Proceedings of the 2007 American Control Conference
Marriott Marquis Hotel at Times Square
New York City, USA, July 11-13, 2007

Relay-Free Sliding Mode Control Technique based Power System Stabilizer for Single Machine Infinite Bus System

Vitthal Bandal and B. Bandyopadhyay *Member, IEEE*

***Abstract*— The paper presents a new method for design of power system stabilizer (PSS) based on relay-free sliding mode control technique. The control objective is to enhance the stability and to improve the dynamic response of the single machine infinite bus (SMIB) system. We apply this relay-free sliding mode controller to design power system stabilizer for demonstrating the availability of the proposed approach.**

***Index Terms*— Relay-free sliding mode control, power system stabilizer, fast output sampling, robust control.**

I. INTRODUCTION

In recent years, considerable efforts have been made to enhance the dynamic stability (or small signal stability) [1] of power systems. Modern voltage regulators and excitation systems with fast response and high ceiling voltages can be used to improve the transient stability by increasing the synchronizing torque of a machine. However, they may have a negative impact on the damping of rotor swings. In order to reduce this undesirable effect and improve the system dynamic performance, it is useful to introduce supplementary signals to increase the damping.

Over the past four decades, various control methods have been proposed for PSS design to improve overall system performance. Among these, conventional PSS of the lead-lag compensation type [2] have been adopted by most utility companies because of their simple structure, flexibility and ease of implementation. However, the performance of these stabilizers can be considerably degraded with the changes in the operating condition during normal operation. Since power systems are highly nonlinear, conventional fixed-parameter PSSs cannot cope with great changes in the operating conditions. There are two main approaches to stabilizing a power system over a wide range of operating conditions, namely adaptive control and robust control [3]. Adaptive control is based on the idea of continuously updating the controller parameters according to recent measurements. However, adaptive controllers have generally poor performance during the learning phase, unless they are properly initialized. Successful operating of adaptive controllers requires the measurements to satisfy strict persistent excitation conditions. Otherwise the adjustment of the controller's parameters fails. Robust control provides an effective approach to dealing with uncertainties introduced by variations of operating conditions.

Prof. Vitthal Bandal is with Electrical Engineering Department, Govt. College of Engineering Pune, Pune-411 005, INDIA vsb@coep.org.in

Prof. B. Bandyopadhyay is with Systems and Control Engineering, Indian Institute of Technology, Bombay Mumbai-400076, INDIA bijnan@ee.iitb.ac.in

Among many techniques available in the control literature, H_∞ and variable structure have received considerable attention in the design of PSSs. The H_∞ approach is applied by Chen [3] to PSS design for a single machine infinite bus system. The basic idea is to carry out a search over all possible operating points to obtain a frequency bound on the system transfer function. Then a controller is designed so that the worst-case frequency response of the closed loop system lies within prespecified frequency bounds. It is to be noted that the H_∞ design requires an exhaustive search and results in a high order controller. On the other hand the variable structure control is designed to drive the system to a sliding surface on which the error decays to zero [4]. Perfect performance is achieved even if parameter uncertainties are present. However, such performance is obtained at the cost of high control activities (chattering)

One of the major disadvantages of a switching function based discrete time sliding mode control is the chattering problem. This is due to the presence of relay in the control. The control effort cannot be made arbitrarily small even when the system state is very close to the sliding surface. A solution to this problem may be a control law that allows reduction in the control signal strength as the system approaches the sliding surface while at the same time retaining the finite time convergence property [5].

In this paper PSS design using relay-free discrete time SMC technique is proposed. In this technique, the control is so tuned that the sliding surface is exactly reached. Thus, the chattering problem is eliminated. Simulations results for single machine infinite bus (SMIB) system are presented to show the effectiveness of the proposed control strategies in damping the oscillation modes.

The paper is organized as follows. Section II presents basics power system modeling. Section III presents the review on power system stabilizer. Section IV Multirate output feedback sliding mode control technique. Section V presents the proposed relay-free sliding mode control method; the same is used for PSS design of SMIB system as discussed in section VI as case study. Conclusions are drawn in Section VII. The controller is validated using non-linear model simulation.

