A Comparative Study Using Simulated Annealing and Fast Output Sampling Feedback Technique based PSS Design for Single machine Infinite bus System Modeling

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Abstract-- The objective of the Power System Stabilizer (PSS) is added to excitation system to enhance the damping during low frequency oscillations. This paper presents a comparison study of Simulated Annealing and fast output sampling based power system stabilizer (PSS) for stability enhancement. Conventional Power system stabilizers (CPSSs) are designed with the phase compensation technique in the frequency domain and include the lead-lag blocks and related parameters are tuned using an optimization method based on Simulated Annealing (SA). The performance of SA-PSS is evaluated at single-machine infinite bus system.

In fast output sampling technique, the nonlinear model of single-machine infinite bus system is linearized at different operating point and a linear model is obtained. For this model, a common state feedback gain is obtained using LMI technique. A robust fast output sampling feedback gain which realizes output injection gain is obtained using LMI approach. This method does not require states of the system for feedback and is easily implementable. This robust fast output sampling control is applied to non-linear model of a single machine system at different operating (equilibrium) points. The simulation results clearly indicate the effectiveness and validity of the fast output sampling technique method.

Keywords*-- *SMIB system, power system stabilizer, fast output sampling feedback, Simulated Annealing (SA).

I. INTRODUCTION

Power system stabilizers were developed to aid in damping these oscillations via modulation of the generator excitation. This development has brought an improvement in the use of various tuning techniques and input signals and in the ability to deal with turbine-generator-shaft torsional modes of vibrations [1]. In the past five decades the PSS have been used to provide the desired system performance under condition that requires stabilization. Stability of synchronous generator depends on a number of factors such as the setting of automatic voltage regulator (AVR). Many generators are designed with high gain, fast acting AVRs to enhance large scale stability to hold the generator in synchronism with the power system during large transient fault conditions. But with the high gain of excitation systems, it can decrease the damping torque of generator. A supplementary excitation controller referred to as PSS have been added to synchronous generators to counteract the effect of high gain AVRs and other sources of negative damping [2].

To provide damping, the stabilizers must produce a component of electrical torque on the rotor which is in phase with speed variations. The application of a PSS is to generate a supplementary stabilizing signal, which is applied to the excitation system or control loop of the generating unit to produce a positive damping. The most widely used conventional PSS is the lead-lag PSS, where the gain settings are fixed at certain value which are determined under particular operating conditions to result in optimal performance for that specific condition. However, they give poor performance under different synchronous generator loading conditions [3].

Conventional PSS (CPSS) is widely used in existing power systems and has made a contribution in enhancing power system dynamic stability. The parameters of CPSS are determined based on a linearised model of the power system around a nominal operating point where they can provide good performance. Since power systems are highly non-linear systems, with configurations and parameters that change with time, the CPSS design based on the linearised model of the power system cannot guarantee its performance in a practical operating environment [4],[5]. To improve the performance of CPSS, numerous techniques have been proposed for their design, such as using intelligence optimization methods (simulated annealing, genetic algorithm, Tabu search, fuzzy, neural networks and many other non linear techniques. The intelligent optimization algorithms are used to determine the optimal parameters for CPSS by optimizing an Eigen value based cost function in an off-line mode. Since the method is based on a linearised model and the parameters are not updated on-line, therefore, they lack satisfactory performance during practical operation. The rule-based fuzzy logic control methods are well known for the difficulty in obtaining and adjusting the parameters of the rules especially on-line. Recent research indicates that more emphasis has been placed on the combined usage of fuzzy logic systems and other technologies such as neural networks to add adaptability to the design [6]-[8].

Recently modern control methods have been used by several researchers to take advantage of optimal control techniques. These methods utilize a multivariable state space representation of multimachine power system model and calculate a gain matrix which when applied as a state feedback control will minimize a prescribed objective function. In practice, not all of the states are available for measurement. In this case, the optimal control law requires designing the state observer. This increases the implementation cost and reduces the reliability of the control system. Another disadvantage of the observer based control system is that even a slight variation of the model parameters from their nominal values may result into significant degradation of the closed loop performance. Hence it is desirable to go for an output feedback design. In recent years there have been several attempts at designing power system stabilizer using H_∞ based robust control techniques. In this approach, the uncertainty in the chosen system is modeled in terms of bounds on frequency response. An H_∞ optimal controller is then synthesized which guarantees robust stability of the closed loop system. But, this will lead to dynamic output feedback, which may be feasible but leads to a higher order feedback system [2].

