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Based on Adaptive Backstepping Error Control for Permanent Magnet Synchronous Motor

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Abstract

Permanent Magnet Synchronous Motor (PMSM) displays chaotic phenomenon when PMSM in power on or power off. At present, there are many methods to control chaos in PMSM. However, there appears oscillation in course of control chaos in PMSM, which has an effect on practical application. This paper proposes error control based on adaptive backstepping to control chaos in PMSM; an error control item is added in each step virtual control design which has control effect of unknown dynamical error on system. This scheme can eliminate oscillation in course of control chaos. Finally, the simulation results show the effectiveness of theoretical analysis.

Keywords

PMSM, Error Control, Adaptive Backstepping, Chaos Control

1. Introduction

Research on PMSM has been going on for many years due to the fact that they have many advantages over the conventional internal combustion engine vehicle, such as independence from petroleum, reliability and quiet [1]-[3].

However there appear phenomena of chaos in PMSM when PMSM in turn on or turn off [4] [5]. Chaos of PMSM is harmful. Chaos can degrade performance of PMSM, even destroy PMSM and restrict the operating range of numerous electrical and mechanical devices. The high performance of PMSM depends on the absence of chaos so it is important for PMSM to control chaos [6] [7]. Due to the fact that PMSM is multivariable, nonlinear and strongly coupled plant, controlling chaos of PMSM is very difficult [8].

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With the development of theory of chaos, there are many methods for control and analysis chaotic system [9] [10]. For example, the OGY is a basic methodology for controlling chaos. At the same time, there are variable structure control [11], entrainment and migration control, nonlinear feedback control [12], total sliding-mode control [13] and the backstepping nonlinear control, self-constructing fuzzy neural network speed control [14], dither chaos [15], hybrid control [16] and passivity control [17].

Various ways and techniques had been successfully used to control or suppress chaos in PMSM. For example, in 2009, M. Zribi *et al*. proposed to control chaos in PMSM by instantaneous Lyapunov exponent control algorithm [18]. In 2010, D. Li *et al*. proposed impulsive control for PMSM [19]. In 2010, S. C. Chang proposed synchronous and control chaos in a PMSM [20]. In 2011, J. Yu *et al*. proposed backstepping control for the chaotic permanent magnet synchronous motor drive system [21]. In 2011, S. C. Chang *et al*. proposed dither signal to quenching chaos of a permanent magnet synchronous motor in electric vehicles [22]. However, these methods appear oscillation in course of control chaos in PMSM which has an effect on practical application.

In this paper, a scheme is proposed to suppress oscillation in course of control chaos in PMSM. An error control item is added in the each step virtual control design which has control effect of unknown dynamical error on system. This scheme can gain more smoothly chaotic stabilization process and overcome oscillation in course of control chaos in PMSM. At the same time, all the signals in the system are bounded which based on Lyapunov function. This scheme has better transient response by simulation.

2. Problem Formulation

The dynamics PMSM, which model base on d-q axis, can be described as follows:

$$\begin{cases} \dfrac{\mathrm{d}i_d}{\mathrm{d}t} = \left(u_d - R_1 + \omega L_q i_q\right)/L_d \\ \dfrac{\mathrm{d}i_q}{\mathrm{d}t} = \left(u_q - R_1 i_q - \omega L_q i_q - \omega \psi_\gamma\right)/L_q \\ \dfrac{\mathrm{d}\omega}{\mathrm{d}t} = \left[n_p \psi_\gamma i_q + n_p\left(L_d - L_q\right) i_d i_q - T_L - \beta\omega\right]/J \end{cases} \tag{1}$$

where i_d, i_q and ω are state variables, which denote d-axis stator current, q-axis stator current and rotor angular speed respectively; u_d, u_q and T_L are d-axis external voltage, q-axis external voltage and external torque; L_d and L_q are d-axis stator inductance and q-axis stator inductance. ψ_γ is permanent magnet flues, 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. Applying transformation form, $\boldsymbol{x} = \boldsymbol{\lambda}\tilde{\boldsymbol{x}}$, and a time scaling transformation, $t = \tau\tilde{t}$, where

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

The system (1) can be changed into nondimensionalized form as follows:

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

where

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

$$\xi = L_q\beta^2\left(L_d - L_q\right)/L_d J n_p\psi_\gamma,\quad n_p = 1.$$

System (2) is smooth air-gap when $L_d = L_q$. In order to describe conveniently, assuming $i_d = \tilde{i}_d$, $i_q = \tilde{i}_q$,

$\omega = \tilde{\omega}$, $u_d = \tilde{u}_d$, $u_q = \tilde{u}_q$. The model can be simplified as follows:

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

Now, for model of PMSM of smooth air-gap (3), research motor without external force which can be considered PMSM no-load running and power fail interrupt, namely, $u_d = u_q = T_L = 0$. The system (3) can be shows as follows:

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

the parameters value of system (4), σ and γ, can effect on chaotic motion of PMSM greatly. Theoretically, there are many values of σ and γ which can cause chaos occurred in system (4). For system (4),

$$\Delta V = \frac{\partial \frac{\mathrm{d}\omega}{\mathrm{d}t}}{\partial \omega} + \frac{\partial \frac{\mathrm{d}i_q}{\mathrm{d}t}}{\partial i_q} + \frac{\partial \frac{\mathrm{d}i_d}{\mathrm{d}t}}{\partial i_d} = -\left(\sigma + 2\right).$$

Due to $\sigma > 0$, $\Delta V < 0$, so the system (4) is dissipative system base on dissipation theory. System (4) is chaos when $\gamma = 25$ and $\sigma = 4$ base on above analysis [22]. The system (4) have three equilibrium point: $\left(0,0,0\right)$, $\left(\gamma-1, -\sqrt{\gamma-1}, -\sqrt{\gamma-1}\right)$, $\left(\gamma-1, \sqrt{\gamma-1}, \sqrt{\gamma-1}\right)$.

3. Theory and Method

Set

$$A = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix}, \quad Y = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix}, \quad X = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}, \quad Y = AX .$$

So system (4) can be change as follows:

$$\begin{cases} \dot{y}_1 = \sigma\left(y_2 - y_1\right) \\ \dot{y}_2 = \gamma y_1 - y_2 - y_1 y_3 \\ \dot{y}_3 = y_1 y_2 - y_3 \end{cases} \tag{5}$$

To realize stability of system (4), we may add controller to the third equation of system (4), system (4) can be changed as follows:

$$\begin{cases} \dot{y}_1 = \sigma\left(y_2 - y_1\right) \\ \dot{y}_2 = \gamma y_1 - y_2 - y_1 y_3 \\ \dot{y}_3 = y_1 y_2 - y_3 + u \end{cases} \tag{6}$$

Definite three error variables:

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

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

$$\dot{e}_1 = \dot{y}_1 = \sigma\left(y_2 - y_1\right) = \sigma\left(\alpha_1 + e_2 - e_1\right) = -\sigma e_1 + \sigma e_2 + \sigma a_1 . \tag{8}$$

Choose the Lyapunov function candidate as:

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

then the time derivative of V_1 is computed,

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

The virtual control α_1 is constructed as

$$\alpha_1 = p_1 e_1 - p_2 e_2, \tag{11}$$

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

$$\dot{V}_1 = -\sigma e_1^2 + \sigma e_1 e_2 + \sigma e_1\left(p_1 e_1 - p_2 e_2\right) = -\sigma\left(1-p_1\right)e_1^2 + \sigma\left(1-p_2\right)e_1 e_2. \tag{12}$$

Step 2: Derivative of e_2, we have equation,

$$\dot{e}_2 = \dot{y}_2 - \dot{\alpha}_1 = \gamma y_1 - y_2 - y_1 y_3 - p_1\dot{e}_1 + p_2\dot{e}_2 = \gamma e_1 - \left(e_2 + \alpha_1\right) - e_1\left(e_3 + \alpha_2\right) - p_1\dot{e}_1 + p_2\dot{e}_2, \tag{13}$$

substituting Equation. (8) into Equation (13), the Equation (13) expression is given by

$$\begin{aligned}\dot{e}_2 &= \frac{1}{1-p_2}\left[\left(-\alpha_2 - p_1\right)e_1 + \left(-1 + p_2 + \sigma p_1 p_2 - \sigma p_1\right)e_2 - e_1 e_3 + \sigma p_1 e_1 - \sigma p_1^2 e_1 + \gamma e_1\right] \\ &= \frac{1}{1-p_2}\left[\left(-\alpha_2 - p_1\right)e_1 - \left(1-p_2\right)\left(\sigma p_1 + 1\right)e_2 - e_1 e_3 + p_1\left(1-p_1\right)\hat{\gamma} e_1 + \hat{\gamma} e_1 - p_1\left(1-p_1\right)\tilde{\sigma} e_1 - \hat{\gamma} e_1\right],\end{aligned} \tag{14}$$

where $\hat{\sigma}$, $\hat{\gamma}$ are σ, γ estimated value, $\tilde{\sigma} = \hat{\sigma} - \sigma$, $\tilde{\gamma} = \hat{\gamma} - \gamma$, $\tilde{\sigma}$ and $\tilde{\gamma}$ are parameters estimation error.

