Analysis and Design of PSS Based on Sliding Mode Control Theory for SMIB

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***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 single machine infinite bus (SMIB) 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); single-machine infinite-bus (SMIB); sliding mode control (SMC).

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 [1-6].

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 II presents the dynamic model of a SMIB system. In section III the mathematical model of the single machine infinite bus system is transformed into a form that facilitates the design of nonlinear control schemes. Then the sliding mode controller is proposed. Conclusions are drawn in section V. The controller is validated using non-linear model simulation.

II. DYNAMIC MODEL

A single machine infinite bus system consisting of a synchronous generator with loads, connected through transmission lines to a very large network that can be approximated by an infinite bus. An infinite bus is a source of constant frequency and voltage either in magnitude and angle. Although the case of the SMIB is not a true representation of the real power system, but it is hoped that by analyzing such single machine case can help in the design of sliding mode control technique for multi-machine power systems. A schematic representation of this system is shown in Figure 1.

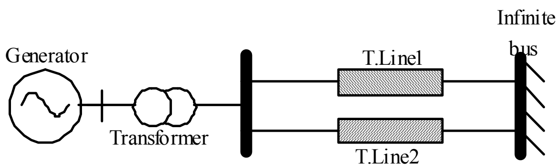

Fig. 1: Single machine connected to a large system through transmission lines

The detailed nonlinear model of a single machine infinite bus system 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 single machine infinite bus system can be written as:

$$\begin{aligned}
&\dot{\delta}(t)=\omega(t)-\omega_o \\
&\dot{\omega}(t)=-\frac{K_D}{2H}(\omega(t)-\omega_o)+\frac{\omega_o}{2H}(P_m-P_e(t)) \\
&\dot{E}'_q(t)=\frac{1}{T'_{do}}(E_F(t)-E_q(t))
\end{aligned} \tag{1}$$

Where:

$$\begin{aligned}
&E_q(t)=\frac{x_{ds}}{x'_{ds}}E'_q(t)-\frac{x_d-x'_d}{x'_{ds}}V_S\cos(\delta(t)) \\
&E_F(t)=k_c u_F(t) \\
&P_e(t)=\frac{V_S E_q(t)}{x_{ds}}\sin(\delta(t)) \\
&x_{ds}=x_d+x_T+\frac{1}{2}x_L \\
&x'_{ds}=x'_d+x_T+\frac{1}{2}x_L
\end{aligned} \tag{2}$$

and $\delta(t)$ is the rotor angle of the generator (radians), $\omega(t)$ is the speed of the rotor of the generator (radian/sec), ω_o is the synchronous machine speed (radian/sec), K_D is the damping constant (pu), H is the inertia constant (sec), P_m is the mechanical input power of the generator (pu), $P_e(t)$ is the active electrical power delivered by the generator (pu), $E_q(t)$ is the EMF of the q-axis of the generator (pu), $E'_q(t)$ the transient EMF in the q-axis of the generator (pu), $E_F(t)$ is the equivalent EMF in the excitation winding of the generator (pu), T'_{do} is the d-axis transient short circuit time constant (sec), K_C is the gain of the excitation amplifier, $u_F(t)$ is the control input of the excitation amplifier with gain K_C, x_{ds} is the total direct reactance of the system (pu), X'_{ds} is the total transient reactance of the system (pu), X_d is the d-axis reactance of the generator (pu), X'_d is the d-axis transient reactance of the generator (pu), X_T is the reactance of the transformer (pu), X_L is the reactance of the transmission line (pu) and V_S is the infinite bus voltage (pu). The states of the system choice as follows:

$$\begin{aligned}
&x_1(t)=\delta(t) \\
&x_2(t)=\omega(t)-\omega_o \\
&x_3(t)=E'_q(t)
\end{aligned} \tag{3}$$

Hence the system state vector will be:

$$\mathbf{x}(t)=[x_1(t)\ x_2(t)\ x_3(t)]^T \tag{4}$$

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

$$u(t)=\frac{k_c}{T'_{do}}u_f(t) \tag{5}$$

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

$$\begin{aligned}
&\alpha_1=-\frac{K_D}{2H} \\
&\alpha_2=-\frac{\omega_o}{2Hx'_{ds}}V_S \\
&\alpha_3=\frac{\omega_o(x_d-x'_d)}{4Hx_{ds}x'_{ds}}V_S^2 \\
&\alpha_4=\frac{\omega_o}{2H}P_m \\
&\alpha_5=-\frac{1}{T'_{do}}\frac{x_{ds}}{x'_{ds}} \\
&\alpha_6=\frac{x_d-x'_d}{T'_{do}x'_{ds}}V_S
\end{aligned} \tag{6}$$

