Design and modeling of FACTS devices

A Thesis Submitted in Partial Fulfilment

Of the Requirements for the Award of the Degree of

MASTER OF TECHNOLOGY

in

Electrical Engineering

(Power Electronics & Drives)

by

JAYANT SHARMA

Roll No.-213EE4337

Under the Supervision of

Prof. Pravat Kumar Ray

Department of Electrical Engineering

National Institute of Technology Rourkela

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Dedicated

To

My beloved parents

Department of Electrical Engineering

National Institute of Technology Rourkela

CERTIFICATE

This is to certify that the thesis entitled, " Design and modeling of FACTS devices" submitted by Mr. Jayant Sharma in partial fulfilment of the requirements for the award of Master of Technology Degree in electrical Engineering with specialization in "Power Electronics and Drives" during session 2013-15 at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance. This work has not been submitted at other University/ Institute for the award of any degree or diploma.

Date:

Prof. Pravat Kumar Ray

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I would also like to acknowledge the entire teaching and non-teaching staff of Electrical department for establishing a working environment and for constructive discussions.

Last but not least I would like to thank my parents, who taught me to work hard by their own example. They provided me much support being apart during the whole tenure of my stay in NIT Rourkela.

JAYANT SHARMA

ROLL NO. 213EE4337

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LIST OF ABBREVIATIONS

C_S	DC link capacitor
V_{DC}	DC link Voltage
P_{ga}	Active Power Generated at bus ‘a’
P_{la}	Active Power consumed at bus ‘a’
Q_{ga}	Reactive Power Generated at bus ‘a’
Q_{la}	Reactive Power consumed at bus ‘a’
Z_{ab}	Impedance between bus ‘a’ and ‘b’
G_{ab}	Conductance between bus ‘a’ and ‘b’
B_{ab}	Susceptance between bus ‘a’ and ‘b’
Ψ_H	Flux linkage of ‘H’ Damper winding

Ψ_G	Flux linkage of 'G' Damper winding
Ψ_q	Flux linkage winding 'q'
Ψ_d	Flux linkage of 'd' winding
Ψ_K	Flux linkage of 'K' Damper winding
Ψ_F	Flux linkage of 'F' Damper winding
X_d	Direct axis Reactance of generator
X'_d	Direct axis Transient Reactance of generator
X''_d	Direct axis Sub transient Reactance of generator
X_q	Quadrature axis Reactance of generator
X'_q	Quadrature axis Transient Reactance of generator
X''_q	Quadrature axis Subtransient Reactance of generator
T'_d	Direct axis Transient Time Constant of generator
T''_d	Direct axis Subtransient Time Constant of generator
T'_q	Quadrature axis Transient Time Constant of generator
T''_q	Quadrature axis Subtransient Time Constant of generator
ω_B	Base Speed of Synchronous Generator
E_{fd}	Field voltage of Synchronous Generator
Z_{Base}	Base Impedance of Synchronous Generator
β	Firing Angle of Thyristor
X_L	Reactance of Thyristor Controlled Reactor
X_C	Capacitance of Fixed Capacitor used in TCSC

ABSTRACT

In this proposed study, application of SVC in a five machine system is shown, where SVC is connected to one of the five buses of multi-machine system, thus reduces the overall requirement of reactive power of the system and finally transmission losses in transmission lines are reduced. Comparison between different parameters of five machine system with and without SVC is observed.

Stability is the main challenge in modern power system. Power System Stabilizer (PSS) is mainly used with AVR (Automatic Voltage Regulator) to damp out oscillations of conventional power system, but use of PSS cannot provide enough damping. Therefore, some other compensators have to be connected with PSS (Power System Stabilizer) to increase controllability and reliability of modern power system during unbalancing conditions. TCSC (thyristor controlled series capacitor) is a FACTS device which is useful in damping small signal oscillations, though its primary function is to increase the power transmission capability of line.

A single machine infinite system is connected with conventional PSS for damping oscillations of the system during fault conditions, where speed signal of generator is used as feedback signal and tested for different mechanical power inputs during faults. Then same system is compensated with TCSC whose reactance can be changed according to the variation in generator speed and so that system will be more stabilized during fault.

CHAPTER 1

INTRODUCTION

1.1 Overview

Transmission lines of existing power system are used near to their thermal and stability limit [1]. Modern transmission system has many limitations when power is transferred between the different systems or within the single area. There are many limitations of existing power systems, some of which are listed below.

- Steady-State Power Transfer
- Voltage Stability
- Dynamic Voltage
- Transient Stability
- System Oscillation
- Inadvertent Loop Flow
- Thermal
- Short-Circuit Current

Flexible AC Transmission Systems (FACTS) devices first introduced in 1970 and since then there are many FACTS devices have been invented according to the need and their applications in industries and power systems and their dynamic performance is continuously getting improved day by day. FACTS technology is integrated technology which is based on the power electronics devices such as Thyristor, GTO and other power electronics converters for the improvement of power system effective utilization, power transferring capability of system, stability of system, reliability of interconnected system and quality of transferred power. Power system depends on certain variables, which can be controlled to control the power flow in power system. This can be understood by considering a single line diagram of single machine infinite bus system, shown in figure 1.1. Although power-angle curve is based on steady state value of power and angle and FACTS devices are implemented to confront the dynamic issues, power-angle curve exhibits that there are three variables that can be controlled in power system to control its performance. These variables are

• Voltage

• Impedance

• Angle

$$P = \frac{E_S E_R}{X} \sin\delta$$

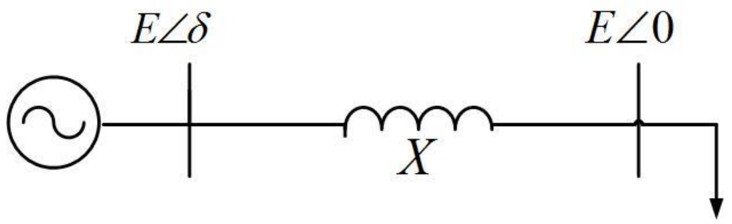

Figure 1.1 Single machine infinite bus system

1.2 Literature review

Great demand of power is needed because the number of utility generators is being increased day by day, which will place demand on the transmission network. Another reason for power demand is competition among the utilities. Added to this, rights of way is also a big problem. Lack of long term planning and increased transmission requirement cause inclinations toward security and power quality is reduced [1]. This shows that there will be need of upgradation of existing system and also construction of new lines will be required. FACTS controllers can be used to overcome this problem. These devices have the potential to interact with each other. Depending on the control and placement of FACTS controllers, this interaction may either deteriorate or enhance system stability. Power flow study is the main objective of power system to determine the steady state operating conditions. Steady state operating conditions of power system can be obtained by calculating active power and reactive power flow in the power network and by calculating the magnitudes and angles of voltages at different nodes of the power network [2]. In order to control the reactive power flow in a power network, SVC controller can be incorporated in the system. The equivalent susceptance of SVC which is the function of firing angle can be changed by changing the firing angle of thyristors. Firing angle of SVC can be made a state variable of the system and steady state value of the same can be obtained for each iteration, until convergence is reached [3]. Use of PSS (power system stabilizer) to damp out the small signal oscillations by controlling the excitation of synchronous generator using the auxiliary stabilization signal [5] and for increasing the power system stability is widely used technique. It is most economical and effective technique. Frequency-domain phase compensation method, which uses Phillips-Heffron model, is a conventional method proposed 3 decades ago [4].

A TCSC (Thyristor controlled series capacitor) based PSS (Power System Stabilizer) can be used for improving the damping characteristic of stabilizer [6]. A TCSC based stabilizer uses a reference reactance of transmission line, and changes the reactance of transmission line according to change in speed of synchronous generator or change in power output of the generator. This technique of using TCSC based stabilizer improves the system damping characteristic over the conventional power system stabilizer (CPSS). A coordinated approach can also be used for more improvement of the damping characteristic, where both conventional power system stabilizer (CPSS) and TCSC based stabilizer are used simultaneously[6].

1.3 Motivations

Oscillation stability of power system is a major area of research from several decades. Any unbalance in the power system causes continuous swing of the rotor around the steady state value. These continuous oscillations make the system relatively less stable when large disturbances like faults occur in any part of power system. Thus the study of small signal stability is as important as Transient stability.

Automatic voltage regulator (AVR) is generally used in power system to damp out the oscillations caused by the small disturbance in the system. But Automatic voltage regulator cannot provide fast control which PSS (Power System Stabilizer) can provide. Stabilizers based on FACTS devices demonstrate superior damping performance over CPSS (Conventional Power System Stabilizer).

1.4 Objectives

- To enhance the steady state performance of multimachine power system using SVC (Static VAR compensator) and to compare it with the performance of power system without any compensating device.
- To ameliorate the oscillation stability of SMIB (Single Machine Infinite Bus) system by using TCSC based Power System Stabilizer (PSS) and to compare the results obtained with CPSS (Conventional Power System Stabilizer).

1.5 Organization of the Thesis

There are 6 chapters in this thesis:

Chapter 1

Gives an overview of the thesis, reviews the range of published material according to the objective of the project and contains the objectives and scope of the project.

Chapter 2

This chapter contains introduction of FACTS, different types of FACTS Controllers and their applications in the power system.

Chapter 3

This chapter contains brief introduction of load flow studies and Newton Raphson Load flow method. It also contains the load flow analysis of five machine system and effect of SVC (Static Var Compensator) in five machine system.

Chapter 4

This chapter presents d-q axis Model of single machine infinite bus system. It also contains modelling of CPSS (Conventional Power System Stabilizer) and TCSC based PSS (Power System Stabilizer).

Chapter 5

This chapter presents simulation results and discussion of the single machine infinite bus system during fault condition with CPSS and TCSC and with no controller connected to the system.

Chapter 6

This chapter concludes the thesis and discusses the future scope of the work.

CHAPTER 2

FACTS CONTROLLERS

FACTS compensators or controllers are used to improve the system dynamic response by controlling the complex power flows through the transmission line. There are various types of FACTS controllers used in modern power system. Some of them are listed below

2.1 Different types of FACTS controllers

- Static Synchronous Compensator (STATCOM)
- Static Var Compensator (SVC)
- Unified Power Flow Controller (UPFC)
- Convertible Series Compensator (CSC)
- Inter-phase Power Flow Controller (IPFC)
- Static Synchronous Series Controller (SSSC)
- Thyristor Controlled Series Compensator (TCSC)
- Thyristor Controlled Phase Shifting Transformer (TCPST)
- Super Conducting Magnetic Energy Storage (SMES)

2.2 Shunt Connected Controllers

2.2.1 Static Var Compensator (SVC)

SVC consists of thyristor controlled or thyristor switched reactor, and/or thyristor switched capacitor or combination of them. It consists of thyristors without turnoff capability. It can supply both leading and lagging VARS and uses separate equipment for them. Thyristor switched and thyristor controlled reactor is used to absorb the reactive power, while thyristor switched capacitor is used to supply the reactive power as shown Figure 2.1.

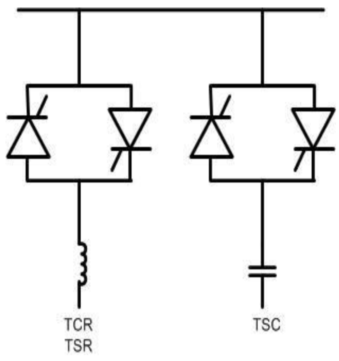

Figure 2.1 Static Var Compensator

2.2.2 Static Synchronous Compensator (STATCOM)

STATCOM is a type of shunt connected controller. STATCOM is an important FACTS Controller, which is based on either voltage sourced or current-sourced converter.

From converter's cost point of view and losses in the inductor, which is used in current source converters; voltage-sourced converters are preferred over current source converters. In Voltage-sourced converters, the dc voltage always has single polarity, and the reversal of power is achieved by reversing dc current flow. STATCOM can be designed in such way that, it can eliminate harmonics of system by acting as an active filter.

