PARAMETER TUNING OF POWER SYSTEM STABILIZER USING META-HEURISTIC ALGORITHMS

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A

Project report

Submitted to the

Department of Electrical and Electronics Engineering

National Institute of Technology Sikkim

By

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B.tech *4th* year

(Enrolment number. B150129ee)

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-:: Acknowledgement ::-

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ABSTRACT

In this dissertation, the design of a conventional power system stabilizer (CPSS) is carried out using the Symbiotic organism search (SOS) to optimize its gain and time constants. The proposed optimization of CPSS parameters is considered with an objective function based on eigenvalue shifting to guaranteeing the stability of nonlinear plant for a wide range of operating conditions of the single-machine infinite-bus power system model. The system performance with SOS optimized CPSS (SOS-CPSS) controller is compared with a particle swarm optimization based CPSS (PSO-CPS S) controller. The robustness is tested by considering several operating conditions to establish the superior performance with SOCPSS over the PSO-CPSS.

Keywords: *Eigenvalues, Power system, PSS, SOS, Small Signal stability.*

CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS

A	State matrix
B	Input matrix
C	Output matrix
c_1	Positive cognitive constant
c_2	social component
D	Damping coefficient
E_d	d-axis component of machine voltage
E_{fd}	Equivalent excitation voltage
E_q	q-axis component of machine voltage
$E_q^{'}$	q-axis component voltage behind transient Reactance
Gi^{best}	The current global best position of the i^{th} particle
I_d	d -axis component of current
K	Gain
P_e	Electrical power output
Pi^{best}	The current best position of the i^{th} particle
T_1, T_2	Time constants of Lead-Lag controller
$T^{'}{d0}$	d-axis transient open-circuit time constant
$T^{'}{d0}$	d-axis transient open-circuit time constant
V_i	The current velocity of the i^{th} particle
X_d	d-axis synchronous reactance
$X_d^{'}$	d-axis transient reactance
X_i	The current position of the i^{th} particle
X_q	q-axis synchronous reactance
δ	Rotor angle of synchronous machine

LIST OF TABLES

CHAPTER 1

Introduction

1.1 General

Electric power systems which include generation, transmission and distribution are the largest and most expensive man-made system ever made. These days power systems are characterized by large complex inter-connections and extensive control mechanisms which provide optimum resource utilization, operating economy and system reliability. With the interconnection of power systems there is a stability problem. The stability analysis of this complex system is of great importance for ensuring its smooth and secure operation. Some of the major outages in recent times like Puerto Rico in 2016, Bangladesh in 2014 [1], India in July 2012 [2], Brazil in 2001 [3], etc highlights the problems associated with secure operation of power system. However, modern power systems operate in extremely stressed conditions with controls, complex interconnections, increased automations, renewable integration and electronic equipment. Also, the power quality is of primary importance. Hence, newer concepts have come up in the power system stability studies like voltage stability, frequency stability, inter-area oscillation, etc. The power system is non-linear and dynamic system, with operating parameters continuously changing. So stability is, a function of the initial operating condition and the nature of the disturbance. Power systems are continually subjected to small disturbances in the form of load and generation changes. Also, with the integration of renewable sources like solar and wind to the grid, the analysis has become more complicated due to the unpredictable or stochastic behavior of these energy sources. The system must be in a position to be able to adjust to the changing conditions and operate satisfactorily. The system must also withstand large disturbances which may even cause structural changes due to isolation of some faulted elements.

1.2 Classification of Power System Stability

1.2.1 Rotor angle stability

Rotor Angle Stability or simply Angle Stability refers to the ability of the synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. Angle stability depends on the ability of each synchronous machine to maintain equilibrium between electromagnetic torque and mechanical torque. Under steady state, there is equilibrium between the input mechanical torque and output electromagnetic torque of each generator, and its speed remains a constant. Under a disturbance, this equilibrium is upset and the generators accelerate (or decelerate) according to the mechanics of a rotating body. Depending on the nature of the disturbance, rotor angle stability is further categorized as follows:

1.2.1.1 Small Signal angle stability

It is the ability of power system when subjected to small disturbance. If the disturbance is small enough so that the nonlinear power system can be approximated as a linear system then the study, then the study of rotor angle stability of that particular system is called as small disturbance angle stability analysis. These could be due to switching on or off of small loads small generator tripping etc.

1.2.1.2 Transient stability

It is the ability of the system to remain in synchronism when subjected to large disturbances. Large disturbances can be faults, switching on or off of large loads, large generators tripping etc. When a power system is subjected to large disturbances they will lead to large excursions of generator rotor angles. Since there are large rotor angle changes the power system cannot be approximated by a linear representation like in the case of small-disturbance stability.

1.2.2 Voltage stability

Voltage Stability is the ability of a power system to maintain steady state voltages at all buses in the power system under normal operating conditions and after being subjected to a disturbance [1]. Here, the normal operating voltages (conditions) should be between the acceptable limits of voltages for the system. A system enters a state of voltage instability when a disturbance, increase in load demand, or change in system conditions cause a progressive and uncontrollable drop in voltage. The main factor causing this instability is the inability of the power system to meet the demand of reactive power i.e. for the system to be stable the reactive power generated should be equal to the reactive power consumed by the system.

Fig. 1.1. is the pictorial representation of classification of power system stability.

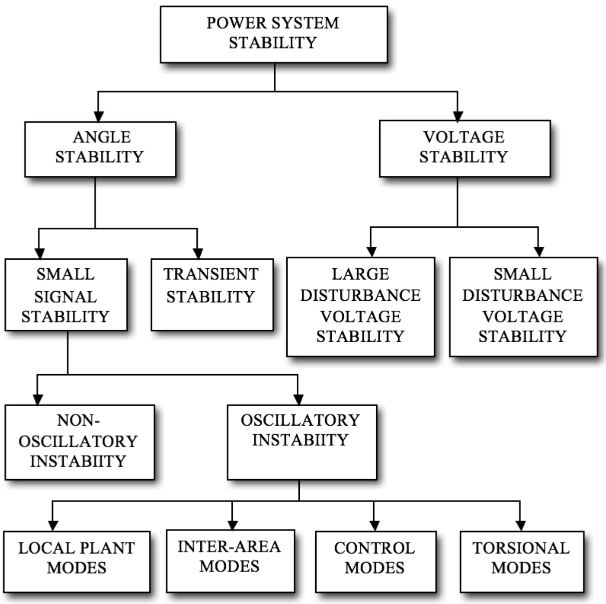


Fig.1.1 Classification of power system stability

As it was discussed earlier that power system is a highly complex and non-linear system and it has always suffered from low frequency oscillations ranging from 0.2 to 2 Hz [1]. These troublesome dynamic oscillations arise due to various disturbances like load variations, line outages and also some other factors like characteristics of various control devices and electrical connections between the components. Due to these low frequency oscillations power-transfer capability of power systems get reduced. Moreover they are associated to the rotor angle of the synchronous machines which continues to grow causing loss of synchronism if adequate damping is not provided to the system. So power system stabilizers are most commonly used to damp out the system oscillations and also to enhance the damping of electromechanical modes. These oscillations can be divided into two main important categories: firstly the local mode of oscillations, ranging from 0.8 to 2 Hz and inter area mode of oscillations ranging from 0.2 to 0.8 Hz. These phenomena can be examined by eigenvalue analysis and can be solved with the help of power system stabilizer. Suitably tuned parameters of PSS introduce a component of electrical torque which is in phase with the generator rotor angle deviations and can damp out low frequency oscillations. Inputs to the stabilizer can be rotor frequency, rotor speed deviation and accelerating power, etc. High gain automatic voltage regulators are used in excitation systems which invites low frequency oscillations in the system. If adequate damping is not provided then system may collapse. Therefore, this dissertation mainly focuses on small signal stability analysis. Understanding of small signal stability analysis is briefly explained below.

1.3 Small Signal Stability

It is the ability of the power system to maintain synchronism under small disturbances which are continually occurring in the system due to variations in loads and generations. These disturbances are considered to be sufficiently small which enables us to linearize the system equations around the initial operating point for the purpose of analysis. The time frame of small signal stability is of the order of 10-20 seconds after a disturbance.

When the system is in steady-state, equilibrium is maintained between the input mechanical torque (T_m) and the output electrical torque (T_e) of each machine of the system and their speed remain constant. If the system is perturbed, the equilibrium ceases to exist and the rotors of the machines either accelerate or decelerate. This change in electrical torque following a perturbation can be resolved in two components:

$$\Delta T_e = T_s \Delta\delta + T_d \Delta\omega \tag{1.1}$$

Where, T_S is the synchronizing torque coefficient and T_D is the damping torque coefficient. Instability that may occur can be of two types:

1) A non oscillatory, steady increase of rotor angle due to lack of sufficient synchronizing toque, or
2) Rotor oscillations of increased amplitude due to lack of sufficient damping toque.

These conditions have been illustrated in Fig 1.2 and 1.3 below.

