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Control Chaos for Permanent Magnet Synchronous Motor Base on Adaptive Backstepping of Error Compensation

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Abstract

Permanent magnet synchronous motor (PMSM) can appear chaos phenomenon when PMSM in turn on or turn off. When control chaotic PMSM to zero, the state variables of the system can appear fluctuate which is not the ideal control result. In order to overcome fluctuate in control chaos. This paper propose adaptive backstepping of error compensation to control chaotic PMSM, an error compensation item is developed in the virtual control design of each backstepping step to compensate the effect of unknown error dynamics on system for obtaining smooth process of chaos control. This scheme can eliminate oscillation in course of control chaos. Numerical simulations further test the effectiveness of the theoretical analysis.

Keywords: *PMSM, error control, adaptive backstepping, chaos control*

1. Introduction

Chaos is a kind of widespread phenomenon, which exists in the circuit [1], power network [2], fluid dynamics [3, 4], thermodynamic [5, 6].

Since the 1980s, with the power electronic technology, microelectronics technology and the rapid development of new type of motor control theory. Comparing with frequency converting driving system for asynchronous machine and adjustable speed for DC motor, PMSM has no commutator and brush unreliable components. Compared with asynchronous motor, PMSM does not need to reactive excitation current. Permanent magnet synchronous motor (PMSM) has been widely used due to PMSM with high air gap flux density, small torque ripple, high torque and high efficiency. Compared with ordinary synchronous motor, it leaves out the excitation device, simplify the structure, improve the efficiency, at the same time, the flexible and varied in shape and size of the machine.

Permanent magnet synchronous motor (PMSM) have better properties than the conventional internal combustion engine vehicle, such as independence from petroleum, reliability and quiet and so on [7-9].

However there appear chaos in PMSM when PMSM in turn on or turn off [10, 11]. Chaos is harmful for PMSM, chaos state of the PMSM can influence performance of PMSM even destroy PMSM, the high performance PMSM cannot appear chaotic state. Control chaos of PMSM is an important test [12, 13]. Due to PMSM is multivariable, nonlinear and strongly coupled plant, control of chaos in PMSM is very difficult [14]. The chaotic control of the PMSM is a research hot spot.

With the development of the theory and technology of chaos control, scholars have studied many methods for control and analysis chaotic system [15, 16]. Such as the OGY is an effective way to control the chaotic motion, the subsequent period, there are variable structure control [17], entrainment and migration control, nonlinear feedback control [18], total sliding-mode control [19] and the backstepping nonlinear

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control, self-constructing fuzzy neural network speed control [20], dither chaos [21], hybrid control [22], passivity control [23]. Feedback control [24], delay control [25], nonlinear control [26], time-delayed feedback control [27], adaptive control based particle swarm optimization and chebyshev neural network [28], restricted feedback control [29], adaptive chatter free sliding mode control [30], optimal and adaptive control [31], hopf bifurcation control [32].

Various methods and techniques had been successfully used to control or suppress chaos in PMSM. For example, In 2007, C Kuo et al. proposed fuzzy slide-mode controller to control chaos in PMSM [33]. In 2010, D Li et al. proposed impulsive control for PMSM [34]. In 2010, S C Chang proposed synchronous and control chaos in a PMSM [35]. In 2011, J Yu et al. proposed backstepping control for the chaotic PMSM [36]. In 2011, S C Chang et al. proposed dither signal to control chaotic PMSM [37]. However, these methods appear oscillation in course of control of chaos in PMSM which effect on practical application. In 2014, Chen et al. proposed adaptive backstepping control of the PMSM system [38]. In 2014, Tang et al. proposed single input state feedback control for PMSM [39]. In 2014, Wei et al. proposed optimal control for PMSM [40]. In 2014, Antonio et al. proposed Global adaptive linear control for PMSM [41].

In this paper, a scheme is proposed to suppress oscillation in course of control of chaos in PMSM. An error compensation item is developed in the virtual control design of each backstepping step to compensate the effect of unknown error dynamics on system for obtaining smooth process of chaos control. This scheme can eliminate oscillation in course of control chaos. Finally, the simulation shows the effectiveness of theoretical analysis.