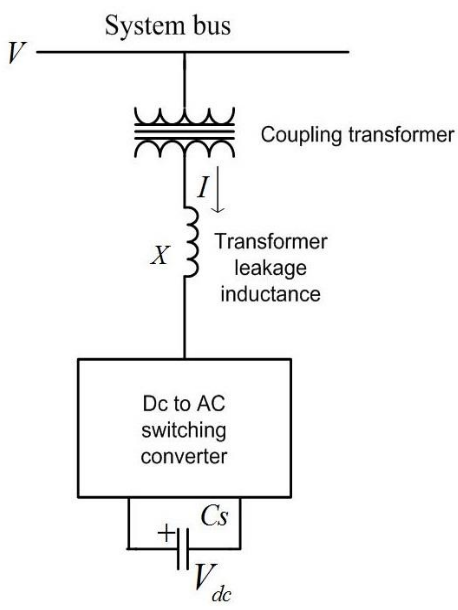

Figure 2.2 STATCOM (Static Compensator)

2.3 Series connected Controllers

2.3.1 TCSC (Thyristor controlled series capacitor)

TCSC consists of a reactor which can be varied by varying the firing angle of thyristor such as TCR (thyristor controlled reactor) is connected across a series capacitor. Change in firing angle of TCR changes reactance of TCR accordingly, so that overall reactance of TCSC changes. For 90 degrees firing, the reactor of TCSC turn out to be fully conducting and when it is 180, the reactor becomes nonconducting. TCSC can also be used to reduce the fault current level by maintaining the firing angle 90. Figure 2.3 shows TCSC as a parallel combination of fixed capacitor and TCR (Thyristor Switched Reactor).

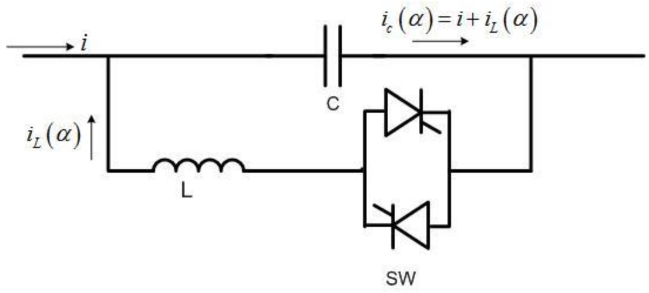

Figure 2.3 TCSC (Thyristor controlled series capacitor)

2.3.2 Static synchronous series compensator (SSSC)

The series Controller can be impedance which can be varied, such as reactor, capacitor or a switching converter based variable source of system frequency, different harmonic frequencies and sub-synchronous frequency for serving the required system necessity.

All Converters of these kinds adds variable voltage, which is in series with the transmission line. SSSC is nothing but variable impedance multiplied with current in transmission line shows a series voltage injection in the line. If the line current makes 90 degrees angle with the line voltage, SSSC only consumes or supplies reactive power with the system.

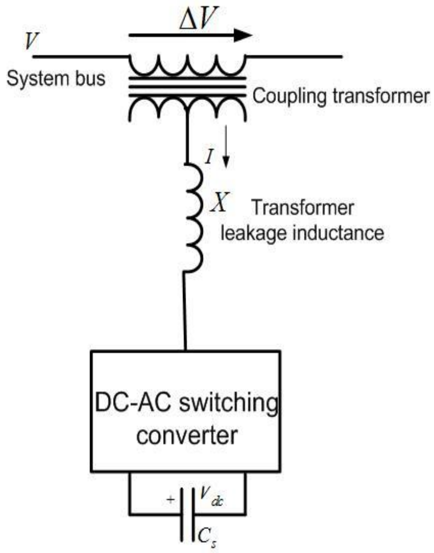

Figure 2.4 SSSC (Static Synchronous Series Compensator)

2.4 Combined Shunt and series Connected Controllers

2.4.1 Unified power flow controller (UPFC)

UPFC is combination of STATCOM and SSSC. Active power requirement of SSSC is provided by STATCOM through the line itself. STATCOM also controls the voltage through control of reactive power flow. Thus this converter can control both active power and reactive power of line. Superconducting magnets are also used for the further enhancement of the UPFC. Figure 2.5 shows UPFC as a combination of STATCOM and SSSC.

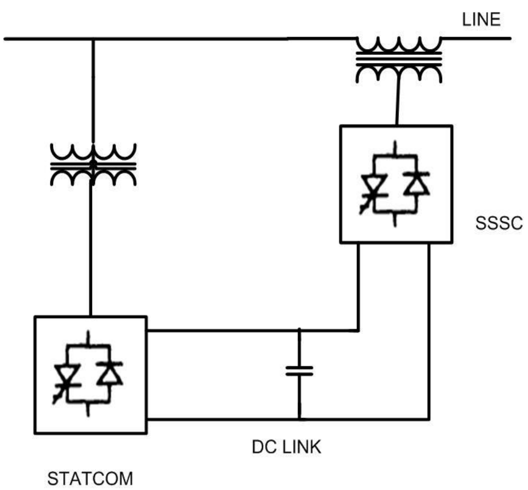

Figure 2.5 UPFC (Unified Power Flow Controller)

CHAPTER 3

EFFECT OF STATIC VAR COMPENSATOR IN A MULTIMACHINE SYSTEM

Before studying the effect of SVC (Static Var Compensator) in a multimachine system, it is important to study load flow analysis and to study various methods used for load flow study.

3.1 Load flow analysis

The satisfaction of the consumers, who are using the electrical power, is the main concern of electrical power system. In the modern power system, the main problem occurs when the following demands must be inevitably met in a complex power system.

(1) Magnitudes of Node voltages and frequency of respective nodes must be kept within the limits.

(2) Waveforms of voltage and current must follow the sinusoidal wave largely.

(3) Thermal stability is the main concern in short Transmission lines and transient and steady state stabilities affect long transmission lines, so transmission lines of different sizes must be used below the thermal and transient stability limits accordingly.

The aim of load flow studies is to find the steady-state operating values of different parameters of electrical network. Power system Planning and Expansion rely on extensive power flow study. Calculation of active power and reactive power of network is done, for obtaining the steady-state values of network. Upon getting the information of these steady state values the next thing is to check whether voltages, active power and reactive power of different nodes are within the prescribed limits or not. Once found that voltage of particular bus is crossing the prescribed limits then necessary active must be taken to bring that voltage within the limits.

Similar approach must be followed when it is found that power carried by any transmission line is beyond the power handling capacity of transmission line.

Since the equations represent the power system are nonlinear equations, iterative methods are applied to find out the solution of these equations. These studies of finding the steady state values of different parameters of power system are applied by presuming that all three phases are 120 degrees out of phase with each other so that a three phase system can be easily analyzed with single phase system.

3.1.1 Formulation of load flow

For the steady state study of power flow, the main approach is to write the power equations by assuming that at a particular bus, addition of power generated, consumed and exchanged must be zero. This approach is applicable to both active and reactive powers.

These are called as 'power mismatch equations'. For a bus 'a' these equations can be written as

$$\Delta P_a = P_{ga} - P_{la} - P_a^{calc} = P_a^{schd} - P_a^{calc} = 0 \quad (3.1)$$

$$\Delta Q_a = Q_{ga} - Q_{la} - Q_a^{calc} = Q_a^{schd} - Q_a^{calc} = 0 \quad (3.2)$$

Pa and Qa show the mismatch in the active power and reactive power respectively to given bus 'a'. Pga and Qga shows, the active power and reactive power supplied by synchronous generator at given bus 'a'. In load flow studies, it is presumed that power plant operator can control these parameters. Pla represent the active power taken by the given load connected to bus 'a' and Qla represent the reactive power consumed by the given load connected to bus 'a'. When the power flow study is done these parameters are assumed to be known.

$$P_a^{schd} = P_{ga} - P_{la} \quad (3.3)$$

$$Q_a^{schd} = Q_{ga} - Q_{la} \tag{3.4}$$

P_a^{calc} and Q_a^{calc} depend on node voltages and impedance of the network. These are found out with the use of equations of power flow. As soon as voltages of the node are known then the power transmitted is calculated easily. For this condition the power mismatch will be zero for a particular purpose and balance of power for any particular node will be fulfilled. On contrary, when node voltages are not accurately known, then the transmitted power which is calculated will contain approximated value only. For this condition, the mismatched power cannot be zero. Load flow approaches to correct this calculated node voltages and powers, until the accurate and precise values arrive which will lead mismatch which is fairly close to zero.

Nowadays computer programs are able to satisfy a tolerance value as close as 10^{-12}.

Upon completion of the convergence, voltage magnitude and angle of different nodes provide necessary information for the operating conditions of steady state of the given power systems.

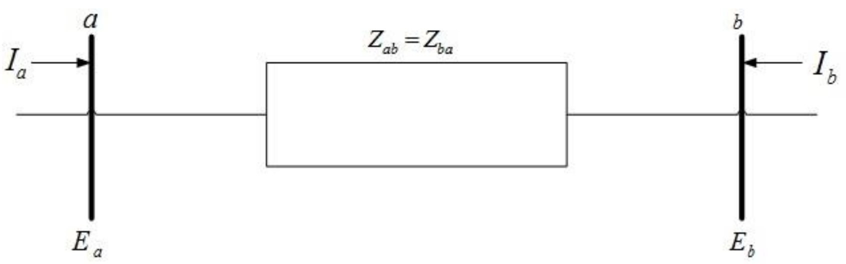

Figure 3.1 Impedance diagram of two bus system

Figure 3.1 shows a two bus diagram with impedance which is similar for both buses

Relationship between the bus currents and bus voltages

$$I_a = \frac{1}{Z_{ab}}(E_a - E_b) = y_{ab}(E_a - E_b) \tag{3.5}$$

$$I_b = \frac{1}{Z_{ab}}(E_b - E_a) = y_{ba}(E_b - E_a) \tag{3.6}$$

These given equations can also be shown in the form of a matrix

$$\begin{bmatrix} I_a \\ I_b \end{bmatrix} = \begin{bmatrix} y_{ab} & -y_{ab} \\ -y_{ba} & y_{ba} \end{bmatrix} \begin{bmatrix} E_a \\ E_b \end{bmatrix} \tag{3.7}$$

$$\begin{bmatrix} I_a \\ I_b \end{bmatrix} = \begin{bmatrix} Y_{aa} & Y_{ab} \\ Y_{ba} & Y_{bb} \end{bmatrix} \begin{bmatrix} E_a \\ E_b \end{bmatrix} \tag{3.8}$$

Admittance and voltage of the buses are given below

$$\mathrm{Y_{ij} = G_{ij} + jB_{ij}} \tag{3.9}$$

$$\mathrm{E_i = V_i e^{j\theta_i} = V_i\left(\cos\theta_i + j\sin\theta_i\right)} \tag{3.10}$$

Where i=a, b and j=a, b

Power which is transferred to bus 'a' consist of the active and reactive power. This power is called as complex power and can easily be written in the form of current and voltage transferred to that bus 'a'.

$$\mathrm{S_a = P_a + jQ_a = E_a I_a^*} \tag{3.11}$$

$$= E_a\left(Y_{aa}E_a + Y_{ab}E_b\right)^* \tag{3.12}$$

Where Ia* is complex conjugate of current injected at bus 'a'

Substituting equations (1) and (2) in (3)

$$\mathrm{P_a^{calc} = V_a^2 G_{aa} + V_a V_b\left[G_{ab}\cos(\theta_a - \theta_b) + B_{ab}\sin(\theta_a - \theta_b)\right]} \tag{3.13}$$

$$\mathrm{Q_a^{calc} = -V_a^2 B_{aa} + V_a V_b\left[G_{ab}\sin(\theta_a - \theta_b) - B_{ab}\cos(\theta_a - \theta_b)\right]} \tag{3.14}$$

According to equations (1) and (2), the mismatch in power will be

$$\mathrm{\Delta P_a = P_{ga} - P_{la} - \{V_a^2 G_{aa} + V_a V_b\left[G_{ab}\cos(\theta_a - \theta_b) + B_{ab}\sin(\theta_a - \theta_b)\right]\}} \tag{3.15}$$

$$\mathrm{\Delta Q_a = Q_{ga} - Q_{la} - \{-V_a^2 B_{aa} + V_a V_b\left[G_{ab}\sin(\theta_a - \theta_b) - B_{ab}\cos(\theta_a - \theta_b)\right]\}} \tag{3.16}$$

We can write the similar equations for bus 'b' also for which all we need to do is just to exchange 'a' and 'b' subscripts.

It is important to remember that, equations (3.1) and (3.2) shows transferred power at single bus only that is 'a'. However, power system of today consists of more than one buses and transmission lines connected to each other. So equations (3.3) and (3.4) can be written in more general form. This generalized form shows the total power flow transferred to 'a' bus represented as the sum of the powers which flow at each transmission component ending at bus ‘a’. It can be shown in below figures.

