CHAPTER 2

POWER SYSTEM STABILIZER

2.1. INTRODUCTION

Power system stabilizers have been employed for many years to add damping to electromechanical oscillations. They act through the generator excitation system in such a manner that a portion of electrical torque proportional to speed change is generated (Watson Manchur1973- DeMello 1978). Of course, it is easy to say that this is done, and the mechanism varies depending on whether the mode is a local mode or an inter-area mode (Klein et al 1992) Nevertheless, an effective stabilizer does produce a damping torque over a wide range of input frequencies (Larsen 1981) Less efficient stabilizers may only produce a damping torque over a very small frequency range, which leads to problems when system changes cause the system's oscillatory modes to change.

The power frequency and the tie-line power deviations persist for a long duration. In these situations, the governor system may no longer be able to absorb the frequency fluctuations due to its slow response (Elgerd 1970). To stabilize power oscillation, PSS is often employed as an efficient device to raise the damping of electromechanical oscillations in power systems. The power system stabilizer is a supplementary control system, which is often used as part of an excitation control system. The core part of the PSS is to give a signal to the excitation system, creating electrical torques to the rotor, in phase with speed variation, that damp out power oscillations.
In the past decades, the utilization of additional excitation control signals for improving the dynamic stability of power systems has got much attention. Extensive research has been conveyed in many subjects such as the effect of PSS on power system stability, PSS input signals, PSS optimum locations, and PSS tuning techniques. In (DeMello), the concept of synchronous machine stability as affected by excitation control has been tested.

Since the primary function of the PSS is to add damping to the power oscillations, basic control theories have been applied to select the most suitable input signal of PSS. Some readily available signals are generator rotor speed, calculated bus frequency, and electrical power. In (Larsen 1981), the application of PSS utilizing either of speed, frequency or power input signals has been presented. Guidelines were submitted for tuning PSS that enables the user to achieve desired dynamic performance with limited effort. The need for torsional filters in the PSS path for speed input PSS was also discussed. The most PSS controls today use the generator rotor speed as the feedback input signal. They would provide robust damping over a wide range of operating conditions with minimum interaction (Murdoh et al 2000).

The basic function of a PSS is to extend the angular stability of a power system. This is done by providing supplemental damping to the oscillation of synchronous machine rotors through the generator excitation (Asgharian 1994). This damping is provided by an electric torque applied to the rotor that is in phase with the speed variations. The oscillations of concern typically occur in the frequency range of 0.2 to 3.0 Hz, and insufficient damping of these oscillations may limit the ability to transmit power. Fig. 2.1 shows the schematic representation of sample power system.
The distinction between local modes and inter-area modes applies mainly to those systems which can be divided into distinct areas which are separated by long distances. For systems in which the generating stations are distributed uniformly over a geographic area, it would be difficult to distinguish between local and inter-area models from physical considerations. However, a common observation is that the inter-area modes have the lowest frequency and participation from most of the generators in the system spread over a wide geographic area. The PSSs are designed mainly to stabilize local and inter-area modes (Feliachi and Zhang 1988, Hui Ni et al 2002).

The main objective of providing PSS is to increase the power transfer in the network, which would otherwise be limited by oscillatory instability. The PSS also must function properly when the system is subjected to large disturbances. PSS can extend power transfer stability limits which are characterized by lightly damped or spontaneously growing oscillations in the 0.2 to 3.0 Hz frequency range. This is accomplished via excitation control to contribute damping to the system modes of oscillations (Abe and Doi 1983, Zhou et al 1991).
Consequently, it is the stabilizer’s ability to enhance damping under the least stable conditions is important. Additional damping is primarily required under the conditions of weak transmission and heavy load which may occur, while attempting to transmit power over long transmission lines from the remote generating plants or relatively weak tie between systems (Boukarim et al 2000). Contingencies, such as line outage, often rushed such conditions. The Hence system normally has adequate damping can often benefit from stabilizers during such conditions.

