

Design of Power System Stabilizer Based on Sliding Mode Control Theory for Multi-Machine Power System

Hossein Shahinzadeh, Ladan Darougaran, Ebrahim Jalili Sani, Hamed Yavari, Mahdi Mozaffari Legha

Abstract—This paper present a new method for design of power system stabilizer (PSS) based on sliding mode control (SMC) technique. The control objective is to enhance stability and improve the dynamic response of the multi-machine power system. In order to test effectiveness of the proposed scheme, simulation will be carried out to analyze the small signal stability characteristics of the system about the steady state operating condition following the change in reference mechanical torque and also parameters uncertainties. For comparison, simulation of a conventional control PSS (lead-lag compensation type) will be carried out. The main approach is focusing on the control performance which later proven to have the degree of shorter reaching time and lower spike.

Keywords—Power system stabilizer (PSS), multi-machine power system, sliding mode control

I. INTRODUCTION

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In recent years, considerable efforts have been made to enhance the dynamic stability of power systems. Modern voltage regulators and excitation systems with fast response 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 swing. In order to reduce this undesirable effect and improve the system dynamic performance, it is useful to introduce supplementary signal to increase the damping. One of the cost effective solution to this problem is fitting the generators with a feedback controller to inject a supplementary signal at the voltage reference input of the automatic voltage regulator to damp the oscillations. This is device known as a PSS [1-6].

Various control methods have been proposed for PSS design to improve overall system performance. Among these, conventional PSS of lead-lag compensation type have been adapted by most utility companies because of their simple structure, flexibility and ease of implementation. The power system is a highly complex system and the system equations are nonlinear and the parameters can vary due to noise and load fluctuation. However, the performance of conventional stabilizer can be considerably degraded with the change in the operation condition. In addition if some changes occur in AVR parameters, there will be great changes in system conditions. Therefore the conventional stabilizer won't have a good performance in action [7-9].

Now there are many studies on PSS in power systems that contain PSS optimal placement, PSS coordination and using more effective methods in PSS designing [10]. In recent context using of optimal control theory [11], adaptive controllers [12] and some techniques such as artificial neural networks [13] and genetic algorithm [14, 15] are performed. A nonlinear adaptive back-stepping controller design based on the fourth order power system model including the unknown parameters for multi-machine power systems proposed in [16]. In [17] the dynamic characteristics of the proposed PSS based on synergetic control theory are studied in a typical single-machine infinite-bus power system and compared with the cases with a conventional PSS and without a PSS.

Sliding mode control is one of the main methods employed to overcome the uncertainty of the system. This controller can be applied very well in presence of both parameter uncertainties and unknown nonlinear function such as disturbance. Sliding mode control technique has been used to control robots, motors, mechanical systems, etc and assure the desired behavior of closed loop system [18]. Sliding mode controllers rely on high speed switching to achieve the desired output tracking. This high speed switching phenomenon is called chattering. The high frequency components of the chattering are undesirable because they may excite un-modeled high frequency plant dynamics which could cause system instabilities. This chattering can be eliminated by choosing a boundary layer in sliding surface.

This paper is organized as follows. Section 2 presents the dynamic model of a synchronous generator. Section 3 presents a brief review on sliding mode control technique. In section 4

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the mathematical model of the synchronous generator is transformed into a form that facilitates the design of nonlinear control schemes. Then the sliding mode controller is proposed. Section 5 present the conventional control PSS (lead-lag compensation type) and conclusions are drawn in section 6. The controller is validated using non-linear model simulation .

II. DYNAMIC MODEL

A multi-machine power system consisting of four synchronous generators with loads is shown in Fig.1 . This system is a two area power system, the two areas are identical and each include two generators equipped with fast acting excitation systems.