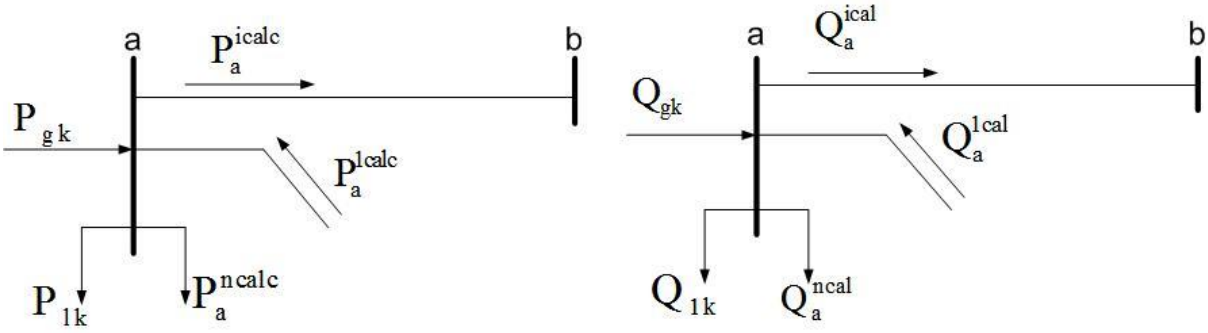

Figure 3.2 Power balance at bus ‘a’

The generic terms for net active and reactive powers will be

$$P_a^{calc} = \sum_{i=1}^{n} P_a^{icalc} \tag{3.17}$$

$$Q_a^{calc} = \sum_{i=1}^{n} Q_a^{icalc} \tag{3.18}$$

Where P_a^{calc} and Q_a^{calc} are calculated from equations (3.5) and (3.6)

Finally generic terms for power mismatch equations will be

$$\Delta P_a = P_{ga} - P_{la} - \sum_{i=1}^{n} P_a^{icalc} = 0 \tag{3.19}$$

$$\Delta Q_a = Q_{ga} - Q_{la} - \sum_{i=1}^{n} Q_a^{icalc} = 0 \tag{3.20}$$

3.1.2 Variables and Bus Classification

Load PQ bus: - Power generation capacity of this bus is zero, since there is no Synchronous Generator connection to load bus. It is possible to measure the active power and reactive power consumed by the load connected to this bus from measurement. Generally, Net active and reactive powers are specified for these types of buses and Voltage and angle are calculated.

Generator PV bus: - A synchronous generator capable of generating active and reactive power is connected to PV bus. By adjusting field current of the generator, node voltage magnitude V can be controlled and made constant. Thus it is possible generate or absorb reactive power. Active power Pg which is generated by PV bus is specified for this bus. The remaining two variables δ and Qg need to be calculated. It is possible to operate this bus at constant voltage which is possible only when the reactive power limit is not violated.

Generator PQ bus: - In case the generator cannot supply the reactive power requirement for maintaining the bus voltage at some predefined value then reactive power of this bus is kept fixed which is same as the violated value and the magnitude of respective bus voltage is varied. For Generator PQ bus, the active and reactive power are specified and bus voltage magnitude and angle are need to be calculated or we can say that PV bus is converted to PQ bus.

Slack (swing) bus: - Out of all the generator buses, the bus where magnitude and angle of nodal voltage are specified is generally given the status of the slack bus. Power system has only one slack bus. Slack bus is used to supply adequate power consumed by unmet load and for losses of the transmission lines which cannot be predicted prior of the calculation of the power flow. Slack bus voltage angle is always kept as the reference angle. And with respect to this angle all other voltage angles of different buses are calculated. This angle value is normally kept at zero value.

3.2 The Newton–Raphson load flow method

Due to fast and strong convergence, Newton Raphson load flow method is used universally over other load flow methods, when there is large scale load flow study is required.

$$\left.\begin{array}{c} f_1(z_1, z_2 \ldots\ldots z_n) = 0 \\ f_2(z_1, z_2 \ldots\ldots z_n) = 0 \\ . \\ . \\ f_1(z_1, z_2 \ldots\ldots z_n) = 0 \end{array}\right\}, \ or \ F(z) = 0 \tag{3.21}$$

When Taylor series expansion is done F (Z) for an initial value of Z(0)

$$F\left(Z\right)=F\left(Z^{(0)}\right)+J\left(Z^{(0)}\right)\left(Z-Z^{(0)}\right)+\textit{higher order terms} \tag{3.22}$$

Here J(Z (0)) is defined as the partial derivatives of F(Z) with respect to Z, called as the Jacobian, which is calculated at Z = Z(0) value

After neglecting all higher order terms of equation (1.22), we get

$$\underbrace{\begin{bmatrix} f_1\left(Z^{(1)}\right) \\ f_2\left(Z^{(1)}\right) \\ \vdots \\ f_n\left(Z^{(1)}\right) \end{bmatrix}}_{F\left(Z^{(1)}\right)} \approx \underbrace{\begin{bmatrix} f_1\left(Z^{(0)}\right) \\ f_2\left(Z^{(0)}\right) \\ \vdots \\ f_n\left(Z^{(0)}\right) \end{bmatrix}}_{F\left(Z^{(0)}\right)} + \underbrace{\left.\begin{bmatrix} \frac{\partial f_1(Z)}{\partial z_1} & \frac{\partial f_1(Z)}{\partial z_2} & \cdots & \frac{\partial f_1(Z)}{\partial z_n} \\ \frac{\partial f_2(Z)}{\partial z_1} & \frac{\partial f_2(Z)}{\partial z_2} & \cdots & \frac{\partial f_2(Z)}{\partial z_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_n(Z)}{\partial z_1} & \frac{\partial f_1(Z)}{\partial z_1} & \ddots & \frac{\partial f_n(Z)}{\partial z_n} \end{bmatrix}\right|_{Z=Z^{(0)}}}_{J\left(Z^{(0)}\right)} \underbrace{\begin{bmatrix} Z_1^{(1)}-Z_1^{(0)} \\ Z_2^{(1)}-Z_2^{(0)} \\ \vdots \\ Z_n^{(1)}-Z_n^{(0)} \end{bmatrix}}_{Z^{(1)}-Z^{(0)}} \tag{3.23}$$

Equation shown above can also be written in the generalized form for ith iteration

$$F\left(Z^{(i)}\right)\approx F\left(Z^{(i-1)}\right)+J\left(Z^{(i-1)}\right)\left(Z^{(i)}-Z^{(i-1)}\right) \tag{3.24}$$

Where i = 1, 2 . . . . Furthermore.

Hence above Equation (1.25) becomes

$$F\left(Z^{(i-1)}\right)+J\left(Z^{(i-1)}\right)\left(Z^{(i)}-Z^{(i-1)}\right)=0 \tag{3.25}$$

Now solving above equation for X (i),

$$Z^{(i)}=Z^{(i-1)}-J^{-1}\left(Z^{(i-1)}\right)F\left(Z^{(i-1)}\right) \tag{3.26}$$

The iterative solution can be expressed as a function of the correction vector

$$\Delta Z^{(i)}=Z^{(i)}-Z^{(i-1)}$$

$$\Delta Z^{(i)}=-J^{-1}\left(Z^{(i-1)}\right)F\left(Z^{(i-1)}\right) \tag{3.27}$$

And the initial estimates are updated using the following relation

$$Z^{(i)}=Z^{(i-1)}+\Delta Z^{(i)} \tag{3.28}$$

Equation (1.28) shows that, after each iteration corrected values of voltages and angles are found when this method is applied for the load flow studies and the values of these variables are repeated until satisfactory answer is achieved for X in equation (1.28). The process of iteration repeated for some mismatch value ΔX, for which a limit is set (i.e. 1e-12).

$$\underbrace{\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}^{(i)}}_{F\left(Z^{(i-1)}\right)} = -\underbrace{\begin{bmatrix} \dfrac{\partial P}{\partial \theta} & \dfrac{\partial P}{\partial V}V \\ \dfrac{\partial Q}{\partial \theta} & \dfrac{\partial Q}{\partial V}V \end{bmatrix}^{(i)}}_{J\left(Z^{(i-1)}\right)} \underbrace{\begin{bmatrix} \Delta \theta \\ \dfrac{\Delta V}{V} \end{bmatrix}^{(i)}}_{\Delta Z^{(i)}} \tag{3.29}$$

Matrices in the Jacobian matrix can have r (nb-1) × (nb-1) elements, which can be shown in the form as given below

$$\left.\begin{matrix} \dfrac{\partial P_a}{\partial \theta_b}, & \dfrac{\partial P_a}{\partial V_b}V_b, \\ \dfrac{\partial Q_a}{\partial \theta_b}, & \dfrac{\partial Q_a}{\partial V_b}V_b \end{matrix}\right\} \tag{3.30}$$

Where a = 1. . . nm, and b = 1. . . nm but discarding the corresponding values for slack bus. For PV buses, the rows and columns which indicates reactive power and voltage magnitudes are omitted. It is also remembered that, when there is no transmission line connection between bus ‘a’ and bus ‘b’, then the respective a–b values present in the Jacobian matrix is zero. As we know that there are few connections of transmission lines in a practical power system, power flows Jacobian matrix has much more sparsity.

Suppose that the connection between a’ and ‘b’ elements shown as an lth element then self and mutual Jacobian terms will be

$$\frac{\partial P_{a,l}}{\partial \theta_{b,l}} = V_a V_b \left[G_{ab} \sin\left(\theta_a - \theta_b\right) - B_{ab} \cos\left(\theta_a - \theta_b\right) \right], \tag{3.31}$$

$$\frac{\partial P_{a,l}}{\partial V_{b,l}} = V_a V_b \left[G_{ab} \cos\left(\theta_a - \theta_b\right) + B_{ab} \sin\left(\theta_a - \theta_b\right) \right], \tag{3.32}$$

$$\frac{\partial Q_{a,l}}{\partial \theta_{b,l}} = -\frac{\partial P_{a,l}}{\partial V_{b,l}} V_{b,l} \tag{3.33}$$

$$\frac{\partial Q_{a,l}}{\partial V_{b,l}} V_{a,l} = \frac{\partial P_{a,l}}{\partial \theta_{b,l}} \tag{3.34}$$

For a=b,

$$\frac{\partial P_{a,l}}{\partial \theta_{\mathrm{a},l}} = -Q_a^{calc} - V_a^2 B_{aa}$$

$$\frac{\partial Q_{a,l}}{\partial V_{\mathrm{a},l}} V_{a,l} = Q_a^{calc} - V_a^2 B_{aa}$$

$$\frac{\partial Q_{a,l}}{\partial \theta_{\mathrm{a},l}} = P_a^{calc} - V_a^2 G_{aa},$$

$$\frac{\partial P_{a,l}}{\partial V_{\mathrm{a},l}} V_{a,l} = P_a^{calc} + V_a^2 G_{aa},$$

Suppose that, bus ‘a’ contain n elements of transmission l, the self-elements of the bus will take the form as given below

$$\frac{\partial P_a}{\partial \theta_{\mathrm{a}}} = \sum_{l=1}^{n} \frac{\partial P_{a,l}}{\partial \theta_{\mathrm{a},l}},$$

$$\frac{\partial P_a}{\partial V_{\mathrm{a}}} V_a = \sum_{l=1}^{n} \frac{\partial P_{\mathrm{a},l}}{\partial V_{\mathrm{a},l}} V_{\mathrm{a},l},$$

$$\frac{\partial Q_a}{\partial \theta_{\mathrm{a}}} = \sum_{i=1}^{n} \frac{\partial Q_{\mathrm{a},l}}{\partial \theta_{\mathrm{a,l}}},$$

$$\frac{\partial Q_a}{\partial V_a} V_a = \sum_{l=1}^{n} \frac{\partial Q_{a,l}}{\partial V_{\mathrm{a},l}} V_{a,l}$$

The mutual elements given by Equations (3.32)–(3.34) will not change for any number of transmission elements terminating at node ‘a’.

3.3 Load flow analysis of a five machine system

In this section a five bus system is taken without any compensator and different bus voltages and respective active and reactive powers generated or consumed by them is calculated.

There are many various methods for the load flow studies for multimachine system. In this system, there are some predefined values of loads at different buses are taken. Then same system is connected with the SVC at third number bus of the system and all above mentioned calculations are performed for this system. Initial values of voltages are given as follows and bus 1 is chosen as the slack bus. Bus number 3, 4 and 5 are load buses and bus 2 is the generator bus. Tolerance value for mismatch of active and reactive powers is taken as 10^{-12}.

Table 3.1 Initial voltage and phase angle of five bus system

Nodal voltage	1	2	3	4	5
Magnitude (p.u.)	1.06	1	1	1	1
Phase angle (deg)	0	0	0	0	0

For starting the load flow analysis, magnitudes and angles of different bus voltages must be taken. All bus voltages are initially taken as 1 p.u. except slack bus voltage which is taken as 1.06 p.u. similarly all the bus voltage angles are taken as 0 degree.

