CHAPTER 3

SYSTEM MODELLING

3.1 INTRODUCTION

Models for power system components have to be selected according to the purpose of the system study, and hence, one must be aware of what models in terms of accuracy and complexity should be used for a certain type of system studies, while keeping the computational burden as low as possible. Selecting improper models for power system components may lead to erroneous conclusions (Hassan Ghasemi 2006). Also one is required to have necessary background knowledge in order to understand the actual process that takes place in the power system in order to design a power system simulation as closely as possible. Setting up a linearized power system model has been a tedious and demanding task earlier. New digital simulators feature automatic functions for this and can export a complete matrix model of the entire system. This considerably improves the reliability of the linear model at the same time allowing the analyst to concentrate on the analysis itself. An important prerequisite is that the structure and the properties of the exported model are apriori. The mathematical models needed for small signal analysis of synchronous machine, excitation system and the lead-lag power system stabilizer are briefly reviewed. The guidelines for the selection of objective function power system stabilizer parameters are also presented.
3.1.1 General Procedure for System Modelling

Setting up a linearized power system model for control design purposes typically involves five of the following consecutive steps (Olof Samuelsson 1997):

- Selecting component models.
- Merging component models into a usually non-linear system model.
- Forming a matrix equation through linearization.
- Eliminating algebraic variables.
- Forming transfer functions.

3.2 BASIC POWER SYSTEM COMPONENTS

The complex non-linear model related to an n-machine interconnected power system, can be described by a set of algebraic differential by assembling the models for each generator, load, and other devices such as controls in the system, and connecting them appropriately via the network algebraic equations. The three essential parts of the system for stability analysis are the Synchronous machine, Automatic Voltage Regulator and Power System Stabilizer.

3.2.1 Synchronous Machine Model

Generally, the generator is a synchronous machine. The electrical characteristic equations describing a three-phase synchronous machine are commonly defined by a two-dimensional reference frame. This involves in the use of Parks transformations (Yao NanYu 1983) to convert currents and flux linkages into two fictitious windings located 90 degree apart. A typical
synchronous machine consists of three stator windings mounted on the stator and one field winding mounted on the rotor. These axes are fixed with respect to the rotor (d-axis) and the other lies along the magnetic neutral axis (q-axis), which model the short-circuited paths of the damper windings.

The system dynamics of the synchronous machine can be expressed as a set of four first order linear differential equations given in Equations (3.1 - 3.4). These equations represent a fourth order generator model suggested by the (IEEE Task Force 1986). These electrical quantities can then be expressed in terms of d and q-axes parameters. All the variables have standard meaning (Padiyar, 1996).

\[
\begin{align*}
\dot{\delta} &= \omega_p S_m \\
\dot{S}_m &= \frac{1}{2H}[-DS_m + T_m - T_e] \\
\dot{E}_q &= \frac{1}{T_{do}}[-E_q^\prime + (X_{d} - X_q^\prime)i_d + E_{fd}] \\
\dot{E}_d &= \frac{1}{T_{dq}}[-E_d^\prime - (X_q - X_q^\prime)i_q]
\end{align*}
\]

where \(S_m = \omega_0 \Delta \delta\)

The expressions for \(T_e\) and \(E_{fd}\) are given by

\[
T_e = E_d^\prime i_d + E_q^\prime i_q + (X_d - X_q^\prime)i_d i_q
\]

\[
\dot{E}_{fd} = \frac{1}{T_e}[-E_{fd}^\prime + K_e (V_{ref} + V_{PSS} - V_i)]
\]
The stator algebraic equations are

\[ E'_q + X_d i_d - R_d i_q = V_q \]  \hspace{1cm} (3.7)

\[ E'_d - X_q i_q - R_q i_d = V_d \]  \hspace{1cm} (3.8)

Figure 3.1 shows the phasor diagram representation of a single machine connected to an infinite bus system shown in Figure 3.6 (Gurunath Gurrala and Indraneel Sen 2010). The expressions for \( \delta_s \), \( E_q' \), \( i_d \), and \( i_q \) can be derived from Figure 3.1.