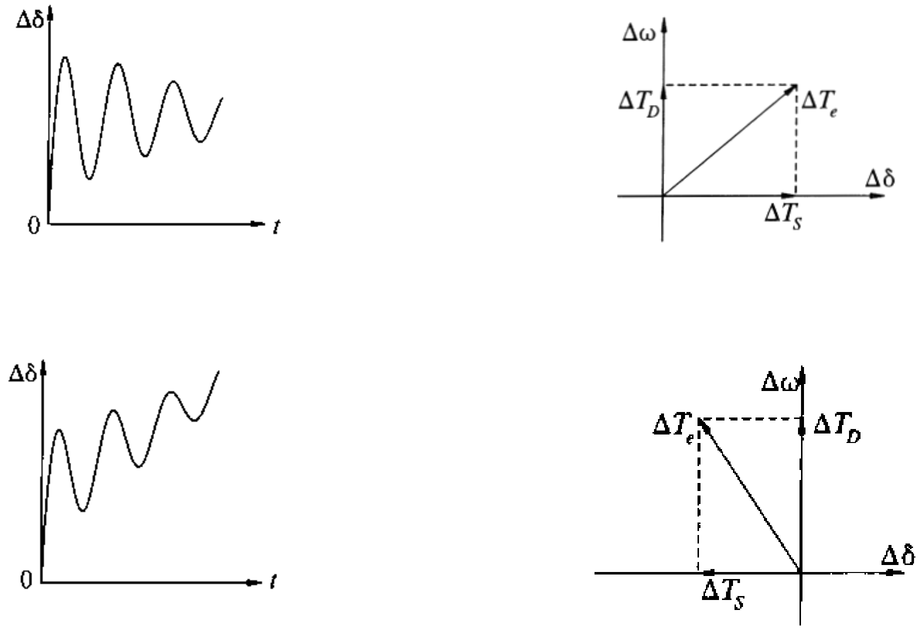


Fig. 1.2 Oscillations with constant field voltage [2]

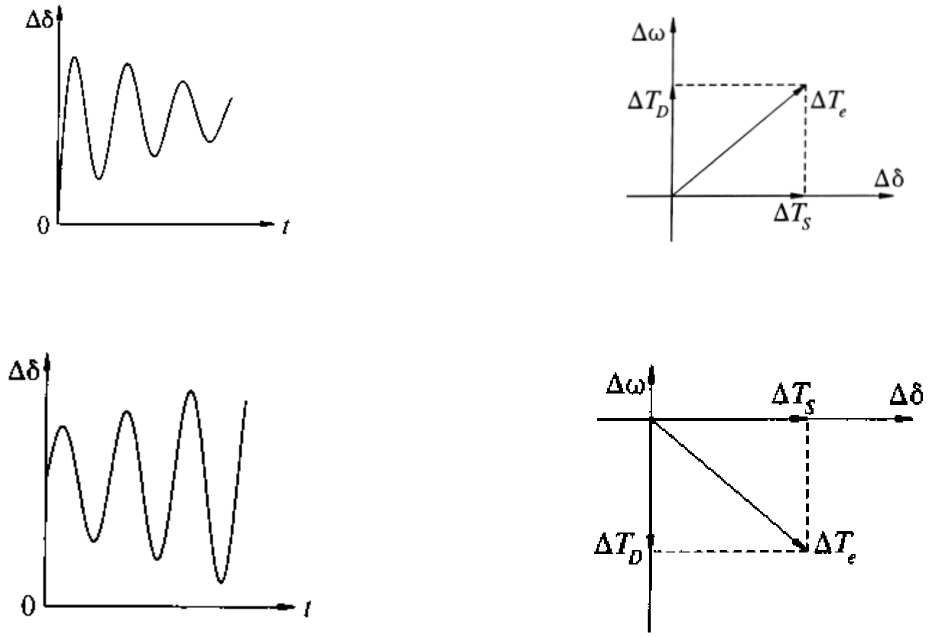


Fig. 1.3 Oscillations with excitation control [2]

Practically in modern power systems, small signal stability is largely a problem of insufficient damping of oscillations. The different types of oscillation which occurs in the power system are addressed in [4] and are of concern in terms of stability of the system:

- *Local Modes* are associated with the swinging of units at a generating station with respect to the rest of the power system. These oscillations are in the range of 0.8 to 2 Hz.

- *Inter-area Modes* are associated with the swinging of many machines in one part of the system against machines in other parts. Weak tie lines between two or more areas of closely coupled machines cause inter-area oscillations. These oscillations are in the range of 0.2 to 0.8 Hz.
- *Control Modes* are associated with the generating units and other control mechanisms. These are caused by poorly tuned exciters, governors, SVCs, HVDC converters, etc.
- *Torsional Modes* are associated with the turbine-generator shaft system rotational components.

1.4 Dissertation Objective

The main objectives of dissertation are:

- To develop the overall system matrix of the system and perform Eigen Value Analysis.
- To analyze the effect on the system stability under diverse operating conditions.
- To perform proper tuning of the parameters of Power System Stabilizer (PSS).

1.5 Dissertation Organization

This dissertation is organized in six chapters. The current chapter i.e, **Chapter 1** discusses briefly about the power system stability and its various classifications. It describes the small signal stability in detail and also the different types of oscillations associated with it. Also the motivation and dissertation objectives are discussed in this chapter

Chapter 2 presents the literature review of modeling of synchronous system, the power system stabilizer, etc. Various books, journals and conferences which were referred to or studied during the course of this dissertation have been provided here.

Chapter 3 presents the Small Signal Stability Analysis of SMIB and the exciter model used along with the results. The references which were used have been mentioned at the end.

Chapter 4 presents the Tuning of Power System Stabilizer; the algorithms which have been used to tune the PSS have been mentioned along with the results.

Chapter 5 presents the Conclusion and future work of the project.

1.6 References

[1] Kabir, M. A., Sajeeb, M. M. H., Islam, M. N., & Chowdhury, A. H. (2015, December). Frequency transient analysis of countrywide blackout of Bangladesh Power System on 1st November, 2014. In Advances in Electrical Engineering (ICAEE), 2015 International Conference on (pp. 267-270). IEEE.

[2] Romero, J. J. (2012). Blackouts illuminate India's power problems. IEEE spectrum, 49(10).

[3] Liu, Y., Zhihuai, S., & Xiao, C. (2011). Analyzing principle of protection through the blackout in Brazil power grid on February 4, 2011. Autom Electr Power Syst, 35(8), 12-15.

[4] Kundur, P. (1994). Power system stability and control (Vol. 7). N. J. Balu, & M. G. Lauby (Eds.). New York: McGraw-hill.

CHAPTER 2

Literature Review

This chapter is broadly divided into various sections. The following section discusses about the literatures studied for modeling of synchronous machine, assessment of small signal stability of SMIB, Power System Stabilizer (PSS) and various optimization techniques that has been used previously for tuning of its parameters. Also a new meta-heuristic optimization technique named Particle Swarm Optimization (PSO) [13] has been discussed in detail, which has been used in this dissertation to tune the PSS parameters.

2.1 Small Signal Stability of Single Machine Infinite Bus concepts and issues

There are several literatures on stability and the dynamics of power system which are referred for understanding, modelling and simulating purposes. Most of them, especially [1-3] have provided the concepts of power system stability and modeling of conventional synchronous machines, loads, transmission lines, excitation systems, power system stabilizer, etc. [2] and [4] provided a better mathematical approach in deriving the mathematical equations to perform the stability analysis in single-machine systems. However, this dissertation is targeted to investigate the system stability due to the effect of small signal stability in a single-machine infinite bus system.

2.2 Modeling of synchronous machine

It is necessary to model the Single-machine system. [1-4] have provided a very detailed mathematical model for small signal as well as transient analysis of synchronous machine dynamic models. These literatures have explained the basic theory and provided systematic development of dynamic models and their use in single-machine simulation.

2.3 PSS and Optimization Techniques for the tuning of control parameters

The primary function of the power system stabilizer (PSS) is to add damping to the generator rotor oscillations by controlling its excitation using auxiliary stabilizing signal(s) [1]. The PSS produces a component of electrical torque which is phase with the rotor speed deviations [5]. Extensive literature on application of PSS to improve the system stability by damping the critical oscillation can be found in [5-9]. In [5] it has been concluded that although designing of PSS is mainly to provide damping to local modes and inter-area mode, other modes may also be influenced by the PSS like the torsional modes, control modes such as the exciter mode associated with excitation system and field circuit. It has also stated that the control design and tuning procedures of PSS have a very significant influence on their effectiveness in enhancing the overall system stability. The significance of the phase-lead compensation, wash-out filter and stabilizer gain on the effectiveness of PSS has been also described. A fundamental study on the nature of inter-area oscillations in power systems has been presented in [6]. Here, the effects of the system structure, generator modeling, excitation type, and system loads are discussed in detail. Both small signal and transient stability analyses have been used to determine the characteristics of the system.

2.3.1 Suitable optimization technique for tuning of PSS parameters

The problem of PSS parameter tuning is a multimodal optimization problem, which restricts the use of several optimization techniques. Also, conventional optimization methods that make use of derivatives and gradients, in general, are not able to locate or identify the global optimum as the objective function is highly multi-modal. Several literatures could be found where PSS parameters are tuned using classical optimization techniques using heuristic and metaheuristic approach [10-11]. In these references, different optimization techniques have been used and results have been compared with the other techniques on the basis of robustness, exploration capability, computational burden and time, etc. In [10] Particle-Swarm-Optimization (PSO) technique has been used and the performance is examined under different disturbances, loading conditions and system configurations.

In this dissertation, a new meta-heuristic algorithm called Symbiotic organism search (SOS) [12] for tuning PSS parameters in a SMIB has been presented. State space representation of the system is done for performing small signal stability analysis. There are various methods available for small signal stability analysis, such as Eigen value analysis, synchronizing and damping torque analysis, frequency response and residue based analysis. Behaviour of the system has been studied with the help of eigenvalue analysis because of its simplicity and efficiency over other techniques. The main advantage of eigenvalue technique is that it can easily identify various electromechanical modes which are otherwise very difficult to obtain with other mentioned techniques. Also, the oscillations can be characterized very easily and accurately. Results so obtained by this algorithm is compared with PSO which shows that this proposed technique enhances overall stability and mitigates the problem related to low frequency oscillations.

