2009 American Control Conference
Hyatt Regency Riverfront, St. Louis, MO, USA
June 10-12, 2009

Adaptive Robust H_∞ Control of the Generator Excitation System

Li-Ying Sun, Jiaxin Feng, Georgi M. Dimirovski and Jun Zhao

***Abstract*— The robust H_∞ control problem for the generator excitation system with the damping coefficient uncertainty and external disturbances, is addressed. Storage functions of the control system are constructed based on modified adaptive backstepping sliding mode control method and Lyapunov method. A nonlinear robust H_∞ controller and a parameter updating law are obtained simultaneously. The controller can not only attenuate the influences of external disturbances on the system output, but also has strong robustness for system parameters variation. Since the controller design is based completely on the nonlinear dynamic system without any linearization, the nonlinear property of the dynamic system is well preserved. The simulation results show that more rapid speed response and stronger robustness can be obtained by the proposed method than the conventional adaptive backstepping and adaptive backstepping sliding mode control methods.**

I. INTRODUCTION

Modern power systems are in large scale, distributed and with highly nonlinear characteristics as well as the complicated transients. The control systems are supposed to suppress the potential instability and poorly damped power angle oscillations. Synchronous generator excitation control is one of the most important, effective and economic methods to enhance the stability of power systems. Generator excitation control can not only enhance the power system static stability limit, but also attenuate low-frequency electromechanical oscillations inherent to power systems, during transient conditions. Therefore it is a very active area of research [1-7].

The traditional controllers that are designed based on linearized model around an operating point, such as proportion integral differential (PID) control, power system stabilizer (PSS) and linear optimal excitation control (LOEC), vary significantly with respect to the changes of operating condition. Recently, nonlinear control techniques such as feedback linearization [8-9], Hamiltonian techniques [10], and sliding mode control [11] have been successfully applied to achieve high dynamic performance under large and unexpected contingencies. The design synthesis based on feedback linearization using the differential geometric approach has the disadvantage that the parameters of the system have to be exactly and precisely known. In the feedback linearization approach the parameter uncertainties problem can be tackled only if combined with the some other robust control method. Therefore, in many cases, it cannot achieve robustness to system model and parameter variations. In most control system, however, there exist various uncertainties due to modelling errors, parametric variations, unknown dynamics, disturbances, unmodeled dynamics *et al*. Power systems are subject to several disturbances including line faults and sudden change in the system loading. There is thus a need for controllers which are insensitive to changes in the parameters of the plant. To improve system stability and performance, modern nonlinear robust control approaches were applied to power systems. Robust controllers based on H_∞ control theory are particularly suited for this purpose.

In terms of the sliding mode control method, a dynamic system is insensitive to model uncertainties and external disturbances with matching conditions. However, uncertainties and external disturbances in power systems sometimes do not conform to matching conditions. In the past decades, there have been more research results on adaptive backstepping control [12-13]. Adaptive backstepping method is based on a systematic procedure for the design of feedback control strategies suitable for the design of a large class of feedback linearizable nonlinear systems with constant uncertainties, and guarantees global regulation and tracking for the class of nonlinear systems transformable into the parametric-strict feedback form. Adaptive backstepping sliding mode control method combines the advantages of both adaptive backstepping and sliding mode control [14]. In [15], nonlinear excitation controller was designed by using adaptive backstepping method. In [16], an adaptive backstepping sliding mode controller was designed to control the position of the mover of the linear induction motor (LIM).

Transient response and controller gain are two important performance indexes in power systems. Transient response is expected to be as fast as possible, while the controller gain which represents input energy requires to be as small as possible. However, a faster transient response usually needs a larger controller gain. Therefore, some "trade-off" between fast response and small controller gain is needed. How to achieve a fast response when the error is large without exploiting a large controller gain in a long term is a very

This work was supported by the Dogus University Fund for Science, National Natural Science Foundation of China under Grants 60874024 and 90816028, and the Specialized Research Fund for the Doctoral Program of Higher Education of China under Grant 200801450019.

Li-Ying Sun and Jun Zhao are with Key Laboratory of Integrated Automation of Process Industry, Ministry of Education, Northeastern University, Shenyang, Liaoning, 110004, P.R. of China, and Jun Zhao is also with the Department of Information Engineering, Research School of Information Sciences and Engineering, The Australian National University, Canberra ACT 0200, Australia. lgsunliying@ 163.com; zhaojun@ise.neu.edu.cn

Jiaxin Feng is with School of Information Management and Engineering, Shanghai University of Finance & Economics, Shanghai, 200433, P.R. of China. jiaxinf@126.com

G. M. Dimirovski is with the Department of Computer Engineering, Faculty of Engineering, Dogus University, Acibadem, Kadikoy, TR-34722 Istanbul, Rep. of Turkey, and also with SS Cyril and Methodius University, Faculty of Electrical Engineering, MK-1000 Skopje, Rep. of Macedonia. gdimirovski@ dogus.edu.tr

978-1-4244-4524-0/09/$25.00 ©2009 AACC

important problem, which motivates the present study.