The static output feedback problem is one of the most investigated problems in control theory. The complete pole assignment and guaranteed closed loop stability is still not obtained by using static output feedback. Another approach to pole placement problem is to consider the potential of time varying fast output sampling feedback. It was shown by Chammas and Leondes [2] that a controllable and observable plant was discrete time pole assignable by periodically time-varying piecewise constant output feedback. Since the feedback gains are piecewise constant, their method could be easily implemented and indicated a new possibility. Such a control law can stabilize a much larger class of systems than the static output feedback [9]-[12].

Therefore, an adaptive PSS which considers the nonlinear nature of the plant and adapts to the changes in the environment is required for the power system (Liu et al., 2005). In order to improve the performance of CPSSs, numerous techniques have been proposed for designing them, such as intelligent optimization methods (Sumathi et al., 2007; Jiang et al., 2008; Sudha et al., 2009; Linda & Nair, 2010; Yassami et al., 2010) and Fuzzy logic method (Dubey, 2007; Hwanga et al., 2008). Also the application of robust control methods for designing PSS has been presented earlier (Bouhamida et al., 2005; Gupta et al., 2005; Mocwane & Folly, 2007; Sil et al., 2009).

II. POWER SYSTEM STABILIZERS

Implementation of a power system stabilizer implies adjustment of its frequency characteristic and gain to produce the desired damping of the system oscillations in the frequency range of 0.2 to 3.0 Hz.

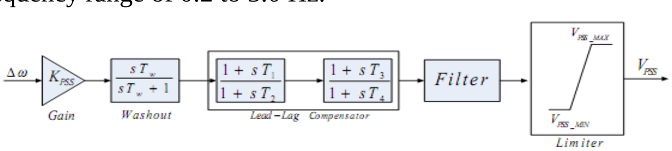

Figure 2.1: Block-diagram of Convential Power System Stabilizer

Convential Power System Stabilizer as shown in figure 2.1, where Kpss represents stabilizer gain and the stabilizer frequency characteristic is adjusted by varying the time constant Tw, T1, T2, T3 and T4. A power system stabilizer can be made more effective if it is designed and applied with the knowledge of associated power characteristics. Power system stabilizer must provide adequate damping for the range of frequencies of the power system oscillation modes. To begin with, simple analytical models, such as that of a single machine connected to an infinite bus, can be useful in determining the frequencies of local mode oscillations. Power system stabilizer should also be designed to provide stable operation for the weak power system conditions and associated loading. Designed stabilizer must ensure for the robust performance and satisfactory operation with an external system reactance ranging from 20% to 80% on the unit rating [2].

III. STATE SPACE MODEL OF SINGLE MACHINE SYSTEM

From the block diagram shown in Figure 3.1, the following state space equations for the entire system can be derived using Heffron -Phillip's model [13] - [16].

$$\dot{x} = [A]x + [B\ ](\Delta V_{ref} + \Delta V_s)\,, \tag{1}$$

$$y = [C]x$$

Where,

$$x^T = [\ \Delta\delta \quad \Delta S_m \quad \Delta E'_q \quad \Delta E_{fd}\ ], \tag{2}$$

$$[A] = \begin{bmatrix} 0 & \omega_B & 0 & 0 \\ -\frac{K_1}{2H} & -\frac{D}{2H} & -\frac{K_2}{2H} & 0 \\ -\frac{K_4}{T'_{d0}} & 0 & -\frac{1}{T'_{d0}K_3} & -\frac{1}{T'_{d0}} \\ -\frac{K_E K_5}{T_E} & 0 & -\frac{K_E K_6}{T_E} & -\frac{1}{T_E} \end{bmatrix}, \tag{3}$$