2.2. STRUCTURE OF POWER SYSTEM STABILIZER (PSS)

The block diagram of classical power system stabilizer is shown in Fig. 2.2. It consists of a gain block, washout circuit, phase compensation block and a limiter. The major target of providing PSS is to increase the power transfer in the mesh, which would otherwise limit by oscillatory instability. The PSS must also function properly when the system is subjected to large disturbances (Parniani and Lesani 1994).

![Fig. 2.2 Power System Stabilizer](image)

The major target of providing PSS is to increase the power transfer in the mesh, which would otherwise limit by oscillatory instability. The PSS must also function properly when the system is subjected to large disturbances (Parniani and Lesani 1994).
2.2.1 Washout Block

The washout circuit is supplied to eliminate steady-state bias in the output of PSS which will modify the generator terminal voltage. The PSS is expected to respond only to transient variations in the input signal (say rotor speed) and not to the DC offsets in the signal. This is achieved by subtracting from it the low-frequency components of the signal obtained by passing the signal through a low pass filter.

The washout circuit acts essentially as a high pass filter, and it must fall out all frequencies that are of interest. If merely the local modes are of interest, the time constant TW can be selected in the orbit of 1 to 2 minutes. However, if inter-area modes are also to be damped, then Tw must be chosen in the range of 10 to 20 seconds. The higher value of Tw also improved the overall terminal voltage response during system islanding conditions.

2.2.2 Phase Compensation Block

It provides the appropriate phase-lead characteristic to compensate for the phase lag between the exciter input and the generator electrical (airgap) torque. The Fig. 2.3 shows a single first-order block. In practice, two or more first-order blocks may be employed to reach the desired phase compensation. In some cases, second-order blocks with complex roots have been used.

Usually, the frequency range of interest is 0.1 to 3.0 Hz, and the phase-lead network should provide compensation over this entire frequency range. The phase characteristic to be compensated changes with system conditions; so, a compromise is reached, and a feature acceptance for different system conditions is selected. More often than not some under compensation are desirable so that the PSS, in addition to
significantly increasing the damping torque, results in a slight increase of the synchronizing torque.

\[ \text{Power System Stabilizer} \]

\[ \text{Gain} \quad K_{\text{STAB}} \quad \text{Washout} \quad \frac{s T_w}{1 + s T_w} \quad \text{Phase Compensation} \quad \frac{1 + s T_1}{1 + s T_2} \]

Fig. 2.3 Single first order block (PSS)

2.2.3 Gain Block

The stabilizer gain \( K_{\text{STAB}} \) determines the amount of damping introduced by the PSS. Ideally, the gain should be set at a value comparable to maximum damping; however, it is frequently set by other considerations. The stabilizer gain \( K_{\text{STAB}} \) is chosen by analyzing the consequence of a wide range of values. Ideally, the stabilizer gain should be set at a value comparable to maximum damping. Gain shall be fixed to a value which results in satisfactory damping of the critical system mode(s) without compromising the stability of other modes, or transient stability, and which does not cause excessive amplification of stabilizer input signal noise.

2.2.4 Stabilizer Output Limiter

To restrict the level of generator terminal voltage fluctuation during transient conditions, limits are imposed on the PSS output. The result of the two limits is to allow maximum forcing capability while maintaining the terminal potential difference.
within the desired limits (Choi et al 2000). The input for PSS is a change in rotor speed, and the production is controlled voltage for the exciter.

2.3 STATE SPACE MODEL WITH PSS

Chow et al (2004) designed PSSs using root locus design, frequency response development and state space design. In root locus method a PI controller was applied to a voltage regulator. As the proportional gain increased, the closed loop step response became faster and steady state error became smaller, but the oscillation due to the swing mode became less damped. In the frequency-response method, a phase lag-lead controller was used to plot the compensated system frequency response and to find the gain and phase margins. In state space design full-state feedback laws and observers derived from pole placement were used to design the voltage regulator and PSS. Choi et al (2000), Hui Ni et al (2002), Gupta et al (2003, 2005) and Elices et al (2004) used state space design for SMIB and multimachine systems.