Table 3.2 Loads at different buses

Node	2	3	4	5
P_{load} (MW)	20	45	40	60
Q_{load} (MVar)	10	15	5	10

Loads at different buses are given in above table where slack bus has no load connected to it while other buses are connected to some loads.

Table 3.3 System network and Transmission line parameters

System network and line parameters				
Sending end	Receiving end	R (p.u.)	X (p.u.)	B (p.u.)
1	2	0.02	0.06	0.06
1	3	0.08	0.24	0.05
2	3	0.06	0.18	0.04
2	4	0.06	0.18	0.04
2	5	0.04	0.012	0.03
3	4	0.01	0.03	0.02
4	5	0.08	0.24	0.05

Five buses are connected to each other with reactances and resistances which are taken as lumped values. Table number 3.1, 3.2 and 3.3 shows initial voltages, their angles, loads at all five buses and network parameters like resistances, reactances and susceptances of multimachine system.

Table 3.4 Results obtained after each iteration

Iteration	Nodal voltage	1	2	3	4	5
1	Magnitude (p.u.)	1.0600	1.0000	0.9895	0.9864	0.9745
	Phase angle (deg)	0	-1.9765	-4.5281	-4.8350	-5.5847
2	Magnitude (p.u.)	1.06	1.0000	0.9873	0.9841	0.9717
	Phase angle (deg)	0	-2.0610	-4.6364	-4.9567	-5.7644
3	Magnitude (p.u.)	1.0600	1.00	0.9872	0.9841	0.9717
	Phase angle (deg)	0	-2.061	-4.6367	-4.9570	-5.7649
4	Magnitude (p.u.)	1.0600	1.000	0.9872	0.9841	0.9717
	Phase angle (deg)	0	-2.0612	-4.6367	-4.9570	-5.7649
5	Magnitude (p.u.)	1.0600	1.00	0.9872	0.9841	0.9717

It is observed that load flow convergence has taken five iterations. Voltage magnitudes and angles are given above for each iteration. It can be seen that for fourth and fifth iteration, voltage phase angles and magnitudes are same for each bus, so there is no need to go for next Iteration. It is seen that the active and reactive power generated by slack bus is 131.12 MW and 90.82 MVar respectively. Node 2 generator was kept at 40 MW generation and after Convergence it is found that this bus is absorbing 61.59 MVar in order to maintain bus voltage at predefined value of 1 p.u. table 3.4 shows magnitudes and angles of different buses for each iteration and table 3.5 shows maximum tolerance values of mismatch in active and reactive powers among all buses for each iteration.

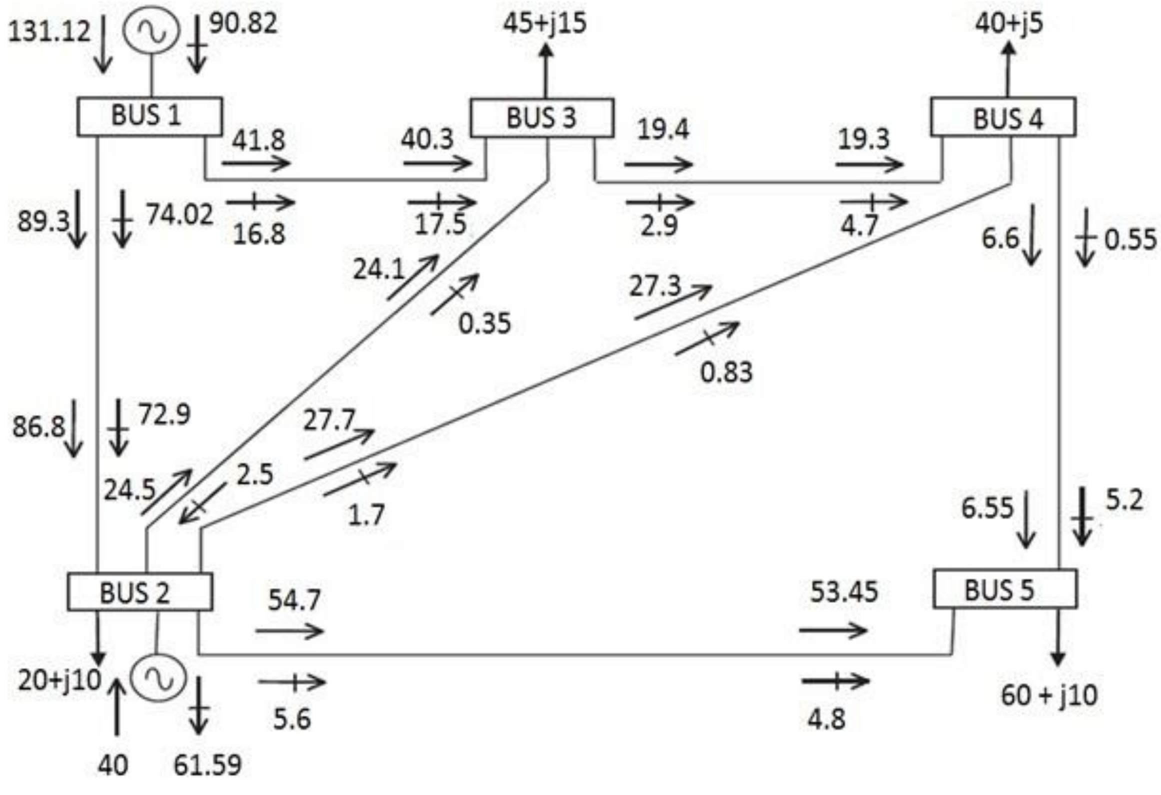

Figure 3.3 Power flow in five bus system

Table 3.5 Maximum tolerance values for Active and Reactive Power

Iteration number	1	2	3	4	5
DPQ (Tolerance)	0.6000	0.0212	7.8126e-05	9.8210e-010	2.4841e-015

Table 3.6 Active and Reactive Power generated by each bus

Bus number	Active power generated (MW)	Reactive power generated (MVar)
1	131.12	90.82
2	40.00	- 61.59
3	-45.00	- 15.00
4	-40.00	- 5.00
5	-60.00	- 10.00

Figure 3.3 shows active and reactive power flow among different buses with their loads. It also shows generation and consumption of active and reactive power at each bus.

Table 3.6 shows active and reactive power generation at different buses of five machine system. Slack bus generates 131.12 MW active and 90.82 MVar reactive power.

3.4 Load flow analysis of a five machine system with SVC (Static Var Compensator):-

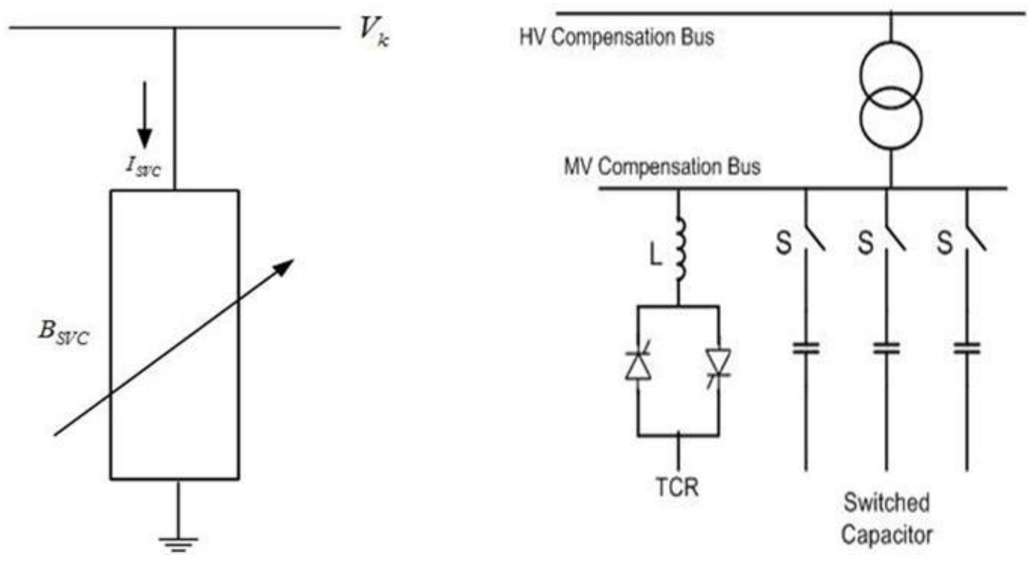

Figure 3.4 SVC as a Variable Impedance

SVC can be represented as an adjustable reactance. For this reactance either firing angle or reactance itself can be taken as the state variable so that their steady state values can be obtained for each iteration.

SVC reactive power compensation can be given by

$$Q_k = \frac{-2V_k^2}{\pi X_l}\left\{X_l - \frac{X_c}{\pi}\left[2(\pi-\alpha)+\sin(2\alpha)\right]\right\} \qquad (3.35)$$

Differentiation of above equation with respect to"α"

$$\frac{\Delta Q_k}{\Delta \alpha} = \frac{2V_k{}^2}{\pi X_l}\left[\cos(2\alpha)-1\right] \qquad (3.36)$$

$$\begin{bmatrix}\Delta P_k \\ \Delta Q_k\end{bmatrix}^{(i)} = \begin{bmatrix}0 & 0 \\ 0 & \frac{2V_k^2}{\pi X_l}\left[\cos(2\alpha-1)\right]\end{bmatrix}^{(i)} \begin{bmatrix}\Delta \delta_k \\ \Delta \alpha\end{bmatrix}^{(i)} \qquad (3.37)$$

Updated value of after ith iteration "α"

$$\alpha_{SVC}^{(i)} = \alpha_{SVC}^{(i-1)} + \Delta\alpha_{SVC}^{(i)}$$

This lineralized equation is implemented in Jacobian matrix by replacing value of (ΔQk/ΔVk) (Where k=3 for this case) element of Jacobian matrix with the equation (3.37). It is to be noted that ΔQk is dependent only on α in order to maintain bus k voltage at 1 p.u. Since the value of voltage at bus k (k=3 in this case) is kept 1 p.u., element of Jacobian matrix is also corrected to new value by subtracting it with the value Vk2 Bk.

SVC Specification

Capacitor value, Xc (1) = 1.07,

Inductor value, X_L (1) = 0.288,

Initial estimated value of firing angle FA (1) =140 degrees

Table 3.7 Tolerance values of firing angle of SVC

Iteration Number	1	2	3	4	5
DPQ (max)	0.6098	0.0838	0.0034	4.352e-06	7.2387e-12
Firing Angle (deg)	130.217	132.4586	132.5392	132.5393	132.5393

Table 3.8 Active and Reactive Power generated by each bus

Bus number	Active power generated(MW)	Reactive power generated (MVar)
1	131.06	85.34
2	40.00	- 77.07
3	-45.00	5.47
4	-40.00	- 5.00
5	-60.00	- 10.00

Table 3.9 Results obtained after each iteration for Voltages

Iteration Number	Nodal voltage	1	2	3	4	5
1	Magnitude (p.u.)	1.0600	1.0000	1.0000	0.9948	0.9773
	Phase angle (deg)	0	-1.9729	-4.7205	-4.9887	-5.633
2	Magnitude (p.u.)	1.06	1.0000	1.0000	0.9944	0.9752
	Phase angle (deg)	0	-2.0532	-4.8378	-5.1071	-5.7972
3	Magnitude (p.u.)	1.0600	1.00	1.0000	0.9944	0.9752
	Phase angle (deg)	0	-2.0533	-4.8379	-5.1073	-5.7975
4	Magnitude (p.u.)	1.0600	1.000	1.0000	0.9944	0.9752
	Phase angle (deg)	0	-2.0533	-4.8379	-5.1073	-5.7975
5	Magnitude (p.u.)	1.0600	1.00	1.0000	0.9944	0.9752
	Phase angle (deg)	0	-2.0533	-4.8379	-5.1073	-5.7975

Table 3.7 shows maximum tolerance values of mismatch in active and reactive powers among all buses for each iteration. Table 3.8 shows active and reactive power generated by each bus with SVC connection at bus 3. It can be seen active power generated by slack bus is reduced by 0.6 MW. Table 3.9 shows magnitudes and angles of different buses for each iteration.