Choose the Lyapunov function as follows,

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

the time derivative of V_2 is given by

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

Choose parameters adaptive rule:

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

where $m > 0, n > 0$.

Construct the virtual control α_2 as

$$\alpha_2 = \left[\left(1-p_2\right)^2 + p_1\left(1-p_1\right)\right]\hat{\sigma} + p_2\hat{y} - p_3 e_3, \tag{17}$$

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

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

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

$$\begin{cases} -m\tilde{\sigma}\hat{\sigma} \le -m\tilde{\sigma}\left(\tilde{\sigma}+\sigma\right) \le -\frac{1}{2}m\tilde{\sigma}^2 + \frac{1}{2}m\sigma^2 \\ -n\tilde{\gamma}\hat{\gamma} \le -n\tilde{\gamma}\left(\tilde{\gamma}+\gamma\right) \le -\frac{1}{2}n\tilde{\gamma}^2 + \frac{1}{2}n\gamma^2 \end{cases} \tag{19}$$

so a straightforward calculation produces the following inequality

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

Step 3: Derivative of e_3 results in the following differential equation,

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

choose $p_3 \ne 1$, Equation (21) can be written as follows,

$$\dot{e}_3 = \frac{1}{1-p_3}\left\{u + e_1e_2 + \alpha_1e_1 - \left(e_3+\alpha_2\right) - \left[\left(1-p_2\right)^2 + p_1\left(1-p_1\right)\right]\dot{\hat{\sigma}} - \dot{\hat{\gamma}}\right\}, \tag{22}$$

choose the Lyapunov function candidate as

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

The time derivative of V_3 is

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

setting

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

substituting Equation (25) into Equation (24), we have the following equation.

$$V_3 = -\sigma\left(1-p_1\right)e_1^2 - \left(\sigma p_1+1\right)e_2^2 - p_4e_3^2 - m\tilde{\sigma}\hat{\sigma} - n\tilde{\gamma}\hat{\gamma}. \tag{26}$$

Similar to $\dot{V}_2$,

$$\dot{V}_3 \le -\sigma\left(1-p_1\right)e_1^2 - \left(\sigma p_1+1\right)e_2^2 - p_4e_3^2 - \frac{1}{2}m\tilde{\sigma}^2 - \frac{1}{2}n\tilde{\gamma}^2 + \frac{1}{2}m\sigma^2 + \frac{1}{2}n\gamma^2, \tag{27}$$

set

$$\beta \triangleq \left(m\sigma^2 + n\gamma^2\right)/2,$$

$$\tau = \min\left\{2\sigma\left(1-p_1\right), 2\left(\sigma p_1+1\right), 2p_4\left(1-p_2\right), m, n\right\},$$

inequality can be obtained as follows,

$$\dot{V}_3 \le \left[-\tau\left(e_1^2+e_2^2+\frac{e_3^2}{1-p_3}+\tilde{\sigma}^2+\tilde{\gamma}^2\right)+m\sigma^2+n\gamma^2\right]\Big/2 \le -\tau V_3+\beta . \tag{28}$$

4. Stability Analysis

Theorem 1. Consider chaotic system (6) and parameter identification (16), for bounded initial conditions, the following conclusion was established:

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

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

(2) Reasonable choosing parameters *m*, *n* and $p_i\left(i=1,2,3,4\right)$, state of chaotic system y_1, y_2 and y_3 can be stability in bounded point neighborhood $\left(0,0,0\right)$.

Proof: Choose Laypunov function $V=V_3$, by Equation (28) can be obtained as follows,

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

Equation (29) above both sides by the same e^{rt}, inequality can be obtained as follows

$$\mathrm{e}^{\tau t}\dot{V} \le -\tau \mathrm{e}^{\tau t}V+\beta \mathrm{e}^{\tau t},$$

namely

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(V\left(t\right)\mathrm{e}^{\tau t}\right) \le \beta \mathrm{e}^{\tau t}, \tag{30}$$

integral of formulas (30) in $\left[0,t\right]$,

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

For bounded initial conditions $V\left(0\right)$, we can draw a conclusion that $V\left(t\right)$ is bounded base on theorem of Laypunov. We can get e_1, e_2, e_3, $\hat{\sigma}$ and $\hat{\gamma}$ consistent bounded to inequality (28). Base on virtual control $\alpha_j\left(j=1,2\right)$, y_1, y_2 and 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 $t \to \infty$,