2. Dynamics Analysis of PMSM System

The model of PMSM [36] can be described as follows:

$$\begin{cases} \frac{di_d}{dt} = (u_d - R_1 + \omega L_q i_q)/L_d \\ \frac{di_q}{dt} = (u_q - R_1 i_q - \omega L_d i_d - \omega \psi_\gamma)/L_q \\ \frac{d\omega}{dt} = [n_p \psi_\gamma i_q + n_p (L_d - L_q) i_d i_q - T_L - \beta\omega]/J \end{cases} \tag{1}$$

where i_d, i_q and ω are state variables, i_d is d-axis stator current, i_q is q-axis stator current, and ω is rotor angular speed. The u_d is d-axis external voltage, u_q is q-axis external voltage, and T_L is external torque. The L_d is d-axis stator inductance and L_q is q-axis stator inductance. ψ_γ is permanent magent flus, R_1 is stator winding resistance, β is the viscous damping coefficient, J is rotor rotational inertia, n_p is the number of pole-pairs, R_1 , β, J, L_q, L_d , T_L are all positive. We apply time transform, $\boldsymbol{x} = \boldsymbol{\lambda}\tilde{\boldsymbol{x}}$, $t = \tau\tilde{t}$, where

$\tilde{\boldsymbol{x}} = \begin{bmatrix} \tilde{i}_d & \tilde{i}_q & \tilde{\omega} \end{bmatrix}^{\mathrm{T}}$, $\boldsymbol{\lambda} = \begin{bmatrix} \lambda_d & 0 & 0 \\ 0 & \lambda_q & 0 \\ 0 & 0 & \lambda_\omega \end{bmatrix} = \begin{bmatrix} bk & 0 & 0 \\ 0 & k & 0 \\ 0 & 0 & 1/\tau \end{bmatrix}$, $b = L_q/L_d$, $k = \beta/n_p\tau\psi_\gamma$, $\tau = L_q/L_{R_1}$

.

The system (1) can be transformed to the following nondimensionalized forms:

$$\begin{cases} \dot{\tilde{i}}_d = -\dfrac{L_q}{L_d}\tilde{i}_d + \tilde{\omega}\tilde{i}_q + \tilde{u}_d \\ \dot{\tilde{i}}_q = -\tilde{i}_q - \omega\tilde{i}_d + \gamma\tilde{\omega} + \tilde{u}_q \\ \dot{\tilde{\omega}} = \sigma(\tilde{i}_q - \tilde{\omega}) + \xi\tilde{i}_d\tilde{i}_q - \tilde{T} \end{cases} \quad \begin{cases} \dot{\tilde{i}}_d = -\dfrac{L_q}{L_d}\tilde{i}_d + \tilde{\omega}\tilde{i}_q + \tilde{u}_d \\ \dot{\tilde{i}}_q = -\tilde{i}_q - \omega\tilde{i}_d + \gamma\tilde{\omega} + \tilde{u}_q \\ \dot{\tilde{\omega}} = \sigma(\tilde{i}_q - \tilde{\omega}) + \xi\tilde{i}_d\tilde{i}_q - \tilde{T} \end{cases} \qquad 2)$$

where

$\gamma = n_p\psi_\gamma / R_1\beta$, $\sigma = L_q\beta / R_1 J$, $\tilde{u}_q = n_p L_q \psi_\gamma u_q / R_1^2\beta$, $T_L = L_q^2 T_L / R_1^2 J$, $\tilde{u}_d = n_p L_q \psi_r u_d / R_1^2 \beta$,

$\xi = L_q\beta^2(L_d - L_q) / L_d J n_p \psi_r$, $n_p = 1$.

The system (2) is smooth air-gap when $L_d = L_q$. In order to describe conveniently, we assume $i_d = \tilde{i}_d$, $i_q = \tilde{i}_q$, $\omega = \tilde{\omega}$, $u_d = \tilde{u}_d$, $u_q = \tilde{u}_q$. Thus, the system (2) can be expressed as follows:

$$\begin{cases} \dot{i}_d = -i_d + \omega i_d + u_d \\ \dot{i}_q = -i_q - \omega i_d + \gamma\omega + u_q \\ \dot{\omega} = \sigma(i_q - \omega) - T_L \end{cases} \qquad (3)$$

At present, if model of the system (3) without external force, namely, $u_d = u_q = T_L = 0$. The system (3) can be showed as follows:

$$\begin{cases} \dot{i}_d = -i_d + \omega i_d \\ \dot{i}_q = -i_q - \omega i_d + \gamma\omega \\ \dot{\omega} = \sigma(i_q - \omega) \end{cases} \qquad (4)$$

the parameters σ and γ of the system (4) can decide chaotic state of the system (4). Figure.1 illustrates bifurcation diagram of the system (4).