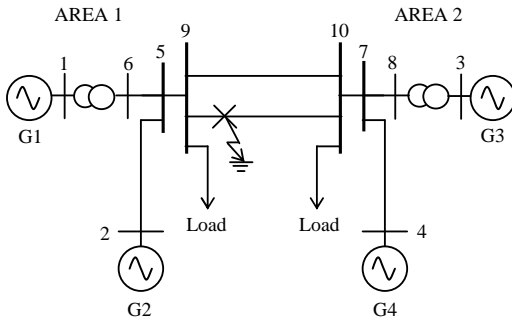


Fig. 1 Single diagram of a 4-Machines 10-Bus System

The detailed nonlinear model of a synchronous generator is a sixth order model. However this model is usually reduced to a generalized one-axis nonlinear third order model. The equations describing a third order model of a synchronous generator (for j th generator) can be written as:

$$\begin{aligned}\dot{\delta}_j(t) &= \omega_j(t) - \omega_{oj} \\ \dot{\omega}_j(t) &= -\frac{K_{Dj}}{2H_j}(\omega_j(t) - \omega_{oj}) + \frac{\omega_{oj}}{2H_j}(P_{mj} - P_{ej}(t))\end{aligned}\quad (1)$$

$$\dot{E}'_{qj}(t) = \frac{1}{T'_{doj}}(E_{Fj}(t) - E_{qj}(t))$$

Where:

$$\begin{aligned}E_{qj}(t) &= \frac{X_{dj}}{X'_{dj}}E'_{qj}(t) - \frac{x_{dj} - x'_{dj}}{X'_d}V_s \cos(\delta_j(t)) \\ E_{Fj}(t) &= k_{cj}u_{Fj}(t) \\ P_{ej}(t) &= \frac{V_s E_{qj}(t)}{X_d} \sin(\delta_j(t))\end{aligned}\quad (2)$$

and $\delta_j(t)$ is the rotor angle of the j th generator (radians), $\omega_j(t)$ is the speed of the rotor of the j th generator (radian/sec), ω_{oj} is the synchronous machine speed of the j th generator (radian/sec), K_{Dj} is the damping constant of the j th generator (pu), H_j is the inertia constant of the j th generator (sec), P_{mj} is the mechanical input power of the j th generator (pu), $P_{ej}(t)$ is the active electrical power delivered by the j th generator (pu), $E_{qj}(t)$ is the EMF of the q-axis of the j th generator (pu), $E'_{qj}(t)$ is the transient EMF in the q-axis of the j th generator (pu), $E_{Fj}(t)$ is the equivalent EMF in the excitation winding of the

j th generator (pu), T'_{doj} is the d-axis transient short circuit time constant of the j th generator (sec), k_{cj} is the gain of the excitation amplifier of the j th generator, $u_{Fj}(t)$ is the control input of the excitation amplifier with gain k_{cj} , x_{dj} is the d-axis reactance of the j th generator (pu), x'_{dj} is the d-axis transient reactance of the j th generator (pu), X_{dj} is the total direct reactance of the system (pu), X'_{dj} is the total transient reactance of the system (pu), and V_s is the infinite bus voltage (pu). The states of the system for j th generator choice as follows:

$$\begin{aligned}x_{1j}(t) &= \delta_j(t) \\ x_{2j}(t) &= \omega_j(t) - \omega_{oj} \\ x_{3j}(t) &= E'_{qj}(t)\end{aligned}\quad (3)$$

Hence the system state vector for each generator will be:

$$\mathbf{x}_j(t) = [x_{1j}(t) \ x_{2j}(t) \ x_{3j}(t)]^T \quad (4)$$

Also the control input $u_j(t)$ is taken to be:

$$u_j(t) = \frac{k_{cj}}{T'_{doj}}u_{Fj}(t) \quad (5)$$

Whit a view to clear presentment of nonlinear equations of the system, define the following constants for each generator:

$$\begin{aligned}\alpha_{1j} &= -\frac{K_{Dj}}{2H_j} \\ \alpha_{2j} &= -\frac{\omega_{oj}}{2H_j X'_{dj}} V_s \\ \alpha_{3j} &= \frac{\omega_{oj}(x_{dj} - x'_{dj})}{4H_j X_{dj} X'_{dj}} V_s^2 \\ \alpha_{4j} &= \frac{\omega_{oj}}{2H_j} P_{mj} \\ \alpha_{5j} &= -\frac{1}{T'_{doj}} \frac{X_{dj}}{X'_{dj}} \\ \alpha_{6j} &= \frac{x_{dj} - x'_{dj}}{T'_{doj} X'_{dj}} V_s\end{aligned}\quad (6)$$