Table3.10 Comparison between system with and without SVC

Nodal voltage	1	2	3	4	5
System without SVC					
Magnitude (p.u.)	1.0600	1.00	0.9872	0.9841	0.9717
Phase angle (deg)	0.00	-2.0612	-4.6367	-4.9570	-5.7649
System with SVC					
Magnitude (p.u.)	1.0600	1.00	1.0000	0.9944	0.9752
Phase angle (deg)	0.00	-2.0533	-4.8379	-5.1073	-5.7975

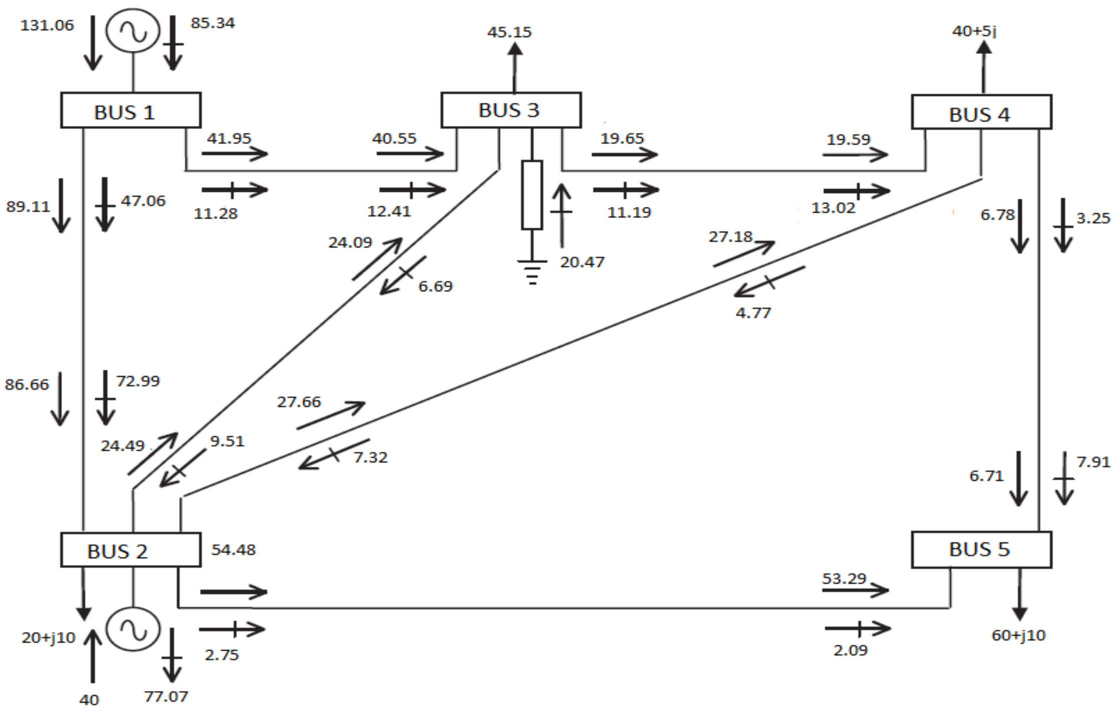

Figure 3.5 Five Machine System with SVC

Table 3.10 shows comparison between system with and without SVC. From this table, it is observed that with SVC at bus 3, voltage of bus 3 is maintained at 1 p.u. and voltage angles of bus 3 and another buses also reduced. It can be seen in figure 3.5 that 20.47 MVar power is generated at bus 3 by SVC at steady state. It reduces the reactive power requirement of bus 3 and finally losses in transmission lines connected between buses 1, 2 and 3 are reduced.

CHAPTER 4

MODELLING OF TCSC BASED POWER SYSTEM STABILIZER IN A SINGLE MACHINE INFINITE BUS SYSTEM

4.1 d-q axis model of synchronous generator

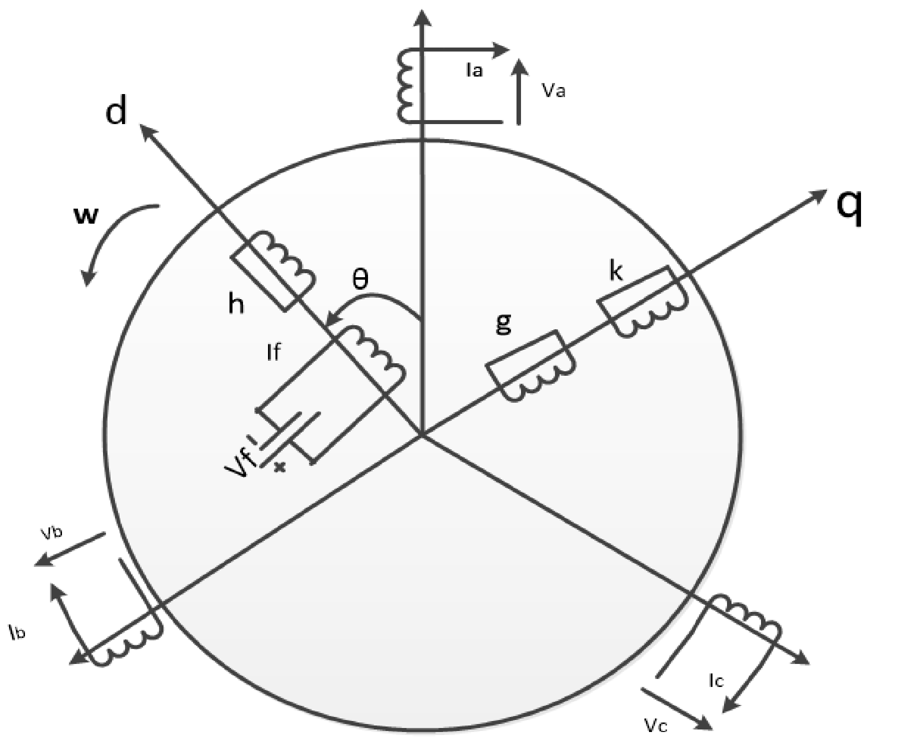

Figure 4.1 d-q Axis Representation of synchronous machine

Figure shows conversion model of a synchronous generator, where stator has three phase windings a, b and c. since stator phase voltages vary with time, this system cannot be analyzed as linear time invariant system. So, in order to convert this time variant system into time invariant system, park's transformation is applied on stator phases of generator. Park's transformation converts rotating three phase voltages into stationary d-q axis. It is also assumed that generator has three damper winding. Damper winding g and k are kept on q-axis and h winding is kept on d-axis. It is also assumed that the field winding is on d-axis. Generator is rotating in anti-clockwise direction. It is also assumed that, the generator is rotating in anti-clockwise direction.

$$\frac{d\psi_H}{dt} = \frac{1}{T_d^{''}}\left(-\psi_H + \psi_d\right)$$

$$\frac{d\psi_F}{dt} = \frac{1}{T_d^{'}}\left(\psi_F + \psi_d + \frac{x_d^{'}}{\left(x_d - x_d^{'}\right)}E_{fd}\right)$$

$$\psi_d = x_d^{''}i_d + \frac{\left(x_d - x_d^{'}\right)}{x_d}\frac{x_d^{''}}{x_d^{'}}\psi_F + \frac{\left(x_d^{'} - x_d^{''}\right)}{x_d^{'}}\psi_H$$

$$\frac{d\psi_d}{dt} = -\omega\psi_q - \omega_B R_a i_d - v_d \omega_B$$

$$\frac{d\psi_G}{dt} = \frac{1}{T_q^{'}}\left(-\psi_G + \psi_q\right)$$

$$\frac{d\psi_K}{dt} = \frac{1}{T_q^{''}}\left(-\psi_K + \psi_q\right)$$

$$\psi_q = x_q^{''}i_q + \frac{\left(x_q - x_q^{'}\right)}{x_q}\frac{x_q^{''}}{x_q^{'}}\psi_G + \frac{\left(x_q^{'} - x_q^{''}\right)}{x_q^{'}}\psi_K$$

$$\frac{d\psi_q}{dt} = \omega\psi_d - \omega_B R_a i_q - v_q \omega_B$$

Above equations show the compact form of d-q axis model of synchronous generator. This model shows 6 state space variables. d-axis, q-axis and field winding flux linkages and three variables are due to damper windings. There are two algebraic equations also there, which show relation between d and q-axis flux linkages and stator currents. Six state space variables make the system complicated. In order to remove complicacy, fast transients can be removed by putting derivatives of d-axis and q-axis flux linkages zero, so that system can be converted into four state space variables which can be easily analyzed.

$$\begin{bmatrix} \dot{\psi}_d \\ \dot{\psi}_q \\ \dot{\psi}_F \\ \dot{\psi}_H \\ \dot{\psi}_G \\ \dot{\psi}_K \end{bmatrix} = A_1 \begin{bmatrix} \psi_d \\ \psi_q \\ \psi_F \\ \psi_H \\ \psi_G \\ \psi_K \end{bmatrix} + A_2 \begin{bmatrix} i_d \\ i_q \end{bmatrix} + B_1 \begin{bmatrix} v_d \\ v_q \end{bmatrix} + B_2 E_{fd}$$

$$A_1 = \begin{bmatrix} 0 & -\omega & 0 & 0 & 0 & 0 \\ \omega & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{T_d^{'}} & 0 & -\frac{1}{T_d^{'}} & 0 & 0 & 0 \\ \frac{1}{T_d^{''}} & 0 & 0 & -\frac{1}{T_d^{''}} & 0 & 0 \\ 0 & \frac{1}{T_q^{'}} & 0 & 0 & -\frac{1}{T_q^{'}} & 0 \\ 0 & \frac{1}{T_q^{''}} & 0 & 0 & 0 & -\frac{1}{T_d^{''}} \end{bmatrix}$$

$$B_1 = \begin{bmatrix} -\omega_B & 0 \\ 0 & -\omega_B \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \qquad B_2 = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_d^{'}} \frac{x_d^{'}}{\left(x_d - x_d^{'}\right)} \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad A_2 = \begin{bmatrix} -R_a & 0 \\ 0 & -R_a \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \omega_B$$

Per unit torque equation in d-q axis model

$$\frac{2H}{\omega_B} \frac{d\omega}{dt} = T_m - \left(\psi_d i_q - \psi_q i_d\right)$$

4.2 d-q axis model of infinite bus and transmission line

Infinite bus voltages are given as

$$E_b = \sqrt{\frac{2}{3}} v \sin(\omega_0 \,\mathrm{t} - \frac{2\pi}{3})$$

$$E_a = \sqrt{\frac{2}{3}} v \sin(\omega_0 \,\mathrm{t})$$

$$E_c = \sqrt{\frac{2}{3}} v \sin(\omega_0 \,\mathrm{t} - \frac{4\pi}{3})$$

d-q axis conversion of above equations

$$E_d = -\sin(\delta)$$
$$E_q = \cos(\delta)$$

Equations relating speed ‘ω’ and rotor angle ‘δ’ are shown below

$$\theta = \omega_0 t + \delta$$
$$\frac{d\delta}{dt} = \omega - \omega_0$$

Transmission line model:-

Transmission line voltage equations can be written in matrix form as

$$\begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix}$$

Here L is inductance of transmission line. Resistance and capacitance of line are neglected. Va, Vb and Vc are generator terminal voltages. Now converting this equation into per unit d-q axis model.

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \left(\frac{\omega_B}{x}\right)\left(\begin{bmatrix} v_d \\ v_q \end{bmatrix} - \begin{bmatrix} E_d \\ E_q \end{bmatrix}\right)$$

Here $x = \dfrac{\omega_B L}{Z_{Base}}$

4.3 Modeling of TCSC (Thyristor Controlled Series Capacitor)

TCSC can be implemented as the parallel combination of thyristor controlled reactor (TCR) and fixed capacitor. TCR can be varied by varying its firing angle so that inductance value changes from zero to maximum. Since the value of capacitive reactance is larger than that of inductive reactance, for any value of firing delay angle total impedance of the circuit is always capacitive. Firing delay angle can be varied from 0 to 90 degrees.

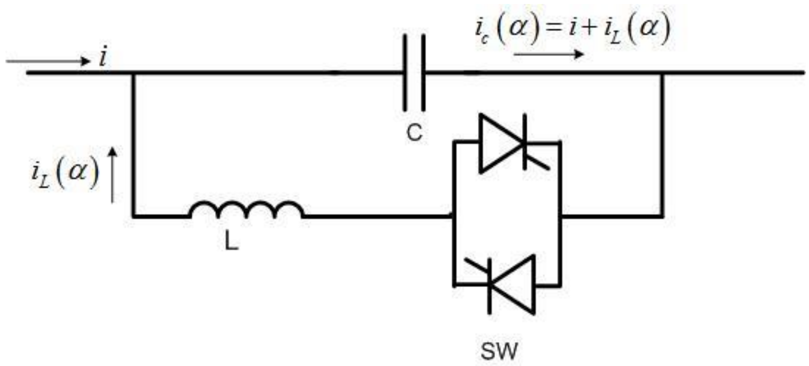

Figure 4.2 TCSC as a Controllable Reactor

$$X_{TCSC}(\beta) = \frac{X_C X_L(\beta)}{X_L(\beta) - X_C}$$

$$X_L(\beta) = X_L \frac{\pi}{\pi - 2\beta - \sin(2\beta)}, X_L \le X_L(\beta) \le \infty$$

Where β is firing angle of the thyristor. Above figure 4.2 shows TCSC as a parallel combination of fixed capacitor and TCR (Thyristor Switched Reactor).