$$[B]' = \begin{bmatrix} 0 & 0 & 0 & \frac{K_E}{T_E} \end{bmatrix}, \tag{4}$$

$$[C]' = [0 \quad 1 \quad 0 \quad 0], \tag{5}$$

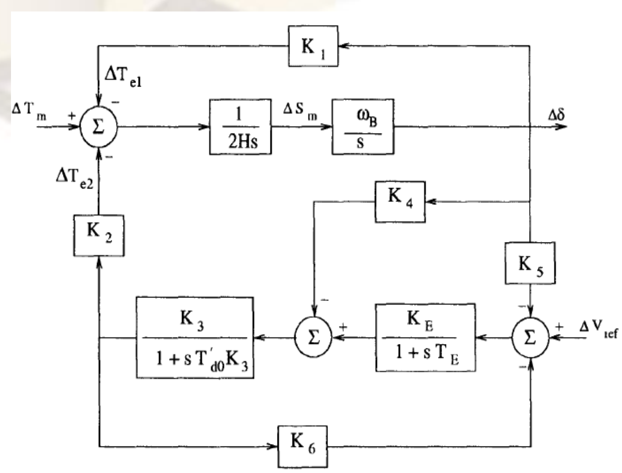

Figure 3.1: Block diagram of Single Machine Infinite Bus System.

IV. SIMULATED ANNEALING ALGORITHM

In the early 1980s the method of simulated annealing (SA) was introduced in 1983 based on ideas formulated in the early 1950s. This method simulates the annealing process in which a substance is heated above its melting temperature and then gradually cooled to produce the crystalline lattice, which minimizes its energy probability distribution. This crystalline lattice, composed of millions of atoms perfectly aligned, is a beautiful example of nature finding an optimal structure. However, quickly cooling or quenching the liquid retards the crystal formation, and the substance becomes an amorphous mass with a higher than optimum energy state. The key to crystal formation is carefully controlling the rate of change of temperature.

The algorithmic analog to this process begins with a random guess of the cost function variable values. Heating means randomly modifying the variable values. Higher heat implies greater random fluctuations. The cost function returns the output, f, associated with a set of variables. If the output decreases, then the new variable set replaces the old variable set. If the output increases, then the output is accepted provided that:

$$r \le e^{[f(old)-f(new)]/T} \quad (6)$$

Where, r is a uniform random number and T is a variable analogous to temperature. Otherwise, the new variable set is rejected. Thus, even if a variable set leads to a worse cost, it can be accepted with a certain probability.

The new variable set is found by taking a random step from the old variable Set as (6.1).

$$P^{new}=d*P^{old} \quad (6.1)$$

The variable d is either uniformly or normally distributed about P^{old}. This control variable sets the step size so that, at the beginning of the process, the algorithm is forced to make large changes in variable values. At times the changes move the algorithm away from the optimum, which forces the algorithm to explore new regions of variable space. After a certain number of iterations, the new variable sets no longer lead to lower costs. At this point the value of T and d decrease by a certain percent and the algorithm repeats. The algorithm stops when T≃0.The decrease in T is known as the cooling schedule. Many different cooling schedules are possible. If the initial temperature is T_0 and the ending temperature is T_N, then the temperature at step n is given by (6.2).

$$T_n=f\,(T_0, T_N, N, n) \quad (6.2)$$

Where, f decreases with time. Some potential cooling schedules are as follows:

a. Linearly decreasing: $T_n = T_0 - n\,(T_0-T_n)/N$

b. Geometrically decreasing: T_n = 0.99 Tn-1

c. Hayjek optimal: T_n = c/log(1+n), where c is the smallest variation required to get out of any local minimum.

Many other variations are possible. The temperature is usually lowered slowly so that the algorithm has a chance to find the correct valley before trying to get to the lowest point in the valley. This algorithm has been applied successfully to a wide variety of problems [16].

V. PSS DESIGN USING SIMULATED ANNEALING ALGORITHM

In this section the PSS parameters tuning based on the Simulated Annealing is presented. In this study the performance index is considered as (6). In fact, the performance index is the Integral of the Time multiplied Absolute value of the Error (ITAE). The ranges of the PSS parameters for design procedure are as follows:

1< Kpss <100 and 0.01< T < 1

It should be noted that SA algorithm is run several times and then optimal set of PSS parameters is selected. The optimum values of the PSS parameters are obtained using SA and summarized in the Table 8.1[17].

