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Transient Stability of Power Systems Using Sliding Mode Controllers

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Abstract: This study addresses the control problem of a synchronous generator using sliding mode control techniques. The mathematical model of the synchronous generator is first transformed into a form that facilitates the design of nonlinear control schemes. Then, a static sliding mode controller is proposed. To alleviate the chattering problem associated with the static sliding mode controller, a dynamic sliding mode controller is developed. Both control schemes guarantee the convergence of the states of the system to their desired values. The simulations results indicate that both controllers work well. Moreover, the simulations results show that both control schemes are robust to changes in the parameters of the system and to disturbances. In addition, the performance of the controlled system is compared to the performance of the system when a conventional Auto-Voltage Regulator (AVR) is used in conjunction with a Power System Stabilizer (PSS).

Key words: Synchronous generator, sliding mode controllers

INTRODUCTION

Power system stability is defined as the property of a power system to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to disturbances[1]. Kundur[1] classifies power system stability into three categories: rotor angle stability, voltage stability and mid-term/long term stability. Rotor angle stability is the ability of interconnected synchronous generators of the power system to remain in synchronism; synchronous generators are machines which are used to convert mechanical power to electrical power. Moreover, rotor angle stability can be categorized into small signal stability and transient stability. Small signal stability is defined as the ability of the power system to maintain synchronism when subjected to small disturbances[1]. When analyzing the small signal stability of a power system, the dynamic equations of the system are usually linearized since the disturbances are small. Transient stability of a power system is defined as the ability of the power system to maintain synchronism when subjected to severe transient disturbances such as a fault on transmission lines, loss of generation, loss of a large load, etc. Transient stability is affected by the nonlinear characteristics of the power system and hence the nonlinear dynamic model of the system should be used in the analysis. This study deals with the transient stability of power systems; two control schemes are proposed to stabilize synchronous generators and to prevent the loss of synchronism between the generators within an electric power system.

Many control techniques have been used to control synchronous generators and to improve the transient stability of power systems. Smith *et al.*[2] shows an excellent bibliography on power system stability controls in 1986-1994. Several types of nonlinear control schemes have been proposed to control synchronous generators and to enhance the stability of power systems[3-24]. The feedback linearization technique has been used[4,8,13]. Different variable structure control schemes has been designed[3,6,10,20,21] to control synchronous generators. Robust nonlinear controllers have been proposed[4,14,16,17] for synchronous generators. Observer-based controllers[15,19] and predictive control[9] have been used for synchronous generators. Adaptive control has been used to control power systems[5,23,24]. Fuzzy logic controllers have also been used to enhance the stability of power systems[12].

Because of their robustness, Variable Structure Control (VSS) schemes and Sliding Mode Control (SMC) schemes have been widely used to control different types of systems. For example, VSS and SMC techniques have been used to control robots, motors, mechanical systems, etc. Excellent surveys on variable structure control and sliding mode control can be found[25-27]. The VSS and SMC schemes assure the desired behavior of the closed loop system. However, these controllers require an

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infinitely (in the ideal case) fast switching mechanism; the phenomenon of non-ideal but fast switching is labeled as chattering[28]. The high frequency components of the chattering are undesirable because they may excite unmodeled high frequency plant dynamics resulting in instability. Some researchers proposed the idea of boundary layers to reduce the chattering problem. Other researchers used dynamic sliding mode controllers to alleviate the chattering problem[29].

In this study, a static and a dynamic sliding mode control schemes are proposed for the control of synchronous generators. To maintain a high degree of reliability and to show the robustness of the controllers, parameters uncertainties and large disturbances, such as temporary and permanent faults, are considered in the simulations studies. Simulations results indicate that the proposed controllers work well. Comparison of the proposed control schemes with a conventional AVR+PSS controller show that the proposed controllers compare favorably with the AVR+PSS controller. However, the simulation results indicate that the performance of the dynamic sliding mode controller is better than the performance of the static sliding mode controller as the latter suffers from the chattering problem.

DYNAMIC MODEL OF A SYNCHRONOUS GENERATOR

A power 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, is considered in this study. Although the case of a single machine connected to an infinite bus is not a true representation of the real power system, it is hoped that the insights gained by analyzing such single machine case can help in the design of sliding mode control schemes for multi-machine power systems. A schematic diagram of the system is shown in Fig. 1. The detailed nonlinear model of a synchronous generator with a solid round rotor is a sixth order model[30]. However, this model is usually reduced to a generalized one-axis nonlinear third order model[31]. It should be mentioned that this modeling is consistent with normal power system modeling practice, where more detailed linear models are used for analyzing oscillatory stability and simplified nonlinear models are used for studying large disturbance stability, i.e. transient stability.

The equations describing a third order model of a synchronous generator can be written as:

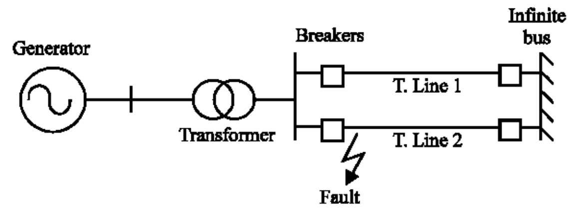

Fig. 1: Schematic diagram of a generator connected to an infinite bus

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

Where:

$$
\begin{aligned}
E_q(t) &= \frac{x_{ds}}{x'_{ds}}E'_q(t)-\frac{x_d-x'_d}{x'_{ds}}V_s\cos(\delta(t)) \\
E_f(t) &= k_c u_f(t) \\
P_e(t) &= \frac{V_s E_q(t)}{x_{ds}}\sin(\delta(t)) \\
V_t(t) &= \frac{1}{x_{ds}}\left\{x_s^2E_q^2(t)+V_s^2x_d^2+2x_sx_dx_{ds}P_e(t)\mathrm{ctg}(\delta(t))\right\}^{\frac{1}{2}} \quad (2) \\
x_{ds} &= x_d+x_T+\frac{1}{2}x_L \\
x'_{ds} &= x'_d+x_T+\frac{1}{2}x_L \\
x_s &= x_T+\frac{1}{2}x_L
\end{aligned}
$$

and

- $\delta(t)$: The power angle of the generator (radians);
- $\omega(t)$: The speed of the rotor of the generator (radian/sec);
- $E_q(t)$: The EMF of the quadrature axis of the generator (p.u.);
- $E'_q(t)$: The transient EMF in the quadrature axis of the generator (p.u.);
- $E_f(t)$: The equivalent EMF in the excitation winding of the generator (p.u.);
- $P_e(t)$: The active electrical power delivered by the generator (p.u.);
- $V_t(t)$: The generator terminal voltage (p.u.);
- $u_f(t)$: The control input of the excitation amplifier with gain k_c;

x_{ds}: The total direct reactance of the system (p.u.);
x'_{ds}: The total transient reactance of the system (p.u.);
P_m: The mechanical input power of the generator (p.u.);
x_d: The direct axis reactance of the generator (p.u.);
x'_d: The direct axis transient reactance of the generator (p.u.);
x_T: The reactance of the transformer (p.u.);
x_L: The reactance of the transmission line (p.u.);
T_{do}: The direct axis transient short circuit time constant (sec);
V_s: The infinite bus voltage (p.u.);
k_c: The gain of the excitation amplifier;
ω_o: The synchronous machine speed $\omega_o = 2\pi f_o$ (rad/sec);
H: The inertia constant (sec);
D: The damping constant (p.u).