2.3.1 Single Machine Connected to Infinite Bus (SMIB) System

A general system configuration for the single machine connected to the large organization is presented in Fig. 2.4. This general scheme is employed for the study of small signal stability study (Kundur 1994).
Fig. 2.4 General configuration of a single machine power system

The general system configuration can be reduced to the Thevenin’s equivalent circuit shown in Fig. 2.5.

\[ Z_{eq} = R_E + jX_E \]

Fig. 2.5 Equivalent circuit of a single machine power system

For any given system condition, the magnitude of the infinite bus voltage \( E_B \) remains constant when the machine is perturbed.

The state-space model of the scheme with PSS can be obtained as follows by using field circuit dynamics and effects of AVR (Kundur 1994).

\[
\Delta v_2 = \frac{pT_W}{I + pT_W} \left( K_{STAB} \Delta \omega_r \right) 
\]

(2.1)

Hence,

\[
p \Delta v_2 = K_{STAB} p \Delta \omega_r - \frac{I}{T_W} \Delta v_2 
\]

(2.1a)
The expression for $p\Delta v_2$ can be written in terms of the state variables as follows,

$$p\Delta v_2 = K_{STAB}\left[ a_{11}\Delta\omega_r + a_{12}\Delta\delta + a_{13}\Delta\psi_{fd} + \frac{I}{2H}\Delta T_m \right] - \frac{I}{T_w}\Delta v_2 \quad (2.1b)$$

$$p\Delta v_2 = a_{51}\Delta\omega_r + a_{52}\Delta\delta + a_{53}\Delta\psi_{fd} + a_{54}\Delta v_2 + a_{55}\Delta v_2 + \frac{K_{STAB}}{2H} \Delta T_m \quad (2.1c)$$

Where

$$a_{51} = K_{STAB}a_{11} \quad a_{53} = K_{STAB}a_{12} \quad (2.2)$$

$$a_{53} = K_{STAB}a_{13} \quad a_{55} = -\frac{I}{T_w}$$

Since $p\Delta v_2$ is not a function of $\Delta v_3$, $a_{54} = a_{56} = 0$. From block 5 of Figure 2.3

$$\Delta v_s = \Delta v_2 \frac{(I + pT_1)}{(I + pT_2)} \quad (2.2a)$$

Hence

$$p\Delta v_s = \frac{T_1}{T_2} p\Delta v_2 + \frac{I}{T_2} \Delta v_2 - \frac{I}{T_2} \Delta v_s \quad (2.2b)$$

Substituting for $p\Delta v_s$, given by equation (2.1b) then

$$p\Delta v_s = a_{61}\Delta\omega_r + a_{62}\Delta\delta + a_{63}\Delta\psi_{fd} + a_{64}\Delta v_1 + a_{65}\Delta v_2 + a_{66}\Delta v_s + \frac{T_1}{T_2} \frac{K_{STAB}}{2H} \Delta T_m$$

Where

$$a_{61} = \frac{T_1}{T_2} a_{51} \quad a_{62} = \frac{T_1}{T_2} a_{52} \quad (2.4)$$
\[ a_{63} = \frac{T_I}{T_2} a_{53} \quad a_{65} = \frac{T_I}{T_2} a_{55} + \frac{I}{T_2} \]

\[ a_{66} = -\frac{I}{T_2} \]

From block 2 of Figure 2.3,

\[ \Delta E_{fd} = K_A (\Delta v_f - \Delta v_I) \]

The field circuit equation, with PSS included becomes,

\[ p \Delta \psi_{fd} = a_{32} \Delta \delta + a_{33} \Delta \psi_{fd} + a_{34} \Delta v_I + a_{36} \Delta v_s \quad (2.5) \]

Where

\[ a_{36} = \frac{\omega_0 R_{fd}}{L_{adu}} K_A \quad (2.6) \]

