Master Thesis

on

Analysis of Power System Stability by Using Optimally Located SVC and STATCOM

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# Table of Contents

1. Introduction...........................................................................................................1  
   1.1 Objectives of this thesis..................................................................................1  
   1.2 Background.....................................................................................................1  
   1.3 FACTS devices..............................................................................................2  
   1.4 Optimal placement of FACTS devices............................................................3  
   1.5 Supplementary control..................................................................................3  
   1.6 Wide area monitoring systems.......................................................................4  
   1.7 Work organization.........................................................................................4  

2. Modelling of various components in this thesis..................................................5  
   2.1 Generators.....................................................................................................5  
   2.2 Transmission lines........................................................................................5  
   2.3 Loads.............................................................................................................6  
   2.4 Static var compensator..................................................................................7  
   2.5 Static synchronous compensator..................................................................11  
   2.6 Power system................................................................................................14  

3. Modal Analysis and voltage stability..................................................................16  
   3.1 Small signal stability.....................................................................................16  
      3.1.1 Linearization..............................................................................................17  
      3.1.2 Modal and eigenvalue analysis.................................................................18  
      3.1.3 Controllability and observability..............................................................19  
      3.1.4 Residue technique for POD tuning...........................................................20  
   3.2 Control Lyapunov Functions..........................................................................21  
   3.3 Voltage Stability............................................................................................21
4. Methods and procedure

4.1 Basic approach

4.2 Approach for SVC

4.2.1 Optimal placement of an SVC

4.2.2 Choice of input signal to the POD

4.2.3 Input signals used with the SVC

4.3 Approach for a STATCOM

4.3.1 Optimal placement of a STATCOM

4.3.2 Choice of input signals for the STATCOM

4.3.3 Input Signals used with STATCOM

5. Simulations and results with SVC

5.1 Test power system

5.2 Identifying the critical oscillatory modes

5.3 Results for the location of the SVC

5.4 Results for the input to the POD for the SVC

5.5 Fault cases for an SVC

5.6 Transient stability

6. Simulations and results with STATCOM

6.1 Test power system

6.2 Identifying the critical oscillatory modes

6.3 Results for the location of the STATCOM

6.4 Results for the input to the POD for a STATCOM

6.5 Fault cases for a STATCOM
6.6 Transient stability ...............................................................59

7. Comparison between an SVC and a STATCOM ........................................61
   7.1 Damping of oscillatory modes .....................................................61
   7.2 Transient stability .................................................................65

8. Conclusions and future work .........................................................67
   8.1 Conclusions ...........................................................................67
   8.2 Future work ...........................................................................67

Appendix A ..................................................................................69

References ...............................................................................74
Chapter 1: Introduction

1.1 Objectives of this thesis

The main objectives of the project were:

- To see how the optimally located shunt FACTS devices namely the SVC and STATCOM impact the rotor angle stability and voltage stability of the system
- To see how the rotor angle oscillations of the critical modes can be reduced. Both rotor angle stability and transient stability were to be analyzed in the presence of supplementary control to enhance the stability in the system with the objective being finding the best input signal to the controller.
- Finally a choice based on the results obtained was to be made for the more suitable of the two devices.

1.2 Background

With the constant increase in the demand of electricity throughout the world, more power needs to be transferred in order to feed the growing load. In previous years, environment concerns and high costs of right of ways have delayed or even made it impossible to build new transmission corridors for the transfer of power. Hence Flexible AC Transmission Systems (FACTS) devices are becoming an important part of power systems today. Due to increasing demand of electricity, the transmission corridors are being operated close to their limits which may lead to reduced stability margins. FACTS devices are being installed in the power systems to improve system stability by reducing undesirable loop flows, enhancing transient and voltage stability and improving damping of low frequency power oscillation [1].

Transient stability means that the generators within a system are able to retain synchronism after a large disturbance [2]. Instability that could occur would lead to an eventual loss of synchronism of the machines oscillating within that system.

On the other hand, voltage stability is the ability of the power system to maintain steady voltages at all the buses after being subjected to a disturbance [2]. A low voltage at any one of the buses could have a cascading effect leading to a total collapse of the system and a partial or complete blackout.

Small signal stability is the ability of a system to remain stable after a small disturbance such as fluctuation of load or disconnection of some line for a short time. In small signal stability although the electromechanical oscillations are usually well damped but insufficient damping of one or more critical oscillatory modes might cause the system to become unstable as the low frequency oscillations may get undamped [3]. These oscillations if not controlled properly could lead to a partial or total system blackout and hence tremendous losses to the companies running the power grids.
Power system stabilizers are generally used to damp these oscillations, but now with the development of FACTS devices the focus is being shifted towards them. FACTS devices with supplementary control not only damp the critical oscillations in the system, but with the right choice and placement of the device they can be used for load curtailment, voltage support, congestion management, improved steady state and dynamic performance of the system due to fast operation [4] as well as improve transient stability.

1.3 FACTS Devices

There are basically three types of FACTS devices. Devices connected in shunt with the power system, devices connected in series with the power system and a combination of shunt and series connected devices [1].

A brief explanation of the different types of FACTS devices is given below:

- **Shunt connected devices**

  These devices are connected in shunt with the power systems. The two most common are the static var compensator (SVC) and the static compensator (STATCOM). Basically the aim of these devices is to provide voltage support to the system by exchanging reactive power with the system and maintaining the voltage of a bus close or equal to a certain reference level. They will be explained in detail later on as the focus of this work was on these devices. A newer version of STATCOM is being developed which can exchange active power with the system with the help of energy storage systems. If there is a need for injecting active power in the system, the energy storage system will provide it while an excess of active power in the system would be used to charge those energy storage systems. These devices with proper external control can also be used to damp rotor angle oscillations within a system.

  Thyristor controlled braking resistor is another shunt connected FACTS device which is installed to exclusively improve the transient stability of the system. It generally acts as a resistive load which is capable of absorbing some of the generation in case of a large disturbance so as to avoid the loss of synchronism of the oscillating machines [5].

- **Series connected devices**

  These devices as their name suggests are connected in series with the power system. The three common devices are the series capacitors, thyristor controlled series capacitor (TCSC) and the static synchronous compensator (SSSC). The series capacitor is a fixed capacitor which when connected in the line, reduces its reactance. The TCSC acts as a controllable impedance connected in series with the line. It can operate both in the inductive and capacitive modes and thereby help in changing the reactance of the line thus allowing more or less power to flow through it. In an SSSC, a controllable voltage both in magnitude and phase is injected in series to the line it is connected in. By control
over these parameters the current, active and reactive power through a line can then be controlled.

- Shunt-series connected devices

These devices usually operate in a way so as to provide both support in series to the line and in shunt with the bus they are connected. The most common of these devices are the unified power flow controller (UPFC) and thyristor controlled phase shifting transformer (TCPST). A UPFC mainly consists of two voltage source converters. One inserts a controllable voltage in magnitude and phase in series with the line it is connected. The second converter provides or absorbs the active power demand of converter 1. It can also generate or absorb reactive power at the bus it is connected and hence provide voltage support. TCPST is another FACTS device that can exchange both active and reactive power with the system. Although the combination of shunt series devices is quite effective for the stability of power systems, their extremely high costs are one of the drawbacks.

Thus FACTS devices can be used to provide voltage support, control power flows and currents through lines. But another advantage of these devices is that with an appropriate supplementary control, these devices can be used to damp rotor angle oscillations. Just in the same way a power system stabilizer is connected to the generators for damping, power oscillation dampers can be used for damping with FACTS devices as a supplementary controller. This controller can then in a similar way to the PSS be used to move the unstable eigenvalues of a system to the left half plane in order to make the system stable. Further like a PSS these controllers can be used to also improve the large disturbance (transient) stability of the system.

1.4 Optimal Placement of FACTS devices

In most of the work done on FACTS devices in the past, a lot of emphasis has been placed on the location of the devices. The idea has always been to find the best location for the devices in order to get the maximum of the purpose out of them and/or have the greatest impact on system stability.

1.5 Supplementary Control

A FACTS device without supplementary control may not provide sufficient damping in the system. It can even in certain cases excite other oscillatory modes which may lead to eventual system instability due to increased oscillations in the rotor angle. Hence a supplementary controller may be needed to damp the modes being excited. Different signals could be used as the input to the damping controller. As with the advancement in technology, wide area monitoring systems have emerged which have made it possible to get data from other parts of the system using phase measurement units with minor time delays. Hence signals far off from the location of the damping controller and FACTS
devices are available in no time which can be used to improve the damping in the system and the transient stability.

1.6 WAMS (Wide area monitoring and control systems)

Wide area monitoring systems can provide streaming measurements at quite fast rates in the range of 10-20 Hz so not only slow phenomenon such as voltage but faster ones such as transient stability and oscillations can be monitored. Hence they provide an infrastructure for wide area stability control of the systems [6]. Phase measurement units (PMU’s) are usually placed in different parts of the system. Since these PMU’s are synchronized, the comparison of the data at each end can give valuable measurements such as voltages and angles. This data can then be transmitted to central control stations or FACTS devices via various communication channels. Hence signals such as speeds of generators, power flows or currents through a particular line can be obtained from any location with a PMU and used as an input to the power oscillation damper controller. Some applications of WAMS are as follows:

- Voltage stability monitoring for critical buses in transmission corridors
- Oscillatory stability monitoring
- Thermal stability monitoring of transmission lines [6].

Hence wide area monitoring systems can be of use in providing valuable information regarding the system state in some other parts of the system which may be useful for damping critical oscillatory modes and improving the system stability. The information obtained from far off areas in the system can be referred to as global information or a global signal.

Thus it was assumed in this work that all possible information was available and could be used in order to improve the small signal and transient stability of the system.

1.7 Work Organization

The organization of work in the following thesis has been done as follows. A brief introduction has been given in this chapter regarding the topic of the work. Chapter 2 provides the models and explanation for the various components within the power system and the power system itself. A brief description of modal analysis for small signal analysis has been discussed in chapter 3 with some theoretical frame for voltage stability. Chapter 4 presents the approach for the SVC and the STATCOM respectively. In chapter 5 the results and discussion for the SVC are presented. Chapter 6 includes the results and discussion for the STATCOM connected in the system. Chapter 7 presents a comparison between an SVC and a STATCOM and the more suitable of the two has been selected as the appropriate choice to be used for the test IEEE 9 bus system. The work has been concluded in the final chapter along with some ideas for future work.
Chapter 2: Modeling of various components in this thesis

2.1 Generators

One of the most common generator models used in order to carry small signal and transient stability analysis as well as voltage stability studies is the one axis model. The model is not as detailed as the two axis model which includes extra damper windings and also not as simple as the classical model.

The generators were hence modeled using the one axis generator model with one field winding and no damper windings. The d-axis transient emf is assumed to remain constant \[5\] in this model. Saturation was also not included. In this representation, the generator is modeled as a variable voltage source meaning that the mechanical power of the generator is not constant as it is in the case of classical model. The synchronous machine model TYPE 3A in SIMPOW which represented a generator with the characteristics mentioned above was used to carry out the dynamic studies.

2.2 Transmission lines

Transmission lines used to deliver power usually have a resistance due to the resistivity of the conductors. They also have an inductive part owing to the magnetic flux surrounding the line. A shunt capacitance is also present due to the electric field between the lines and the ground and in between lines \[7\]. Thus a transmission line can be represented by several cascading resistive, inductive and capacitive components. The most important from among these parameters is the inductance of the line which has a large influence on the voltage drop, transfer capability and line losses \[7\]. Thus in order for maximum accuracy, these parameters of a transmission line should be represented as accurately as possible.