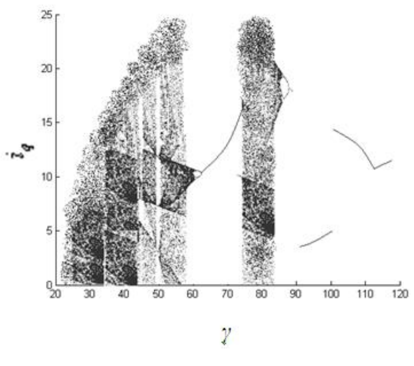


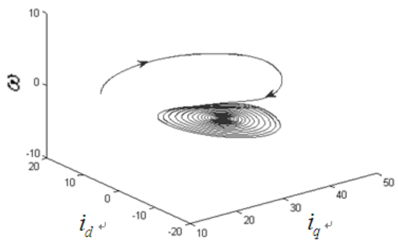
Figure 1. Bifurcation diagram of System (4)

For system (4),

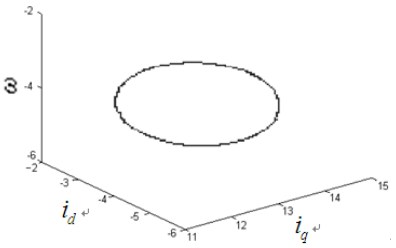
$$\Delta V = \frac{\partial \frac{d\omega}{dt}}{\partial\omega} + \frac{\partial \frac{di_q}{dt}}{\partial i_q} + \frac{\partial \frac{di_d}{dt}}{\partial i_d} = -(\sigma + 2)$$

Due to $\sigma > 0$, $\Delta V < 0$. So the system (4) is dissipative system based on dissipation theory.

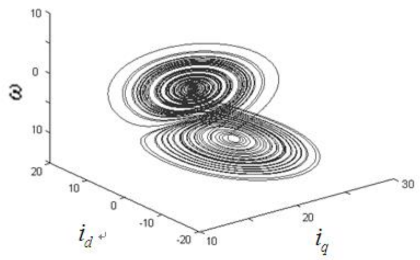
A few numerical simulations are done to comprehend clearly the chaos properties of the system (4). Figure 2 displays phase portrait of system (4) to explain the dynamical behaviors when parameters $\sigma = 4$ and γ change. Among Figure 2 phase portrait relate to i_d, i_q, ω. Figure 2 (a), Figure 2 (b), Figure 2 (c) display phase portrait when $\gamma = 10$, $\gamma = 14.3$ and $\gamma = 25.0$, respectively.



(a) Phase portrait of system (4) when γ = 10



(b) Phase portrait of system (4) when γ = 14.3



(c) Phase portrait of system (4) when γ = 25

Figure 2. Phase Portrait of System (4) When Parameters and Changed

The conclusion can be drawn from Figure 2 that the system (4) is nonchaos when $\gamma = 10$, the system (4) is periodical motion when $\gamma = 14.3$ and the system (4) is chaos when $\gamma = 25$.The system (4) is chaos when $\gamma \geq 14.3$, the system (4) is not chaos when $\gamma < 14.3$ [28]. The system (4) is chaos when $\gamma = 25$ and $\sigma = 4$ base on above analysis [28]. The system (4) have three equilibrium point: $(0,\ 0,\ 0)$, $(\gamma - 1,\ -\sqrt{\gamma - 1},\ -\sqrt{\gamma - 1})$, $(\gamma - 1,\ \sqrt{\gamma - 1},\ \sqrt{\gamma - 1})$ [28].

