controlling the flow of power in the transmission line. The variable of control is noted to be the index of modulation mb and the phase angle δb of the source voltage converter [50, 51].

According to Anderson and Fouad in the model, a generator that is synchronous is portrayed by the third order none linear mathematical model. The terminal voltage of the synchronous generator can be represented by V̑t. A transformer with a reactance xt is noted to step up the voltage of the generator to V̑Et. By doing so, the static synchronous series compensator (SSSC) injection transformer boosts up the current voltage V̑cnv to V̑Bt. Thus, the relation between the direct current capacitor voltage Vdc and the fundamental frequency component of V̑Bt becomes;

$$\check{V}Bt = \frac{\text{mbVdc} < \delta b}{2}. \tag{4.8}$$

In the SSSC model, both the V̑2 and the V̑b are noted to be the mid-bus as well as the voltage of infinite bus respectively. The reactance of the transmission lines that are parallel is then represented by XL1 and XL2. Nonetheless, the voltage of the infinite bus is then taken as the reference with a magnitude that is constant. Therefore, the swing equation of the synchronous generator becomes [50, 52];

$$\delta = w_0(w-1) \tag{4.9}$$

$$w = \frac{P_m - P_c - D(w-1)}{M} \tag{4.10}$$

Thereafter, the transient dynamics voltage on the q-axis is given as follows;

$$\Sigma' q = \frac{\Sigma fd\, 0 + \Delta\Sigma fd - \Sigma' q - (xd - x'd)Itd}{T'do} \tag{4.11}$$

Tentatively, the dynamics of the exciter are given as follows;

$$\Delta\Sigma fd = \frac{Ka(Vref - Vt)}{Ta} - \frac{\Delta\Sigma fd}{Ta} \quad (4.12)$$

Then, the dynamics of the static synchronous series compensator (SSSC) direct current voltage become;

$$Vdc = \frac{3mbItdcos\delta b}{4Cdc} + \frac{3mbItqsin\delta b}{4Cdc} \quad (4.13)$$

The quantities of the algebras that appear in the above equations are then given as follows;

$$Pe = VtdItd + VtqItq \quad (4.14)$$

$$Vtq = \Sigma' q - x'dItd \quad (4.15)$$

$$Vtd = xqItq \quad (4.16)$$

After applying the KVL at the different nodes of the model, the equations are as follows;

$$\bar{V}t = jXt\bar{I}t + \bar{V}et \quad (4.17)$$

$$\bar{V}et = \bar{V}bt + jXl\bar{I}t + \bar{V}b \quad (4.18)$$

Combining two of the previous equations from the algebraic quantities, the following is obtained;

$$\bar{V}td + j\bar{V}tq = xq\bar{I}tq + j(\Sigma' q - x'dId) \quad (4.19)$$

The booster transformer is noted to have the voltages VBtd and VBtq, whereby the d and q components are expressed as follows;

$$Vbtd = \frac{MbVd\,ccos\delta b}{2} \quad (4.20)$$

$$Vbtq = \frac{MbVdcsin\delta b}{2} \quad (4.21)$$

In the voltage of the infinite bus, the d and q components can be noted as follows;

$$\bar{V}bd = \bar{V}bsin\delta \quad (4.22)$$

$$\bar{V}bq = \bar{V}bcos\delta \quad (4.23)$$

4.8.4 Controller Selection Process of the SSSC

A technique known as the Wideband Delphi was used that involved the incorporation of different technical committees whose purpose was to determine as well as to develop a consensus that was prolific to allot submission criteria and significance values that were estimated. The following equation represents a calculation method that was used to identify the value of the static synchronous series (SSSC) compensator device based on the provided statistical data that was estimated.

$$CRVz = \sum_{n=1}^{12} \frac{Bn}{100} xCn = \left(\frac{B1}{100} xC1 + \frac{B2}{100} xC2 + \frac{B3}{100} xC3 \ldots + \frac{B12}{100} xC12 \right) \quad (4.24)$$

where by;

‘Z’ is the static synchronous series compensator device, CRV is the credible value, and ‘C’ is the value that is constant of the static synchronous series compensator (SSSC) device. After an evaluation that was successful, the SSSC device was determined to be effective. Hence, the technique of Wideband Delphi can then be effectively used to create a consensus that is prolific [52, 53].

CHAPTER 5

SIMULATION STUDIES

5.1 General

Voltage and power must be delivered reliably from the source to the loads without any disturbance and within the constraints placed on the system operated by reliability consideration, the system will be operated more economically, and Transmission line's transmitting capability will be increased. To obtain above goals SSSC has been added to the weakest bus under different transient conditions such as single & three phase fault. Power system with four machines and six buses has been simulated in the SOFTWARE environment, and then voltages and powers are obtained. Simulation results have been focused on the bus-4 because of the variation in the powers at this bus; SSSC has to be installed at Bus no4 as a candidate bus.

5.2 System Model

In the simulation one SSSC has been applied to control the flow of power in 500 KV transmission systems. This system consisting of 6 buses (B1 to B6), connecting each other by three phase transmission lines L1-1, L1-2, L2-1, L2-2 and L3 with (170, 170, 160, 160 and 50 km) the length of lines respectively. L1 is separated into two parts of 170 km using a fault breaker at the midsection or the midpoint of the line in order to create a single and three-phase fault. The four power plants have been supplied to the system and at bus B3 one major load center of nearly 2200 MW is modeled using a dynamic load model where the load absorbed the active & reactive power as a function of the system voltage. The generators G1 & G2 have a rating of 2100 MVA and G3 & G4 each taken as 1000 MVA. Through the Table 5.1&5.2 entered the block parameters of synchronous machine model [47].

Table 5.1 Parameters of synchronous machine model (G1 and G2)

Nominal power, line-to-line voltage, frequency [Pn(VA) Vn(Vrms) fn(Hz)]:	[2100E6 13800 60]
Reactances [Xd Xd' Xd" Xq Xq" Xl] (pu):	[1.305, 0.296, 0.252, 0.474, 0.243, 0.18]
d axis time constants:	Short Circuit
q axis time constants:	Open circuit
Time constants [Td' Td" Tqo"] (s):	[1.01, 0.053, 0.1]
Stator resistance Rs (pu):	2.8544e-3
Inertia coeficient, friction factor, pole pairs [H(s) F(pu) p()]:	[3.7 0 32]
Initial conditions [dw(%) th(deg) ia,ib,ic(pu) pha,phb,phc(deg) Vf(pu)]:	[0 -58.9841 0.763417 0.763417 0.763417 14.3746 -105.625 134.375 1.2256]

Table 5.2 Parameters of synchronous machine model (G3 and G4)

Nominal power, line-to-line voltage, frequency [Pn(VA) Vn(Vrms) fn(Hz)]:	[1000E6 13800 60]
Reactances [Xd Xd' Xd" Xq Xq" Xl] (pu):	[1.305, 0.296, 0.252, 0.474, 0.243, 0.18]
d axis time constants:	Short Circuit
q axis time constants:	Open circuit
Time constants [Td' Td" Tqo"] (s):	[1.01, 0.053, 0.1]
Stator resistance Rs (pu):	2.8544e-3
Inertia coeficient, friction factor, pole pairs [H(s) F(pu) p()]:	[3.7 0 32]
Initial conditions [dw(%) th(deg) ia,ib,ic(pu) pha,phb,phc(deg) Vf(pu)]:	[0 -58.9841 0.763417 0.763417 0.763417 14.3746 -105.625 134.375 1.2256]

By three phases step up transformers the generators with output voltages 13.8KV are connected to an Intertie. During the Table 5.3&5.4 entered the block parameters of three Phase Transformer models 2100MVA, 1000MVA respectively [47].

Table 5.3 Parameters of three Phase Transformer model (2100MVA)

Units	Pu
Nominal power and frequency [Pn(VA) , fn(Hz)]	[2100e6 60]
Winding 1 parameters [V1 Ph-Ph(Vrms) , R1(pu) , L1(pu)]	[13.8e3 0.002 0.0]
Winding 2 parameters [V2 Ph-Ph(Vrms) , R2(pu) , L2(pu)]	[500e3 0.002 0.12]
Magnetization resistance Rm (pu)	500
Magnetization inductance Lm (pu)	500

Table 5.4 Parameters of three Phase Transformer model (1000MVA)

Units	Pu
Nominal power and frequency [Pn(VA) , fn(Hz)]	[1000e6 60]
Winding 1 parameters [V1 Ph-Ph(Vrms) , R1(pu) , L1(pu)]	[13.8e3 0.002 0.0]
Winding 2 parameters [V2 Ph-Ph(Vrms) , R2(pu) , L2(pu)]	[500e3 0.002 0.12]
Magnetization resistance Rm (pu)	500
Magnetization inductance Lm (pu)	500

The SSSC is taken place at Bus B4 connected in series with the line L2. The rating is 100MVA and has a capability of injecting up to about 10 percent of the nominal voltage in the power transmission system. A SSSC has a DC link nominal voltage and its total equivalent impedance on the AC side, it can be seen in Table 5.5. Through the utilization of SSSC the power quality problems, mitigate and it controls the active and reactive power and also improving the stability of power system [47].