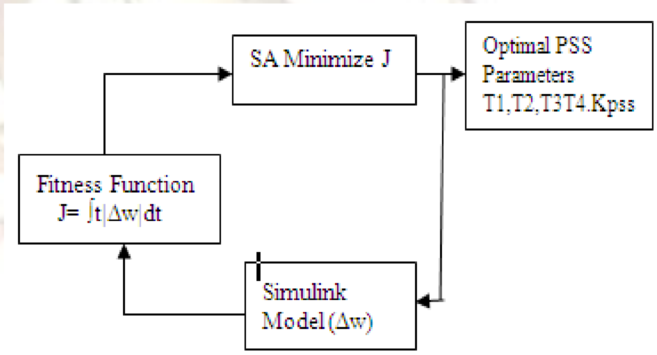

Figure 5.1: PSS Design with SA

VI. FAST OUTPUT SAMPLING FEEDBACK

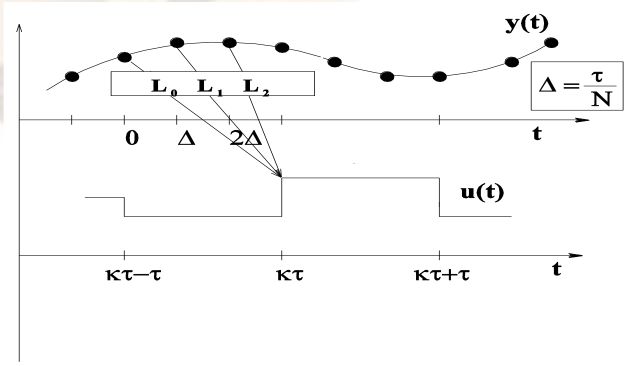

Figure 6.1: Fast Output Sampling Method

In this technique an output feedback law is used to realize a discrete state feedback gain by multirate observations of the output signal. The control signal is held constant during each sampling interval τ. Let (Φ,Γ,C) be the system [2] sampled at rate $1/\Delta$ where $\Delta = \tau/N$. Let υ denote the observability index of (Φ,C). N is chosen to be greater than or equal to υ. Output measurements are taken at time instants $t = l\Delta, l = 0,1,......, N-1$. The control signal u (t), which is applied during the interval, $k\tau \le t \prec (k+1)\tau$ is then constructed as a linear combination of the last N output observations [10].

Consider a discrete -time system having at time $t = k\tau$, the fast output samples

$$y_k = \begin{bmatrix} y(k\tau-\tau) & y(k\tau-\tau+\Delta) & .. & .. & y(k\tau-\Delta) \end{bmatrix} \quad (7)$$

Then a representation for this system is

$$x(k+1) = \Phi_\tau xk + \Gamma_\tau uk, \quad (8)$$
$$y(k+1) = C_0 xk + D_0 uk,$$

Where C_0 and D_0 are defined as

$$C_0 = \begin{bmatrix} C \\ C\Phi \\ . \\ . \\ C\Phi^{N-1} \end{bmatrix}, \quad D_0 = \begin{bmatrix} 0 \\ C\Gamma \\ . \\ .C\sum_{j=0}^{N-2}\Phi^j\Gamma \end{bmatrix}$$

Let F be an initial state feedback gains such that the closed loop system matrix $(\Phi_\tau + \Gamma_\tau F)$ has no eigenvalues at the origin. Then one can define a fictitious measurement matrix,

$$\tilde{C}(F,N) = (C_0 + D_0 F)(\Phi_\tau + \Gamma_\tau F)^{-1} \quad (9)$$

, which satisfies the fictitious measurement equation

$$y(k) = \tilde{C}x(k) \quad (10)$$

The control law is of form

$$uk = Ly_k \quad (11)$$

For the output feedback gain L to realize the effect of F it must satisfy

$$x_{k+1} = (\Phi_\tau + \Gamma_\tau F)x_k = (\Phi_\tau + \Gamma_\tau LC)x_k$$

i.e. $LC = F$ (12)

