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Analysis and Design of PSS for Multi-Machine Power System Based on Sliding Mode Control Theory

Ghazanfar Shahgholian[1], Amin Rajabi[1], Bahram Karimi[2]

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, Sliding Mode Control, Multi-Machine Power System, Controller Design*

Nomenclature

$\delta(t)$	Rotor angle
$\omega(t)$	Speed of the rotor
ω_0	Synchronous machine speed
K_D	Damping constant
H	Inertia constant
P_m	Mechanical input power
$P_e(t)$	Active electrical power
$E_q(t)$	EMF of the q-axis
$E'_q(t)$	Transient EMF in the q-axis
$E_F(t)$	Equivalent EMF in the excitation winding
T'_{do}	D-axis transient short circuit time constant
k_C	Gain of the excitation amplifier
$u_F(t)$	Control input of the excitation amplifier
x_d	D-axis reactance
x'_d	D-axis transient reactance
X_d	Total direct reactance of the system
X'_d	Total transient reactance of the system
V_S	Infinite bus voltage
T_R	Time constant of the voltage transducer
V_1	Output of the terminal voltage transducer
V_{supp}	Output of the power system stabilizer
V_{ref}	Reference voltage

I. Introduction

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 [1-8].

Various control methods have been proposed for PSS design to improve overall system performance [9, 10]. 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 [11-13].

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 [14]. In recent context using of optimal control theory [15], adaptive controllers [16] and some techniques such as artificial neural networks [17] and genetic algorithm [18, 19] 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 [20]. In [21] the

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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 [22]. 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 II presents the dynamic model of a synchronous generator. Section III presents a brief review on sliding mode control technique. In section IV 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 V present the conventional control PSS (lead-lag compensation type) and conclusions are drawn in section VI. 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 includes two generators equipped with fast acting excitation systems.

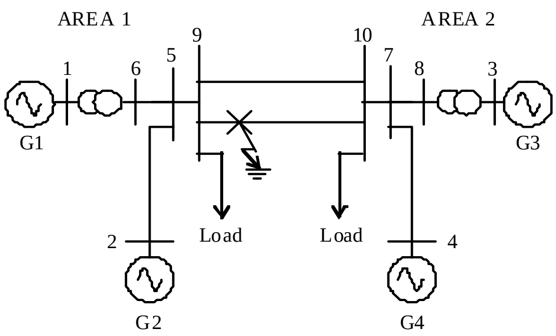


Fig. 1. Single diagram of a 4-Machines 10-Bus System

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 jth generator, can be written as:

$$\begin{aligned}
&\dot{\delta}_j(t) = \omega_j(t) - \omega_{oj} \\
&\dot{\omega}_j(t) = -\frac{K_{Dj}}{2H_j}\left(\omega_j(t) - \omega_{oj}\right) + \frac{\omega_{oj}}{2H_j}\left(P_{mj} - P_{ej}(t)\right) \\
&\dot{E}'_{qj}(t) = \frac{1}{T'_{doj}}\left(E_{Fj}(t) - E_{qj}(t)\right)
\end{aligned} \quad (1)$$

where:

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

and $\delta_j(t)$ is the rotor angle of the jth generator (radians), $\omega_j(t)$ is the speed of the rotor of the jth generator (radian/sec), ω_{oj} is the synchronous machine speed of the jth generator (radian/sec), K_{Dj} is the damping constant of the jth generator (pu), H_j is the inertia constant of the jth generator (sec), P_{mj} is the mechanical input power of the jth generator (pu), $P_{ej}(t)$ is the active electrical power delivered by the jth generator (pu), $E_{qj}(t)$ is the EMF of the q-axis of the jth generator (pu), $E'_{qj}(t)$ is the transient EMF in the q-axis of the jth generator (pu), $E_{Fj}(t)$ is the equivalent EMF in the excitation winding of the jth generator (pu), T'_{doj} is the d-axis transient short circuit time constant of the jth generator (sec), k_{Cj} is the gain of the excitation amplifier of the jth 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 jth generator (pu), x'_{dj} is the d-axis transient reactance of the jth 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 jth 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:

$$x_j(t) = \left[x_{1j}(t)\ x_{2j}(t)\ x_{3j}(t)\right]^T \quad (4)$$

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 defines the following constants for each generator:

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

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

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

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:

$$x_{Dj}=\left[x_{1dj}\ \ x_{2dj}\ \ x_{3dj}\right]^T \tag{8}$$

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:

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

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

$$\begin{aligned} &\left(-\frac{\alpha_{1j}\alpha_{6j}}{2\alpha_{5j}}+\alpha_{3j}\right)\sin\left(2x_{1dj}\right)+ \\ &-\frac{\alpha_{2j}}{\alpha_{5j}}u_{dj}\sin\left(x_{1dj}\right)+\alpha_{4j}=0 \\ &x_{2dj}=0 \\ &x_{3dj}=-\frac{\alpha_{6j}}{\alpha_{5j}}\cos\left(x_{1dj}\right)-\frac{1}{\alpha_{5j}}u_{dj} \end{aligned} \tag{10}$$

