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Power System Stabilizer Controller Design for SMIB Stability Study

Balwinder Singh Surjan, Ruchira Garg

Abstract*-- *The low frequency oscillations (LFOs) are related to the small signal stability of a power system and are detrimental to the goals of maximum power transfer and power system security. As power systems began to be operated closer to their stability limits, the weakness of a synchronizing torque among the generators was recognized as a major cause of system instability instead of damping torque. Automatic voltage regulators (AVRs) can improve the steady-state stability of the power systems. The addition of a supplementary controller into the control loop, such as power system stabilizers (PSSs) to the AVRs on the generators, provides the means to reduce the inhibiting effects of low frequency oscillations. The power system stabilizers work well at the particular network configuration and steady state conditions for which they were designed. Once conditions change the performance degrades To overcome the drawbacks of power system stabilizer (PSS), numerous techniques are available in the literature. In the present work, the effectiveness of conventional PSS and PID-PSS has been compared.

Keywords*- *LFOs, AVRs, PSSs, PSS, PID-PSS.

I. INTRODUCTION

The disturbances occurring in power system because of changes in load, include electro mechanical oscillations of electrical generators. These oscillations are also called power swings and these must be effectively damped to maintain the system stability. Electromechanical oscillations can be classified in two main categories (i) Local Plant Mode Oscillations**:** One type is associated with units at a generating station swinging with respect to the rest of the power system. Such oscillations are referred to as 'local plant mode oscillations'. The frequencies of these oscillations are typically in the range 0.8Hz to 2.0 Hz., (ii) Inter-area Oscillations: The second type of oscillation is associated with the swinging of many machines in one part of the system against machines in other parts. These are referred to as 'inter area mode' oscillations and have frequencies in the range 0.1 to 0.7 Hz. The stability criterion with respect to synchronous machine equilibrium has been presented. The mathematical model presented for small scale stability state is a set of linear time invariant differential equations [1]. P.M. Anderson and A.A. Fouad, had mentioned , the stability under the condition of small load changes has been called steady state stability[2]. The concepts of synchronous machine stability as affected by excitation control and the phenomenon of stability of synchronous machines under small perturbations in the case of single machine connected to an infinite bus through external reactance has been presented by F.P.demello and C. Concordia. The analysis also develops insights into effects of thyristor-type excitation systems and establishes understanding of the stabilizing requirements for such systems [3]. These stabilizing requirements include the voltage regulator gain parameters as well as the transfer function characteristics for a machine speed derived signal superposed on the voltage regulator reference for providing damping machine oscillations [4]. Trends in design of power system components have resulted in lower stability and led to increased reliance on the use of excitation control to improve stability [2]. IEEE Committee Report (1981), the working group of IEEE on computer modeling of excitation systems, in their report has discussed excitation system models suitable for use in large scale stability studies [5]. Michael J. Basler Richard C. Schaefer discusses power system instability and the importance of fast fault clearing performance to aid in reliable production of power [6]. In the past decades, the utilization of supplementary excitation control signals for improving the dynamic stability of power systems has received much attention. Extensive research has been conducted in such fields as effect of PSS on power system stability, PSS input signals, PSS optimum locations, and PSS tuning techniques. The k-constant model developed by Phillips and Heffron, is used to explain the small signal stability, high impedance transmission lines, line loading, and high gain, fast acting excitation systems. The paper discusses the various types of power system instability. It will cover the effects of system impedance and excitation on stability. Synchronizing torque and damping torque is discussed and a justification is made for the need for supplemental stabilization [1,4, 7]. Kundur et al. presented a detailed analytical work to determine the parameters of phase- lead PSSs so as to enhance the steady-state as well as transient stability of both local and inter-area modes. These parameters included the signal washout, stabilizer gain, and the stabilizer output limits. They concluded that by proper tuning, the fixed-parameter PSS can satisfy the requirements for a wide range of system conditions and hence the need of adaptive PSS is of little incentive [7]. Larsen and Swann [8-10] deeply discussed, in a three-part paper, the general concepts associated with PSSs. Yuan Yih Hsu and Kan Lee Liou in their paper, "Design of PID power system stabilizers for synchronous generators" proposed a self -tuning proportional integral derivative (PID) power system stabilizer in order to improve the dynamic performance of a synchronous machine under a wide range of operating conditions [11].