In this paper, a nonlinear robust H_∞ controller for generator excitation system based on a modifying adaptive backstepping sliding mode control method is proposed. Transient response and controller gain are considered simultaneously. In the recursive design procedure of the feedback control law, the class-κ functions are introduced into the selection of virtual stabilizing functions to obtain faster convergent speed. The controller gain tends to that of the conventional backstepping method, when time goes to infinity. In this way, the response is greatly improved without remarkably increasing the controller gain. The adjustable parameters in the class-κ functions keep the balance between transient response and controller gain. The proposed method not only improves the comprehensive performance index of transient response and controller gain, but also retains the advantages of adaptive backstepping sliding mode control with mismatched uncertainties and strong robustness. For a single machine infinite bus system with excitation control, when the damping coefficient is measured inaccurately and there are the external disturbances, a nonlinear robust H_∞ controller and a parameter updating law are obtained simultaneously via the proposed method. The simulation results show that this proposed controller gives better performances. This paper is organized as follows. Section II gives the system model and control objective. The novel design synthesis is derived in Section III. Section IV presents simulation results. Conclusions follows thereafter.

II. SYSTEM MODEL AND CONTROL OBJECTIVE

Consider a dynamic model of single-machine infinite-bus (SMIB) electrical power system with generator excitation, which is widely known and used as a benchmark example in the literature[15]. The schematic diagram is depicted in Figure 1.

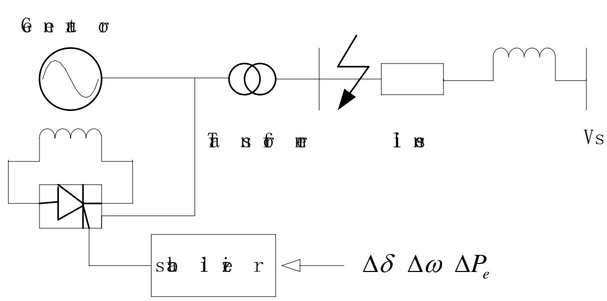

Fig. 1. A Single Machine Infinite Bus system with generator excitation

The dynamics of this plant system can be expressed by means of the following nonlinear differential equations [15]:

$$\begin{cases} \dot{\delta} = \omega - \omega_0 \\ \dot{\omega} = -\dfrac{D}{H}(\omega - \omega_0) + \dfrac{\omega_0}{H}P_m - \dfrac{\omega_0 E_q^{'} V_s sin\delta}{H X_{d\Sigma}^{'}} + w_1 \\ \dot{E}_q^{'} = -\dfrac{1}{T_d^{'}}E_q^{'} + \dfrac{X_d - X_d^{'}}{T_{d0} X_{d\Sigma}^{'}} V_s cos\delta + \dfrac{1}{T_{d0}} V_f + w_2 \end{cases} \tag{1}$$

where δ and ω are the angle and speed of the generator rotor, respectively; H is the inertia constant; P_m is the mechanical power on the generator shaft; D is the damping coefficient; E_q' and V_s are the inner generator voltage and infinite bus voltage, respectively; $X_{d\Sigma}' = X_d' + X_T + X_L$, X_d', X_T, and X_L are the direct axis transient reactance of the generator, the reactance of the transformer, and the line reactance, respectively; T_{d0} and $T_d^{'}$ are the time constants of excitation winding with excitation winding and stator winding in closed circuit; V_f is the input. We assume the disturbance vector $w = [w_1 \quad w_2]^T$ with w_1,w_2 unknown functions in L_2 space, which is also a realistic assumption[12].

It should be noted that, generally speaking, the damping coefficient D can not be measured accurately. Hence D is an unknown and/or uncertain constant parameter. Therefore $\theta = -\dfrac{D}{H}$ is also an unknown and/or uncertain constant parameter.

Let $(\delta_0, \omega_0, E_{q0}^{'})$ represent an operating point of the power system. Define the system state variables as $x_1 = \delta - \delta_0, x_2 = \omega - \omega_0$, and $x_3 = E_q^{'} - E_{q0}^{'}$. Then define $\dfrac{\omega_0}{H} = a_0$, $k_1 = -\frac{\omega_0 V_s}{H X_{d\Sigma}^{'}}$ and $k_2 = \dfrac{X_d - X_d^{'}}{T_{d0} X_{d\Sigma}^{'}} V_s$. The system (1) is thus transformed into the following form

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \theta x_2 + a_0 + k_1 sin(x_1 + \delta_0)(x_3 + E_{q0}^{'}) + w_1 \\ \dot{x}_3 = -\dfrac{1}{T_d^{'}}(x_3 + E_{q0}^{'}) + k_2 cos(x_1 + \delta_0) + \dfrac{1}{T_{d0}} V_f + w_2 \end{cases}$$

$$z = \begin{bmatrix} q_1 x_1 \\ q_2 x_2 \end{bmatrix}. \tag{2}$$

where vector $z = [q_1 x_1 \quad q_2 x_2]^T$ is representing the regulated output. Quantities q_1 and q_2 are nonnegative weighted coefficients, representing the weighted proportion of state variables x_1 and x_2 into the system output, which are to be determined by the designer in each particular case study.

The control problem addressed in this paper is as follows: for any given $\gamma > 0$, find a controller u and positive storage function $V(x)$ such that the following dissipativity inequality holds for any final time $T > 0$:

$$V(x(t)) - V(x(0)) = \int_0^T (\gamma^2 \|w\|^2 - \|z\|^2) dt. \tag{3}$$

And when $w_1 = 0, w_2 = 0$, the closed-loop system is asymptotically stable at $x = 0$. Then the L_2 gain from the disturbance to the output of the system is smaller than or equal to γ, where γ is disturbance attenuation constant.

