# DECENTRALIZED SLIDING MODE CONTROL TECHNIQUE BASED POWER SYSTEM STABILIZER (PSS) FOR MULTIMACHINE POWER SYSTEM

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Abstract: Power System Stabilizers (PSSs) are added to excitation system to enhance the damping of low frequency oscillations. In this paper, the design of PSS for multimachine power system (MMPS) using output feedback sliding mode control is proposed. The non-linear model of a multimachine power system is linearized about an operating point and the linearized model of the plant is obtained. The output feedback sliding mode controller is designed and is applied to non-linear plant model of the multimachine power system at that operating (equilibrium) point. This method does not require the complete states of the system for feedback and is easily implementable.

## 1 INTRODUCTION

In recent years considerable efforts have been made to enhance the dynamic stability (or small perturbation stability) of power systems. Although modern voltage regulators and excitation systems with fast response speeds and high ceiling voltages can be used to improve the transient stability by increasing the synchronizing torque of a machine, their effect on the damping torque is small. In cases where system may operate with negative damping characteristics, the voltage regulator usually aggravates the situation by increasing the negative damping and hence instability may result in the system (Ramamurthy et al., 1996),(DeMello et al., 1980).

In order to reduce this undesirable effect and improve the system dynamic performance, it is useful to introduce supplementary signals to increase the damping. Several approaches have been reported in the literature to provide the damping torque required for improving the dynamic stability. A conventional power system stabilizer consists of a lead-lag network using filtered speed or power as input that is used to generate supplementary signal. In this paper, PSS design using output feedback sliding mode control technique has been proposed.

The brief outline of the paper is as follows: Section 2 presents basics of power system stabilizer. Section 3 presents the review on fast output sampling and state feedback sliding mode control. Section 4 presents output feedback sliding mode control method; the same is used for decentralized PSS design of a 10-machine 39-bus system. The designed controller is used to perform simulation on a non-linear model of the multimachine power system, to obtain the system response against disturbances.

## 2 POWER SYSTEM STABILIZER

### 2.1 Basic Concept of conventional PSS design

The basic function of a power system stabilizer is to extend stability limits by modulating generator excitation to provide damping to the oscillation of synchronous machine rotors relative to one another. The oscillations of concern typically occur in the frequency range of approximately 0.2 to 3.0 Hz, and insufficient damping of these oscillations may limit ability to transmit power. To provide damping, the stabilizer must produce a component of electrical torque, which is in phase with the speed changes. The implementation details differ, depending upon the stabilizer input signal employed. However, for any input signal, the transfer function of the stabilizer must compensate for the gain and phase of excitation system, the gen-

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erator and the power system, which collectively determines the transfer function from the stabilizer output to the component of electrical torque which can be modulated via excitation system (E.V.Larsen and D.A.Swann, 1981a).

## 2.2 Classical Stabilizer implementation procedure

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. The transfer function of a generic power system stabilizer may be expressed as

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

where $K_s$ represents stabilizer gain and $G_f(s)$ represents combined transfer function of torsional filter (if required) and input signal transducer. The stabilizer frequency characteristic is adjusted by varying the time constant $T_w, T_1, T_2, T_3$ and $T_4$. A torsional filter may not be necessary with signals like power or *delta-P-omega* signal (Kundur, 1993).

A power system stabilizer can be most effectively applied if it is tuned with an understanding of the associated power characteristics and the function to be performed by the stabilizer. Knowledge of the modes of power system oscillation to which the stabilizer is to provide damping establishes the range of frequencies over which the stabilizer must operate. Simple analytical models, such as that of a multimachine power systems(MMPS), can be useful in determining the frequencies of local mode oscillations during the planning stage of a new plant. It is also desirable to establish the weak power system conditions and associated loading for which stable operation is expected, as the adequacy of the power system stabilizer application will be determined under these performance conditions. Since the limiting gain of the some stabilizers, viz., those having input signal from speed or power, occurs with a strong transmission system, it is necessary to establish the strongest credible system as the “tuning condition” for these stabilizers. Experience suggest that designing a stabilizer for satisfactory operation with an external system reactance ranging from 20% to 80% on the unit rating will ensure robust performance (E.V.Larsen and D.A.Swann, 1981b).

## 2.3 Multi-machine System Analysis

Analysis of practical power system involves the simultaneous solution of equations consisting of synchronous machines, associated excitation system, prime movers, interconnecting transmission network, static and dynamic ( motor ) loads, and other devices such as HVDC converters, static var compensator. The dynamics of the machine rotor circuits, excitation systems, prime mover and other devices are represented by differential equations. This results in the complete system model consisting of large number of ordinary differential and algebraic equations (Kundur, 1993).