The complete state space model including PSS can be written as,

\[
\begin{bmatrix}
\Delta \omega_r \\
\Delta \delta \\
\Delta \psi_{fd} \\
\Delta v_1 \\
\Delta v_2 \\
\Delta v_s
\end{bmatrix} =
\begin{bmatrix}
a_{11} & a_{12} & a_{13} & 0 & 0 & 0 \\
a_{21} & 0 & 0 & 0 & 0 & 0 \\
0 & a_{32} & a_{33} & a_{34} & 0 & a_{36} \\
0 & a_{42} & a_{43} & a_{44} & 0 & 0 \\
a_{51} & a_{52} & a_{53} & 0 & a_{55} & 0 \\
a_{61} & a_{62} & a_{63} & 0 & a_{65} & a_{66}
\end{bmatrix}
\begin{bmatrix}
\Delta \omega_r \\
\Delta \delta \\
\Delta \psi_{fd} \\
\Delta v_1 \\
\Delta v_2 \\
\Delta v_s
\end{bmatrix}
\]

\[(2.7)\]

Where
\[ a_{11} = -\frac{K_D}{2H} \]

\[ a_{12} = -\frac{K_I}{2H} \]

\[ a_{13} = -\frac{K_2}{2H} \]

\[ a_{21} = \omega_o = 2\pi f_o \]

\[ a_{32} = -\frac{\omega_o R_{fd}}{L_{fd}} m_1 \dot{L}_{ads} \]

\[ a_{33} = -\frac{\omega_o R_{fd}}{L_{fd}} \left[ 1 - \frac{\dot{L}_{ads}}{L_{fd}} + m_2 \dot{L}_{ads} \right] \]

\[ a_{34} = -b_{32} K_A = -\frac{\omega_o R_{fd}}{L_{ads}} K_A \]

\[ a_{41} = 0 \]

\[ a_{42} = \frac{K_5}{T_R} \]

\[ a_{43} = \frac{K_6}{T_R} \]

\[ a_{44} = -\frac{1}{T_R} \quad (2.8) \]

The K-constants can be written as follows (Kundur 1994).

\[ K_1 = n_1 (\psi_{ado} + L_{ads} \dot{i}_{do}) - m_1 (\psi_{aqq} + \dot{L}_{ads} i_{qo}) \]

\[ K_2 = n_2 (\psi_{aqq} + L_{ads} \dot{i}_{do}) - m_2 (\psi_{aqq} + \dot{L}_{ads} i_{qo}) + \frac{\dot{L}_{ads}}{L_{fd}} i_{qo} \quad (2.9) \]
The above state space model is used in this thesis. The generator and transmission line data are given in Appendix 1.

2.3.2 Multi-machine Power System

Analysis of the practical power system involves the simultaneous solution of equations representing the following:

- Synchronous machines, the associated excitation system, and prime movers
- Interconnecting transmission network Static and dynamic (motor) load
- Other devices such as HVDC converters, static VAR compensators

![Diagram of power system model]

**Fig. 2.6 Structure of the complete power system model**
Differential equations represent the dynamics of the machine rotor circuits, excitation systems, prime mover and other devices. The result is that the complete system model consists of a large number of ordinary differential and algebraic equations (Hsu and Chen 1987, Tse G.T. Tso 1993). The general construction of the perfect model is presented in Fig. 2.6. The formulation of the state equations for small-signal analysis involves the development of linearized equations about an operating point and the elimination of all variables other than the state variables (Lim and Elangovan 1985).

The multimachine system consists of extensive transmission networks, loads, a variety of excitation systems and prime mover models, HVDC links, and static var compensators (Rogers 2000, Simoes Costa et al 1997). Thus the state equations are developed by treating a full range of devices.