II. POWER SYSTEM MODELING

1) Small Signal Analysis of Single Machine Infinite Bus System: Consider a single machine infinite bus system shown in Fig. 1. For simplicity, we assume a synchronous machine represented by model 1.0 (neglecting damper windings both in d and q axes). Also, the armature resistance of the machine

1-4244-0989-6/07/$25.00 ©2007 IEEE.

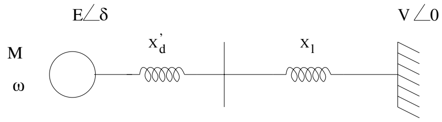


Fig. 1. Single line diagram of Single Machine Infinite Bus System

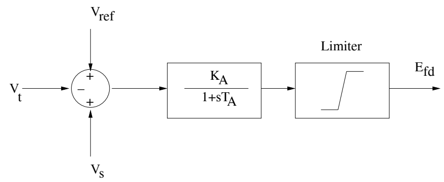


Fig. 2. Block diagram of Excitation System

is neglected. AVR and exciter is represented by a first order transfer function as shown in Fig. 2 [1]

The rotor mechanical equations are

$$\frac{d\delta}{dt} = \omega_B \left(S_m - S_{mo}\right), \tag{1}$$

$$2H\frac{dS_m}{dt} = -DS_m + T_m - T_e, \tag{2}$$

$$T_e = \left[E_q^{'} i_q - \left(x_q - x_d^{'}\right) i_d i_q\right]. \tag{3}$$

These equations are used to build up SIMULINK model for analysis.

The block diagram excitation system is shown in Fig. 2.

2) System Representation: The state space representation is concerned not only with input and output properties, but also with its complete internal behavior. In contrast, the transfer function representation specifies only the input/output behavior. If state space representation of a system is known, the transfer function is uniquely defined. In this sense, the state space representation is a more complete description of the system.

The overall block diagram of the system, consisting of the representation of the rotor swing equations, flux decay and excitation system is shown in Fig. 3. Here the damping term (D) in the swing equations is neglected for convenience.

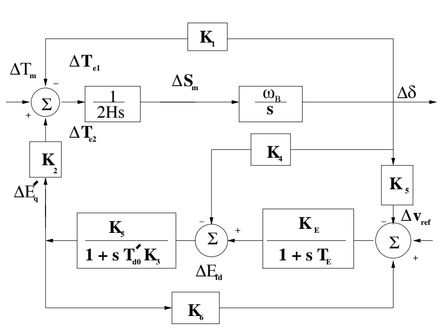


Fig. 3. Overall block diagram of Single Machine Infinite Bus System

A. State Space Model of Single Machine Infinite Bus System

From the block diagram shown in Fig. 3, the following state space equations for the entire system can be derived using Heffron-Phillip's model: [1], [6]

$$\begin{aligned} \dot{x} &= [A]x + [B]\left(\Delta V_{ref} + \Delta V_s\right) \\ y &= Cx \end{aligned} \tag{4}$$

where

$$x = \begin{bmatrix} \Delta S_m & \Delta\delta & \Delta E_{fd} & \Delta E_q^{'} \end{bmatrix}^T \tag{5}$$

$$[A] = \begin{bmatrix} 0 & \omega_B & 0 & 0 \\ -\frac{K_1}{2H} & -\frac{D}{2H} & -\frac{K_2}{2H} & 0 \\ -\frac{K_4}{T_{do}^{'}} & 0 & -\frac{1}{T_{do}^{'}K_3} & \frac{1}{T_{do}^{'}} \\ -\frac{K_E K_5}{T_E} & 0 & -\frac{K_E K_6}{T_E} & -\frac{1}{T_E} \end{bmatrix} \tag{6}$$

$$[B]^T = \begin{bmatrix} 0 & 0 & 0 & \frac{K_E}{T_E} \end{bmatrix} \tag{7}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} \tag{8}$$

Also, S_m is machine slip, δ is machine shaft angular displacement in degrees, E_{fd} is generator field voltage in pu and $E_q^{'}$ is voltage proportional to field flux linkages of machine in p.u. Similarly, y denotes the output equation of the machine.

The mechanical damping term D, is included in the swing equation. The eigenvalues of the matrix should lie in LHP in the 's' plane for the system to be stable. The effect of various parameters (for example K_E & T_E) can be examined from eigenvalue analysis. The elements of matrix $[A]$ are dependent on the operating condition.

