第 26 卷 第 10 期 中 国 电 机 工 程 学 报 Vol.26 No.10 May 2006
2006 年 5 月 Proceedings of the CSEE ©2006 Chin.Soc.for Elec.Eng.

文章编号：0258-8013 (2006)10-0007-05 **中图分类号**：TM712 **文献标识码**：A **学科分类号**：470·40

静态无功补偿器鲁棒控制的一种新自适应逆推方法

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Robust Control of SVC: a New Adaptive Backstepping Method

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ABSTRACT: A new extended adaptive backstepping algorithm for general nonlinear systems in parametric feedback form is proposed. The method preserves useful nonlinearities and the real-time estimation of uncertainty parameter, and does not follow the classical certainty equivalence principle. Then the proposed method is applied to nonlinear adaptive control of Static VAR Compensator (SVC) of a single-machine infinite-bus system containing some unknown parameters. This novel adaptation mechanism is introduced into power systems, and a novel adaptive control law for this SMIB system is presented. The simulation results demonstrate that the proposed method is better than the design based on classical adaptive backstepping in terms of properties of stability and parameter estimation. Hence, it will be an alternative to practice engineering and applications. In addition, this algorithm is applicable to other control systems.

KEY WORDS: power systems; static VAR compensator (SVC); nonlinear control; extended adaptive backstepping

摘要：针对一般的参数反馈型非线性系统提出了一种扩展自适应逆推方法。该方法不仅保留系统的非线性特性和对未知参数的实时在线估计，而且突破了经典的确定性等价性原理。将该方法应用到含有未知参数带有静态无功补偿器(SVC)的单机无穷大系统。将这种新自适应机制引入电力系统，得到了带有 SVC 单机无穷大系统的自适应控制律。仿真结果表明，该方法在提高系统稳定性和参数估计方面优于传统的逆推方法，为工程应用提供了一种有效的选择。另外，该文中的算法可以应用到其他控制系统。

关键词：电力系统；静态无功补偿器；非线性控制；扩展自适应逆推

基金项目：国家自然科学基金项目(60574013，60274009)；高等学校博士学科点专项科研基金项目(20020145007)；辽宁省自然科学基金项目(20032020)。

Project supported by National Natural Science Foundation of China(60574013，60274009).

0 引言

Due to the environmental constraint and the huge cost of building new transmission lines, the existing power systems are operating ever closer to their utility limits with the rapid increase of load demand. As a result, many power grids are highly stressed and the problems of system stability, security and reliability are one of those issues of great importance and urgency in the current situation[1]. The rapid improvement in power electronics makes them a novel way to above mentioned problems because of their ability to enable fast and easy control. Such electronic devices are called Flexible AC Transmission System (FACTS) devices. Static VAR Compensator(SVC) is one of the most widely used FACTS devices. It is very effective on providing dynamic voltage support and reactive power compensation[2]. The study about SVC has attracted more attentions of researchers, especially about the control mode of SVC[1-7]. Such as conventional linear stabilizer[3] and exactly linearized controller for SVC[1, 4-6].

In recent years, backstepping technique as a powerful tool is applied to nonlinear control[8] to preserve the useful nonlinearities. This technique is more suitable for the situation where the system model has unknown parameters[7-14]. Several types of controllers have been designed for systems of lower triangular structure in practical applications such as the robust adaptive control of multi-machine power systems[9] and steam valve control[11] by using the so-called adaptive backstepping, whereas the adaptive law is based on certainty equivalence principle. More recently, a novel backstepping algorithm presented in Ref. [12], which relies on the Immersion and Invariance (I&I) stabilization and I&I adaptive control tools developed in Ref. [13], is better than the "classical" adaptive backstepping one with respect to the response of the system and the speed of adaptation. Unfortunately, it is only suitable in situation where the "virtual" control coefficients are ones and limits its range of applications.