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II. POWER SYSTEM STABILIZER

Power system stabilizers (PSS) were developed to aid in damping these oscillations via modulations of excitation system of generators. The action of a PSS is to extend the angular stability limits of a power system by providing supplemental damping to the oscillation of synchronous machine rotors through the generator excitation. To provide damping, stabilizers must produce a component of electrical torque on the rotor which is in phase with speed variations This supplementary control is very beneficial during line outages and large power transfers. However, power system instabilities can arise in certain circumstances due to negative damping effects of the PSS on the rotor. The reason for this is that PSSs are tuned around a steady-state operating point; their damping effect is only valid for small excursions around this operating point. During severe disturbances, a PSS may actually cause the generator under its control to lose synchronism in an attempt to control its excitation field. [10,12,13]

A. *Structure of PSS*

The block diagram of the PSS is shown below in Fig. 1. It consists of a signal washout block, phase compensation block and a gain block.

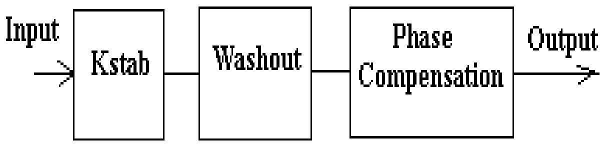

Fig. 1 Block diagram of Power System Stabilizer

1) *Gain block*

The stabilizer gain K_{stab} determines the amount of damping introduced by the PSS. Ideally the gain should be set at a value corresponding to maximum damping; however it is often limited by other considerations.

2) *Washout Circuit*

The signal washout block serves as a high-pass filter, with the time constant T_w high enough to allow signals associated with oscillations in w_r to pass unchanged. Without it steady changes in speed would modify the terminal voltage. It allows the PSS to respond only to changes in speed. From the viewpoint of the washout function, the value of T_w is not critical and may be in the range of 1 to 20 seconds. The main consideration is that it be long enough to pass stabilizing signals at the frequencies of interest unchanged, but not so long that it leads to undesirable generator voltage excursions during system islanding conditions.

3) *Phase Compensation Block*

The phase compensation block provides the appropriate phase – lead characteristic to compensate for the phase lag between the exciter input and the generator electrical (air-gap) torque. The figure shows a single first order block. In practice, two or more first–order blocks may be used to achieve the desired phase compensation. Normally the frequency range of interest is 0.1 to 2.0 Hz, and the phase lead network should provide compensation over this entire frequency range. The phase characteristic to be compensated changes with system conditions, therefore a compromise is made and a characteristic acceptable for different system conditions is selected.

4) *Input Signals*

The input signals that have been identified as valuable include deviations in the rotor speed ($\Delta\omega$), the frequency (Δf), the electrical power (ΔPe) and the accelerating power (ΔPa). Since the main action of the PSS is to control the rotor oscillations, the input signal of rotor speed has been the most frequently advocated in the literature.

However, it had been found that frequency is highly sensitive to the strength of the transmission system that is, more sensitive when the system is weaker – which may offset the controller action on the electrical torque of the machine. Other limitations include the presence of sudden phase shifts following rapid transients and large signal noise induced by industrial loads. On the other hand, the frequency signal is more sensitive to inter-area oscillations than the speed signal and may to better oscillation attenuation [8-10] .In this thesis work a speed signal is used as input signal.

B. *Tuning techniques*

A wide spectrum of PSS tuning approaches has been proposed. These approaches have included pole placement, damping torque concepts, H∞ and LQG/LTR, non linear and variable structure and the different optimization and artificial intelligence techniques. Some of the proposed PSS are analog and others are digital. Self-tuning PSSs have been proposed along with fixed parameter PSSs. The conventional and widely used PSS structure is the lead lag compensator. However, state feedback and PID controllers are also being used.