III. Sliding Mode Control

Sliding mode control is one of the main methods that used to design controllers for nonlinear systems and indicate that can achieve effective, robust, decoupled tracking for a nonlinear time-varying multi-input multi-output (MIMO) system with disturbance and parameter variations. Sliding mode control forces the nonlinear plant's state trajectory to move onto a specified and user chosen surface (called the sliding or switching surface), and maintains the plant's state trajectory on this surface for all subsequent time. By properly designing the sliding surface, the sliding mode control acquires the desired output tracking solution for the system. Sliding mode controllers rely on high speed switching to achieve the desired output tracking. This high speed switching phenomenon is called chattering. This chattering can be eliminated by choosing a boundary layer in sliding surface. The design processes of the sliding mode control approach consist of three steps. The first step is to transform the original system into a normal form. The second step is to design the linear sliding surface. The third step is to design the control function that provides the motion on the sliding surface [23, 24]. For illustration this method a nonlinear multi-input multi out-put (MIMO) system as follow is considered:

$$\begin{cases} \dot{x}=f(x)+G(x)u \\ y=h(x) \end{cases} \tag{11}$$

where x is the n*1 state vector, u is the m*1 control input vector, y is the m*1 vector of system outputs, and *f(x)*, *G(x)* and *h(x)* are smooth vector field. Transforming the given system to a normal form is a necessary first step of the sliding mode control design process. This normal form is used to simplification the design of sliding mode controller for the original system. Hence the change of variable $z(t)=T(x)$ with $z(t)=[z_1(t),\ z_2(t),\ z_3(t)]$ is considered such that the nonlinear system (11) transformed to a normal form as follows:

$$\begin{cases} \dot{z}_1(t)=z_2(t) \\ \dot{z}_2(t)=z_3(t) \\ \vdots \\ \dot{z}_{n-1}(t)=z_n(t) \\ \dot{z}_n(t)=f(z)+G(z)u \end{cases},\quad y(t)=z_1(t) \tag{12}$$

The second step of the sliding mode control design process is the design of the sliding surface. The design process of the sliding surface is to choose the desired linear homogeneous sliding surface. The motion in the sliding surface is invariant to external disturbances and parameter variations. The degree of sliding surface is chosen as one less than the degree of the system. The sliding surface is defined as:

$$S_i(x)=\sum_{k=0}^{n-1}\rho_{ik}y_i^{(k)}(t)=0\quad \forall i=\overline{1,m} \tag{13}$$

where in (13), n is the degree of the system and the coefficients ρ_{ik} are chosen to obtain the desired transient response of the output of the system. In third step, for the control function design, the sliding surface in (13) must be attractive after the system's trajectory hits the sliding surface; it must be in the sliding surface for all subsequent time. In sliding mode control method for the control function u_i, utilizes a bounded value of control magnitude to achieve the desired output tracking. Each component of high speed switched control function u_i, has the nonlinear structure given by:

$$u_i = \begin{cases} u_i^+(t,x) & S_i(x) > 0 \\ u_i^-(t,x) & S_i(x) < 0 \end{cases} \qquad \forall i = \overline{1,m} \tag{14}$$

The control functions in (14) must be chosen to satisfy the sliding mode existence condition as shown in [25], in some vicinity of sliding surface:

$$S_i(x)\dot{S}_i(x) < 0 \qquad \forall i = \overline{1,m} \tag{15}$$

IV. 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:

$$\begin{aligned} z_{1j}(t) &= x_{1j}(t) - x_{1dj} \\ z_{2j}(t) &= x_{2j}(t) \\ z_{3j}(t) &= \alpha_{1j}x_{2j}(t) + \alpha_{2j}x_{3j}(t)\sin\left(x_{1j}(t)\right) + \\ &\quad + \alpha_{3j}\sin\left(2x_{1j}(t)\right) + \alpha_{4j} \end{aligned} \tag{16}$$

Using (10) and (16) it is obvious that if $Z_i(t)$ converges to zero as $t\to\infty$, then $x_j(t)$ converges to x_{Dj} as $t\to\infty$. For $\sin\left(x_{1j}(t)\right) \neq 0$, the inverse of the transmitssi-on given in (16) is:

$$\begin{aligned} x_{1j}(t) &= z_{1j}(t) + x_{1dj} \\ x_{2j}(t) &= z_{2j}(t) \\ x_{3j}(t) &= 1/\left(\alpha_{2j}\sin\left(z_{1j}(t) + x_{1dj}\right)\right)\cdot \\ &\cdot\begin{pmatrix} z_{3j}(t) - \alpha_{1j}z_{2j}(t) + \\ -\alpha_{3j}\sin\left(2\left(z_{1j}(t) + x_{1dj}\right)\right) - \alpha_{4j} \end{pmatrix} \end{aligned} \tag{17}$$