The linearized model of each active device is shown in the accompanying pattern,

\[
x_i = A_i x_i + B_i \Delta v
\]

\[
\Delta i_i = C_i x_i - Y_i \Delta v
\]

Where

\( x_i \) are the perturbed values of the individual device state variables

\( i_i \) is the current injection into the network from the device

\( v \) is the vector of network bus voltage
In equations (2.10) and (2.11), \(B_i\) and \(Y_i\) have non-zero elements corresponding only to the terminal voltage of the device and any remote bus voltages used to control the device. The current vector \(i\) has two elements corresponding to the real and imaginary components. Likewise, the voltage vector \(v\) has two elements per bus associated with the device. Such state equations for all the dynamic devices in the system may be combined into the form,

\[
\begin{align*}
\dot{x} &= A_D x + B_D \Delta v \\
\Delta i &= C_D x_i - Y_D \Delta v
\end{align*}
\]  

(2.12)

(2.13)

Where \(x\) is the state vector of the complete system, and \(AD\) and \(CD\) are block diagonal matrices composed of \(Ai\) and \(Ci\) associated with the individual devices.

The interconnecting transmission network is represented by the node equation,

\[
\Delta i = Y_N \Delta v
\]  

(2.15)

The elements of \(y_N\) include the effects of nonlinear static loads. Equating equation (2.13) associated with the devices and Equation (2.14) associated with the network, then

\[
C_D x - Y_D \Delta v = Y_N \Delta v
\]  

(2.16a)

Hence

\[
\Delta v = (Y_N + Y_D)^{-1} C_D x
\]  

(2.16b)
Substituting the above expression for $\Delta v$ in equation (2.12) yields the overall system state equation,

$$\dot{x} = A_D x + B_D (Y_N + Y_D) C_D x$$  \hspace{1cm} (2.17)

$$x = A x$$

Where the state matrix $A$ of the complete system is given by,

$$A = A_D + B_D (Y_N + Y_D)^{-1} C_D$$ \hspace{1cm} (2.18)

Fig. 2.7 Single line diagram of 4-Machine, 10-Bus System

Fig. 2.8 Single line diagram of 10-Machine, 39-Bus System
The single line diagram for 4-Machine, 10-Bus system, and 10-machine, 39-Bus System are shown in Figs. 2.7 and 2.8 respectively. Fig. 2.9 represents the overall excitation system including PSS.

2.4 SELECTION OF PSS PARAMETERS

The overall excitation control system is contrived so as to:

(i) Maximize the damping of the local plant mode as well as inter-area mode oscillations without compromising the stability of other ways;

(ii) Enhance system transient stability;

(iii) Not adversely affect system operation during major system upsets which cause large frequency excursions; and

(iv) Minimize the effects of excitation system malfunction due to component failures.

Fig. 2.9 Block diagram including excitation system and PSS
The block diagram of the PSS used to achieve the desired performance objectives is shown in Fig. 2.9. The last stage in stabilizer design involves the evaluation of its outcome on the overall system functioning. Foremost, the result of the stabilizer on various modes of system oscillations is determined over a broad range of system conditions by applying a low signal stability program (Fleming et al 1981). This includes analysis of the effects of the PSS on local plant models, inter-area modes, and control modes (Arredondo 1997). In particular, it is important to ensure that there are no adverse interactions with the controls of other nearby generating units and devices.

The excitation control systems, designed and describe above provide effective decentralized controllers for the damping of electromechanical oscillations in power systems (Fleming et al 1990). Generally, the resulting design is much more robust that can be achieved through the use of other methods. The overall approach is applied in the acknowledgment of the physical facets of the power system stabilization problem. The method utilized for establishing the characteristics of the PSS in simple and required only the dynamic features of the concerned machines to be modeled in detail. Detailed analysis of the operation of the power system is applied to establish other parameters and to guarantee the sufficiency of the overall operation of the excitation control. The result is a control that enhances the overall stability of the system under different operating conditions (Gibbard 1991).