Let the states of the system $x_1(t)$, $x_2(t)$ and $x_3(t)$ be such that,

$$x_1(t) = \delta(t)$$
$$x_2(t) = \omega(t) - \omega_o$$
$$x_3(t) = E'_q(t)$$

and let $x(t) = [x_1(t)\ x_2(t)\ x_3(t)]^T$.
The control input u(t) is taken to be,

$$u(t) = \frac{k_c}{T_{do}} u_f(t)$$

Define the following constants of the generator:

$$p_1 = -\frac{D}{2H}$$
$$p_2 = -\frac{\omega_o}{2Hx'_{ds}} V_s$$
$$p_3 = \frac{\omega_o(x_d - x'_d)}{4Hx_{ds}x'_{ds}} V_s^2$$
$$p_4 = \frac{\omega_o}{2H} P_m$$
$$p_5 = -\frac{1}{T_{do}} \frac{x_{ds}}{x'_{ds}}$$
$$p_6 = \frac{x_d - x'_d}{T_{do}x'_{ds}} V_s$$

Therefore, using Eq. 1 and 2 and the above definitions, the equations describing the synchronous generator can be written as:

$$\begin{aligned} \dot{x}_1(t) &= x_2(t) \\ \dot{x}_2(t) &= p_1x_2(t) + p_2x_3(t)\sin x_1(t)) + p_3\sin(2x_1(t)) + p_4 \\ \dot{x}_3(t) &= p_5x_3(t) + p_6\cos(x_1(t)) + u(t) \end{aligned} \quad (3)$$

Let x_{1d}, x_{2d} and x_{3d} be the constant desired states of the synchronous generator system and let $x_D = [x_{1d}\ x_{2d}\ x_{3d}]^T$. We will denote by u_d the control input which enables the system to achieve the desired states.

The controlled output of the system is the deviation of the power angle from its desired value. Hence,

$$y(t) = x_1(t) - x_{1d} \quad (4)$$

It is clear from Eq. 3 that x_{1d}, x_{2d} and x_{3d} satisfy the following equations:

$$\begin{aligned} &\left(-\frac{p_2p_6}{2p_5} + p_3\right)\sin(2x_{1d}) - \frac{p_2}{p_5}u_d\sin(x_{1d}) + p_4 = 0 \\ &x_{2d} = 0 \\ &x_{3d} = -\frac{p_6}{p_5}\cos(x_{1d}) - \frac{1}{p_5}u_d \end{aligned} \quad (5)$$

The objective of the controller was to regulate the states of the synchronous generator to their desired values. The equations describing the synchronous generator system given by Eq. 3 and 4 are highly nonlinear. Therefore, to facilitate the design of nonlinear control schemes, a change of variables was proposed.

Consider the change of variables $z(t) = T(x)$, with $[z_1(t)\ z_2(t)\ z_3(t)]^T$ such that:

$$\begin{aligned} z_1(t) &= x_1(t) - x_{1d} \\ z_2(t) &= x_2(t) \\ z_3(t) &= p_1x_2(t) + p_2x_3(t)\sin(x_1(t)) + p_3\sin(2x_1(t)) + p_4 \end{aligned} \quad (6)$$

Remark 1: Using Eq. 5 and 6, it is easy to check that if z(t) converges to zero as $t \to \infty$, then x(t) converges to x_D as $t \to \infty$.

For $\sin(x_1(t)) \neq 0$, the inverse of the transformation given in Eq. 6 is such:

$$\begin{aligned} x_1(t) &= z_1(t) + x_{1d} \\ x_2(t) &= z_2(t) \\ x_3(t) &= 1/(p_2\sin(z_1(t) + x_{1d}))(z_3(t) - p_1z_2(t) \\ &\quad - p_3\sin(2(z_1(t) + x_{1d})) - p_4) \end{aligned} \quad (7)$$

Remark 2: The condition $\sin(x_1(t)) \neq 0$ means that $x_1(t) = \delta(t) \neq n\pi$ ($n = 0, \pm1, \pm2,...$). However, the operating region of the power angle of the generator $x_1(t) = \delta(t)$ is $(0, \pi)$; hence the condition $\sin(x_1(t)) \neq 0$ is always satisfied in the operating region. It should be mentioned that if $\delta(t)$ is not in $(0, \pi)$, then, generally, synchronism will be lost. The objective of the proposed control schemes was to avoid loss of synchronism.

Using Eq. 3 through 6, the equations of the synchronous generator can be written as functions of the new variables $z_1(t)$, $z_2(t)$ and $z_3(t)$ such that,

$$\begin{aligned}\dot{z}_1(t) &= z_2(t)\\ \dot{z}_2(t) &= z_3(t)\\ \dot{z}_3(t) &= f(z)+g(z)u\end{aligned} \tag{8}$$

$$y(t)=z_1(t) \tag{9}$$

Where:

$$\begin{aligned}f(z) = &\begin{pmatrix}(p_1+p_5)z_3 - p_1p_5z_2\\ +\left(\frac{1}{2}p_2p_6 - p_3p_5\right)\sin(2(z_1+x_{1d})\end{pmatrix}\\ &+2p_3z_2\cos(2(z_1+x_{1d}))\\ &+z_2\cot(z_1+x_{1d})\begin{pmatrix}z_3-p_1z_2\\ -p_3\sin(2(z_1+x_{1d}))-p_4\end{pmatrix}\\ &-p_4p_5\end{aligned} \tag{10}$$

$$g(z)=p_2\sin(z_1+x_{1d}) \tag{11}$$

It should be noted that in the original coordinates, the functions $f(z) = f_1(x)$ and $g(z) = g_1(x)$ are such that:

$$\begin{aligned}f_1(x) = &\,p_1(p_1x_2+p_2x_3\sin(x_1)+p_3\sin(2x_1)+p_4)\\ &+p_2(p_5x_3+p_6\cos(x_1))\sin(x_1)\\ &+p_2x_2x_3\cos(x_1)+2p_3x_2\cos(2x_1)\end{aligned} \tag{12}$$

$$g_1(x)=p_2\sin(x_1) \tag{13}$$

The model of the synchronous generator given by Eq. 8 and 9 will be used when designing the sliding mode control schemes. Then, the designed control schemes will be transformed into the original coordinates using the transformation $x = T^{-1}(z)$ given by Eq. 7.