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

$$x_{1j}(t) = \delta_j(t) \neq n\pi \quad n = 0, \pm1, \pm2, \ldots \tag{18}$$

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 (16), the equations of the synchronous generator can be written as function of the new variable such that:

$$\begin{aligned} \dot{z}_{1j}(t) &= z_{2j}(t) \\ \dot{z}_{2j}(t) &= z_{3j}(t) \\ \dot{z}_{3j}(t) &= f_j(z) + G_j(z)u_j \\ y_j(t) &= z_{1j}(t) \end{aligned} \tag{19}$$

where:

$$\begin{aligned} f_j(z) &= \begin{pmatrix} \left(\alpha_{1j} + \alpha_{5j}\right)z_{3j} - \alpha_{1j}\alpha_{5j}z_{2j} + \\ + \left(\frac{1}{2}\alpha_{1j}\alpha_{6j} - \alpha_{3j}\alpha_{5j}\right)\sin 2\left(z_{1j} + x_{1dj}\right) \end{pmatrix} + \\ &+ 2\alpha_{3j}z_{2j}\cos\left(2\left(z_{1j} + x_{1dj}\right)\right) + \\ &+ z_{2j}\cot\left(z_{1j} + x_{1dj}\right)\begin{pmatrix} z_{3j} - \alpha_{1j}z_{2j} + \\ -\alpha_{3j}\sin\left(2\left(z_{1j} + x_{1dj}\right)\right) + \\ -\alpha_{4j} \end{pmatrix} + \\ &- \alpha_{4j}\alpha_{5j} \end{aligned} \tag{20}$$

and:

$$G_j(z) = \alpha_{2j}\sin\left(z_{1j} + x_{1dj}\right) \tag{21}$$

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

$$\begin{aligned} f_{1j}(x) &= \alpha_{1j}\begin{pmatrix} \alpha_{1j}x_{2j} + \alpha_{2j}x_{3j}\sin\left(x_{1j}\right) + \\ + \alpha_{3j}\sin\left(2x_{1j}\right) + \alpha_{4j} \end{pmatrix} + \\ &+ \alpha_{2j}\left(\alpha_{5j}x_{3j} + \alpha_{6j}\cos\left(x_{1j}\right)\right)\sin\left(x_{1j}\right) + \\ &+ \alpha_{2j}x_{2j}x_{3j}\cos\left(x_{1j}\right) + 2\alpha_{3j}x_{2j}\cos\left(2x_{1j}\right) \end{aligned} \tag{22}$$

and:

$$G_{1j}(x) = \alpha_{2j}\sin\left(x_{1j}\right) \tag{23}$$

The model of the synchronous generator given by (19) 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 (17). The second step of the sliding mode control design process is the design of the sliding surface. Using (13) the sliding surface for each generator is as follows:

$$\begin{aligned} S_j &= \ddot{y}_j + \rho_{1j}\dot{y}_j + \rho_{2j}y_j = \\ &= z_{3j} + \rho_{1j}z_{2j} + \rho_{2j}z_{1j} \end{aligned} \tag{24}$$

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. Using (16) the switching surface can be written as a function of $x_{1j}(t)$, $x_{2j}(t)$ and $x_{3j}(t)$ such that:

$$\begin{aligned} S_j &= \alpha_{1j}x_{2j} + \alpha_{2j}x_{3j}\, sin\left(x_{1j}\right) + \\ &+\alpha_{3j}\, sin\left(2x_{1j}\right) + \alpha_{4j} + \\ &+\rho_{1j}x_{2j} + \rho_{2j}\left(x_{1j} - x_{1dj}\right) \end{aligned} \tag{25}$$

Note that the choice of the switching surface guarantees that the output of the system converges to zero as $t\to\infty$ 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:

$$u_j(t) = \frac{-1}{G_j(z)}\begin{pmatrix} f_j(z) + \rho_{1j}z_{3j} + \rho_{2j}z_{2j} + \\ +\eta_j sign\left(z_{3j} + \rho_{1j}z_{2j} + \rho_{2j}z_{1j}\right) \end{pmatrix} \tag{26}$$

That η_j is a positive scalar and determined by designer. For examination the sliding mode existence condition given in (15), differentiating equation (24) with respect to the time and using (19), it follows that:

$$\begin{aligned} \dot{S}_j &= \dddot{y}_j + \rho_{1j}\ddot{y}_j + \rho_{2j}\dot{y}_j = \\ &= f_j(z) + G_j(z)u_j + \rho_{1j}z_{3j} + \rho_{2j}z_{2j} \end{aligned} \tag{27}$$