In this paper, we extend the above-mentioned adaptive backstepping algorithm in Ref. [12] to systems in general form, where the proposed adaptive mechanism does not follow the classical certainty-equivalence philosophy, and apply it to a SMIB power system with SVC to realize our goal which is an improvement upon the speeds of both adaptation and response of systems. Both the proposed algorithm and its application to this SMIB power system have the following advantages in comparison with those of the classical adaptive backstepping: ①the improved responses of system; ②a desired property, which is absent in classical adaptive backstepping design, namely, the speed of adaptation may be regulated by a related parameter imposed on the error dynamics.

1 AN EXTENDED ALGORITHM

1.1 Problem formulation

This section extends the adaptive backstepping algorithm in Ref. [12] which is for systems in so-called parametric feedback to a general form whose "virtual" control parameters are functions of feedback states.

Consider a class of systems described by equations

$$\dot{x}_i = f_i(x_1,\cdots,x_i) + g_i(x_1,\cdots,x_i)x_{i+1} + j_i^{\mathrm{T}}(x_1,\cdots,x_i)q_i \qquad 1 \le i \le n \qquad (1)$$

where $x \in \mathbf{R}^n$ is the system state, $x_{n+1} = u \in \mathbf{R}$ is the control input and f, g are smooth functions, $g_i(x_1,\cdots,x_i) \neq 0$ and $j_i(x_1,\ldots,x_i)$ are smooth vector fields, q_i is unknown constant vector.

Our control objective is to enforce x_1 to track a given sufficient smooth bounded reference signal x_1^*.

1.2 Adaptive law design

Firstly, we define the error variable

$$z_i = \hat{q}_i - q_i + b_i(x_1,\cdots,x_i), i = 1,2,\cdots n \qquad (2)$$

where $\hat{q}_i$ is the estimate of q_i, and $b_i(\cdot)$ is smooth function yet to be defined.

Secondly, differentiating Equ.(2), we have the dynamics of z_i given by the equation

$$\dot{z}_i = \dot{\hat{q}}_i + \sum_{k=1}^{i}\frac{\partial b_i}{\partial x_k}[f_k(x_1,\cdots,x_k) + g_k(x_1,\cdots,x_k)x_{k+1} + j_k^{\mathrm{T}}(x_1,\cdots,x_k)\cdot(\hat{q}_k + b_k(x_1,\cdots,x_k) - z_k)] \qquad (3)$$

with $x_{n+1} = u$.

The update law can be selected as follows

$$\dot{\hat{q}}_i = -\sum_{k=1}^{i}\frac{\partial b_i}{\partial x_k}[f_k(x_1,\cdots,x_k) + g_k(x_1,\cdots,x_k)x_{k+1} + j_k^{\mathrm{T}}(x_1,\cdots,x_k)\cdot(\hat{q}_k + b_k(x_1,\cdots,x_k))] \qquad (4)$$

Thus, the error dynamics are

$$\dot{z}_i = -\sum_{k=1}^{i}\frac{\partial b_i}{\partial x_k}j_k^{\mathrm{T}}(x_1,\cdots,x_k)\mathbf{z}_k \qquad (5)$$

Note that Equ. (5) is in lower triangular form.

In what follows, we adopt the selection of the functions $b_i(\cdot)$ and its assumption in Ref. [12].

In Equ. (5), its diagonal terms can be rendered negative semi-definite by selecting $b_i(\cdot)$ as

$$b_i(\cdots,x_i) = \int_0^{x_i} k_i(\cdots,c_i)j_i(\cdots,c_i)\mathrm{d}c_i \qquad (6)$$

where $k_i(\cdot)$ is positive function.

Consider now the following assumption.

Assumption1: There exist a function $k_i(\cdot)$ and a constant $k_i(\cdot) \ge k_i > 0$ such that, for $j = 1,\cdots,i-1$

$$\frac{\partial b_i}{\partial x_j} = d_{ij}(x_1,\cdots,x_i)j_i(x_1,\cdots,x_i) \qquad (7)$$

for some bounded functions $d_{ij}(\cdot)$, where $b_i(\cdot)$ is given by Equ.(6).

