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基于奇异摄动方法的同步发电机二阶滑模控制器的设计

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DESIGN OF SECOND ORDER SLIDING MODE CONTROLLER FOR SYNCHRONOUS GENERATORS BASED ON SINGULAR PERTURBATION METHOD

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ABSTRACT: Power system stability can be strengthened by controlling excitation of synchronous generators. In this paper, the singular perturbation method is applied to decouple the synchronous generator into two subsystems with different time scales. Based on the composite control theory of the singular perturbation system and the robustness of the sliding mode variable control, the suboptimal second order sliding mode control algorithm is applied to realize the control of each subsystem. Thus the control algorithm of each subsystem is obtained. The composite control of the synchronous generator is realized according to algorithms for each subsystem. The second order sliding mode control algorithm is presented in this paper, such that the chattering is eliminated and the robustness of the system is ensured. The singular perturbation algorithm is proposed to reduce the system dimension. The simulation results prove the effectiveness of the proposed algorithm.

KEY WORDS: Synchronous generator; Singular perturbation; Composite control; Second order sliding mode

摘要：通过同步发电机激磁控制，可以增强电力系统稳定性。该文首先利用奇异摄动方法将同步发电机解耦为两个不同时标的子系统。根据奇异摄动系统的复合控制原理和滑模变结构控制的鲁棒性，然后采用次最优二阶滑模控制算法实现每个子系统的控制，得到每个子系统的控制算法，再由每个子系统的算法得到同步发电机的复合控制。该文采用二阶滑模控制算法消去了颤抖现象并保证了系统的鲁棒性；采用奇异摄动算法使系统降维。仿真结果证明了该算法的有效性。

关键词：同步发电机；奇异摄动；复合控制；二阶滑模

1　INTRODUCTION

The traditional function of an excitation system[1-3] is to provide a proper exciting current to the excitation winding of a synchronous generator when there is a change in the output voltage. However, these lineari-zation methods are designed based on the existent of relatively accurate nonlinear system arithmetic models. In electrical systems accurate arithmetic model is hardly obtained. Thus the performances of these controllers are inevitably not assured. Model reference adaptive controls with different identification techniques are proposed to improve the scheme but these algorithms only applicable when system parameters change slowly. For various advantages such as the strong robustness under system parameter perturbation, external disturbance and the loose requirement of accurate system models, variable structure control (VSC) [4] is one possible solution for electrical systems. However, the existence of chattering in the system output is undesirable and the elimination of chattering in the system output is the key issue in applying VSC to electrical systems [4-7]. This paper proposed the application of second order sliding model control[8-10] to the synchronous genera-tors. The synchronous generator model is first decomposed to lower order models according to the singular perturbation theory [11-12] followed by the application of second order suboptimal sliding mode control to the decomposed slow and fast subsystems. This method retains the advantages of VSC, greatly strengthens the robustness of the control system, and effectively eliminates chattering in the system output.

2 DOUBLE TIME SCALES COMPOSITE CONTROL IN SINGULAR SYSTEM

2.1 Time scale transformation

Consider a nonlinear singular perturbation system characterized by equations

$$\begin{cases}\dot{x}=f_1(x)+F_1(x)z+g_1(x)u & x(t_0)=x_0\\ \varepsilon\dot{z}=f_2(x)+F_2(x)z+g_2(x)u & z(t_0)=z_0\end{cases} \tag{1}$$

where $x\in B_x\subset R^n$ and $z\in B_z\subset R^m$ represent the slow and fast moving states respectively, B_x and B_z are both enclosed bounded subsets, $u\in R^n$ is the control input, and $\varepsilon\in[0,1)$ is a scalar minor perturbation parameter such that $\varepsilon=\|\dot{x}\|/\|\dot{z}\|$ and $\|\dot{z}\|>>\|\dot{x}\|$. Suppose f_1, f_2, g_1, g_2 and all elements in matrices F_1 and F_2 are all smooth bounded functions, $F_2(x)$ is a nonsingular matrix for $x\in B_x$. When $\varepsilon=0$, an n-th order slow moving subsystem can be obtained from (1) as