Using (26) through (27), it follows that:

$$\begin{aligned} \dot{S}_j &= f_j(z) + \rho_{1j}z_{3j} + \rho_{2j}z_{2j} + \\ &+\begin{pmatrix} -f_j(z) - \rho_{1j}z_{3j} - \rho_{2j}z_{2j} + \\ -\eta_j sign\left(z_{3j} + \rho_{1j}z_{2j} + \rho_{2j}z_{1j}\right) \end{pmatrix} = \\ &= -\eta_j sign\left(z_{3j} + \rho_{1j}z_{2j} + \rho_{2j}z_{1j}\right) = \\ &= -\eta_j sign\left(S_j\right) \end{aligned} \tag{28}$$

Hence:

$$S_j\dot{S}_j = -S_j\eta_j sign\left(S_j\right) = -\eta_j\left|S_j\right| < 0 \tag{29}$$

Therefore the dynamics of S_j in (28) 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 $t\to\infty$ because ρ_{1j} and ρ_{2j} are positive scalars. Since $z_{1j}(t)$ converges to zero as $t\to\infty$. Then $z_{2j}(t)$ and $z_{3j}(t)$ will also converge to zero as $t\to\infty$. Therefore it can be concluded that the proposed sliding mode controller guarantees the asymptotic convergence of $z_j(t)$ to zero as $t\to\infty$. Using (17) the controller function given in (26) can be written in the original coordinate as follow:

$$\begin{aligned} u_j &= \frac{1}{\alpha_{2j}\, sin\left(x_{1j}\right)}\left(-\alpha_{1j} + \rho_{1j}\right)\cdot \\ &\cdot\begin{pmatrix} \alpha_{1j}x_{2j} + \alpha_{2j}x_{3j}\, sin\left(x_{1j}\right) + \\ +\alpha_{3j}\, sin\left(2x_{1j}\right) + \alpha_{4j} \end{pmatrix} + \frac{1}{\alpha_{2j}\, sin\left(x_{1j}\right)}\cdot \\ &\cdot\begin{pmatrix} -\alpha_{2j}\left(\alpha_{5j}x_{3j} + \alpha_{6j}\, cos\left(x_{1j}\right)\right) sin\left(x_{1j}\right) + \\ -\alpha_{2j}x_{2j}x_{3j}\, cos\left(x_{1j}\right) - 2\alpha_{3j}x_{2j}\, cos\left(2x_{1j}\right) \end{pmatrix} + \\ &+\frac{1}{\alpha_{2j}\, sin\left(x_{1j}\right)}\left(-\rho_{2j}x_{2j} - \eta_j sign\left(S_j\right)\right) \end{aligned} \tag{30}$$

where:

$$\begin{aligned} S_j &= \alpha_{1j}x_{2j} + \alpha_{2j}x_{3j}\, sin\left(x_{1j}\right) + \\ &+\alpha_{3j}\, sin\left(2x_{1j}\right) + \alpha_{4j} + \\ &+\rho_{1j}x_{2j} + \rho_{2j}\left(x_{1j} - x_{1dj}\right) \end{aligned} \tag{31}$$

Therefore, the proposed controller given by (30) and (31) when applied to the system that given in (7) and (9) guarantees the asymptotic convergence of $x_j(t)$ to x_{Dj} as $t\to\infty$. 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 (30) is rewritten as:

$$u_j = \frac{1}{\alpha_{2j}\, sin\left(x_{1j}\right)}\cdot\left\{\begin{aligned} &\left(-\alpha_{1j} + \rho_{1j}\right)\cdot \\ &\cdot\begin{pmatrix} \alpha_{1j}x_{2j} + \alpha_{2j}x_{3j}\, sin\left(x_{1j}\right) + \\ +\alpha_{3j}\, sin\left(2x_{1j}\right) + \alpha_{4j} \end{pmatrix} + \\ &+\begin{pmatrix} -\alpha_{2j}\left(\alpha_{5j}x_{3j} + \alpha_{6j}\, cos\left(x_{1j}\right)\right) sin\left(x_{1j}\right) + \\ -\alpha_{2j}x_{2j}x_{3j}\, cos\left(x_{1j}\right) - 2\alpha_{3j}x_{2j}\, cos\left(2x_{1j}\right) \end{pmatrix} + \\ &+\left(-\rho_{2j}x_{2j} - \eta_j sat\left(\frac{S_j}{\varepsilon_j}\right)\right) \end{aligned}\right\} \tag{32}$$

where $\varepsilon_j>0$ form boundary layer in the vicinity of sliding surface in (13).

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_1 in (13) are chosen to obtain the desired transient response of the output dynamics.