3. Theory and Method

This paper studies how to control chaotic PMSM to zero when PMSM is in power off. In order to convenient derivation, we should do the following transform,

$$\boldsymbol{A}=\begin{bmatrix}0&0&1\\0&1&0\\1&0&0\end{bmatrix},\quad \boldsymbol{Y}=\begin{bmatrix}\mathrm{y}_1\\y_2\\y_3\end{bmatrix},\quad \boldsymbol{X}=\begin{bmatrix}x_1\\x_2\\x_3\end{bmatrix},\ \boldsymbol{Y}=\boldsymbol{AX}\ .$$

So the system (4) can be changed as follows,

$$\begin{cases}y_1=\sigma(y_2-y_1)\\y_2=\gamma y_1-y_2-y_1y_3\\y_3=y_1y_2-y_3\end{cases}\tag{5}$$

In order to control chaotic the system (4) to the zero, we may add controller to the third equation of the system (4), the system (4) can be changed as follows,

$$\begin{cases}y_1=\sigma(y_2-y_1)\\y_2=\gamma y_1-y_2-y_1y_3\\y_3=y_1y_2-y_3+u\end{cases}\tag{6}$$

Define three error variables of the system (6) as follows:

$$\begin{cases}e_1=y_1\\e_2=y_2-\alpha_1\\e_3=y_3-\alpha_2\end{cases}\tag{7}$$

We need the following steps to realize our chaos control of the PMSM.

Step 1: Base on system (7), the first derivative of e_1 is,

$$\dot{e}_1=\dot{y}_1=\sigma(y_1-y_2)=\sigma(\alpha_1+e_2-e_1)=-\sigma e_1+\sigma e_2+\sigma\alpha_1\tag{8}$$

Choose the Lyapunov function is as:

$$V_1=\frac{1}{2}e_1^2\tag{9}$$

then the time derivative of   is computed,

$$\dot{V}_1=e_1\dot{e}_1=e_1(-\sigma e_1+\sigma e_2+\sigma\alpha_1)=-\sigma e_1^2+\sigma e_1e_2+\sigma\alpha_1e_1\tag{10}$$

The virtual control variable α_1 is designed as follows,

$$\alpha_1=p_1e_1-p_2e_2\tag{11}$$

where p_1 and p_2 are control parameters, $\frac{1}{\sigma}\le p_1\le 1$ and $0\le p_2<1$, substituting Equation (11) into Equation (10) that

$$\dot{V}_1=-\sigma e_1^2+\sigma e_1e_2+\sigma e_1(p_1e_1-p_2e_2)=-\sigma(1-p_1)e_1^2+\sigma(1-p_2)e_1e_2\tag{12}$$

Step 2: Derivative of e_2 ,

$$\begin{aligned}\dot{e}_2&=\dot{y}_2-\dot{\alpha}_1=\gamma y_1-y_2-y_1y_3-p_1\dot{e}_1+p_2\dot{e}_2\\&=\gamma e_1-(e_2+\alpha_1)-e_1(e_3+\alpha_2)-p_1\dot{e}_1+p_2\dot{e}_2,\end{aligned}\tag{13}$$

ubstituting Equation (8) into Equation (13), the Equation (13) can be described as follows,

$$\dot{e}_2 = \frac{1}{1-p_2}[(-\alpha_2 - p_1)e_1 + (-1 + p_2 + \sigma p_1 p_2 - \sigma p_1)e_2$$
$$- e_1 e_3 + \sigma p_1 e_1 - \sigma p_1^2 e_1 + \gamma e_1]$$
$$= \frac{1}{1-p_2}[(-\alpha_2 - p_1)e_1 - (1-p_2)(\sigma p_1 + 1)e_2 - e_1 e_3$$
$$+ p_1(1-p_1)\hat{\gamma} e_1 + \hat{\gamma} e_1 - p_1(1-p_1)\tilde{\sigma} e_1 - \hat{\gamma} e_1] \quad (14)$$

Where $\hat{\sigma}$ and $\hat{\gamma}$ are σ and γ estimates respectively. $\tilde{\sigma} = \hat{\sigma} - \sigma$, $\tilde{\gamma} = \hat{\gamma} - \gamma$, $\tilde{\sigma}$ and $\tilde{\gamma}$ are parameter estimation error.