\[ \delta_s = \tan^{-1} \left[ \frac{P_s (X_t + X_q) - Q_s (R_a + R_i)}{P_s (R_a + R_i) + Q_s (X_t + X_q) + V_s^2} \right] \]  \hspace{1cm} (3.9)

where \( P_s = V_s I_a \cos \phi \)

\( Q_s = V_s I_a \sin \phi \)
From stator algebraic equation, $E_q'$ is given by

$$E_q' = \frac{(X_q + X'_d)}{X_t} \sqrt{V_i^2 - \left( \frac{X_d}{(X_i + X_q)} V_i \sin \delta_S \right)^2} - \frac{X_d}{X_t} V_s \cos \delta_S \quad (3.10)$$

The expression for $i_d$ and $i_q$ are as follows:

$$i_d = BE_q' \cos (\delta_S + \alpha_t) \quad (3.11)$$

$$i_q = GE_q' \sin (\delta_S + \alpha_t) \quad (3.12)$$

For IEEE model 1.1 stator equation is given by

$$E_q' + jE_d' - (R_e + jX_e) (i_q + ji_d) = V_q + jV_d \quad (3.13)$$

For IEEE machine Model 1.1, the constraint for no dynamic saliency is given by $X_q' = X_d'$. The complex terminal voltage can be expressed as

$$V_q + jV_d = (i_q + ji_d) (R_e + jX_e) + E_b e^{-j\delta} \quad (3.14)$$

Separating real and imaginary parts we get

$$V_q = R_e i_q - X_e i_d + E_b \cos \delta \quad (3.15)$$

$$V_d = R_e i_d - X_e i_q + E_b \sin \delta \quad (3.16)$$

The expressions for $i_d$ and $i_q$ are given by

$$i_d = \frac{1}{A} \left[ R_e E_b \sin \delta + (X_q + X_e) (E_b \cos \delta - E_q') \right] \quad (3.17)$$
\[
    i_q = \frac{1}{A} \left[ -R_c (E_b \cos \delta - \dot{E}_q) + (X_d' + X_e) E_b \sin \delta \right]
\]  

(3.18)

where  

\[ A = (X_d' + X_e)(X_q + X_e) + R_c^2 \]

The aforementioned model is non-linear. It clearly indicates all the relationship between different parameters. But the non-linear dynamic model of synchronous machine is too sophisticated to be used directly in AVR and PSS. The equations describing the dynamic of the system must be linearized around the equilibrium point where the system is at rest. The notation “\( \Delta \)” is used to represent the small perturbation of each variable or signal and for linearization of the quantities. Thus, the simplified linear model becomes very important and is also more convenient to use in controller design. The simplified linearized Heffron-Philips model is commonly used (Padiyar 1996). There are six parameters \((K_1, K_2, K_3, K_4, K_5, \text{ and } K_6)\) in the simplified linear model, which depend on the physical parameters of the synchronous machine and the infinite power grid. For the system thus modeled by Heffron-Philips constants considering the external resistance but neglecting the armature resistance, the constants are given by

\[
    K_1 = E_{qo} C_3 - (X_q - X_d') i_{qo} C_1
\]

(3.19)

\[
    K_2 = E_{qo} C_4 + X_q' i_{qo} - (X_q - X_d') i_{qo} C_2
\]

(3.20)

\[
    K_3 = \frac{1}{1 - (X_q - X_d') C_2}
\]

(3.21)

\[
    K_4 = -(X_q - X_d') C_1
\]

(3.22)

\[
    K_5 = -\frac{V_{do}}{V_{to}} X_q C_3 + \frac{V_{qo}}{V_{bo}} X_d' C_1
\]

(3.23)
\[ K_b = -\frac{V_{do}}{V_{to}} X_q C_4 + \frac{V_{vo}}{V_{to}} (1 + X'_d C_2) \]  \hspace{1cm} (3.24)

where \[ E_{vo} = E_{vo}' - (X_q - X'_d) i_{do} \]

\[ C_1 = \frac{1}{A} \left[ R_x E_b \cos \delta_o - (X_q + X_e) E_b \sin \delta_o \right] \]

\[ C_2 = -\frac{1}{A} (X_q + X_e) \]

\[ C_3 = \frac{1}{A} \left[ (X'_d + X_e) R_x E_b \cos \delta_o - (X_q + X_e) E_b \sin \delta_o \right] \]

\[ C_4 = \frac{R_e}{A} \]