V. Conventional PSS

The conventional fixed power system stabilizer is designed using a linearized model of the system using control theory. Therefore, this provides optimum performance for a nominal operating condition and system parameters with the input being small enough to justify the linear model. However, its performance becomes suboptimal following variations in system parameters and loading conditions from their nominal values or when the disturbance applied is large. The block diagram of this controller is given in Fig. 2.

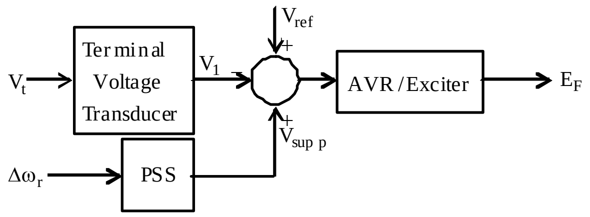


Fig. 2. Block diagram of AVR+PSS controller

This model represents a bus-fed thyristor excitation system (classified as IEEE type ST1A excitation system model with an automatic voltage regulator (AVR) and a power system stabilizer (PSS)). A high exciter gain K_A without transient gain reduction or derivative feedback is used. This transfer function of the terminal voltage transducer is such:

$$G_{TVT}(s) = \frac{1}{1+sT_R} \quad (33)$$

where, T_R is the time constant of the voltage transducer. The transfer function of AVR/exciter is such:

$$G_{AVR}(s) = K_A \quad (34)$$

Hence, the equation of the conventional AVR+PSS controller can be written as:

$$E_F = K_A\left(V_{ref} - V_1 + V_{sup\,p}\right) \quad (35)$$

where V_1 is the output of the terminal voltage transducer, V_{supp} is output of the power system stabilizer and V_{ref} is the reference voltage. The transfer function of power system stabilizer is such:

$$G_{PSS}(s) = K_{PSS}\frac{(1+sT_1)}{(1+sT_2)}\frac{(1+sT_3)}{(1+sT_4)}\frac{sT_W}{(1+sT_W)} \quad (36)$$

The block diagram of this power system stabilizer used in industry is shown in Fig. 3.

The basic structure of this power system stabilizer is gain block, signal washout block, lead/lag compensation block and limiter block. The input to the conventional PSS is speed deviation. The PSS gain K_{PSS} is an important factor as the damping provided by the PSS increase in proportion to an increase in the gain up to a certain critical gain value, after which the damping begins to decrease. 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.

VI. Simulation Results

The proposed sliding mode control scheme given by (32) and (31), is applied to the multi-machine power system given in Figure 1. The nominal parameters of the synchronous generators that shown in Figure 1, are given in Appendix. 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 Fig. 1 is assumed at t=1 s. The responses of the rotor speed deviation of the generators when the sliding mode controller, AVR+ PSS controller and without any controller are used, are shown in Figs. 4.

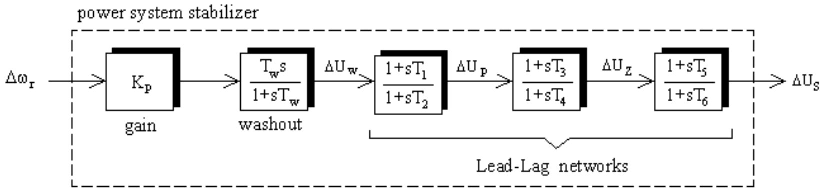
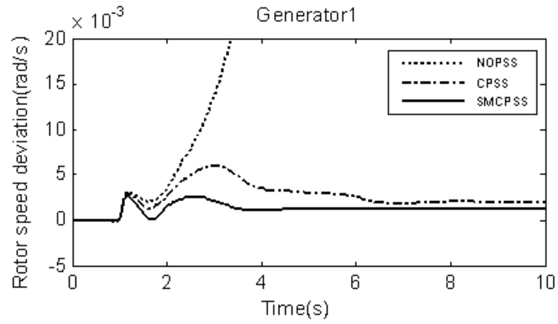
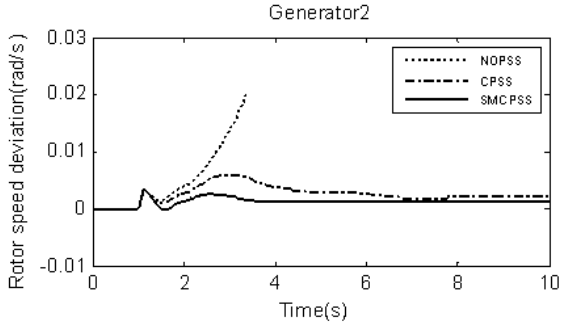


Fig. 3. Block diagram of a PSS



(a)