III. Power System Stabilizer

It is well established that fast acting exciters with high gain AVR can contribute to oscillatory instability in power systems. This type of instability is characterized by low frequency (0.2 to 3.0 Hz) oscillations which can persist (or even grow in magnitude) for no apparent reasons [1]. The major factors that contribute the instability are

(a) loading of the generator or tie line
(b) power transfer capability of transmission lines
(c) power factor of the generator(leading power factor operation is more problematic than lagging power factor operation)
(d) AVR gain.

A cost efficient and satisfactory solution to the problem of oscillatory instability is to provide damping for generator rotor oscillations. This is conveniently done by providing Power System Stabilizers (PSS) which are supplementary controllers in the excitation systems. The signal V_s in Fig. 2 is the output from PSS which has input signal derived from rotor speed, frequency, electrical power or a combination of these variables. The objective of designing PSS is to provide additional damping torque without affecting the synchronizing torque at critical frequencies [6].

A. Basic Concept

The basic function of a PSS is to extend the angular stability of a power system. This is done by providing supplemental damping to the oscillation of synchronous machine rotors through the generator excitation. This damping is provided by a electric torque applied to the rotor that is in phase with the speed variations. The oscillations of concern typically occur in the frequency range of 0.2 to 3.0 Hz, and insufficient damping of these oscillations may limit ability to transmit power.

In practical system, the various modes (of oscillation) can be grouped into three broad categories [7].

A. Intra-plant modes (generator G_1 swings against G_2) in which only the generators within a power plant participate. The oscillation frequencies are generally high in the range of 1.5 to 3.0 Hz.
B. Local modes in which several generators (G_1 and G_2 swing together against G_3) in an area participate. The frequencies of oscillations are in the range of 0.8 to 1.8 Hz.
C. Inter area modes in which generators (generators G_1 to G_3 swing against G_4) over an extensive area participate. The oscillation frequencies are low and in the range of 0.2 to 0.5 Hz.

The above categorization can be illustrated with the help of a system consisting of two areas connected by weak AC tie as shown in Fig. 4. Area 2 is represented by a single generator G_4. The area 1 contains 3 generators G_1, G_2 and G_3.

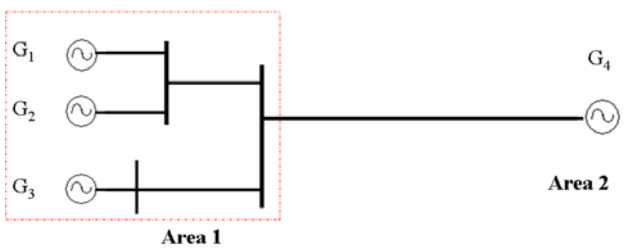


Fig. 4. A sample power system

The distinction between local modes and inter area modes applies mainly for those systems which can be divided into distinct areas which are separated by long distances. For systems in which the generating stations are distributed uniformly over a geographic area, it would be difficult to distinguish between local and inter area modes from physical considerations. However, a common observation is that the inter area modes have the lowest frequency and participation from most of the generators in the system spread over a wide geographic area [1].

The PSS are designed mainly to stabilize local and inter area modes.

1) Performance objectives: The main objective of providing PSS is to increase the power transfer in the network, which would otherwise be limited by oscillatory instability. The PSS also must function properly when system is subjected to large disturbances.

PSS can extend power transfer stability limits which are characterized by lightly damped or spontaneously growing oscillations in the 0.2 to 3.0 Hz frequency range. This is accomplished via excitation control to contribute damping to the system modes of oscillations. Consequently, it is the stabilizer's ability to enhance damping under the least stable conditions is important. Additional damping is primarily required under the conditions of weak transmission and heavy load which may occur, while attempting to transmit power over long transmission lines from the remote generating plants or relatively weak tie between systems. Contingencies, such as line outage, often precipitate such conditions. Hence system normally have adequate damping can often benefit from stabilizers during such conditions.