Table 5.5 Block Parameters of SSSC

Display	Power data
System nominal voltage and frequency: [Vrms L-L, f(Hz)]	[500e3, 60]
Series converter rating: [Snom(VA) Max. Injected voltage(pu)]	[100e6, 0.1]
Series converter impedance: [R(pu) L(pu)]	[0.16/30, 0.16]
Series converter initial current: [Mag(pu) Pha(deg.)]	[0 0]
DC link nominal voltage (V):	40000
DC link total equivalent capacitance (F):	375e6

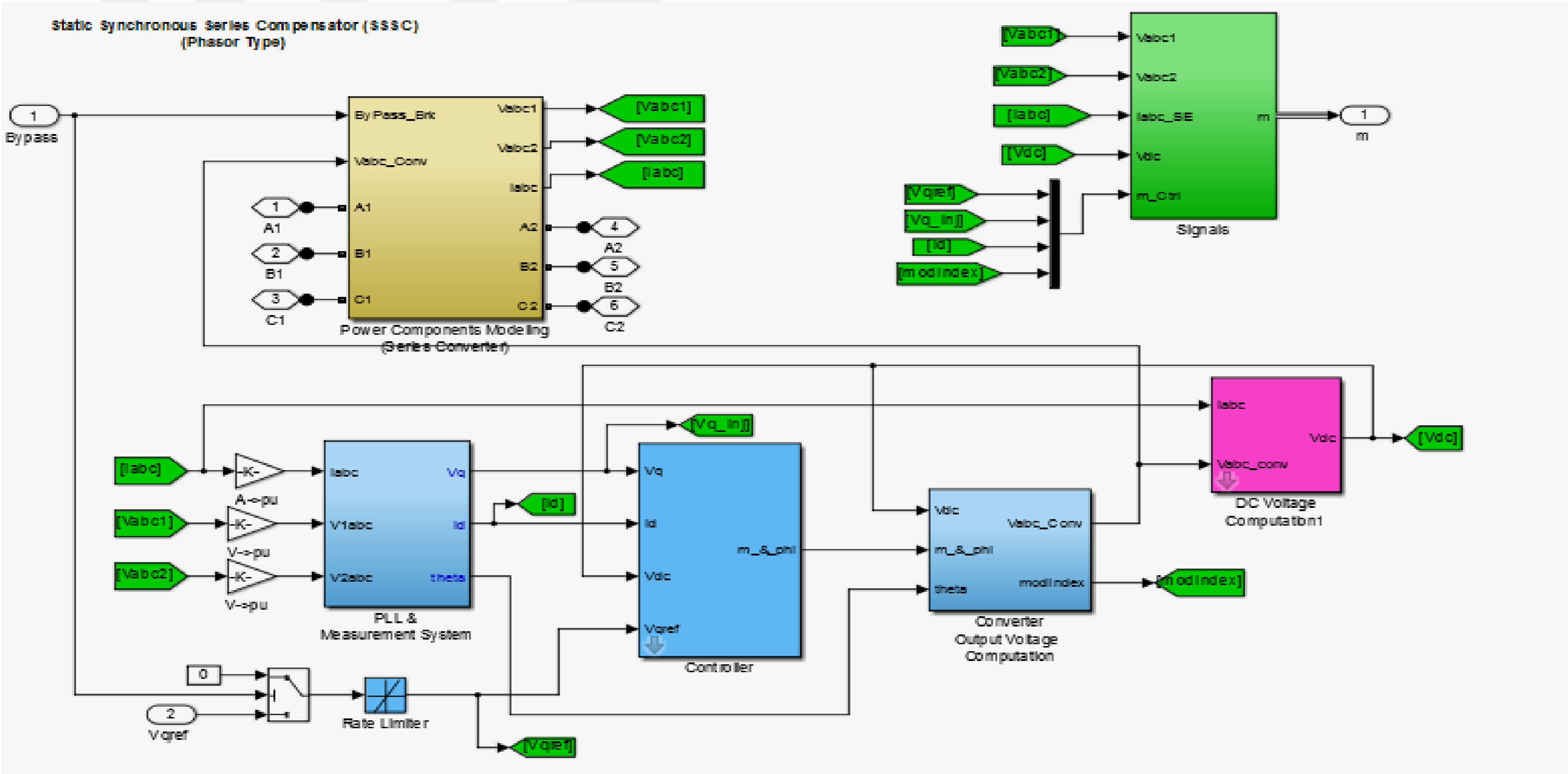


Figure 5.1 Block Diagram of SSSC and its Control System

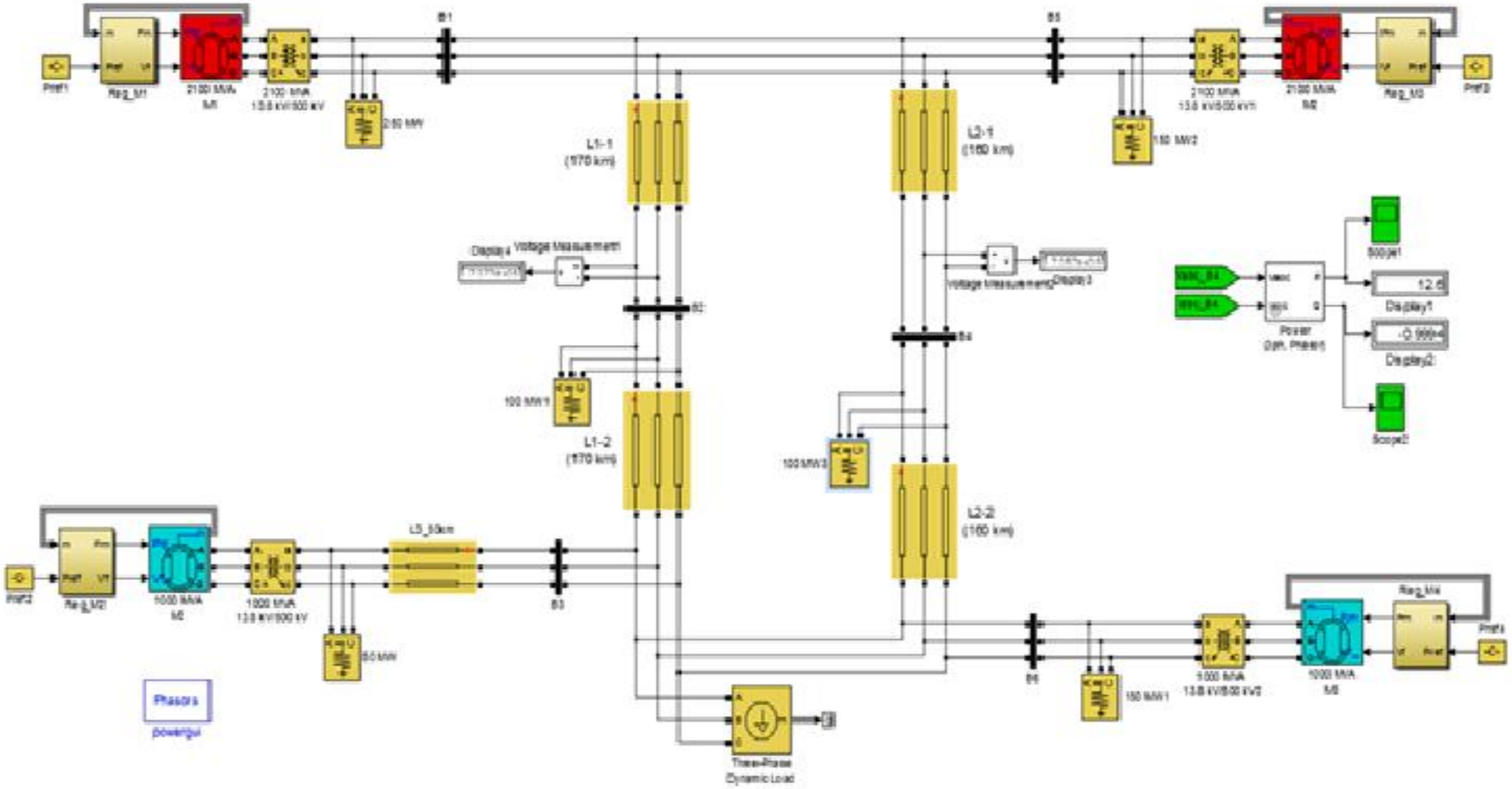


Figure 5.2 Four Machine System without SSSC

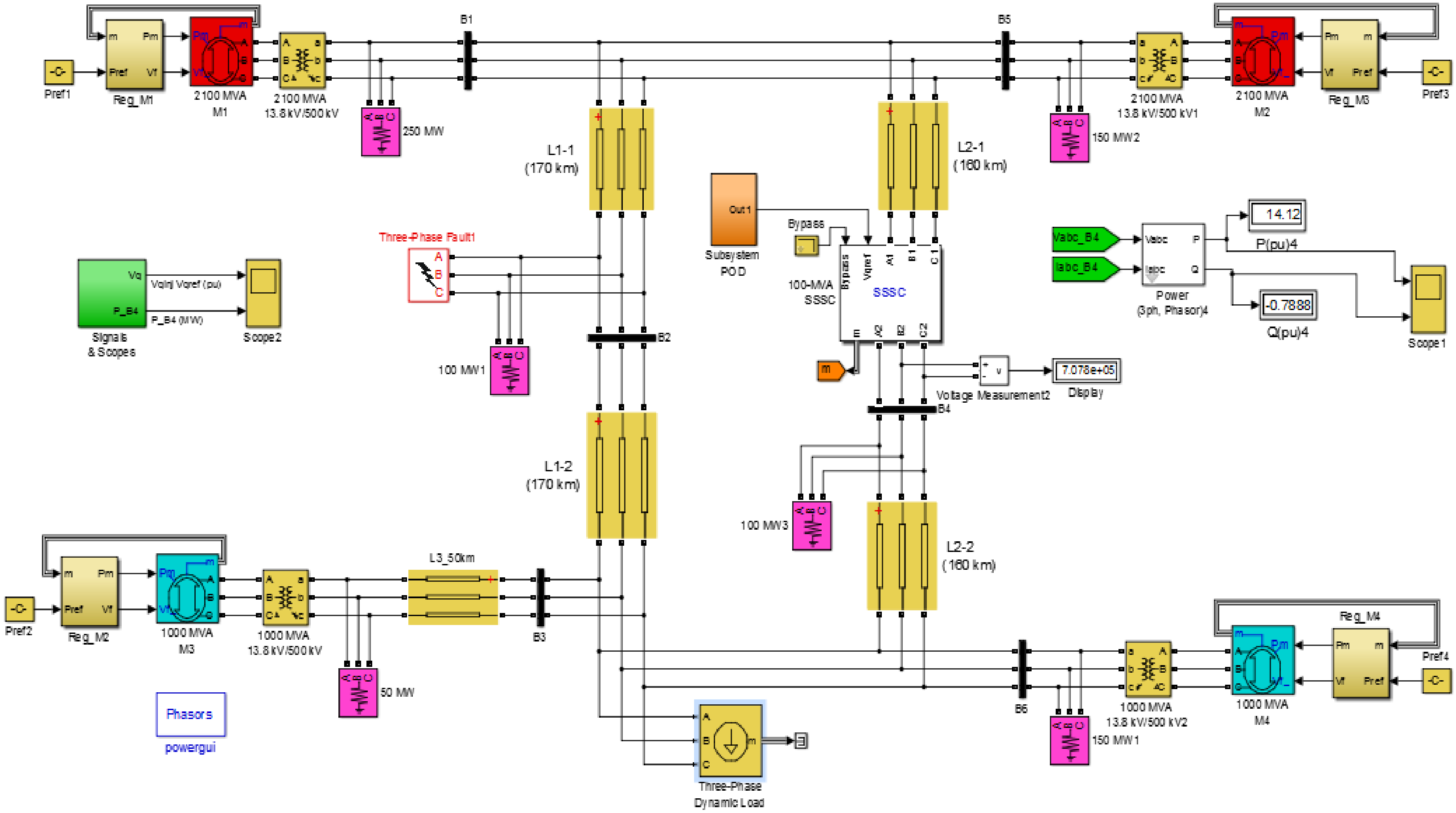


Figure 5.3 Four Machine System with SSSC

Normally a POD (Power Oscillation Damping) controller sets the SSSC injected voltage reference.The output of POD is connected to the Vqref input of the SSSC. It consists of a general gain, an active power measurement system, a low-pass filter, a washout high-pass filter, a lead compensator, and an output limiter as shown in Figure (5.4) bellow. The bus voltage at B4 and the current flowing in L2 are the inputs to the POD controller [47].