### 3.2.2 Automatic Voltage Regulator Model

Automatic Voltage Regulator is a controller that senses the generator output voltage (and sometimes the current) then initiates corrective action by changing the exciter control in the desired direction. For the small scale analysis, a simple thyristor excitation system as shown in Figure 3.2 is considered. The non-linearity associated with the ceiling on the exciter output voltage represented by \( E_f^{\text{max}} \) and \( E_f^{\text{min}} \), which is ignored for small-disturbance studies (Kundur 1994).

![Figure 3.2 Thyristor excitation system with AVR](image_url)
3.2.3 Power System Stabilizer Model

All new synchronous generators are equipped with a PSS, which is the most widely used damping controller. It is a low-cost add-on device to the AVR of the generator and operates by adding a signal to the voltage reference signal. High AVR gain gives good voltage control and increases the possibilities of keeping the generator synchronized at large disturbances, but contribute negatively to damping (DeMello and Concordia 1969). This conflict is mostly solved by limiting the PSS output to ± 5 % of the AVR set point. The trade-off can be solved more elaborately by integrating the AVR and the PSS and use a design that simultaneously takes voltage control and damping into account.

Figure 3.3 Thyristor excitation system with AVR and PSS

Figure 3.3 shows the block diagram representation of PSS along with the excitation system (Kundur 1994). The input to the PSS is derived from the rotor angle deviation (Δω₉). The output of the PSS is the additional voltage signal (Vₚₚₚₛₛ) injected through the AVR. The stabilizer itself mainly consists of two lead-lag filters. These are used to compensate for the phase lag.
introduced by the AVR and the field circuit of the generator. Other filter sections are usually added to reduce the impact on torsional dynamics of the generator, and to prevent voltage errors due to a frequency offset. The lead-lag filters are tuned so that speed oscillations give a damping torque on the rotor. By varying the terminal voltage the PSS affects the power flow from the generator, which efficiently damps local modes. In PSS block, the input signal of PSS is the rotor speed $\omega$. Because it only uses the AC value of these signals, $\omega_r$ can be replaced by $\Delta \omega_r$. The overall transfer function of two stage lead-lag $i^{th}$ PSS is given by

$$V_{PSS_i}(s) = \frac{K}{1+sT} \left[ \frac{1+sT_1}{1+sT_2} \right] \Delta \omega_r(s)$$

(3.25)

### 3.2.4 Complete System Model

Based on the above equations the complete linearized block diagram with AVR and PSS of a Single Machine Infinite Bus (SMIB) is given in Figure 3.4 (Kundur 1994).

![Complete block diagram of SMIB system](image)
The aforementioned block diagram, stabilization of the generator system is equivalent to stabilization of the power angle $\delta$, which means to reduce the oscillation of the rotor. In a short period, the mechanical torque $T_m$ from turbine can be considered as constant because of the high inertia of turbine system. The key to increase the stability of the system is to control $T_e$ in order to generate more damping. From the above diagram, the maximum damping can be got when $\Delta T_e$ changes in phase with $\Delta \omega_r$. However, the amplitude of $\Delta T_e$ is also need to be taken into consideration. If the amplitude is too large, the damping also will decrease. So, it cannot be too large. Hence, we use frequency response method to adjust its phase and use root locus method to control its amplitude. According to the above block diagram, the parameters that we can adjust are in AVR block and PSS block. AVR block is used to control the output voltage of the generator. Its goal is to make the output voltage track quickly the reference voltage. So, its parameters have usually been fixed before PSS is equipped in the whole control system. Thus, we only have to adjust the parameters in PSS block.