III. DESIGN OF NONLINEAR ROBUST H_∞ CONTROLLER

In the following procedure, the control law by using modified adaptive backstepping sliding mode control method for the system (2) with the damping coefficient uncertainty and external disturbance will be designed.

Step1: For the first subsystem of system (2), x_2 is assumed to be the virtual control variable. Then choose the virtual control of x_2 as $x_2^* = -(\varphi_1(|e_1|) + c_1)e_1$, where $c_1 > 0$ is a design parameter, and $\varphi_1(\cdot)$ is a class-κ function to be designed. Define error variable $e_2 = x_2 - x_2^*$ and $e_1 = x_1$. Then

$$\dot{e}_1 = -(\varphi_1(|e_1|) + c_1)e_1 + e_2. \tag{4}$$

For system (4), choose the first storage function

$$V_1 = \frac{\sigma}{2}e_1^2 + \frac{\varepsilon_1}{4}e_1^4. \tag{5}$$

where $\sigma > 0, \varepsilon_1 > 0$ are design constants. Then the time derivative of V_1 along the system (4) trajectory is $\dot{V}_1 = \sigma e_1\dot{e}_1 + \varepsilon_1 e_1^3\dot{e}_1 = \sigma e_1 e_2 - \sigma(\varphi_1(|e_1|) + c_1)e_1^2 + \varepsilon_1 e_1^3 e_2 - \varepsilon_1(\varphi_1(|e_1|) + c_1)e_1^4$. Select $\varphi_1(\cdot)$ as $\varphi_1(|e_1|) = \varepsilon_1 e_1^2$. It is apparent that $\dot{V}_1 \leq 0$ when $e_2 = 0$.

Step2: Augment storage function of *Step 1* as

$$V_2 = V_1 + \frac{1}{2}e_2^2. \tag{6}$$

Define function $H_1 = \dot{V}_2 + \frac{1}{2}(\|z\|^2 - \gamma^2\|w_1\|^2)$, thus

$$\begin{aligned}
H_1 &= \dot{V}_1 + e_2\dot{e}_2 + \tfrac{1}{2}(\|z\|^2 - \gamma^2\|w_1\|^2) \\
&= \sigma(\varphi_1(|e_1|) + c_1)e_1^2 - \varepsilon_1(\varphi_1(|e_1|) + c_1)e_1^4 + e_2 w_1 \\
&\quad + e_2[\sigma e_1 + \varepsilon_1 e_1^3 + \theta x_2 + a_0 + k_1 sin(x_1 + \delta_0)(x_3 + E_{q0}^{'}) \\
&\quad + 3\varepsilon_1 e_1^2 x_2 + c_1 x_2] + \tfrac{1}{2}q_1^2 e_1^2 + \tfrac{1}{2}q_2^2[e_2 - (\varphi_1(|e_1|) + c_1)e_1]^2 \\
&\quad - \tfrac{1}{2}\gamma_2 w_1^2 \\
&= -(\sigma c_1 - \tfrac{1}{2}q_1^2 - \tfrac{1}{2}q_2^2 c_1^2)e_1^2 - (\sigma + c_1 - q_2^2 c_1)\varepsilon_1 e_1^4 - \\
&\qquad (1 - \tfrac{1}{2}q_2^2)\varepsilon_1^2 e_1^6 - (\tfrac{\gamma}{2}w_1 - \tfrac{e_2}{\gamma})^2 - \tfrac{1}{4}\gamma_2 w_1^2 + \tfrac{e_2^2}{\gamma^2} + \tfrac{1}{2}q_2^2 e_2^2 \\
&\qquad - q_2^2\varepsilon_1 e_1^3 e_2 - q_2^2 c_1 e_1 e_2 + e_2[\sigma e_1 + \varepsilon_1 e_1^3 + \theta x_2 + a_0 \\
&\qquad + k_1 sin(x_1 + \delta_0)(x_3 + E_{q0}^{'}) + 3\varepsilon_1 e_1^2 x_2 + c_1 x_2] \\
&= -\lambda e_1^2 - (\sigma + c_1 - q_2^2 c_1)\varepsilon_1 e_1^4 - (1 - \tfrac{1}{2}q_2^2)\varepsilon_1^2 e_1^6 - \\
&\quad (\tfrac{\gamma}{2}w_1 - \tfrac{e_2}{\gamma})^2 - \tfrac{1}{4}\gamma_2 w_1^2 + e_2[m_1 x_1 + m_2 x_2 + m_3 x_1^3 \\
&\quad + 3\varepsilon_1 x_1^2 x_2 + \theta x_2 + a_0 + k_1 sin(x_1 + \delta_0)(x_3 + E_{q0}^{'})],
\end{aligned}$$

where $\lambda = \sigma c_1 - \frac{1}{2}q_1^2 - \frac{1}{2}q_2^2 c_1^2, m_1 = \frac{c_1}{\gamma^2} - \frac{1}{2}c_1 q_2^2 + \sigma, m_2 = \frac{1}{\gamma^2} + \frac{1}{2}q_2^2 + c_1, m_3 = \frac{\varepsilon_1}{\gamma^2} + \frac{1}{2}q_2^2\varepsilon_1 + \varepsilon_1$.