4.4 TCSC (Thyristor Controlled Series Capacitor) based Power System Stabilizer

In this section, our attention will be focused on single machine infinite bus (SMIB) power systems, because an SMIB system qualitatively shows a performance of a system having more than one machine. Main reason for choosing single machine system is because it can be analyzed without much complex calculations, which is needed for a multimachine system. Simplicity in calculation for SMIB is also helpful in ascertaining the concepts of the stability of power system and to find, as to how other factors of power system affect the stability. This SMIB study is also helpful in getting the concepts of controllers. An infinite bus is a source of constant frequency and voltage in magnitude and angle.

Dynamic response of synchronous generator in a practical power system during the fault Conditions are difficult to analyze due to the nonlinearity present in the system. This nonlinearity is caused by the magnetic saturation. Even then, the third order classical dynamic generator system model is used when controller of excitation system is designed.

Besides various advantages of FACTS devices, one important advantage of these devices is there capability to improve the small signal stability of power system by damping the Oscillations occur in synchronous generator due to sudden increment of mechanical power input. Stabilizers damp out the oscillations occur during the transient state. However they have no impact on steady state stability of power system. For simplicity a SMIB (single machine infinite bus system) is taken, where a TCSC based stabilizer is used and its performance against the AVR (automatic voltage regulator) is observed.

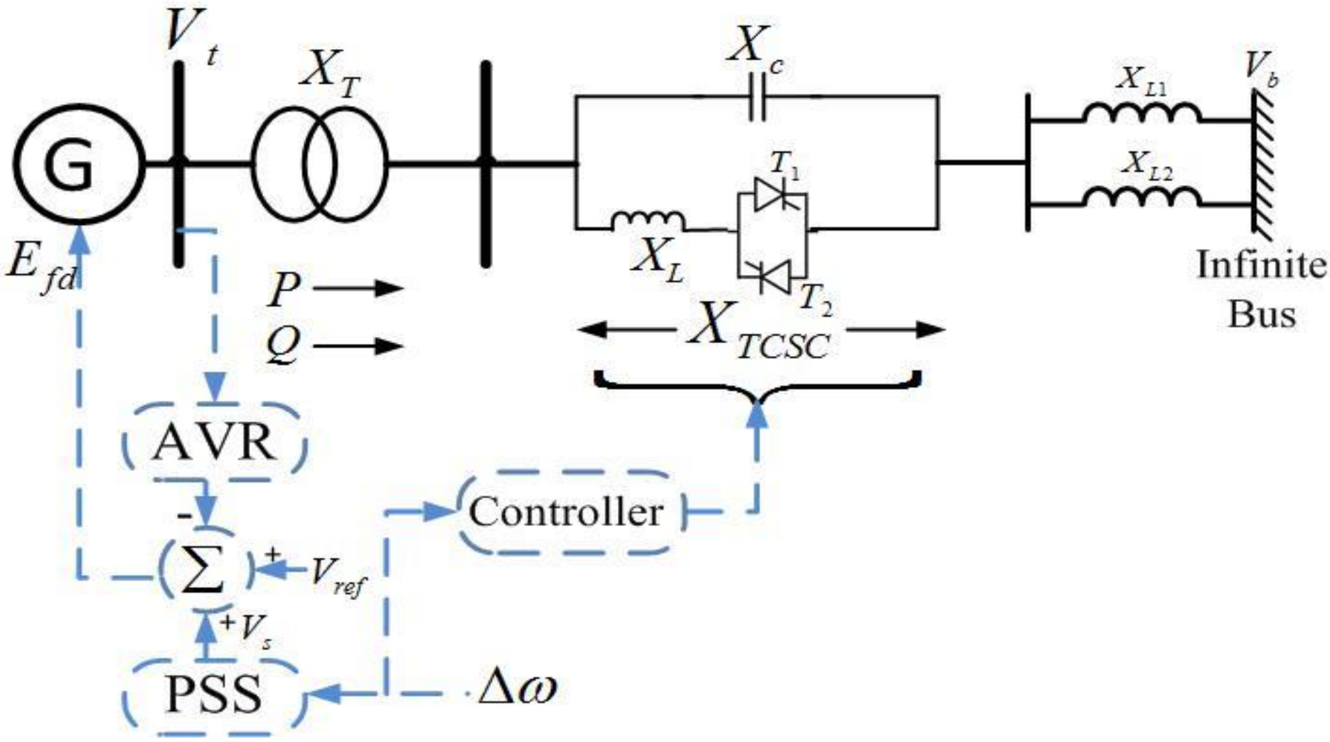

Figure 4.3 Single Machine System with AVR and PSS

Above figure 4.3 shows a single machine infinite bus system connection with AVR (Automatic Voltage Regulator) and PSS (Power System Stabilizer). As shown in figure 4.4 that PSS can have its input as the electric power output or speed of the synchronous generator. This configuration of PSS (power system stabilizer) consists of proportional controller, a washout block and lead-lag blocks. An additional voltage of ΔUPSS is added to Vref by PSS in order to improve the damping characteristic of AVR (Automatic Voltage Regulator). ΔUPSS is zero under the steady state condition. This characteristic of PSS is achieved by using the washout block.

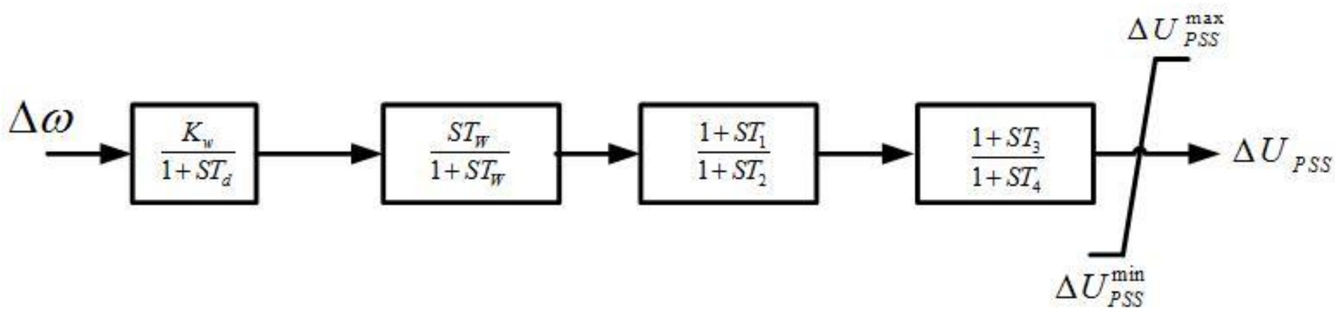

Figure 4.4 Power System Stabilizer

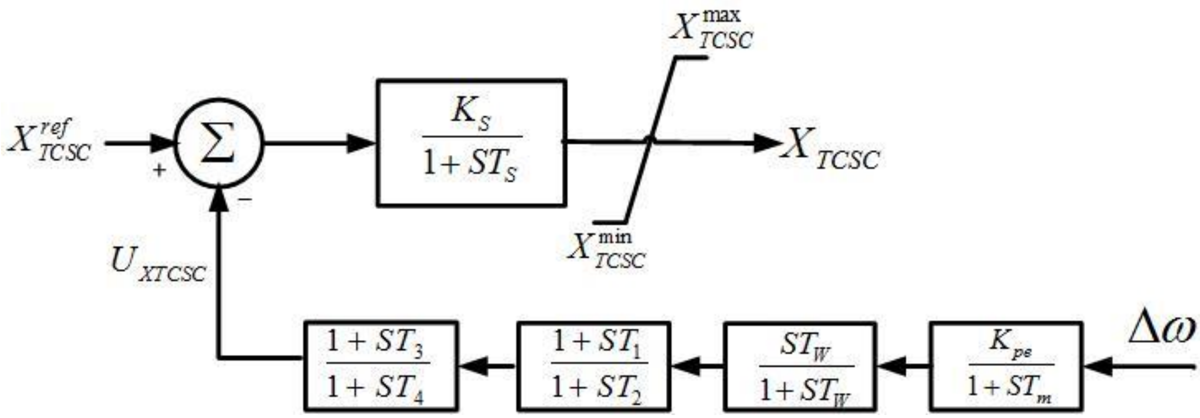

Figure 4.5 TCSC based Power System Stabilizer

This figure 4.5 shows TCSC based PSS, where speed signal of generator is used as the input to the PSS and output of PSS is continuously compared with the reference reactance of transmission line so that an error signal is generated and this error signal is improved by using a proportional controller. This generated signal is the improved transmission line reactance which is obtained by continuous high frequency switching.

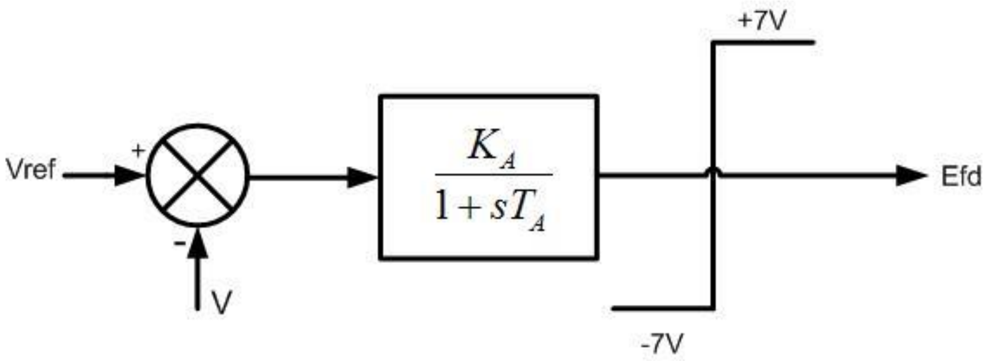

Figure 4.6 Excitation System of Synchronous Generator

Figure 4.6 shows an AVR (Automatic Voltage Regulator) which continuously compared the output voltage of generator with the reference voltage and generates an error signal which is further passed through the proportional controller and used as the field voltage of generator so that output voltage is maintained constant continuously during unbalanced conditions. Limited is used to limit the Efd value. If this limit is crossed, then Efd value is fixed at that limited value.

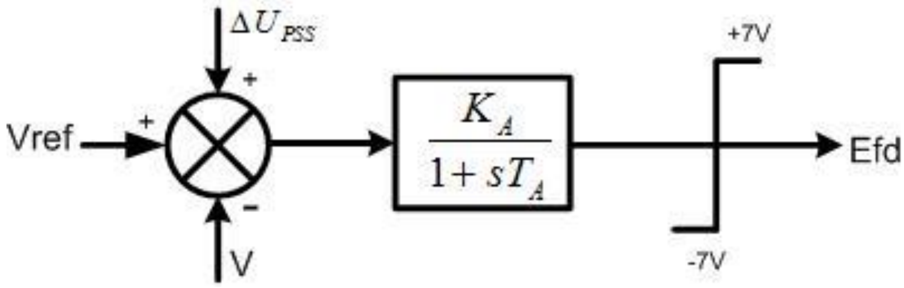

Figure 4.7 Excitation System with Power System Stabilizer

Figure 4.7 shows an excitation system with PSS (Power System Stabilizer). State space equations for aforementioned diagrams can be written as

$$\dot{E}_{fd} = \frac{1}{T_A}\left[K_A\left(V_{ref} + U_{PSS} - V\right) - E_{fd}\right]$$

$$\dot{X}_{TCSC} = \frac{1}{T_S}\left[K_S\left(X_{TCSC}^{ref} - U_{XTCSC}\right) - X_{TCSC}\right]$$

These equations along with generator equations are used for simulating the performance of FACTS device in single machine infinite bus system.

CHAPTER 5

SIMULATION RESULTS AND DISCUSSION

Generator model along with TCSC based PSS is simulated for a fault condition. Since generator model is not a linearized model due to presence of speed term in the matrix A1, it is necessary to perform a linearized analysis of this system around an equilibrium point. Analysis is done for different fault conditions of system for different loading. Three loading conditions are taken

(1) Light loading for mechanical input Pm=0.3 p.u.

(2) Normal loading for mechanical input Pm=0.6 p.u.

(3) Heavy loading for mechanical input Pm=0.85 p.u.