Choose the Lyapunov function as follows,

$$V_2 = V_1 + (e_2^2 + \tilde{\sigma} + \tilde{\gamma}^2)/2$$

the time derivative of is as follows,

$$\dot{V}_2 = \dot{V}_1 + e_2 \dot{e}_2 + \tilde{\sigma}\dot{\hat{\sigma}} + \tilde{\gamma}\dot{\hat{\gamma}}$$
$$= -\sigma(1-p_1)e_1^2 - \frac{e_1 e_2 e_3}{1-p_2} - \frac{p_1}{1-p_2} e_1 e_2 -$$
$$(\sigma p_1 + 1)e_2^2 + \tilde{\sigma}[\dot{\hat{\sigma}} - (1-p_2)e_1 e_2 - \frac{p_1(1-p_1)}{1-p_2} e_1 e_2]$$
$$+ \tilde{\gamma}(\dot{\hat{\gamma}} - \frac{e_1 e_2}{1-p_2}) -$$
$$\frac{e_1 e_2}{1-p_2}\left\{\alpha_2 - \hat{\sigma}[(1-p_2)^2 + p_1(1-p_1)] - \hat{\gamma}\right\}. \quad (15)$$

Parameter adaptive law can be expressed as follows,

$$\begin{cases} \dot{\hat{\sigma}} = \dfrac{p_1(1-p_1)}{1-p_2} e_1 e_2 + (1-p_2)e_1 e_2 - m\hat{\sigma} \\ \dot{\hat{\gamma}} = \dfrac{1}{1-p_2} e_1 e_2 - n\hat{\gamma} \end{cases} \quad (16)$$

where $m > 0,\ n > 0$.

The virtual control variable α_2 is designed as follows,

$$\alpha_2 = [(1-p_2)^2 + p_1(1-p_1)]\hat{\sigma} + p_2\hat{\gamma} - p_3 e_3 \quad (17)$$

where $p_3 \in R$, p_3 is a control parameter, substituting Equation (16) and Equation (17) into Equation (15), Equation (15) is as follows,

$$\dot{V}_2 = -\sigma(1-p_1)e_1^2 - \frac{1-p_3}{1-p_2} e_1 e_2 e_3 - \frac{p_1}{1-p_2} e_1 e_2$$
$$+ e_1 e_2(\gamma + \tilde{\gamma}) - (\sigma p_1 + 1)e_1^2 - m\tilde{\sigma}\hat{\sigma} - n\tilde{\gamma}\hat{\gamma} \quad (18)$$

Base on Young inequality [21], inequality (19) can be formulated as follows

$$\begin{cases} -m\tilde{\sigma}\hat{\sigma} \le -m\tilde{\sigma}(\tilde{\sigma} + \sigma) \le -\dfrac{1}{2}m\tilde{\sigma}^2 + \dfrac{1}{2}m\sigma^2 \\ -n\tilde{\gamma}\hat{\gamma} \le -n\tilde{\gamma}(\tilde{\gamma} + \gamma) \le -\dfrac{1}{2}n\tilde{\gamma}^2 + \dfrac{1}{2}n\gamma^2 \end{cases} \quad (19)$$

so the inequality(20) can be gotten as follows,

$$\dot{V}_2 \le -\sigma(1-p_1)e_1^2 - \frac{1-p_3}{1-p_2}e_1e_2e_3 - \frac{p_1}{1-p_2}e_1e_2 + e_1e_2(\gamma+\tilde{\gamma}) - (\sigma p_1+1)e_2^2 - \frac{1}{2}m\tilde{\sigma}^2 - \frac{1}{2}n\tilde{\gamma}^2 + \frac{1}{2}m\sigma^2 + \frac{1}{2}n\gamma^2. \tag{20}$$