The π-equivalent model can be used to represent the transmission lines. The line can be modeled as an impedance with shunt capacitance. The model looks as follows:
In Figure 2,

- $\bar{Z}$ is the impedance of the line
- $R$ is the resistance of the line
- $X$ is the reactance of the line
- $B$ is one half of the line charging

where $X = \omega L$ 

(Eq 2.1)

is given by the product of the inductance of the line $L$ and the frequency of the system.

### 2.3 Loads

Loads can be represented using different load models but in this thesis, the loads were represented using the static load model. This model expresses the characteristics of the load at any time as functions of the bus voltage magnitude and the frequency at the same instant [2]. This model is further divided into exponential and ZIP models. The exponential model was used to represent the loads. In this model, the loads can be represented either with constant power, constant current or constant impedance characteristic. The general representation of active and reactive components of the loads using the exponential model is given as

\[ P_L = P_{L0} \left( \frac{U_L}{U_{L0}} \right)^{mp} \]  

(Eq 2.2)
\[ Q_L = Q_{L0} \left( \frac{U_L}{U_{L0}} \right)^{mq} \]  

(Eq 2.3)

where \( P_{L0}, Q_{L0} \) and \( U_{L0} \) are the nominal active power, reactive power and nominal bus voltage magnitude respectively. \( U_L \) is the actual bus voltage magnitude. The parameters \( mp \) and \( mq \) determine the characteristics of the load and if

- \( mp = mq = 0 \), the model represents constant power characteristic
- \( mp = mq = 1 \), the model represents constant current characteristic
- \( mp = mq = 2 \), the model represents constant impedance characteristic

In this work, the active power load was modeled with a constant current characteristic whereas reactive load was modeled using constant impedance characteristic i.e. \( mp = 1 \) and \( mq = 2 \).

### 2.4 Static Var Compensator.

Loads can generate and absorb reactive power. Since the loads in a system can vary considerably from time to time within a power system, the reactive power balance of the system also varies. This can lead to unacceptable voltage levels at some buses and sometimes may eventually lead to voltage collapse causing a blackout in some parts or the entire system [6]. In order to avoid such situations, FACTS devices can be installed in a system to provide voltage support. One such device is the static var compensator (SVC).

A static var compensator (SVC) is a flexible ac transmission systems (FACTS) device which is connected in shunt to a bus. Its purpose is to provide reactive power support to a bus and hence keep the voltage stable on that bus since an SVC can both generate and consume reactive power depending on in which mode it is operating. Several types of SVCs are available. In this work the SVC was modeled as a variable controllable susceptance. By controlling the susceptance of the SVC, it can operate in the capacitive (i.e. injects reactive power) and inductive (i.e. consumes reactive power) modes. Further unlike the synchronous condensers, an SVC has no inertia and hence can have a very fast response [17].

The model of an SVC as a variable controllable admittance looks as follows:
By controlling $B_{\text{syc}}$, the direction of current $\bar{I}_{\text{syc}}$ can be controlled and hence reactive power can be exchanged between the system and the SVC. With the direction of flow of $\bar{I}_{\text{syc}}$ out from the power system, the SVC is absorbing reactive power and hence operating in the inductive mode. On the other hand, if $\bar{I}_{\text{syc}}$ is flowing into the system, the SVC is injecting power into the system and hence operating in the capacitive mode.

The operation of an SVC can be more clearly understood by looking at its operation characteristics for different scenarios occurring within a power system. For this we assume that seen from the SVC terminal bus the power system can be modeled as a Thevinen equivalent voltage behind a reactance $U_{\text{TH}}$ and $X_{\text{TH}}$ respectively. The linear and non linear control ranges have been shown. With the SVC operating within its limits, the bus where the SVC is connected can be considered as a PU. Figure 2.2 shows the operation characteristics of an SVC.
In Figure 2.2 [19], $U$ is the SVC terminal voltage and $I_{SVC}$ is the current through the SVC. The SVC linear control range is defined by $I_{max}^{cap}$ and $I_{max}^{ind}$ which are the currents at the minimum and maximum voltage for the operation of the SVC. The region within this range defines the linear control range of the SVC.

$U_{ref}$ is the reference SVC bus voltage. If the bus voltage will be equal to this value the SVC will not exchange any reactive power with the system. The side to the right of the vertical axis in Figure 2.2 represents the inductive while the left side represents the capacitive operation mode of the SVC. If the SVC bus voltage due to some disturbance in the system will be higher then the set reference voltage, the SVC will operate in its inductive mode and absorb reactive power from the system in order to bring the voltage back to the reference value. On the other hand if the SVC terminal voltage will be lower than the reference voltage, the SVC will operate in capacitive mode and provide reactive power to the system.

Thus the SVC has the capability of both absorbing and injecting reactive power into the system and providing voltage support to the system. But it can also play an important role in the damping of electromechanical oscillations. With sufficient supplementary control the SVC can play a vital role in improving the damping of critical oscillatory modes.

The dynamic model used for the SVC in this work consisted of voltage control with a PI regulator and a time delay filter. The purpose of the time delay filter was to include the
effects of the delays caused by the relays. The figure below taken from [13] represents the dynamic model used:

\[
\sum_{\text{ref}U} + U - \sum_{\text{POD}} + 1
\]

\[
\text{Signal1}
\]

\[
\frac{K_p}{1 + sT_f}
\]

\[
\sum_{\text{SVC}}\quad B_{\text{SVC}}^{\max}
\]

\[
B_{\text{SVC}}^{\min}
\]

\[
\frac{1}{sT_i}
\]

\[
B_{\text{min}}^{\text{SVC}}
\]

\[
B_{\text{max}}^{\text{SVC}}
\]

\[
\text{Signal2}
\]

\[
\text{POD}
\]

\[
\text{Sig}_{\text{out}}
\]

\[
U_{\text{ref}}
\]

\[
U
\]

\[
\text{Figure 2.3: Dynamic model of an SVC}
\]

Note that if the POD controller is absent $\text{Sig}_{\text{out}} = 0$.

The model shows that the SVC tries to maintain the voltage of the SVC bus equal or close to $U_{\text{ref}}$. Thus in doing so, the value of the admittance of the SVC varies. When an SVC reaches its limits, the SVC terminal is treated as a PQ node as the generated or consumed reactive power at that node is known which is given by

\[Q_{\text{limit}} = -BU^2\quad (Eq\ 2.4)\]

where

\[B = B_{\text{max}}^{\text{SVC}}\] or \[B_{\text{min}}^{\text{SVC}}\] depending on the SVC mode of operation.

In Figure 2.3, POD is the power oscillation damping control. This is the supplementary controller which can be used with an SVC to improve the damping of electromechanical oscillations. Note that the PSS (Power System Stabilizer) is used with generators to improve the damping of the electromechanical modes and is placed at the generator buses. On the other hand the POD can be placed in the system with an SVC in such a way that it is present in between oscillating machines and hence help in the improved damping of the rotor angle oscillations.

Typically used POD controllers consist of a wash out filter, lead-lag filters and some gain. The washout filter is present so as to not include the effects of the steady state
frequency deviations. The lead lag filter is present to tune the controller so as to give a positive contribution to damping. One method for tuning is the residue technique which was used and is explained later. The POD gain determines the magnitude of damping provided [3]. The dynamic model of the lead-lag type POD is given in Figure 2.4

The first block is the wash out filter. Typical values of $T_w$ vary from 5 to 10 [18]. The value used in this work was $T_w = 10$. The next two blocks are the lead lag filters. Multiple lead lag filters were used in some cases in order to compensate less than or equal to 60 degrees per filter [8].

The input to the POD can be the generator rotor angle deviation, generation speed deviation, power flowing through a line of interest; current flowing through a line or signals derived using Lyapunov theory [8]. Hence the right choice of the input signal along with appropriate POD gain and tuned filter parameters can provide sufficient damping to electromechanical oscillations leading to improved system stability.

### 2.5 STATCOM

A STATCOM, acronym for static synchronous compensator is another FACTS device that is connected in shunt to the power system. It is a device used to provide voltage support to the system by injecting or absorbing reactive power to/from the system. In this work it was assumed that the STATCOM only exchanges reactive power with the system although with some additions to the structure of the STATCOM it can also serve the purpose of exchanging active power with the system.

A STATCOM can be represented by the following diagram [1].

---

Figure 2.4: Dynamic model of a POD

The first block is the wash out filter. Typical values of $T_w$ vary from 5 to 10 [18]. The value used in this work was $T_w = 10$. The next two blocks are the lead lag filters. Multiple lead lag filters were used in some cases in order to compensate less than or equal to 60 degrees per filter [8].
It can be seen that the STATCOM is connected to the power system via a transformer with its reactance given by $x_{ST}$. VSC represents the voltage source converter which transforms the dc voltage $U_d$ to the ac voltage $E_{sh}$ which is controllable both in magnitude and phase [1]. Since in this work it was assumed that the STATCOM only exchanged reactive power with the system, the generated ac voltage $E_{sh}$ was taken to be in phase with the STATCOM bus voltage $U$ i.e. $\theta = \gamma_{sh}$. This is because the active power coming into the STATCOM is given by

$$P_{ST} = \frac{UE_{sh} \sin(\theta - \gamma_{sh})}{x_{ST}} \tag{Eq 2.5}$$

if the bus voltage is in phase with the generated ac voltage, the active power exchange will be zero. The exchanged reactive power of the STATCOM with the system is given by

$$Q_{ST} = \frac{U(U - E_{sh})}{x_{ST}} \tag{Eq 2.6}$$

If the direction of the current $I_{ST}$ is taken as given in Figure 2.5 then it is given by

$$I_{ST} = \frac{U - E_{sh}}{x_{ST}} \tag{Eq 2.7}$$
as both the voltages are in phase. Also seeing Figure 2.5, it can be deduced that if \( U > E_{sh} \) the current will be flowing out of the power system and the STATCOM will behave in its inductive mode absorbing reactive power given by Eq 2.6. If \( U < E_{sh} \) the STATCOM will inject reactive power into the system and if \( U = E_{sh} \) there will be no exchange of power between the system and the STATCOM [1]. The voltage current characteristic of a STATCOM can be represented using the following diagram [20]:

![Figure 2.6: Voltage-current characteristic of a STATCOM](image-url)

The range between \( I_{cap}^{\text{max}} \) and \( I_{ind}^{\text{max}} \) is defined as the linear control range of the STATCOM. Seen from Figure 2.6 and Figure 2.2, the STATCOM and the SVC both behave similarly during their limits. But the difference in operation is outside the linear control range where the STATCOM can provide maximum capacitive or inductive current independent of the bus voltage and hence the reactive power is proportional to the bus voltage according to Eq 2.6 and 2.7 as \( I_{St} \) is constant.

The dynamic model of the STATCOM used in this work is given below and taken from [13]:
The regulator used for the STATCOM was a PI regulator. The figure shows that the STATCOM tries to keep the bus terminal voltage close to the set reference value by controlling the ac voltage $E_{sh}$ produced by the voltage source converters.