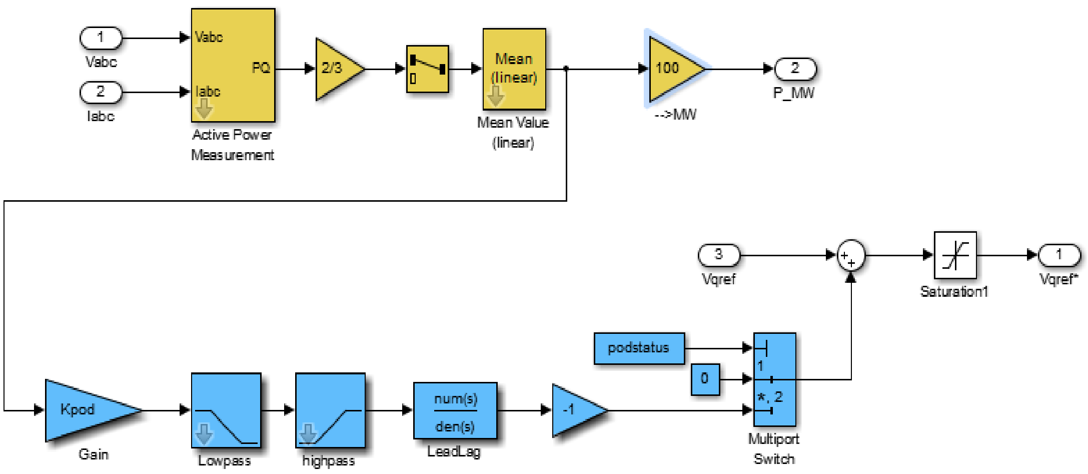


Figure 5.4 Simulink Model of POD controller

5.3 Simulation Studies

The system model in Figure (5.2) is tested under normal condition without SSSC.

Figure 5.3 is tested under normal, single-phase & three-phase fault conditions with POD and without POD.

The simulation results are obtained for four cases (6steps):

5.3.1 Case Study 1: Test System without Connecting SSSC

In this case SSSC is bypassed from the power system. The simulation results like voltage profile, active power and reactive power show the system performances under normal condition. Active power is more than reactive power oscillations because of the ohmic loads. The simulation diagram of a four machine six bus system without SSSC shown in Figure (5.2). The results have been given in Table 5.6 below.

Table 5.6 Simulation results without SSSC

No of Bus	Voltage Per unit	Current Per unit	Real power Per unit	Reactive power Per unit
1	0.964	7.912	11.71	-1.5
2	1.016	7.054	10.44	-0.956
3	0.962	4.326	6.403	0.762
4	0.966	8.513	12.6	-0.999
5	0.964	-8.912	-13.19	1.535
6	1.04	-3.337	-4.94	-0.55

The Figures below represent voltage, Active Power and Reactive Power for all Buses under normal condition.

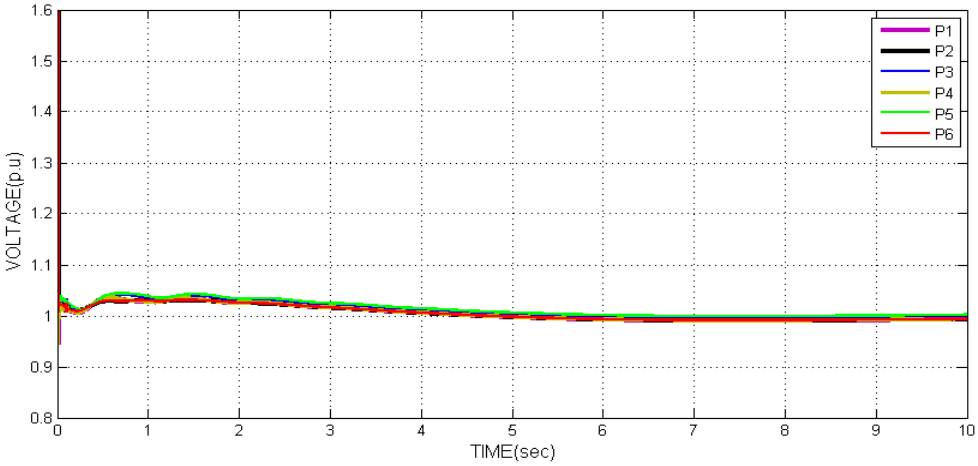
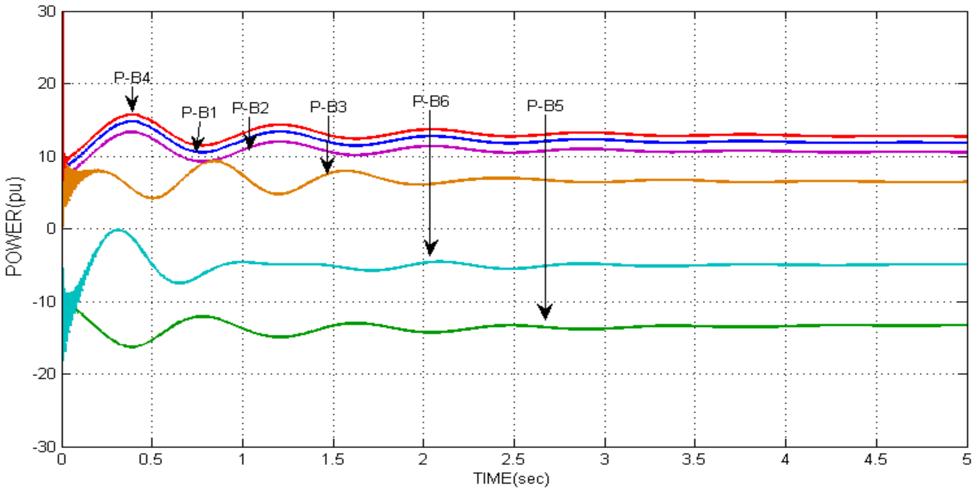


Figure 5.5 Positive sequence voltages at all Buses without SSSC

a



b

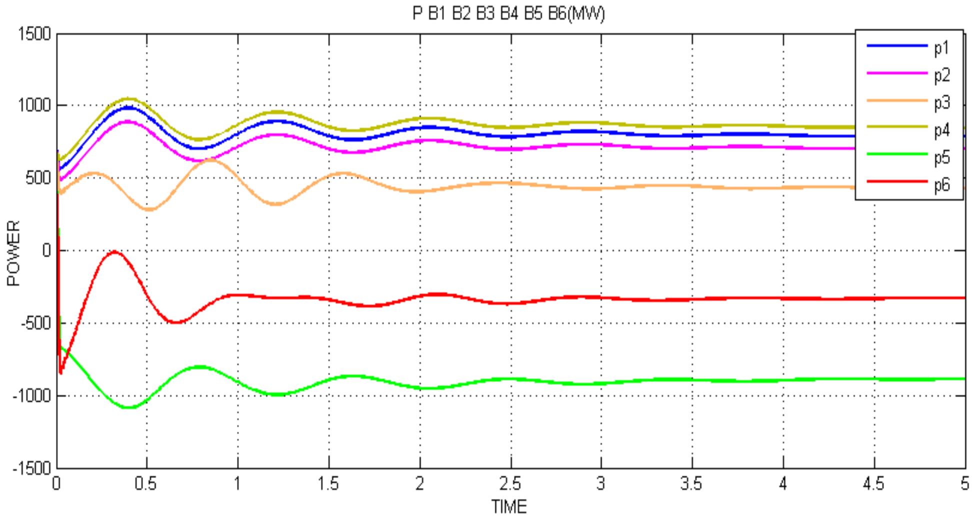


Figure 5.6 (a) Active Power in (Pu) at all Buses without SSSC

(b) Active Power in (Mw) at all Buses without SSSC

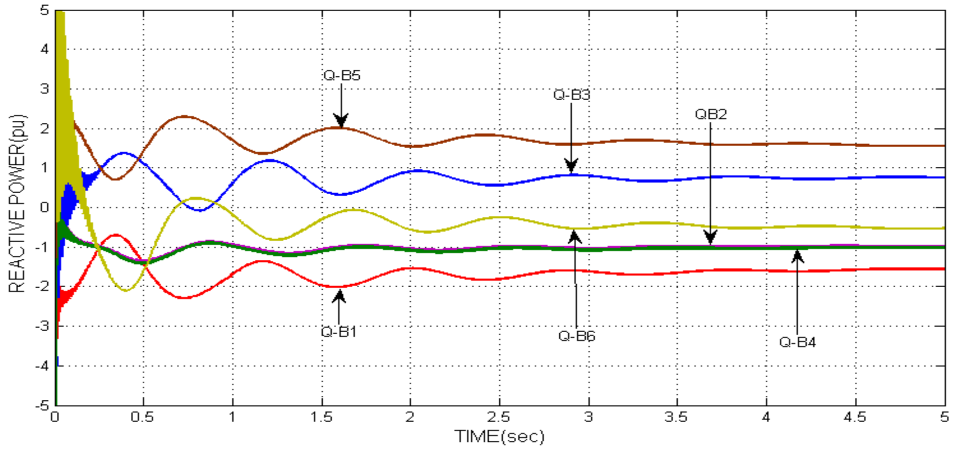


Figure 5.7 Reactive Power at all Buses without SSSC

Figure (5.8) shows the active power for bus B4 under normal condition and its value equal to 840 MW:

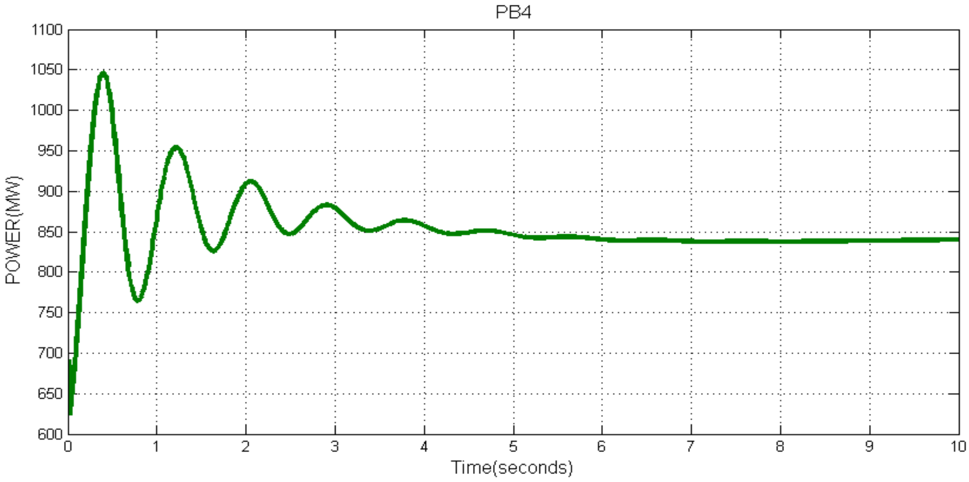


Figure 5.8 Active Power at Bus 4 under normal condition without SSSC

5.3.2 Case study 2: Test System with the SSSC (when POD is off)

In this case normal condition, single-phase fault & three- phase fault are considered. Initially Vqref is set to zero. At 2 Sec. It is set to - 0.08Pu which makes SSSC to operate in inductive mode. At 6 Sec. Vqref is set to 0.08 Pu which operates SSSC in capacitive mode. A single-phase & three-phase fault is applied at Bus no. 2 at 0.33 Sec. The simulation diagram for a 4 machine 6 bus system with SSSC is established.

It is evident that after installation of SSSC the oscillation is reduced as shown in Figures bellow and damping time will be less than the mode without SSSC. Also, it improves the transient stability of the system. Results have been given in Table5.7 below. It is clear that the SSSC maintains the flow of power, constant during the fault. Also voltage in all buses remains close to 1p.u.

Table 5.7 Simulation results with SSSC

No of Bus	Voltage Per unit	Current Per unit	Real power Per unit	Reactive power Per unit
1	1	7.952	11.77	-2.013
2	1	7.24	10.44	-0.822
3	1	4.383	6.487	0.650
4	1	9.567	14.16	-0.788
5	1	-8.959	-13.26	2.013
6	1	-3.331	-4.931	-0.371

When we compare between the results from Tables 5.6 &5.7 it will be clear that after connecting the series FACTS controllers the voltage improved, the active power transfer is increased, reactive power transfer decreased in most Buses and made the system more stable. Above results presented a goal of this thesis.

Case 5.3.2.1: normal condition

Figure 5.9 shows the Active power for Bus no. 4 under normal condition, the value of the Active power increases to 944 MW in the presence of SSSC. It is clear from the Figure that the oscillation of the Active power is reduced when compared to the case of without SSSC:

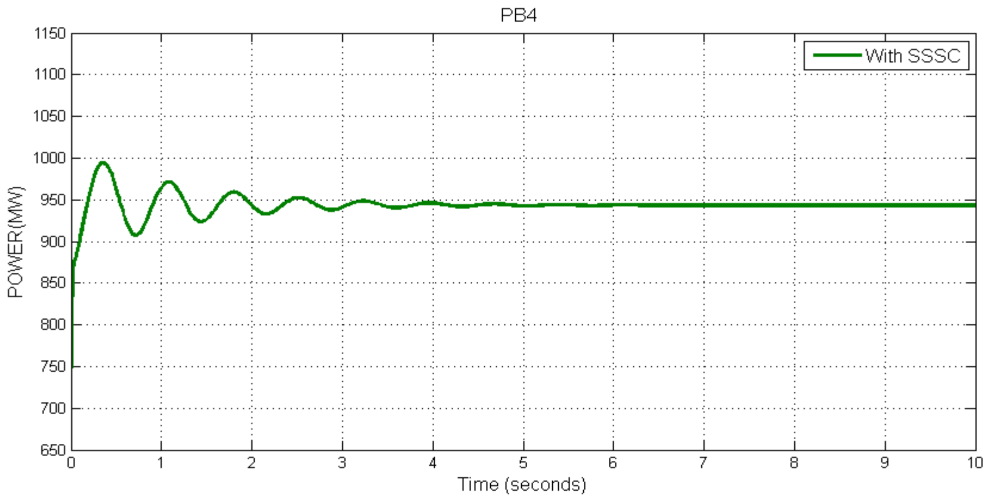


Figure 5.9 Active Power at Bus 4 under normal condition

The block diagram of the VPQ measurement for 4 machine 6 bus system in the presence of SSSC is shown in Figure (5.10).

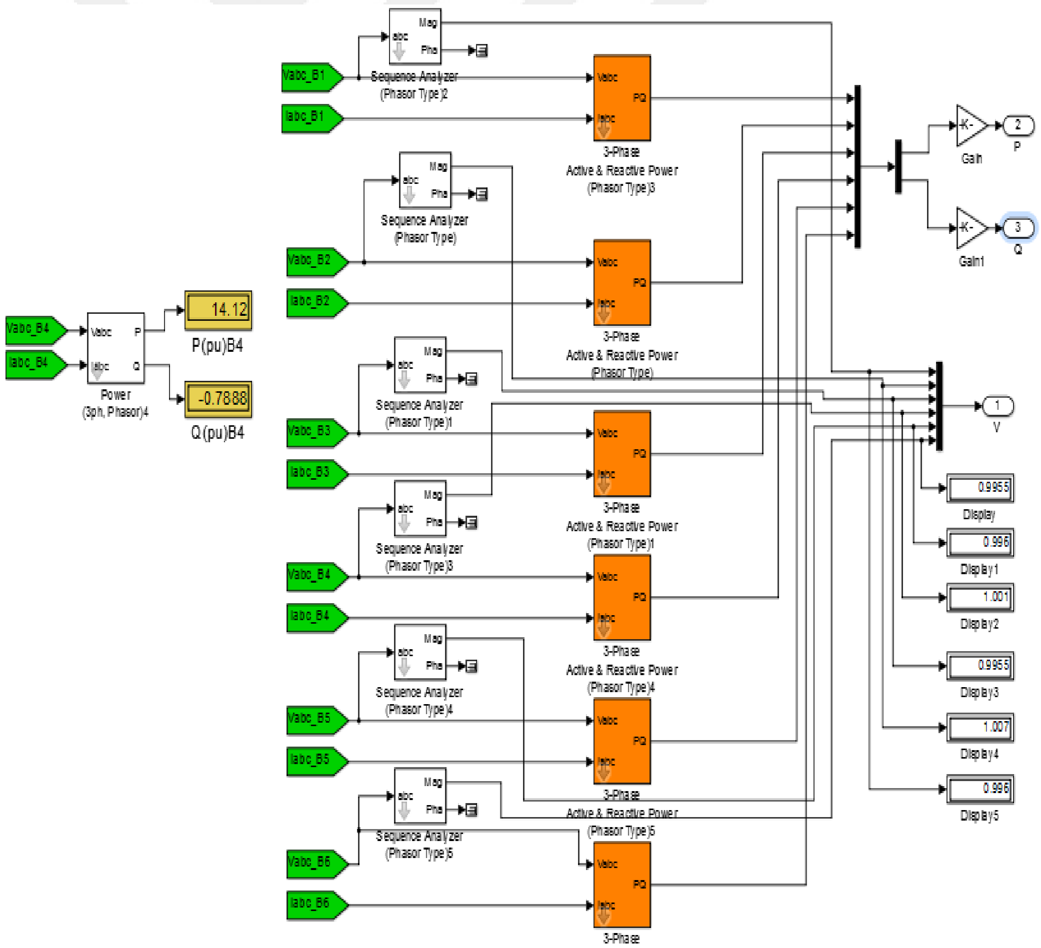


Figure 5.10 VPQ measurements

Case 5.3.2.2: single-phase fault & three-phase fault

The Simulation results of the system when the single-phase and three-phase fault occurred at the Bus no. 2 during (0.33 to 0.50) in the presence of SSSC at Bus no. 4 (POD is off):

Active Power at Bus no. 4 under single-phase fault can be seen in Figure (5.11). It is clear that the variation increases during the time of fault and reach to 1110 MW at the top and 875 MW at the bottom.

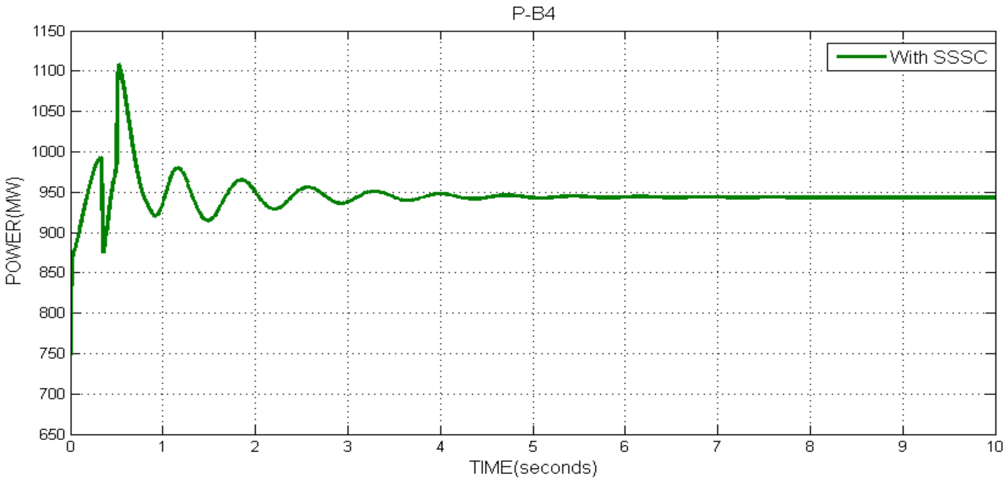


Figure 5.11 Active Power at Bus 4 under single-phase fault

Active Power at Bus no. 4 under three-phase fault can be seen in Figure (5.12). It is obvious that the variation during the time of fault reach to 1350 MW at the top and 400 MW at the bottom.