3.3 PROBLEM FORMULATION

A problem well defined is a problem half solved. It is argued that in order to tackle a complex problem domain the basic thing is to construct a well-structured problem formulation, i.e. a "representation". Representations are analyzed as systems of distinctions, hierarchically organized towards securing the survival of an agent with respect to the situation.

3.3.1 Objective Function

The main objective is to design a PSS to minimize the power system oscillations after a large disturbance, so that the power system stability is improved. For analysis purpose number of objective functions can be used
among which the below mentioned single objective and multi-objective functions are used in this research.

3.3.1.1 Single Objective Function

The low frequency oscillations are affected by the parameters like rotor speed deviation, power angle deviation and the line power. Thus minimizing any one or all of the above deviations could be chosen as the single objective. Among the three parameters rotor speed deviation has more impact on damping the low frequency oscillations. Minimization of the integral of sum of the squares of the rotor speed deviation signal $\Delta \omega_r$ is considered as the objective function (Sumathi et al 2007) and is expressed as

$$ J = \int_0^\infty \left[ \Delta \omega_r(t) \right]^2 dt \quad (3.26) $$

This objective function reflects the small steady state errors, small overshoots and oscillations. In the above equation, $\Delta \omega_r$ denotes the rotor speed deviation for a set of controller parameters that represents the parameters to be optimized. The time-domain simulation is carried out for a particular time period in order to calculate the objective function. Minimization of this objective function will improve the system response in terms of the settling time and overshoots.

3.3.1.2 Multi-Objective Function

During an unstable condition, the diminishing rate of the power system oscillation is determined by the highest real part of the eigenvalue (damping factor) in the power system and the magnitude of each oscillation mode is determined by its damping ratio. Hence, the objective function
naturally contains both the damping ratio and the damping factor in the formulation for the optimal setting of PSS parameters.

- The closed-loop modes are specified to have some degree of relative stability. In this case, the closed loop eigenvalues are constrained to lie to the left of a vertical line corresponding to a specified damping factor. The parameters of the PSS may be selected to minimize the following objective function $J_1$ (Abido and Abdel Magid 2002).

$$J_1 = \sum_{j=1}^{NP} \sum_{\sigma_j \in \Sigma_{\sigma}} \left( \sigma_0 - \sigma_j \right)^2$$  \hspace{1cm} (3.27)

where, $\sigma_i$ is the real part of the $i^{th}$ eigenvalue, and $\sigma_0$ is a chosen threshold. The value of $\sigma_0$ represents the desirable level of system damping. This level can be achieved by shifting the dominant eigenvalues to the left of $s=\sigma_0$ line in the s-plane. This also ensures some degree of relative stability. The relative stability is determined by the value of $\sigma_0$. This will place the closed-loop eigenvalues in a sector in which $\sigma_i \leq \sigma_0$ as shown in Figure 3.5.

- To limit the maximum overshoot, the parameters of the PSS may be selected to minimize the following objective function $J_2$ (Mukherjee and Goshal 2007) :

$$J_2 = \sum_{j=1}^{NP} \sum_{\zeta_j \in \Sigma_{\zeta}} \left( \zeta_0 - \zeta_j \right)^2$$  \hspace{1cm} (3.28)

where $\zeta_i$ is the damping ratio of the $i^{th}$ eigenvalue. This will place the closed-loop eigenvalues in a wedge-shape sector in
which \( \zeta_i \geq \zeta_0 \) as shown in Figure 3.5. \( NP \) is the total number of operating points for which the optimization is carried out.

- An eigenvalue based multi-objective function \( J \) reflecting the combination of damping factor \( (J_1)\) and damping ratio\( (J_2)\) with different weights is considered as follows:

\[
J = \sum_{j=1}^{NP} \sum_{\sigma_j, \sigma_o = \sigma_j} (\sigma_o - \sigma_j)^2 + \alpha \times \sum_{j=1}^{NP} \sum_{\zeta_j, \zeta_o = \zeta_j} (\zeta_o - \zeta_j)^2
\] (3.29)

where \( \alpha \) is the weighing factor of the objective function. By minimizing \( J \), all the closed loop system poles should lie within a D-shaped sector are shown in Figure 3.5 in the negative half plane of the \( j\omega \) axis for which \( \sigma_i < 0 \) and \( \zeta_i > \zeta_{\text{min}} \).