C. *Phase Compensation Design Technique*

Phase compensation technique consists of adjusting the stabilizer parameters to compensate for the phase lags through the generator excitation system, and power system such that the torque changes in phase with speed changes. This is the most straightforward approach, easily understood and implemented. The phase lag depends on the operating point and the system parameters. The algorithm for computing the PSS parameters is as follows:

STEP 1: Obtain w_n from the mechanical loop:

The characteristic equation of the mechanical loop can be written as:

$$Ms^2+Ds+w_bK_1=0 \tag{1}$$

Where w_b is the system frequency in rad/s and w_n is the undamped natural frequency of the mechanical mode and is given below:

$$w_n=\sqrt{(K_1w_b)/M} \tag{2}$$

STEP 2: Compute phase lag ∟Ge between U and Tm of the loop to be compensated by PSS. Ge(s) is the transfer function

STEP 3: Design of phase lead lag compensator:

The transfer function of phase lead compensator Gc is

$$Gc=\frac{(1+sT1)(1+sT2)}{(1+sT3)(1+sT4)} \tag{3}$$

For the full compensation ∟Ge + ∟Gc = 180°

The PSS parameters to be optimized are T1-T4 and Kstab. Considering two identical cascade lead-lag networks for PSS. T1= T3 and T2=T4 and hence the problem reduces to that of optimization of Kstab, T1 and T2 only. Tw = 10s has been chosen[ref].

one lead lag block is used for compensating about 50° of phase lag and accordingly lead lag blocks are chosen. The PSS parameters T1 and T2 are chosen so as to fully compensate the phase lag as follows:
Let β is the phase lag compensated by one block, then

$$T_2 = \frac{1}{wn\sqrt{a}} \tag{4}$$

where

$$a = \frac{1+\sin\beta}{1+\sin\beta} \tag{5}$$

and $T_1 = aT_2$

STEP 4: Gain setting

The amount of damping introduced depends on the gain of PSS transfer function at that frequency. Ideally, the gain should be set at a value corresponding to maximum damping. The desired PSS gain K_{stab} is computed from

$$K_{stab} = \frac{2\varsigma wnM}{|Gc|\,|Ge|} \tag{6}$$

where ς is the desired damping ratio.

D. *Performance Indices*

The design of control system is an attempt to meet a set of specifications which define the overall performance of the system in terms of certain measurable quantities. A number of performance measures have been introduced so far in respect of dynamic response to step input and the steady state error to both step and higher order inputs. The most common performance index is the integral square error (ISE), given by:

$$\textbf{ISE} = \int_0^\infty e^2(t)dt \tag{7}$$

III. PID CONTROLLER DESIGN[14,15]

Designing and tuning a proportional – integral – derivative (PID) controller appears to be conceptually intuitive, but can be hard in practice, if multiple (and often conflicting) objectives such as short transient and high stability are to be achieved. A PID controller may be considered as an extreme form of a phase lead-lag compensator with one pole at the origin and the other at infinity. Similarly, its cousins, the PI and the PD controllers, can also be regarded as extreme forms of phase lag and phase – lead compensators, respectively. A standard PID controller is also known as the "three-term" controller, whose transfer function is generally written in the "parallel form" given by (8) or the ideal form (9).

$$G(s) = K_p + K_i(1/s) + K_d s \tag{8}$$

$$= K_p(\ 1+1/T_1 s + T_d s) \tag{9}$$

where K_p is the proportional gain, Ki is the integral gain, K_d is the derivative gain, T_1 the integral time constant. The individual effects of K_p, K_i , K_d on the closed loop performance are summarized in Table I. This table serves as a guide for stable open loop plants only. For optimum performance, K_p, K_i and K_d are mutually dependent in tuning.

A. *Tuning methods for PID controllers [15]:*

With tuning objectives, the tuning methods for PID controllers can be grouped according to their nature and usage as follows:

1) *Analytical methods*

PID parameters are calculated from analytical or algebraic relations between a plant model and an objective (such as an internal mode control (IMC) or lambda tuning). These can lead to an easy-to-use formula and can be suitable for use with online tuning, but the objective needs to be in an analytical form and the model must be accurate.

2) *Heuristic methods*

These are evolved from practical experience in manual tuning (such as the Z-N tuning rule) and from artificial intelligence (including expert systems, fuzzy logic and neural networks). Again, these can serve in the form of a formula or a rule base for online use, often with tradeoff design objectives.

3) *Frequency response methods*

Frequency characteristics of the controlled process are used to tune the PID controller (such as loop-shaping). These are often offline and academic methods, where the main concern of design is stability robustness.

4) *Optimization methods*

These can be regarded as a special type of optimal control, where PID parameters are obtained ad hoc using an offline numerical optimization method for a single composite objective or using computerized heuristics or an evolutionary algorithm for multiple design objectives. These are often time-domain methods and mostly applied offline.

5) *Adaptive tuning methods*

These are for automated online tuning, using one or a combination of the previous methods based on real-time identification.