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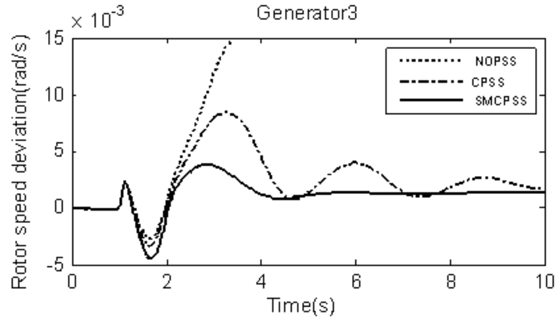
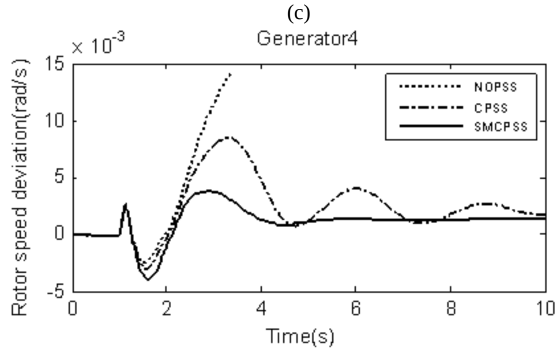


(c)

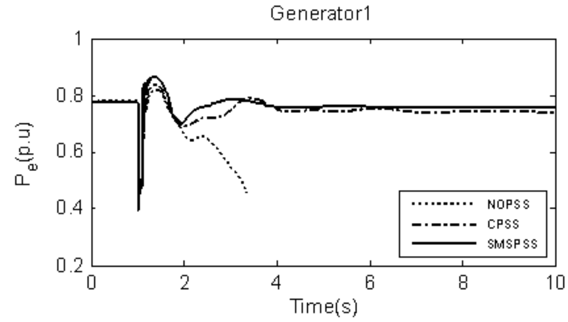


(d)

Figs. 4. Rotor speed deviation of the generators (case 1)

It can be seen that the response of SMCPSS converges to constant value earlier than AVR+PSS controller. Figures 5 and Figure 6 show the responses of the electrical power of the generators and 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 these two 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.



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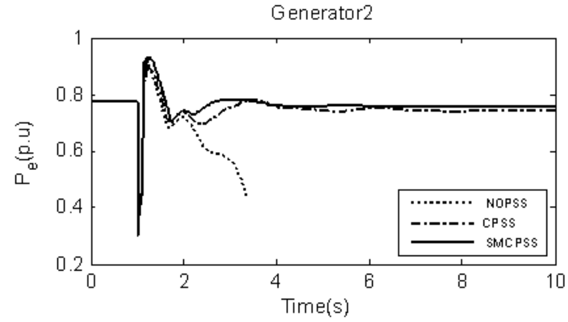

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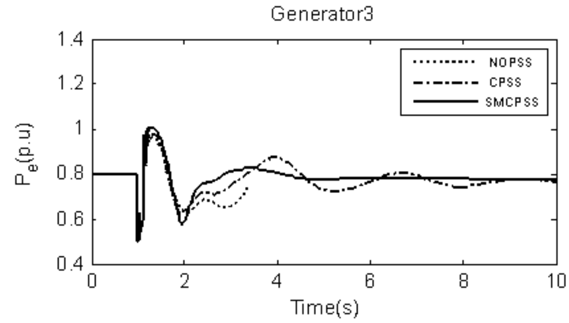

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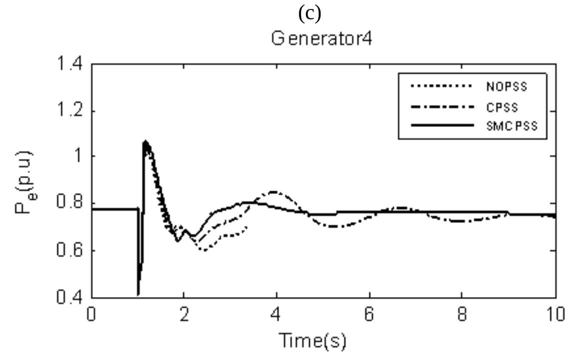


(d)

Figs. 5. Electrical power of the generators (case 1)

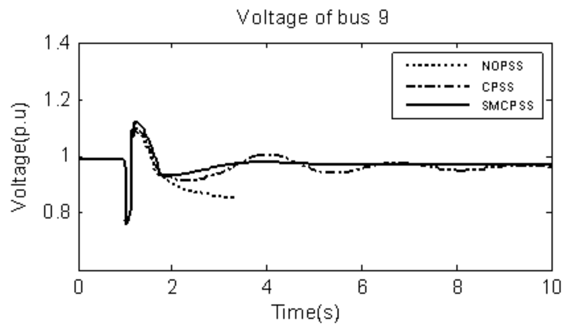
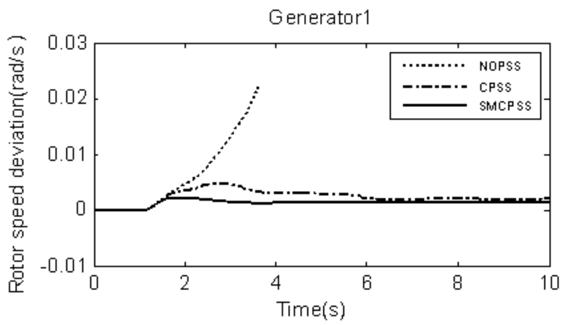