In order to establish the stability properties of the estimator, we propose the following lemma:

Lemma 1: Consider the system (5) with the functions $b_i(\cdot)$ given by Equ.(6), and suppose that assumption 1 holds for all $i = 1,\cdots,n$. Then there exist constant $e_i > 0$ such that

$$\frac{\mathrm{d}}{\mathrm{d}t}\Big(\sum_{i=1}^{n} e_i \boldsymbol{z}_i^{\mathrm{T}} \boldsymbol{z}_i\Big) \le -\sum_{i=1}^{n}[j_i^{\mathrm{T}}(x_1,\cdots,x_i)\boldsymbol{z}_i]^2 \tag{8}$$

Proof: Similar to Ref. [12].

Remark 1: Since $\sum_{i=1}^{n} e_i \boldsymbol{z}_i^{\mathrm{T}} \boldsymbol{z}_i$ is a decreasing function of time, $\boldsymbol{z}_i$ is bounded. Integrating both sides of Equ.(8), we can know that $j_i \boldsymbol{z}_i$ is square- integrable.

1.3 Controller design

This section proposes a control law to render $j_i^{\mathrm{T}} \boldsymbol{z}_i$ converge to zero, which implies from Equ. (2) that an asymptotic estimate of each term $j_i^{\mathrm{T}} q_i$ in Equ. (1) is given by $j_i^{\mathrm{T}}(\hat{q}_i + b_i)$, and to ensure global asymptotic stability of the desired equilibrium. Now a controller can be designed by the following procedure.

Step 1: Define $\tilde{x}_1 = x_1 - x_1^*$, whose dynamics are governed by

$$\dot{\tilde{x}}_1 = f_1(x_1) + g_1(x_1)x_2 + j_1^{\mathrm{T}}(x_1)q_1 - \dot{x}_1^* \tag{9}$$

Take x_2 as a "virtual" control and define

$$\tilde{x}_2 = x_2 - x_2(x_1, \hat{q}_1, \dot{x}_1^*) \tag{10}$$

Select

$$x_2 = [1/g_1(x_1)][-f_1(x_1) - j_1^{\mathrm{T}}(x_1)(\hat{q}_1 + b_1(x_1)) + \dot{x}_1^* - a_1(\tilde{x}_1, \hat{q}_1)] \tag{11}$$

where $a_1(\cdot)$ yet to be designed.

Substituting Equ. (11) into Equ. (10) and noticing Equ. (9) yield

$$\dot{\tilde{x}}_1 = -a_1(\tilde{x}_1, \hat{q}_1) - j_1^{\mathrm{T}}(x_1)z_1 + g_1(x_1)\tilde{x}_2$$

Step 2: Differentiating Equ. (10) gives dynamics

$$\dot{\tilde{x}}_2 = f_2(x_1,x_2) + g_2(x_1,x_2)x_3 + j_2^{\mathrm{T}}(x_1,x_2)\cdot q_2 - \frac{\partial x_2}{\partial x_1}\dot{x}_1 - \frac{\partial x_2}{\partial \hat{q}_1}\dot{\hat{q}}_1 - \frac{\partial x_2}{\partial \dot{x}_1^*}\ddot{x}_1^*. \tag{12}$$

Take x_3 as a "virtual" control and define

$$\tilde{x}_3 = x_3 - x_3(x_1, x_2, \hat{q}_1, \hat{q}_2, \ddot{x}_1^*) \tag{13}$$

By selecting

$$x_3 = \frac{1}{g_2(x_1,x_2)}\{-f_2(x_1,x_2) - j_2^{\mathrm{T}}(x_1,x_2)\cdot(\hat{q}_2 + b_2(x_1,x_2)) + \frac{\partial x_2}{\partial x_1}[f_1(x_1) + g_1(x_1)x_2 + j_1^{\mathrm{T}}(x_1)(\hat{q}_1 + b_1(x_1))] + \frac{\partial x_2}{\partial \hat{q}_1}\dot{\hat{q}}_1 + \frac{\partial x_2}{\partial \dot{x}_1^*}\ddot{x}_1^* - a_2(\tilde{x}_1, \tilde{x}_2, \hat{q}_1, \hat{q}_2)\} \tag{14}$$

Following this procedure step by step, we can derive the dynamics of the rest of states until the real control appears.