Since the PSS is tuned to increase the damping torque component for a full range of frequencies, it leads to the damping of all system modes in which the respective generator has a high participation. This includes any new modality that
may emerge as a consequence of varying system conditions. It is possible to meet the requisites for a broad range of system conditions with specified parameters. Here, the effects of stabilizer on various modes of oscillations are determined for a wide range of system conditions using eigenvalue programs. Besides, the outcome of the stabilizer was determined using the discrete domain.

2.5  POWER SYSTEM MODEL

A two-area four-machine interconnected power system with wind farms in Fig. 2.10 is used to design PSS. Each generator is represented by a 5th-state transient model (Kundur 1994).

![Fig. 2.10 Two area four machines power system](image)

The system consists of two similar areas connected by a weak tie. Each area consists of two coupled units, each having a rating of 900 MVA and 20 KV. The generator parameters in per unit on the rated MVA and kV base are as follows.

\[
X_d = 1.8 \quad X_q = 1.7 \quad X_l = 0.2 \quad X_d' = 0.3 \quad X_q' = 0.55
\]

\[
X_d'' = 0.25 \quad X_q'' = 0.25 \quad R_a = 0.0025 \quad T_d0' = 8.0s \quad T_q0' = 0.4s
\]

\[
T_d0'' = 0.3s \quad T_q'' = 0.05s \quad A_{Sat} = 0.015 \quad B_{Sat} = 9.6 \quad \psi_{T1} = 0.9
\]
H = 6.5 (for M1 and M2)  H=6.175 (for M3 and M4)  KD=0

Each step-up transformer has an impedance of 0+j0.15 per unit on 900 MVA and 20/230kV base, and has an off-nominal ratio of 1.0. The transmission system nominal voltage is 230kV. The line lengths are identified in Fig. 2.1. The parameters of the line in per unit on 100 MVA, 230 kV base are,

\[
\begin{align*}
R &= 0.0001 \, \text{pu/km} \\
\chi &= 0.001 \, \text{pu/km} \\
\end{align*}
\]

\[b_C = 0.00175 \, \text{pu/km} \quad (2.22)\]

The system is operating with area 1 exporting 400 MVA to area 2, and the generating units are loaded as,

M1: \( P = 700 \, \text{MW}, \quad Q = 185 \, \text{MVar}, \quad E_t = 1.03 \angle 20.2^\circ \)

M2: \( P = 700 \, \text{MW}, \quad Q = 235 \, \text{MVar}, \quad E_t = 1.01 \angle 10.5^\circ \)

M3: \( P = 719 \, \text{MW}, \quad Q=176\,\text{MVar}, \quad E_t = 1.03 \angle -6.8^\circ \)

M4: \( P = 700 \, \text{MW}, \quad Q=202\,\text{MVar}, \quad E_t = 1.03 \angle -17.0^\circ \)  \( (2.23) \)

The test system consists of two fully symmetrical areas linked together by two 230 KV lines of 220 km length. It was specifically designed in (Klein et al 1992, Kundur 1994), to study low frequency electromechanical oscillations in large interconnected power systems. Despite its small size, it mimics the behavior of typical systems in actual operation very closely. Each area is equipped with two identical round rotor generators rated 20 kV/900 MVA. The synchronous machines have identical parameters (Watson 1973, deMello et al 1978), except for inertias which are \( H = 6.5s \) in area 1 and \( H = 6.175s \) in area 2 (Kundur 1994). Thermal plants having
identical speed regulators are further assumed at all locations, in addition to fast static exciters with a 200 gain (Klein 1992 - Kundur 1994). The load is represented as constant impedances and split between the areas in such a way that area 1 is exporting 413MW to area 2. Since the surge impedance loading of a single line is about 140 MW (Kundur 1994), the system is somewhat stressed, even in steady-state. The reference load-flow with M2 considered.

2.6 SUMMARY

In this chapter, the importance and structure of PSS were studied. In, state space design full state feedback laws and observers derived from pole placement were used to design PSS. The state space design was better than root locus and frequency response methods and is used in the present study.