Fig. 6. Voltage magnitude at the faulted bus (case 1)

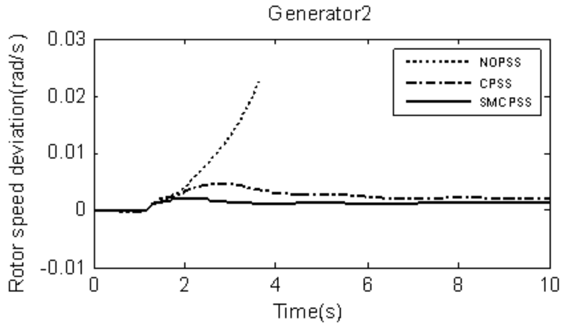
Under the AVR+PSS controller the system response is stable. Additionally the response time and the settling time are too large, which is obviously a poor performance of the overall system. When the four generator units were provided with sliding mode power system stabilizers, the effect on the damping 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 (G_1), 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 are shown in Figs. 7. It can be seen that the response of SMCPSS converges to constant value earlier than AVR+PSS controller. Also the responses of the electrical power and voltage magnitude at faulted bus when the sliding mode controller, AVR+PSS controller and without any controller are used are shown in Figs. 8 and Fig. 9 respectively.



(a)



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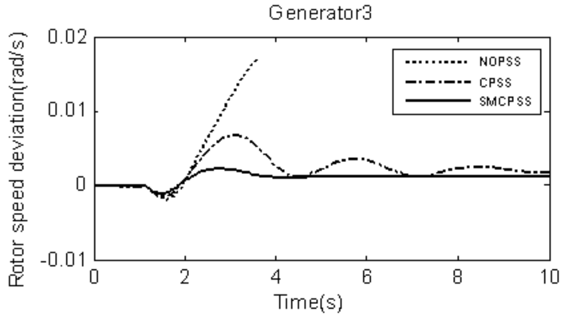

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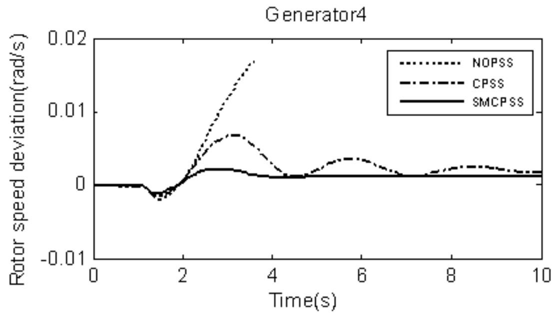
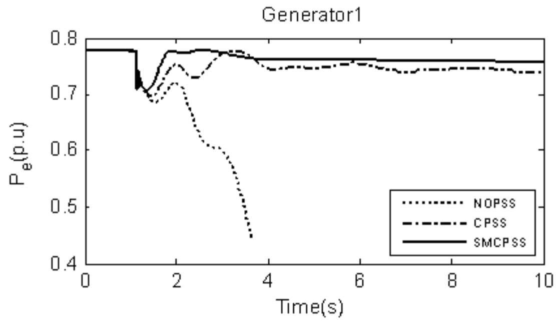
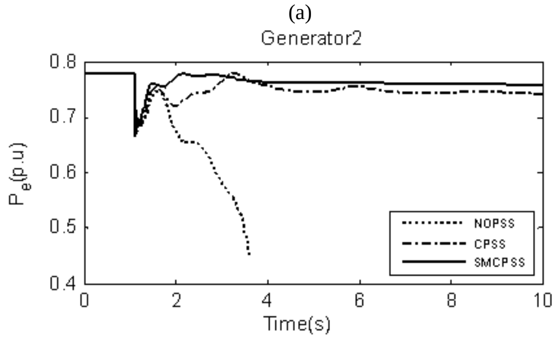


(d)

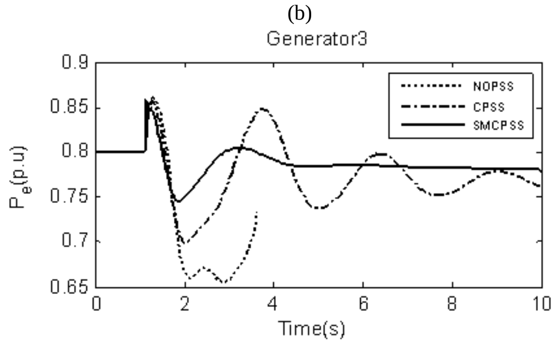
Fig. 7. Rotor speed deviation of the generators (case 2)