Step n : The n-th dynamics are given by

$$\dot{\tilde{x}}_n = f_n(x_1,\cdots,x_n) + g_n(x_1,\cdots,x_n)u + j_n^{\mathrm{T}}(x_1,\cdots,x_n)q_n - \sum_{k=1}^{n-1}\frac{\partial x_n}{\partial x_k}[f_k(x_1,\cdots,x_k) + g_k(x_1,\cdots,x_k)x_{k+1} + j_k^{\mathrm{T}}(x_1,\cdots,x_k)q_k] - \sum_{k=1}^{n-1}\frac{\partial x_n}{\partial \hat{q}_k}\dot{\hat{q}}_k - \frac{\partial x_n}{\partial (x_1^*)^{(n-1)}}(x_1^*)^{(n)} \tag{15}$$

The real control input is:

$$u = \frac{1}{g_n(x_1,\cdots,x_n)}\{-f_n(x_1,\cdots,x_n) - j_n^{\mathrm{T}}(x_1,\cdots,x_n)\cdot(\hat{q}_n + b_n(x_1,\cdots,x_n)) + \sum_{k=1}^{n-1}\frac{\partial x_n}{\partial x_k}[f_k(x_1,\cdots,x_k) + g_k(x_1,\cdots,x_k)x_{k+1} + j_k^{\mathrm{T}}(x_1,\cdots,x_k)\cdot(\hat{q}_k + b_k(x_1,\cdots,x_k))] + \frac{\partial x_n}{\partial (x_1^*)^{(n-1)}}(x_1^*)^{(n)} + \sum_{k=1}^{n-1}\frac{\partial x_n}{\partial \hat{q}_k}\dot{\hat{q}}_k - a_n(\tilde{x}_1,\cdots,\tilde{x}_n,\hat{q}_1,\cdots,\hat{q}_n)\} \tag{16}$$

So, the close-loop system is given by

$$\begin{cases} \dot{\tilde{x}}_1 = -a_1(\tilde{x}_1,\hat{q}_1) - j_1^{\mathrm{T}}(x_1)z_1 + g_1(x_1)\tilde{x}_2, \\ \dot{\tilde{x}}_2 = -a_2(\tilde{x}_1,\tilde{x}_2,\hat{q}_1,\hat{q}_2) + \dfrac{\partial x_2}{\partial x_1}j_1^{\mathrm{T}}(x_1)z_1 - j_2^{\mathrm{T}}(x_1,x_2)^{\mathrm{T}}z_2 + g_2(x_1,x_2)\tilde{x}_3, \\ \quad\vdots \\ \dot{\tilde{x}}_n = -a_n(\tilde{x}_1,\cdots,\tilde{x}_n,\hat{q}_1,\cdots,\hat{q}_n) + \displaystyle\sum_{k=1}^{n-1}\frac{\partial x_n}{\partial x_k}\cdot j_k^{\mathrm{T}}(x_1,\cdots,x_k)\boldsymbol{z}_k - j_n^{\mathrm{T}}(x_1,\cdots,x_n)\boldsymbol{z}_n \end{cases} \tag{17}$$

The following theorem gives the main results.

Theorem 1: There exist functions $a_i(\cdot)$ such that the system (17) together with (5) is globally asymptotically stable at $\tilde{x} = 0$ and $\lim_{i\to t} j_i(x_1(t),\cdots x_i(t))^{\mathrm{T}} z_i(t) = 0$.