$$\dot{x}_s=f_s(x_s)+g_s(x_s)u_s\ ,\ x_s(t_0)=x_0 \tag{2}$$

where x_s, z_s and u_s are the slow moving portions of the original variables x, z and u respectively. The $f_s(x_s)$, $g_s(x_s)$ are described in the reference [12]. Influenced by the slow moving subsystem, the steady-state value of the fast moving states can be obtained from (1) as

$$z_s=-F_2^{-1}(x_s)(f_2(x_s)+g_2(x_s)u_s) \tag{3}$$

Fast moving subsystem can be obtained in replacing the slow time scale t with the fast time scale τ which is given by $\tau=(t-t_0)/\varepsilon$ Introduce

$$z_f=z-z_s\ ,\ u_f=u-u_s \tag{4}$$

and assume x_s and z_s remain constant in short time interval, differentiate (4) with respect to τ gives

$$\frac{\mathrm{d}z_f}{\mathrm{d}\tau}=F_2(x)z_f+g_2(x)u_f,\ z_f(t_0)=z_0-z_s(t_0) \tag{5}$$

For slow moving subsystem (2), the feedback control law can be selected as [11-12]

$$u_s=h(x) \tag{6}$$

to make the closed-loop system stable and for fast moving subsystem (5), the feedback control law is chosen as

$$u_f=H(x,z_f) \tag{7}$$

The composite control law as

$$u=u_s+u_f$$

2.2 Design of second order sliding mode controller

Applying local coordinate transformation [3, 9] to the slow moving subsystem (2) gives

$$\begin{cases}\dot{x}_{s_i}=x_{s_{i+1}} & i=1,\dots,n-1\\ \dot{x}_{sn}=f_s(\boldsymbol{x}_s)+g_s(\boldsymbol{x}_s)u_s\end{cases} \tag{8}$$

where $\boldsymbol{x}_s(t)=[x_{s_1},x_{s_2},\dots,x_{s_n}]^{\mathrm{T}}$ represent all observable slow moving states, $f_s(x)$ and $g_s(x)$ are uncertain smooth functions whose solutions maintain the characteristic of existence and uniqueness. Furthermore, $f_s(x)$ and $g_s(x)$ meets the conditions given by [9]. Consider system (8) with uncertain conditions described in [9]

$$\sigma_s(\boldsymbol{x}_s)=x_{s_n}+\sum_{i=1}^{n-1}c_{s_i}x_{s_i}=0 \tag{9}$$

where c_{s_i}, $i=1,\dots,n-1$ are positive real constants and all characteristic roots of (9) have negative real parts. Define $y_{s_1}=\sigma_s(\boldsymbol{x}_s)$ and $y_{s_2}=\dot{\sigma}_s(\boldsymbol{x}_s)$, then

$$\begin{cases}\dot{\hat{\boldsymbol{x}}}_s=A_s\hat{\boldsymbol{x}}_s+\boldsymbol{B}_s y_{s_1}\\ x_{s_n}=-\boldsymbol{c}_s\hat{x}+y_{s_1}\\ \dot{y}_{s_1}=y_{s_2}\\ \dot{y}_{s_2}=F_s(\boldsymbol{x}_s,u_s)+g_s(\boldsymbol{x}_s)v_s\end{cases} \tag{10}$$

where $\hat{\boldsymbol{x}}_s=[x_{s_1},x_{s_2},\dots x_{s_{n-1}}]^{\mathrm{T}}$, $\boldsymbol{c}_s=[c_{s_1},c_{s_2},\dots,c_{s_{n-1}}]$, $\boldsymbol{B}_s=[0,0,\dots,0,1]^{\mathrm{T}}$, $v_s=\dot{u}_s$, $F_s(\cdot,\cdot)$ represents all uncertain terms and

$$\boldsymbol{A}_s=\begin{bmatrix}0 & 1 & 0 & & \cdots & 0\\ 0 & 0 & 1 & 0 & \cdots & 0\\ \vdots & & & & & \\ 0 & & \cdots & & 0 & 1\\ -c_{s_1} & -c_{s_2} & \cdots & & & -c_{s_{n-1}}\end{bmatrix}$$