2.4 Refrences

[1] Kundur, P. (1994). Power system stability and control (Vol. 7). N. J. Balu, & M. G. Lauby (Eds.). New York: McGraw-hill.

[2] Sauer, P. W., & Pai, M. A. (1998). Power system dynamics and stability. Urbana.

[3] Padiyar, K. R. (2008). Power system dynamics. BS Publ.

[4] Ranjan, R. K. (1992). Parametric approach to steady-state stability analysis of power systems (Doctoral dissertation, University of Illinois at Urbana-Champaign).

[5] Shah, R., Mithulananathan, N., & Lee, K. Y. (2012, July). Design of robust power oscillation damping controller for large-scale PV plant. In Power and Energy Society General Meeting, 2012 IEEE (pp. 1-8). IEEE.

[6] Kundur, P., Klein, M., Rogers, G. J., & Zywno, M. S. (1989). Application of power system stabilizers for enhancement of overall system stability. IEEE Transactions on Power Systems, 4(2), 614-626.

[7] Klein, M., Rogers, G. J., & Kundur, P. (1991). A fundamental study of inter-area oscillations in power systems. *IEEE Transactions on Power Systems*, *6*(3), 914-921.

[8] Klein, M., Rogers, G. J., Moorty, S., & Kundur, P. (1992). Analytical investigation of factors influencing power system stabilizers performance. *IEEE Transactions on Energy Conversion*, *7*(3), 382-390.

[9] Ghosh, A., Ledwich, G., Malik, O. P., & Hope, G. S. (1984). Power system stabilizer based on adaptive control techniques. *IEEE transactions on power apparatus and systems*, (8), 1983-1989.

[10] Abido, M. A. (2002). Optimal design of power-system stabilizers using particle swarm optimization. IEEE Transactions on Energy conversion, 17(3), 406-413.

[11] Goldberg (2016). Genetic Algorithms in Search, Optimization and Machine Learning. Pearson.

[12] Cheng, Min-Yuan, and Doddy Prayogo. "Symbiotic organisms search: a new metaheuristic optimization algorithm." *Computers & Structures* 139 (2014): 98-112.

[13] Kennedy, James. "Particle swarm optimization." Encyclopedia of machine learning (2010): 760-766.

CHAPTER 3

Small Signal Stability Analysis of SMIB

3.1 Modelling of synchronous machine

While modelling a synchronous machine, different ways of representation, conventions and notations are followed in the available literature. Hence, at the outset the notations and conventions used for representing a synchronous machine should be clear. In this study, IEEE standard (1110-1991) “IEEE guide to synchronous machine modelling” has been followed for representing the synchronous machine [1].

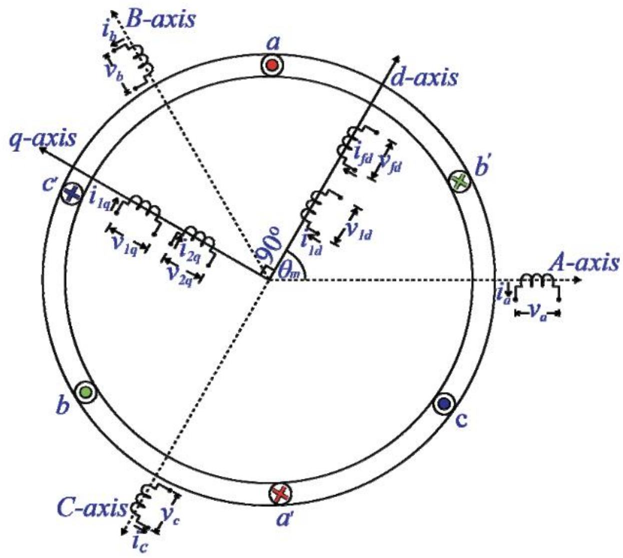


Fig.3.1. Representation of synchronous machine.

The schematic diagram in Fig 3.1 shows the orientation of the coils, polarities assumed, and the rotor position frame. It is a three-damper-winding model, where the stator circuit consists of three-phase armature windings (a-b-c) whose axes are 120 electrical degrees apart and carries alternating current. The rotor circuit consists of the field winding and the damper or amortisseur winding. The field winding is connected to direct current source and produces magnetic field, which induces alternating voltages in the armature winding. For the purpose of identifying the synchronous machine characteristics and for ease of modelling and calculation of parameters, two axes are defined:

- The direct axis (d-axis), centered magnetically in the center of north pole;
- The quadrature axis (q-axis), 90 electrical degrees ahead of the d-axis.

The position of the rotor with respect to the stator is measured by the angle θ_m or simply θ between the q-axis and the magnetic axis of phase *a* winding.

Rotors are often provided with damper windings or amortisseurs. These windings are short-circuited and they provide damping to the oscillations when synchronism is lost during periods of transient. Under steady-state conditions, the field current is the only rotor current that exists in the field winding. However, during any transient condition, the synchronous machine is pulled out of synchronism – as there will be relative motion between the rotor and stator (hunting effect). The damper winding provides flux which compensates the transient effect and the machine returns back to synchronism.

While performing the small signal stability analysis on the detailed model of the synchronous machine (two axis model) with IEEE Type I exciter, the transient effect are taken into consideration while the sub-transient effect is neglected [2].

The small-perturbation behaviour of the power system in the vicinity of a steady-state operating point can be described to first order by a set of linear, time-invariant (LTI) differential equations in the state space form:

$$\dot{X} = AX + BU \tag{3.1}$$

Where the *N*-dimensional state vector *X* represents the perturbations of the system state variables from their nominal values at the given operating condition, and the vector U represents perturbations of the system inputs such as voltage reference, desired real power or load demands. The numerical values of the matrices *A* and *B* depend on the operating condition as well as on the system parameters.

Differential Equations

$$\frac{d\delta}{dt} = \omega - \omega_s \tag{3.2}$$

$$\frac{dE_q'}{dt} = \frac{1}{T_{do}'}\left(E_q' + (X_d - X_d')I_d - E_{fd}\right) \tag{3.3}$$

$$\frac{d\omega}{dt} = \frac{\omega_s}{2H}\left(T_m - \left(E_q{'} I_q + \left(X_q - X_d{'}\right) I_d I_q + D\left(\omega - \omega_s\right)\right)\right) \tag{3.4}$$

3.2 Modelling of exciter

Excitation system provides the current required for the field winding of a synchronous generator to produce the rated terminal voltage at the generator terminals. The basic blocks that are involved in the excitation system [2] is shown in Fig. 3.2.

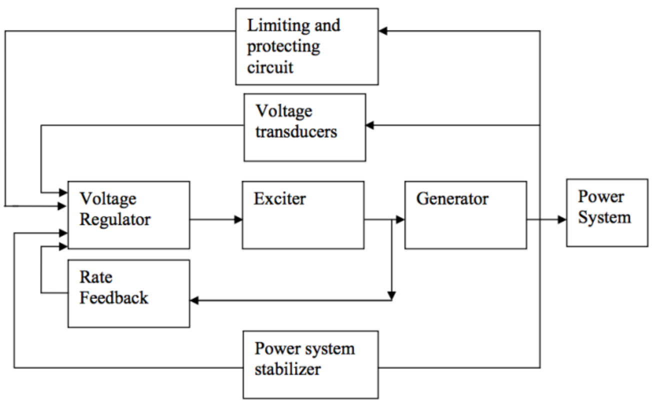


Fig.3.2 Excitation system block diagram

Exciter can be of three types DC exciter, AC exciter and Static exciter and are discussed below.

DC exciter: In this type of exciter a separately or self excited DC generator driven by a motor or connected to the same shaft as that of the main generator rotor is used. In case of separately excited DC generator the field winding of the DC generator is energised through a permanent magnet AC generator, the three-phase out of which is converted to DC through rectifiers. Example of DC excitation system is IEEE type DC1A [3], [4]. This type of excitation was widely used up to 1960 but now-a-days AC excitation or static excitation is being used. For older generating stations where DC excitation is still used the voltage regulator alone is replaced with electronic regulators.

AC exciter: In this type of exciter the AC generator whose armature is mounted on the same shaft as that of the main generator, with its field stationary, is used for supplying field current to the main generator field winding. The output of AC exciter generator is converted to DC through rotating rectifiers, as the armature is now rotating at the main generator rotor speed, and the output is directly connected to the main field winding. The filed of the AC exciter generator itself is energised through a pilot permanent magnet AC generator whose three-phase output is converted to DC through rectification. Example IEEE type AC1A.

Static exciter: In this exciter the output of the main synchronous generator is converted from AC to DC through static rectification and then the output is supplied to the main generator field winding through slip rings. Example IEEE type ST1A. Fig. 3.3 represents the block diagram of static exciter.