B. Classical Stabilizer implementation procedure

1) Control and Tuning: The conflicting requirements of local and inter-area mode damping and stability under both small signal and transient conditions have led to many different approaches for the control and tuning of PSSs. Methods investigated for the control and tuning include state-space/frequency domain techniques, residue compensation, phase compensation/root locus of a lead-lag controller, desensitization of a robust controller, pole-placement for a PID-type controller, sparsity techniques for a lead-lag controller and a strict linearization technique for a linear quadratic controller. The diversity of the approaches can be accounted for by the difficulty of satisfying the conflicting design goals, and each method having its own advantages and disadvantages. This is the crux of the problem of low frequency oscillation damping by the application of PSSs.

Implementation of a PSS 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. The transfer function of a generic PSS having washout circuit, dynamic compensator and torsional filter may be expressed as

$$G_p(s) = K_s \frac{T_w s\,(1+sT_1)\,(1+sT_3)}{(1+T_w s)\,(1+sT_2)\,(1+sT_4)} G_f(s), \quad (9)$$

where K_s represents stabilizer gain and $G_f(s)$ represents combined transfer function of torsional filter and input signal transducer.

$$G_f(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}. \quad (10)$$

The stabilizer frequency characteristic is adjusted by varying the time constant T_w, T_1, T_2, T_3 and T_4. It will be noted that the stabilizer transfer function includes the effect of both the input signal transducer and filtering required to attenuate the stabilizer gain at turbine-generator shaft torsional frequencies. These effects, dictated by other considerations, must be considered in addition to the "plant". The torsional filter in the PSS is essentially a band rejection filter to attenuate the first torsional modes frequency. The maximum possible change in damping (ζ) of any torsional mode is less than some fraction of the inherent torsional damping. The phase lag of the filter in the frequency (ω_n) range of 1 to 3 Hz is minimized. This filter may not be needed in case torsional modes are well damped or if other signals are used. The output of PSS must be limited to prevent the PSS acting to counter the action of AVR.

The block diagram of the PSS used in industry is shown in Fig. 5. It consists of a washout circuit, dynamic compensator, torsional filter and limiter.

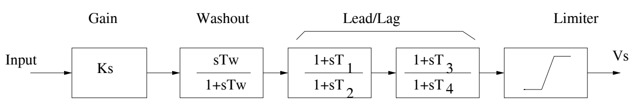


Fig. 5. Structure of PSS

Since the PSS must produce a component of electrical torque in phase with the speed deviation, phase lead blocks circuits are used to compensate for the lag (hence, lead-lag) between the PSS output and the control action, the electrical torque. The number of lead-lag blocks needed depends on the particular system and the tuning of the PSS. The PSS gain K_S 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 gain value, after which the damping begins to decrease. All of the variables of the PSS must be determined for each type of generator separately because of the dependence on the machine parameters.

To determine the time constants of a lead-lag block, we need to find out the plant transfer function $GEP(s)$ for each generator. The plant transfer function can be obtained from the relation,

$$GEP(s) = \left.\frac{\Delta T_e}{\Delta V_s}\right|_{\Delta\omega=0.} \tag{11}$$

where,
T_e = Electrical torque
V_s = Output voltage of PSS
ω = Speed of the generator.
$\Delta\omega = 0$ can be achieved by selecting very high value of inertia of the generator for which one wants to design PSS. Using this transfer function, the frequency response can be obtained over a range of frequencies. The time constants of the lead/lag block can be selected such that they provide a phase lead for the input signal in the range of frequencies that are of interest (0.2 Hz to 3 Hz). Based on the above procedure, PSSs are designed for the power system [1].

The design of conventional PSS based on a trial an error procedure condition is inadequate, inefficient and time consuming. Since power systems are nonlinear and their dynamic characteristics change with time and operating conditions, it is important to take into consideration the changes in the dynamic characteristics of the system when designing the PSS. One way of achieving this is to consider multiple operating conditions of the power system when designing the PSS.

IV. Multirate Output feedback Sliding Mode Control Technique

In the following, multirate output feedback technique and multirate output to state relationship are briefly reviewed.

A. *Multirate output feedback technique*

In this technique an output feedback gain is obtained to realize a discrete state feedback gain by multi-rate observations of the output signal. The control signal is held constant during each sampling interval τ [8].