respectively. If v_s is set to drive y_{s1} and y_{s2} to zero, second order sliding mode control is realized and the whole system is equivalent to a linear autonomous stable system lying on the sliding manifold. Make the following suppositions

$$0<G_{s_1}\le g_s(\boldsymbol{x}_s)\le G_{s_2} \tag{11}$$

$$|F_s(x_s,u_s)|<F_s \tag{12}$$

The last two equations of (10) could be transformed to an auxiliary second order system. The aim is to seek a control law w to drive y_{s1} and y_{s2} to zero in finite time interval with the existence of uncertain terms of (11) and (12). According to [9], because y_{s1} is observable and y_{s2} is unobservable, an algorithm whose switching logic only based on y_{s1} is required. The optimal traces for y_{s1} and y_{s2} are a series of dual parabolic arcs and the second arc lies on the switching line $y_{s1}+(y_{s2}|y_{s2}|)/(2U_{\max})=0$. The initial point y_{s1} in the second arc is equal to the half maximum model as y_{s1} in the first arc. According to [9], the optimal control law could be translated into sub-optimal control. Suppose the extreme of y_{s1} is observable and is set to $y_{s\max}$ the suboptimal control algorithm can be summarized as follows

(a) Set $\alpha^*\in(0,1]\cap(0,3G_{s1}/D_{s2})$.

(b) Set $y_{1\max}=y_{s1}(0)$.

(c) $\alpha=\alpha^*$ if $\left(y_{s1}-\frac{1}{2}y_{1\max}\right)(y_{1\max}-y_{s1})>0$, otherwise set $\alpha=1$.

(d) Set $y_{s1}=y_{1\max}$ if y_{s1} is an extreme.

(e) Apply the control law as

$$w=-\alpha U_{\max}\operatorname{sgn}\left(y_{s1}-\frac{1}{2}y_{1\max}\right) \tag{13}$$

3 ARITHMETIC MODEL OF SYNCHRONOUS GENERATOR

3.1 System model

Suppose the generator is connected to an infinite bus through a transmission line with resistance and inductance as shown in Fig.1, the arithmetic model of the generator is given by

$$\begin{cases}\dfrac{d\delta}{dt}=\omega-\omega_s\\ M\dfrac{d\omega}{dt}=T_m-P_g\\ T'_{d_0}\dfrac{dE'_q}{dt}=-\dfrac{X_d}{X'_d}E'_q-\left(\dfrac{X_d-X'_d}{X'_d}\right)V\sin(\delta)+E_{fd}\end{cases} \tag{14}$$

$$\begin{cases}P_g=\dfrac{1}{X'_d}E'_qV\sin(\delta)+\dfrac{1}{2}\left(\dfrac{1}{X_q}-\dfrac{1}{X'_d}\right)V^2\sin(2\delta)\\ E_{fd}=\dfrac{\omega_sM_f}{\sqrt{2}r_f}v_f\end{cases} \tag{15}$$

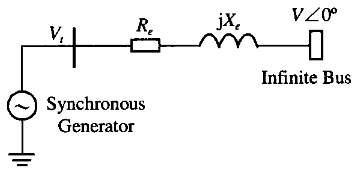


图1 单机系统

Fig.1 Single generator system

where the symbols are depicted in [3], v_f is the magnetization exciting voltage, X_q is the q-axis synchronous reactance, M_f is the mutual induction between stator coils and r_f is the impedance of the exciting coil. For the regularized exciting voltage $E_{fd}=E^*_{fd}$, the generator maintains a stable equilibrium point as well as an unstable one. The stable equilibrium will be analyzed here while the method could also be applied to the unstable equilibrium one. Suppose $(\delta^*,\omega^*,E'^*_q)$ is the stable equilibrium point of the system described by (14) and the bias are $\Delta\delta=\delta-\delta^*$, $\Delta\omega=\omega-\omega^*$, $\Delta E'_q=E'_q-E'^*_q$ and $u=E_{fd}-E^*_{fd}$, (14) can be rewritten as