Therefore, using (6) through (1) and (2), the equations describing the j th generator can be written as:

$$\begin{aligned}\dot{x}_{1j}(t) &= x_{2j}(t) \\ \dot{x}_{2j}(t) &= \alpha_{1j}x_{2j}(t) + \alpha_{2j}x_{3j}(t)\sin(x_{1j}(t)) \\ &\quad + \alpha_{3j}\sin(2x_{1j}(t)) + \alpha_{4j} \\ \dot{x}_{3j}(t) &= \alpha_{5j}x_{3j}(t) + \alpha_{6j}\cos(x_{1j}(t)) + u_j(t)\end{aligned}\quad (7)$$

Also desired values of the system states for each generator implemented with x_{1dj} , x_{2dj} and x_{3dj} . Therefore the desired system state vector will be:

$$\mathbf{x}_{Dj} = [x_{1dj} \ x_{2dj} \ x_{3dj}]^T \quad (8)$$

The control input which enables the system to achieve the desired states is denoted by u_{dj} . In addition the deviations of the rotor angle of each generator from its desired value take as output of each system. Hence:

$$y_j(t) = x_{1j}(t) - x_{1dj} \quad (9)$$

Therefore using (7), the values of x_{1dj} , x_{2dj} and x_{3dj} to be

derived as follows :

$$\left(-\frac{\alpha_{1j}\alpha_{6j}}{2\alpha_{5j}} + \alpha_{3j} \right) \sin(2x_{1dj}) - \frac{\alpha_{2j}}{\alpha_{5j}} u_{dj} \sin(x_{1dj}) + \alpha_{4j} = 0 \quad (10)$$

$$x_{2dj} = 0$$

$$x_{3dj} = -\frac{\alpha_{6j}}{\alpha_{5j}} \cos(x_{1dj}) - \frac{1}{\alpha_{5j}} u_{dj}$$

III. DESIGN CONTROLLER

The objective of this section is to design a controller based on sliding mode theory for synchronous generator so that regulate the states of the system to their desired values and maintain the stability of the system in operation point and uncertainty and also increase the rate of oscillation damping. The equations (7) and (9) those describing the synchronous generator are highly nonlinear. Therefore, in first step, to facilitation design of nonlinear controller for each generator, a change of variable $z_j(t) = T_j(x)$ is considered, such that:

$$\begin{aligned} z_{1j}(t) &= x_{1j}(t) - x_{1dj} \\ z_{2j}(t) &= x_{2j}(t) \\ z_{3j}(t) &= \alpha_{1j}x_{2j}(t) + \alpha_{2j}x_{3j}(t)\sin(x_{1j}(t)) \\ &\quad + \alpha_{3j}\sin(2x_{1j}(t)) + \alpha_{4j} \end{aligned} \quad (11)$$

Using (10) and (11) it is obvious that if $z_j(t)$ converges to zero as $t \rightarrow \infty$, then $x_j(t)$ converges to x_{Dj} as $t \rightarrow \infty$. For $\sin(x_{1j}(t)) \neq 0$, the inverse of the transmission given in (11) is:

$$\begin{aligned} x_{1j}(t) &= z_{1j}(t) + x_{1dj} \\ x_{2j}(t) &= z_{2j}(t) \\ x_{3j}(t) &= 1/(\alpha_{2j}\sin(z_{1j}(t) + x_{1dj}))(z_{3j}(t) - \alpha_{1j}z_{2j}(t) \\ &\quad - \alpha_{3j}\sin(2(z_{1j}(t) + x_{1dj})) - \alpha_{4j}) \end{aligned} \quad (12)$$

The condition $\sin(x_{1j}(t)) \neq 0$ means that:

$$x_{1j}(t) = \delta_j(t) \neq n\pi \quad n = 0, \pm 1, \pm 2, \dots \quad (13)$$

whereas, the operating region of rotor angle is in $(0, \pi)$, hence this condition is always satisfied in operation region. However if rotor angle is not in $(0, \pi)$, then synchronism will be lost. Using (7) through (11), the equations of the synchronous generator can be written as function of the new variable such that:

$$\begin{aligned} \dot{z}_{1j}(t) &= z_{2j}(t) \\ \dot{z}_{2j}(t) &= z_{3j}(t) \\ \dot{z}_{3j}(t) &= f_j(z) + G_j(z)u_j \\ y_j(t) &= z_{1j}(t) \end{aligned} \quad (14)$$