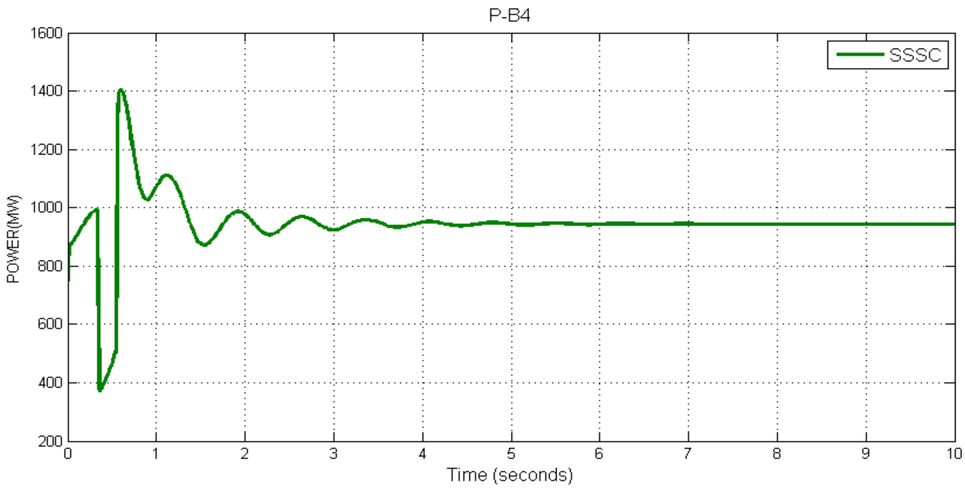


Figure 5.12 Active Power at Bus 4 under three-phase fault

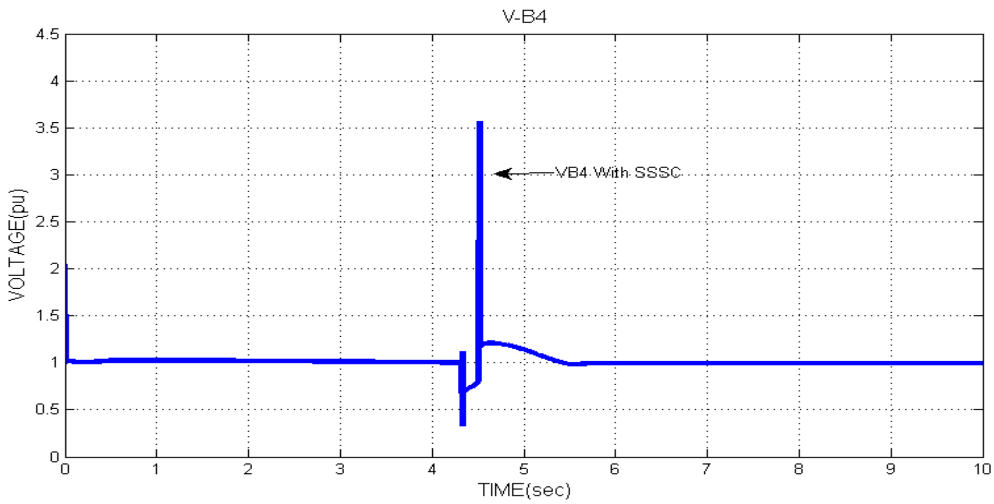


Figure 5.13 Voltage at Bus 4 under three-phase fault in presence of SSSC

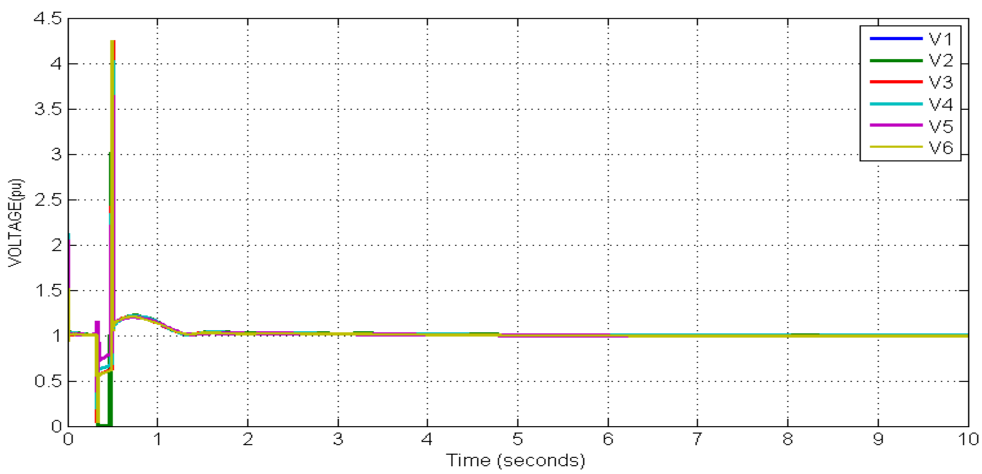


Figure 5.14 Positive sequence voltage at all Buses under three-phase fault in the presence of SSSC

Active powers of all Buses under three-phase fault when SSSC without POD controller is shown in Figure (5.15) below:

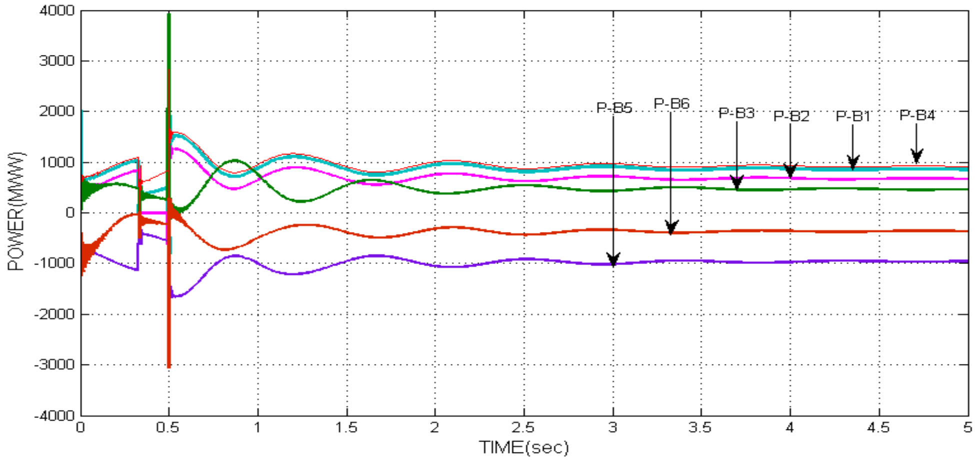


Figure 5.15 Active power of all Buses under three- phase fault

Comparisons between the power flows at Bus no.4 which is a candidate bus with and without SSSC can be seen in Table 5.8.

Table 5.8 Voltage profiles and power flows at bus 4

BUS NO	**VOLTAGE(Pu)**		**ACTIVE(MW)**		**REACTIVE(Mvar)**	
	Without SSSC	With SSSC	Without SSSC	With SSSC	Without SSSC	With SSSC
4	0.966	1	840	944	-67.9	-53.6

5.3.3 Case study 3: Test system with the SSSC (when POD is on)

Here normal condition, single-phase & three- phase fault are considered. The fault is applied at Bus no. 2 during (0.33 to 0.50) Sec. By installing the SSSC with POD the voltage stability has been enhanced and power oscillations are damped perfectly when compared to the four machine system without POD. The simulation results show that this controller gives the best performance to the system during normal and fault conditions. POD controller can accomplish oscillation damping, rapid response and finally stabilizing power system [10]. Figures below show that after implementing SSSC with POD parameters become stable & its performance becomes higher than without a controller. The overshoot of oscillation is slightly reduced if compare with the case study 2 without POD controller.

Case 5.3.3.1: normal condition

Figure 5.16 shows the Active power at Bus no. 4 under normal condition, the value of the Active power is remained 944 MW. It is clear from the Figure that the oscillation of the Active power is reduced or damped out when compared to the case of SSSC without POD controller they can be seen together in Figure 5.17:

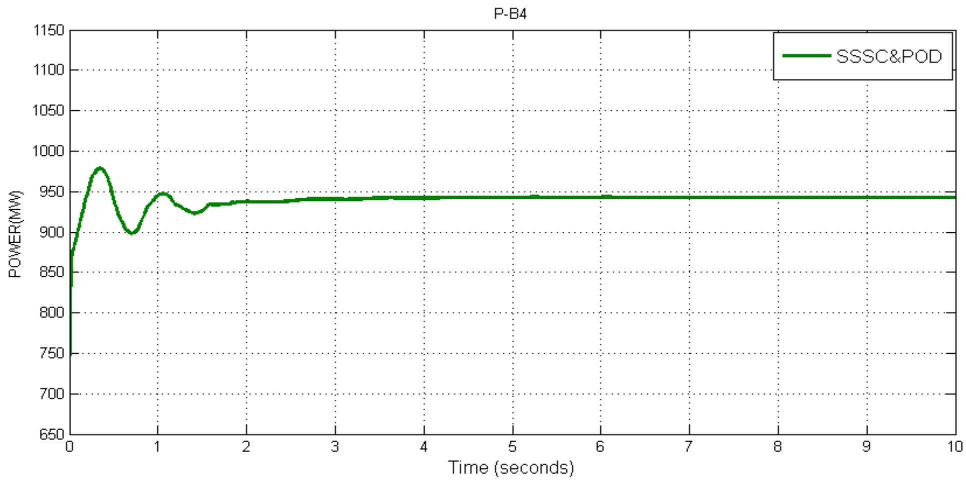


Figure 5.16 Active Power at Bus no.4 under normal condition

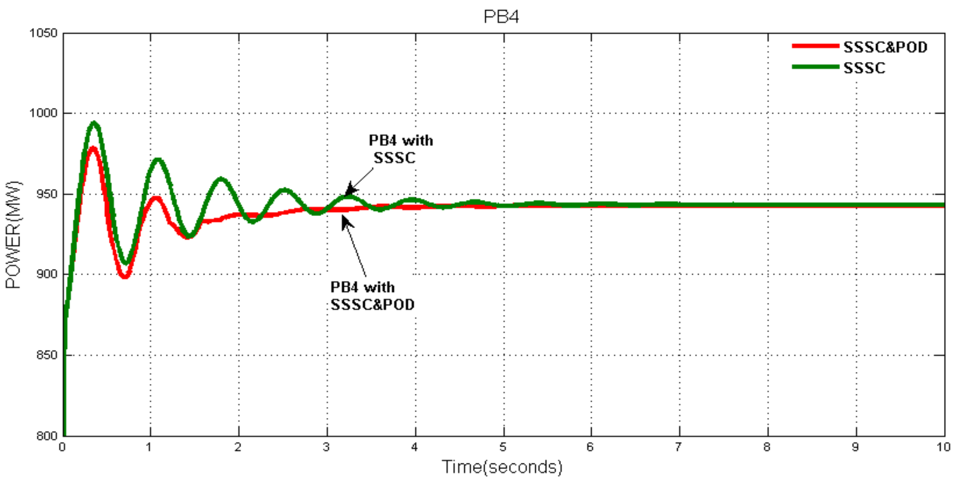


Figure 5.17 Active Power when SSSC with and without POD controller under normal condition