DESIGN OF A STATIC SLIDING MODE CONTROLLER

Here, a sliding mode control scheme is designed for the synchronous generator system.

The first step in designing a sliding mode controller is to design a switching surface. Let the switching surface σ sigma be such that:

$$\begin{aligned}\sigma &= \ddot{y}+\alpha_1\dot{y}+\alpha_2 y\\ &= z_3+\alpha_1z_2+\alpha_2z_1\end{aligned} \tag{14}$$

Where, α_1 and α_2 are positive scalars. Using Eq. 6, the switching surface σ can be written as a function of $x_1(t)$, $x_2(t)$ and $x_3(t)$ such that:

$$\begin{aligned}\sigma = &\,p_1x_2+p_2x_3\sin(x_1)+p_3\sin(2x_1)\\ &+p_4+\alpha_1x_2+\alpha_2(x_1-x_{1d})\end{aligned} \tag{15}$$

Note that the choice of the switching surface guarantees that $y(t) = z_1(t) = x_1(t) - x_{1d}$ converges to 0 as $t \to \infty$ on the sliding surface $\sigma = 0$.

Let W be a positive scalar.

The following theorem gives the first result of the study.

Theorem 1: The static sliding mode controller,

$$\begin{aligned}u(t) = &\frac{-1}{g(z)}(f(z)+\alpha_1z_3+\alpha_2z_2\\ &+W\,\mathrm{sign}(z_3+\alpha_1z_2+\alpha_2z_1))\end{aligned} \tag{16}$$

When applied to the synchronous generator system represented by Eq. 8 and 9, asymptotically stabilizes $z_1(t)$, $z_2(t)$ and $z_3(t)$ to zero as $t \to \infty$.

Proof: Differentiating Eq. 14 with respect to time and using Eq. 8 and 9, it follows that:

$$\begin{aligned}\dot{\sigma} &= y^{(3)}+\alpha_1\ddot{y}+\alpha_2\dot{y}\\ &= f(z)+g(z)u+\alpha_1z_3+\alpha_2z_2\end{aligned} \tag{17}$$

Substituting u by its value from Eq. 16, it follows that:

$$\begin{aligned}\dot{\sigma} &= f(z)+\alpha_1z_3+\alpha_2z_2\\ &\quad+(-f(z)-\alpha_1z_3-\alpha_2z_2-W\,\mathrm{sign}(z_3+\alpha_1z_2+\alpha_2z_1))\\ &= -W\,\mathrm{sign}(z_3+\alpha_1z_2+\alpha_2z_1)\\ &= -W\,\mathrm{sign}(\sigma)\end{aligned} \tag{18}$$

From the theory of variable structure systems, it is a well known fact that, to guarantee switching, one needs to have $\sigma\dot{\sigma} < 0$ [25]. Using Eq. 18, it follows that:

$$\sigma\dot{\sigma} = -W\sigma\,\mathrm{sign}(\sigma) = -W|\sigma| < 0 \tag{19}$$

Therefore the dynamics of σ in Eq. 18 guarantees that $\sigma\dot{\sigma} < 0$. The trajectories associated with the discontinuous dynamics given by Eq. 18 exhibit a finite time reachability to zero from any given initial condition provided that the scalar W is chosen to be strictly positive. Since σ is driven to zero in finite time, the output $y(t) = z_1(t)$ is governed after such finite amount of time by the second order differential equation $\ddot{y}(t)+\alpha_1\dot{y}(t)+\alpha_2 y(t)=0$. Thus the output $y(t) = z_1(t)$ will converge to 0 as $t \to \infty$ because α_1 and α_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 static sliding mode controller given by Eq. 16 guarantees the asymptotic convergence of $z_1(t)$, $z_2(t)$ and $z_3(t)$ to zero as $t \to \infty$.

Remark 3: The controller given in Eq. 16 can be written in the original coordinates using the transformation given in Eq. 7. Hence the controller in the original coordinates is such:

$$\begin{aligned} u = & \frac{1}{p_2\sin(x_1)}\left(-(p_1+\alpha_1)\begin{pmatrix} p_1x_2+p_2x_3\sin(x_1) \\ +p_3\sin(2x_1)+p_4 \end{pmatrix}\right. \\ & +\frac{1}{p_2\sin(x_1)}\begin{pmatrix} -p_2(p_5x_3+p_6\cos(x_1))\sin(x_1) \\ -p_2x_2x_3\cos(x_1)-2p_3x_2\cos(2x_1) \end{pmatrix} \\ & +\frac{1}{p_2\sin(x_1)}(-\alpha_2x_2 - W\,\mathrm{sign}(\sigma)) \end{aligned} \quad (20)$$

With,

$$\begin{aligned} \sigma = & p_1x_2+p_2x_3\sin(x_1)+p_3\sin(2x_1) \\ & +p_4+\alpha_1x_2+\alpha_2(x_1-x_{1d}) \end{aligned} \quad (21)$$

Moreover, the controller given by Eq. 20 and 21 when applied to the synchronous generator system given by Eq. 3 and 4 guarantees the asymptotic convergence of $x_1(t)$, $x_2(t)$ and $x_3(t)$ to their desired values as $t \to \infty$.

Like any other variable structure controller, the proposed controller is confronted with the problem of chattering which is undesirable in practice. To cope with this problem, dynamic sliding mode controllers have been proposed. Therefore, a dynamic sliding mode controller for the synchronous generator system was also proposed.

DESIGN OF A DYNAMIC SLIDING MODE CONTROLLER

Sira-ramirez *et al.*[32] proposed the use of a robust redundant feedback controller, based on dynamical sliding mode control, for nonlinear systems for which a smooth feedback control policy is available. Motivated by their work, a dynamic sliding mode controller is designed for the synchronous generator system.

Let the scalars β_1, β_2 and β_3 be real positive constants such that the polynomial $P(s) = s^3 + \beta_3 s^2 + \beta_2 s + \beta_1 = 0$ is Hurwitz (i.e., the roots of P(s) lie to the left of the $j\omega$ axis of the s-plane).

The following feedback linearization controller,

$$u_f = \frac{-1}{g(z)}(f(z)+\beta_1z_1+\beta_2z_2+\beta_3z_3) \quad (22)$$

When applied to the synchronous generator system given by Eq. 8 and 9 guarantees the asymptotic convergence of $z_1(t)$, $z_2(t)$ and $z_3(t)$ to zero as $t \to \infty$.