### 2.6 Power System

Power systems throughout the world are currently operating on the basis of AC transmission. There are several advantages of ac systems such as that the ac motors are cheaper compared to dc motors, ac generators are simpler than dc generators and voltage levels in an ac system can be easily transformed [9]. Since the voltage levels can be easily transformed, the power can be transferred at a high voltage and low current meaning lower transmission losses in the system. A complete power system comprises of synchronous generators, transmission lines, loads, protection circuitry and other devices for the optimal operation of the system.

The dynamic of a multi machine power system can be represented in several ways. It can be modeled as a set of differential-algebraic equations or just differential equations based on the way the power system is modeled. In this work, the dynamic of the power system has been represented using a set of differential-algebraic equations. The differential equations representing the dynamic of a power system are usually those representing the dynamic of the generators. If some other devices are installed in the system, their dynamics are included in those differential equations.

The algebraic equations on the other hand represent the power mismatches at each of the buses. Thus the power system as a whole can be represented as
\[
\dot{x} = f(x,y,u) \quad \text{(Eq 2.8)}
\]

\[
0 = g(x,y,u) \quad \text{(Eq 2.9)}
\]

In Eq 2.8 and 2.9, \(x\) represents the system state variables, \(y\) represents the algebraic variables and \(u\) represents the control variables. The state variables include the generator rotor angle \(\delta\) and rotor speed \(\omega\) and the q-axis transient e.m.f. The algebraic variables include the bus voltage \(U\) and angle \(\theta\). Control variables are those variables which are kept constant throughout the experiment such as some reference voltage level. Introduction of FACTS devices and damping controllers in the system can be represented in the dynamic of the system by adding and or changing some of the equations given by Eq 2.8 and 2.9.

The following assumptions were made:

- Generators were modeled using the one axis model
- Active loads were represented using the constant current characteristic while reactive loads were modeled using the constant impedance characteristic
- Inherent damping of the generators was taken as 0
- Transmission lines were represented using the \(\pi\)-equivalent model
Chapter 3: Modal Analysis and Voltage Stability

3.1 Small Signal Stability

Oscillations in a system are undesirable as they limit power transfer capacity of transmission lines and in some cases can cause stress on the mechanical shaft of the generators [10]. Generally electromechanical oscillations are of two types:

- **Local**

  In this case generators within a certain area oscillate against each other. The frequency of such oscillations is usually in the range of 1-3 Hz [10].

- **Inter-area**

  In an inter-area oscillation, generators in one area oscillate against generators in another area. The frequency range of such oscillations is usually less than 1 Hz [10].

The study of a power system for small disturbances is referred to as small signal stability analysis. Small signal stability is the ability of a power system to retain synchronism after being subjected to a small disturbance [9]. It is important to notice here that the magnitude of the disturbance should be small. A disturbance is considered small if the equations representing the system can be linearized around an equilibrium point for that disturbance [9]. At times a small disturbance can cause the critical modes to be excited resulting in either rotor oscillations of increasing amplitude or increase in generator rotor angle. The former is caused due to lack of damping torque whereas the later is due to lack of synchronizing torque leading to eventual loss of synchronism of the machines oscillating in the system.

The non-linear system is represented by Eq 2.8 and 2.9. For simplicity, the equations are shown again

\[
\dot{x} = f(x, y, u) \quad (Eq \ 3.1) \\
0 = g(x, y, u) \quad (Eq \ 3.2)
\]

- $x$ represents the system state variables,
- $y$ represents the algebraic variables and
- $u$ represents the control variables

In order to carry out small signal analysis, the non linear system has to be linearized around an equilibrium point. Modal analysis can then be used so as to make a study of the system stability and the characteristics of the oscillatory modes of interest.
3.1.1 Linearization

The method for linearization of a system as discussed in [16] was used in this work. Let \((x_0, y_0)\) represent the equilibrium point around which the system has to be linearized. Load flow solution using the Newton-Raphson Method can be used to find the equilibrium point. Linearizing Eq 3.1 and 3.2 around the equilibrium point gives:

\[
\Delta \dot{x} = f_x \Delta x + f_y \Delta y + f_u \Delta u \\
0 = g_x \Delta x + g_y \Delta y + g_u \Delta u
\]

(Eq 3.3)

(Eq 3.4)

Here \(f_x, f_y, g_x, g_y\) are matrices of the order \(n_x \times n_x, n_x \times n_y, n_y \times n_x\) and \(n_y \times n_y\) respectively

where

\(n_x\) is the number of state variables \(x\)

\(n_y\) is the number of algebraic variables \(y\)

Note that the dimensions of the matrices are for the system without any FACTS device as with a FACTS device in the system, the number of state variables changes.

The matrices \(f_x, f_y, g_x\) and \(g_y\) are given by:

\[
f_x = \frac{\partial f(x, y)}{\partial x},
\]

(Eq 3.5)

\[
f_y = \frac{\partial f(x, y)}{\partial y},
\]

(Eq 3.6)

\[
g_x = \frac{\partial g(x, y)}{\partial x},
\]

(Eq 3.7)

\[
g_y = \frac{\partial g(x, y)}{\partial y},
\]

(Eq 3.8)

\[
f_u = \frac{\partial f(x, y)}{\partial u},
\]

(Eq 3.9)

\[
g_u = \frac{\partial g(x, y)}{\partial u},
\]

(Eq 3.10)

Further by rearranging Eq 3.4 and substituting it in Eq 3.3, the linearized system is obtained which is given by

\[
\Delta \dot{x} = A_{\text{system}} \Delta x + B \Delta u
\]

(Eq 3.11)
And
\[ A_{\text{system}} = f_x - f_y \cdot g_y^{-1} g_x \]  \hspace{1cm} (Eq 3.12)
\[ B = f_u - f_y \cdot g_y^{-1} \cdot g_u \]  \hspace{1cm} (Eq 3.13)

\( A_{\text{system}} \) is known as the system state matrix whose eigenvalues can be used to analyze system stability. \( B \) is known as the system input matrix.

Now let \( G \) be the input to the controller for damping
\[ G = h(x, y, u) \]  \hspace{1cm} (Eq 3.14)

Linearization of \( G \) around the equilibrium point gives:
\[ \Delta \dot{G} = C.\Delta x + D.\Delta u \]  \hspace{1cm} (Eq 3.15)

where the matrices \( C \) and \( D \) are given as
\[ C = \frac{\partial h(x, y, u)}{\partial x} - \frac{\partial h(x, y, u)}{\partial y} \cdot \frac{\partial g(x, y, u)}{\partial y}^{-1} \cdot \frac{\partial g(x, y, u)}{\partial x} \]  \hspace{1cm} (Eq 3.16)
\[ D = \frac{\partial h(x, y, u)}{\partial u} - \frac{\partial h(x, y, u)}{\partial y} \cdot \frac{\partial g(x, y, u)}{\partial y}^{-1} \cdot \frac{\partial g(x, y, u)}{\partial u} \]  \hspace{1cm} (Eq 3.17)

\( C \) is known as the output matrix and \( D \) is the feed forward matrix which defines the proportion of input which appears directly in the output [12].

The matrices \( A_{\text{system}}, B, \) and \( C \) are used in modal analysis to find the system eigenvalues, the controllability and observability of the modes respectively.

3.1.2 Modal and eigenvalue analysis

Modal analysis can provide valuable information about the dynamic characteristics of a system regarding system stability and damping for small disturbances. Using Eq 3.12 the eigenvalues of the system state matrix can be determined as
\[ \det(A_{\text{system}} - \lambda I) = 0 \]  \hspace{1cm} (Eq 3.18)

where
\[ \det \] stands for determinant
\[ I \] is a unity matrix

Generally each eigenvalue is associated with a mode of a system. Lyapunov’s indirect method can be used to study the eigenvalues of the system state matrix. It states that a system is stable if the eigenvalues have negative real parts and unstable if the real parts
are positive. Also if the real part is 0 it cannot be determined whether a system is stable or not [2]. Eigenvalues associated with oscillatory modes always occur in conjugate pairs [3]. The eigenvalue of the $i_{th}$ oscillatory mode can be represented as follows:

$$\lambda_i = \sigma_i \pm j \omega_i$$  \hspace{1cm} (Eq 3.19)

The damping of the $i_{th}$ mode is associated with the real part of the eigenvalue whereas its frequency is determined using the imaginary part. Using Eq 3.19 the damping and frequency of oscillation of the $i_{th}$ mode can be determined as follows:

$$\zeta_i = \frac{-\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}}$$  \hspace{1cm} (Eq 3.20)

$$f_i = \frac{\omega_i}{2\pi}$$  \hspace{1cm} (Eq 3.21)

where

- $\zeta_i$ is the damping ratio of the $i_{th}$ mode
- $f_i$ is the oscillation frequency of the $i_{th}$ mode

Note that a minus sign is used in Eq 3.20 so that a positive value means that the system is damped and a negative value represents a negatively damped system.

Right and left eigenvectors of the system state matrix can also provide valuable information regarding the modes and the states associated with them. The left eigenvector of mode $i$ is a row vector and its $k^{th}$ element determines the weight of the contribution of the $k^{th}$ state in that mode [3]. On the other hand the right eigenvector is a column vector which provides valuable information regarding the mode shape and the critical machines involved in that mode. Critical machines can be identified by looking at the magnitudes of each of the elements of the right eigenvector while its argument gives information regarding the mode shape i.e. which machine(s) are oscillating against which machine(s) for a particular mode. The product of the left and right eigenvectors of a particular mode gives the participation factors for that mode which gives a measure of the net participation of the $k^{th}$ state variable in the $i^{th}$ mode.

### 3.1.3 Controllability and observability

Controllability matrix can be used in order to identify whether a mode is controllable with the desired control variable. The controllability index of an any mode $i$ by the $j^{th}$ control variable is represented as:

$$CI_{ij} = V_i^j . B_j$$  \hspace{1cm} (Eq 3.22)
where
\[ V_i^l \] is the left eigenvector of the \( i^{th} \) mode
\[ B_j \] is the \( j^{th} \) column of the input matrix given by \( Eq \ 3.13 \)

If the value of controllability comes out to be 0, the mode is not controllable by that control variable while a non-zero value represents that the mode is controllable.

Observability on the other hand can be used to identify which state is the most observable in a particular mode. Hence that can be used as the input to the damping controller in order to control the dynamic characteristics of that mode. The observability index of a mode \( i \) for the \( j^{th} \) output variable is given as

\[ OI_{ji} = C_j V_i^r \] \hspace{1cm} (\text{Eq} \ 3.23)

where
\[ C_j \] is the \( j^{th} \) row of matrix \( C \) given by \( Eq \ 3.16 \)
\[ V_i^r \] is the column of the right eigenvector corresponding to mode \( i \)

### 3.1.4 Residue Technique for POD tuning

The closed loop system of the power system along with the POD controller can be represented as follows:

![Figure 3.1: Closed loop system with POD control](image)

The power system when linearized gives the system state matrix \( A \) and the matrix \( B \) given by \( Eq \ 3.12 \) and \( Eq \ 3.13 \). The output of the system transfer function which is the input to the POD controller when linearized gives the matrices \( C \) and \( D \) given by \( Eq \ 3.16 \) and \( Eq \ 3.17 \). Hence the controllability index is dependent on the input matrix while the observability index on the output matrix of the system. In Figure 3.1, \( u(s) \) is the control
variable which in case of the SVC and the STATCOM is the reference voltage at the bus the devices are connected.