---

**Figure 3.5 Region of eigenvalue location**

**3.3.2 Inequality Constraints**

A stabilizer is designed by suitable time constants \( T_{wi}, T_{1i}, T_{2i}, T_{3i}, T_{4i} \), and the stabilizer gain \( K_{Si} \) (Sumathi et al 2007). The design problem can be formulated as the following constrained optimization problem, where the constraints are the PSS parameter bounds. If all the closed loop poles are located to the left of the contour, then the constraints on the damping factor
and the real part of rotor mode eigenvalues are satisfied and a well damped small disturbance response is guaranteed.

\[
\begin{align*}
K_{Si}^{\text{min}} & \leq K_{Si} \leq K_{Si}^{\text{max}} \\
T_{1i}^{\text{min}} & \leq T_{1i} \leq T_{1i}^{\text{max}} \\
T_{2i}^{\text{min}} & \leq T_{2i} \leq T_{2i}^{\text{max}} \\
T_{3i}^{\text{min}} & \leq T_{3i} \leq T_{3i}^{\text{max}} \\
T_{4i}^{\text{min}} & \leq T_{4i} \leq T_{4i}^{\text{max}} \\
T_{wi}^{\text{min}} & \leq T_{wi} \leq T_{wi}^{\text{max}}
\end{align*}
\]  

(3.30)

3.3.3 Fitness Function

The fitness function is used to transform the objective function value into a measure of relative fitness (Manisha and Nikos 2010). The fitness function transforms the value of objective function to a nonnegative. The mapping is required whenever the objective function is to be minimized as the lower objective function values correspond to fitter individuals. In this study, fitness function transformation is linear. The transformation offsets the objective function, which is susceptible to rapid convergence.

3.4 DESCRIPTION OF TEST SYSTEMS

3.4.1 Single Machine Infinite Bus Test System

This system under study is one machine connected to infinite bus system through a transmission line having resistance \( R_e \) and inductance \( X_e \) (Gurunath Gurrala and Indraneel Sen 2010) through a transformer. Different types of single machine infinite bus test system models have been reported in the literature depending upon the specific application. Figure 3.6 shows the diagrammatic representation of single machine infinite bus system specified in Gurunath and Indraneel Sen (2010). The system data is given in
Appendix 1. IEEE model 1.1 is used to model the synchronous generator with thyristor type excitation system.

![Diagram](image)

**Figure 3.6 One machine to infinite bus system**

### 3.4.2 Western System Coordinated Council Test System

Western System Coordinated Council (WSCC) is a three-machine nine-bus system which is shown in Figure 3.7 is documented in (Anderson and Fouad 1977). This is one of the test systems considered for stability analysis that includes three generator and three large equivalent loads connected in a meshed transmission network through transmission lines. The generators are dynamically modeled with the classical equivalent model. IEEE standard excitation, neglecting the saturation of the exciter is considered for each generator model. Otherwise, these machines can be equipped with simple commonly used Type-AC8B AVR. The machine in each area is not equipped with PSS. The dynamics of the system are described by a set of non-linear differential equations. For the purpose of controller design these equations are linearized around the nominal operating conditions. Figure 3.7 shows the diagrammatic representation of WSCC test system. For analysis purpose, the system data is taken from Anderiou (2004) and is given Appendix 2.
3.4.3 Two-area Test System (TATS)

Two-area Test System (TATS) is an asymmetrical four-machine eight-bus power system. The dynamic equivalent of that realistic power system is as shown in Figure 3.8. The system is clearly split into two-areas, one comprising generators 1 and 2 and the other comprising generators 3 and 4. The generators are rated at 900 MVA and 20 kV, with connection to the network through a 20/230 kV step-up transformer. The nominal system is operating with Area 1 exporting 400 MW to Area 2. From Figure 3.8 (Kashki et al 2010) the electrical loads 967 MW and 1767 MW from the system are static loads and supplies equal active power. Load 1 can be varied in the range [1140 - 1540] MW while Load 2 can be varied in the range [1400 - 1800] MW. Results of the initially performed modal analysis (Gegov 1996) identified three electromechanical modes in the system, which include two local oscillatory modes (between generators 1 and 4 and between generators 2 and 3, respectively) and an inter-area mode (generators 1 and 4 oscillating against generators 2 and 3). It is assumed that all the four generators are provided with static excitation systems. IEEE type ST1 model of the static
excitation system is used. The generators 1 and 2 are located in Area I while the generators 3 and 4 are located in Area II.