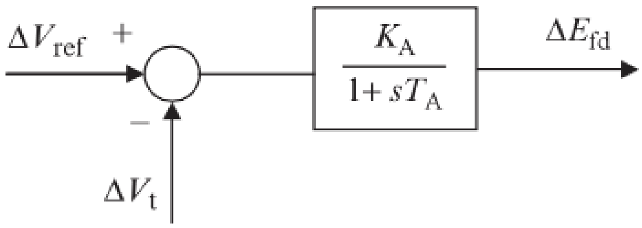


Fig.3.3 Static exciter block diagram

The equation governing this exciter is given by (3.5)

$$\dot{E}_{fd} = -\frac{E_{fd}}{T_A} + \frac{K_A}{T_A}\left(V_{ref} - V_t + V_s\right) \tag{3.5}$$

3.3 k_1-k_6 constants [1]

A single machine connected to an infinite bus is chosen to analyse the local (plant) mode of oscillation in the 1- to 3-Hz range [5]. A flux-decay model is linearized with E_{fd} as an input, and the model so obtained is put in a block diagram form. Then a fast-acting exciter between ΔV_t and ΔE_{fd} is introduced in the block diagram. In the resulting state-space model, certain constants called the K1-K6 are identified. These constants are functions of the operating point. The state-space model is then used to examine the eigenvalues, as well as to design supplementary controllers to ensure adequate damping of the dominant modes. The real and imaginary parts of the electromechanical mode are associated with the damping and synchronizing torques, respectively.

The single machine connected to an infinite bus through an external reactance X_e and resistance R_e is the widely used configuration with a flux- decay model and stator resistance equal to zero. No local load is assumed at the generator bus. Fig 3.4 shows SMIB system [1] to be studied.

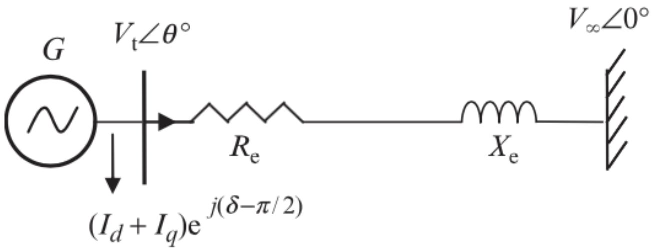


Fig.3.4 Single machine infinite bus system.

The dynamics of the machine is given by (3.6)-(3.9), with E_{fd} being treated as an input.

$$\Delta \dot{E}_q' = \frac{-1}{K_3 T_d'}\Delta E_q' - \frac{K_4}{K_3 T_d'}\Delta\delta + \frac{1}{T_d'}\Delta E_{fd} \tag{3.6}$$

$$\Delta\dot{\delta} = \omega_s \Delta\nu \tag{3.7}$$

$$\Delta\dot{\nu} = \frac{-K_2}{2H}\Delta E_q' - \frac{K_1}{2H}\Delta\delta - \frac{D\omega_s}{2H}\Delta\nu + \frac{1}{2H}\Delta T_m \tag{3.8}$$

$$\Delta\dot{E}_{fd} = \frac{-1}{T_A}\Delta E_{fd} - \frac{K_A K_5}{T_A}\Delta\delta - \frac{K_A K_6}{T_A}\Delta E_q' + \frac{K_A}{T_A}\Delta V_{ref} \tag{3.9}$$

Constant $K_1 - K_6$ are often called Demello-Concordia constant and are given below:

$$K_1 = \frac{1}{\Delta_e}[\, I_q V_\infty (X_d' - X_q)\{(X_q + X_e)\sin\delta - R_e\cos\delta\} + V_\infty\{(X_d' - X_q)I_d - E_q'\}\{(X_d' + X_e)\cos\delta + R_e\sin\delta\}\,]$$

$$K_2 = \frac{1}{\Delta_e}[\, I_q\Delta_e - I_q(X_d' - X_q)(X_q + X_e) - R_e(X_d' - X_q)I_d + R_e E_q'\,]$$

$$K_3 = \frac{1}{(1 + ((X_d - X_d')(X_q + X_e)/\Delta_e)}$$

$$K_4 = \frac{V_\infty(X_d - X_d')}{\Delta_e}[\,(X_q + X_e)\sin\delta - R_e\cos\delta\,]$$

$$K_5 = \frac{1}{\Delta_e}[\frac{V_d}{V_t}X_q\{R_e V_\infty\sin\delta + V_\infty\cos\delta(X_d' - X_e)\} + \frac{V_q}{V_t}X_d'\{R_e V_\infty\cos\delta - V_\infty(X_q + X_e)\sin\delta\}]$$

$$K_6 = \frac{1}{\Delta_e}\left[\frac{V_d}{V_t} X_q R_e - \frac{V_d}{V_t} X'_d(X_q + X_e)\right] + \frac{V_d}{V_t}$$

The equations (3.6)-(3.9) can be represented by the block diagram shown in Fig 3.5, commonly known as Heffron-Phillips model [1].

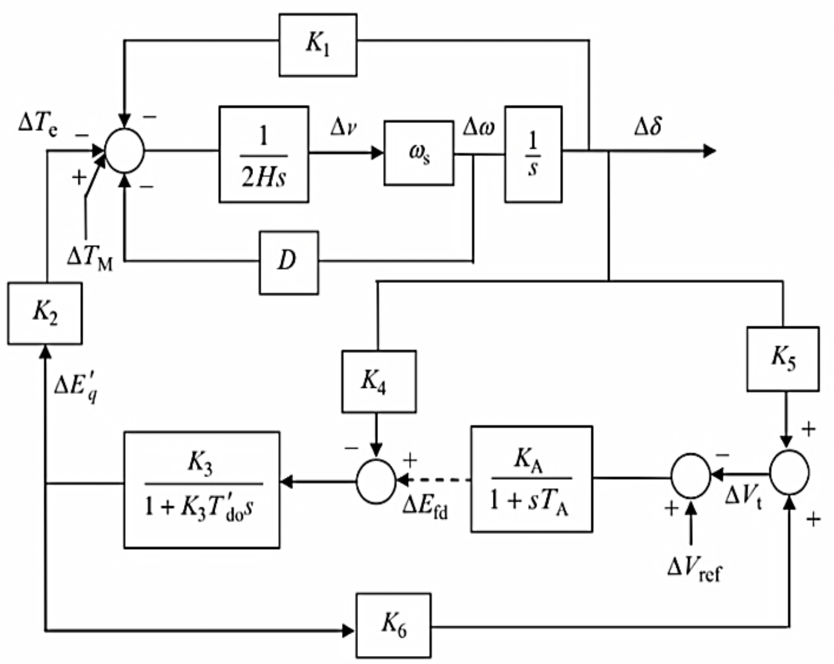


Fig.3.5. Heffron-Phillips model for SMIB [1].

3.4 Results and discussions

The line diagram of the single-machine infinite-bus power sys- tem as in Fig 3.4 and with the system, data are as in Appendix. The generator speed is sensed from the shaft and applied as input to the PSS and output of the PSS is added to the AVR at the junction of reference voltage. Here, the test power system is considered to be operated within the range of reactance of the transmission line as in Fig 3.4, which is represented in (3.10).

$$0.5 < X_e < 0.9 \tag{3.10}$$

The operating point of power system covered as above encompasses all operating conditions and constituting a set of different plants (operating conditions). Here, for system analysis, only five plants have been considered as shown in **Table 3.2**. These five plants are represented in terms of line reactance in p.u and associated eigenvalue, damping ratio and frequency of oscillations. The preferred damping ratio is >0.1 and the eigenvalues should lie in the left-hand side of the s-plane to meet the stability condition. In this section, the nature of plants of the SMIB power systems has been analysed using eigenvalue analysis technique. The total number of plants as defined by (3.2) with step size of 0.1, results to be 5 plants. The algorithm used for calculating and plotting of eigenvalue for 5 plants is mentioned in **Table 3.1**.

Table 3.1 Pseudo code for finding out of eigenvalue for different operating conditions of SMIB

```
Clear all
Define fault & fault clearing time
   for i = 0.5:0.1:0.9
         X_e = 0.5  (as in Eq. (3.10))
         Load SMIB data with initial conditions
         Load SOS-CPSS parameters for system with BA-CPSS
         Calculate System matrix A_sys matrices for SMIB system
         Calculate eigenvalue Plot real & imaginary part of eigenvalue & hold on
   end
```

Table 3.2 Eigenvalue, damping ratio and oscillatory frequency of the Electro-mechanical modes for Plant 1–5 without PSS

Power system model	Line reactance	Mode	eigenvalue	State	Damping ratio	frequency
Plant 1	0.5	#1	-2.5933±8.4992i	$\Delta E_q'$	0.29184	1.3527
		#2	**-0.0823 ±7.0601i**	$\Delta v, \Delta\delta$	0.011656	1.1236
Plant 2	0.6	#1	-2.4327±9.4671i	$\Delta E_q'$	0.24888	1.5067
		#2	**-0.2304±6.2351i**	$\Delta v, \Delta\delta$	0.036927	0.99235
Plant 3	0.7	#1	-2.4589±10.1236i	$\Delta E_q'$	0.23603	1.6112
		#2	**-0.1940±5.7201i**	$\Delta v, \Delta\delta$	0.033896	0.91038
Plant 4	0.8	#1	-2.4949±10.6060i	$\Delta E_q'$	0.22898	1.688
		#2	**-0.1496±5.3686i**	$\Delta v, \Delta\delta$	0.027855	0.85444
Plant 5	0.9	#1	-2.5231±10.9843i	$\Delta E_q'$	0.22387	1.7482
		#2	**-0.1142±5.1072i**	$\Delta v, \Delta\delta$	0.022355	0.81284

From the Table 3, it can be seen that as the value of X_e is increased the corresponding eigenvalue (mode #2) tends to move towards origin i.e., the eigenvalue tends to move towards the right-hand side (RHS) of s-plane. In this case, where, the system is not equipped with PSS. In 'Conventional PSS', the stability of a system can be guaranteed if the eigenvalues associated to electromechanical mode lie in the D-shape sector of the s-plane. Hence to enhance the overall system stability that requires the optimization of controller parameters and the next chapter will deal with the tuning of PSS parameters.