The closed loop system, when controller in Eq. 22 is applied to the synchronous generator system given by Eq. 8 and 9, can be written as:

$$\dot{z}(t) = A_c z(t) \quad (23)$$

Where:

$$A_c = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -\beta_1 & -\beta_2 & -\beta_3 \end{bmatrix}$$

The solution of Eq. 23 is $z(t) = e^{A_c t}z(0)$. Since A_c is a stable matrix (as β_1, β_2 and β_3 are chosen such that P(s) is Hurwitz), then z(t) converges to 0 as $t \to \infty$. Hence, the feedback linearization controller given by Eq. 22 when applied to the synchronous generator system given by Eq. 8 and 9 guarantees the asymptotic convergence of $z_1(t)$, $z_2(t)$ and $z_3(t)$ to zero as $t \to \infty$.

The feedback linearization controller given by Eq. 22 is not robust, therefore a robust dynamic sliding mode controller is presented next. The proposed dynamic sliding mode controller contains the same terms as the feedback linearization controller given by Eq. 22 plus an additional term which will help in the robustness of the closed loop system.

Let the input-dependent switching surface $\rho(z,u)$ be such that:

$$\rho(z,u) = u + \frac{1}{g(z)}(f(z)+\beta_1z_1+\beta_2z_2+\beta_3z_3) \quad (24)$$

Let Γ be a sufficiently large, strictly positive scalar.

The following theorem gives the main result of this section.

Theorem 2: The dynamic sliding mode control scheme,

$$u = \frac{-1}{g(z)}(f(z)+\beta_1z_1+\beta_2z_2+\beta_3z_3)+\upsilon \quad (25)$$

With,

$$\dot{\upsilon} = -\Gamma\,\mathrm{sign}\left(u + \frac{1}{g(z)}(f(z)+\beta_1z_1+\beta_2z_2+\beta_3z_3)\right) \quad (26)$$

When applied to the synchronous generator system given by Eq. 8 and 9, guarantees the asymptotic convergence of $z_1(t)$, $z_2(t)$ and $z_3(t)$ to zero as $t \to \infty$.

Proof: Using Eq. 24 through 26, it can be easily checked that $\rho(z.u)\dot{\rho}(z.u) < 0$. The trajectories associated with the discontinuous dynamics given by Eq. 26 exhibit a finite time reachability to zero from any given initial condition provided that the scalar Γ is chosen to be sufficiently large, strictly positive scalar. Since $\rho(z, u)$ is driven to zero in finite time, then the closed loop system is governed on the sliding surface $\rho(x, u) = 0$ by the following equation:

$$\dot{z}(t) = A_c z(t) \tag{27}$$

Where:

$$A_c = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -\beta_1 & -\beta_2 & -\beta_3 \end{bmatrix}$$

The solution of Eq. 27 is $z(t) = e^{A_c t} z(0)$. Since A_c is a stable matrix, then z(t) converges to zero as $t \to \infty$. Thus, $z_1(t)$, $z_2(t)$ and $z_3(t)$ converge to zero as $t \to \infty$.

Thus, it can be concluded that the dynamic sliding mode controller described by Eq. 25 and 26 when applied to the synchronous generator system given by Eq. 8 and 9, guarantees the asymptotic convergence of $z_1(t)$, $z_2(t)$ and $z_3(t)$ to zero as $t \to \infty$.

Remark 4: The controller given by Eq. 25 and 26 can be transformed into the original coordinates of the system by using transformation given by Eq. 7. Hence, the controller in the original coordinates is such:

$$u = \frac{-1}{p_2 \sin(x_1)} \begin{pmatrix} f_1 + \beta_1(x_1 - x_{1d}) + \beta_2 x_2 \\ +\beta_3(p_1 x_2 + p_2 x_3 \sin(x_1) \\ +p_3 \sin(2x_1) + p_4) \end{pmatrix} + \upsilon \tag{28}$$

With,

$$\dot{\upsilon} = -\Gamma \text{sign} \begin{pmatrix} u + \frac{1}{p_2 \sin x_1}(f_1 + \beta_1(x_1 - x_{1d}) \\ +\beta_2 x_2 + \beta_3 \begin{pmatrix} p_1 x_2 + p_2 x_3 \sin x_1 \\ +p_3 \sin(2x_1) + p_4 \end{pmatrix} \end{pmatrix} \tag{29}$$

$$\begin{aligned} f_1 = {} & p_1 \begin{pmatrix} p_1 x_2 + p_2 x_3 \sin(x_1) \\ +p_3 \sin(2x_1) + p_4 \end{pmatrix} \\ & + p_2 (p_5 x_3 + p_6 \cos(x_1)) \sin(x_1) \\ & + p_2 x_2 x_3 \cos(x_1) + 2p_3 x_2 \cos(2x_1) \end{aligned} \tag{30}$$

Moreover, the controller given by Eq. 28 through 30 when applied to the synchronous generator system described by Eq. 3) and 4 guarantees the asymptotic convergence of $x_1(t)$, $x_2(t)$ and $x_3(t)$ to their desired values as $t \to \infty$.

SIMULATION STUDIES

The static and dynamic sliding mode control schemes given by Eq. 20, 21, 28-30, respectively are applied to the synchronous generator system given by Eq. 3 and 4. The controlled system is simulated using MATLAB.

The performances of the proposed control schemes will be compared to the performance of a conventional AVR+PSS controller. The block diagram of this controller is given in Fig. 2. This model represents a bus-fed thyristor excitation system (classified as IEEE type ST1A excitation system model[1] with an automatic voltage regulator (AVR) and a power system stabilizer (PSS) (Fig. 2). A high exciter gain K_A without transient gain reduction or derivative feedback is used. The transfer function of the terminal voltage transducer $G_{TVT}(s)$ is such:

$$G_{TVT}(s) = \frac{1}{1 + sT_R} \tag{31}$$

The transfer function of the power system stabilizer $G_{PSS}(s)$ is such:

$$G_{PSS}(s) = K_{stab} \frac{sT_w}{1 + sT_w} \frac{1 + sT_1}{1 + sT_2} \frac{1 + sT_3}{1 + sT_4} \tag{32}$$

The transfer function of the AVR/exciter is such:

$$G_{avr}(s) = K_A \tag{33}$$

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

$$E_f = K_A(V_{ref} - v_1 + v_{ps}) \tag{34}$$

Where, v_1 is the output of the terminal voltage transducer, v_{ps} is the output of the power system stabilizer and V_{ref} is the reference voltage.