![Two-area Test System Diagram](image)

**Figure 3.8 Two-area Test System**

The corresponding dynamic model consists of generators, governors, static exciters, PSS and non-linear voltage and frequency dependent loads. Although a simple network, it has very interesting dynamics and provides an example for the assessment of AVR or PSS performance. This power network is specifically designed to study low frequency electromechanical oscillations in large interconnected power systems. Despite the small size of this power network, it mimics very closely the behavior of typical systems in actual operation (Klein et al 1991). It is specifically designed to study low frequency electromechanical oscillations in large interconnected power systems. System data is taken from (Kundur 1994) and is given in Appendix 3.

### 3.4.4 New England Test System (NETS)
New England Test System (NETS) is a 39-bus standard for testing new methods. It represents a greatly reduced model of the power system in New England. This IEEE 39-bus system is well known as 10-machine New-England Power System. Synchronous machines are modeled by two-axis model. Generator 1 represents the aggregation of a large number of generators. It has been used by numerous researchers to study both static and dynamic problems in power systems. The 39-bus system has 10 generators, 19 loads, 36 transmission lines and 12 transformers. The 39-bus system is organized into three areas. Area 3 contains two portions of the network which are not directly connected. This 10M39B (10 Machine 39 bus system) system documented in Mishra et al (2006) is a widely recognized New England test system, used in many different studies in the past. The data for 10M39B system was obtained from Pai (1989) and is given in Appendix 4. Figure 3.9 shows the one line diagram of New England Test System.

Figure 3.9 New England Test System

3.4.5 South/Southeast Brazilian Test System
The next well-known system is the seven – bus five-machine equivalent of the unstable South/Southeastern Brazilian system (SBTS) as pictured in Figure 3.10. The study system is a slightly modified 7-bus equivalent of the model used in the initial planning studies of the Itaipu generation and AC transmission complex. The Itaipu generator is connected to the Southeast region (represented by a static load together with a large synchronous motor) through a series compensated 765 kV bus. An intermediate 765 kV bus is connected to a 500 kV transmission ring containing three other hydro stations: S. Santiago, S. Segredo and Foz do Areia. The AVR models used in the original system were disregarded in favor of a simpler first-order model which is common to all machines. All loads are of the constant impedance type. System data is taken from Martins and Lima (1989) and is given in Appendix 5.

![Figure 3.10 South/Southeast Brazilian Test System](image)

The model analysis of the small Brazilian test system indicates that there are two interarea modes. Mode 1 is due to the Southeast (SE) equivalent
system oscillating against the Itaipu Generator, Mode 2 is due to the South system (represented by Santiago, Segredo and Areia) oscillating against the Southeast system together with the Itaipu Generator. The system also has two local modes of oscillations within the south system: Mode 3 consisting of Areia and Segredo oscillating against Santiago, and Mode 4 consisting of Area oscillating against Segredo.

3.5 TESTING STRATEGY

The Conventional and ACO techniques are applied to design the PSS problem and the coding are written on MATLAB 7.4 package and executed on Core2Duo, 2.1 GHz, and 3GB RAM processor.

3.6 CONCLUSION

The basic modelling of power system components is described in this chapter. The complete system model is also presented in this chapter. The equality and inequality constraints, objective function, and fitness function are described. Five standard test systems considered for stability analysis and for evaluating the performance of the proposed methods are also specified with the diagrammatic representations. Among the five standard test systems only the classical GA approach is applied in SMIB Test System. Other meta-heuristic approaches are implemented on the four multi-machine test systems described in this chapter.