$$\begin{cases}\dfrac{d\Delta\delta}{dt}=\Delta\omega\\ \dfrac{d\Delta\omega}{dt}=\dfrac{T_m}{M}-\dfrac{V}{MX'_d}(\Delta E'_q+E'^*_q)\sin(\Delta\delta+\delta^*)+\\ \quad\dfrac{V^2}{M}(\dfrac{1}{X'_d}-\dfrac{1}{X_q})\cos(\Delta\delta+\delta^*)\sin(\Delta\delta+\delta^*)\\ \dfrac{d\Delta E'_q}{dt}=-\dfrac{X_d}{T'_{d_0}X'_d}(\Delta E'_q+E'^*_q)-\left(\dfrac{X'_d-X_d}{T'_{d_0}X'_d}\right)V\cdot\\ \quad\sin(\Delta\delta+\delta^*)+\dfrac{1}{T'_{d_0}}(u+E^*_{fd})\end{cases} \tag{16}$$

3.2 Nonlinear analysis of small generator

For small machines

$$MX'_d<\frac{T'_{d_0}X'_d}{X_d}<\sqrt{MX'_d} \tag{17}$$

A singular perturbation system for a small generator can be formed by selecting $\varepsilon=\left(\dfrac{T'_{d_0}X'_d}{X_d}\right)\dfrac{1}{\sqrt{MX'_d}}$.

The fast moving states are referring to the electrical subsystem and the slow moving states are referring to the mechanical part of the generator. The state variables of slow moving and fast moving states are

$\boldsymbol{x}=[\Delta\delta,\Delta\omega]^{\mathrm{T}}$ and $z=\Delta E'_q=E'_q-E'^{*}_q$ respectively. Equation (16) could be transformed to the normal singular perturbation form of (1) as

$$\begin{cases}\dfrac{\mathrm{d}\Delta\delta}{\mathrm{d}t}=\Delta\omega\\ \dfrac{\mathrm{d}\Delta\omega}{\mathrm{d}t}=\dfrac{T_m}{M}-\dfrac{V}{MX'_d}(\Delta E'_q+E'^{*}_q)\sin(\Delta\delta+\delta^*)+\\ \quad\dfrac{V^2\cos(\Delta\delta+\delta^*)\sin(\Delta\delta+\delta^*)}{M}\left(\dfrac{1}{X'_d}-\dfrac{1}{X_q}\right)\\ \varepsilon\dfrac{\mathrm{d}\Delta E'_q}{\mathrm{d}t}=-\dfrac{1}{\sqrt{MX'_d}}\Delta E'_q+\left(\dfrac{X'_d}{X_d}\right)\dfrac{1}{\sqrt{MX'_d}}u+\\ \quad\dfrac{(X_d-X'_d)}{\sqrt{MX'_d}X_d}V\sin(\Delta\delta+\delta^*)+\dfrac{1}{T'_{d_0}}(u+E^*_{fd})\end{cases}\tag{18}$$

such that

$$\begin{cases}\boldsymbol{f}_1(x)=\begin{pmatrix}\Delta\omega\\ \dfrac{T_m}{M}-\dfrac{V}{MX'_d}E'^{*}_q\sin(\Delta\delta+\delta^*)+\\ [V^2\cos(\Delta\delta+\delta^*)\sin(\Delta\delta+\delta^*)]/\\ M[(1/X'_d)-(1/X_q)]\end{pmatrix}\\ \boldsymbol{F}_1(x)=\begin{pmatrix}0\\ -\dfrac{V}{MX'_d}\sin(\Delta\delta+\delta^*)\end{pmatrix}\\ g_1(x)=0\\ f_2(x)=\dfrac{(X_d-X'_d)}{\sqrt{MX'_d}X_d}V\sin[(\Delta\delta+\delta^*)-\sin(\delta^*)]\\ F_2(x)=-\dfrac{1}{\sqrt{MX'_d}}\\ g_2(x)=(\dfrac{X'_d}{X_d})\dfrac{1}{\sqrt{MX'_d}}\end{cases}\tag{19}$$