B. *PID Controller Design*

Controllers or single input single output systems consists of three elements proportional (P), integral (I), and Derivative (D) action. The transfer function of a controller which includes all three terms is called three term PID controller, given by

$$G_c = K_p\left(1 + T_d s + \frac{1}{T_i s}\right) \tag{9}$$

Where K_p, T_d and T_i, are constants for proportional, derivative and integral controller respectively.

Based on the three-term PID controller, there may be derived a number of other controllers. The majority of the industrial control elements are of P or PI type. These controllers are derived from three term PID controller $G_c(s)$ by making adjustments to T_d and T_i, as

$T_d = 0$ and T_i, $= \infty$ gives a P-controller

$T_d = 0$ and T_i, = finite gives a PI-controller

Commercially available pneumatic or electronic controllers may be of non-interacting or interacting type depending on the principle of action. Only the derivative action is never implemented in practice because of noise problem. It may be noted that interacting controller means that an adjustment of any parameter affects the other parameters, where non interacting means the other way round.

C. *Zieglar- Nicholas Rules for Controller Tuning*

The process to be control is shown in figure. Under pure proportional control, the system is asymptotically stable in the range $0 \leq K_p < K_c$, and goes unstable in the oscillatory manner where $K_p > K_c$. The following steps are done

1. Increase the gain K_p from 0 to K_c (decrease the proportional band X_p until the process starts to oscillate).

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At this critical gain K_c the closed loop system is marginally stable so any gain adjustments must be carried out with extreme care. (if the output does not exhibit sustained oscillations for whatever for whatever value K_p may take, then this method does not apply).

2. Note the value K_c and the period of oscillation T.
3. The recommended settings of K_p, T_d and T_i, are given below in table for different types of controller design.

Table I. Controller Constants

Type of Controller	K_p	T_i	T_d
Proportional	0.5 K_c	∞	0
Proportional-Integral	0.45 K_c	0.83T	0
Proportional-Integral-Derivative	0.6 K_c	0.5T	0.125T

Thus PID controller as per equation is given by

$$G_c = K_p\left(1 + T_d s + \frac{1}{T_i s}\right) \quad (11)$$

$$G_c = 0.6K_c\left(1 + 0.125Ts + \frac{1}{0.5Ts}\right)$$

$$= 0.075K_c T\,\frac{(s+{}^{4}/_{T})^2}{s} \quad (12)$$

Thus the PID controller has a pole at the origin and double zeros at s= - 4/T.

As the transfer function model of the plant is available, Routh's array may be used to establish the critical gain K_c and the corresponding period of oscillation. The procedure is:

1. Find the system's closed loop characteristic equation under pure proportional control.
2. From the Routh's array and establish the critical gain K_c that produces an all zero row. If the system goes unstable in an oscillatory manner, the all zero row will be the row associated with s^1, the auxiliary equation will be second order and there will be no roots of the remainder polynomial with positive real part. The system should remain stable for all positive values of K_p below the critical value.
3. Use the auxiliary polynomial to find the period of oscillation T and apply the recommended settings given above in table.

IV. SYSTEM DATA

The following are the nominal parameters of the system and the operating conditions used for the sample problem investigated. All data are given in the per units of value except H and time constants are in seconds [12].

Table II Generator parameters

Generator parameters	Values
H	5.0s
T'_{do}	6.0s
X_d	1.6
X'_d	0.2
X_q	1.55

Table III Exciter Data

K_A	50
T_A	0.05

Table IV Transmission line

X_e	0.4
R_e	0.0

Table V Operating Conditions

P	0.8
Q	0.6
V_{to}	1.0
f	50

A. Evaluation of initial conditions:

The steady state values of d-q axis voltage and current components for the machine infinite bus system for the normal operating condition are given below. These are expressed as function of steady state terminal voltage Vto and steady state real and reactive load currents Ipo and Iqo respectively.