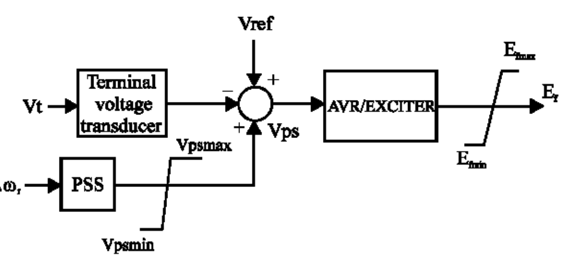

Fig. 2: Block diagram of the AVR+PSS controller

Table 1: Parameters of the synchronous generator

Parameter	Value
x_d	1.863 p.u.
x'_d	0.257 p.u.
x_T	0.127 p.u.
x_L	0.4853 p.u.
T_{do}	6.9 sec
V_s	1 p.u.
ω_o	314.16 rad sec^{-1}
H	4 sec
D	5 p.u.

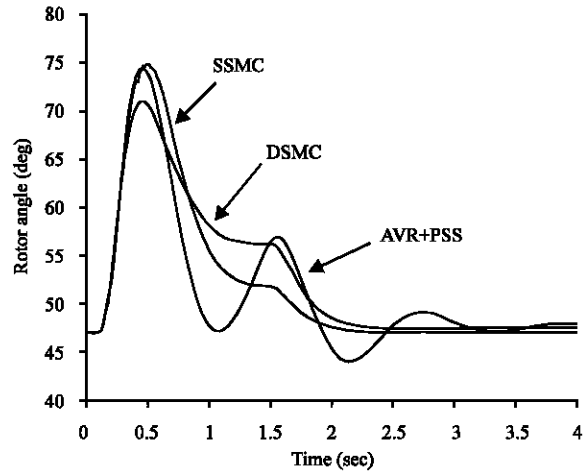

Fig. 3: The power angle of the generator, δ(t) (case 1, TF)

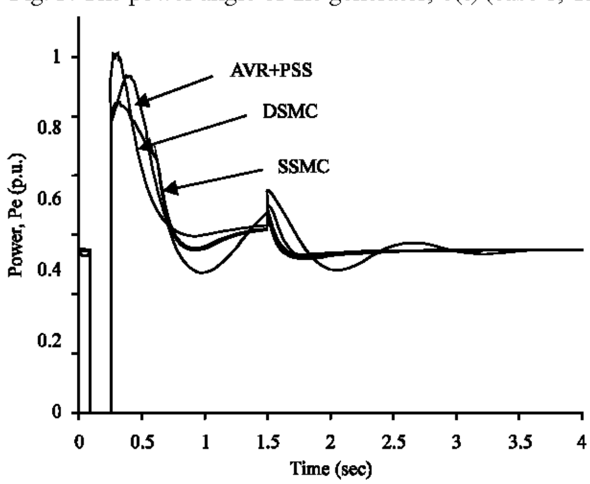

Fig. 4: The electrical power, $P_e(t)$ (case 1, TF)

The nominal parameters of the synchronous generator are given in Table 1.

A limiter is employed when using the different controllers. The limiter is such $-5 \le k_c u_f(t) \le 5$.

Four different cases are considered for simulation purposes.

Case 1. Temporary fault: The nominal parameters of the synchronous generator are used. A temporary fault occurs in the system; the fault considered in this study is a symmetrical 3-phase short circuit fault which occurs on

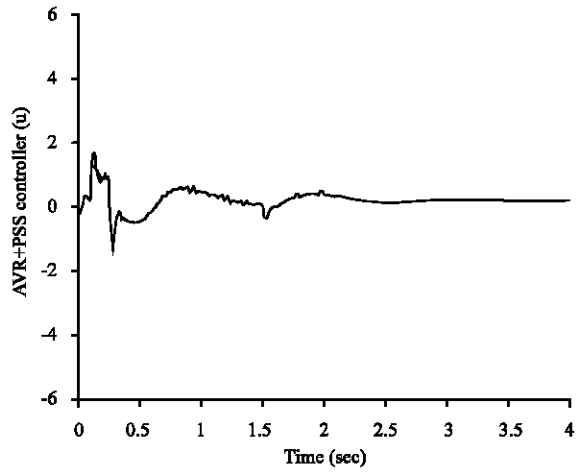

Fig. 5: The AVR+PSS controller (case 1, TF)

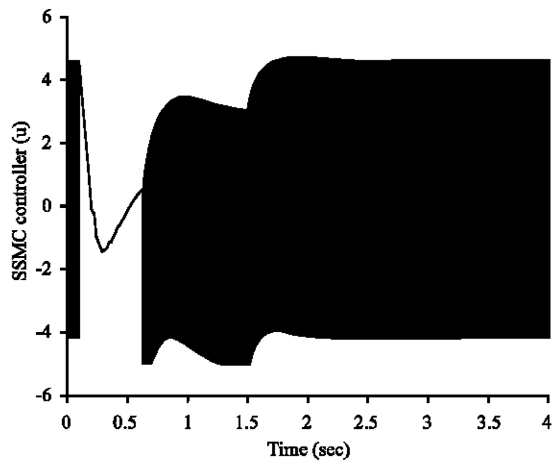

Fig. 6: The static sliding mode controller (case 1, TF)

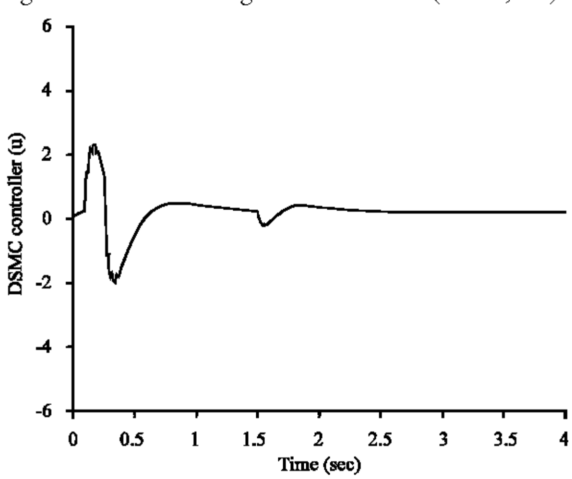

Fig. 7: The dynamic sliding mode controller (case 1, TF)

one of the transmission lines[4]. The fault is considered to be in the middle of the line. The sequence of the temporary fault is as follows. The system is in a pre-fault