Consider the m-input, p-output, n^{th} order continuous time LTI system

$$\begin{aligned} \dot{x} &= Ax + Bu, \\ y &= Cx. \end{aligned} \tag{12}$$

Where $x \in R^n$, $u \in R$, $y \in R$ and the matrices A, B and C are of appropriate dimensions.

Let the system given by Eqn. (12) be sampled at a sampling interval of τ sec be represented as,

$$x(k+1) = \Phi_\tau x(k) + \Gamma_\tau u(k), \tag{13}$$
$$y(k) = Cx(k). \tag{14}$$

Let the control input u be applied with a sampling interval of τ sec and the system output is sampled with a faster sampling period of $\Delta = \tau/N$ sec., where N is an integer greater than or equal to the observability index ν of the system. Let the system sampled at the Δ interval be represented using the triplet (Φ, Γ, C). It is assumed, without loss of generality that the pair (Φ_τ, Γ_τ) is controllable and the pair (Φ, C) is observable.

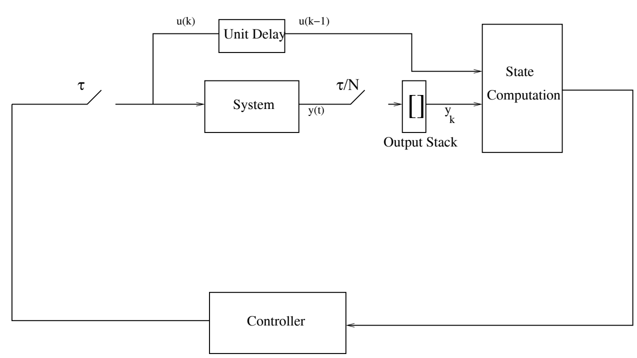


Fig. 6. Illustration of Multirate Output Feedback based Control Philosophy

Using the fact that u is unchanged in the interval $\tau \le t < (k+1)\tau$, the τ system state dynamics may be constructed from the Δ system dynamics. Further, if the past N multirate-sampled system outputs are represented as

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

and the notation k is used to represent $k\tau$, for brevity, then the multirate output sampled system dynamics can be represented as in the following manner.

$$x(k+1) = \Phi_\tau x(k) + \Gamma_\tau u(k) \quad (15)$$
$$y_{k+1} = C_0 x(k) + D_0 u(k) \quad (16)$$

where,

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

B. Multirate Output to State Relationship

The state $x(k)$ can be expressed in terms of system outputs y_{k+1} and control input $u(k)$ using Eqn. (16) as [9]

$$x(k) = (C_0^T C_0)^{-1} C_0^T (y_{k+1} - D_0 u(k)) \quad (17)$$

Remark 1: Since the value of N is chosen to be greater than the observability index of the system, C_0 would be a $pN \times n$ matrix of rank n. Hence, $\left(C_0^T C_0\right)$ would also be a matrix of rank n. Moreover, it would be a $n \times n$ matrix, and hence would be invertible.

Substituting the value of $x(k)$ from Eqn. (17) in Eqn. (15), expression for $x(k+1)$ can be derived as

$$x(k+1) = L_y y_{k+1} + L_u u(k),$$

where

$$L_y = \Phi_\tau (C_0^T C_0)^{-1} C_0^T,$$
$$L_u = \Gamma_\tau - \Phi_\tau (C_0^T C_0)^{-1} C_0^T D_0,$$

or equivalently, the state $x(k)$ can be expressed using the past multirate output samples y_k and the immediate past control input $u(k-1)$ as

$$x(k) = L_y y_k + L_u u(k-1). \quad (18)$$

Thus, using the relation given by Eqn. (18), any control of the form $u(k) = fu(x(k))$ can be realized using past input and output samples as $u(k) = fu(L_y y_k + L_u u(k-1))$.

An illustration of this multirate control philosophy is given in Fig. 6

V. Relay-free Sliding Mode Control

In this technique, the control structure is changed so as to deactivate the relay when system is close to the sliding surface [5].