3.5 References

[1] Sauer, Peter W., and Mangalore Anantha Pai. Power system dynamics and stability. Vol. 101. Upper Saddle River, NJ: Prentice hall, 1998.

[2] Kundur, P. (1994). Power system stability and control (Vol. 7). N. J. Balu, & M. G. Lauby (Eds.). New York: McGraw-hill.

[3] IEEE Task Force, "Current usage and suggested practices in power system stability simulations for synchronous machines", *IEEE Trans. On Energy Conversion*, Vol. EC-1, No. 1, 1986, pp. 77-93.

[4] A. Blondel, "The two-reaction method for study of oscillatory phenomena in coupled alternators," *Revue Generale de L Electricite*, Vol. 13, pp.235-251, February 1923, March 1923.

[5] Rogers, Graham. *Power system oscillations*. Springer Science & Business Media, 2012.

Chapter 4
Tuning of Power System Stabilizer

So far the discussion was regarding the linearized model of the SMIB system under different operating condition and also investigation was done to study the effects on small signal stability. The focus of analysis now shifts to a stabilizing device called the Power System Stabilizer (PSS) [1]. The main function of the PSS is to damp out the system oscillations by providing additional damping to the synchronous machine by controlling its excitation using auxiliary stabilizing signal(s) [1]. In this chapter, first the modelling of two-stage PSS is performed, which is followed by implementation of a new optimization technique for tuning the parameters of the PSS. Later, the PSS is integrated to the system model and the effect of PSS on system stability in damping out the electromechanical oscillations is studied and the results obtained are compared between different optimization techniques.

4.1 Components of Power System Stabilizer

During periods of transient, it has been observed that the voltage regulator introduces negative damping to the system [2]. In order to offset this effect and to improve the system damping in general, artificial means of producing torque in phase with the speed deviation are introduced. Stabilizing signals are introduced to the excitation system at the summing junction where the reference voltage and the signal produced from the terminal voltage are added to obtain the error signal, which is fed to the regulator-exciter system. This has been shown in **Fig. 4.1.**

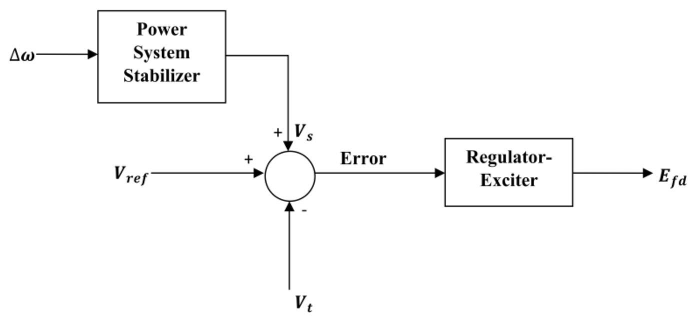


Fig 4.1 Schematic diagram of the stabilizing signal from speed deviation

The basic block diagram of the single-stage Power System Stabilizer is provided in **Fig. 4.2.** It consists of three blocks: one phase compensation block, a signal washout filter block and a gain.

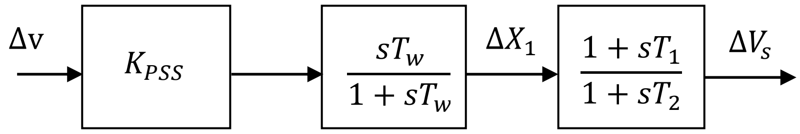


Fig 4.2 Block diagram of single-stage PSS

The phase-compensation block provides the appropriate phase-lead characteristic to compensate for the phase lag between the exciter input and the electrical torque. These blocks are practically used to achieve the desired phase compensation. The requirement of the phase-lead block is to provide compensation over the oscillation frequency range i.e. 0.2 to 2 Hz.

The signal washout filter block acts as a high pass filter, and the time constant T_w is high enough to allow signals associated with oscillations in ω_r to pass unchanged. Without the washout filter, any steady change in speed would modify the terminal voltage. Hence, it allows the PSS to respond only to the changes in speed. The value chosen for T_w is insignificant and can be anywhere between 1 to 20 seconds. In this dissertation this value was chosen as 10 seconds.

The stabilizer gain K_{PSS}determines the amount of damping introduced into the system. The gain should be set to a value which corresponds to maximum damping. The PSS gain is an important factor as the damping provided by the PSS increases in proportion to an increase in the gain up to a certain critical level, after which the damping begins to decrease with further increase of PSS.

4.2 Modeling of Power System Stabilizer

From the block diagram given in Fig. 4.2, the following linearized equations can be derived:

$$\Delta X_1 = \frac{sK_{PSS} T_w}{1 + sT_w} \Delta v \tag{4.1}$$

$$\Delta V_s = \frac{1 + sT_1}{1 + sT_2} \Delta X_1 \tag{4.2}$$

Where, $\Delta v = \frac{\Delta \omega_i}{\omega_s}$ and ω_s is the synchronous speed.

Using Eqn. (4.1) to (4.2), the linearized model of the PSS model is obtained, and state equations of PSS are given below:

$$\frac{dX_1}{dt} = \frac{-X_1}{T_w} + K_{pss}\left[\frac{K_2}{2H}\Delta E'_q - \frac{K_1}{2H}\Delta\delta - \frac{D\omega_s}{2H}\Delta v + \frac{1}{2H}\Delta T_m\right] \tag{4.3}$$

$$\frac{dV_s}{dt} = \frac{X_1}{T_2} - \frac{V_s}{T_2} + \left[\frac{T_1 X_1}{T_2 T_w} - \frac{K_{pss} T_1 K_2}{2HT_2}\Delta E'_q - \frac{K_1 T_1 K_{pss}}{2HT_2}\Delta\delta - \frac{\Delta\omega_s K_{pss} T_1}{2HT_2}\Delta v + \frac{K_{pss} T_1}{2HT_2}\Delta T_m\right] \tag{4.4}$$

4.3 Components of Power System Stabilizer

During periods of transient, it has been observed that the voltage regulator introduces negative damping to the system [2]. In order to offset this effect and to improve the system damping in general, artificial means of producing torque in phase with the speed deviation are introduced. Stabilizing signals are introduced to the excitation system at the summing junction where the reference voltage and the signal produced from the terminal voltage are added to obtain the error signal, which is fed to the regulator-exciter system. This has been shown in Fig. 4.1.

4.4 Optimization technique

Optimization is the act of obtaining the best result under given circumstances. The ultimate goal of all such decisions is either to minimize the effort required or to maximize the desired benefit. There is no single method available for solving all optimization problems efficiently. Hence a number of optimization methods have been developed for solving different types of optimization problems. In this dissertation PSO and SOS algorithm were used for tuning of Power system stabilizer.

4.4.1 Particle Swarm Optimization Algorithm

Through cooperation and competition among the population, population based optimization approaches often can find very good solutions efficiently and effectively. Most of the population based search approaches are motivated by evolution as seen in nature. Four well known examples are genetic algorithms, evolutionary programming, evolutionary strategies and genetic programming. Particle swarm optimization, on the other hand, is motivated from the simulation of social behaviour. Nevertheless, they all work in the same way, that is updating the population of individuals by applying some kinds of operators according to fitness information obtained from the environment so that individuals of the population can be expected to move towards better solution areas.
The PSO algorithm was first introduced by Dr. Russel C. Eberhart and Dr. James Kennedy (1995), inspired by social behaviour of bird flocking or fish schooling [3]. The system is initialized with a population of random solutions and searches for optima by updating generations. However, unlike GA, PSO has no evolution operators such as crossover and mutation. In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles. Each particle keeps track of its coordinates in the problem space which are associated with the best solution (fitness) it has achieved so far. (The fitness value is also stored.) This value is called pbest. Another "best" value that is tracked by the particle swarm optimizer is the best value, obtained so far by any particle in the neighbors of the particle. This location is called lbest. when a particle takes all the population as its topological neighbors, the best value is a global best and is called gbest.

The particle swarm optimization concept consists of, at each time step, changing the velocity of (accelerating) each particle toward its pbest and lbest locations (local version of PSO). Acceleration is weighted by a random term, with separate random numbers being generated for acceleration toward pbest and lbest locations.

In past several years, PSO has been successfully applied in many research and application areas. It is demonstrated that PSO gets better results in a faster, cheaper way compared with other methods.

Another reason that PSO is attractive is that there are few parameters to adjust. One version, with slight variations, works well in a wide variety of applications. Particle swarm optimization has been used for approaches that can be used across a wide range of applications, as well as for specific applications focused on a specific requirement [3].

4.4.1.1 Basic particle swarm optimization

Particle swarm optimization method is based on the social behaviour that a population of individuals adapts to its environment by returning to promising regions that were previously discovered. This adaptation to environment is a stochastic process that depends on both the memory of each individual, called particle, and the knowledge gained by the population, called swarm.

In a PSO system, particles change their positions by flying around in a multidimensional search space until a relatively unchanged position has been encountered, or until computational limitations are exceeded. In social science context, a PSO system combines a social-only model and a cognition-only model. The social-only component suggests that individuals ignore their own experience and adjust their behaviour according to the successful beliefs of individuals in the neighbourhood. On the other hand, the cognition-only component treats individuals as isolated beings. A particle changes its position using these models.