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

So state error $e_i\left(i=1,2,3\right)$ and parameter estimation errors $\tilde{\gamma}$, $\tilde{\sigma}$ eventually converge to a bounded set

$$\Omega \triangleq \left\{e_1, e_2, e_3, \tilde{\gamma}, \tilde{\sigma} \mid V < \beta/\tau\right\}.$$

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

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

where $g_1=g_2=1$, $g_3=1-p_2$, $\tilde{\Theta}=\left[\tilde{\sigma},\tilde{\gamma}\right]^{\mathrm{T}}$. setting $g_m=\max\left\{g_1,g_2,g_3\right\}$, base on Equation (32) inequality can be obtained as follows,

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

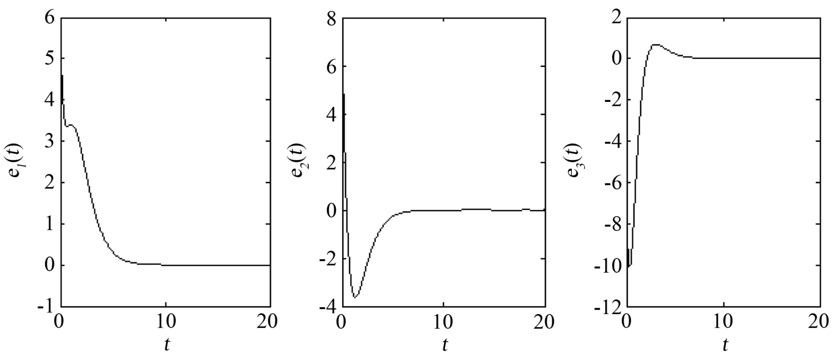

Figure 1. The synchronization errors.

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 reasonable choose values of *m*, *n* and $p_i(i = 1,2,3,4)$ which lead to the value of μ can be decreased. So, $e_i(i = 1,2,3)$ may 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, (α_1,α_2) can be stabled in bounded neighborhood $(0,0)$. So system (5) can be stable in bounded neighborhood $(0,0,0)$.

5. Simulation Results

Choose $\gamma = 25$, $\sigma = 4$, the system (4) is chaos. Let $y_0 = [8,8,12]^{\mathrm{T}}$ due to $Y = AX$, $x_0 = [12,8,8]^{\mathrm{T}}$, $(\hat{\sigma}_0, \hat{y}_0) = (10,10)$, $p_1 = 0.5, p_2 = 0.56, p_3 = -0.3, p_4 = 1.0, (m,n) = (100,100)$. **Figure 1** shows the synchronization errors. From **Figure 1**, we can see that the proposed controller and the parameters update law are effective.

6. Conclusion

This paper puts forward error control for permanent magnet synchronous motor with uncertain parameter based on adaptive backstepping which can effectively eliminate oscillation during the course of control chaos in PMSM. An error control item is added in the each step virtual control design which has control effect of unknown dynamical error on system. This scheme can gain more smoothly chaotic stabilization process. At the same time, all the signals in the system are bounded base on Lyapunov function. This scheme has better transient response by simulation.

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References

[1] Tung, P.C. and Chen, S.C. (1993) Experiment and Analytical Studies of the Sinusoidal Dither Signal in a DC Motor System. *Dynamics and Control*, **1**, 53-69. http://dx.doi.org/10.1007/BF01968359

[2] Hoang, L.H., Slimani, K. and Viarouge, P. (1994) Analysis and Implementation of a Real-Time Predictive Current Controller for Ermanentmagnet Synchronous Servo Drives. *IEEE Transactions on Industrial Electronics*, **41**, 110-117. http://dx.doi.org/10.1109/41.281616

[3] Chan, C.C. and Chau, K.T. (1997) An Overview of Power Electronics in Electric Vehicles. *IEEE Transaction on Industrial Electronics*, **44**, 3-13. http://dx.doi.org/10.1109/41.557493

[4] Chang, S.C. and Lin, H.P. (2005) Nonlinear Dynamics and Chaos Control for an Electromagnetic System. *Journal of Sound and Vibration*, **1**, 327-344. http://dx.doi.org/10.1016/j.jsv.2003.11.033

[5] Gan, J., Chan, K.T., Chan, C.C. and Jiang, J.Z. (2000) A New Surface-Inset Permanent Brushless DC Motor Drive for Electric Vehicles. *IEEE Transaction on Magnetic*, **36**, 3810-3818. http://dx.doi.org/10.1109/20.908381

[6] Harb, A.M. (2004) Nonlinear Chaos Control in a Permanent Magnet Reluctance Machine. *Chaos*, *Solition & Fractals*, **5**, 1217-1224. http://dx.doi.org/10.1016/S0960-0779(03)00311-4

[7] Zhang, B. and Mao, Z.Y. (2002) Entrainment and Migration Control of Permanent-Magnet Synchronous Motor System. *Control Theory and Application*, **19**, 53-56.