Therefore, using (6) through (1) and (2), the equations describing the single machine infinite bus system can be written as:

$$\begin{aligned}
&\dot{x}_1(t)=x_2(t) \\
&\dot{x}_2(t)=\alpha_1 x_2(t)+\alpha_2 x_3(t)\sin(x_1(t))+\alpha_3\sin(2x_1(t))+\alpha_4 \\
&\dot{x}_3(t)=\alpha_5 x_3(t)+\alpha_6\cos(x_1(t))+u(t)
\end{aligned} \tag{7}$$

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

$$x_D=[x_{1d}\ \ x_{2d}\ \ x_{3d}] \tag{8}$$

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

$$y(t)=x_1(t)-x_{1d} \tag{9}$$

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

$$\left(-\frac{\alpha_1\alpha_6}{2\alpha_5}+\alpha_3\right)\sin(2x_{1d})-\frac{\alpha_2}{\alpha_5}u_d\sin(x_{1d})+\alpha_4=0$$
$$x_{2d}=0 \tag{10}$$
$$x_{3d}=-\frac{\alpha_6}{\alpha_5}\cos(x_{1d})-\frac{1}{\alpha_5}u_d$$

III. DESIGN CONTROLLER

The objective of this section is to design a controller based on sliding mode theory for a single machine infinite bus system so that regulate the states of the SMIB 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 SMIB system are highly nonlinear. Therefore, in first step, to facilitation design of nonlinear controller a change of variable z(t)=T(x) is considered, such that:

$$\begin{aligned} z_1(t)&=x_1(t)-x_{1d}\\ z_2(t)&=x_2(t)\\ z_3(t)&=\alpha_1x_2(t)+\alpha_2x_3(t)\sin(x_1(t))+\alpha_3\sin(2x_1(t))+\alpha_4 \end{aligned} \tag{11}$$

If z(t) converges to zero as t→∞, then x(t) converges to x_D as t→∞. For $\sin(x_1(t))\neq 0$, the inverse of the transmission given in (16) is:

$$\begin{aligned} x_1(t)&=z_1(t)+x_{1d}\\ x_2(t)&=z_2(t)\\ x_3(t)&=1/(\alpha_2\sin(z_1(t)+x_{1d}))(z_3(t)-\alpha_1z_2(t)\\ &\quad-\alpha_3\sin(2(z_1(t)+x_{1d}))-\alpha_4) \end{aligned} \tag{12}$$

The condition $\sin(x_1(t))\neq 0$ means that:

$$x_1(t)=\delta(t)\neq n\pi \quad n=0,\pm1,\pm2,\ldots \tag{13}$$

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. The equations of the SMIB system can be written as function of the new variable such that:

$$\begin{aligned} \dot z_1(t)&=z_2(t)\\ \dot z_2(t)&=z_3(t)\\ \dot z_3(t)&=f(z)+G(z)u\\ y(t)&=z_1(t) \end{aligned} \tag{14}$$

Where:

$$\begin{aligned} f(z)=&\begin{pmatrix}(\alpha_1+\alpha_5)z_3-\alpha_1\alpha_5z_2\\ +\left(\frac{1}{2}\alpha_1\alpha_6-\alpha_3\alpha_5\right)\sin(2(z_1+x_{1d}))\end{pmatrix}\\ &+2\alpha_3z_2\cos(2(z_1+x_{1d}))\\ &+z_2\cot(z_1+x_{1d})\begin{pmatrix}z_3-\alpha_1z_2\\ -\alpha_3\sin(2(z_1+x_{1d}))-\alpha_4\end{pmatrix}\\ &-\alpha_4\alpha_5 \end{aligned} \tag{15}$$

and

$$G(z)=\alpha_2\sin(z_1+x_{1d}) \tag{16}$$

In the original coordinate, the functions $f(z)=f_1(x)$ and $G(z)=G_1(x)$ are:

$$\begin{aligned} f_1(x)=&\alpha_1\begin{pmatrix}\alpha_1x_2+\alpha_2x_3\sin(x_1)\\ +\alpha_3\sin(2x_1)+\alpha_4\end{pmatrix}\\ &+\alpha_2(\alpha_5x_3+\alpha_6\cos(x_1))\sin(x_1)\\ &+\alpha_2x_2x_3\cos(x_1)+2\alpha_3x_2\cos(2x_1) \end{aligned} \tag{17}$$