In the numerical implementation of this simplified social model, each particle has three attributes: the position vector in the search space, the current direction vector, the best position in its track and the best position of the swarm. The process can be outlined as follows.

Step1: Generate the initial swarm involving N particles at random.
Step2: Calculate the new direction vector for each particle based on its attributes.
Step3: Calculate the new search position of each particle from the current search position and its new direction vector.
Step4: If termination condition is satisfied, stop. Otherwise, go to step 2.

As the particle can fly in D dimension search space, the position and velocity of i^{th} particle can be represented as

$$X_i = [x_{i1,2}, x_{i3}, x_{i4}, \dots \dots . x_{iD}] , V_i = [v_{i1}, v_{i2}, v_{i3}, v_{i4}, \dots \dots . v_{iD}]$$

With increased iteration, the swarm will move towards its global best position by keeping track of their personal best. In D dimensional search space the $pbest$ of i^{th} particle can be represented as p_{best}=[$p_{i1}, p_{i2}, p_{i3}, p_{i4}, \dots\dots p_{iD}$] , and g_{best} of the whole swarm is presented as $g_{best} = [g_1, g_2, g_3, g_4 \dots\dots g_D]$.

The new direction vector of the i^{th} particle at time t, V_i^{t+1} is calculated by the following scheme introduced by Shi and Eberhart.

$$V_{id}^{t+1} = w^t V_{id}^t + c_1 R_1^t (P_{bestid}^t - X_{id}^t) + c_2 R_2^t (g_{bestid}^t - X_{id}^t) \quad (4.5)$$

R_1^t and R_2^t are random numbers between *0* and *1*. V_{id}^t and X_{id}^t is the velocity and position of the i^{th} particle in d^{th} dimension at its time track t. P_{bestid}^t is the best id position of the i^{th} particle (personal best) in d^{th} dimension in its track at time t and g_{bestid}^t is the best position of the swarm in d^{th} dimension at time *t*. There are three parameters such as the inertia of the particle w^t, and two parameters c_1 and c_2.Where c_1 and c_2 are the learning factors which determine the relative influence of the cognitive and social components to update the position and velocity component.

Then, new position of the i-th particle at time *t*, X_{id}^{t+1} , is calculated from

$$X_{id}^{t+1} = X_{id}^t + V_{id}^{t+1} \quad (4.6)$$

The inertia weight is used to control the impact of the previous velocities on the current velocity, influencing the trade-off between the global and local experience. Although Zheng claimed that PSO with increasing inertia weight performs better, linear decreasing of the inertia weight is recommended by Shi and Eberhart.

$$w = w_{max} - \left(\frac{w_{max} - w_{min}}{iter_{max}}\right) * iter \quad (4.7)$$

Where w_{max} and w_{min} are maximum and minimum of inertia weight value respectively, $iter_{max}$ is maximum iteration number and iter is the current iteration. A so-called constriction factor K, is factor that increases the algorithm‘s ability to converge to a good solution and can generate higher quality solution than the conventional PSO approach. In this case, the expression used to update the particle‘s velocity becomes.

$$V_{id}^{t+1} = k * [w^t V_{id}^t + c_1 R_1^t (P_{bestid}^t - X_{id}^t) + c_2 R_2^t (g_{bestid}^t - X_{id}^t)] \quad (4.8)$$

$$K = \frac{2}{|2 - \varphi - \sqrt{(\varphi^2 - 4\varphi)}|}, \quad \varphi = c1 + c2, \quad \varphi > 4$$

$$K = 1, \quad \varphi < 4$$

The general search procedure of PSO is shown in figure (**Fig. 4.3**).

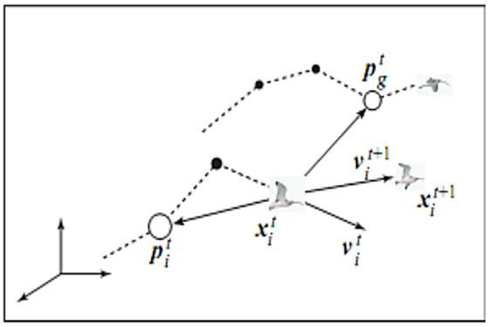


Fig. 4.3 Movement of an individual

The flowchart for PSO algorithm is represented as follows (in Fig. 4.4)

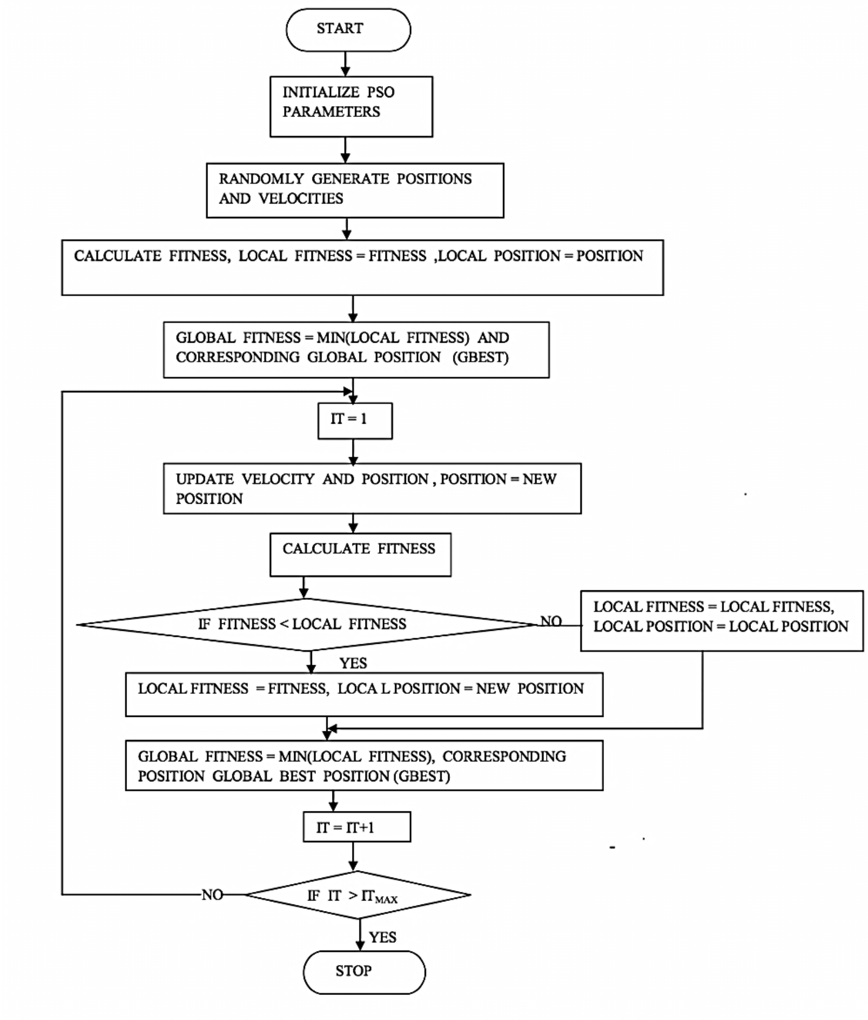


Fig.4.4 Basic flowchart of PSO

Where,

x_i^t =current search position of i^{th} particle at time *t*.

x_i^{t+1}= next search position of i^{th} particle.

p_i^t = best search position of i^{th} particle at time *t*.

p_g^t =best position of the swarm(global best)at time *t*.

v_i^t =velocity of i^{th} particle at time *t*.

v_i^{t+1} =updated velocity of i^{th} particle.

If the next search position of the i^{th} particle at time *t*, x_i^{t+1}, is better than the best search position in its track at time t, p_i^t , i.e, $f(x_i^{t+1}) \leq f(p_i^t)$, the best search position in its track is updated as p_i^{t+1}=x_i^{t+1}.Otherwise, it is updated as p_i^{t+1} =p_i^{t},Similarly, if p_i^{t+1} is better than the best position of the swarm,p_g^{t}, i.e.,$f(p_i^{t+1}) \leq f(p_g^{t})$, then the best position of the swarm is updated as $p_g^{t+1} = p_i^{t+1}$, otherwise it is updated as $p_g^{t+1} = p_g^{t}$.

4.4.2 Symbiotic Organism Search Algorithm

Symbiosis is used to describe a relationship between any two distinct species [4]. Symbiotic relationships may be either obligate or facultative. Obligate defines the condition when two organisms depend on each other for their survival, and facultative defines the condition when two organisms choose to cohabitate in a mutually beneficial but nonessential relationship.

In nature, mainly three types of symbiotic relations are found: mutualism, commensalism, and parasitism. Mutualism denotes the symbiotic relationship between two different species in which both are benefitted. Commensalism denotes the symbiotic relationship between two different species in which one benefit and the other is unaffected. Parasitism denotes the symbiotic relationship between two different species in which one is benefitted and the other is actively harmed. Symbiotic relationships are essential for the organism's survival in the ecosystem. Organisms develop symbiotic relationship to adapt themselves in the changing environment. These relationships help the organism to increase their fitness level and chances of survival in the long run.

4.4.2.1 Mutualism Phase

As described earlier, mutualism refers to the mutually benefitted symbiotic relationship between two distinct organisms. An example of this is the relationship between bee and flowers. Here, the bees collect nectar from different flowers for producing honey which benefits the bee. Also, the bees distribute the pollens in the process, which facilitates pollination, hence benefitting the flowers as well.