When $\varepsilon=0$

$$z_s=\Delta E'_q=\frac{(X_d-X'_d)}{X_d}V\sin[(\Delta\delta+\delta^*)-\sin(\delta^*)]+\left(\frac{X'_d}{X_d}\right)u_s\tag{20}$$

and from (2), (3) and (5) the slow moving reduced subsystem becomes

$$\begin{cases}\dot{x}_s=f_s(x_s)+g_s(x_s)u_s,\boldsymbol{f}_s(x_s)=\begin{pmatrix}x_{s_2}\\ \boldsymbol{\Phi}\end{pmatrix}\\ g_s(x_s)=\begin{pmatrix}0\\ n_4\sin(x_{s_1}+\delta^*)\end{pmatrix}\end{cases}\tag{21}$$

where

$$\boldsymbol{\Phi}=n_1+[n_2\cos(x_{s_1}+\delta^*)+n_3+n_5]\sin(x_{s_1}+\delta^*)$$

and

$$\begin{cases}n_1=\dfrac{T_m}{M}\\ n_2=\dfrac{V^2}{M}\left(\dfrac{1}{X'_d-X_q}\right)\\ n_3=-\dfrac{V}{MX'_d}E'^{*}_q+\dfrac{V^2}{M}\left(\dfrac{1}{X'_d}-\dfrac{1}{X_d}\right)\sin(\delta^*)\\ n_4=-\dfrac{V}{MX'_d},n_5=-\dfrac{V^2}{M}\left(\dfrac{1}{X'_d}-\dfrac{1}{X_d}\right)\end{cases}\tag{22}$$

For fast moving subsystem select the time scale $\tau=t/\varepsilon$ to give

$$\frac{\mathrm{d}\Delta E'_q}{\mathrm{d}\tau}=n_6\Delta E'_q+n_7u_f\tag{23}$$

where $n_6=-\dfrac{1}{\sqrt{MX'_d}}$ and $n_7=\dfrac{X'_d}{\sqrt{MX'_d}X_d}$

4　DESIGN OF SECOND ORDER SLIDING MODE CONTROLLER FOR SYNCHRONOUS GENERATOR

The slow moving subsystem of the generator could be described as

$$\begin{cases}\dot{x}_{s_1}=x_{s_2}\\ \dot{x}_{s_2}=\boldsymbol{\Phi}+n_4\sin(x_{s_1}+\delta^*)u_s\end{cases}\tag{24}$$

If there is a disturbance, the balance between prime mover torque and electromagnetic torque is violated and the revolution rate of generator rotor is increased causing a change in the power angle. After the magnetic poles of the rotor vibrate to a new equilibrium point, the generator would continue to run steadily. Therefore the position of rotor should follow a reference signal. Since the frequency of an infinite power source remains unchanged, the revolution rate remains unchanged and there is no need to track the revolution rate and the sliding manifold of the slow moving subsystem can be set as

$$\sigma_s=s_1e_1+e_2\tag{25}$$

where $e_1=x_{s_1}-x_{sd_1}$, $e_2=x_{s_2}$ and x_{sd_1} is the desired change of load angle. Define an auxiliary variable as

$$y_{s_1}=\sigma_s=s_1e_1+e_2\tag{26}$$

From (10), the synchronous system could be changed to

$$\begin{cases} \dot{e}_1 = -s_1 e_1 + y_{s_1} \\ e_2 = -s_1 e_1 + y_{s_1} \\ \dot{y}_{s_1} = y_{s_2} \\ \dot{y}_{s_2} = F_s(\boldsymbol{e}, u_s) + g_s(\boldsymbol{e}) v_s \end{cases} \quad (27)$$

satisfying the condition $|F_s(\boldsymbol{e},u_s)| < F_s$ and $0 < D_{s_1} \le g_s(\boldsymbol{e}) \le D_{s_2}$ where $\boldsymbol{e} = [e_1, e_2]^{\mathrm{T}}$, $v_s = \dot{u}_s$, $F_s(\boldsymbol{e},u_s)$ and $g_s(\boldsymbol{e})$ are uncertain terms. (27) could be regarded as two connected systems coupled between signal y_{s_1} and nonlinear terms $F_s(\boldsymbol{e},u_s) + g_s(\boldsymbol{e})v_s$. With second order sub-optimal sliding mode control law y_{s_1} and y_{s_2} could be driven to zero. After reaching the sliding manifold the synchronous system would change to an autonomous first order linear exponential stable system with e_1 and e_2 converging to zero.