and

$$G_1(x)=\alpha_2\sin(x_1) \tag{18}$$

The model of the synchronous generator will be used for designing the sliding mode controller. Then the designed controller will be transformed into the original coordinate using $x=T^{-1}(z)$ 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 the SMIB system is as follows:

$$S=\ddot y+\rho_1\dot y+\rho_2y=z_3+\rho_1z_2+\rho_2z_1 \tag{19}$$

Where coefficients ρ_1 and ρ_2 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 $x_1(t)$, $x_2(t)$ and $x_3(t)$ such that:

$$\begin{aligned} S=&\alpha_1x_2+\alpha_2x_3\sin(x_1)+\alpha_3\sin(2x_1)+\alpha_4\\ &+\rho_1x_2+\rho_2(x_1-x_{1d}) \end{aligned} \tag{20}$$

Note that the choice of the switching surface guarantees that the output of the system converges to zero as t→∞ on the sliding surface S(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:

$$u(t)=\frac{-1}{G(z)}(f(z)+\rho_1z_3+\rho_2z_2+\eta\,\mathrm{sign}(z_3+\rho_1z_2+\rho_2z_1)) \tag{21}$$

That η is a positive scalar and determined by designer. For examination the sliding mode existence with respect to the time, it follows that:

$$\dot{S} = \dddot{y} + \rho_1 \ddot{y} + \rho_2 \dot{y} = f(z) + G(z)u + \rho_1 z_3 + \rho_2 z_2 \quad (22)$$

Therefore:

$$\begin{aligned} \dot{S} &= f(z) + \rho_1 z_3 + \rho_2 z_2 \\ &\quad + (-f(z) - \rho_1 z_3 - \rho_2 z_2 - \eta \operatorname{sign}(z_3 + \rho_1 z_2 + \rho_2 z_1)) \\ &= -\eta \operatorname{sign}(z_3 + \rho_1 z_2 + \rho_2 z_1) \\ &= -\eta \operatorname{sign}(S) \end{aligned} \quad (23)$$

Hence:

$$S\dot{S} = -S\eta \operatorname{sign}(s) = -\eta |S| < 0 \quad (24)$$

Therefore the dynamics of S guarantees that $S\dot{S} < 0$. Since S 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 $y(t)=z_1(t)$ will converge to zero as $t \to \infty$ because ρ_1 and ρ_2 are positive scalars. Since $z_1(t)$. converges to zero as $t \to \infty$. Then $z_2(t)$ and $z_3(t)$ 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(t) to zero as $t \to \infty$. The controller function given can be written in the original coordinate as follow:

$$\begin{aligned} u &= \frac{1}{\alpha_2 \sin(x_1)}(-(\alpha_1 + \rho_1)\begin{pmatrix} \alpha_1 x_2 + \alpha_2 x_3 \sin(x_1) \\ + \alpha_3 \sin(2x_1) + \alpha_4 \end{pmatrix} \\ &+ \frac{1}{\alpha_2 \sin(x_1)}\begin{pmatrix} -\alpha_2(\alpha_5 x_3 + \alpha_6 \cos(x_1))\sin(x_1) \\ -\alpha_2 x_2 x_3 \cos(x_1) - 2\alpha_3 x_2 \cos(2x_1) \end{pmatrix} \\ &+ \frac{1}{\alpha_2 \sin(x_1)}(-\rho_2 x_2 - \eta \operatorname{sign}(S)) \end{aligned} \quad (25)$$

where:

$$\begin{aligned} S &= \alpha_1 x_2 + \alpha_2 x_3 \sin(x_1) + \alpha_3 \sin(2x_1) + \alpha_4 \\ &\quad + \rho_1 x_2 + \rho_2 (x_1 - x_{1d}) \end{aligned} \quad (26)$$