Fig 4.5 Mutualism between honey bee and flower

In SOS, an organism X_i is matched to the ith member of the ecosystem. Another organism X_j is selected randomly from the ecosystem to interact with X_i. Both organisms are in a mutual relationship, to increase their fitness level and their chances of survival in the ecosystem. Based on the mutual symbiotic relationship between X_i and X_j, new candidate solutions are calculated using equations given below:

$$X_{inew} = X_i + rand(0,1) * (X_{best} - Mutual\_Vector * BF_1) \quad (4.9)$$

$$X_{jnew} = X_j + rand(0,1) * (X_{best} - Mutual\_Vector * BF_2) \quad (4.10)$$

$$Mutual\_Vector = \frac{X_i + X_j}{2} \quad (4.11)$$

In Eqs (4.9) and (4.10), *rand(0,1)* is a vector or random numbers between 0 and 1. BF_1 and BF_2denotes the benefit factor that one organism might have over the other. Their values are randomly selected to be either 1 or 2, denoting the level of benefit to each organism i.e. whether an organism benefits fully or partially from the interaction. *Mutual_Vector* represents the relationship characteristic between organism X_i and X_j and is their mean value.

4.4.2.2 Commensalism Phase

In commensalism symbiotic relationship between two organisms, only one of them is benefitted while the other remains unaffected or neutral. An example of this is the relationship between shark and remora fish. The remora attaches itself to the shark and eats the leftover food, thus receives benefit. Whereas the shark is unaffected by the activity of remora fish and thus receives no benefit from this relationship.

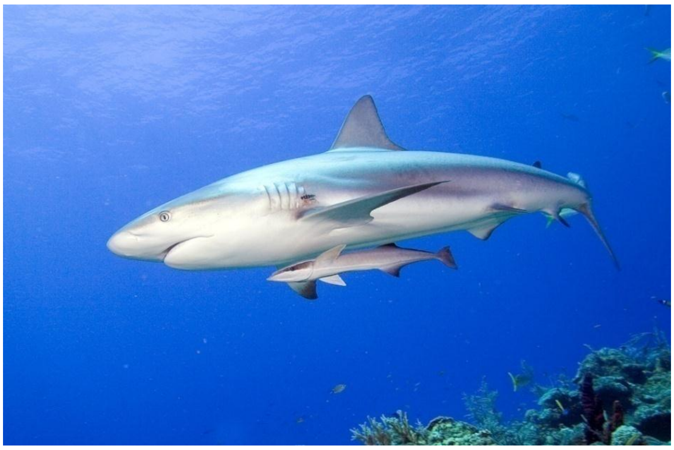


Fig 4.6 Commensalism between shark and remora fish

Similarly in commensalism, an organism X_i is randomly selected from the ecosystem to interact with X_j. Here, X_i is the organism that attempts to benefit and X_j neither benefits or suffers from the interaction. The new candidate solution for X_i is calculated according to commensalism between X_i and X_j and is given by Eqs (2.4) given below:

$$X_{inew} = X_i = rand\ (-1,1) * (X_{best} - X_j) \tag{4.12}$$

Organism X_i is updated only if its new fitness is better than its pre-interaction fitness.

4.4.2.3 Parasitism Phase

In parasitism symbiotic relationship between two organisms, one of them (parasite) is benefitted while the other is harmed (host). An example of this is the plasmodium parasite, which uses its relationship with the anopheles mosquito to pass between human hosts. The parasite thrives inside the human body and reproduces, while the human host suffers from malaria and may die as a result.

Fig 4.7 Parasitism between plasmodium parasite and human host

In SOS, organism X_i is given a role similar to the anopheles mosquito through the creation of an artificial parasite called *Parasite_Vector*. *Parasite_Vector* is created in the search space by duplicating organism X_i, then modifying the randomly selected dimensions using a random number. Organism X_j is selected randomly from the ecosystem and serves as a host to the parasite vector. *Parasite_Vector* tries to replace X_j in the ecosystem. Both organisms are then evaluated to measure their fitness. If *Parasite_Vector* has a better fitness value, it will kill organism X_j and assume its position in the ecosystem. If the fitness value of X_j is better, X_j will have immunity from the parasite and the *Parasite_Vector* will no longer be able to live in that ecosystem.

4.5 Objective Function

When power system is subjected to any disturbance, the decaying rate of oscillation is taken care of by damping factors of the system and the amplitude is determined by the damping ratio. Two sub objective functions have been considered here for tuning PSS parameters and the assessment is done using eigenvalue analysis. First sub objective function considers minimizing real part of eigenvalue and second part, considers maximizing the damping ratio, as shown in **[5]**. Eigenvalue having larger negative real part with higher value of damping ratio ensures a stable system. The damping co-efficient is derived from real and oscillatory parts of eigenvalues. The objective function contains real part of the eigenvalues as well as the damping co-efficient in order to tune PSS parameters. Therefore main objective is to improve the real part of eigenvalues and damping ratio. Mathematically it can be represented as:

Minimize $J = J_1 + J_2$ (4.13)

Where $J_1 = \sum_{i=1}^{n} (\sigma_0 - \sigma_i)^2$; $J_2 = \sum_{i=1}^{n} (\zeta_0 - \zeta_i)^2$; (4.14)

Here, *n* is the number eigenvalues that is associated with the electromechanical modes. J_1 represents the objective function related to real part of eigenvalues that leads the negatives towards left half of *S* plane and J_2 refers to the improvement of damping ratios. σ represents the real part and ζ , the damping ratio of the eigenvalues. Values of σ_0 and ζ_0 are taken as -2.5 and 0.1 respectively **[6]**. T_1 is phase-lead time constant and vary in the range of 0.1-1.5 seconds **[6]**. T_2 phase-lag time constant and vary between 0.01-0.15 seconds **[6]**. Three parameters namely, K_{PSS} , T_1 and T_2 are optimized using different optimization techniques and T_w is kept constant at 10 seconds. The effect of the objective function is shown in the **Fig. 4.8** subjected to the following inequality constraints.

$$\left.\begin{aligned} K_{PSS}^{\min} &\le K_{PSS} \le K_{PSS}^{\max} \\ T_1^{\min} &\le T_1 \le T_1^{\max} \\ T_2^{\min} &\le T_2 \le T_2^{\max} \end{aligned}\right\} \quad (4.15)$$

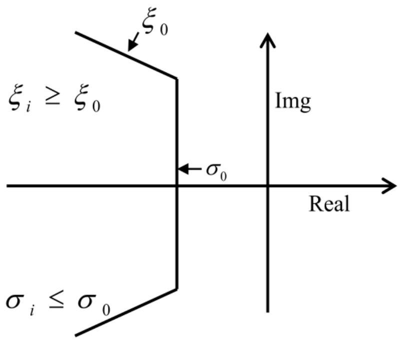


Fig. 4.8 Region of eigenvalue locations for objective function ***J*** **[6].**

This dissertation mainly focuses on PSO and SOS algorithms for tuning PSS parameters to improve system stability under different operating conditions.

4.6 Results and Discussions

Optimized CPSS parameters

In order to assess effectiveness the PSO-CPSS algorithm and SOS-CPSS is programmed in MATLAB environment and executed on Intel (R) Core (TM)–2GHz Dual-Core Intel Core i5 with 8 GB RAM, 64-bit operating system. The plant (SMIB power system) operating at nominal operating condition (where $X_e = 0.4$) is considered for optimal tuning of CPSS parameters.

The purpose of this section is to analyze system performances with the help of a newly proposed algorithm.

Table 4.1 Eigenvalue, damping ratio and oscillatory frequency of the Electro-mechanical modes for Plant 1–5 with PSO-CPSS and SOS-CPSS.

Power system model	Line reactance	Mode	Without PSS	PSO based PSS	SOS based PSS	States
				Eigenvalues with Damping Ratio	Eigenvalues with Damping Ratio	
Plant 1	0.5	#1	-2.5933±8.4992i; 0.29184	-1.0937±8.6243i; 0.12581	-0.541±8.4559i; 0.063848	$\Delta E_q'$
		#2	**-0.0823 ±7.0601i; 0.011656**	**-1.3639±6.8578i; 0.19506**	**-2.0602±7.0276i; 0.28132**	$\Delta \nu$, $\Delta \delta$
		#3		-7.1026; 1	-6.8154; 1	ΔV_s
Plant 2	0.6	#1	-2.4327±9.4671i; 0.24888	-1.7553±9.5883i; 0.18007	-1.6656±9.3446i; 0.17548	$\Delta E_q'$
		#2	**-0.2304±6.2351i; 0.036927**	**-0.7306±6.0528i; 0.11983**	**-0.9374±6.2987i; 0.1472**	$\Delta \nu$, $\Delta \delta$
		#3		-7.0210; 1	-6.7870; 1	ΔV_s
Plant 3	0.7	#1	-2.4589±10.1236i; 0.23603	-2.0076±10.2062i; 0.19301	-1.9720±10.0553i; 0.19245	$\Delta E_q'$
		#2	**-0.1940±5.7201i; 0.033896**	**-0.4990±5.5882i; 0.088941**	**-0.6314±5.7416i; 0.10931**	$\Delta \nu$, $\Delta \delta$
		#3		-6.9593; 1	-6.7657; 1	ΔV_s
Plant 4	0.8	#1	-2.4949±10.6060i; 0.22898	-2.1570 ±10.6658i; 0.19822	-2.1377±10.5583i; 0.19245	$\Delta E_q'$
		#2	**-0.1496±5.3686i; 0.027855**	**-0.3646±5.2685i; 0.069039**	**-0.4653±5.3785i; 0.10931**	$\Delta \nu$, $\Delta \delta$
		#3		-6.9123; 1	-6.7495; 1	ΔV_s
Plant 5	0.9	#1	-2.5231±10.9843i; 0.22387	-2.2555 ±11.0301i; 0.20034	-2.2434±10.9480i; 0.20074	$\Delta E_q'$
		#2	**-0.1142±5.1072i; 0.022355**	**-0.2771±5.0278i; 0.05503**	**-0.3587±5.1123i; 0.069992**	$\Delta \nu$, $\Delta \delta$
		#3		-6.8761; 1	-6.7371; 1	ΔV_s

System eigenvalues and damping ratios of electromechanical mode are shown in the **Table 4.1**, when system is subjected to different operating conditions. Here the electro-mechanical mode can be represented by mode #2 for all the plants. It has been observed that in all the cases SOS based PSS is giving improved damping to the system. Eigenvalues obtained using SOS is used to determine stability of the system and is compared with those achieved by PSO. Results demonstrate supremacy of SOS over PSO in assessing small signal stability of the system.