Step 3 Derivative of e_3 is as follows,

$$\begin{aligned}\dot{e}_3 &= u + e_1(e_2+\alpha_1) - (e_3+\alpha_2) - \dot{\alpha}_2 \\ &= u + e_1e_2 + e_1\alpha_1 - (e_3+\alpha_2) \\ &\quad -[(1-p_2)^2 + p_1(1-p_1)]\dot{\hat{\sigma}} - \dot{\hat{\gamma}} + p_3\dot{e}_3,\end{aligned} \tag{21}$$

choose $p_3 \ne 1,$ Equation (21) is as follows,

$$\dot{e}_3 = \frac{1}{1-p_3}\{u + e_1e_2 + e_1\alpha_1 - (e_3+\alpha_2) - [(1-p_2)^2 + p_1(1-p_1)]\dot{\hat{\sigma}} - \dot{\hat{\gamma}}\} \tag{22}$$

choose the Lyapunov function as follows,

$$V_3 = V_2 + \frac{1}{2}\frac{1}{1-p_2}e_3^2 \tag{23}$$

The time derivative of V_3 is as follows,

$$\begin{aligned}\dot{V}_3 &= \dot{V}_2 + \frac{1}{1-P_2}e_3\dot{e}_3 \\ &= -\sigma(1-p_1)e_1^2 - \frac{1-p_3}{1-p_2}e_1e_2e_3 \\ &\quad - \frac{p_1}{1-p_2}e_1e_2 + e_1e_2(\gamma+\tilde{\gamma}) - (\sigma p_1+1)e_2^2 - m\tilde{\sigma}\hat{\sigma} - n\tilde{\gamma}\hat{\gamma} \\ &\quad + \frac{1}{1-p_2}e_3\frac{1}{1-p_3}\{u + e_1(e_2+\alpha_1) - \\ &\quad (e_3+\alpha_2) - [(1-p_2)^2 + p_1(1-p_1)]\dot{\hat{\sigma}} - p_2\dot{\hat{\gamma}}\} \\ &= -\sigma(1-p_1)e_1^2 - (\sigma p_1+1)e_2^2 - m\tilde{\sigma}\hat{\sigma} - \\ &\quad n\tilde{\gamma}\hat{\gamma} + \frac{e_3}{(1-p_2)(1-p_3)}\{u - \frac{p_1(1-p_3)}{e_3}e_1e_2 + \frac{\gamma+\hat{\gamma}}{e_3}e_1e_2 \\ &\quad + e_1e_2 + e_1\alpha_1 - (e_3+\alpha_2) - (1-p_3)^2e_1e_2 - \\ &\quad [(1-p_2)^2 + p_1(1-p_1)]\dot{\hat{\sigma}} - p_2\dot{\hat{\gamma}}\},\end{aligned} \tag{24}$$

control input u is as follows,

$$\begin{aligned}u = -[&-\frac{p_1(1-p_3)}{e_3}e_1e_2 + \frac{\gamma+\hat{\gamma}}{e_3}e_1e_2 + e_1e_2 \\ &+ e_1\alpha_1 - (e_3+\alpha_2) - (1-p_3)^2e_1e_2 \\ &-[(1-p_2)^2 + p_1(1-p_1)]\dot{\hat{\sigma}} - p_2\dot{\hat{\gamma}}],\end{aligned} \tag{25}$$

substituting Equation (25) into Equation (24) , equation (26) is as follows,

$$\dot{V}_3 = -\sigma(1-P_1)e_1^2 - (\sigma P_1 + 1)e_2^2 - P_4 e_3^2 - m\tilde{\sigma}\hat{\sigma} - n\tilde{\gamma}\hat{\gamma} \tag{26}$$

Similar to $\dot{V}_2$,

$$\dot{V}_3 \le -\sigma(1-p_1)e_1^2 - (\sigma p_1 + 1)e_2^2 - p_4 e_3^2 - \frac{1}{2}m\tilde{\sigma}^2 - \frac{1}{2}n\tilde{\gamma}^2 + \frac{1}{2}m\sigma^2 + \frac{1}{2}n\gamma^2 \tag{27}$$

set $\beta = (m\sigma^2 + n\gamma^2)/2$, $\tau = \min\{2\sigma(1-p_1),\ 2(\sigma p_1 + 1),\ 2p_4(1-p_2),\ m,\ n\}$,inequality (29) can be gotten as follows,

$$\dot{V}_3 \le [-\tau(e_1^2 + e_2^2 + \frac{e_3^2}{1-p_3} + \tilde{\sigma}^2 + \tilde{\gamma}^2) + m\sigma^2 + n\gamma^2]\Big/2 \le -\tau V_3 + \beta.$$

4. Stability Analysis of the System

Theorem 1 Chaotic system (6) and parameter identification (16), for bounded initial conditions, the following conclusion was gotten:

(1) All the signals the consistent bounded in chaos system, state error $e_i (i = 1, 2, 3)$ and parameter estimates $\tilde{\gamma}$ and $\tilde{\sigma}$ eventually converge to bounded sets:

$$\Omega \triangleq \{e_1,\ e_2,\ e_3,\ \tilde{\gamma},\ \tilde{\sigma} \,|\, V < \beta/\tau\}$$

(2) Choose reasonable parameters m, n and $p_i (i = 1, 2, 3, 4)$, state of chaotic system y_1, y_2, y_3 can be stable in bounded neighborhood point (0, 0, 0).