x_3 is assumed to be the virtual control variable. Define error variable $e_3 = x_3 - x_3^*$. Then choose the virtual control of x_3 as $x_3^* = -\frac{1}{ksin(x_1 + \delta_0)}[m_1 x_1 + m_2 x_2 + m_3 x_1^3 + 3\varepsilon_1 x_1^2 x_2 + \hat{\theta}x_2 + a_0 + (\varphi_2(|e_2|) + c_2)e_2] - E_{q0}^{'}$, where $\hat{\theta}$ stands for the estimate of θ, $c_2 > 0$ is a design parameter, and $\varphi_2(\cdot)$ is a class-κ function to be designed. Next, define the estimation error $\tilde{\theta} = \theta - \hat{\theta}$, and then it follows:

$$\begin{aligned}
H_1 = &-\lambda e_1^2 - (\sigma + c_1 - q_2^2 c_1)\varepsilon_1 e_1^4 - (1 - \tfrac{1}{2}q_2^2)\varepsilon_1^2 e_1^6 - (\tfrac{\gamma}{2}w_1 \\
&- \tfrac{e_2}{\gamma})^2 - \tfrac{1}{4}\gamma_2 w_1^2 - (\varphi_2(|e_2|) + c_2)e_2^2 + e_2\tilde{\theta}x_2 + k_1 sin(x_1 \\
&+ \delta_0)e_2 e_3.
\end{aligned}$$

Then select $\varphi_2(\cdot)$ as $\varphi_2(|e_2|) = \varepsilon_2 e_2^2$, where $\varepsilon_2 > 0$ is a design parameter.

Step3: Define the sliding surface $s = d_1 e_1 + d_2 e_2 + e_3 = 0$, where d_1, d_2 are the design parameters. Augment storage function of *Step 2*, and thus the new storage function is

$$V_3 = V_2 + \frac{1}{2}s^2 + \frac{1}{2\rho}\tilde{\theta}^2, \tag{7}$$

where $\rho > 0$ is the adaptive gain coefficient.

Define function $H_2 = \dot{V}_3 + \frac{1}{2}(\|z\|^2 - \gamma^2\|w\|^2)$. Note that $\dot{e}_3 = \dot{x}_3 - \dot{x}_3^*$ and $\dot{s} = d_1\dot{e}_1 + d_2\dot{e}_2 + \dot{e}_3$, then

$$\begin{aligned}
H_2 &= \dot{V}_2 + s\dot{s} + \tfrac{1}{2}(\|z\|^2 - \gamma^2\|w\|^2) + \tfrac{1}{\rho}\tilde{\theta}\dot{\tilde{\theta}} \\
&= H_1 - \tfrac{1}{2}\gamma^2 w_2^2 + s\dot{s} - \tfrac{1}{\rho}\tilde{\theta}\dot{\hat{\theta}} \\
&= -\lambda e_1^2 - (\sigma + c_1 - q_2^2 c_1)\varepsilon_1 e_1^4 - (1 - \tfrac{1}{2}q_2^2)\varepsilon_1^2 e_1^6 - \\
&\quad (\tfrac{\gamma}{2}w_1 - \tfrac{e_2}{\gamma})^2 - \tfrac{1}{4}\gamma_2 w_1^2 - (\varphi_2(|e_2|) + c_2)e_2^2 + e_2\tilde{\theta}x_2 \\
&\quad + k_1 sin(x_1 + \delta_0)e_2 e_3 - \tfrac{1}{2}\gamma^2 w_2^2 - \tfrac{1}{\rho}\tilde{\theta}\dot{\hat{\theta}} + s[d_1 x_2 + \\
&\quad d_2\dot{x}_2 + 3\varepsilon_1 e_1^2 x_2 + c_1 x_2 - \tfrac{1}{T_d^{'}}(x_3 + E_{q0}^{'}) + k_2 cos(x_1 \\
&\quad + \delta_0) + \tfrac{1}{T_{d0}}V_f + w_2 - \dot{x}_3^*]
\end{aligned}$$

Note that $\theta = \hat{\theta} + \tilde{\theta}, e_3 = s - d_1 e_1 - d_2 e_2$, thus