Coordinated design of CPSS (Conventional power System Stabilizer) and TCSC based stabilizer is done for which Particle Swarm Optimization technique is used to calculate the values of various time constants and gains of CPSS (Conventional power System Stabilizer) and TCSC based stabilizer.

Generalized parameters of machine:-

M = 9.26 p.u. Tdo=7.76, D=0, X=0.997 p.u., KA=200, TA=0.015 s, KS=1, TS=0.05 s, V=1.0s, TB=10s, TC=1.0s., Ra=0.003, Xd =1.8, Xd'=0.3, Xd''=0.23, Xq=1.7, Xq'=0.65, Xq''=0.25, Td0''=0.03, Td0'=5, Tq0'=1, Tq0''=0.07, H=3, KA=200, TA=0.02

Optimized parameters using PSO (Particle Swarm Optimization):-

UTCSCmax = UTCSCmin = 0.1 p.u. Td=0.02s, Tm =0.05s, Tw = 5s, T2=T4=0.ls, Kw= 3.1278, Kpe= 0.0121, T1CPSS = 0.1753, T3CPSS =0.2391, T1TCSC = 0.4385, T3TCSC = 0.3457 [4].

Fault simulation is done by considering a three phase fault near to terminals of generator at t=1 sec and it is cleared after 5 cycles (at t=1.1 sec). Variation in rotor speed, rotor angle and

Output power is simulated by using Euler's method for 20 seconds for heavy loading, 12 seconds for normal loading and 6 seconds for light loading. System frequency is 50 Hz.

(1) Light loading (P_m=0.3)

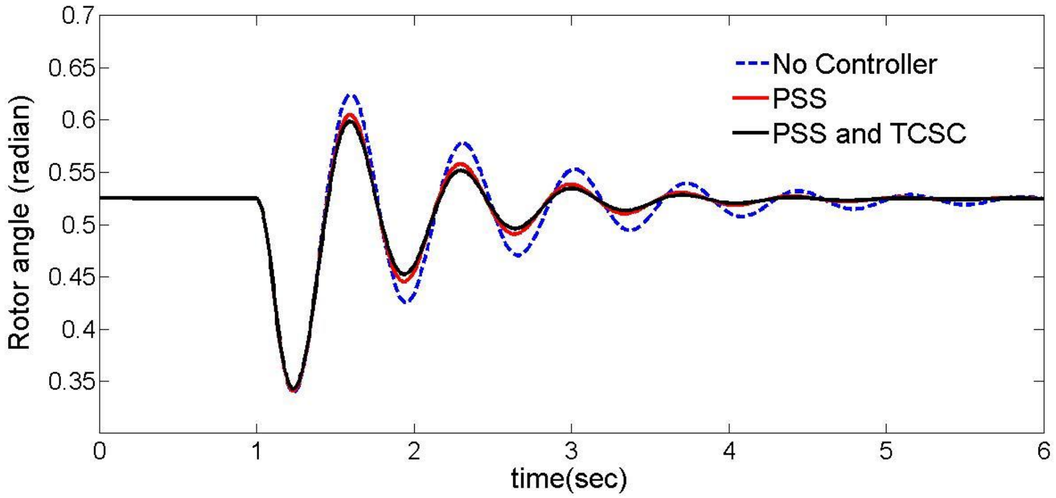

Figure 5.1 Rotor angle response for light loading (Pm=0.3)

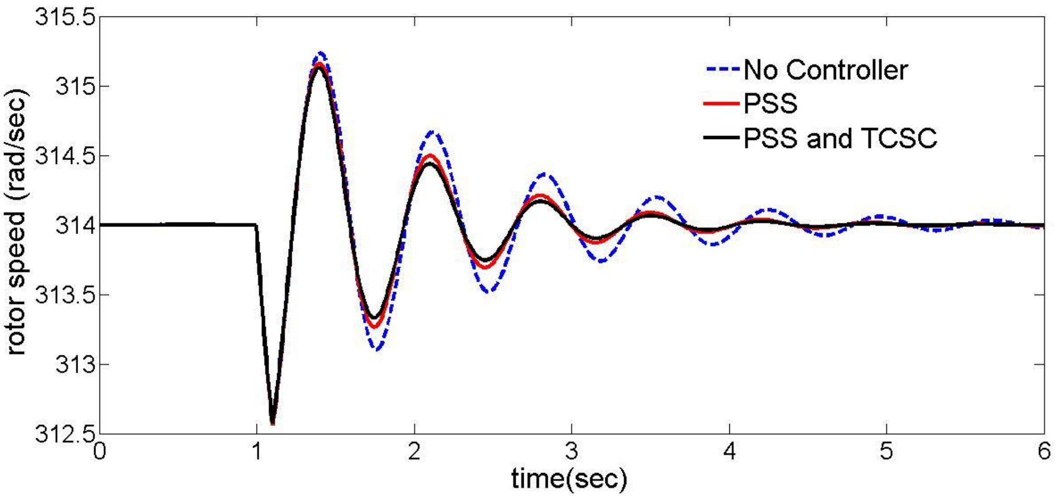

Figure 5.2 Rotor speed response for light loading (Pm=0.3)

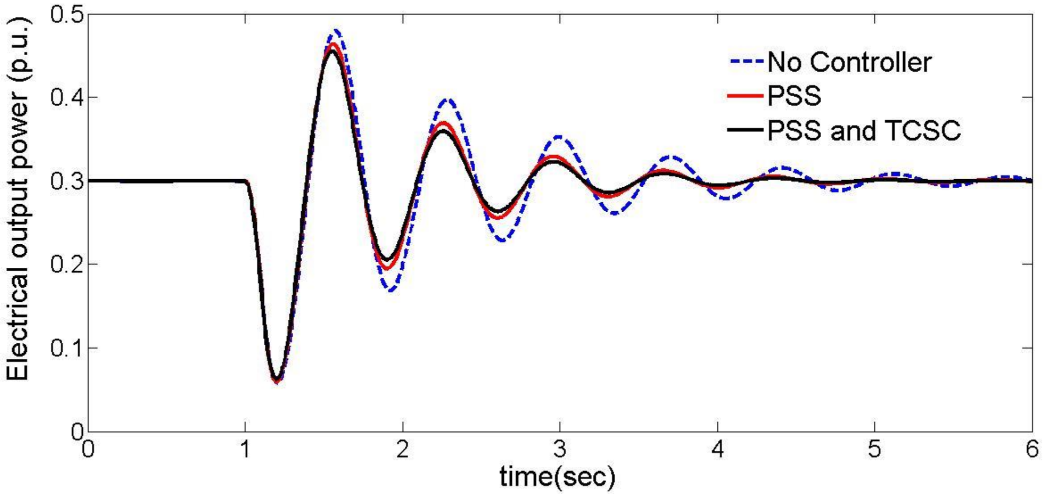

Figure 5.3 Output Power response for light loading (Pm=0.3)

Discussion: - Simulation of synchronous generator connected with TCSC based PSS is performed for light load of Pm=0.3 p.u. and result is compared with system with CPSS (Conventional Power System Stabilizer) and system with no controlled (only AVR).

Initially 0.3 p.u. mechanical power is applied to the generator and at t=1 sec a three phase fault is created, which is cleared after 5 cycles (at t=1.1 for 50 Hz).

(2) Normal Loading (P_m=0.6)

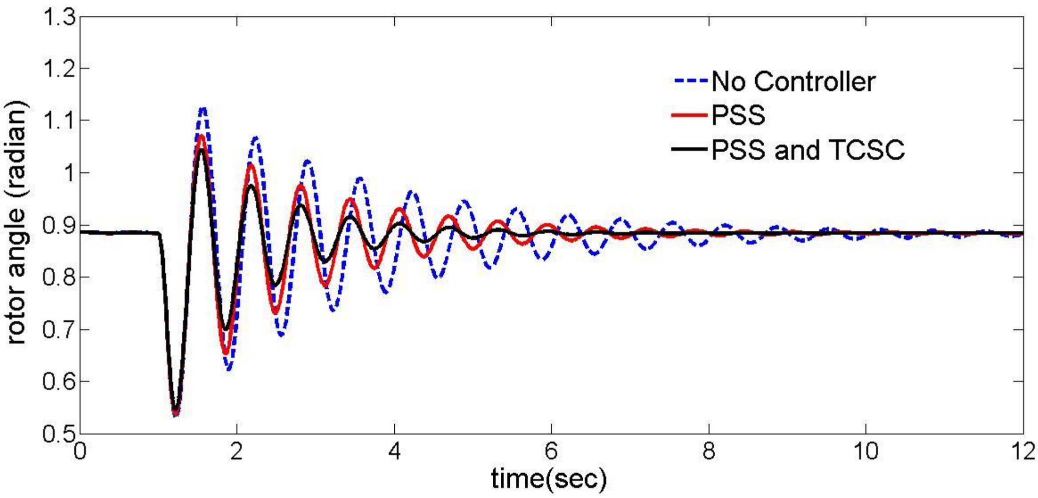

Figure 5.4 Rotor angle response for light loading (Pm=0.6)

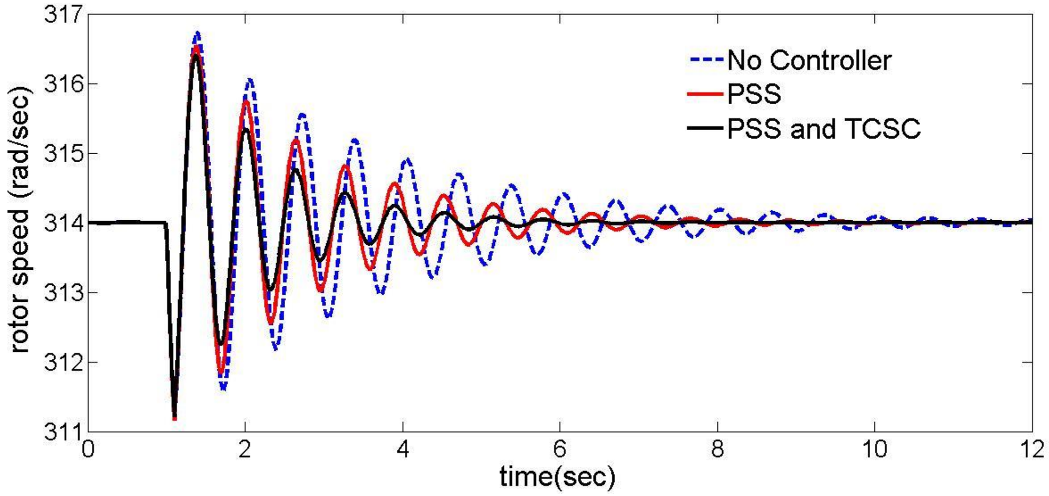

Figure 5.5 Rotor speed response for light loading (Pm=0.6)

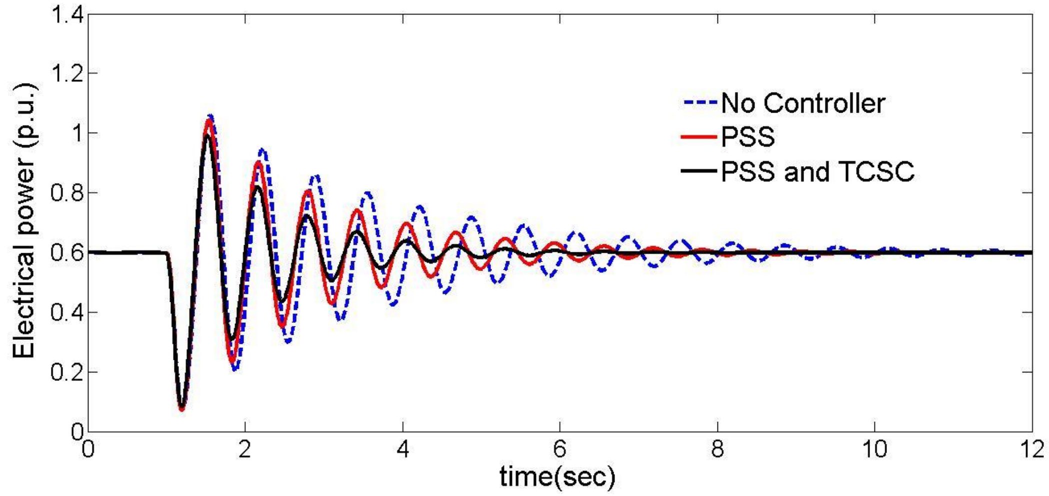

Figure 5.6 Output Power response for light loading (Pm=0.6)

Discussion: -

Simulation of synchronous generator connected with TCSC based PSS is performed for normal load of Pm=0.6 p.u. and result is compared with system with CPSS (Conventional Power System Stabilizer) and system with no controlled (only AVR).