Case 5.3.3.2: single-phase fault & three-phase fault

The Simulation results of the system when the single and three-phase fault occurred at the Bus no. 2 in the presence of SSSC at Bus no. 4 (POD is on):

Active Power at Bus no. 4 under single-phase fault can be seen in figure (5.18). It is obvious that the variation during the time of fault reduced in the present of POD when compare to the case of SSSC without POD controller both of them can be seen together in Figure (5.19).

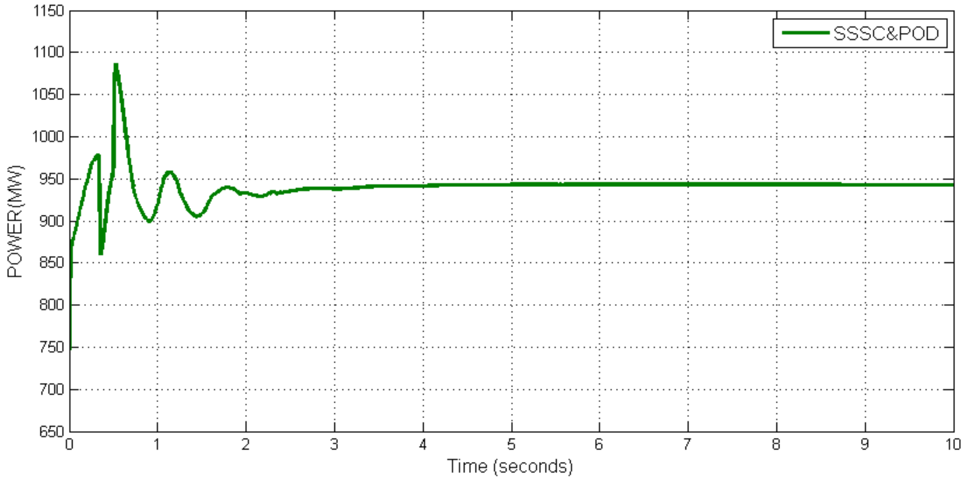


Figure 5.18 Active Power at Bus no.4 under single-phase fault

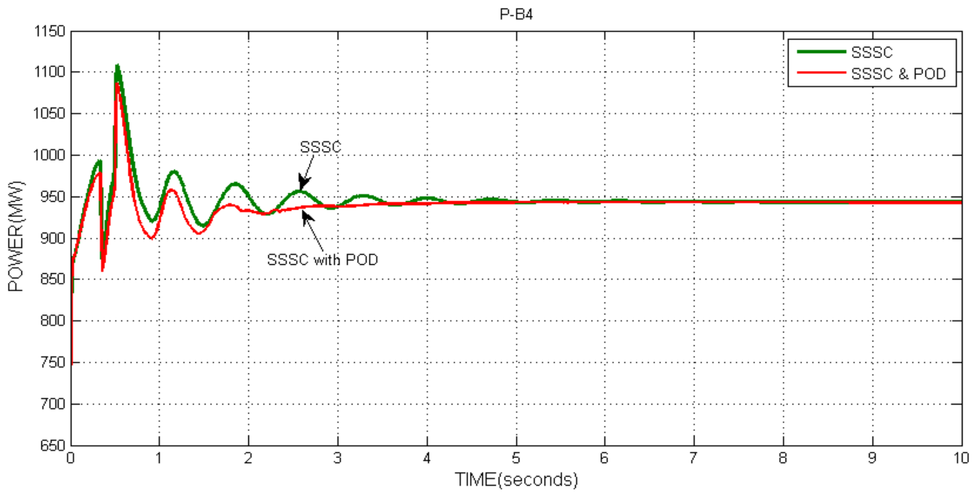


Figure 5.19 Active Power when SSSC with and without POD controller under single-phase fault

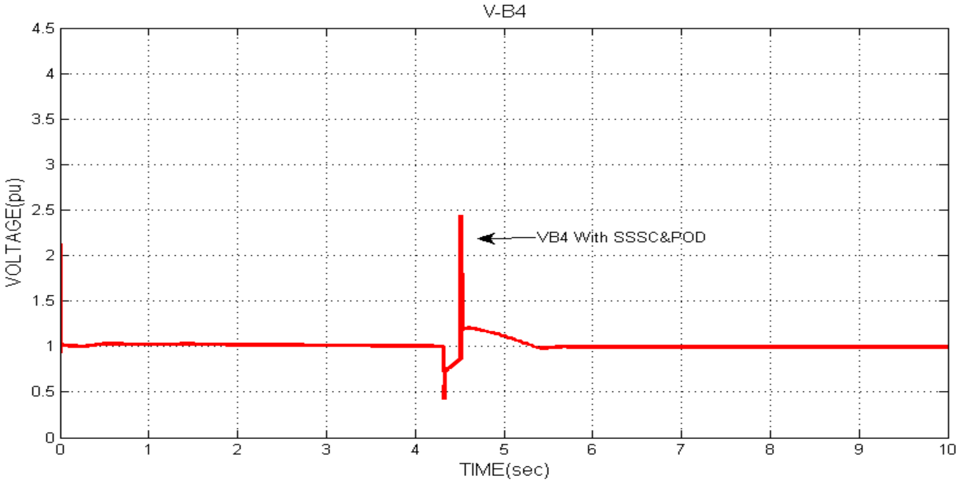


Figure 5.20 Voltage at Bus 4 under three-phase fault in the presence of SSSC with POD controller

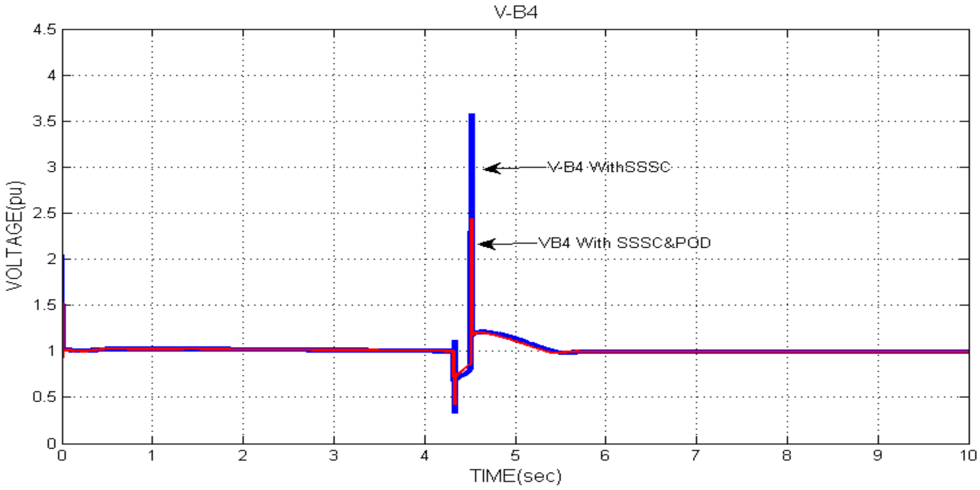


Figure 5.21 Voltage at Bus no.4 under three-phase fault when SSSC with and without POD controller

Active Power at Bus no. 4 under three-phase fault can be seen in Figure (5.22). It is evident that the variation during the time of fault reduced when compared to the case when SSSC without POD controller. The difference between them is shown in Figure (5.23) together.

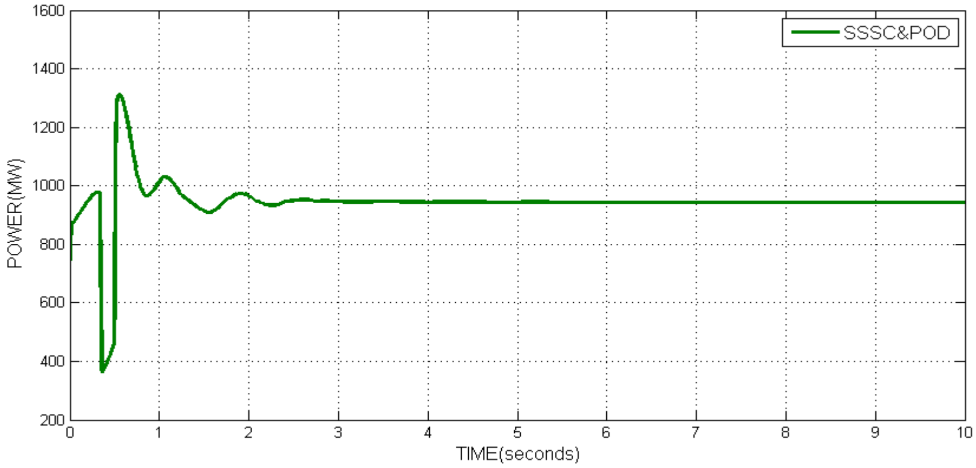


Figure 5.22 Active Power at Bus no.4 under three-phase fault

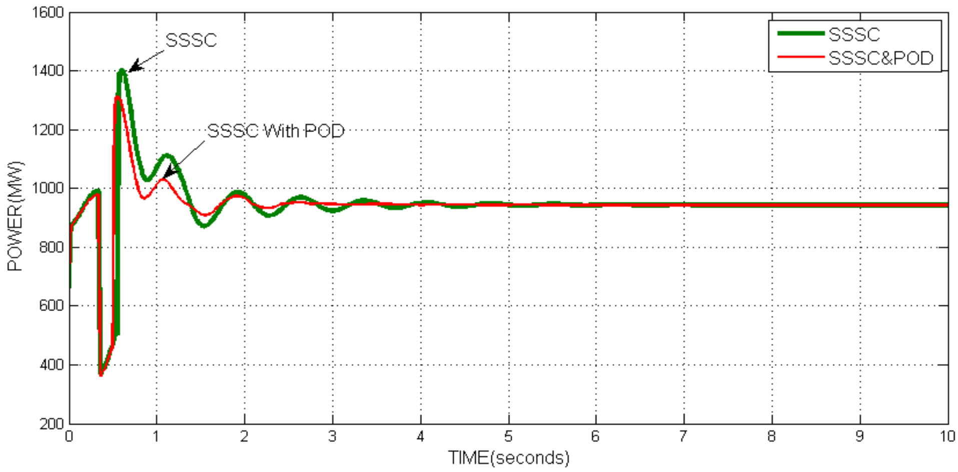


Figure 5.23 Active Power at Bus no.4 when SSSC with and without POD controller under three-phase fault