$$\begin{aligned}
H_2 = &-(\lambda - d_1^2)e_1^2 - (\sigma + c_1 - q_2^2 c_1)\varepsilon_1 e_1^4 - (1 - \tfrac{1}{2}q_2^2)\varepsilon_1^2 e_1^6 \\
&- (\tfrac{\gamma}{2}w_1 - \tfrac{e_2}{\gamma})^2 - \varepsilon_2 e_2^4 - [c_2 - \tfrac{1}{4}k_1^2 sin^2(x_1 + \delta_0) + \\
&d_2 k_1 sin(x_1 + \delta_0)]e_2^2 - [d_1 e_1 + \tfrac{1}{2}k_1 sin(x_1 + \delta_0)e_2]^2 - \\
&\tfrac{1}{2}(\gamma w_2 - \tfrac{s}{\gamma})^2 - [\tfrac{\gamma}{2}w_1 - \tfrac{s}{\gamma}(d_2 + \tfrac{3\varepsilon_2 e_2^2 + c_2 + m_2 + 3\varepsilon_1 e_1^2 + \hat{\theta}}{k_1 sin(x_1 + \delta_0)})]^2 \\
&+ [e_2 + s(d_2 + \tfrac{3\varepsilon_2 e_2^2 + c_2 + m_2 + 3\varepsilon_1 e_1^2 + \hat{\theta}}{k_1 sin(x_1 + \delta_0)})]\tilde{\theta}x_2 - \tfrac{1}{\rho}\tilde{\theta}\dot{\hat{\theta}} + \\
&s\{k_1 sin(x_1 + \delta_0)e_2 + \tfrac{s}{\gamma^2}(d_2 + \tfrac{3\varepsilon_2 e_2^2 + c_2 + m_2 + 3\varepsilon_1 e_1^2 + \hat{\theta}}{k_1 sin(x_1 + \delta_0)})^2 + \\
&(d_1 + d_2\hat{\theta} + 3\varepsilon_1 e_1^2 + c_1)x_2 + d_2 k_1 sin(x_1 + \delta_0)(x_3 + E_{q0}^{'}) \\
&+ \tfrac{s}{2\gamma^2} + d_2 a_0 - \tfrac{1}{T_d^{'}}(x_3 + E_{q0}^{'}) + k_2 cos(x_1 + \delta_0) + \tfrac{1}{T_{d0}}V_f \\
&+ \tfrac{1}{k_1 sin(x_1 + \delta_0)}[m_1 x_2 + 3m_3 x_1^2 x_2 + 6\varepsilon_1 x_1 x_2^2 + \dot{\hat{\theta}}x_2 + \\
&(3\varepsilon_2 e_2^2 + c_2)(3\varepsilon_1 e_1^2 + c_1)x_2 + (3\varepsilon_2 e_2^2 + c_2 + m_2 + \\
&3\varepsilon_1 e_1^2 + \hat{\theta})(\hat{\theta}x_2 + a_0 + k_1 sin(x_1 + \delta_0)(x_3 + E_{q0}^{'}))] - \\
&\tfrac{cos(x_1 + \delta_0)x_2}{k_1 sin^2(x_1 + \delta_0)}[m_1 x_1 + m_2 x_2 + m_3 x_1^3 + 3\varepsilon_1 x_1^2 x_2 + \hat{\theta}x_2 \\
&+ a_0 + \varepsilon_2 e_2^3 + c_2 e_2]\}
\end{aligned}$$

The real control input is

$$
\begin{aligned}
V_f = T_{d0}\{&-k_1 sin(x_1+\delta_0)e_2 - \tfrac{s}{\gamma^2}(\tfrac{3\varepsilon_2 e_2^2+c_2+m_2+3\varepsilon_1 e_1^2+\hat{\theta}}{k_1 sin(x_1+\delta_0)} \\
&+d_2)^2 - (d_1+d_2\hat{\theta}+3\varepsilon_1 e_1^2+c_1)x_2 - d_2 k_1 sin(x_1+ \\
&\delta_0)(x_3+E'_{q0}) - \tfrac{s}{2\gamma^2} - d_2 a_0 + \tfrac{1}{T'_d}(x_3+E'_{q0}) - k_2 cos(x_1 \\
&+\delta_0) - \tfrac{1}{k_1 sin(x_1+\delta_0)}[m_1 x_2 + 3m_3 x_1^2 x_2 + 6\varepsilon_1 x_1 x_2^2 + \dot{\hat{\theta}} x_2 \\
&+(3\varepsilon_2 e_2^2+c_2)(3\varepsilon_1 e_1^2+c_1)x_2 + (3\varepsilon_2 e_2^2+c_2+m_2+ \\
&3\varepsilon_1 e_1^2+\hat{\theta})(\hat{\theta}x_2+a_0+k_1 sin(x_1+\delta_0)(x_3+E'_{q0}))] \\
&+\tfrac{cos(x_1+\delta_0)x_2}{k_1 sin^2(x_1+\delta_0)}[m_1 x_1 + m_2 x_2 + m_3 x_1^3 + 3\varepsilon_1 x_1^2 x_2 + \hat{\theta} x_2 \\
&+a_0+\varepsilon_2 e_2^3 + c_2 e_2] - \beta s\}
\end{aligned} \tag{8}
$$

where $\beta > 0$ is the constant sliding mode gain.

The parameter update law is selected as

$$\dot{\hat{\theta}} = \rho[e_2 + sd_2 + \frac{s(3\varepsilon_2 e_2^2+c_2+m_2+3\varepsilon_1 e_1^2+\hat{\theta})}{k_1 sin(x_1+\delta_0)}]x_2.$$

Appropriately select parameters $\sigma, c_i, d_i, i=1,2$, such that $\lambda - d_1^2 \geq 0$, and $c_2 - \frac{1}{4}k_1^2 sin^2(x_1+\delta_0+d_2 k_1 sin(x_1+\delta_0) \geq 0$, then

$$
\begin{aligned}
H_2 = &-(\lambda-d_1^2)e_1^2 - (\sigma+c_1-q_2^2 c_1)\varepsilon_1 e_1^4 - (1-\frac{1}{2}q_2^2)\varepsilon_1^2 e_1^6 - \\
&(\frac{\gamma}{2}w_1 - \frac{e_2}{\gamma})^2 - \varepsilon_2 e_2^4 - [c_2 - \frac{1}{4}k_1^2 sin^2(x_1+\delta_0) + d_2 k_1 sin(x_1+ \\
&\delta_0)]e_2^2 - [d_1 e_1 + \frac{1}{2}k_1 sin(x_1+\delta_0)e_2]^2 - \frac{1}{2}(\gamma w_2 - \frac{s}{\gamma})^2 - [\frac{\gamma}{2}w_1 - \\
&\frac{s}{\gamma}(d_2 + \frac{3\varepsilon_2 e_2^2+c_2+m_2+3\varepsilon_1 e_1^2+\hat{\theta}}{k_1 sin(x_1+\delta_0)})]^2 - \beta s^2 \leq 0.
\end{aligned} \tag{9}
$$