Table VI Initial Conditions

I_{po}	0.8
I_{qo}	0.6
E_{qo}	2.2940
V_o	0.8246
δ_o	.9884
I_{qo}	.3487
I_{do}	.9372
V_{qo}	.8413
V_{do}	.5405
E'_{qo}	1.1412

Table VII Heffron- Phillips Constants

K_1	0.9439
K_2	0.9565
K_3	0.3600
K_4	1.2243
K_5	-0.0626
K_6	0.4674

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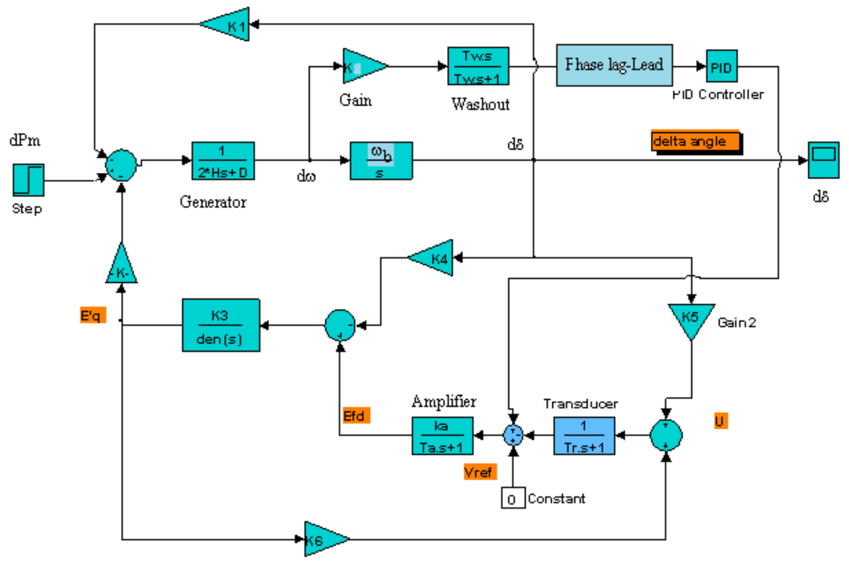

Fig. 2 Heffron-Phillips Model of SMIB with PID-PSS Controller

V. SYSTEM RESPONSE

The SMIB system shown in Fig. 2 has been subjected to step change in P_m, indicating power imbalance. The Response of the system has been given Fig. 3- Fig. 14. The response has been obtained in MATLAB Simulink and Script Programming.