Where :

$$\begin{aligned} f_j(z) &= \begin{pmatrix} (\alpha_{1j} + \alpha_{5j})z_{3j} - \alpha_{1j}\alpha_{5j}z_{2j} \\ + \left(\frac{1}{2}\alpha_{1j}\alpha_{6j} - \alpha_{3j}\alpha_{5j} \right) \sin(2(z_{1j} + x_{1dj})) \\ + 2\alpha_{3j}z_{2j}\cos(2(z_{1j} + x_{1dj})) \\ + z_{2j}\cot(z_{1j} + x_{1dj}) \left(\begin{matrix} z_{3j} - \alpha_{1j}z_{2j} \\ - \alpha_{3j}\sin(2(z_{1j} + x_{1dj})) - \alpha_{4j} \end{matrix} \right) \\ - \alpha_{4j}\alpha_{5j} \end{pmatrix} \end{aligned} \quad (15)$$

and

$$G_j(z) = \alpha_{2j}\sin(z_{1j} + x_{1dj}) \quad (16)$$

In the original coordinate, the functions $f_j(z) = f_{1j}(x)$ and $G_j(z) = G_{1j}(x)$ are:

$$\begin{aligned} f_{1j}(x) &= \alpha_{1j} \begin{pmatrix} \alpha_{1j}x_{2j} + \alpha_{2j}x_{3j}\sin(x_{1j}) \\ + \alpha_{3j}\sin(2x_{1j}) + \alpha_{4j} \end{pmatrix} \\ &\quad + \alpha_{2j}(\alpha_{5j}x_{3j} + \alpha_{6j}\cos(x_{1j}))\sin(x_{1j}) \\ &\quad + \alpha_{2j}x_{2j}x_{3j}\cos(x_{1j}) + 2\alpha_{3j}x_{2j}\cos(2x_{1j}) \end{aligned} \quad (17)$$

and

$$G_{1j}(x) = \alpha_{2j}\sin(x_{1j}) \quad (18)$$

The model of the synchronous generator given by (14) will be used for designing the sliding mode controller. Then the designed controller will be transformed into the original coordinate using $x_j = T^{-1}(z_j)$ that given in (12).

The second step of the sliding mode control design process is the design of the sliding surface. The sliding surface for each generator is as follows:

$$S_j = \ddot{y}_j + \rho_{1j}\dot{y}_j + \rho_{2j}y_j = z_{3j} + \rho_{1j}z_{2j} + \rho_{2j}z_{1j} \quad (19)$$

Where coefficients ρ_{1j} and ρ_{2j} are positive scalars and are chosen to obtain the desired transient response of the output of the system. The switching surface can be written as a function of $x_{1j}(t)$, $x_{2j}(t)$ and $x_{3j}(t)$ such that:

$$\begin{aligned} S_j &= \alpha_{1j}x_{2j} + \alpha_{2j}x_{3j}\sin(x_{1j}) + \alpha_{3j}\sin(2x_{1j}) + \alpha_{4j} \\ &\quad + \rho_{1j}x_{2j} + \rho_{2j}(x_{1j} - x_{1dj}) \end{aligned} \quad (20)$$

Note that the choice of the switching surface guarantees that the output of the system converges to zero as $t \rightarrow \infty$ on the sliding surface $S_j(X) = 0$. The third step of the proposed sliding mode controller process is to design the control function that provides the motion on the sliding surface, such that:

$$\begin{aligned} u_j(t) &= \frac{-1}{G_j(z)} (f_j(z) + \rho_{1j}z_{3j} + \rho_{2j}z_{2j} \\ &\quad + \eta_j \text{sign}(z_{3j} + \rho_{1j}z_{2j} + \rho_{2j}z_{1j})) \end{aligned} \quad (21)$$

That η_j is a positive scalar and determined by designer. For examination the sliding mode existence condition,

differentiating equation (19) with respect to the time, it follows that:

$$\begin{aligned}\dot{S}_j &= \ddot{y}_j + \rho_{1j}\dot{y}_j + \rho_{2j}\dot{y}_j \\ &= f_j(z) + G_j(z)u_j + \rho_{1j}z_{3j} + \rho_{2j}z_{2j}\end{aligned}\quad (22)$$