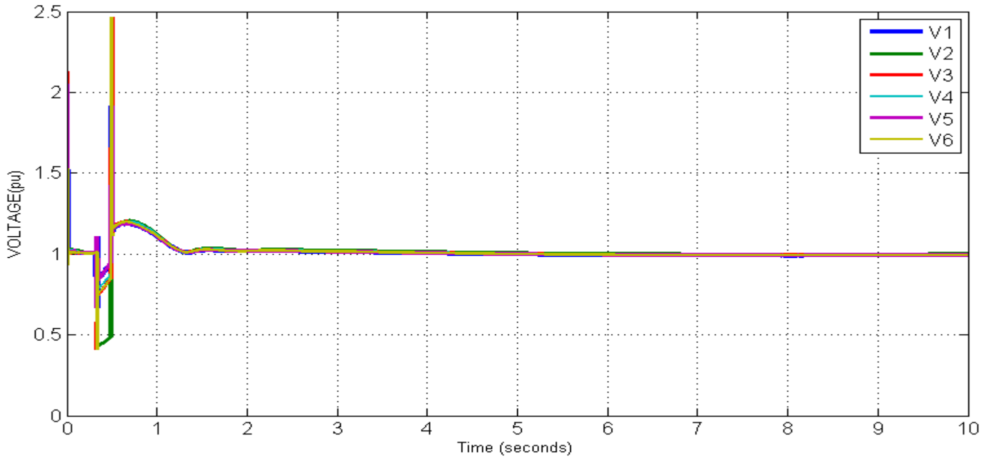


Figure 5.24 Positive sequence voltages at all Buses under three-phase fault when SSSC with POD controller

Figure (5.25) below Shows the Active power at all Buses under three-phase fault when SSSC with POD:

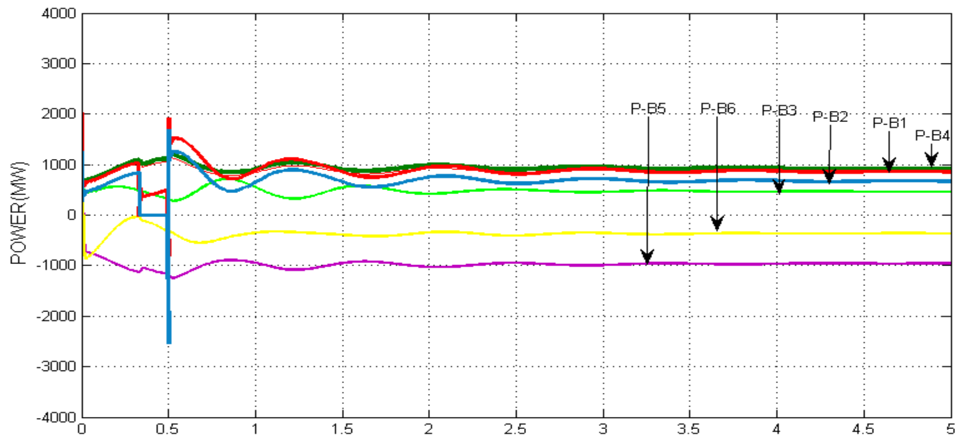


Figure 5.25 Active powers of all Buses under three- phase fault

5.3.4 Case study 4: combination between case study 2 & 3 with changing the time of occurring the fault

In this case figure (5.26), (5.27) represent active power at Bus no. 4 when SSSC with and without POD controller under single & three phase fault respectively when the Fault occur during the time (4.33 to 4.50) second.

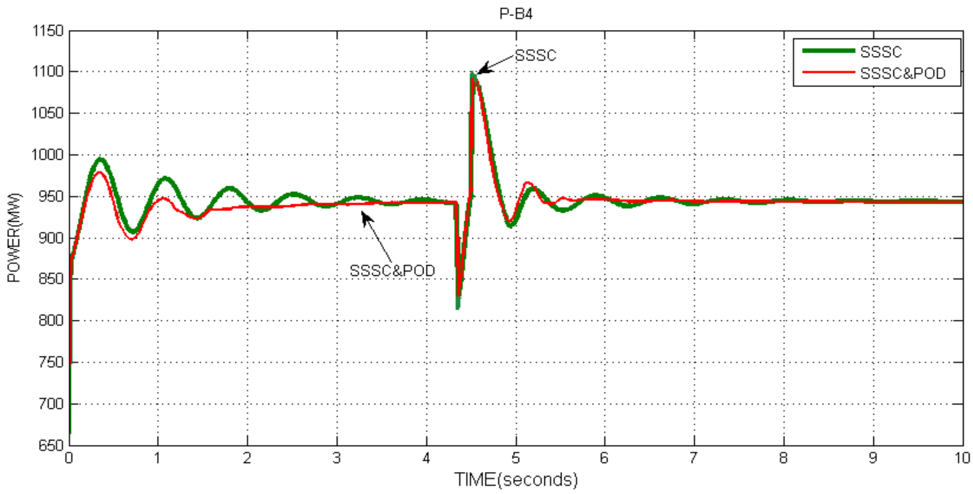


Figure 5.26 Active Power when SSSC with and without POD controller under single-phase fault

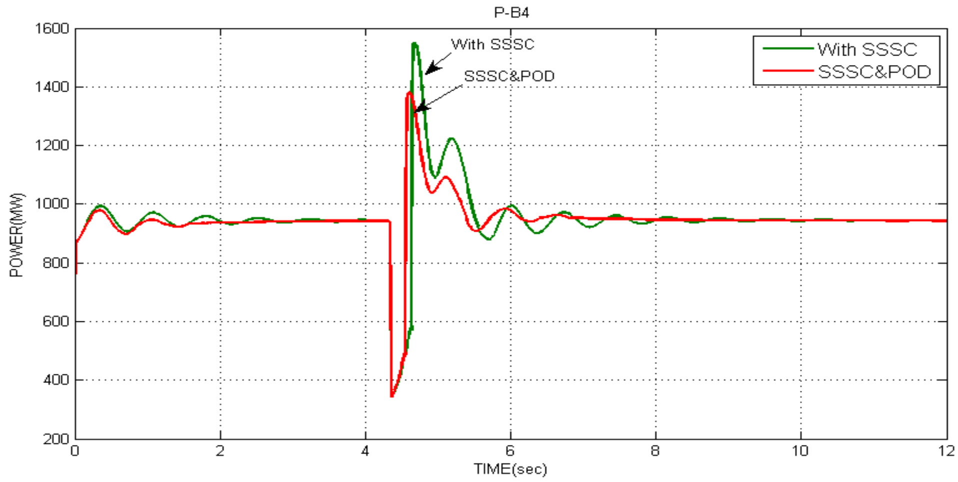


Figure 5.27 Active Power when SSSC with and without POD controller under three-phase fault

Voltages at all Buses under single phase fault when SSSC without and with POD controller are shown in the Figure (5.28), (5.29) respectively, when the fault occurs during the time (4.33 to 4.50) second.

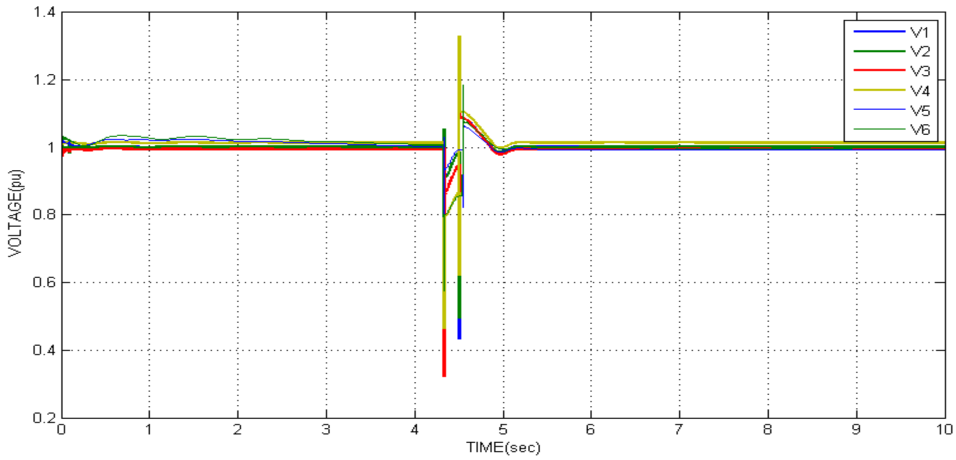


Figure 5.28 Positive sequence voltage at all Buses under single-phase fault when SSSC without POD

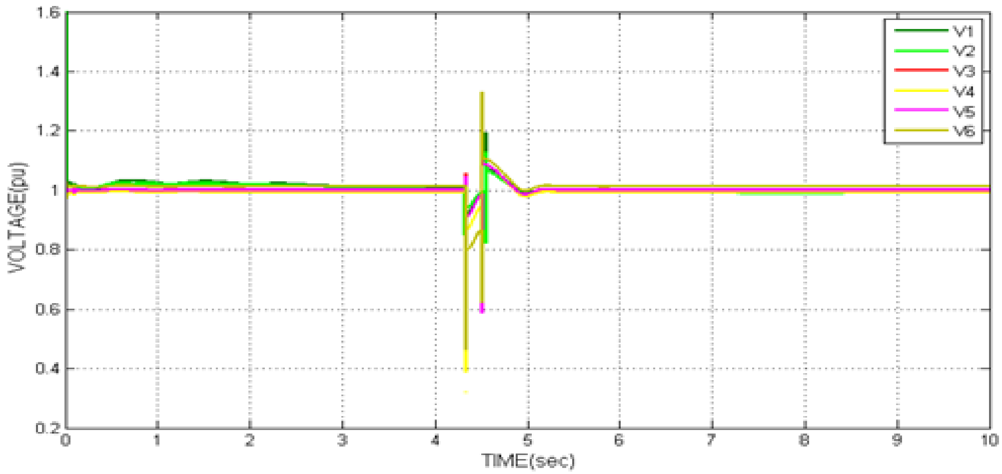


Figure 5.29 Positive sequence voltage at all Buses under single-phase fault when SSSC with POD

Active powers at all Buses under three phase fault when SSSC without and with POD controller can be seen in the Figure (5.30), (5.31) respectively, when the fault occurs during the time (4.40 to 4.70) second.