To reduce this effect we relax the condition that **L** exactly satisfy the above linear equation and include a constraint on the **L**

$$\|\mathbf{L}\| < \rho_1$$
$$\|\mathbf{L}D_0 - F\Gamma_\tau\| < \rho_2 \quad (13)$$
$$\|\mathbf{L}\mathbf{C} - F\| < \rho_3$$

LMI Formulation of above equations is

$$\begin{bmatrix} -\rho_1^2 I & \mathbf{L} \\ \mathbf{L}^T & -I \end{bmatrix} < 0$$
$$\begin{bmatrix} -\rho_2^2 I & (\mathbf{L}D_0 - F\Gamma_\tau) \\ (\mathbf{L}D_0 - F\Gamma_\tau)^T & -I \end{bmatrix} < 0 \quad (14)$$
$$\begin{bmatrix} -\rho_3^2 I & (\mathbf{LC} - F) \\ (\mathbf{LC} - F) & -I \end{bmatrix} < 0$$

VII. MULTI MODEL SYNTHESIS

Let us consider a family of plant S = { A_i, B_i, C_i} , defined by [10]

$$\dot{\mathbf{x}} = \mathbf{A_i x} + \mathbf{B_i u} \quad (15)$$
$$\mathbf{y} = \mathbf{C_i x} \qquad \mathbf{i = 1,......M}$$

By sampling at the rate of 1/Δ, we get a family of discrete systems

$$\{\mathbf{\Phi_i, \Gamma_i, C_i}\}$$

Augmented system defined below

$$\tilde{\Phi} = \begin{bmatrix} \Phi_1 & 0 & . & 0 \\ 0 & \Phi_2 & . & . \\ . & . & . & . \\ . & . & . & \Phi_M \end{bmatrix}, \quad \tilde{\Gamma} = \begin{bmatrix} \Gamma_1 & 0 & . & 0 \\ 0 & \Gamma_2 & . & . \\ . & . & . & . \\ . & . & . & \Gamma_M \end{bmatrix},$$

$$\tilde{C} = [\,\mathbf{C_1} \quad \mathbf{C_2} \quad . \quad \mathbf{C_M}\,] \quad (16)$$

Let (Φ_i, Γ_i, C_i) denote the system at the rate 1/Δ

$$x_{k+1} = \Phi_{\tau i} x_k + \Gamma_{\tau i} u_k \quad (17)$$
$$y_{k+1} = C_{0i} + D_{0i} u_k$$

Where

$$C_{0i} = \begin{bmatrix} C_i \\ C_i\Phi_i \\ . \\ . \\ C_i\Phi_i^{N-1} \end{bmatrix}, \quad \mathbf{D_{0i}} = \begin{bmatrix} 0 \\ C_i\Gamma_i \\ . \\ . \\ C_i\sum_{j=0}^{N-2}\Phi_i^{\,j}\Gamma_i \end{bmatrix} \quad (18)$$

Assume that the state feedback gain F has been designed that ($\Phi_{\tau i}+\Gamma_{\tau i}$ F) has no eigenvalues at the origin.

Then, assuming that in intervals k τ < t < kτ +τ

$$u(t) = Fx(k\tau) \quad (19)$$

One can define the fictitious measurement matrix

$$\mathbf{C_i}(F,N) = (C_{0i} + D_{0i}F)(\Phi_{\tau i} + \Gamma_{\tau i}F)^{-1} \quad (20)$$

which satisfies the fictitious measurement equation y_k =$\mathbf{C}_i x_k$.