Using (21) through (22), it follows that:

$$\begin{aligned}\dot{S}_j &= f_j(z) + \rho_{1j}z_{3j} + \rho_{2j}z_{2j} \\ &+ (-f_j(z) - \rho_{1j}z_{3j} - \rho_{2j}z_{2j} - \eta_j \text{sign}(z_{3j} + \rho_{1j}z_{2j} + \rho_{2j}z_{1j})) \\ &= -\eta_j \text{sign}(z_{3j} + \rho_{1j}z_{2j} + \rho_{2j}z_{1j}) \\ &= -\eta_j \text{sign}(S_j)\end{aligned}\quad (23)$$

Hence:

$$S_j \dot{S}_j = -S_j \eta_j \text{sign}(S_j) = -\eta_j |S_j| < 0 \quad (24)$$

Therefore the dynamics of S_j in (24) guarantees that $S_j \dot{S}_j < 0$. Since S_j driven to zero in a finite time, the output $y(t)=z_1(t)$ is governed after such finite amount of time by the second order differential equation $\ddot{y}(t) + \rho_1 \dot{y}(t) + \rho_2 y(t) = 0$. Thus the output $y_j(t)=z_{1j}(t)$ will converge to zero as $t \rightarrow \infty$ because ρ_{1j} and ρ_{2j} are positive scalars. Since $z_{1j}(t)$ converges to zero as $t \rightarrow \infty$, Then $z_{2j}(t)$ and $z_{3j}(t)$ will also converge to zero as $t \rightarrow \infty$. Therefore it can be concluded that the proposed sliding mode controller guarantees the asymptotic convergence of $z_j(t)$ to zero as $t \rightarrow \infty$. Using (15) the controller function given in (21) can be written in the original coordinate as follow:

$$\begin{aligned}u_j &= \frac{1}{\alpha_{2j} \sin(x_{1j})} \left(-(\alpha_{1j} + \rho_{1j}) \left(\alpha_{1j} x_{2j} + \alpha_{2j} x_{3j} \sin(x_{1j}) \right) \right. \\ &+ \frac{1}{\alpha_{2j} \sin(x_{1j})} \left(-\alpha_{2j} (\alpha_{5j} x_{3j} + \alpha_{6j} \cos(x_{1j})) \sin(x_{1j}) \right. \\ &\left. \left. - \alpha_{2j} x_{2j} x_{3j} \cos(x_{1j}) - 2\alpha_{3j} x_{2j} \cos(2x_{1j}) \right) \right) \\ &+ \frac{1}{\alpha_{2j} \sin(x_{1j})} (-\rho_{2j} x_{2j} - \eta_j \text{sign}(S_j))\end{aligned}\quad (25)$$

where:

$$\begin{aligned}S_j &= \alpha_{1j} x_{2j} + \alpha_{2j} x_{3j} \sin(x_{1j}) + \alpha_{3j} \sin(2x_{1j}) + \alpha_{4j} \\ &+ \rho_{1j} x_{2j} + \rho_{2j} (x_{1j} - x_{1dj})\end{aligned}\quad (26)$$

Therefore, the proposed controller given by (25) and (26) when applied to the system that given in (7) and (9) guarantees the asymptotic convergence of $x_j(t)$ to x_{Dj} as $t \rightarrow \infty$. The proposed controller is confronted with the problem of chattering which is undesirable in practice. This chattering can be eliminated by choose a boundary layer of width ϵ_j , in $S_j(x) = 0$ such that the discontinuous control function given in (25) is rewritten as:

$$\begin{aligned}u_j &= \frac{1}{\alpha_{2j} \sin(x_{1j})} \left\{ -(\alpha_{1j} + \rho_{1j}) \left(\alpha_{1j} x_{2j} + \alpha_{2j} x_{3j} \sin(x_{1j}) \right) \right. \\ &+ \left(-\alpha_{2j} (\alpha_{5j} x_{3j} + \alpha_{6j} \cos(x_{1j})) \sin(x_{1j}) \right. \\ &\left. \left. - \alpha_{2j} x_{2j} x_{3j} \cos(x_{1j}) - 2\alpha_{3j} x_{2j} \cos(2x_{1j}) \right) \right\} \\ &+ (-\rho_{2j} x_{2j} - \eta_j \text{sat}(\frac{S_j}{\epsilon_j}))\end{aligned}\quad (27)$$

where $\epsilon_j > 0$ form boundary layer in the vicinity of sliding surface.

Using the standard second order homogeneous equation $s^2 + 1.4\omega_n s + \omega_n^2 = 0$ in ITAE criterion, the coefficients ρ_1 and ρ_2 in (19) are chosen to obtain the desired transient response of the output dynamics.