Similar design technique can be applied to the fast moving subsystem. Set the sliding manifold for fast moving subsystem as

$$\sigma_f = z_f = \Delta E'_q \quad (28)$$

and define the auxiliary variables y_{f_1} and y_{f_2} such that

$$y_{f_1} = \sigma_f$$

The fast moving subsystem could be written as

$$\begin{cases} z_f = y_{f_1} \\ \dot{y}_{f_1} = y_{f_2} \\ \dot{y}_{f_2} = F_f(z_f, u_f) + g_f(z_f) v_f \end{cases} \quad (29)$$

satisfying the condition $|F_f(z_f,u_f)| < F_f$ and $0 < D_{f_1} \le g_f(z_f) \le D_{f_2}$
where $v_f = \dot{u}_f$, $F_f(z_f,u_f)$ and $g_f(z_f)$ are both uncertain terms. A second order suboptimal sliding mode controller can be obtained to drive y_{f_1} and y_{f_2} to zero.

5 SIMULATION RESULTS

The generator parameters per machine unit for (18) were chosen as T_m=1, M=1, ω_s=1, $T'_{do} = 4$, X_q=X_d=0.9, $X'_d = 0.3$ and V=1.0. In addition, the equalized stator excitation voltage was set to $E^*_{fd} = 1.1773$. From (18), the equilibrium points of the system were $\delta^* = 0.22889, \omega^* = 1$ and $E'^*_q = 3.1084$.

For slow moving subsystem, the parameters of the second order sub-optimal sliding mode control algorithm were chosen as

$$\alpha^* \in (0,1], D_{s_1} = 0.1, D_{s_2} = 1, F_s = 3, U_{\max} = 7, s_1 = 2$$

The reference signal was set to $x_{sd_1} = 0.1$ and the initial conditions were given as $x_{s_1}(0) = 0.3$ and $x_{s_2}(0) = 0.5$. Figure 2 shows the simulation results. Clearly $\Delta\delta$ and $\Delta\omega$ quickly converged to zero.

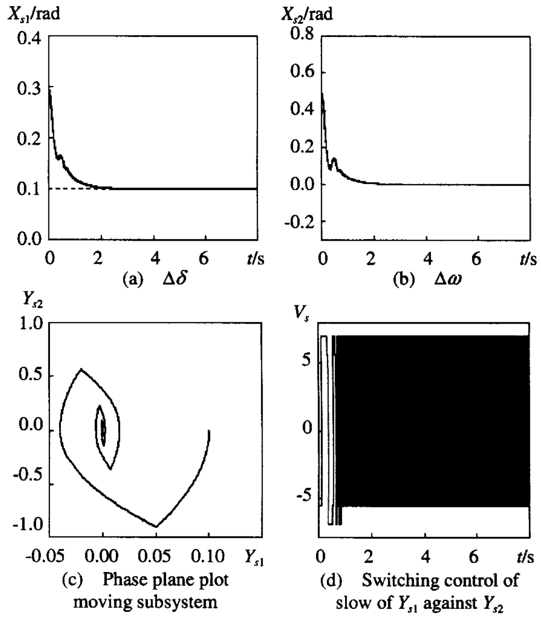


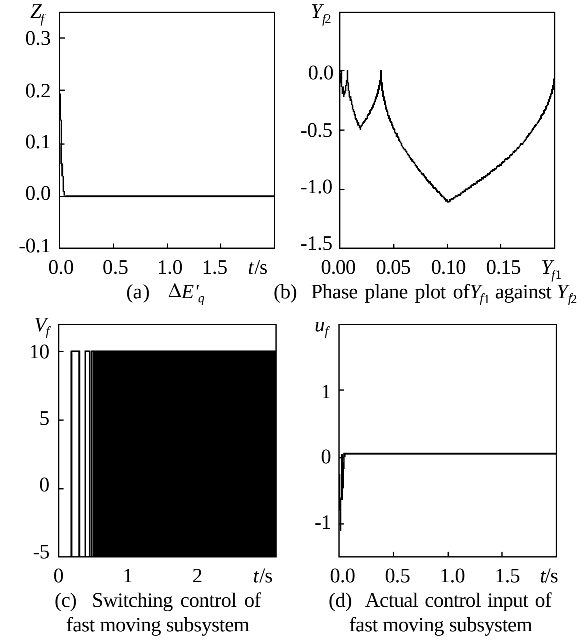
图2 慢运动子系统控制

Fig. 2 Control of the slow moving subsystem

For fast moving subsystem, the parameters of second order sub-optimal sliding mode control algorithm were selected as