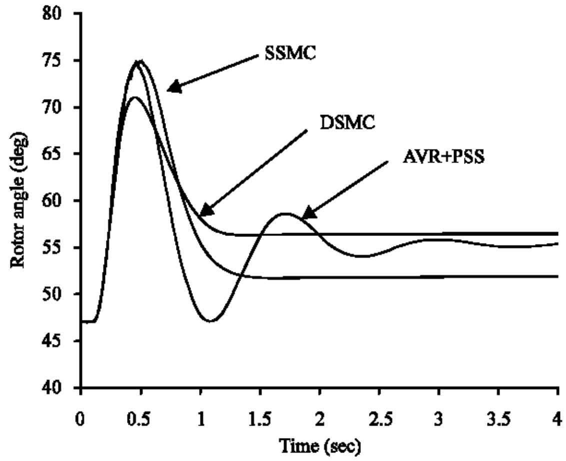

Fig. 8: The power angle of the generator, δ(t) (case 2, PF)

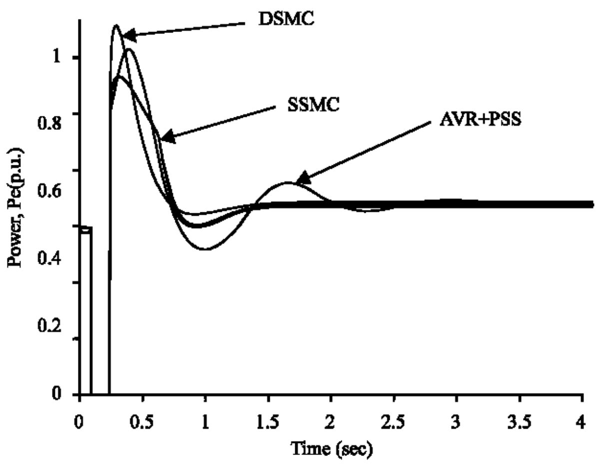

Fig. 9: The electrical power, $P_e(t)$ (case 2, PF)

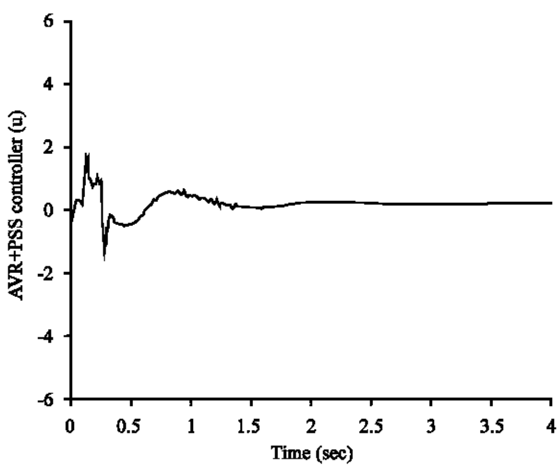

Fig. 10: The AVR+PSS controller (case 2, PF)

steady-state. A fault occurs at t = 0.1 sec. The fault is removed by opening the breakers of the faulted line at t = 0.25 sec. The transmission lines are restored at

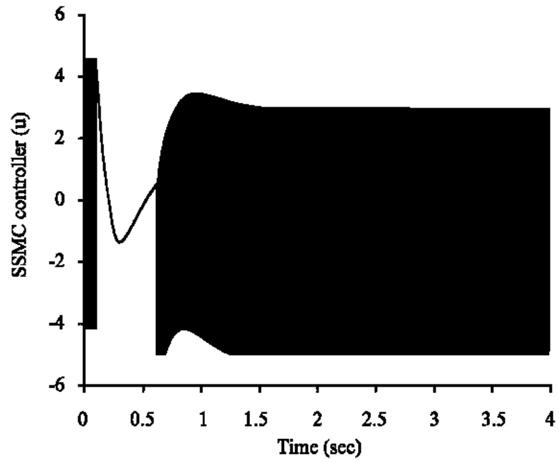

Fig. 11: The static sliding mode controller (case 2, PF)

t = 1.5 sec; the system is in a post-fault state[4]. The responses of the rotor angle δ(t) when the static sliding mode controller (SSMC), the dynamic sliding mode controller (DSMC) and the AVR+PSS controller are used are shown in Fig. 3. It can be seen that δ(t) converges to its desired value in about 3 sec. The responses of the electrical power $P_e(t)$ when the three controllers are used are shown in Fig. 4. It can be seen that $P_e(t)$ converges to its desired value in about 2.5 sec. It can be seen from these two figures that the best responses are obtained when the dynamic sliding mode controller is used. Furthermore, the responses of the AVR+PSS controller, the static sliding mode controller and the dynamic sliding mode controller are plotted versus time (Fig. 5-7), respectively. The chattering of response of the static sliding mode controller is evident in Fig. 6.

Case 2. Permanent fault: The nominal parameters of the synchronous generator are used. A permanent fault occurs in the system. The sequence of the permanent fault is as follows. The system is in a pre-fault steady-state. A fault occurs at t = 0.1 sec. The fault is removed by opening the breakers of the faulted line at t = 0.25 sec; the system is in a post-fault state. The responses of the rotor angle δ(t) when the Static Sliding Mode Controller (SSMC), the Dynamic Sliding Mode Controller (DSMC) and the AVR+PSS controller are used are shown in Fig. 8. The responses of the power $P_e(t)$ when the three controllers are used are shown in Fig. 9. It can be seen from these two figures that the best responses are obtained when the dynamic sliding mode controller is used. The responses of the AVR+PSS controller, the static sliding mode controller and the dynamic sliding mode controller are plotted versus time (Fig. 10-12), respectively. It can be seen that the static sliding mode controller exhibits a lot of chattering.

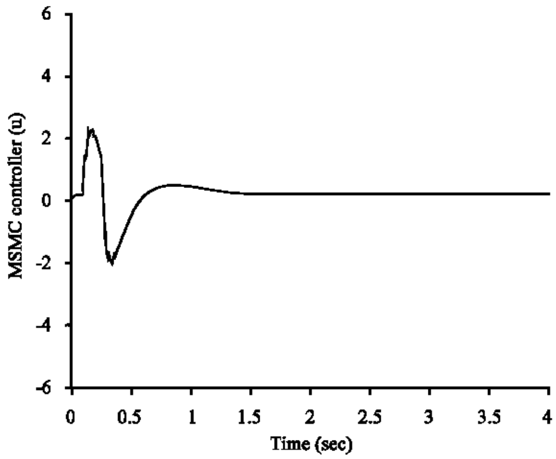

Fig. 12: The dynamic sliding mode controller (case 2, PF)

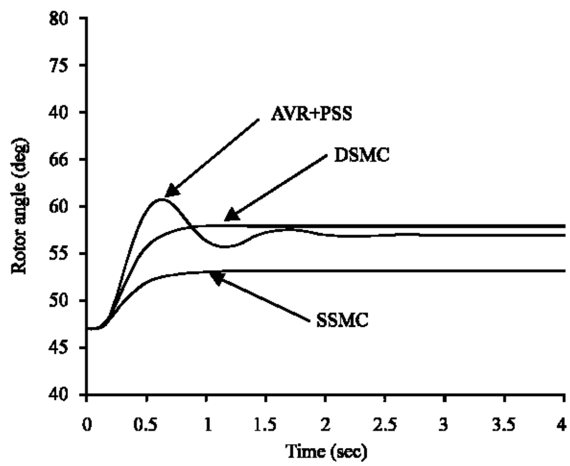

Fig. 13: The power angle of the generator, δ(t) (case 3)