Initially 0.6 p.u. mechanical power is applied to the generator and at t=1 sec a three phase fault is created, which is cleared after 5 cycles (at t=1.1 for 50 Hz).

(3) Heavy loading (P_m=0.85)

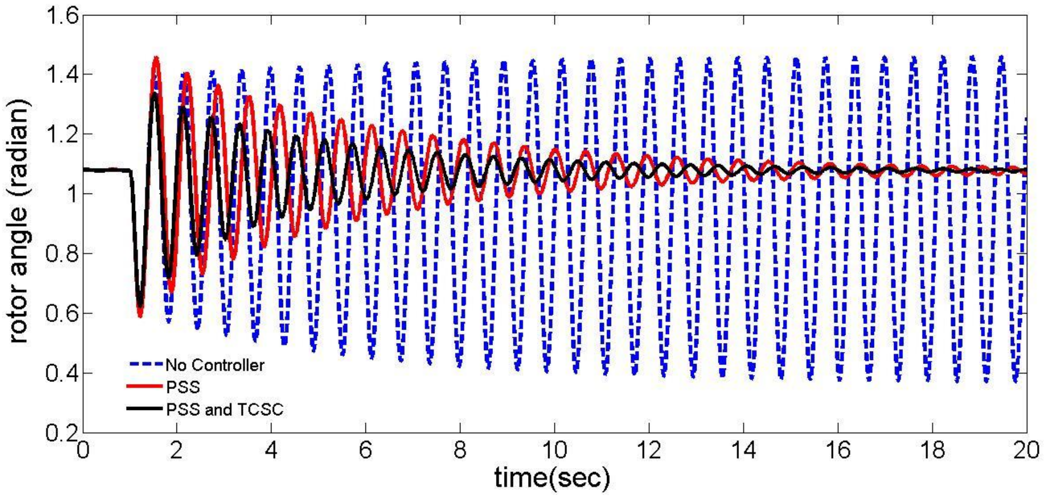

Figure 5.7 Rotor angle response for light loading (Pm=0.85)

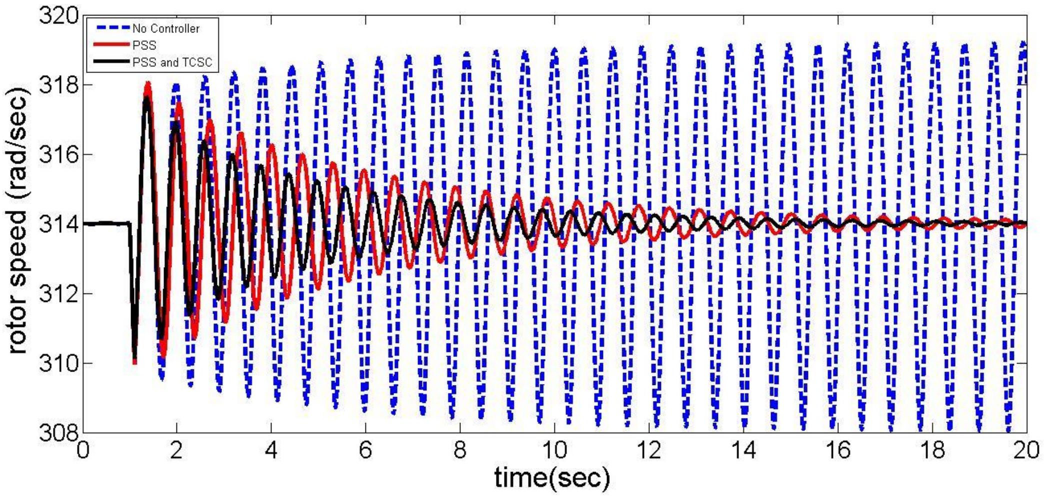

Figure 5.8 Rotor speed response for light loading (Pm=0.85)

Discussion: -

Simulation of synchronous generator connected with TCSC based PSS is performed for normal load of Pm=0.85 p.u. and result is compared with system with CPSS (Conventional Power System Stabilizer) and system with no controlled (only AVR).

Initially 0.85 p.u. mechanical power is applied to the generator and at t=1 sec a three phase fault is created, which is cleared after 5 cycles (at t=1.1 for 50 Hz).

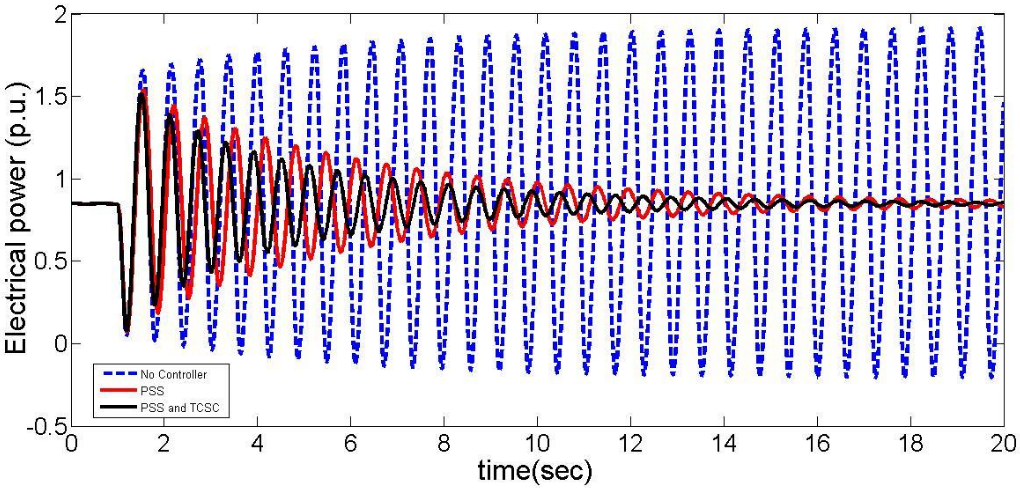

Figure 5.9 Output Power response for light loading (Pm=0.85)

CHAPTER 6

CONCLUSIONS AND SCOPE FOR FUTURE WORK

6.1 Conclusions

In this report, effect of SVC (Static Var Compensator) in a multimachine power system is discussed by using load Newton Raphson load flow method and results are compared with the system with no controller connected to the system. It is observed that SVC improved the

Performance of the system In terms of reduction in the Reactive Power requirement and losses in transmission line. In another chapter, a TCSC (Thyristor Controlled Series Capacitor) based PSS (Power System Stabilizer) is used in a Single Machine Power System to improve the dynamic response of system. A three phase fault is simulated near the synchronous generator terminals for 5 cycles and it is observed that oscillations stability of rotor speed, rotor angle and output power is improved with TCSC based PSS over CPSS (Conventional Power System Stabilizer) and system with no PSS.

6.2 Scope for future work

- Same co-ordination technique can be extended for multimachine system.
- Stabilizers based on STATCOM (Static Compensator) and SSSC (Static Synchronous Series Compensator) can be also be modelled and coordinated with CPSS for more improvement in oscillation stability.
- Advanced optimization techniques can be used for modelling of controllers.

REFERENCES

[1] N. G. Hingorani and L. Gyugyi, "Understanding FACTS: Concepts and Technology of Flexible AC Transmission System". IEEE Press. 2000.

[2] E. Acha,; V.G. Agelidis; O. Anaya-lara and T.J.E. Miller; 'Power electronics control in electrical systems', 2002.

[3] P. Kundur, "Power System Stability and Control", EPRI Power System Engineering Series, Mc Graw-Hill, New York, 1994.

[4] Kundur, P.; Klein, M.; Rogers, G.J.; Zywno, M.S., "Application of power system stabilizers for enhancement of overall system stability," *Power Systems, IEEE Transactions on*, vol.4, no.2, pp.614-626, May 1989.

[5] Ambriz-Perez, H.; Acha, E.; Fuerte-Esquivel, C.R., "Advanced SVC models for Newton-Raphson load flow and Newton optimal power flow studies," *Power Systems, IEEE Transactions on* , vol.15, no.1, pp.129-136, Feb 2000 .

[6] Morsali, J.; Kazemzadeh, R.; Azizian, M.R., "Simultaneously design of PSS3B dual-input stabilizer and TCSC damping controller for enhancement of power system stability," *Electrical Engineering (ICEE), 2012 20th Iranian Conference on*, vol. 2, no. 3, pp.558-563, 15-17 May 2012.`

[7] Chaudhuri, B.; Pal, B., "Robust damping of multiple swing modes employing global stabilizing signals with a TCSC," *Power Engineering Society General Meeting, 2004. IEEE*, vol.5, no.3, pp.1709 Vol.2, 6-10 June 2004.

[8] Tehrani, F.M.; Shahgholian, G.; Pourghassem, H., "Dynamic study and stability analyze of damping cohefision and reactance in TCSC controller connected on optimization SMIB system," *Communication Software and Networks (ICCSN), 2011 IEEE 3rd International Conference on* , vol.5 no.1, pp.270-274, 27-29 May 2011.

[9] Magaji, N.; Mustafa, M.W., "TCSC Damping controller design based on Self-learning fuzzy controller Techniques," *Power Engineering and Optimization Conference (PEOCO), 2011 5th International*, vol.11, no.1, pp.387-391, 6-7 June 2011.

[10] Del Rosso, A.D.; Canizares, C.A.; Dona, V.M., "A study of TCSC controller design for power system stability improvement," *Power Systems, IEEE Transactions on*, vol.18, no.4, pp.1487, 1496, Nov.2003.

[11] Abdel-Magid, Y.L.; Abido, M.A.; Mantawy, A.H., "Robust tuning of power system stabilizers in multimachine power systems," *Power Engineering Society Winter Meeting, 2000. IEEE*, vol.2, no.7, pp.1425, vol.2, 2000.

[12] Wang, H.F.; Swift, F.J., "A unified model for the analysis of FACTS devices in damping power system oscillations. I. Single-machine infinite-bus power systems," *Power Delivery, IEEE Transactions on*, vol.12, no.2, pp.941-946, Apr 1997.

[13] Haque, M.H., "Evaluation of First Swing Stability of a Large Power System With Various FACTS Devices," *Power Systems, IEEE Transactions on*, vol.23, no.3, pp.1144-1151, Aug. 2008.

[14] Xuechun Yu; Khammash, M.; Vittal, V., "Robust design of a damping controller for static Var compensators in power systems," *Power Systems, IEEE Transactions on*, vol.16, no.3, pp.456-462, Aug 2001.

[15] Gibbard, M.J.; Vowles, D.J.; Pourbeik, P., "Interactions between, and effectiveness of power system stabilizers and FACTS device stabilizers in multimachine systems," *Power Engineering Society Winter Meeting, 2000. IEEE*, vol.2, no.12, pp.1532, 2000.

[16] Magzoub, M.A.; Saad, N.B.; Ibrahim, R.B., "Power system stabilizer for single machine in infinite bus based on optimal control methods," *Power Engineering and Optimization Conference (PEOCO), 2014 IEEE 8th International*, vol.23, no.9, pp.313-317, 24-25 March 2014.

[17] Abido, M.A., "Genetic-based TCSC damping controller design for power system stability enhancement," *Electric Power Engineering, 1999. PowerTech Budapest 99. International Conference on*, vol.12, no.6, pp.165, Aug. 29 1999-Sept. 2 1999.

[18] Abido, M. A., and Y. L. Abdel-Magid. "Analysis and design of power system stabilizers and FACTS based stabilizers using genetic algorithms." *14th Power Systems Computation Conference PSCC-2002, Session*. Vol. 14. 2002.

[19] Kumar, B.K.; Singh, S.N.; Srivastava, S.C., "Placement of FACTS controllers using modal controllability indices to damp out power system oscillations," *Generation, Transmission & Distribution, IET*, vol.1, no.2, pp.209-217, March 2007.

[20] Do Bomfim, A.L.B.; Taranto, G.N.; Falcao, D.M., "Simultaneous tuning of power system damping controllers using genetic algorithms," *Power Systems, IEEE Transactions on*, vol.15, no.1, pp.163-169, Feb 2000.

LIST OF PUBLICATIONS

[1] Jayant Sharma and Pravat Kumar Ray, “Modeling of TCSC based Power System Stabilizer in a Single Machine Infinite Bus System", Transactions of the institute of Measurement and Control, Sage, (Communicated).

[2] Jayant Sharma and Pravat Kumar Ray, “Improvement of Steady State Stability in a Multimachine Power System using SVC", Transactions of the institute of Measurement and Control, Sage, (Communicated).