Proof: Differentiating the function

$$V_1(\tilde{x}_1,\cdots,\tilde{x}_n) = \frac{1}{2}\sum_{k=1}^{n}\tilde{x}_k^2 \tag{18}$$

along the trajectories of (17) and selecting the functions $a_i(\cdot)$ as

$$\begin{cases} a_1 = (c_1 + \dfrac{n}{4g})\tilde{x}_1 \\ a_i = g_{i-1}(x_1,\cdots x_{i-1})\tilde{x}_{i-1} + (c_i + \dfrac{n-i+1}{4g})\tilde{x}_i + \displaystyle\sum_{k=1}^{i-1}\frac{n-k+1}{4g}\Big(\frac{\partial x_i}{\partial x_k}\Big)^2\tilde{x}_i \qquad i = 2,\cdots,n \end{cases} \tag{19}$$

for $i = 2,\cdots,n$, where $c_i > 0, g > 0$ are arbitrary constants, we have

$$\dot{V}_1 \le -\sum_{k=1}^{n} c_k \tilde{x}_k^{\,2} + g\sum_{k=1}^{n} (j_k^{\mathrm{T}}(x_1,\cdots,x_k)\boldsymbol{z}_k)^2 \qquad (20)$$

The proof is completed by combining the above function with the one in Lemma 1 and invoking standard Lyapunov arguments.

Remark2: When $f_i(x_1,\cdots x_i)\equiv 0, g_i(x_1,\cdots x_i)\equiv 1$ in Ref. (1), and the sufficient smooth reference signal x_1^* is constant, our result coincides with that of Ref.[12].

2 ADAPTIVE CONTROL OF SVC

2.1 Dynamic Model of SMIB Systems with SVC

In this section, we apply the proposed method in Section 2 to coping with the adaptive control problem of the SMIB power systems with SVC.

The system model is expressed as follows Equ.[7]:

$$\begin{cases} \dot{d} = w - w_0 \\ \dot{w} = \dfrac{w_0}{H}[P_m - E_q' V_S y_{\mathrm{svc}} \sin d - \dfrac{D}{w_0}(w - w_0)] \\ \dot{y}_{\mathrm{svc}} = 1/T_{\mathrm{svc}}(-y_{\mathrm{svc}} + y_{\mathrm{svc0}} + u) \end{cases} \qquad (21)$$

where the meaning of all variables is referred to Ref[7].

Generally speaking, the damping coefficient can not be measured accurately in practical situations[9]. Hence D is considered as an unknown constant parameter, so is $q_2 = -D/H$ in Equ.(21). By comparing Equ. (22) with Equ. (21), q should be defined as $[q_1, q_2, q_3]^{\mathrm{T}} = [0, -D/H, 0]^{\mathrm{T}}$.

Let $x_1 = d - d_0, x_2 = w - w_0, x_3 = y_{\mathrm{svc}} - y_{\mathrm{svc0}}$, so we can put the model (21) in the parameter feedback form of Equ.(1), where

$$\begin{cases} f_1(x_1) = 0 \\ g_1(x_1) = 1 \\ j_1(x_1) = 0 \\ f_2(x_1, x_2) = w_0 / H[P_m - E_q' V_s y_{\mathrm{svc0}} \sin(x_1 + d_0)] \\ g_2(x_1, x_2) = -w_0 / H \cdot E_q' V_s \sin(x_1 + d_0) \\ f_3(x_1, x_2, x_3) = -1/T_{\mathrm{svc}} \cdot x_3 \\ g_3(x_1, x_2, x_3) = 1/T_{\mathrm{svc}} \\ j_2(x_1, x_2) = x_2 \\ j_3(x_1, x_2, x_3) = 0 \end{cases} \qquad (22)$$

2.2 Design of adaptive control law

The control objective is to ensure x_1 to track zero. In other words, synchronism between generators in power systems is kept.

We construct the error

$$z_2 = \hat{q}_2 - q_2 + b_2(x_1, x_2) \qquad (23)$$

Selecting the function $b_2(\cdot)$ according to Equ.(6) as $b_2(x_1, x_2) = 0.5kx_2^2$ with k an positive tuning constant, yields the error dynamics

$$\dot{z}_2 = -kx_2^2 z_2 \qquad (24)$$

with the update law (4). Clearly, Assumption 1 holds, for any constant $k>0$, Lemma 1 also does. Following the design methodology of the previous section, the controller is gotten by Equ.(14), (16), (22) and the meaning of $\tilde{x}_i(\cdot)$ and the update law is given from (4) and $b_2(\cdot)$, respectively.