Should further it be defined $V(x) = 2V_3(x)$, then it follows at once

$$\dot{V} \leq \gamma^2 \|w\|^2 - \|z\|^2. \tag{10}$$

because of $V(x(0)) = 2V_3(x(0))$. In turn, the dissipative inequality (3) is readily obtained by integrating both sides of the inequality (10). Hence, the system effectively has L_2 gain from the disturbance to its output.

At the same time, given this finding and also following the above derivations, one can conclude that the closed-loop error system dynamics when $w=0$

$$
\left\{
\begin{aligned}
\dot{e}_1 = &-(\varepsilon_1 e_1^2 + c_1)e_1 + e_2 \\
\dot{e}_2 = &\, k_1 sin(x_1+\delta_0)e_3 - (\sigma - c_1 q_2^2)e_1 - \varepsilon_1 e_1^3 \\
&-(\frac{1}{\gamma^2}+\frac{1}{2}q_2^2+c_2)e_2 - \varepsilon_2 e_2^3 + \tilde{\theta}x_2 \\
\dot{e}_3 = &-k_1 sin(x_1+\delta_0)(e_2+d_2 e_3) - \beta s \\
&+\frac{(3\varepsilon_2 e_2^2+c_2+m_2+3\varepsilon_1 e_1^2+\hat{\theta})}{k_1 sin(x_1+\delta_0)}x_2\tilde{\theta} - \frac{s}{2\gamma^2} \\
&-\frac{s}{\gamma^2}(d^2 + \frac{3\varepsilon_2 e_2^2+c_2+m_2+3\varepsilon_1 e_1^2+\hat{\theta}}{k_1 sin(x_1+\delta_0)})^2 \\
&+d_2 m_1 e_1 + d_2 m_3 e_1^3 + (d_2 m_2 - d_1 - c_1)x_2 \\
&+3(d_2-1)\varepsilon_1 e_1^2 x_2 + d_2\varepsilon_2 e_2^3 + d_2 c_2 e_2
\end{aligned}
\right. \tag{11}
$$

is asymptotically stable. In fact, due to (9), we have $\dot{V}_3 + \frac{1}{2}\|z\|^2 = -(\lambda - d_1^2)e_1^2 - (\sigma + c_1 - q_2^2 c_1)\varepsilon_1 e_1^4 - (1 - \frac{1}{2}q_2^2)\varepsilon_1^2 e_1^6 - \frac{e_2^2}{\gamma^2} - \varepsilon_2 e_2^4 - [c_2 - \frac{1}{4}k_1^2 sin^2(x_1 + \delta_0) + d_2 k_1 sin(x_1 + \delta_0)]e_2^2 - [d_1 e_1 + \frac{1}{2}k_1 sin(x_1 + \delta_0)e_2]^2 - \frac{s^2}{\gamma^2}(d_2 + \frac{3\varepsilon_2 e_2^2+c_2+m_2+3\varepsilon_1 e_1^2+\hat{\theta}}{k_1 sin(x_1+\delta_0)})^2 - \beta s^2 \leq 0$. Then $\dot{V}_3 \leq 0$, implies $V_3(t) \leq V_3(0)$, i.e. e_1, e_2, s, x_1, x_2 are all bounded. Define $\Omega = -\dot{V}_3$, then $\int_0^t \Omega(\tau)d\tau = V_3(0) - V_3(t)$. Since $V(0)$ is bounded, and $V_3(t)$ is non-increasingly bounded, then $\lim_{t\to\infty}\int_0^t \Omega(\tau)d\tau < \infty$. In addition, since $\dot{\Omega}$ is bounded, $\lim_{t\to\infty}\Omega = 0$ holds due to Barbalat's lemma. So $e_1 \to 0, e_2 \to 0, s \to 0, x_1 \to 0$, and $x_2 \to 0$ as $t \to \infty$. From the definition of $x_1, x_2, x_3, x_2^*, x_3^*, s$, it is apparent that $e_3 \to 0$, and x_3 is also bounded.

From the design procedure, the parameters $\sigma, c_i, d_i, i = 1,2$ should be appropriately selected such that $\lambda - d_1^2 \geq 0$, and $c_2 - \frac{1}{4}k_1^2 sin^2(x_1 + \delta_0 + d_2 k_1 sin(x_1 + \delta_0) \geq 0$. The other design parameters $\varepsilon_1, \varepsilon_2, \gamma, \beta$ can be appropriately selected according to practical requirements.

Remark 1. If $sin(x_1+\delta_0) = 0$, that is if $\delta = k\pi, k = 0,1,2,\cdots$, synchronism of the power system will be lost and there is no longer normal operation. Fortunately, under the normal operating conditions in the system $0 < \delta < \pi$ holds, and therefore the condition $sin(x_1+\delta_0) \neq 0$ can be guaranteed in (8).