For **L** to realize the effect of F, it may satisfy

LCi=F i=1,… …… M (21)

This equation can be written as

$$\mathbf{L}\tilde{C} = \tilde{F}$$

Where $\tilde{\mathbf{C}} = [\mathbf{C_1} \quad \mathbf{C_2} \quad . \quad . \quad \mathbf{C_M}],$

$$\tilde{F} = [F \quad F \quad . \quad . \quad F] \quad (22)$$

To reduce this effect we relax the condition that L exactly satisfy the above linear equation and include a constraint on the L

$$\|\mathbf{L}\| < \rho_1$$
$$\|\mathbf{L}D_{0i} - F\Gamma_{\tau i}\| < \rho_{2i} \quad i = 1,....., \ M$$
$$\|\mathbf{L}C_i - F\| < \rho_3$$

(23)

LMI Formulation of above equations are

$$\begin{bmatrix} -\rho_1^{\,2} I & \mathbf{L} \\ \mathbf{L}^T & -I \end{bmatrix} < 0$$

$$\begin{bmatrix} -\rho_{2i}^{\,2} I & (\mathbf{L}D_{0i} - F\Gamma_{\tau i}) \\ (\mathbf{L}D_{0i} - F\Gamma_{\tau i})^T & -I \end{bmatrix} < 0 \qquad (24)$$

$$\begin{bmatrix} -\rho_{3i}^{\,2} I & (\mathbf{L}\mathbf{C}_i - F) \\ (\mathbf{L}\mathbf{C}_i - F) & -I \end{bmatrix} < 0$$

VIII. CASE STUDY

A SIMULINK based block diagram including all the nonlinear blocks is generated with single machine data as given in [13]. SA is used in this paper to tune PSS parameters as described in the section 5. Table 8.1 presents the PSS parameters as designed by SA and Tw=10. The sixteen models of single machine infinite bus with different generating power (P_{go}) from 0.4 pu to 1.0 pu and different external impedances x_e from 0.2 to 0.8. pu. Response of all sixteen plants has been studied and found that the same SA and fast output sampling method are working satisfactorily. The figures 8.1-8.6 shows comparison of the responses of the plants for SA and fast output sampling method based PSS. Fast output sampling method gives better results compared to SA-PSS.

Table 8.1

Optimal PSS parameters as designed by SA [17].

T1	T2	T3	T4	Kpss
0.3044	0.0198	0.3044	0.0198	7.4099

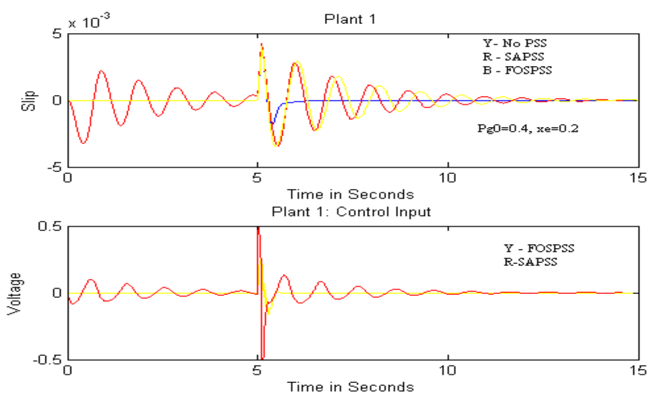

Figure 8.1: Closed loop Responses of Single Machine Infinite bus with No PSS, Robust Fast Output Sampling and SA PSS.

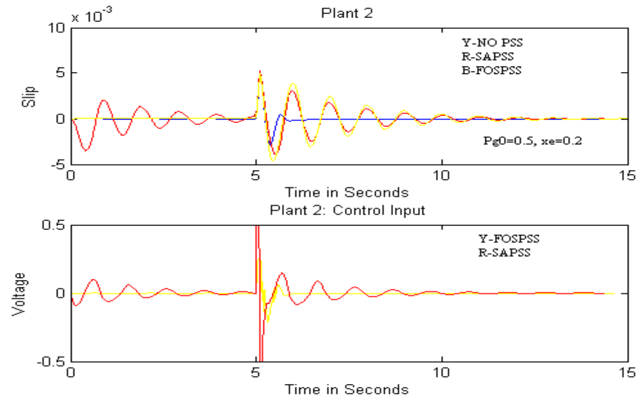

Figure 8.2: Closed loop Responses of Single Machine Infinite bus with No PSS, Robust Fast Output Sampling and SA PSS