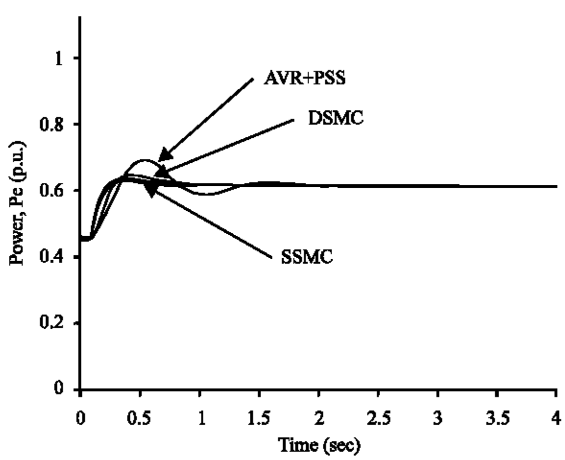

Fig. 14: The electrical power, $P_e(t)$ (case 3)

Case 3. Change in mechanical power: The nominal parameters of the synchronous generator are used. A step change in the mechanical input power of the generator is assumed. The sequence of the change is as follows. The system is in steady state. A change in P_m from 0.45 to

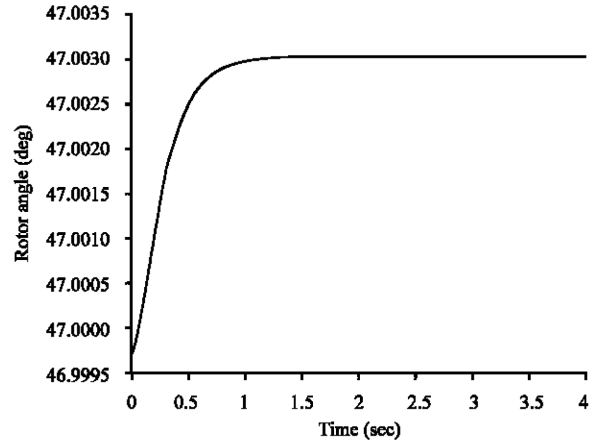

Fig. 15: δ(t) when the static sliding mode controller is used (case 4)

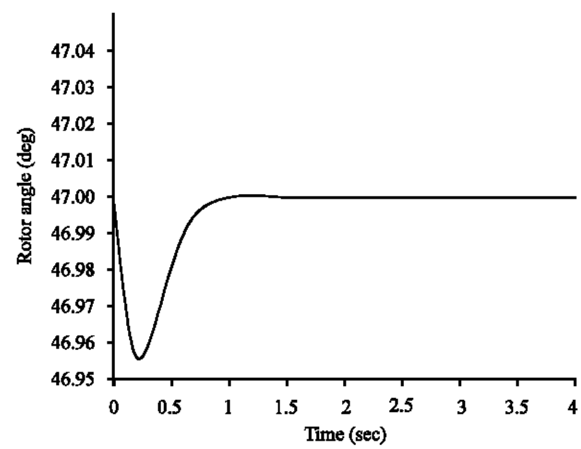

Fig. 16: δ(t) when the dynamic sliding mode controller is used (case 4)

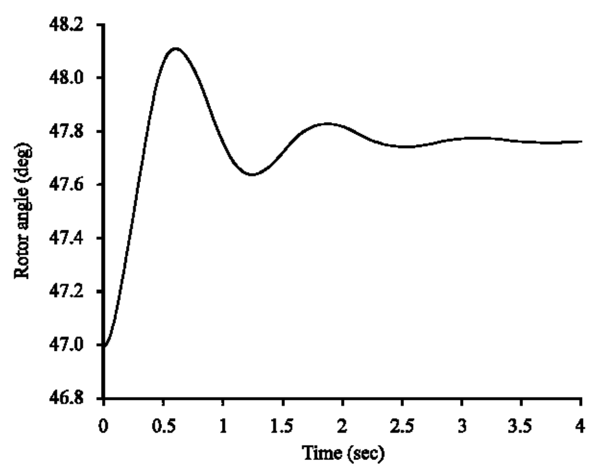

Fig. 17: δ(t) when the AVR+PSS controller is used (case 4)

0.6 p.u. occurs at t = 0.1 sec. The responses of the angle of the generator δ(t) when the static sliding mode controller, the dynamic sliding mode controller and the

AVR+PSS controller are used are shown in Fig. 13. It can be seen that the responses converge to constant values in about 2 sec. The responses of the electrical power $P_e(t)$ when the static sliding mode controller, the dynamic sliding mode controller and the AVR+PSS controller are used are shown in Fig. 14. It can be seen that the responses converge to the desired value in about 1.5 sec. The chattering is evident in the response of $P_e(t)$ when the static sliding mode controller is used. Again, it can be seen from these two figures that the best responses are obtained when the dynamic sliding mode controller is used.

Case 4. Change in the Inertia: The nominal parameters of the synchronous generator are used. A 15% step change in the rotor inertia of the synchronous generator is assumed. The sequence of the change is as follows. The system is in steady state. A 15% change in the rotor inertia occurs at t = 0.1 sec; the rotor inertia is restored to its original value at t = 0.25 sec. The responses of the angle of the generator $\delta(t)$ when the static sliding mode controller, the dynamic sliding mode controller and the AVR+PSS controller are used are shown in Fig. 15-17, respectively. It can be seen that the responses converge to constant values in about 2 sec. It can be seen from these figures that the best response is obtained when the dynamic sliding mode controller is used.

It should be mentioned that simulations were also carried out when other parameters of the system are changed. The simulation results are not shown because of space limitations. However, the simulation results indicate that the proposed sliding mode controllers work well and a re robust to changes in the parameters of the system.

Hence, the simulation results of the four different cases indicate that the proposed static and dynamic sliding mode control schemes work well when applied to the synchronous generator system. Moreover, the simulation results show that the proposed controllers are robust to parameter uncertainties and to disturbances. In addition, the dynamic sliding mode controller gave better results than the static sliding mode controller and the conventional AVR+PSS controller.