Therefore, the proposed controller given by (25) and (26) when applied to the SMIB system that given in (7) and (9) guarantees the asymptotic convergence of x(t) to x_D as $t \to \tilde{\infty}$. 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, in S(x)=0 such that the discontinuous control function given in (25) is rewritten as:

$$\begin{aligned} u &= \frac{1}{\alpha_2 \sin(x_1)}\{(-(\alpha_1 + \rho_1)\begin{pmatrix} \alpha_1 x_2 + \alpha_2 x_3 \sin(x_1) \\ + \alpha_3 \sin(2x_1) + \alpha_4 \end{pmatrix} \\ &+ \begin{pmatrix} -\alpha_2(\alpha_5 x_3 + \alpha_6 \cos(x_1))\sin(x_1) \\ -\alpha_2 x_2 x_3 \cos(x_1) - 2\alpha_3 x_2 \cos(2x_1) \end{pmatrix} \\ &+ (-\rho_2 x_2 - \eta \operatorname{sat}(\frac{S}{\varepsilon}))\} \end{aligned} . \quad (27)$$

where ε>0 form boundary layer in the vicinity of sliding surface. The coefficients ρ_1 and ρ_1 are identified to provide desired eigenvalue placement of the differential equation (19). The settling time (t_S) is 1 sec. The natural frequency (ω_n) is calculated by $\omega_n \approx 10/t_S = 10$.

Using the standard second order homogeneous equation $s^2 + 1.4\omega_n s + \omega_n^2 = 0$ in ITAE criterion, the coefficients are chosen to obtain the desired transient response of the output dynamics as $\rho_1=14$ and $\rho_2=100$.

IV. Simulation Results

The proposed sliding mode control scheme given by (26) and (27), is applied to the single machine infinite bus system given by (7) and (9). 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. Change in mechanical torque

The nominal parameters of the synchronous generator are used. The system is in steady state. A 10% step change in the reference mechanical torque is assumed at t=7.5 sec. In this case the exciter gain K_A is equal to 200. The responses of the angle of the generator δ(t), speed deviation and electrical power $P_e(t)$, when the sliding mode controller is used are shown in Figure4, Figure 5 and Figure 6 respectively.

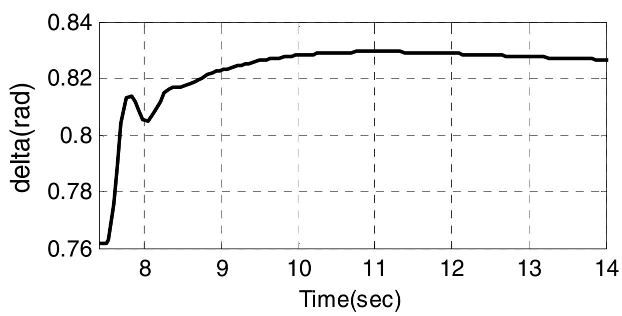

Fig. 2: The rotor angle of the generator using SMCPSS (case 1)

Also the responses of the angle of the generator δ(t) when the sliding mode controller, AVR+PSS controller and without any controller are used, are shown in Figure 7. It can be seen that the response of SMCPSS converges to constant value earlier than AVR+PSS controller. Figure 8 and Figure 9 show the responses of the speed deviation and electrical power when

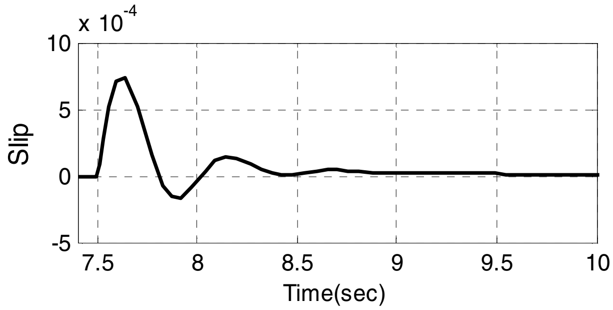

Fig. 3: The speed deviation using SMCPSS (case 1)

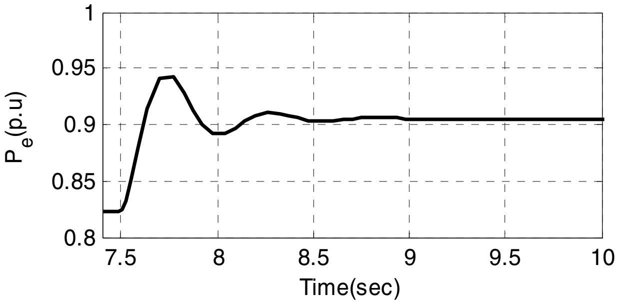

Fig. 4: The electrical power using SMCPSS (case 1)