Consider the m-input, p-output, n-th order discrete-time system representation, sampled at a sampling interval of τ sec.

$$x(k+1) = \Phi_\tau x(k) + \Gamma_\tau u(k), \quad (19)$$
$$y(k) = Cx(k).$$

The adaptive sliding mode control as given by Utkin et. al., [10] is

$$u(k) = \begin{cases} u_{eq}(k) & \text{when} \|u_{eq}(k)\| \le u_0 \\ u_0 \frac{u_{eq}(k)}{\|u_{eq}(k)\|} & \text{when} \|u_{eq}(k)\| > u_0 \end{cases} \quad (20)$$

where,

$$u_{eq}(k) = -\left(c^T\Gamma_\tau\right)^{-1}\left(s(k) + \left(c^T\Phi_\tau - c^T\right)x(k)\right) \quad (21)$$

and the bound on the control signal, u_0 satisfies the inequality

$$u_0 > \left\|\left(c^T\Gamma_\tau\right)^{-1}\right\| \left\|\left(c^T\Phi_\tau - c^T\right)x(k)\right\| \quad (22)$$

The equivalent control given by Eqn. 21 is based on states of the system. But all states of the power system may not be available for measurement. Hence, the control law can be computed using output information by representing the system state in terms of output as discussed in Section IV-B and given by Eqn. 18.

$$u_{eq}(k) = F_y y_k + F_u u(k-1) \quad (23)$$

where

$$F_y = -\left(c^T\Gamma_\tau\right)^{-1}\left(c^T\Phi_\tau\right)L_y,$$
$$F_u = -\left(c^T\Gamma_\tau\right)^{-1}\left(c^T\Phi_\tau\right)L_u.$$

This control law given by Eqn. (23) is used to design relay-free sliding mode control technique based PSS as discussed below.

VI. Case Study: PSS design for single machine infinite bus (SMIB) system

A. Linearization of power system

The nonlinear differential equations governing the behavior power system can be linearized about a particular operating point to obtain a linear model which represents the small signal oscillatory response of a power system. A SIMULINK based block diagram including all the nonlinear blocks can also be used to generate the linear state space model of the system is obtained. This linear model is then discretized with the sampling time $\tau = 0.05$ sec.

The following parameters are used for simulation of the single machine infinite bus system model [1]:

H = 5, T'_{do} = 6 sec., D = 0.0, K_E = 100, T_E = 0.02 sec., x_e = 0.6 p.u.

B. Classical power system stabilizer design for a power system

The classical power system stabilizer (PSS) is designed as discussed in section III-B.

The transfer function for classical PSS used in this analysis is

$$CPSS = 9\left(\frac{10s}{1+10s}\right)\left(\frac{1+0.0643s}{1+0.0321s}\right) \quad (24)$$

1) Design of PSS using Relay-free sliding mode control technique for Single Machine Infinite Bus (SMIB) system: The single machine infinite bus power system data is considered for designing relay-free sliding mode control technique based power system stabilizer. The single line diagram of the system is shown in Fig. 1.

As discussed in the section II, the SISO linearized model of SMIB system at nominal operating condition is obtained, which is represented by Eqn. (4) and the discrete time representation of the same is given by Eqn. (19).

The relay-free sliding mode control given by Eqn. (23) is used for PSS design for SMIB and is given as,

$$u_{eq}(k) \quad = \quad F_y y_k + F_u u(k-1).$$

where the numerical values of F_y and F_u are as given below.

$$\begin{aligned} F_y &= 10^3 \times \left[\begin{array}{cccc} 1.5144 & -5.4028 & 6.1664 & -2.2604 \end{array} \right], \\ F_u &= -1.8974, \end{aligned}$$

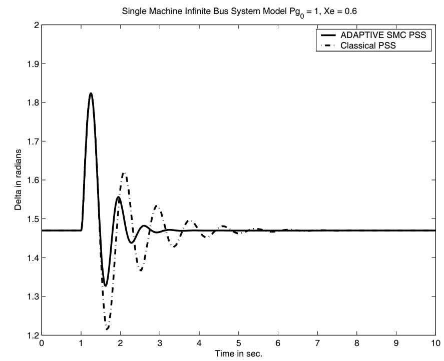
Also, bound on the control is given as

$$u_0 = 0.1$$

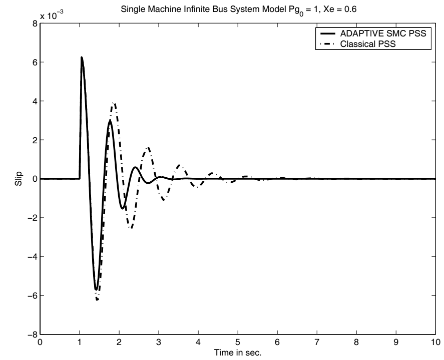
2) Simulation with Non-linear model: The slip of the machine is taken as output. Using this output signal a relay-free sliding mode control as discussed in section V is designed.

