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Sliding mode control of chaos in the noise-perturbed permanent magnet synchronous motor with non-smooth air-gap

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ABSTRACT

Permanent magnet synchronous motor (PMSM) is widely used in mining, and there exists chaotic behavior when it runs. In order to dispel its adverse effect on security in mining, the chaotic system of PMSM was analyzed. With noise disturbances, the complex dynamic characteristics of chaos were also analyzed, and proved the objective existence of chaos. As we all know, it is very difficult for conventional PMSM control to meet the design requirements, therefore, in order to ensure the robustness of the system, the chaotic orbits were stabilized to arbitrary chosen fixed points and periodic orbits by means of sliding mode method. Finally MATLAB simulations were presented to confirm the validity of the controller. The results show that the PMSM with the sliding mode control has a good dynamic performance and steady state accuracy.

1. Introduction

The exciting materials of PMSM are rare earth permanent magnet, so it is simple in structure, efficiency and no slip loss [1]. PMSM is widely applied in well elevating conveyor during mining, mining ventilation systems and pumps and so on [2–4]. But PMSM with non-uniform breath is chaotic at specific parameters and working conditions. And its phenomenon is the intermittent oscillation of torque and rotational speed, irregular current noise of the system and unstable control performance, therefore, this seriously affected the stability of the system and safety as well [5]. So it is valuable in theory and production.

The objective of chaos control is to stabilize chaotic system to periodic orbits or equilibrium points by keeping or adjusting the parameters, while the system parameters cannot be changed or it must pay a terrible price for great changing. Typical control methods include the OGY method, linear feedback control, adaptive control, fuzzy control, nonlinear anti-control method and so on [6–17]. These control methods are mostly for systems with no external disturbance, however, the disturbance is ubiquity. Therefore, a proportional plus integral sliding surface was defined and a sliding mode controller was proposed to make the system track target the orbit strictly based on variable structure control theory.

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2. Model of PMSM with non-uniform breath

The model of PMSM with non-uniform breath was proposed [18].

$$\begin{cases} \tau_1 \frac{di_d}{dt} = \alpha(\omega i_q - i_d) + u_d \\ \tau_2 \frac{di_q}{dt} = -\beta i_q - \chi\omega i_d - \delta\omega + u_q \\ \tau_3 \frac{d\omega}{dt} = \gamma i_d i_q + \eta i_q - \lambda\omega - T_L \end{cases} \tag{1}$$

where $\tau_1 = 6.45$, $\tau_2 = 7.125$, $\tau_3 = 1$, $\alpha = 1$, $\beta = 1$, $\chi = 1$, $\delta = 1$, $\gamma = 1.516$, $\eta = 16$, $\lambda = 1.8$, $u_d = -12.70$, $u_q = 2.34$, $T_L = 0.525$.

Thus, Eq. (1) can be rewritten as the mathematical model without quantification:

$$\begin{cases} \dot{x}_1 = \frac{1}{\tau_1}(x_2x_3 - x_1 + u_d) \\ \dot{x}_2 = \frac{1}{\tau_2}(-x_2 - x_1x_3 - x_3 + u_q) \\ \dot{x}_3 = \frac{1}{\tau_3}(ax_1x_2 + bx_2 - cx_3 - T_L) \end{cases} \tag{2}$$

where $\tau_1 = 6.45$, $\tau_2 = 7.125$, $\tau_3 = 1$, $a = 1.516$, $b = 16$, $c = 1.8$, $u_d = -12.70$, $u_q = 2.34$, $T_L = 0.525$.

Therefore, the model in the noise-perturbed PMSM is

$$\begin{cases} \dot{x}_1 = \frac{1}{\tau_1}(x_2x_3 - x_1 + u_d) + d_1 \\ \dot{x}_2 = \frac{1}{\tau_2}(-x_2 - x_1x_3 - x_3 + u_q) + d_2 \\ \dot{x}_3 = \frac{1}{\tau_3}(ax_1x_2 + bx_2 - cx_3 - T_L) + d_3 \end{cases} \tag{3}$$

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where d_1, d_2 and d_3 in Eq. (3) are the noise-perturbances, and they are bounded, i.e., $\|d_i\| \leqslant \delta < 1$, and δ is constant. In order to not lose the generality, set $d_1 = 0.1$, $d_2 = 0.1 \sin t$, and $d_3 = 0.8$.