The residue $R_i$ of the $i^{th}$ mode is given by the product of the controllability and observability of that mode. When a feedback control as in Fig 3.1 is applied the eigenvalues of the initial system change [18]. The residue of an eigenvalue determines the direction of the departure of the eigenvalue for small changes in the system parameters. Hence the residue technique can be used to determine the phase shift for the eigenvalue and hence determine how many lead-lag filters are required. Further mathematical procedures were carried out to tune the lead-lag filters of the POD to find the appropriate values of the time constants $T_1$, $T_2$, $T_3$ and $T_4$ in order to move the poorly damped or unstable modes well into the left half plane [3]. Since usually two lead-lag filters are used [18] the number of lead-lag filters used in this work were either one or two depending on the phase angle by which the eigenvalue was to move. Details about tuning are given in both [3] and [18].

### 3.2 Control Lyapunov Functions

Control Lyapunov functions (CLF) are basically obtained by the use of Lyapunov functions in feedback design by making the Lyapunov derivative negative. A detailed derivation of control Lyapunov functions for various FACTS devices can be found in [1]. The CLF functions for the SVC and STATCOM given in [1] were used for this work.

### 3.3 Voltage Stability

Voltage stability of a power system refers to its ability to maintain optimum steady voltages at all the buses in the system after a disturbance in the system. It is known that the voltage of the system and the reactive power are closely linked [14]. In case there is not sufficient reactive power available in the system, the voltage at one or more buses will start to drop. In case the voltages drop to very low values, a voltage collapse might occur in the system. This could eventually lead to a cascading effect causing a partial or complete blackout in the system.

The problem of voltage stability usually occurs at the buses with very long interconnecting transmission lines. The reason for this is due to the high reactive losses in the lines caused by the reactance of the lines. Voltage support is usually provided on such buses where there is not sufficient reactive power in the system. Additional components such as shunt capacitors or FACTS devices can provide the required reactive power so as to keep the system voltages at a desirable level.

Another reason for voltage instability is caused by the dynamics of the loads. Since the generation in a system is limited along with the capability of the transmission system to deliver power and also the loads are usually voltage dependent, the dynamic of the loads tries to restore the consumption which at times might be beyond the capability of the
transmission or generation system [14]. In such cases, the voltages in the system are affected and in case the demand for power is too high and the available power is fixed, the voltage starts to drop.

In recent years, many black-outs have occurred throughout the world partially or entirely due to voltage instability. One such blackout occurred in Sweden and Denmark in 2003 [15] which were due to a voltage collapse in the system.

Voltage stability problems might also occur due to line outages in a system. With a line outage, there might not be any other corridor available in the system to provide power in that area which could cause the voltage in the system to drop.

On the other hand, too high voltages on the buses are also not acceptable in the system. Too high voltages might cause very high power to flow in the system. This might cause the transferred power to be higher than the line rating causing the line to disconnect. This could then lead to voltage stability problems due to low voltages in the system.

One way to prevent voltage instability would be disconnect load in areas having stability problem i.e. load shedding. Alternate means could be to install shunt compensation in the system. FACTS devices can play an important role in order to provide voltage support in the system. The shunt connected FACTS devices namely the SVC and the STATCOM have been designed with their main aim of providing reactive power and hence voltage support in the system. With a disturbance in the system, the dynamic of the FACTS devices reacts and either provides or absorbs reactive power to/from the system. In this way, the voltage at a particular bus can be kept close to some reference value. The location of the bus generally depends on the criticality of the system near or around that bus. It would be best to place such devices in between long transmission lines or heavily stressed areas in the system. But in this work, since the primary aim is rotor angle stability, the location will be decided on the basis of damping of the critical mode.
Chapter 4: Methods and procedure

4.1 Basic Approach

The SVC and STATCOM in this particular work were modeled using the injection models in which both were represented as loads.

The idea of the entire study was to find a suitable location for an SVC for the damping of the oscillatory modes of interest. But as we know that an SVC without supplementary control does not improve the damping and at times can excite the modes to go unstable, a damping controller had to be designed to damp the oscillations.

The first step involved in finding the optimal location of the SVC was to find the critical mode of interest. The system without an SVC was linearized and the eigenvalues obtained. Low frequency oscillations with less damping are the ones of importance in small signal studies and are the modes which are considered critical. Modes with frequencies around 1 Hz or less are not acceptable if they have low damping ratios usually less than 0.05 [12].

Once the critical mode was identified, the controllability index was used to find the optimal location of the SVC for controlling that mode. It was assumed that the SVC could only be placed on the non generator buses as generators can provide voltage support to buses they are connected. The following procedure was followed:

4.2 Approach for SVC

As mentioned in the earlier chapters, the location of a FACTS device can have a large impact on its functionality. Hence the optimal location for the damping of the critical mode for the SVC was found as described below:

4.2.1 Optimal placement of an SVC

An SVC was placed at each of the non generator buses individually. The system was linearized in SIMPOW with the dynamic of the SVC included.

Since it was considered that the SVC is placed only at the non generator buses and exchanges only reactive power the algebraic equation corresponding to the reactive power mismatch of the SVC terminal changes where the reactive power exchanged by the SVC with the system is also included.

After including the effects of the SVC on the system in the differential algebraic equations and linearization, the matrices $A_{sys}$ and $B$ given by Eq 3.12 and 3.13 were
found. These matrices were obtained using SIMPOW. The controllability index was used to further find the best location for placing the SVC to control the critical mode. The voltage at the SVC terminal was being controlled so the controllability index gave a measure of how much a mode could be controlled by varying the SVC bus voltage. The controllability index for the critical mode given by Eq 3.22 was found for each of the locations of the SVC considered (non generator buses). The location giving the maximum controllability would be the best location to control the critical mode or the mode under study.

4.2.2 Choice of input signal for the SVC

In order to find the best input signal for POD the concept of observability was used. The analysis was carried out in SIMPOW and MATLAB. The results from the output of the power system transfer function as shown in Figure 3.1 were to be used as the input to the POD controller.

Not only does the location of the FACTS device affect the damping of critical modes, but the choice of the input signal to the POD controller also affects the results obtained. Some signals might provide good results for one mode but at the same time might excite other modes leading to an unstable system. Hence an appropriate choice of the input signal and tuning of filters (if used) for the damping controller had to be carried out in order to achieve significant damping for the critical modes without affecting system stability.

The system output matrix \( C \) was found by the linearization of the system. The observability indices for different input signals were found using Eq 3.23. The signal giving the maximum observability index would be the desired input signal to damp the oscillatory mode.

In order to obtain good damping ratios and to move the critical eigenvalues more into the left half plane, the POD controller was tuned. The residue technique was used to tune the controller with lead lag filters and damp the oscillatory mode to the desired level. Usually damping ratios higher then 5% are considered acceptable [12]. The damping ratio of the critical mode was set to be much larger than 5% for stability margins. Further non linear simulations for small and large disturbances were carried out in order to confirm the small signal analysis and calculations.

Various inputs were used for the SVC and the STATCOM. In this study the speeds of one or more generator were used based on the observability indices. Furthermore, the power and current flowing through a line as well as CLF based control laws were also used and the results analyzed.
4.2.3 Input signals used with the SVC

As mentioned earlier, the generator speed deviation, power or current through a line and CLF based control laws can be used as the input to the POD. But the choice of which generator speed to use, whether to use the speeds of multiple generators or which power or current flow to use depend on the results based on observability indices. Finally, by analyzing the results one signal based on generator speeds, one local (power or current) signal and a CLF based control signal were used as the input to the POD.

➢ No POD

First of all the results without any POD in the system were analyzed so as to use them as a basis to compare the results of other input signals with.

➢ Speed of generators as the POD input

The speed of one or more machine was to be used as the input to the POD so as to damp the critical oscillatory mode. Firstly, the speeds of individual generators were used and the observability indices found. Next a combination of speeds of multiple generators was used. The combination was based on the results obtained from modal analysis regarding the oscillating machines in the critical mode. Since machines 2 and 3 were oscillating against machine 1 for the oscillatory modes due to swing equation parameters, the signal for which the observability was found was \( \omega_2 + \omega_3 - \omega_1 \). Finally the signal giving the largest magnitude for observability was chosen as the input to the POD from the various signals available from the generator speeds.

➢ Active power or current as the POD input

The next input signal used was a local signal. The active power or current flowing into/out of the SVC node would be the appropriate signals for the input to the POD as the oscillations in these can be used to damp the oscillations in the system and hence bring the system to a steady state much faster. Power would contain information regarding oscillations for both the voltage and current while the other signal used was just the current. Observability indices were found for all the possible currents and active powers which could be used and the signal giving the largest magnitude was chosen as the input to the POD.

➢ CLF based control law

The control Lyapunov function based control law given in [1] for the SVC was next used as the input to the POD and is given as:

\[
B_{\text{SVC}} = K_{\text{POD}} \sin(\delta_{\text{SIME}})\omega_{\text{SIME}} \quad (Eq \ 4.1)
\]

where
\[ \delta_{\text{SIM}} = \frac{H_2 S_{n2}}{H_2 S_{n2} + H_3 S_{n3}} \delta_2 + \frac{H_3 S_{n3}}{H_2 S_{n2} + H_3 S_{n3}} \delta_3 - \delta_1 \]  
\text{(Eq 4.2)}

\[ \omega_{\text{SIM}} = \frac{H_2 S_{n2}}{H_2 S_{n2} + H_3 S_{n3}} \omega_2 + \frac{H_3 S_{n3}}{H_2 S_{n2} + H_3 S_{n3}} \omega_3 - \omega_1 \]  
\text{(Eq 4.3)}

\( K_{\text{POD}} \) is the gain that determines the magnitude of damping provided by the POD where \( S_{n2} \) and \( S_{n3} \) are the rated powers of generator 2 and 3 respectively.

### 4.3 Approach for a STATCOM

The same procedure as carried out for the SVC was used to perform the analysis for the STATCOM.

#### 4.3.1 Optimal placement of a STATCOM

The concept of controllability was used in order to find the optimal location of the STATCOM in order to damp the critical oscillatory modes. A STATCOM was placed at each of the non-generator buses one at a time and the controllability index found using Eq 3.22. The system with the STATCOM included was linearized around an equilibrium point. After linearization, the matrices \( A_{\text{sys}} \) and \( B \) given by Eq 3.12 and 3.13 were found. The controllability index which was given by the product of the left eigenvector of the mode of interest and the input matrix \( B \) was used to further find the best location for placing the STATCOM and damping the critical mode. The voltage at the STATCOM terminal was being controlled so the controllability index gives a measure of how much a mode can be controlled by varying the STATCOM bus voltage. The controllability index for the critical mode was found for each of the locations of the STATCOM considered (non generator buses). The location giving the maximum controllability magnitude would be the best location to control the critical mode or the mode under study.

#### 4.3.2 Choice of input signal for the STATCOM

In order to choose an appropriate input signal to the POD, the concept of observability was used. Local and remote signals were used and the observability indices found by taking the absolute of the product of the system output matrix \( C \) and the right eigenvector of the critical mode as given by Eq 3.23. The signals with high observability indices were used as inputs to the POD.
4.3.3 Input signals used with STATCOM

The various input signals used to the POD controller with the STATCOM connected were as follows:

- No POD

Results without any POD connected into the system were found and plotted in MATLAB so as to compare the impact of a POD and various input signals used.

- Speed of generators as the POD input

Remote signals such as the speed of one or more generators can be used as inputs to the POD. The idea was to find the most appropriate which would improve the system stability.