### 2.3.1 Generator Equations

The machine equations ( for j$^{th}$machine ) are

$$\frac{dE'_{qj}}{dt} = \frac{-1}{T'_{d0j}}[E'_{qj} - (x_{dj} - x'_{dj})i_{dj} - E_{fdj}] \quad (1)$$

$$\frac{d\delta_j}{dt} = \omega_B(S_{mj} - S_{mj0}), \quad (2)$$

$$\frac{dS_{mj}}{dt} = \frac{-1}{2H}[D_j(S_{mj} - S_{mj0}) - P_{mj} + P_{ej}] \quad (3)$$

Model 1.0 is assumed for synchronous machines by neglecting the damper windings. In addition, the following assumptions are made for simplicity (K.R.Padiyar, 1996).
1. The loads are represented by constant impedances.
2. Transients saliency is ignored by considering $x_q$= $x'_d$.
3. Mechanical power is assumed to be constant.
4. $E_{fd}$ is single time constant AVR.

### 2.3.2 State space model of multimachine system (Machine model 1.0)

The state space model of a 10-machine 39-bus multimachine power system, the single line diagram of which is shown in Fig.1 can be obtained using generator, transformer, network and loadflow data with variation in generator and network data as given below (K.R.Padiyar, 1996),

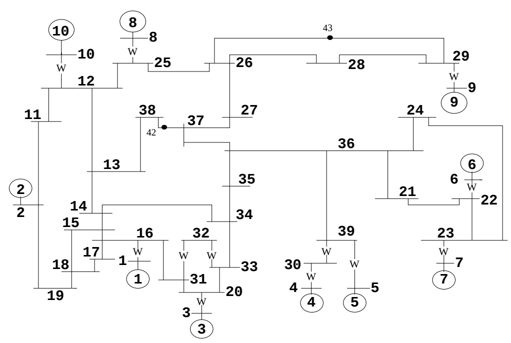

Figure 1: Single Line Diagram of 10 Machine 39-Bus System

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\left(\triangle \mathbf{V}_{ref} + \triangle \mathbf{V}_s\right), \quad (4)$$
$$\mathbf{y} = \mathbf{C}\mathbf{x}, \quad (5)$$

where

$$\mathbf{x} = [\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_{10}]^T, \; and \; \mathbf{y} = [y^1, y^2, \ldots, y^{10}]^T.$$

$\mathbf{x}_1$ denotes the states of $1^{st}$ machine and are given as $\mathbf{x}_1 = [S_m, \delta, Efd, Eq']$. Similarly, $y^1$ denotes the output of the $1^{st}$ machine and is given as $y^1 = [S_m, 0, 0, 0]$.

Where $S_m$ is machine slip, $\delta$ is machine shaft angular displacement in degrees, $Efd$ is generator field voltage in pu and $Eq'$ is voltage proportional to field flux linkages of machine in pu.

The elements of matrix $\mathbf{A}$ are dependent on the operating condition.

# 3 REVIEW OF FAST OUTPUT SAMPLING AND STATE FEEDBACK SLIDING MODE CONTROL

In the following, fast output sampling feedback technique and state feedback sliding mode control are briefly reviewed.

## 3.1 Fast output sampling feedback

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 $\tau$ (H.Werner and K.Furuta, 1995).

Consider a SISO plant described by a continuous time linear model

$$\dot{\mathbf{x}} = A\mathbf{x} + Bu, \quad (6)$$
$$y = C\mathbf{x}.$$

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

Let ( $\Phi_\tau, \Gamma_\tau, C$) be the system given by Eqn.(6) sampled at sampling interval $\tau$ seconds and is represented as,

$$\mathbf{x}(k+1) = \Phi_\tau \mathbf{x}(k) + \Gamma_\tau u(k), \quad (7)$$
$$y(k) = C\mathbf{x}(k). \quad (8)$$

Also, let ( $\Phi, \Gamma, C$ ) be the system given by Eqn.(6) sampled at another sampling rate $1/\Delta$ where $\Delta = \tau/N$. Let, $(\Phi_\tau, \Gamma_\tau)$ and $(\Phi, C)$ are assumed to be controllable and observable, respectively. Let $v$ denote the observability index of ( $\Phi, C$ ). $N$ is chosen to be greater than or equal to $v$. The output is measured at the sampling rate of $\Delta$ and a constant control signal $u(t)$ is applied over a period during the interval $\tau$.