Proof: Design Laypunov function $V = V_3$, Equation (29) can be gotten as follows,

$$\dot{V} \le -\tau V + \beta \tag{29}$$

Equation (29) both sides by the same e^{rt} , inequality (30) can be gotten as follows $e^{\tau t}\dot{V} \le -\tau e^{\tau t} V + \beta e^{\tau t}$,

namely,

$$\frac{d}{dt}(V(t)e^{\tau t}) \le \beta e^{\tau t} \tag{30}$$

integral of inequality (30) in [0, t],

$$V(t) \le V(0)e^{-\tau t} + \beta e^{-\tau t}\int_0^t e^{a\tau} da \le V(0)e^{-\tau t} + \frac{\beta}{\tau}(1 - e^{-\tau t}) \le V(0) + \frac{\beta}{\tau}. \tag{31}$$

For bounded initial conditions $V(0)$, we can draw a conclusion that $V(t)$ is bounded base on theorem of Laypunov. We can get $e_1,\ e_2,\ e_3$ and $\hat{\sigma},\ \hat{\gamma}$ consistent bounded according to inequality (29). Base on virtual control variables $\alpha_j (j = 1, 2)$, $y_1,\ y_2,\ y_3$ are all bounded. Control input u is bounded base on Equation (25), so all the signals in chaotic system are consistent bounded.

When $t \to \infty$,

$$e^{-\tau t} \to 0,\quad V(t) \le V(0)e^{-\tau t} + \frac{\beta}{\tau}(1 - e^{-\tau t}) < \frac{\beta}{\tau}$$

So state error e_i $(i=1,2,3)$ and parameter estimates $\tilde{\gamma}$ and $\tilde{\sigma}$ eventually converge to a bounded set $\Omega \triangleq \{e_1,\ e_2,\ e_3,\ \tilde{\gamma},\ \tilde{\sigma} | V < \beta/\tau\}$.

From inequality (31), inequality can be obtained as follows

$$\frac{1}{2}\sum_{k=1}^{3}\frac{1}{g_k}e_k^2+\frac{1}{2}\tilde{\boldsymbol{\Theta}}^{\mathrm{T}}\tilde{\boldsymbol{\Theta}} \le V(0)e^{-\tau t}+\frac{\beta}{\tau} \tag{32}$$

where

$$g_1=g_2=1,\ g_3=1-p_2,\ \tilde{\boldsymbol{\Theta}}=[\tilde{\sigma},\tilde{\gamma}\ ]^{\mathrm{T}}$$

Set $g_m=\max\{g_1,\ g_2,\ g_3\}$. Base on Equation (32), inequality (33) can be gotten as follows,

$$\sum_{k=1}^{3}e_k^2 \le 2g_m[V(0)e^{-\tau t}+\frac{\beta}{\tau}] \tag{33}$$

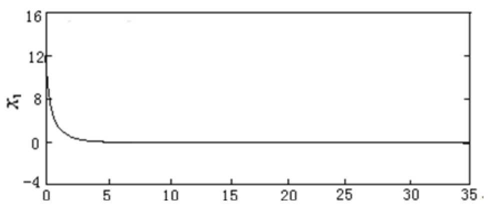
Given constant $\mu > 2g_m\beta/\tau$, existing $T>0$, for all $t \ge T$, error $e_i(i=1,2,3)$ satisfy $\|e_i\| < \mu$. We choose reasonable values of m, n and $p_i(i=1,2,3,4)$ can result in the value of μ decreased. So $(e_1,\ e_2,\ e_3)$ can eventually converge to a stable in bounded neighborhood $(0,\ \alpha_1,\ \alpha_2)$. Accordingly to Equation (10) and Equation (17), p_1, p_2 and p_3 are chosen smaller constant, $(\alpha_1,\ \alpha_2)$ can be stabled in bounded neighborhood (0, 0). So system (5) can be stable in bounded neighborhood $(0,\ 0,\ 0)$.