- Active power or current as the POD input

Local signals such as the current or power flowing to/from the STATCOM bus were next used. The observability indices were found in order to choose the most appropriate signal from amongst the various local signals available.

- CLF based control law

The CLF based control law used for the STATCOM was as follows:

\[ E_{st} = K_{POD} \sin(\delta_{SIME})\omega_{SIME} \]  \hspace{1cm} (Eq 4.4)

where

\[ \delta_{SIME} = \frac{H_2 S_{n2}}{H_2 S_{n2} + H_3 S_{n3}} \delta_2 + \frac{H_3 S_{n3}}{H_2 S_{n2} + H_3 S_{n3}} \delta_3 - \delta_1 \]  \hspace{1cm} (Eq 4.5)

\[ \omega_{SIME} = \frac{H_2 S_{n2}}{H_2 S_{n2} + H_3 S_{n3}} \omega_2 + \frac{H_3 S_{n3}}{H_2 S_{n2} + H_3 S_{n3}} \omega_3 - \omega_1 \]  \hspace{1cm} (Eq 4.6)

\( K_{POD} \) is the gain that determines the magnitude of damping provided by the POD where as \( S_{n2} \) and \( S_{n3} \) are the generator rated powers.
Chapter 5: Simulations and results with SVC

5.1 Test Power System

The IEEE 3-machine, 9 bus system was chosen as a test system in order to carry out the analysis.

Generator 1 was considered as the slack bus in the system given above. The generators were modeled using the one axis model. The inherent damping $D$ of the generators was taken as 0. Further generator had turbines and governors connected with them. No PSS were installed with the generators. The active load was modeled with constant current whereas the reactive load was modeled with constant impedance characteristics. Detailed parameters of the system are given in Appendix A.

The configuration of the system was slightly changed for this particular work. A parallel equivalent for the transmission line between buses 7 and 8 was used instead of having a single line.

Further SIMPOW was used in order to carry out all the calculations for the system with the results plotted using MATLAB.
5.2 Identifying the critical oscillatory modes (No FACTS device)

The system was linearized without any FACTS device. Small signal analysis showed the presence of two oscillatory modes. The following results were obtained.

Table 5.1: Results of linearization without any FACTS device

<table>
<thead>
<tr>
<th>Mode</th>
<th>Damping Ratio</th>
<th>Oscillation Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.207872</td>
<td>1.753362</td>
</tr>
<tr>
<td>2</td>
<td>0.107941</td>
<td>1.208573</td>
</tr>
</tbody>
</table>

Both the modes were not very well damped. Mode 2 with the lowest damping was chosen as the critical mode which was to be damped. Further analysis was thus carried out based on the results obtained for this mode.

Looking at the right eigenvectors of the oscillatory modes, the mode shape and critical machines can be identified. SIMPOW was used to carry out modal analysis in order to identify the machines oscillating in the critical mode. The results obtained were:

![Figure 5.2: Mode shape for the critical mode](image)

It could be seen from Figure 5.2 that in the critical mode, machine 1 oscillated against machines 2 and 3. This information was used in choosing the appropriate signal for the input of the POD controller.
5.3 Results for the location of SVC (SVC without supplementary control)

The optimal location of the SVC was found for the damping of the critical mode 2. An SVC was placed at each non-generator bus individually. The system was linearized and the controllability index found. The results were as follows:

Table 5.2: Controllability indices critical mode for different SVC locations

<table>
<thead>
<tr>
<th>SVC Location</th>
<th>Controllability index</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 5</td>
<td>0.7353</td>
<td>2</td>
</tr>
<tr>
<td>Bus 6</td>
<td>0.6685</td>
<td>3</td>
</tr>
<tr>
<td>Bus 8</td>
<td>1.1618</td>
<td>1</td>
</tr>
</tbody>
</table>

From Table 5.2, it could be seen that the controllability index had its maximum value when the SVC was placed at bus 8. This meant that the critical mode would be most controllable from this location of the SVC. Bus 8 was hence chosen as the location of the SVC. Note that it is not necessary that this bus would be the most suitable location for voltage support, but since bus 8 is present between long transmission lines it would be an appropriate location so as to provide reactive power support to the system in case of a low voltage at bus 8 [12].

The SVC was connected at bus 8 in the system which was found to be the optimal location for controlling the critical mode. With the SVC connected, the system of equations representing the power system was linearized. The results obtained were:

Table 5.3: Results of linearization with an SVC

<table>
<thead>
<tr>
<th>Mode</th>
<th>Damping Ratio</th>
<th>Oscillation Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.235234</td>
<td>1.801805</td>
</tr>
<tr>
<td>2</td>
<td>0.103033</td>
<td>1.218581</td>
</tr>
</tbody>
</table>

It could be seen in Table 5.3 that the introduction of an SVC into the system slightly reduced the damping in the critical oscillatory mode 2. On the other hand, the damping ratio of the other oscillatory mode was larger than when there was no SVC in the system.

5.4 Results for the input to the POD for an SVC (SVC + POD)

In order to identify the states with a high participation in a particular mode, the observability indices were found. The indices for the critical oscillatory mode were found and the results obtained were used to select appropriate input signals to the damping controller.

Firstly, the results for various generator speed deviations as POD input were found. The results for individual as well as multiple speeds as inputs were found. One of the signals
used was $\omega_2 + \omega_3 - \omega_1$, as for the critical mode machines 2 and 3 were oscillating against machine 1. $\omega_1 - \omega_2 - \omega_3$ was not used as the input as it injected negative damping in the system when the load at bus 8 was slightly increased i.e. a small disturbance was applied.

**Table 5.4: Observability indices for generator speed deviations as POD input for the critical mode**

<table>
<thead>
<tr>
<th>Signal</th>
<th>$\omega_1$</th>
<th>$\omega_2$</th>
<th>$\omega_3$</th>
<th>$\omega_2 + \omega_3 - \omega_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observability</td>
<td>0.0051</td>
<td>0.0160</td>
<td>0.0093</td>
<td>0.0304</td>
</tr>
</tbody>
</table>

The results from Table 5.4 showed that the state most observable in the critical mode was the speed of machine 2. But the combined speed deviations gave a much larger magnitude of observability compared to any of the individual speeds. Hence the signal chosen for the POD from the various available signals was $\omega_2 + \omega_3 - \omega_1$. This signal can be considered as a global signal as parameters from far off areas are being used as the input to the POD controller.

Next a local signal was selected as the POD input. With the SVC connected at bus 8, either the active power or current flowing between buses 9 and 8 or the active power or current flowing through one of the lines between buses 7 and 8 could be used as the POD input. The observability indices were found for each of the signals. The results obtained were as follows:

**Table 5.5: Observability indices for active power and current**

<table>
<thead>
<tr>
<th>Signal</th>
<th>$P_{78}$</th>
<th>$I_{78}$</th>
<th>$P_{98}$</th>
<th>$I_{98}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observability</td>
<td>0.2081</td>
<td>0.1999</td>
<td>0.3872</td>
<td>0.3152</td>
</tr>
</tbody>
</table>

The results showed that the signals linked to buses 8 and 9 gave a larger observability index for both the current and the active power flowing. The active power from bus 9 to 8 further gave a larger index and hence was chosen as the POD input. It is important to notice here that the active power would be an appropriate signal compared to the current flowing through the line as it will contain information of both the bus voltages and the current.

Lastly the CLF based control law derived in [1] for the SVC was used as the POD input. For this particular signal, no lead lag filters were used in the dynamic model of the POD. The control law as mentioned earlier is given by the following equation:

$$B_{\text{SVC}} = K_{\text{POD}} \sin(\delta_{\text{SIME}})\omega_{\text{SIME}}$$  \hspace{1cm} (Eq 5.1)
But while tuning the damping controller, it was made sure that all the modes or eigenvalues in the system remained stable and the damping ratio of the oscillatory modes remained close to 15%. Also if the system became unstable for a particular fault due to the high gain of the POD controller, the damping controller was retuned so as to get a stable system for the different fault scenarios discussed later. Hence not too high POD gains were used for some input signals as they impact the voltage profile and the system stability. Also the PI regulator for the SVC was tuned in such a way that when a small or slightly large disturbance such as a load increase or short circuit on a line were applied for a few milliseconds without any POD connected, the voltage returned to the reference value in around 5-7s.

The results for the various input signals as the POD input for the SVC based on modal analysis were as follows:

<table>
<thead>
<tr>
<th>Input Signal</th>
<th>(K_{POD})</th>
<th>(\xi_{CM})</th>
<th>(f_{CM}) (Hz)</th>
<th>(T_1) (s)</th>
<th>(T_2) (s)</th>
<th>(T_3) (s)</th>
<th>(T_4) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No POD</td>
<td>-</td>
<td>0.103033</td>
<td>1.218581</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(\omega_2 + \omega_3 - \omega_1)</td>
<td>8</td>
<td>0.485541</td>
<td>1.239482</td>
<td>0.1911</td>
<td>0.0893</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(P_{98})</td>
<td>0.6</td>
<td>0.167015</td>
<td>1.222988</td>
<td>0.0697</td>
<td>0.2448</td>
<td>0.0697</td>
<td>0.2448</td>
</tr>
<tr>
<td>CLF</td>
<td>40</td>
<td>0.590283</td>
<td>1.294610</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In Table 5.6 subscript CM stands for critical mode.

Note that in Table 5.6 the results for the critical mode are shown only.

Before presenting the non linear simulations, it is important to inform the reader about the rating of the SVC. The maximum and minimum susceptance of the SVC was between 1 p.u and -1 p.u and the rated reactive power between 1 p.u and -1 p.u.

### 5.5 Fault cases for an SVC

Four fault scenarios were simulated for the various input signals to the POD with the SVC connected in the system. A brief description of each scenario along with the results obtained using non linear simulations are given below:

- **Case 1: 10% load increase at bus 8 for 100ms.**

For the first case, a small disturbance was applied in the system in order to analyze the performance of the SVC and the POD based on rotor angle stability and voltage support.

The rotor angle of generator 2 was plotted with and without the POD along with the voltage profile for bus 8. The results obtained were as follows:
The results given in Figure 5.3 showed that for this small disturbance the system remained stable with the machines retaining synchronism.

The results showed that the CLF based control law provided the best damping in the system which was also shown from results of modal analysis. The speed deviations of the generators as the POD input also provided good damping although the results were slightly poorer compared to the CLF based law. $P_{98}$ also provided damping in the system. But it could be seen that the system did not settle down at steady state as quickly as it did for the other signals. On the other hand the other signals gave a completely steady system after around 12s. This shows that global signals can provide much better damping in the system as they contain information which can damp the other oscillatory modes in the system as well as the mode under study. With the power as the POD input, the signal was local and did provide some damping in the system but not as good as the global signals.
Case 1

![Figure 5.4: Voltage profile at bus 8](image)

The results for the voltage profile showed that the voltage at bus 8 came back to the initial steady state value after the disturbance was cleared since the system came back to the same equilibrium point. With the CLF as the POD input, the voltage settled the fastest followed by $\omega_2 + \omega_3 - \omega_1$. With $P_{98}$ the voltage did not settle down at exactly 1 p.u up till 20s showing that the global signals provided better results for the voltage profile compared to the local signal although the magnitude of the deviations was very small.

By analyzing the results for this particular fault, it could be deduced that the CLF based control law for the SVC would be the best signal as the POD input for system stability.