Then a representation for the system given by Eqns. (7) and (8) is

$$\mathbf{x}(k+1) = \Phi_\tau \mathbf{x}(k) + \Gamma_\tau u(k) \quad (9)$$
$$y_{k+1} = C_0 \mathbf{x}(k) + D_0 u(k) \quad (10)$$

where,

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

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

## 3.2 State feedback sliding mode control

Consider a discretized single input single output (SISO) system given by Eqns.(9) and (10). The aim is to make the system states slide along the plane

$$s(k) = c^T \mathbf{x}(k) = 0 \quad (11)$$

where $c$ is the switching plane parameter matrix.

This motion is termed as sliding mode. Ideal sliding mode is not possible in discrete systems because in case of discrete sliding mode, control action can only be activated at sampling instants and the control effort is constant over each sampling period. Also when state reaches the switching surface, the subsequent discrete-time switching cannot generate equivalent control to keep the state on the surface. As a result discrete-time sliding mode can undergo only quasi-sliding mode motion. It is assumed that the pair ( $\Phi_\tau$, $\Gamma\tau$) is controllable and the pair ( $\Phi\tau$, $C$) is observable. The reaching law for discrete time sliding mode is as given by (Gao et al., 1995)

$$s(k+1) - s(k) = -q\tau s(k) - \varepsilon\tau sgn(s(k)) \quad (12)$$

Consider an incremental change in $s(k)$ which is given as

$$s(k+1) - s(k) = c^T x(k+1) - c^T x(k) \quad (13)$$

$$= c^T \Phi_\tau \mathbf{x}(k) + c^T \Gamma_\tau u(k) - c^T \mathbf{x}(k) \quad (14)$$

Comparing Eqn. (12 ) with Eqn. (14) one obtains

$$-\varepsilon\tau sgn(s(k)) - q\tau s(k) =$$
$$c^T\Phi_\tau \mathbf{x}(k) + c^T\Gamma_\tau u(k) - c^T\mathbf{x}(k) \quad (15)$$

Solving for $u(k)$ gives the state feedback based discrete sliding mode control law as (Gao et al., 1995).

$$u(k) = F\mathbf{x}(k) + \gamma sgn(s(k)) \quad (16)$$

Where

$$F = -(c^T\Gamma_\tau)^{-1}\left[(c^T\Phi_\tau - c^T I + q\tau c^T)\right],$$

$$\gamma = -(c^T\Gamma_\tau)^{-1}\varepsilon\tau \quad (17)$$

## 4 OUTPUT FEEDBACK SLIDING MODE CONTROL

A generalized expression for the state feedback based discrete sliding mode control has been derived and is as given by Eqn. (16). Solving Eqn.(9), we get,

$$\mathbf{x}(k) = C_0^{-1}y_k + (\Gamma_\tau - \Phi_\tau C_0^{-1}D_0)u(k-1) \quad (18)$$

Substituting for $\mathbf{x}(k)$ from Eqn. (18) in Eqns. (11) and (16), we get (B.Bandyopadhyay et al., 2004)

$$\begin{aligned} s(k) &= c^T\Phi_\tau C_0^{-1}y_k \\ &\quad + c^T[\Gamma_\tau - \Phi_\tau C_0^{-1}D_0]u(k-1), \end{aligned} \quad (19)$$

$$\begin{aligned} u(k) &= F\Phi_\tau C_0^{-1}y_k \\ &\quad + F[\Gamma_\tau - \Phi_\tau C_0^{-1}D_0]u(k-1) \\ &\quad + \gamma sgn(s(k)). \end{aligned} \quad (20)$$

Thus, it can be seen from the Eqns. (19) and (20) that the states of the system are needed neither for switching function evaluation nor for the feedback purpose.

## 5 DECENTRALIZED PSS DESIGN FOR MULTIMACHINE POWER SYSTEM(10-MACHINE 39-BUS SYSTEM) USING OUTPUT FEEDBACK SLIDING MODE CONTROL

The nonlinear differential equations governing the behavior of 10-machine 39-bus system is linearized

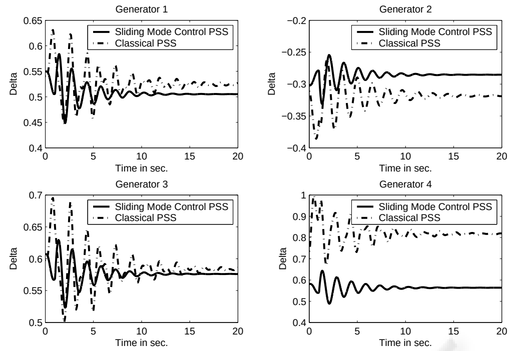


Figure 2: Nonlinear Simulation ( Rotor angle)