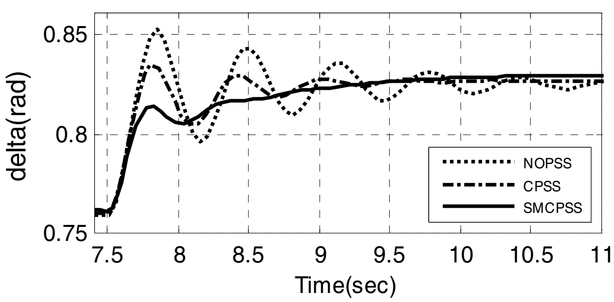

Fig. 5: The rotor angle of the generator (case 1)

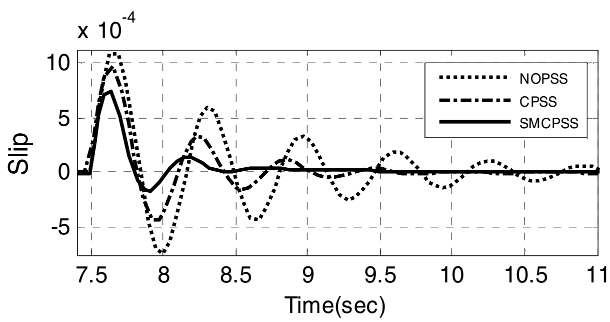

Fig. 6: The speed deviation (case 1)

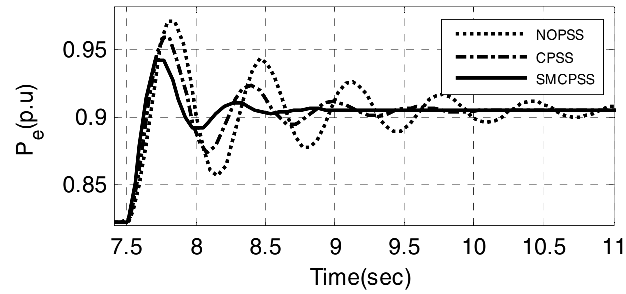

Fig. 7: The electrical power (case 1)

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.

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, is changed from 200 to 100. The responses of the angle of the generator $\delta(t)$ when the sliding mode controller, AVR+PSS controller and without any controller are used are shown in Figure 10. It can be seen that the response of SMCPSS converges to constant value earlier than AVR+PSS controller.

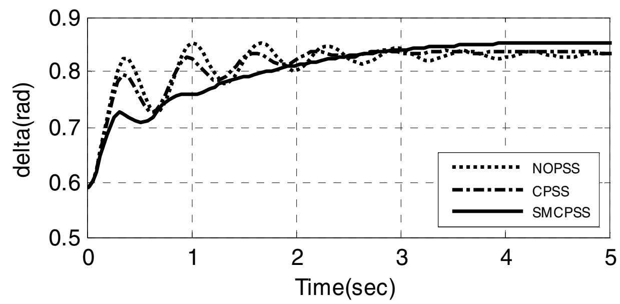

Fig. 8: The rotor angle of the generator (case 2)

Also the responses of the speed deviation and electrical power when the sliding mode controller, AVR+PSS controller and without any controller are used are shown in Figure 11 and Figure 12 respectively. 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 SMIB 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.

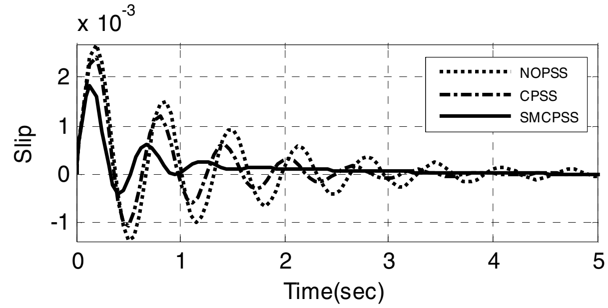

Fig. 9: The speed deviation (case 2)

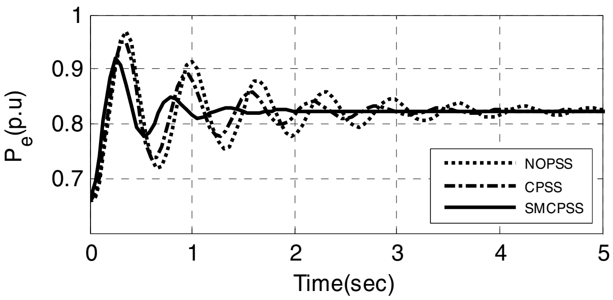

Fig. 10: The electrical power (case 2)

V. CONCULSION

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 SMIB 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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