$$\begin{aligned} u = x_3 + T_{\mathrm{svc}}\{ &\frac{\partial x_3}{\partial x_1}x_2 + \frac{\partial x_3}{\partial x_2}[\frac{w_0}{H}(P_m - E'_q V_s y_{\mathrm{svc0}} \cdot \\ &\sin(x_1 + d_0)) - \frac{w_0}{H}E_q' V_s x_3 \sin(x_1 + d_0) + x_2 \cdot \\ &(\hat{q}_2 + \frac{k}{2}x_2^{\,2})] + x_2\dot{\hat{q}}_2 / [\frac{w_0}{H}E_q' V_s \sin(x_1 + d_0)] - \\ &(c_3 + \frac{1}{2g}(\frac{\partial x_3}{\partial x_2})^2)(x_3 - x_3) + [\frac{w_0}{H}E_q' V_s \cdot \\ &\sin(x_1 + d_0)](x_2 + c_1 x_1)\} \end{aligned}$$

$$\begin{aligned} \dot{\hat{q}}_2 = -kx_2[&\frac{w_0}{H}(P_m - E_q' V_s y_{\mathrm{svc0}} \sin(x_1 + d_0)) - \\ &\frac{w_0}{H}E_q' V_s x_3 \sin(x_1 + d_0) + x_2(\hat{q}_2 + \frac{k}{2}x_2^{\,2})] \end{aligned}$$

3 SIMULATION RESULTS

In order to investigate the effectiveness of the proposed controller, we will make comparisons with the classical adaptive backstepping controller and the full-information controller. The data of the system for simulation are below and others are provided in Ref. [7].

$$c_1 = 0.8, c_2 = 0.5, c_3 = 0.5, k = 80, g = 10$$

Fig.1 shows the response of the system with initial conditions $x_1(0) = 0.3488, x_2(0) = 0, x_3(0) = 0$.

Fig.2 gives the performance of the estimators. Moreover, like the classical backstepping design[7, 9], the proposed method also survives large disturbance. Fig.3 shows the generator maintains synchronism when subjected to a three phase short circuit to ground from 0.1~0.2s.

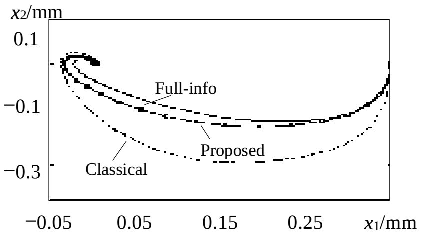

图 1　系统相轨迹的比较

Fig.1　The comparison of phase trajectories

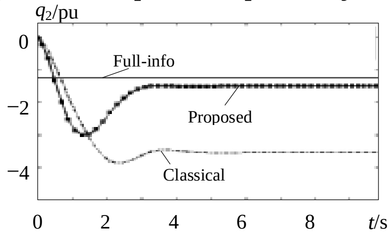

图 2　两种参数估计的比较

Fig.2　The comparison of two parameter estimations

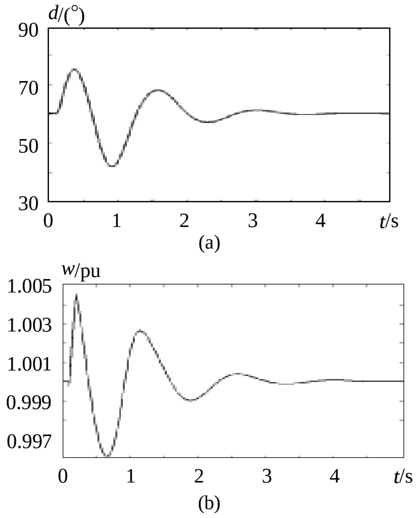

图 3　d 和 w 的响应

Fig. 3　The responses of *d* and *w*.