IV. SIMULATION RESULTS

The proposed sliding mode control scheme given by (27) and (26), is applied to the multi-machine power system given in Figure 1. The controlled system is simulated using MATLAB. The performance of proposed control scheme (SMCPSS) will be compared to the performance of a conventional controller (AVR+PSS) and with the system without PSS (NOPSS). Two different cases are considered for simulation purposes.

A. Symmetrical fault on transmission line

The nominal parameters of the synchronous generator are used. The system is in steady state. A symmetrical fault of 5 ms as depicted in figure 1 is assumed at $t=1$ sec. The responses of the rotor speed deviation of the generators when the sliding mode controller, AVR+PSS controller and without any controller are used. It can be seen that the response of SMCPSS converges to constant value earlier than AVR+PSS controller. The responses of the voltage magnitude at the faulted bus when the sliding mode controller, AVR+PSS controller and without any controller are used, respectively. Again it can be seen from this figures that the best response are obtained when the SMCPSS is used. Also, it can be noticed that without any controller the voltage at the faulted bus is unstable. Under the AVR+PSS controller the system response is stable. Additionally the response time and the settling time are too large, which is obviously a poor performance of the overall system. When the four generator units were provided with sliding mode power system stabilizers, the effect on the damping of the system's oscillation is efficient and the system is properly stabilized.

B. Change in exciter gain

This case is used to indicate the robustness of proposed controller to change in the one of the parameters of the system. Hence, the exciter gain K_A of the first generator(G1), is changed from 200 to 100. The responses of the speed deviation of the generators when the sliding mode controller, AVR+PSS controller and without any controller are used. It can be seen that the response of SMCPSS converges to

constant value earlier than AVR+PSS controller. Also the responses of the voltage magnitude at faulted bus when the sliding mode controller, AVR+PSS controller and without any controller are used. Again it can be seen from this figures that the best response are obtained when the SMC PSS is used.

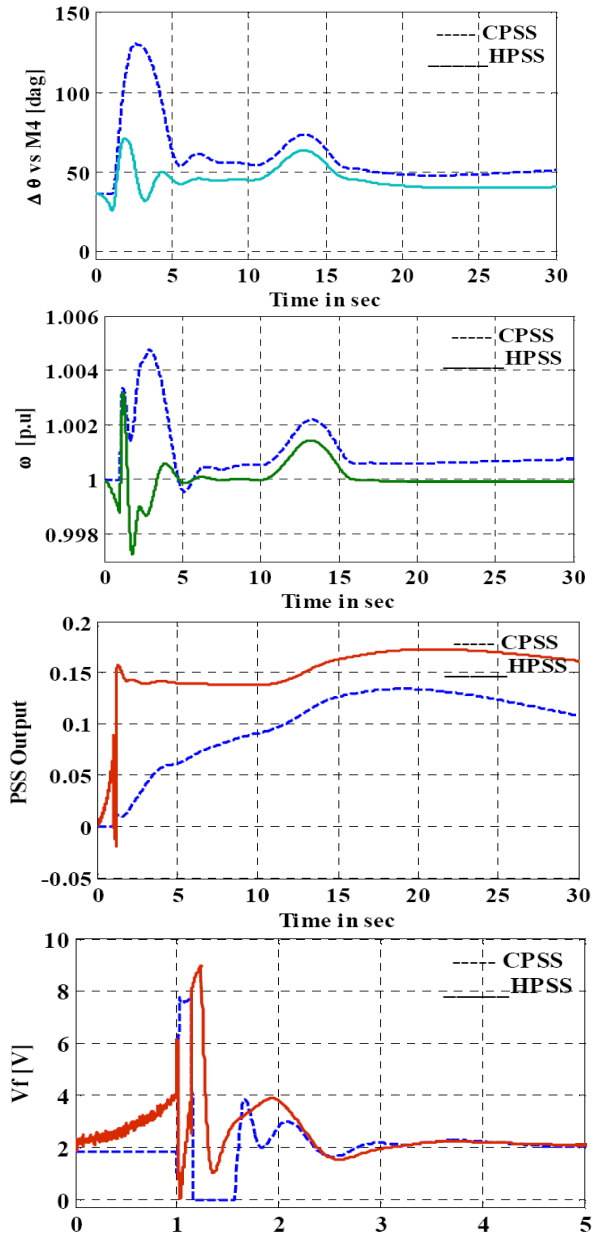


Fig. 2 Rotor of the generators (case 1)