Remark 2. When $\varepsilon_1 \equiv 0, \varepsilon_2 \equiv 0$ in (8) and (11), our results coincide with that of traditional adaptive backstepping sliding mode design; furthermore, when $d_1 \equiv 0, d_2 \equiv 0$, our results coincide with that of based on traditional adaptive backstepping design.

IV. SIMULATION RESULTS

Simulation of the whole system has been carried out by using Matlab software on the grounds of the above control design results. The SMIB case system example solved has the following parameters [15]:

$H = 12.922s, V_s = 1.0pu, T_{d0} = 6.55s, X_d = 0.8258pu, X'_d = 0.1045pu, X_T = 0.0292pu, X_L = X_2 = 0.0266pu, q_1 = 0.4, q_2 = 0.6$. A set of the responses are depicted in the following figures corresponding to arbitrary chosen nonzero initial conditions in the normal range.

The following operating point is considered: $\delta_0 = 57.3^\circ, \omega_0 = 314.159rad/s, E'_{q0} = 0.9361pu$

In order to show the effectiveness of the proposed modified adaptive backstepping sliding mode (MAbSM) controller, we will make comparisons with the conventional adaptive backstepping (Ab) controller and adaptive backstepping sliding mode (AbSM) controller under the same nonzero initial condition. The responses of the generator rotor angle δ, relative speed ω, and control input V_f, under the MAbSM controller, Ab controller and the AbSM controller are shown in Fig. 2-4 with the same initial condition $\delta(0) = 64.5^\circ$.

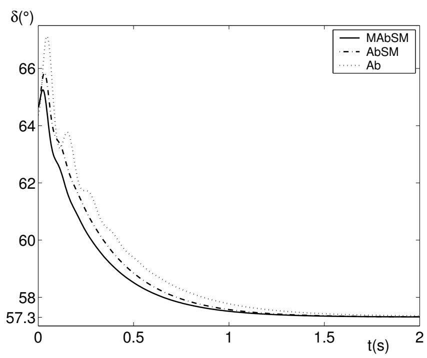

Fig. 2. Transient response curves of the angle

Figure 2 and Figure 3 show that under the modified adaptive backstepping sliding mode controller, the speed response is indeed faster, and the system reach the stable state rather rapidly. Figure 4 shows that under the modified adaptive backstepping sliding mode controller, the control input requires the bigger energy in the initial period, but it reaches the stable state in short time for the same disturbance. Since the selected class-κ functions also converge to zero as the errors converge to zero, then the control energy also coincides with that of adaptive backstepping sliding mode control.

Simulation experiments show that the larger the error is, the more useful the improvement of transient response performances is. Of course, controller gain will increase

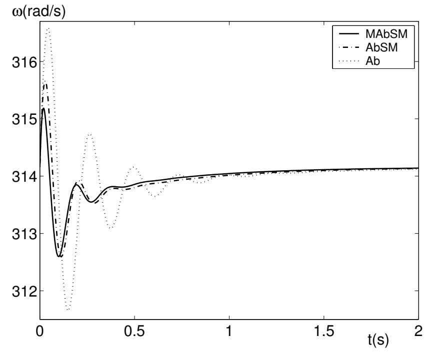

Fig. 3. Transient response curves of the relative speed

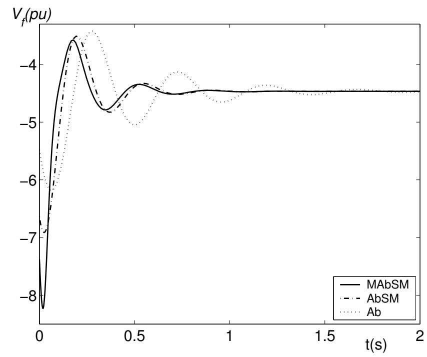

Fig. 4. The control input curves of the excitation voltage

further in the initial period. In fact, the control input of any practical system is bounded. If we solely pursue the transient speed response, controller gain will be too high to be implemented. Therefore, in order to avoid it, the parameters $\varepsilon_i, i = 1, 2$ are added to tune the comprehensive performance in the design stage. When the error is larger, the smaller ε_i is selected such that the initial controller gain does not excessively increase; when the error is smaller, the bigger ε_i is selected such that the system has better transient response performance. That is, the speed response can be tuned by ε_i in order to satisfy the practical requirements. The design based on conventional adaptive backstepping does not have this character.

In order to test the robustness of the MAbSM controller, we do simulation for different values of D at a different operating point and for any initial conditions. The result depicted in Fig. 5 shows that for different values of uncertainties the responses of the system are almost the same, which validates the strong robustness of the proposed MAbSM controller. Transient response curves of the parameter estimations with the different damping coefficient uncertainty are given in

Fig.6. The parameter update variable is quickly forced into its adequate estimated value without oscillations.