5. The Simulation Research

Choose $\gamma=25,\ \sigma=4$, the system (4) is chaos. Let $y_0=[8,\ 8,\ 12]^{\mathrm{T}}$ due to $\boldsymbol{Y}=\boldsymbol{AX}$, $\boldsymbol{x}_0=[12,\ 8,\ 8]^{\mathrm{T}}$, $(\hat{\sigma}_0,\ \hat{\gamma}_0)=(10,\ 10)$, $p_1=0.5,\ p_2=0.56,\ p_3=-0.3,\ p_4=1.0,\ (m,\ n)=(100,\ 100)$.

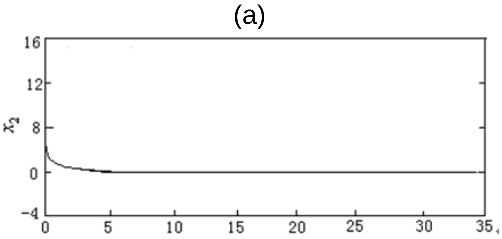
Figure 3 shows state variable $x_1,\ x_2,\ x_3$ control process. Figure 4 shows parameter identification process. Figure 4 (a) shows identification result of estimate $\hat{\gamma}$, Figure 4 (b) shows identification result of estimate $\hat{\sigma}$.

The variable $x_1,\ x_2,\ x_3$ represents variable $i_d,\ i_q,\ \omega$ respectively.



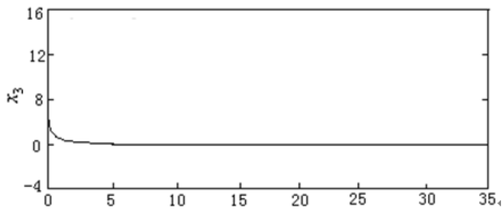
t/s

(a)



t/s

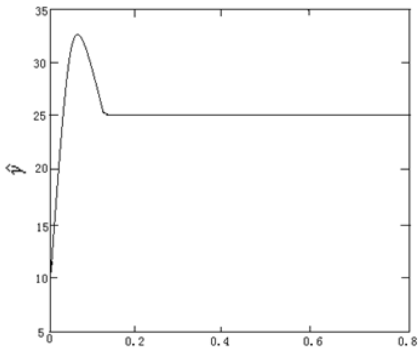
(b)



t/s

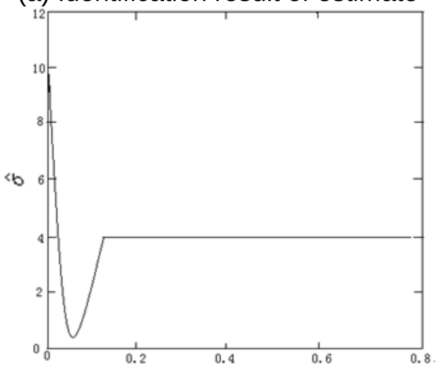
(c)

Figure 3. State Variable x_1, x_2, x_3 Control Process



t/s

(a) Identification result of estimate



t/s

(b) Identification result of estimate

Figure 4. Parameters Identification Process

We can draw a conclusion that from Figure 3 and Figure 4 that variable x_1, x_2, x_3 asymptotically stable to zero smoothly instead of occur oscillation phenomenon, parameter and $\hat{\gamma}$ can asymptotically reach stable state.

6. Conclusions

This paper proposes adaptive backstepping of error compensation to control chaos. When control chaotic PMSM to zero, the state variables of the system can appear fluctuate which is not the ideal control result. In order to overcome fluctuate in control chaos, we came up with the method of the adaptive backstepping of error compensation. An error compensation item is developed in the virtual control design of each backstepping step to compensate the effect of unknown error dynamics on system for obtaining smooth process of chaos control. This scheme can eliminate oscillation in course of control chaos. Numerical simulations further test the effectiveness of the theoretical analysis.

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