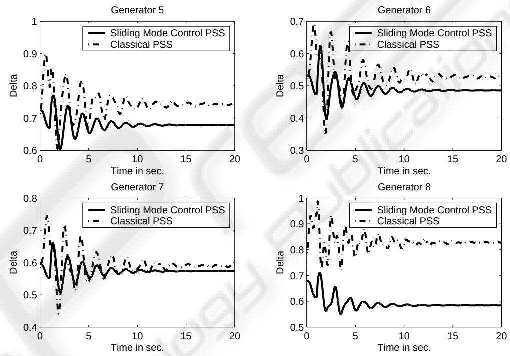


Figure 3: Nonlinear Simulation ( Rotor angle)

about an operating point to obtain a linear model, which represents the small signal oscillatory response of the power system. The single line diagram of the power system used in analysis is shown in Fig.1.

The above 10-machine 39-bus system was modeled using MATLAB. The slip of the machine is taken as output. This output signal with controller output $u(k)$ and a limiter is added to $V_{ref}$ signal and is used to damp out the small signal disturbances via modulating the generator excitation. The disturbance considered is a self clearing fault at bus no. 11 which is cleared after 0.1 second and the real power of the generator 1 is 140 % of it's nominal value. The nonlinear simulation results of different generators( with classical PSS and sliding mode controller PSS) for one model ( i.e. at a particular operating condition) are shown in Fig. 2 to Fig.7 .

## 6 CONCLUSION

In this paper, a design scheme of the power system stabilizer for multimachine power system using output feedback sliding mode control is proposed and substantiated by simulation results. The slip signal is taken as an output and output feedback sliding mode

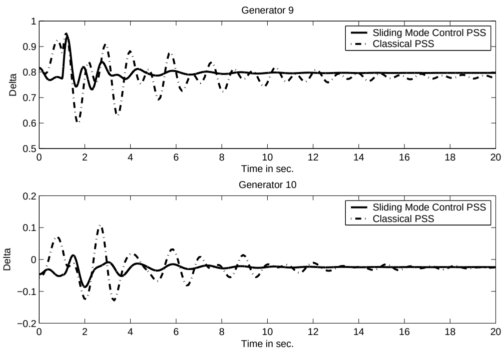


Figure 4: Nonlinear Simulation ( Rotor angle)

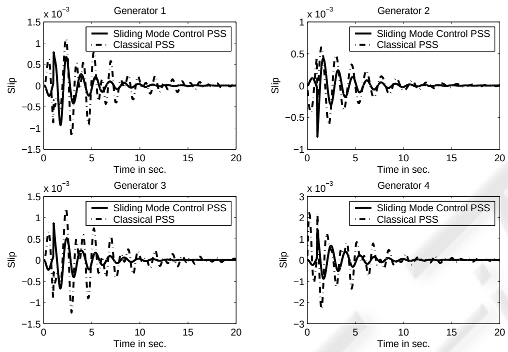


Figure 5: Nonlinear Simulation ( Slip)

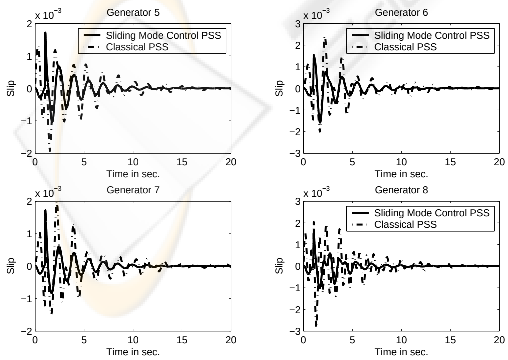


Figure 6: Nonlinear Simulation ( Slip)

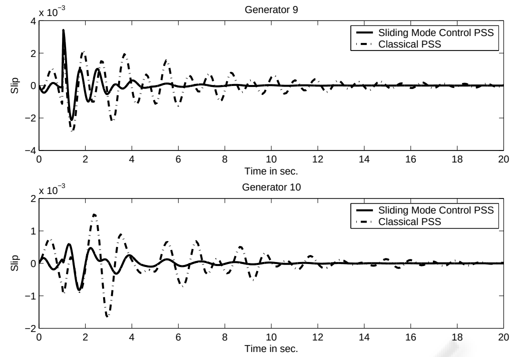


Figure 7: Nonlinear Simulation ( Slip)

control is applied at an appropriate sampling rate. It is found that designed controller provides good damping enhancement for multimachine power system as compared with the classical PSS.

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