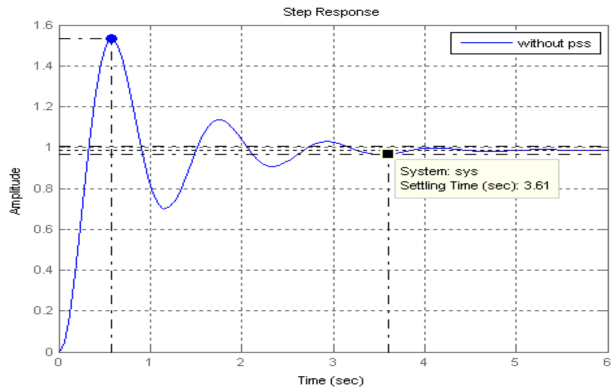

Fig. 3 Step Response of SMIB System Without PSS

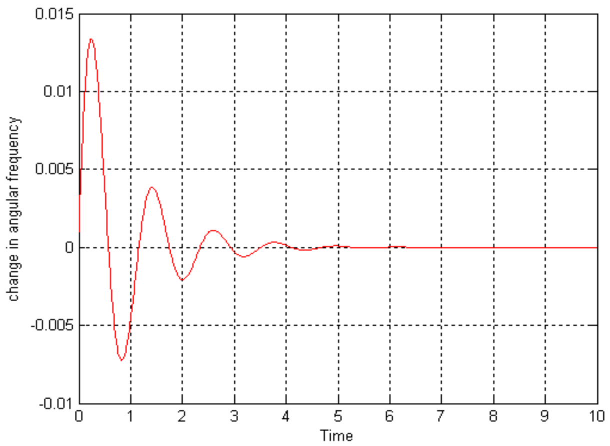

Fig. 4 Generator Angular Frequency Without PSS

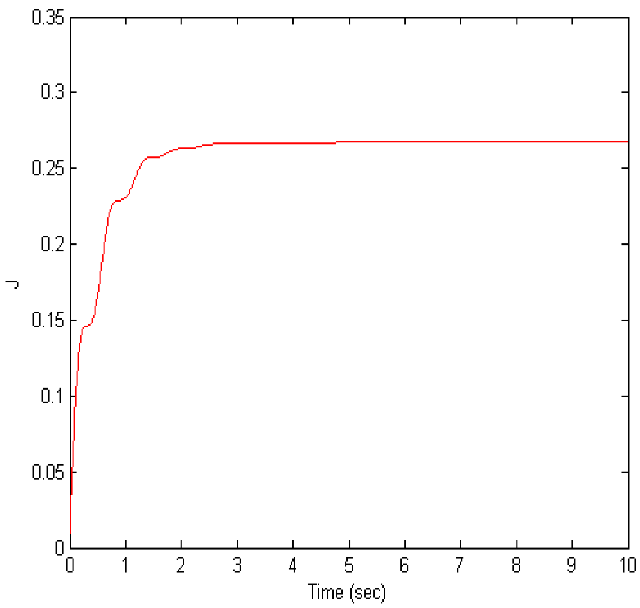

Fig. 5 System ISE Without PSS

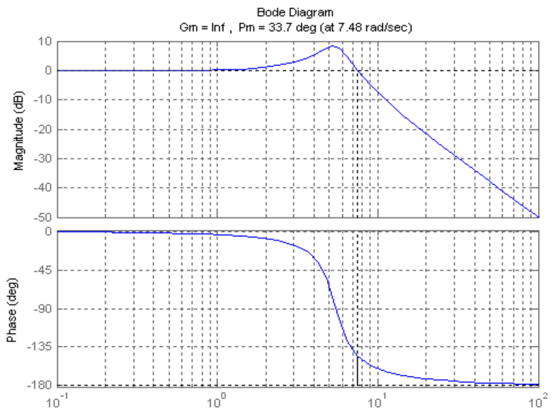

Fig. 6 Bode Response of SMIB System Without PSS

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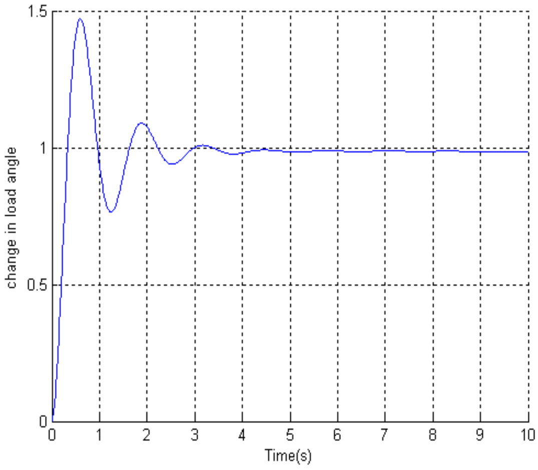