- **Case 2**: A short circuit occurs at the middle of one of the lines between buses 7 and 8. The fault is cleared by removing the faulted line after 100ms.

The severity of the fault was increased for this case. A large disturbance, i.e. a short circuit was applied on one of the lines between buses 7 and 8 with the fault cleared by disconnecting the line permanently. The results obtained from simulations were as follows:
Figure 5.5: Rotor angle of generator 2

The rotor angle oscillations were analyzed by plotting the rotor angle of generator 2. The results showed that without any POD in the system, the rotor angle oscillations were of very large amplitudes initially but the system was stable.

Again the results showed that the best damping was achieved with the CLF based control law as the input signal. $\omega_2 + \omega_3 - \omega_1$ also showed good results. $P_{98}$ was also able to provide some damping in the system but the results were not as good as when the CLF or $\omega_2 + \omega_3 - \omega_1$ were used as the POD input. Further with $P_{98}$ as the POD input, the system took a much longer time to reach a steady state, around 40s. Figure 5.6 shows the results that the system returned to the same steady state point as the other signals.
Case 2
Same equilibrium point with power as POD input

\[ \omega_2 + \omega_3 - \omega_1 \]

Figure 5.6: Rotor angle of generator 2
The plot for the voltage profile showed that SVC was able to bring the voltage at bus 8 back to the initial steady state value although one of the lines between buses 7 and 8 was disconnected and the system configuration slightly changed. The SVC provided the additional reactive power in order to keep the voltage at bus 8 equal to 1 p.u and hence provided voltage support which is one of the main purposes of an SVC in any system. Comparing the results for the various input signals, it could be seen that voltage does not settle at 1 p.u quickly with $P_{98}$ as the POD input compared to the other signals. This is because of the POD controller. The output of the POD controller is large initially hence has a greater weight compared to the voltage control. Hence the SVC improves the deviations in rotor angles but once the output of the POD controller is low, the SVC starts to control the bus voltage and the voltage comes back to 1 p.u.

Analyzing the results for this particular fault, it could be deduced that the CLF based control law would be the best input to the POD controller.
Case 3: A short circuit occurs at the middle of line between buses 5 and 7.
The fault is cleared by the disconnecting the line permanently.

Since machines 1 and 2 had the maximum participation in the critical oscillatory mode, a fault was applied directly between these two machines. The results for rotor angle oscillations and voltage were as follows:

![Figure 5.8: Rotor angle of generator 2](image)

It could be seen that the system oscillated with large amplitudes for this particular fault since the fault was between the machines participating the most in the critical mode as well as the other oscillatory mode. The CLF based control law provided the best damping in the rotor angle oscillations. The results with \( \omega_2 + \omega_3 - \omega_1 \) as the POD input were also good but the CLF gave better results. Next \( P_{98} \) was used as the POD input. The results showed that with the power as the input to the POD, the system took a long time to reach to the same steady state as to the case when other signals were used.

The voltage profile at bus 8 was as follows:
The voltage profile showed that the SVC tried to bring the bus voltage back to 1 p.u. With the POD connected and CLF and $\omega_2 + \omega_3 - \omega_1$ as the input, the voltage settled at 1 p.u which was the reference value for the SVC. But the voltage did not settle immediately at 1 p.u with $P_{98}$ as the POD input. It took a longer time.

The reason for such behavior with $P_{98}$ as the POD input could be explained by looking at the plots for the SVC admittance Figure 5.10 and the output of the POD controller Figure 5.11. The voltage at the bus initially stayed low with $P_{98}$ as the POD input. The reason for this was the large magnitude of the output of the POD controller. Since it was much larger then the difference in the reference voltage and bus voltage and hence was with the greater weight of the two, the controller initially improved the damping of the rotor angle oscillations as can be seen in Figure 5.8. This is why the voltage at the bus initially stayed low. But after some time the output of the POD becomes less than the voltage difference of bus 8 and the reference value. The voltage starts to go back towards 1 p.u. It does eventually go to 1 p.u but takes a long time as can be seen in Figure 5.12.
Figure 5.10: SVC admittance for different POD input signals

Figure 5.11: Output of the POD controller with $P_{98}$ as the input signal
Case 3: Voltage at bus 8 with $P_{98}$ as the POD input

Figure 5.12: Voltage at bus 8 after 100ms with $P_{98}$ as the POD input

- Case 4: A short circuit occurs on both the lines between buses 7 and 8. The fault is cleared by disconnecting the lines after 100ms.

The severity of the fault was further increased with both the lines between buses 7 and 8 disconnected permanently in order to clear the short circuit. Another aspect to notice is that the fault was applied very close to the SVC such that the location of the SVC was also affected.
From the simulations it could be seen that none of the signals was able to inject any significant damping into the system. The reason for this was that since the link between bus 7 and 8 was removed, we got a radial system of the form given in Figure 5.14. Looking at the figure it could be seen that with such a configuration of the system in the post fault period, the SVC was left connected at the end bus and since the SVC and the POD were no longer in between the oscillating machines, there was not a significant impact on the system damping.

Figure 5.13: Rotor angle of generator 2
Figure 5.14: Radial system

Figure 5.15: Voltage profile at bus 8
The results for the voltage profile Figure 5.15 showed that the SVC tried to bring the bus voltage at node 8 close to 1 p.u. But the voltage was not exactly at 1 p.u as the SVC had hit its limit as could be seen in the plot for the SVC susceptance. The SVC could not provide more reactive power to the system.

Figure 5.16: SVC susceptance for various POD input signals

But overall, none of the signals was able to damp the oscillations in the system sufficiently for this fault. A remedy for such severe faults could be to have multiple SVC’s and POD’s connected in the system so even if a fault as severe as mentioned in case 4 occurred, there would be some device and controller connected between oscillating machines to damp out the oscillatory modes. But one of the drawbacks would be the high costs of the devices. Another alternative could be to have power system stabilizers installed with generators.

5.6 Transient Stability

The critical clearing times for the fault mentioned in case 3 were found in order to compare the different input signals. The results obtained were as follows:
Table 5.7: Critical clearing times with and without POD for case 3

- **Case 3**: A short circuit occurs at the middle of line between buses 5 and 7. The fault is cleared by the disconnecting the line permanently.

<table>
<thead>
<tr>
<th>Input signal</th>
<th>Critical Clearing Time $t_{cc}$ (s)</th>
<th>% change compared to without any FACTS device</th>
</tr>
</thead>
<tbody>
<tr>
<td>No FACTS device</td>
<td>0.168</td>
<td>-</td>
</tr>
<tr>
<td>$P_{98}$</td>
<td>0.164</td>
<td>-2.38</td>
</tr>
<tr>
<td>$\omega_2 + \omega_3 - \omega_1$</td>
<td>0.194</td>
<td>15.47</td>
</tr>
<tr>
<td>CLF</td>
<td>0.194</td>
<td>15.47</td>
</tr>
</tbody>
</table>

The results from Table 5.7 showed the inclusion of a POD did improve the clearing times for some input signals. Both $\omega_2 + \omega_3 - \omega_1$ and the CLF based control law gave the highest critical clearing times. With $P_{98}$ as the POD input, the critical clearing time was lower than when there was no FACTS device in the system. For this particular fault it was seen that the system took a very long to come to a stable state when the local signal ($P_{98}$) was used as the input. The reason as to why $P_{98}$ gave a low critical clearing time was that the gain of the POD controller was too high for this particular fault. A low gain gave a higher critical clearing time at the expense of less damping. The results for the critical clearing times showed that $P_{98}$ would not be an appropriate choice as the input to the POD if this particular fault occurs. But the main idea of this analysis was to show that FACTS devices can be used to improve the transient stability of the system which can be seen from the results for $\omega_2 + \omega_3 - \omega_1$ and CLF. Further CLF gave the most appropriate results for damping and transient stability. Hence it would be the most suitable signal as an input to the POD.

**Conclusions:**

The conclusion based on the work done and results obtained was that the location of the SVC had a significant impact on the damping of an oscillatory mode of interest. The controllability index was used to decide the location of the SVC. Also with the proper tuning of the POD controller, a very high damping ratio of the mode of interest was obtained. But it was important to tune the POD controller in such a way that it did not affect the voltage control of the SVC by much i.e. to use a reasonable gain for the POD controller which would not be too high to get good damping but on the other hand have a bad affect on voltage stability and affect other modes.
It was seen for case 3 that the power as the POD input did not give good results for the voltage profile for the initial few seconds after the fault was cleared although the gain used was very small. Even this value of gain for this particular fault was too high to provide good voltage support although the system was damped. Thus a balance should exist in the dynamic of the SVC to provide good voltage support as well as damping in the system. For the fault in case 3, the power would not be a suitable input to the POD although the system remained stable.

Further it was seen that the choice of the input signal also had a significant impact on the damping of the mode being controlled and also on the stability of the system as a whole. It was seen from the simulations that the input signal based on the CLF theory gave the most suitable results based on the damping of the critical mode as well as from the system stability point of view, both rotor angle and voltage stability for small and large disturbances.

But the important aspect to notice was that although the location of the SVC and the choice of the input signal to the POD played a significant role for the system stability, the type of fault also had a great impact on the system. The simulations for case 4 showed that none of the input signals was good enough to damp the oscillations in the system quickly. This was because the removal of the fault by disconnecting the faulted lines caused the system configuration to change. The new configuration was the SVC connected at the end bus of a radial system. In such a situation the SVC could not provide sufficient damping in the system. A good remedy for such severe faults could be to place multiple static var compensators with POD control within the system so as to have a controller in between machines to damp out the oscillations in case of change of system configurations due to severe faults. A single SVC was not able to provide good results with a severe fault such as the one in case 4. But multiple controllers and SVC’s would mean high costs.

Finally it can be concluded that the SVC not only provides reactive power support or voltage support to the system, but with supplementary control can be used as a means to damp oscillations within a power system.
Chapter 6: Simulations and results with STATCOM

6.1 Test Power System

The same power system as given in Figure 5.1 and explained in section 5.1 was used as the test power system for the analysis of the STATCOM.

6.2 Identifying the critical oscillatory modes (No FACTS device)

The same results as mentioned in section 5.2 of chapter 5 were used here with no FACTS device in the system. Mode 2 was identified as the critical mode.

With the critical mode already known, the location of the STATCOM was to be found in order to damp them.

6.3 Results for the location of the STATCOM

The location of the STATCOM was found using the controllability indices for the critical mode. The results obtained were:

Table 6.1: Controllability indices of mode 3 for different STATCOM locations

<table>
<thead>
<tr>
<th>STATCOM Location</th>
<th>Controllability index</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 5</td>
<td>1.7681</td>
<td>2</td>
</tr>
<tr>
<td>Bus 6</td>
<td>1.6428</td>
<td>3</td>
</tr>
<tr>
<td>Bus 8</td>
<td>1.7961</td>
<td>1</td>
</tr>
</tbody>
</table>

The optimal location for controlling the critical mode was chosen as the location with the largest magnitude of the controllability index. Table 6.1 showed that the bus with the highest controllability index was bus 8 and it was chosen as the location for placing the STATCOM as it was between long transmission lines and the bus was quite stressed due to the loading [12].