CONCLUSIONS

The problem of static and dynamic sliding mode control of a synchronous generator system is investigated in this study. At first, a static sliding mode control scheme is derived for the system. To reduce the chattering problem associated with static sliding mode controllers, a dynamic sliding mode controller is proposed. Simulation results of the proposed control schemes are given to illustrate the theoretical developments. It is found that the proposed controllers work well and are robust to changes in the parameters of the system and to disturbances acting on the system.

In addition, the simulation results indicate that the dynamic sliding mode controller achieves a better performance than the conventional AVR+PSS controller especially when the parameters of the system change. The applicability of the proposed sliding mode control schemes to a multi-machine power system will be investigated in the future.

REFERENCES

1. Kundur, P., 1993. Power System Stability and Control. McGraw-Hill, Inc.
2. Smith, J.R., G. Andersson and C.W. Taylor, 1996. Annotated bibliography on power system stability controls: 1986-1994. IEEE Trans. on Power Sys., 11: 794-800.
3. Hsu, Y-Y. and C-H. Cheng, 1988. Variable structure and adaptive control of synchronous generator. IEEE Trans. Aerospace and Elect. Sys., 24: 337-345.
4. Gao, L., L. Chen, Y. Fan and H. Ma, 1992. A Nonlinear control design for power systems. Automatica, 28: 975-979.
5. Song, Y.H., 1992. Novel adaptive control scheme for improving power system stability. IEE Proceedings-C, 139: 423-426.
6. Cao, Y., S. Cheng, D. Chen, O.P. Malik and G.S. Hope, 1994. A nonlinear variable structure stabilizer for power system stability. IEEE Transactions on Energy Conversion, 9: 489-495.
7. Law, K.T., D.J. Hill and N.R. Godfrey, 1994. Robust controller structure for coordinated power system voltage regulator and stabilizer design. IEEE Trans. Control Sys. Technol., 2: 220-232.
8. Mielczarski, W. and A.M. Zajaczkowski, 1994. Nonlinear field voltage control of a synchronous generator using feedback linearization. Automatica, 30: 1625-1630.
9. Saidy, M. and F.M. Hughes, 1995. Predictive excitation control of a turbo-alternator. Intl. J. Control, 61: 507-524.
10. Dash, P.K., N.C. Sahoo, S. Elangovan and A.C. Liew, 1996. Sliding mode control of a static VAR controller for synchronous generator stabilization. Electrical Power and Energy Systems, 18: 55-64.
11. Gao, G., Y. Wang, K.Y. Lim and L. Gao, 1996. Robust nonlinear controller for power system transient stability enhancement with voltage regulation. IEEE Proc. Generation Transmission and Distribution, 143: 407-412.

12. Toliyat, H.A., J. Sadeh and R. Ghazi, 1996. Design of augmented fuzzy logic power system stabilizers to enhance power systems stability. IEEE Transactions on Energy Conversion, 11: 97-103.
13. Lahdhiri, T. and A.T. Alouani, 1997. Design of a nonlinear excitation controller for a Synchronous generator using the concept of exact stochastic feedback linearization. Proceedings of the American Control Conference, New Mexico, 1: 3798-3803.
14. Lahdhiri, T. and A.T. Alouani, 1998. On the robust control of synchronous generators. Proceedings of the American Control Conference, Philadelphia, 1: 1963-1967.
15. Martinez-Guerra, R., J. De Leon-Morales and O. Huerta-Guevara, 1999. Observer-based controller for a synchronous generator. Proceedings of the 38th Conference on Decision and Control, Phoenix, 1: 4644-4649.
16. Shen, T., S. Mei, Q. Lu, Q. and K. Tamura, 1999. Robust nonlinear excitation control with L_2 disturbance attenuation for power systems. Proceedings of the 38th Conference on Decision and Control, Arizona, 1: 2491-2492.
17. Wang, Y. and D.J. Hill, 1996. Robust nonlinear coordinated control of power systems. Automatica, 32: 611-618.
18. Wang, B., L. Tian and Z. Mao, 1999. Variable structure control of a large synchronous generator. Proceedings of the IEEE International Conference on Power Electronics and Drive Systems, PEDS99, Hong Kong, 1: 1134-1139.
19. De Leon-Morales, J., R. Castro-Linares and G. Acosta-Villarreal, 2000. Control of a synchronous generator via a nonlinear controller-observer scheme. Proceedings of the American Control Conference, Chicago, 1: 1093-1097.
20. Loukianov, A.G., J. Cabrera-Vazquez, V. Utkin, J.M. Canedo and J.M. Ramirez, 2000. Control of the system synchronous generator-exciter via VSC. Proceedings of the 39th Conference on Decision and Control, Sydney, 1: 3057-3062.
21. Chang, G.K. and T.L. Chern, 2001. Modified integral variable structure model following control of a synchronous generator. Proceedings of the American Control Conference, Arlington, 1: 823-828.
22. Eberly, T.W. and R.C. Schaefer, 2002. Voltage versus VAR/power-factor regulation on synchronous generators. IEEE Transactions on Industry Applications, 38: 1682-1687.
23. Fregene, K. and D. Kennedy, 2003. Stabilizing control of a high-order generator model by adaptive feedback linearization. IEEE Transactions on Energy Conversion, 18: 149-156.
24. Park, J.W., R.G. Harley and G.K. Venayagamoorthy, 2003. Adaptive-critic-based optimal neuro-control for synchronous generators in a power system using MLP/RBF neural networks. IEEE Transactions on Industry Applications, 39: 1529-1540.
25. Hung, J.Y., W. Gao and J.C. Hung, 1993. Variable structure control: A survey. IEEE Transactions on Industrial Electronics, 40: 2-22.
26. Young, K.D., V.I. Utkin and U. Ozguner, 1999. A control engineer's guide to sliding mode control. IEEE Transactions on Control Systems Technology, 7: 328-342.
27. Kaynak, O., K. Erbatur and M. Ertugrul, 2001. The fusion of computationally intelligent methodologies and sliding-mode control: A survey. IEEE Transactions on Industrial Electronics, 48: 4-17.
28. Levine, W.S., 1996. The Control Handbook, CRC Press, MA, USA.
29. Sira-Ramirez, S. Ahmad and M. Zribi, 1992. Dynamical feedback control of robotic manipulators with joint flexibility. IEEE Transactions on Systems, Man and Cybernetics, 22: 736-747.
30. Anderson, P.M. and A.A. Fouad, 1977. Power System Control and Stability. Iowa State University Press, Iowa, USA.
31. Mielczarski, W., 1987. Observing the state of a synchronous generator: Part 2. Applications. Intl. J. Control, 45: 1001-1021.
32. Sira-Ramirez, H., O. Llanes-Santiago and N.A. Fernandez, 1996. On the stabilization of nonlinear systems via input-dependent sliding surfaces. Intl. J. Robust and Nonlinear Control, 6: 771-780.