Fig. 7 Step Response of SMIB System with PSS

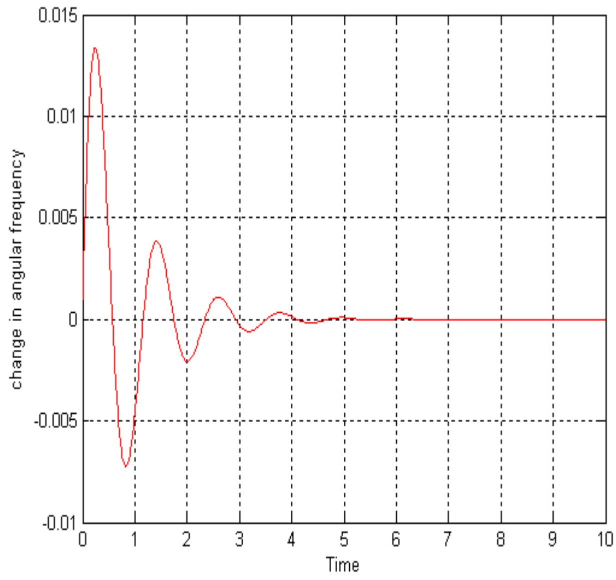

Fig. 8 Generator Angular Frequency With PSS

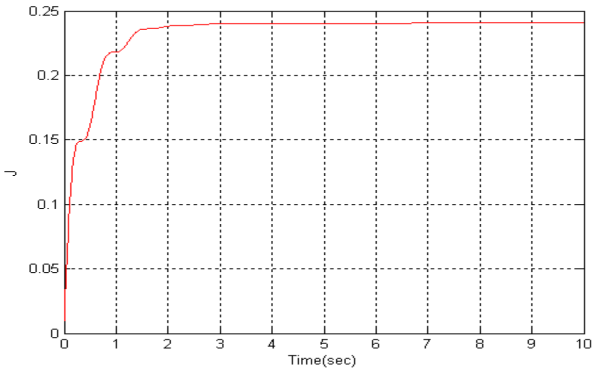

Fig. 9 System ISE WithPSS

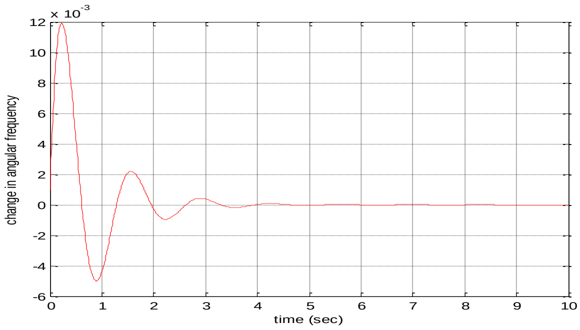

Fig. 12 Generator Speed with Hit-and Trial Method

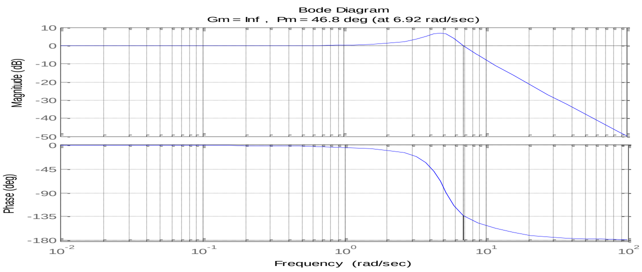

Fig. 10 Bode Response of SMIB System With PSS

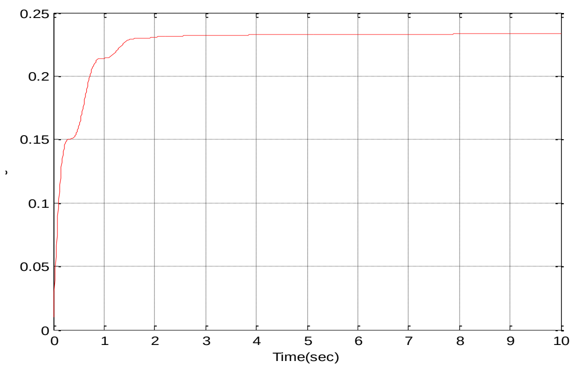

Fig. 13 System ISE With PSS

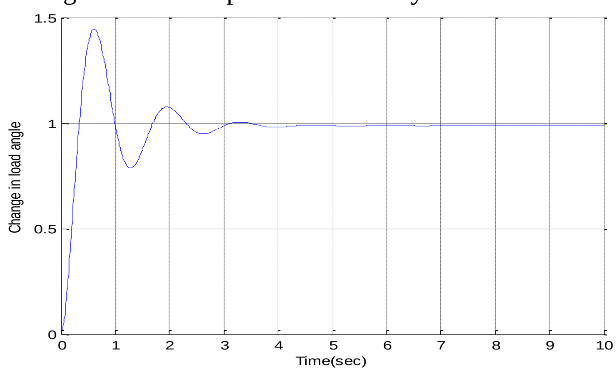

Fig. 11 Generator load angle with Hit-and Trial Method

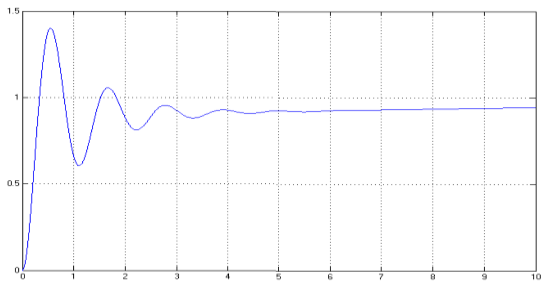

Fig. 14 Rotor angle with PID-PSS Controller

VI. CONCLUSION

The results obtained in the presented work indicates that the power system parameters can be fixed through different approaches mentioned in the literature. In the approaches

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applied in this paper the results obtained for the PSS tuning with hit and trial method are best. However this method takes long time. The settling time for step disturbance with PSS are 3.14 sec for hit and trial and 3.24sec. for Zeigler-Nichols method. The peak overshoot for step disturbance with PSS are 1.37 for hit and trial and 1.47 for Zeigler-Nichols method. The settling time for step disturbance with PID is 4.3 sec. The peak overshoot for step disturbance with PID is 1.3.

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