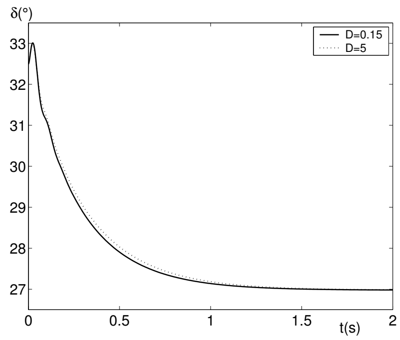

Fig. 5. Transient response curves of the angle with the different damping coefficient uncertainty

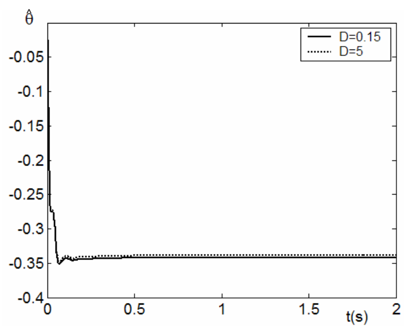

Fig. 6. Transient response curves of the parameter estimations with the different damping coefficient uncertainty

Furthermore, simulation experiments demonstrated that for the smaller value of parameter ρ the effectiveness of adaptation and stability region increase, thus leading to improved forcing of disturbance attenuation.

V. CONCLUSION

We have applied modified adaptive backstepping sliding mode method to design a robust H_∞ controller for the generator excitation system. Since the controller design is based on the nonlinear model of the plant dynamics without linearization, the essentialities of the nonlinear nature of power system dynamics are entirely preserved. The controller does guarantee the system states remain strictly bounded in the closed-loop due to the fact that both internal and external disturbances are taken together into consideration in the control synthesis problem. Hence practical stability operation is guaranteed always. Due to the fact that the system output is also accounted for in the control design, the disturbance effects on the output remain well attenuated too. With regard to internal disturbances, the damping coefficient uncertainty is accounted for hence in this regard the control design is robust to system parameter variations. In the recursive design procedure of the feedback control law, the class-κ functions are introduced to improve the transient response of the closed-loop system without exploiting a large controller gain in a long term.

REFERENCES

[1] W. Sae-Kok , A. koyama , S. C. Verma and S. Ogawa, "Excitation control system design of rotary type frequency converter for performance improvement of power system dynamics," *IEEE Trans. on energy conversion*, Vol. 21, no. 1, 2006, pp. 210-220.

[2] A. S. Bazanellan and C. L. Conceic, "Transient stability improvement through excitation control," *International Journal of Robust Nonlinear Control*, Vol. 14, 2004, pp. 891-910.

[3] Paul MO and EP. Gerardo, "Output feedback excitation control of synchronous generators," *International Journal of Robust Nonlinear Control*, Vol. 14, 2004, pp. 879-890.

[4] Q. Lu, S. Mei, W. Hu , et al., "Nonlinear decentralized disturbance attenuation excitation control via new recursive design for multimachine power systems," *IEEE Trans. on Power Systems*, Vol. 16, no. 4, 2001, pp. 729-736.

[5] A. Kazemi and M. R. Jahed Motlagh, "Application of a new multivariable feedback linearization method for improvement of power systems transient stability," *International Journal of Electrical Power & Energy Systems*, Vol. 29, no. 4, 2007, pp. 322-328.

[6] W. Liu, J. Sarangapani and G K. Venayagamoorthy, "Neural network based decentralized excitation control of large scale power systems," *International Joint Conference on Neural Networks Sheraton Vancouver Wall Centre Hotel*, Vancouver, BC, Canada, July, 2006,1975-1981.

[7] Ali Karimi and Ali Feliachi, "Decentralized adaptive backstepping control of electric power systems," *Electric Power Systems Research*, Vol. 78, no. 3, 2005, pp. 484-493.

[8] Q. Lu, Y. Sun, Z. Xu, et al., "*Decentralized nonlinear optimal excitation control*," *IEEE Trans. on Power Systems*, Vol. 11, no. 4, 1996, pp. 1957-1962.

[9] S. Zhou and X. Wang, "Nonlinear excitation controller based on the dired feedback linearization," *Proceedings of the CSEE* , Vol. 15, no. 4, 1995, pp. 281-288(P. R. of China).

[10] J. Hao, L. B. Shi, J. Wang and C. Chen, "Nonlinear disturbance attenuation excitation control of structure preserving power systems based on Hamiltonian theory," *Power Engineering Society General Meeting, 2005. IEEE* , Vol. 2, pp.1665- 1670.

[11] A. Soto-Cota, L. M. Fridman, A. G. Loukianov, M. Cañedo, "Variable structure control of synchronous generator: singularly perturbed analysis," *Int. J. Control*, Vol. 79, no. 1, 2006, pp. 1-13.

[12] G. M. Dimirovski, Y.-W. Jing, W.-L. Li and X.-P. Liu, "Adaptive backstepping design of TCSC robust nonlinear control for power systems," *Intelligent Automation & Soft Computing* , Vol. 12, no. 1, 2006, pp. 75-87.

[13] H. Khalil, *Nonlinear systems*, 3rd edition, Prentice Hall, 2002.

[14] Ali J. Koshkouei and Alan S. I. Zinober, "Adaptive Backstepping Control of Nonlinear Systems with Unmatched Uncertainty," *Proceedings of the 39'h IEEE Conference on Decision and Control*, Sydney, Australia, 2000, pp. 4765-4770.

[15] T. Shen, S. Mei, Q. Lu, et al., "Adaptive nonlinear excitation control with L2 disturbance attenuation for power systems," *Automatic*, Vol. 39, 2003, pp. 81-89

[16] F.-J. Lin, P.-H. Shen and S.-P. Hsu, "Adaptive backstepping sliding mode control for linear induction motor drive," *IEE Proc. -Electr. Power Appl.*, Vol. 49, 2002, pp. 184-194.