Now the STATCOM was placed at bus 8 and the results obtained for modal analysis were:
Table 6.2: Results of linearization with a STATCOM

<table>
<thead>
<tr>
<th>Mode</th>
<th>Damping Ratio</th>
<th>Oscillation Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.231618</td>
<td>1.800173</td>
</tr>
<tr>
<td>2</td>
<td>0.079004</td>
<td>1.216514</td>
</tr>
</tbody>
</table>

It could be seen from Table 6.2 that the introduction of a STATCOM caused the critical mode to be less damped as compared to when there was no STATCOM in the system. On the other hand, the damping of the other oscillatory mode was better.

6.4 Results for the input to the POD for a STATCOM (STATCOM + POD)

In order to identify the associated states with a particular mode, the observability indices were found. The indices were based on local and remote POD inputs as were as follows:

The results for the various remote signals for the generator speeds for the critical mode were as follow:

Table 6.3: Observability indices for generator speeds of oscillatory modes with a STATCOM

<table>
<thead>
<tr>
<th>Signal</th>
<th>$\omega_1$</th>
<th>$\omega_2$</th>
<th>$\omega_3$</th>
<th>$\omega_2 + \omega_3 - \omega_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observability</td>
<td>0.0051</td>
<td>0.0160</td>
<td>0.0093</td>
<td>0.0304</td>
</tr>
</tbody>
</table>

The results Table 6.3 showed that $\omega_2 + \omega_3 - \omega_1$ would be a better signal to control the critical mode as compared to the other signals.

Next the results for local input signals were found. The active power and current through the lines connected between buses 7 and 8 and buses 8 and 9 were used. The results obtained were:

Table 6.4: Observability indices for power and current

<table>
<thead>
<tr>
<th>Signal</th>
<th>$P_{78}$</th>
<th>$I_{78}$</th>
<th>$P_{98}$</th>
<th>$I_{98}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observability</td>
<td>0.2125</td>
<td>0.2068</td>
<td>0.3888</td>
<td>0.3094</td>
</tr>
</tbody>
</table>

The power through the line between buses 8 and 9 gave the largest magnitude for the observability index and was hence chosen as another input to the POD from the various local signals.

The results for modal analysis with and without POD for various input signals were:
Table 6.5: A comparison of small signal analysis results for a STATCOM with and without POD

<table>
<thead>
<tr>
<th>Input Signal</th>
<th>$K_{POD}$</th>
<th>$\varsigma_{CM}$</th>
<th>$f_{CM}$ (Hz)</th>
<th>$T_1$ (s)</th>
<th>$T_2$ (s)</th>
<th>$T_3$ (s)</th>
<th>$T_4$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No POD</td>
<td>-</td>
<td>0.079004</td>
<td>1.216514</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\omega_2 + \omega_3 - \omega_1$</td>
<td>7</td>
<td>0.516150</td>
<td>1.240710</td>
<td>0.1581</td>
<td>0.1083</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$P_{ss}$</td>
<td>0.4</td>
<td>0.132493</td>
<td>1.2201117</td>
<td>0.0618</td>
<td>0.2768</td>
<td>0.0618</td>
<td>0.2768</td>
</tr>
<tr>
<td>CLF</td>
<td>22</td>
<td>0.581642</td>
<td>1.267629</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

In Table 6.5 subscript $CM$ stands for critical mode

6.5 Fault cases for a STATCOM

The same fault cases as for the SVC were run in this part.

- Case 1: 10% load increase at bus 8 for 100ms.

A small disturbance was initially applied in order to study the small signal stability of the system. The rotor angle oscillations and voltage profile were analyzed.

The results of rotor angle oscillations showed that the system oscillated without any POD in the system although it retained synchronism. The best results for the damping were shown by the CLF based control law as the POD input. Results with $\omega_2 + \omega_3 - \omega_1$ were also good. With the power as the POD input, there was some damping in the system but as a low gain $K_{POD}$ was used for the POD, the results were not that good. A high gain was not used as for some faults; it caused the system to go unstable.
Case 1

Figure 6.2: Rotor angle of generator 2

Figure 6.3: Voltage profile for bus 8
Case 2: A short circuit occurs at the middle of one of the lines between buses 7 and 8. The fault is cleared by removing the faulted line after 100ms.

Without any POD in the system the system oscillated with very large amplitudes in the rotor angles but the system remained stable while maintaining synchronism. Again the CLF based control law provided the best damping in the system followed by $\omega_2 + \omega_3 - \omega_1$ as the POD input. $P_{98}$ also injected some damping in the system but the results were not as good as to the case when the other two signals were used as the input.

Figure 6.4: Rotor angle of generator 2
Figure 6.5: Voltage profile for bus 8

Looking at the voltage profile, it could be seen that with the STATCOM connected the voltage at bus 8 returns to 1 p.u although the system configuration in the post fault state is different compared to pre fault as one of the lines is disconnected.

Case 3: A short circuit occurs at the middle of line between buses 5 and 7. The fault is cleared by the disconnecting the line permanently.

Since the dominant machines in the critical mode were machines 1 and 2, a fault was applied in between these machines so as to analyze the behavior of the STATCOM.

The rotor angle oscillations and voltage profile were studied for the critical mode. The results obtained were:
It could be seen that without the POD in the system, the oscillations in the rotor angles were very large. But with the POD connected the results were much better for some input signals. The CLF based control law showed the best results followed by $\omega_2 + \omega_3 - \omega_1$. But with $P_{98}$ as the POD input the results showed that the system was quite well damped, but it took a long time to reach the steady state.

The results for the voltage profile were as follows:
It could be seen that the voltage at bus 8 returned to 1 p.u without and with POD for all the signals. But with $P_{98}$ as the input to the POD, it took a much longer time for the bus voltage to reach 1 p.u.

The reasons for such a behavior were because of the POD. Looking at the output of the POD controller Figure 6.8, it could be seen that it was much larger than the difference between the voltage at bus 8 and reference voltage. Thus the STATCOM focused on improving the damping in the system as the POD had a larger weight compared to voltage control. But after some time the output of the POD becomes small and voltage control for the STATCOM starts to act causing the bus voltage to go to 1 p.u. The simulation was run for a longer time and it could be seen that the voltage did settle at 1 p.u.
Figure 6.8: Output of the POD
Case 4: A short circuit occurs on both the lines between buses 7 and 8. The fault is cleared by disconnecting the lines after 100ms.

It could be seen in Figure 6.9 that none of the signals was able to inject significant damping in the system and the results were not much different than when no POD was used for the rotor angle oscillations.
Further it could be seen that with the fault cleared, the voltage of the STATCOM terminal did not come back to 1 p.u exactly. This was because the STATCOM had reached its limit and was not able to inject more reactive power into the system. The plots for the generated voltage $E_{sh}$ (Figure 6.11) and the maximum allowable generated voltage $E_{sh}^{\text{max}}$ (Figure 6.12) of the STATCOM explain this. The plots show that the STATCOM terminal bus voltage does not reach 1 p.u as the generated voltage $E_{sh}$ and the maximum generated voltage $E_{sh}^{\text{max}}$ are the same meaning that the STATCOM is operating at its limit.
Case 4

Figure 6.11: Plot of $E_{sh}$ for various POD inputs

Case 4

Figure 6.12: Plot for $E_{sh}^{\text{max}}$ for various POD inputs
The results for case 4 showed that none of the signals was able to introduce significant damping in the system. The rotor angle oscillations were similar to when there was no POD.

The reason for such results was that due to the severity of the fault, the system configuration changed leaving the STATCOM connected at the end bus of a radial system. Hence the damping controller did not give good results. A remedy for this would be to install multiple FACTS devices with damping controllers but a drawback would be the extremely high costs of the STATCOM. A cheaper way to control the oscillations for severe faults could be to install power system stabilizers with the generators.

6.6 Transient Stability

Further the critical clearing times for the fault in case 3 were also found for various input signals. The results obtained based on transient stability study were as follows:

**Table 6.6: Critical clearing times for case 3**

<table>
<thead>
<tr>
<th>Input signal</th>
<th>Critical Clearing Time $t_{cc}$ (s)</th>
<th>% change compared to without any FACTS device</th>
</tr>
</thead>
<tbody>
<tr>
<td>No FACTS device</td>
<td>STATCOM</td>
<td>%</td>
</tr>
<tr>
<td>$P_{g8}$</td>
<td>0.168</td>
<td>-</td>
</tr>
<tr>
<td>$\omega_2 + \omega_3 - \omega_1$</td>
<td>0.230</td>
<td>36.90</td>
</tr>
<tr>
<td>CLF</td>
<td>0.231</td>
<td>37.50</td>
</tr>
</tbody>
</table>

The results from Table 6.6 showed that $\omega_2 + \omega_3 - \omega_1$ and the CLF based input signal gave the largest critical clearing time for the system. The results for $P_{g8}$ were also good unlike the case when SVC was used. The comparison regarding this will be made in the following chapters to come and hence will not be discussed here. Again it could be seen that FACTS devices can be used to improve the critical clearing times of the faults which could play a crucial role from the system stability point of view. Furthermore the CLF based control law would be the most appropriate signal as the POD input.

Conclusions:

A STATCOM was placed on a location based on controllability in order to damp the critical oscillatory mode for the IEEE 3 machine 9 bus test system. It was seen that a
STATCOM without supplementary control could not improve the damping in the power system considerably and hence a supplementary controller was required.

Different input signals for the POD were tested for different disturbance scenarios in the system. Both remote and local signals were used in order to test and select the best possible ones.

The results showed that remote signals provided much better damping in the system compared to the local signals. The reason was that the remote signals can include information which can damp other oscillatory modes in the system and hence provide better results.

Further tuning of the POD filter is also crucial. It was seen that for some signals, a too high POD gain provided good results for some faults but for other faults made the system go unstable. To counter such condition, the POD controller was retuned with a lower gain so that it worked for all the fault scenarios and kept the system stable.

Thus the conclusions derived from the work were that system stability depends on the location of the FACTS device, the appropriate signal to the supplementary POD control, the tuning of the controller and the type and location of the fault. And if the location and input signal along with the tuning of the POD filter are precise, the STATCOM can be used to improve the system stability by improving the damping in the rotor angle oscillations as well as provide voltage support.
Chapter 7: Comparison between an SVC and a STATCOM

The aim of this work was to see the impact of the two shunt FACTS devices on the critical oscillatory modes in the system which could lead to system instability under small or large disturbances if not properly taken care of. The idea was to damp these modes and improve the system stability.

Firstly the location of the FACTS device was to be found for the maximum controllability of the critical modes followed by the introduction of supplementary control and the choice of its input signal. It was seen that the FACTS devices without supplementary control could not damp the critical mode but required a supplementary controller to do so.

In this chapter a comparison has been made between an SVC and a STATCOM based on the damping in the rotor angle oscillations also known as rotor angle stability and transient stability. According to [2], rotor angle stability is the ability of a power system to retain synchronism after a disturbance. Transient stability on the other hand is the ability of a power system to retain synchronism after a large disturbance [2]. For transient stability the critical clearing time was used as a means to distinguish which of the two FACTS devices either the SVC or the STATCOM would be suitable for this particular test system. The critical clearing time is the time after which even if the fault is cleared, the system will go unstable due to loss of synchronism of the machines in the system. Case 3 was chosen as the disturbance case in order to compare the functionalities of the SVC and the STATCOM since for a small disturbance, the SVC and the STATCOM showed almost similar results and also the rotor angle oscillations were not of large amplitudes. This fault is a good way to compare the results for the SVC and the STATCOM based on transient stability i.e. the critical clearing time. In order to remind the reader about the disturbance in case 3, the fault simulated was a short circuit fault at the middle of the line between buses 5 and 7. The fault was cleared by disconnecting the faulted line permanently after 100ms.