[8] Solsona, J. (1996) A Nonlinear Reduced Order Observer for Permanent Magnet Synchronous Motors. *IEEE Transactions on Industrial Electronics*, **43**, 492-497. http://dx.doi.org/10.1109/41.510641

[9] Yahyazadeh, M., Noei, A.R. and Ghaderi, R. (2011) Synchronization of Chaotic Systems with Known and Unknown Parameters Using a Modified Active Sliding Mode Control. *ISA Transactions*, **50**, 262-267. http://dx.doi.org/10.1016/j.isatra.2010.10.009

[10] Wu, J., Singla, M. and Olmi, C. (2010) Digital Controller Design for Absolute Value Function Constrained Nonlinear Systems via Scalar Sign Function Approach. *ISA Transactions*, **49**, 302-310. http://dx.doi.org/10.1016/j.isatra.2010.03.005

[11] Xu, Z. (2007) Direct Torque and Flux Regulation of an IPM Synchronous Motor Drive Using Variable Structure Control Approach. *IEEE Transactions on Power Electronics*, **22**, 2487-2498. http://dx.doi.org/10.1109/TPEL.2007.909208

[12] Ren, H.P. and Liu, D. (2006) Nonlinear Feedback Control of Chaos in Permanent Magnet Synchronous Motor. *IEEE Transaction on Circuits and System* II, **53**, 45-50. http://dx.doi.org/10.1109/TCSII.2005.854592

[13] Wai, R.J. and Li, C. (2001) Total Sliding-Mode Controller for PM Synchronous Servo Motor Drive Using Recurrent Fuzzy Neural Network. *IEEE Transactions on Industrial Electronics*, **48**, 926-944. http://dx.doi.org/10.1109/41.954557

[14] Lin, F.J., Lin, C.H. and Shen, P.H. (2001) Self-Constructing Fuzzy Neural Network Speed Controller for Permanent-Magnet Synchronous Motor Drive. *IEEE Transactions on Fuzzy Systems*, **9**, 751-759. http://dx.doi.org/10.1109/91.963761

[15] Feeny, B.F. and Moon, F.C. (2000) Quenching Stick-Slip Chaos with Dither. *Journal of Sound and Vibration*, **237**, 173-180. http://dx.doi.org/10.1006/jsvi.2000.3007

[16] Elmas, C. and Ustun, O. (2008) A Hybrid Controller for the Speed Control of a Permanent Magnet Synchronous Motor Drive. *Control Engineering Practice*, **16**, 260-270. http://dx.doi.org/10.1016/j.conengprac.2007.04.016

[17] Wu, Z.Q. and Tan. F.X. (2006) Passivity Control of Permanent-Magnet Synchronous Motors Chaotic System. *Proceedings of the CSEE*, **26**, 159-163.

[18] Zribi, M., Oteafy, A. and Smaoui, N. (2009) Controlling Chaos in the Permanent Magnet Synchronous Motor. *Chaos*, *Solitions & Fractals*, **41**, 1266-1276. http://dx.doi.org/10.1016/j.chaos.2008.05.019

[19] Li, D., Wang, S.L., Zhang, X.H. and Yang, D. (2010) Impulsive Control for Permanent Magnet Synchronous Motors with Uncertainties: LMI Approach. *Chinese Physics B*, **19**, 010506. http://dx.doi.org/10.1088/1674-1056/19/1/010506

[20] Chang, S.C. (2010) Synchronization and Controlling Chaos in a Permanent Magnet Synchronous Motor. *Journal of Vibration and Control*, **16**, 1881-1894.

[21] Yu, J., Chen, B., Yu, H.S. and Gao, J.W. (2011) Adaptive Fuzzy Tracking Control for the Chaotic Permanent Magnet Synchronous Motor Drive System via Backstepping. *Nonlinear Analysis*: *Real World Applications*, **12**, 671-681. http://dx.doi.org/10.1016/j.nonrwa.2010.07.009

[22] Chang, S.C., Lin, B.C. and Lue, Y.F. (2010) Dither Signal Effects on Quenching Chaos of a Permanent Magnet Synchronous Motor in Electric Vehicles. *Journal of Vibration and Control*, **17**, 1912-1918. http://dx.doi.org/10.1177/1077546310395978