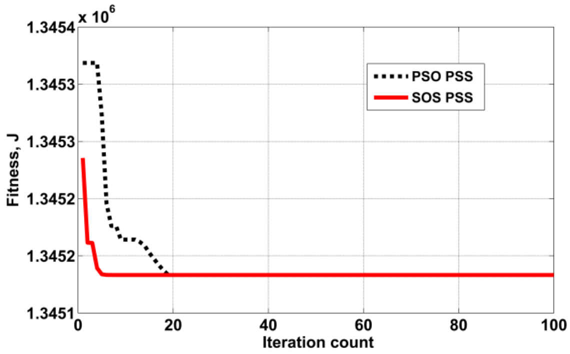
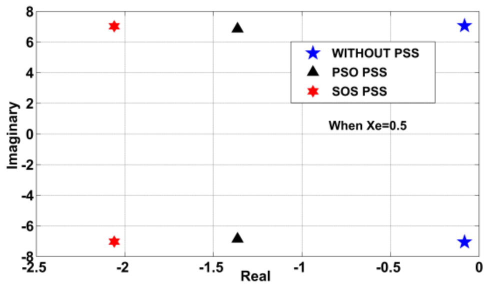
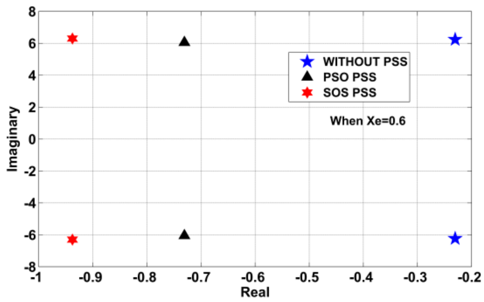


Fig. 4.9 Convergence characteristics.

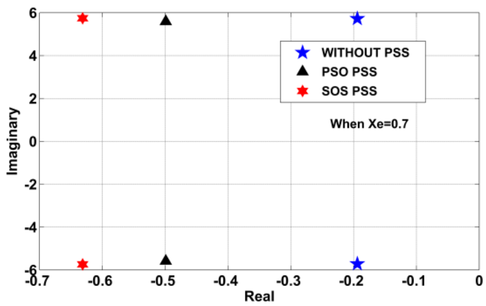
Fig. 4.9 shows decreasing objective function in each iteration for both the optimization techniques. This above figure indicates SOS converges faster (5 iterations) as compared to PSO (20 iterations).



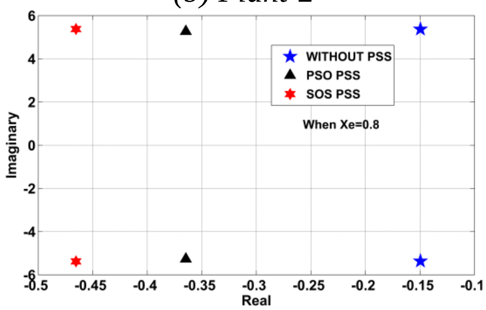
(a) Plant-1



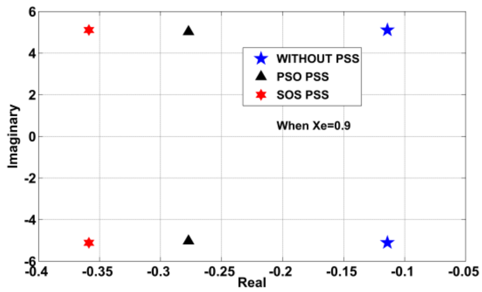
(b) Plant-2



(c) Plant-3



(d) Plant-4



(e) Plant-5

Fig. 4.10 Electromechanical eigenvalues comparison for all scenarios

From **Fig. 4.10**, it can be observed that the system eigenvalues are shifting further towards the left half of s-plane and also the damping ratios are being improved in each case as compared to PSO. This indicates the efficiency of the proposed SOS technique in tuning PSS parameters and stabilizing the system under various operating conditions.

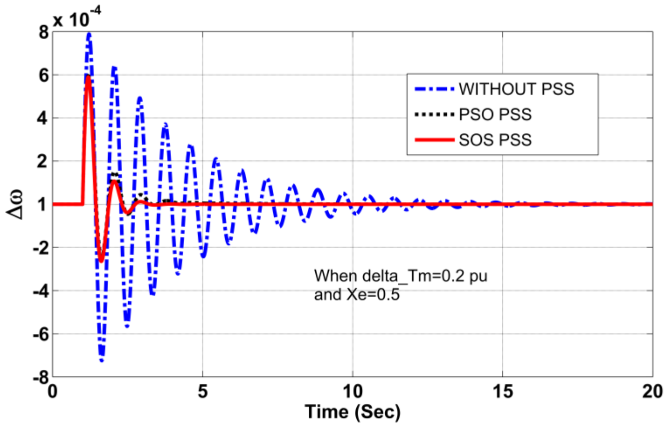


Fig. 4.11 Speed deviation without & with PSS for both optimization technique when (ΔT_m = 0.2 p.u at 1 second).

Further to demonstrate the supremacy of SOS, ΔT_m was chosen 0.2 p.u at the time 0.1s and withdrawn at 0.2s. **Figs. 4.11** show responses of $\Delta\omega_1$ as obtained by each of the algorithms mentioned above. For brevity purpose responses have been considered during only one operating condition. It can be concluded that SOS based design is more stable compared to other techniques and requires lesser settling time to mitigate the system oscillations. The set values for the PSS parameters for both the algorithms are listed in **Tables 4.2**.

Tables 4.2 PSS Parameters for various algorithms

Controller	**Gain of PSS (K_{PSS})**	**T_1(Sec)**	**T_2(Sec)**
PSO-PSS	0.74884	0.60237	0.1500
SOS-PSS	2.24630	0.20000	0.1500

4.7 References

[1] Padiyar, K. R. Power system dynamics: stability and control. New York: John Wiley, 1996.

[2] Kundur, P. (1994). Power system stability and control (Vol. 7). N. J. Balu, & M. G. Lauby (Eds.). New York: McGraw-hill.

[3] Eberhart R, Kennedy J, ―Particle Swarm Optimization‖, PP. 1942 – 1948, IEEE Conference, 1995.

[4] Cheng, M. Y., & Prayogo, D. (2014). Symbiotic organisms search: a new metaheuristic optimization algorithm. Computers & Structures, 139, 98-112.

[5] Dey, Prasenjit, Aniruddha Bhattacharya, and Priyanath Das. "Tuning of power system stabilizer for small signal stability improvement of interconnected power system." *Applied Computing and Informatics* (2017).
[6] Dey, Prasenjit, et al. "Small signal stability improvement of large interconnected power systems using power system stabilizer." *2017 2nd International Conference for Convergence in Technology (I2CT)*. IEEE, 2017.

Chapter 5

Conclusion and future scope of work

5.1 Conclusion

This work considered tuning of PSS parameters for small signal stability improvement using SOS and PSO algorithms. The gain and time constants of CPSS were optimized by using PSO and SOS algorithms with eigenvalue based objective function. The speed response of the generators for the SMIB power system without PSS, with PSO-CPSS and with the SOS-CPSS was compared for power system models with different operating conditions. It was found that the response with PSO-CPSS stabilized the system, but with prolonged settling time as compared to reduced settling time with SOS-CPSS.

5.2 Scope of future work

- The test system chosen for stability study in this dissertation is the SMIB system. Using the system modeling technique shown here, this can be implemented to a more complicated and large multi-area system for better and more practical analysis.
- PSS is a very costly device. So, it will not be economical to install PSS in every synchronous generator. The number of PSSs can be optimized for more economical operation considering the stability of the system.
- Also, the FACTS controllers like STATCOM, UPFC can be designed to improve the stability and they can be coordinated with PSS also.
- The renewable energy sources like Solar PV could be considered along with Wind in a large multi-area system. Wind systems, as well as Solar PV systems, are uncertain in nature, as the power generation from these sources depends heavily on the atmospheric conditions. Hence the stochastic study of the system can be performed to obtain more accurate results than the deterministic approach.

Appendix

$R_e = 0$; $X_e = 0.5\ p.u$; $V_t = 1\angle 15^0\ pu$; $V_\infty \angle 0^0 = 1.05\angle 0^0\ pu$

The machine data are

$H = 3.2\sec$;

$T_d' = 9.6\sec$;

$K_A = 400$;

$T_A = 0.2\sec$;

$R_s = 0$;

$X_q = 2.1\ pu$;

$X_d = 2.5\ pu$;

$X_d' = 0.39\ pu$;

$D = 20$;

$f = 50\ Hz$;