7.1 Damping of oscillatory modes

The rotor angle oscillations were first compared for the SVC and STATCOM. Results for one local signal ($P_{98}$) and one global signal (CLF) were used to compared the two devices.
Case 3 (Comparison of an SVC and STATCOM with $P_{98}$)

Figure 7.1: Rotor angle of generator 2 with $P_{98}$ as POD input

With $P_{98}$ as the POD input, it could be seen in Figure 7.1 that the STATCOM provided better damping of the critical mode compared to an SVC. It could also be seen that with the STATCOM connected the system returned to a steady state much faster.
Case 3 (Comparison of an SVC and STATCOM with $P_{98}$)

![Graph showing voltage profile for bus 8](image)

*Figure 7.2: Voltage profile for bus 8*

The plots for both the rotor angle deviations and voltage profile showed similar results. With the STATCOM in the system the bus voltage returned to 1 p.u faster compared to when an SVC was connected. But one of the reasons for such results was the gain of the POD controller. For the case of the SVC, a high POD gain was required to achieve some damping in the system compared to a STATCOM. This in turn affected the voltage profile of the system leading to a longer time for the system to return to steady state. A lower gain would make the system to reach the stable point faster at the expense of less damping in the system.
Next the results with the CLF based control law were analyzed. Both the SVC and the STATCOM showed good results with this input signal and the results were very much similar for the rotor angle oscillations. The plot for the voltages showed that the magnitude of deviations of the bus voltage was less when a STATCOM was used compared to when an SVC was placed in the system. But the voltage at the bus returned to 1 p.u for both the devices.

*Figure 7.3: Rotor angle of generator 2 relative to generator 1 with CLF control law*
The conclusion drawn by looking at Figure 7.1, 7.2, 7.3 and 7.4 was that although the SVC and STATCOM provided almost identical results, it was the STATCOM that provided slightly better damping in the system. The focus was now shifted to the results on the critical clearing times for this particular fault in order for the comparison.

### 7.2 Transient Stability

The critical clearing times were found for the different input signals with the SVC and STATCOM. The times with no FACTS devices installed were also found. The results for the signals being compared i.e. $P_{08}$ and CLF were as follows:
Table 7.1: Comparison of critical clearing times for SVC and STATCOM

<table>
<thead>
<tr>
<th>Case 3: A short circuit fault on one of the lines between buses 7 and 8. The fault is cleared by disconnecting the faulted line after 100ms</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Critical Clearing Time</strong> $t_{cc}$ (s)</td>
</tr>
<tr>
<td><strong>Input signal</strong></td>
</tr>
<tr>
<td>No FACTS device</td>
</tr>
<tr>
<td>$P_{98}$</td>
</tr>
<tr>
<td>CLF</td>
</tr>
</tbody>
</table>

Note: $% \Delta$ stands for the percentage difference in the critical clearing times between a STATCOM and an SVC with respect to the time without any FACTS device.

Comparing the results given in Table 7.1, it could be seen that for the various input signals given, the STATCOM gave a larger critical clearing time than the SVC. This means that with a STATCOM connected in the system at bus 8 a larger stability margin was achieved compared to connecting an SVC at the same bus. Hence the STATCOM would be the right choice for the better improvement of transient stability.

From these results it could be concluded that the STATCOM although with a higher cost compared to the SVC would be a suitable device to be installed in this power system as it not only provided better damping and voltage profile but also gave higher critical clearing times for the fault.
Chapter 8: Conclusions and Future Work

8.1 Conclusions

This chapter concludes the work done in this project with some ideas for future work. As mentioned in the earlier chapters, oscillatory modes can cause problems in the system if some disturbance occurs. Inter area modes which have a low oscillation frequency may get excited after a disturbance in the system leading to increased rotor angle oscillations or rotor angle instability. The aim was thus to damp the critical oscillatory modes using FACTS devices and also to have a stable voltage profile of the system.

From the results obtained in the previous chapters it can be concluded that both the SVC and the STATCOM without supplementary control cannot damp the oscillatory modes. Supplementary controllers are required which serve the purpose of damping. It was also seen that the damping of the oscillatory modes was dependent on the location of the FACTS device and also on the severity of the fault. Input signals to the controllers played a significant role in the damping of rotor angle oscillations.

Another important aspect noticed was that even with a damping controller installed in the system, it was not necessary that the system remained stable until the controller was tuned properly. A too high gain showed good damping for one fault scenario but at the same time made the system unstable for some other fault. This is one of the reasons as to why a low POD gain was selected for the power signal as the POD input as a slightly higher gain caused the system to go unstable for the fault case 3.

With the right choice of the location of the FACTS device and the correct input signal, significant damping and higher stability margins could be achieved for various disturbance scenarios. Although in case of extremely severe faults such as the one mentioned in case 4 in the earlier chapters, it was seen that one FACTS device was not sufficient in order to provide significant damping in the system although the system remained stable. The solution to this problem could be to install multiple optimally located FACTS devices in the system or using other means to achieve damping such as power system stabilizers although a drawback for the former would be high costs.

8.2 Future Work

Several assumptions were made in this work so as to simplify the work and also to see the effects of the various FACTS devices more clearly.

Hence some proposals concerning future work could be as follows:

- Using other FACTS devices such as those mentioned in section 1.3 of chapter 1.
- More sophisticated dynamic models of the FACTS devices
- Use of multiple FACTS devices in the system and see their affects for extremely severe faults
- Changing the load models and see the impact of these devices on the system
Appendix A

-All data is based on 100 MVAR base power

A.1 Power System Parameters

Line data

*Table A.1: Line data for IEEE 3-machine, 9-bus system*

<table>
<thead>
<tr>
<th>From Bus</th>
<th>To Bus</th>
<th>Resistance</th>
<th>Reactance</th>
<th>Line Charging</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>0.032</td>
<td>0.161</td>
<td>0.306</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>0.0085</td>
<td>0.072</td>
<td>0.149</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>0.01</td>
<td>0.085</td>
<td>0.176</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>0.017</td>
<td>0.092</td>
<td>0.158</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td>0.039</td>
<td>0.17</td>
<td>0.358</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>0.0119</td>
<td>0.1008</td>
<td>0.209</td>
</tr>
</tbody>
</table>

*Table A.2: Transformer data*

<table>
<thead>
<tr>
<th>Transformer</th>
<th>From Bus</th>
<th>To Bus</th>
<th>Resistance</th>
<th>Reactance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>0.0576</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
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<td>0.0625</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>9</td>
<td>0</td>
<td>0.0586</td>
</tr>
</tbody>
</table>

Bus data

*Table A.3: Bus data for IEEE 3-machine, 9-bus system*

<table>
<thead>
<tr>
<th>Bus</th>
<th>Voltage</th>
<th>θ</th>
<th>Generated Active Power</th>
<th>Generated Reactive Power</th>
<th>Active Load</th>
<th>Reactive Load</th>
<th>G</th>
<th>B</th>
<th>Bus Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.04</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Slack</td>
</tr>
<tr>
<td>2</td>
<td>1.02533</td>
<td>0</td>
<td>1.63</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>PV</td>
</tr>
<tr>
<td>3</td>
<td>1.02536</td>
<td>0</td>
<td>0.85</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>PV</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>PQ</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
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<td>0.40</td>
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<td>PQ</td>
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<td>6</td>
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<td>0</td>
<td>0</td>
<td>1.20</td>
<td>0.35</td>
<td>0</td>
<td>0</td>
<td>PQ</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>PQ</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>0</td>
<td>-</td>
<td>1.65</td>
<td>0.95</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>PV</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>PQ</td>
</tr>
</tbody>
</table>
Machine data

Table A.4: Machine data for the IEEE 3-machine, 9-bus system

<table>
<thead>
<tr>
<th>Connected to Bus</th>
<th>$x_d$</th>
<th>$H$</th>
<th>$D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine 1</td>
<td>1</td>
<td>0.0608</td>
<td>23.64</td>
</tr>
<tr>
<td>Machine 2</td>
<td>2</td>
<td>0.1198</td>
<td>6.4</td>
</tr>
<tr>
<td>Machine 3</td>
<td>3</td>
<td>0.1813</td>
<td>3.01</td>
</tr>
</tbody>
</table>

Turbine and governor models [13]

Generator 1 turbine model

![Diagram of Generator 1 turbine model]

Figure A.1: Turbine TYPE HT1. Classical penstock turbine model

$Y$ Gate opening

$Y_0$ Initial gate opening

$T_m$ Mechanical torque
$W$ Speed of the machine

$W_0$ Nominal speed

**Table A.5: Turbine parameters for generator 1**

<table>
<thead>
<tr>
<th></th>
<th>$K_D$</th>
<th>$T_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator 1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Generator 1 governor model**

$$
Y = \frac{K(1+sT_2)}{(1+sT_1)(1+sT_3)} + Y_{ref} - P_{0,ref} + W
$$

**Figure A.2: Governor TYPE SG3. Approximate speed-governing model (hydro turbines)**

$K$ Effective speed-governing system gain

$T_1$ Equivalent time constant

$T_2$ Equivalent time constant

$T_3$ Equivalent time constant

$W$ Speed of machine

$Y$ Gate opening

**Table A.6: Governor Parameters for generator 1**

<table>
<thead>
<tr>
<th></th>
<th>$K$</th>
<th>$T_1$</th>
<th>$T_2$</th>
<th>$T_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator 1</td>
<td>15</td>
<td>20</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
**Generator 2 and 3 turbine model**

![Turbine model diagram](image)

**Figure A.3: Turbine TYPE ST1. Approximate model of steam turbine with single reheat**

- $Y$: Gate opening
- $T_m$: Mechanical torque
- $T_C$: Steam chest time constant
- $K_H$: High pressure turbine power fraction
- $T_R$: Reheat time constant

**Table A.7: Turbine parameters for generator 2 and 3**

<table>
<thead>
<tr>
<th></th>
<th>$T_C$</th>
<th>$K_H$</th>
<th>$T_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator 2</td>
<td>0.3</td>
<td>0.3</td>
<td>7</td>
</tr>
<tr>
<td>Generator 3</td>
<td>0.3</td>
<td>0.3</td>
<td>7</td>
</tr>
</tbody>
</table>
**Generator 2 and 3 governor model**

\[
\frac{K}{(1 + sT_1)}
\]

*Figure A.4: Governor TYPE SGC. WSCC steam turbine governor model*

- \( Y \) Gate opening
- \( W \) Speed of the machine
- \( Y_{\text{max}} \) Gate position limit
- \( Y_{\text{min}} \) Gate position limit
- \( K \) Effective speed-governing system gain
- \( T_1 \) Equivalent time constant

**Table A.8: Governor Parameters for generator 2 and 3**

<table>
<thead>
<tr>
<th></th>
<th>( Y_{\text{max}} )</th>
<th>( Y_{\text{min}} )</th>
<th>( K )</th>
<th>( T_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator 2</td>
<td>1</td>
<td>-1</td>
<td>20</td>
<td>0.1</td>
</tr>
<tr>
<td>Generator 3</td>
<td>1</td>
<td>-1</td>
<td>20</td>
<td>0.1</td>
</tr>
</tbody>
</table>
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