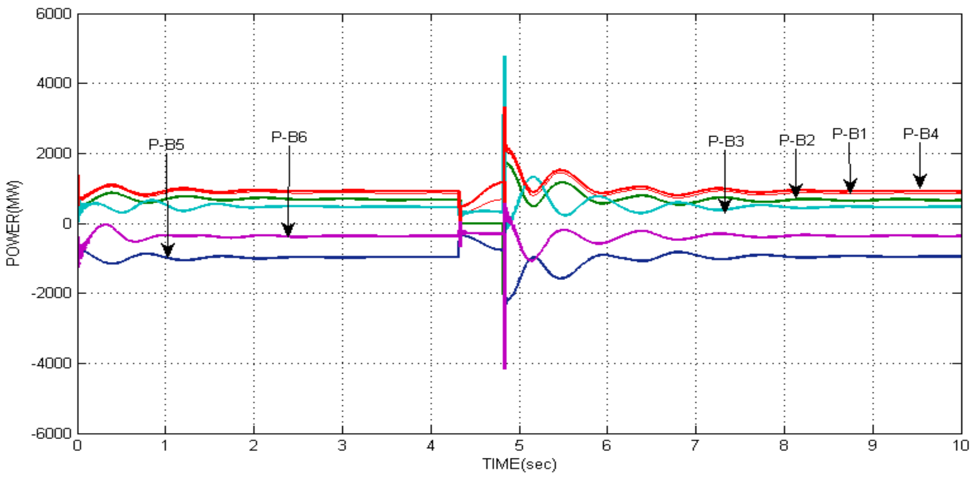


Figure 5.30 Active power at all Buses under three phase fault when SSSC without POD controller

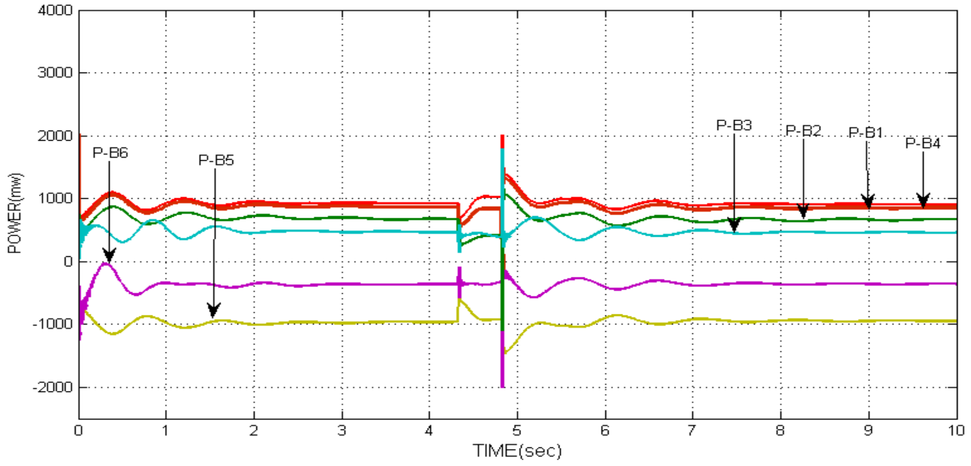


Figure 5.31 Active power at all Buses under three phase fault when SSSC with POD controller

Reactive power at all Buses under single- phase fault when SSSC without and with POD controller are shown in the Figure (5.32), (5.33) respectively, when the fault occurs during the time (4.33 to 4.50) second.

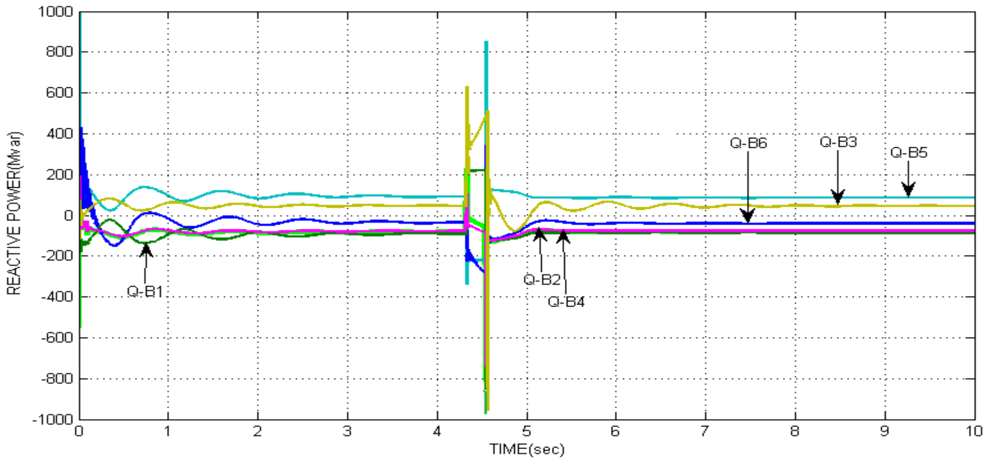


Figure 5.32 Reactive powers of all Buses under a single-phase fault

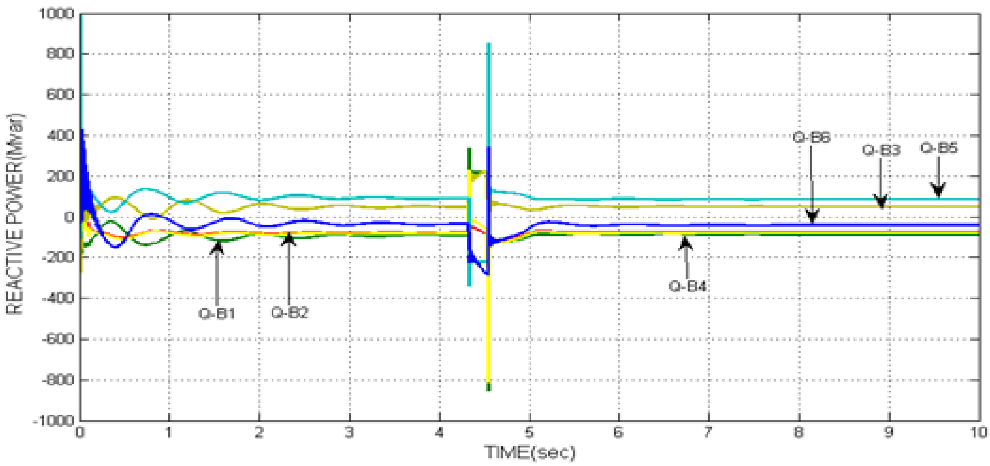


Figure 5.33 Reactive powers of all Buses under a single-phase fault

The results are presented that after occurring fault in the system big oscillations will appear in line power, then the system cannot transfer more active power and cannot minimize reactive power transfer. As shown in figures the overshoot of oscillation is happening in voltage, power and reactive power when the fault is occurring at Bus no. 2, these oscillations will damp gradually very quickly in few seconds after starting SSSC controller. It's clear from the figures that after applying POD controller with SSSC the overshoot of oscillation during the fault will be decreased and the time of damping will be less than the mode without POD and it will be damped much faster.

CHAPTER 6

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

6.1 Conclusion

In conclusion, the improvement of power stability using SSSC with POD is influenced by maintenance of phase angle and magnitude of the voltage. During the control of the power flow from one end to another, it is important to involve the concept of controlling the flow of power together with the injection of voltage. Through the modeling of the system and by examining the results from the simulations performed, it can be clearly indicated that the static synchronous series compensator (SSSC) is very useful when it comes to organizing and maintaining the power system. Through the results that have been obtained, there are certain conclusions that are made. One such observed conclusion is that the control of the flow of power is accomplished, and there is less congestion. Moreover, through the use of the controller in the power system, the transient ability is enhanced. There is also a faster steady state that is accomplished and lastly, the profile of voltage is also improved. So it increases system security and helps to reduce total blackout of the network.

Three different cases are inspected in this study. First case considered in this study is the six bus system without SSSC becomes unstable with oscillations. The second case study is the system with the SSSC (POD is off) becomes stable, after a fault is occurring it can be seen the fast damping of these oscillations and it became a zero value after a few minutes. In the third case study SSSC with Power System Controller (POD) the excellent damping of the oscillations which appeared also the system parameters become more stable in a faster way than without a controller. So with controller the system performance is greatly improved and power system oscillations are reduced and damped out very quickly.

From the simulation results, it’s evident that the SSSC has been achieved to damp the oscillations of multimachine power system. In order to enhance the stability of Power system the Combination way of Power System SSSC and POD not only reduced the system oscillation, also it was significantly helped to improve stability and operate the system within the allowable range.

6.2 Suggestions for Future Work

For purposes of future research, it is recommendable to investigate the design of static synchronous series compensator (SSSC) based damping controller using invasive weed optimization (IWO) algorithm. As a model useful in stabilizing power system, the design of SSSC based damping controller enhances the stability of SMIB (Single Machine Infinite Bus) system through the means of Invasive Weed Optimization technique.

The design of the conventional PID controller is utilised with the SSSC damping controller, which takes the deviation of rotor speed as an input. This is an essential aspect that can be used to more stabilize power system, hence, important for future research.

In future the implementation of the SSSC will be extended to a complex system to inquiry the problems related to the different modes of oscillation in the power systems.

Simulation model to enhance the stability of power system using another type of FACTS device with POD using Genetic Algorithm.

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