Simulation results for SMIB system for nominal operating condition, with relay-free (adaptive sliding) mode controller and classical controller are shown in Fig. 7.

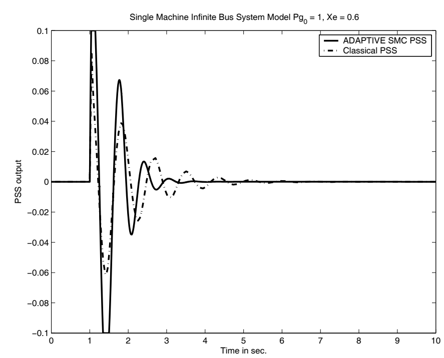
As shown in plots, the proposed controller is able to damp out the oscillations in 2 to 3 seconds after clearing the fault for the active power of $P_{g0} = 1.0$ with external line inductance of $x_e = 0.6pu$. Here fault considered is change in the generator output.



(a) Delta response



(b) Slip response



(c) PSS Output

Fig. 7. Delta, Slip and PSS output response of SMIB with Classical PSS and relay-free sliding mode control PSS ($P_{g0} = 1.0, V_{ref} = 1.0pu$ and $x_e = 0.6$)

VII. Conclusion

This paper proposes, the design of PSS for SMIB power system based on relay-free sliding mode control technique. The slip signal is taken as output and relay-free sliding mode control is applied at an appropriate sampling rate. It is found that designed controller provides good damping enhancement. The simulations clearly show the elimination of chattering in control by the proposed technique.

References

[1] K. R. Padiyar, *Power System Dynamics Stability and Control*. Second Edition, B S Publications, Hyderabad, 2002.

[2] F. P. DeMello, P. J. Nolan, T. F. Laskowski, and J.M.Undrill, "Co-ordinated application of stabilizers in multi-machine power systems," *IEEE Transanctions on Power Apparatus and Systems*, vol. PAS-99, pp. 892–901, May/June 1980.

[3] S. Chen and O. P. Malik, "H_∞ optimization- based power system stabilizer design," in *IEE proceedings Part-C*, vol. 142, no. 2, March 1995, pp. 179–184.

[4] M. L. Kothari, K. Bhattacharya, and J. Nanda, "Adaptive power system stabilizer based on pole shifting technique," in *IEE Proceedings-C*, vol. 143, 1996, pp. 96–98.

[5] R. J. Wai, "Adaptive sliding-mode control for induction servomotor drive," in *IEE Proc: on Electric Power Applications*, vol. 147, no. 6, November 2000, pp. 553–562.

[6] F. D. DeMello and C. Concordia, "Concepts of synchronous machine stability as affected by excitation control," *IEEE Transanctions on Power Apparatus and Systems*, vol. PAS-88, pp. 316–329, 1969.

[7] E. V. Larsen and D. A. Swann, "Applying power system stabilizers, Part I: General Concepts, Part II: Performance Objectives and Tuning Concepts, Part III: Practical Considerations," *IEEE Transanctions on Power Apparatus and Systems*, vol. PAS-100, no. 6, pp. 3017–3046, June 1981.

[8] H. Werner and K. Furuta, "Simultaneous stabilization based on output measurement," *Kybernetika*, vol. 31, pp. 395–411, 1995.

[9] S. Janardhanan and B. Bandyopadhyay, "A new approach for designing a fast output sampling feedback controller," in *Proc.1st National Conference on Instrumentation and Control*, National Inst. of Tech., Trichy, December 2003, p. Paper No. ICECON 160933.

[10] G. Bartolini, A. Ferrara, and V. I. Utkin, "Adaptive sliding mode control in discrete-time systems," *Automatica*, vol. 31, no. 5, pp. 769–773, May 1995.