$$\sigma_f = 0,\ \alpha^* \in (0,1],\ D_{f_1} = D_{f_2} = 0.61,\ F_f = 1,$$
$$U_{\max} = 6,\ s_1 = 2,\ \varepsilon = 0.4$$

and the initial condition was $z_f(0)$=0.2. Figure 3 shows the simulation results. Again the bias voltage quickly converged to zero. Figure 4 shows the control of the slow moving subsystem and the composite control to the generator system. Various disturbances such as load connection, short circuits etc. can be arisen during the operation of an electrical system. If the variations of the system parameters are bounded, the second order sliding mode control could still drive the system back to the equilibrium point. Figure 5 shows the simulation results when there was a 10% change in the power mechanical constant from 1 to 0.9.

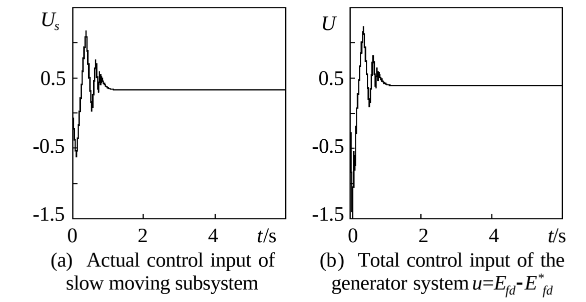


(a) $\Delta E'_q$　(b) Phase plane plot of Y_{f1} against Y_{f2}

(c) Switching control of fast moving subsystem　(d) Actual control input of fast moving subsystem

图 3　快运动子系统控制

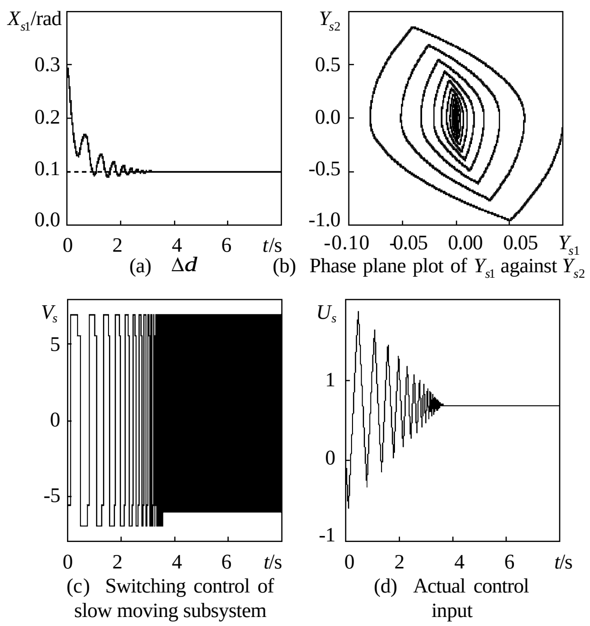
Fig.3　Control of fast moving subsystem



(a) Actual control input of slow moving subsystem　(b) Total control input of the generator system $u=E_{fd}-E^*_{fd}$

图 4　发电机系统输入

Fig.4　Input to the generator system



(a) Δd　(b) Phase plane plot of Y_{s1} against Y_{s2}

(c) Switching control of slow moving subsystem　(d) Actual control input

图 5　有干扰慢运动子系统控制

Fig.5　Control of slow moving subsystem with disturbances

6　CONCLUSION

According to singular perturbation theory, the complicate generator system could be decomposed to fast and slow moving subsystems. Second order sub-optimal sliding mode control could be applied to each of these subsystems. Results show that when the system parameters satisfy the constraints, the gene-rator quickly converges to its equilibrium points and chattering in the system output has been eliminated.

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