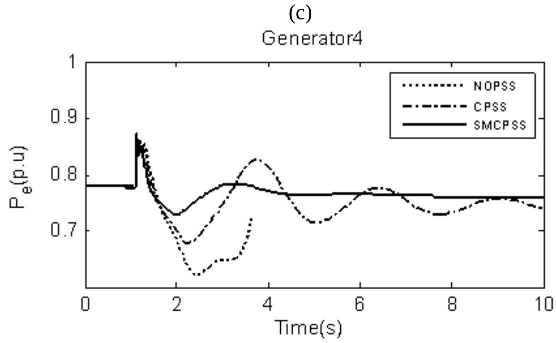
(a)



(b)



(c)



(d)

Figs. 8. Electrical power of the generators (case 2)

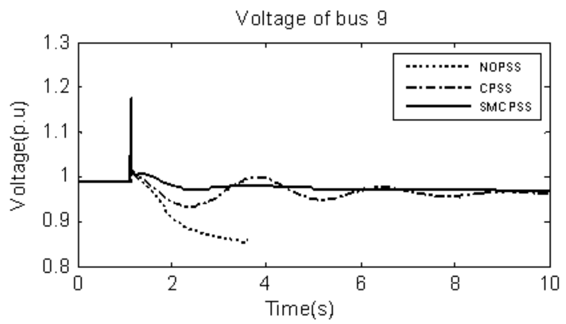


Fig. 9. Voltage magnitude at the faulted bus (case 2)

Again it can be seen from these two figures that the best response are obtained when the SMCPSS is used. 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.

VII. 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.

Appendix

The system depicted in Fig. 1 is two area power system, the two areas are identical and each include two 900 MVA, 20 KV and 60 Hz generators equipped with fast acting excitation systems. The system operates transmitting 400 MW from area 1 to area 2 through two transmission lines. The nominal parameters of the synchronous generators are given in Table A.1 and Table A.2.

TABLE A.1
PARAMETERS OF THE SYNCHRONOUS GENERATORS

Gen	R_s	x_d	x'_d	x_q	x'_q	x_l
	p.u	p.u	p.u	p.u	p.u	p.u
1	0.0025	1.8	0.3	1.7	0.55	0.2
2	0.0025	1.8	0.3	1.7	0.55	0.2
3	0.0025	1.8	0.3	1.7	0.55	0.2
4	0.0025	1.8	0.3	1.7	0.55	0.2

TABLE A.2
PARAMETERS OF THE SYNCHRONOUS GENERATORS

Gen	T'_{do}	T'_{qo}	H	K_D	K_A	T_R
	s	s	s	p.u	-	s
1	8	0.4	6.5	0	200	0.02
2	8	0.4	6.5	0	200	0.02
3	8	0.4	6.175	0	200	0.02
4	8	0.4	6.175	0	200	0.02

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Authors’ information

[1]Department of Electrical Engineering, Islamic Azad University, Najaf Abad Branch, Najaf Abad, Esfahan, Iran.
[2]Department of Electrical Engineering, Malekashtar University, Esfahan, Iran.

Ghazanfar Shahgholian was born in Esfahan, Iran, on December 7, 1968. He graduated in electrical engineering from Esfahan University of Technology (IUT), Esfahan, Iran, in 1992. He received the M.Sc and PhD in electrical engineering from University Tabriz, Tabriz, Iran in 1994 and from Islamic Azad University, Science and Research Branch, Tehran, Iran, in 2006, respectively. He is now an associate professor at Department of Electrical Engineering, Faculty of Engineering, Islamic Azad University – Najaf Abad Branch. His teaching and research interests include application of control theory to power system dynamics, power electronics and power system simulation.

Amin Rajabi was born in Najaf Abad, Iran, on December 1, 1984. He graduated in electrical engineering from IAU Najafabad Branch, Esfahan, Iran, in 2007. He is now a graduate student at Department of Electrical Engineering, Faculty of Engineering, Islamic Azad University – Najafabad Branch. His teaching and research interests include application of power system dynamics, machine and power system simulation.

Bahram Karimi received the M.Sc. degree in control engineering from Isfahan University of Technology, Isfahan, Iran, in 2000, and the Ph.D. degree in control engineering from the Amirkabir University of Technology, Tehran, Iran in 2008. In 2008, he joined Malekashtar University of Technology, Isfahan, Iran, as a Faculty Member, and is currently an Assistant Professor of electrical engineering. His research interests include nonlinear sliding mode and adaptive control, larg-scale systems, and intelligent systems.