4　CONCLUSIONS

The main contributions of this paper are extension of a novel adaptive backstepping algorithm for systems in parameter feedback form to a general case and its application to SVC for SMIB power systems to improve performances of system responses and parameter estimation. The characteristics of the paper are twofold: firstly, the proposed adaptive mechanism does not follow the classical certainty-equivalence philosophy; secondly, we introduce this novel parameter estimation into power systems. Simulation results compared with the classical backstepping and full-information schemes show the validation of the extension and superiority of the proposed controller. This method can be easily applied to multi-machine systems to realize the decentralized control.

REFERENCE

[1] Wang Y，Chen H，Zhou R．A nonlinear controller design for svc to improve power system voltage stability[J]．Electrical Power and Energy Systems，2000，22(7)：463-470．

[2] Qun Gu，Pandey A，Starrett S K．Fuzzy logic control schemes for static VAR compensator to control system damping using global signal [J]．Electrical Power and Energy Systems，2003，67(2)：115-122．

[3] Smith J R，Pierre D A，Sadighi I，et al．A supplementary adaptive var unit controller for power system damping[J]．IEEE Trans. on Power Systems，1989，4(3)：1017-1023．

[4] 邱宇，陈学允. 用于静止无功补偿器的非线性 PID 控制器[J]. 中国电机工程学报，2002，22 (11)：41-44．
Qiu Yu，Chen Xueyun．The new nonlinear PID controller for SVC [J]．Proceedings of the CSEE，2002，22 (11)：41-44(in Chinese)．

[5] 马幼捷，周雪松．静止无功补偿器非线性控制对系统功角稳定的影响[J]．中国电机工程学报，2003，23 (12)：84-88．
Ma Youjie，Zhou Xuesong. Study on nonlinear SVC control for improving power system stability[J]．Proceedings of the CSEE，2003，23 (12)：84-88(in Chinese)．

[6] 王杰，阮映琴，傅乐，等．计及动态负荷的电力系统动态无功补偿器与发电机励磁控制[J]．中国电机工程学报，2004，24 (6)：24-29．
Wang Jie，Ruan Yingqin，Fu Le，et al．The nonlinear control of svc and excitation of generators in power systems with dynamic Loads [J]．Proceedings of the CSEE，2004，24 (6)：24-29(in Chinese)．

[7] Li Wenlei，Liu Shirong，Jing Yuanwei．Nonlinear robust control based on adaptive backstepping design for static VAR compensator [C]．Wuxi，China：The 23rd Chinese Control Conference，2004．

[8] Krstic M，Kanellakopoulos I，Kokotovic P．Nonlinear and adaptive control design[M]．New York：John Wiley & Sons，INC，1995．

[9] Hu W，Mei S，Lu Q，et al.，Nonlinear adaptive decentralized stabilizing control of multi-machine systems[J]．Applied Mathematics and Computation，2002，133(2)：519-532．

[10] Tan H L，Chang J．Adaptive backstepping control of induction motor with uncertainties[C]．California，USA：In：Proc. Of ACC，1999．

[11] 李文磊，井元伟，刘晓平．非线性汽门控制器的自适应鲁棒逆推设计[J]．中国电机工程学报，2003，23 (1)：155-158．
Li Wenlei，Jing Yuanwei，Liu Xiaoping．Adaptive robust backstepping design for nonlinear steam valve controller [J]．Proceedings of the CSEE，2003，23 (1)：155-158(in Chinese)．

[12] Karagiannis D，Astolfi A．Nonlinear adaptive control of systems in feedback form：an alternative to adaptive backstepping[C]．Osaka，Japan：IFAC Symposium on Large Scale Systems：Theory and Applications，2004．

[13] stolfi A，Ortega A R．Immersion and Invariance：a new tool for stabilization and adaptive control of nonlinear systems[J]．IEEE Trans. Automatic Control 2003，48(4)：590-606．

[14] 孙强，程明，周鹗，等．新型双凸极永磁电机调速系统的变参数 PI 控制[J]．中国电机工程学报，2003，23(6)：117-122．
Sun Qiang，Cheng Ming，Zhou E，et al．Variable PI control of novel doubly salient permanent magnet motor drive[J]．Proceedings of the CSEE，2003，23(6)：117-122(in Chinese)．

收稿日期：2005-12-09。

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(编辑　车德竞)