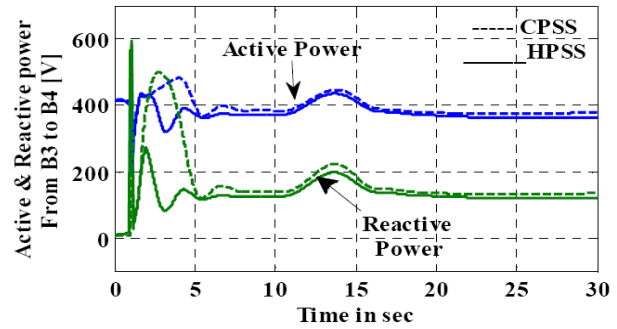


Fig. 3 Active and Reactive Power Bus3 to Bus4 (case 1)

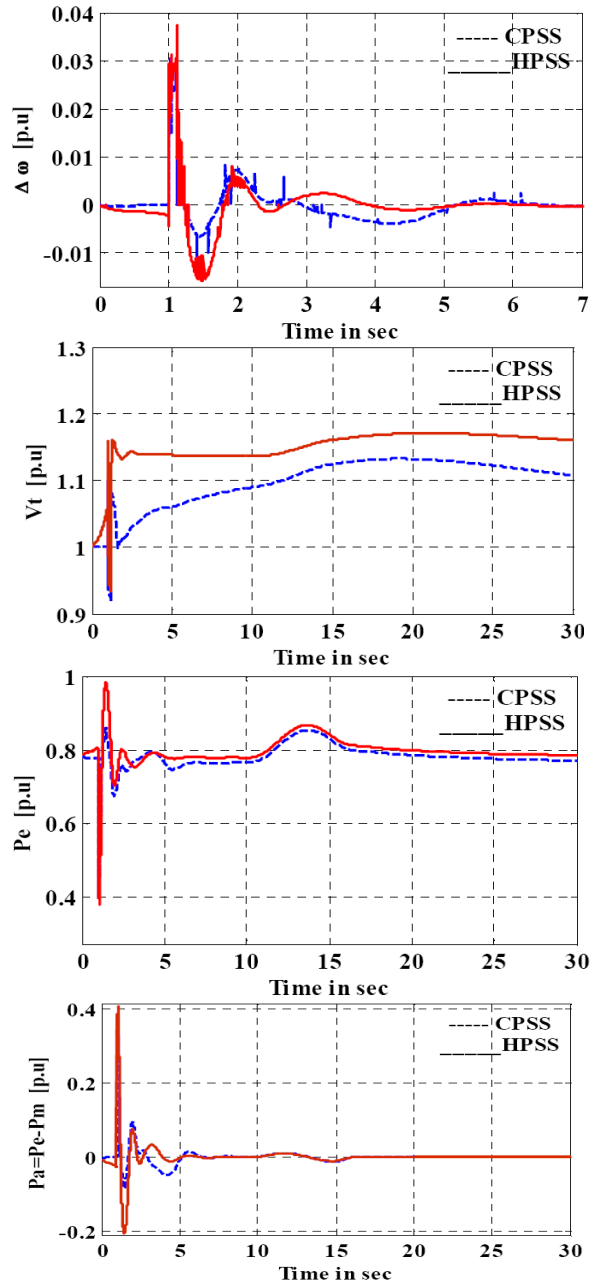


Fig. 4 Rotor of the generators (case 2)

However, the simulation results indicate that the proposed sliding mode controller work well when applied to the multi-machine power system. Moreover, the simulation results show that the proposed controller is robust to parameter uncertainties and to the disturbance. In addition, the sliding mode controller gave better results than the conventional AVR+PSS controller.

V.CONCLUSION

Whereas power system is a highly complex system and the system equations are nonlinear and the parameters can vary due to noise and load fluctuation, it's essential that use a controller that can maintain the stability of the system and provides good damping enhancement and also have a good performance, when occur changes in system operation conditions. According to non-linear simulation results of a multi-machine power system, it is found that the proposed controller work well and are robust to change in parameters of the system and to disturbance acting on the system and also indicate that the sliding mode controller achieves a better performance than the conventional PSS.

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