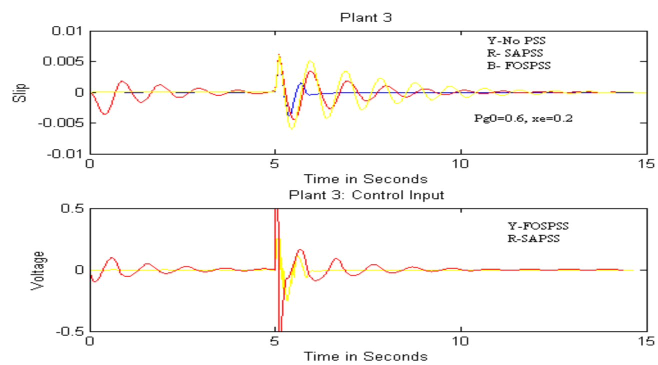

Figure 8.3: Closed loop Responses of Single Machine Infinite bus with No PSS, Robust Fast Output Sampling and SA PSS

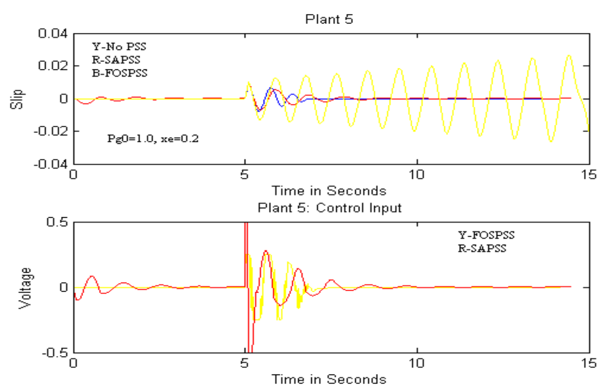

Figure 8.4: Closed loop Responses of Single Machine Infinite bus with No PSS, Robust Fast Output Sampling and SA PSS

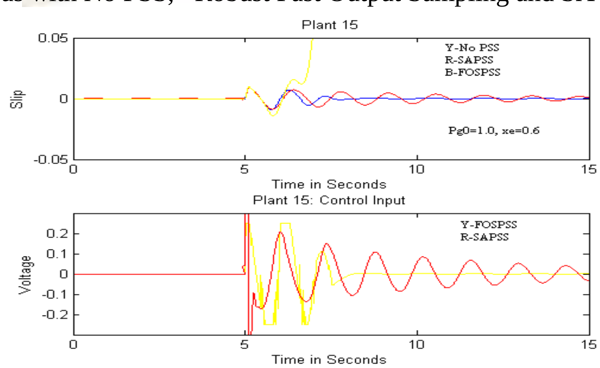

Figure 8.5: Closed loop Responses of Single Machine Infinite bus with No PSS, Robust Fast Output Sampling and SA PSS

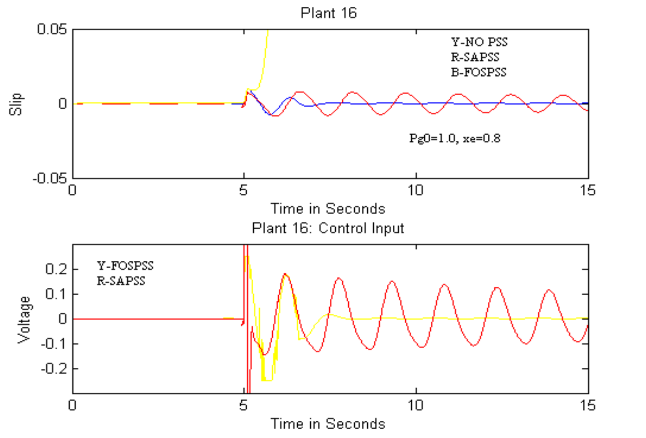

Figure 8.6: Closed loop Responses of Single Machine Infinite bus with No PSS, Robust Fast Output Sampling and SA PSS

IX. CONCLUSION

The system considered for simulations, is single machine infinite bus system with 16 different plants. Simulations with SA and fast output sampling method are carried out with all plants and gives encouraging results. The results show that for different plants, the responses of the SA-PSS and fast output sampling method are stable. Fast output sampling method gives better results compared to SA-PSS.

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