3. Analyses of complex dynamics

3.1. System phase diagram

The three-dimensional phase diagram is shown in Fig. 1.

There are strange attractors as shown in Fig. 1. We can preliminarily infer that system (3) may have complex dynamic characteristics of chaos.

3.2. Lyapunov exponent and bifurcation diagram

If the maximum Lyapunov index is $\lambda_1 > 0$, then the system must be chaotic, otherwise the system is periodic or quasi-periodic. The Lyapunov exponential spectrum with respect to the parameter c is given in Fig. 2.

As it is observed, the maximum Lyapunov exponent is positive when $c = 1.8$, and we can also observe chaotic characteristics of system (3) according to bifurcation diagram (Fig. 3).

4. Sliding mode control

4.1. Design of the controller

The basic idea of the sliding mode control theory: first and foremost, good nature of a sliding surface which should be designed to make the system posses the desired properties when it is limited to the sliding surface; and when the system reaches the sliding surface, should maintains its slide with the exerted control [19]. Thus, the control form of system (3) can be described as follows:

$$\begin{cases} \dot{x}_1 = \frac{1}{\tau_1}(x_2x_3 - x_1 + u_d) + d_1 + u_1 \\ \dot{x}_2 = \frac{1}{\tau_2}(-x_2 - x_1x_3 - x_3 + u_q) + d_2 + u_2 \\ \dot{x}_3 = \frac{1}{\tau_3}(ax_1x_2 + bx_2 - cx_3 - T_L) + d_3 + u_3 \end{cases} \tag{4}$$

where u_1, u_2 and u_3 are control inputs, and

$$\boldsymbol{A} = \begin{bmatrix} -1/\tau_1 & 0 & 0 \\ 0 & -1/\tau_2 & -1/\tau_2 \\ 0 & b/\tau_3 & -c/\tau_3 \end{bmatrix}; \quad \boldsymbol{B} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix};$$
$$\boldsymbol{g} = \begin{bmatrix} x_2x_3/\tau_1 + u_d/\tau_1 \\ -x_1x_3/\tau_2 + u_q/\tau_2 \\ ax_1x_2/\tau_3 - T_L/\tau_3 \end{bmatrix} \tag{5}$$

where A is the linear matrix of the system, B the control matrix and g the nonlinear matrix of the system.

Fig. 4 shows the state variables varying with time without control, when $u_1 = u_2 = u_3 = 0$.

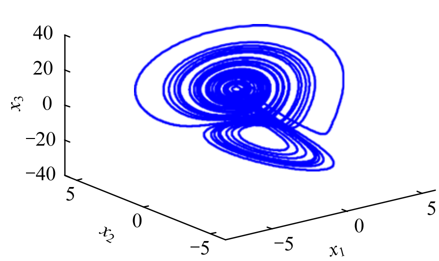

Fig. 1. Three-dimensional phase diagram.

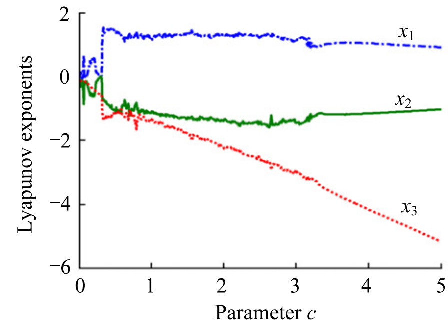

Fig. 2. Lyapunov exponential spectrum.

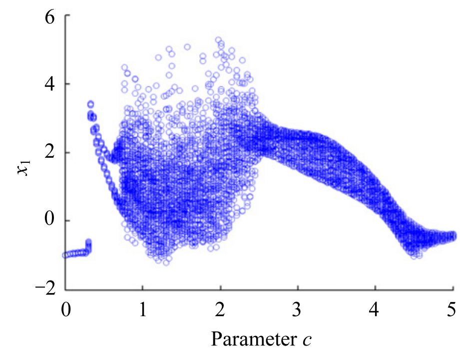

Fig. 3. Bifurcation diagrams of PMSM.

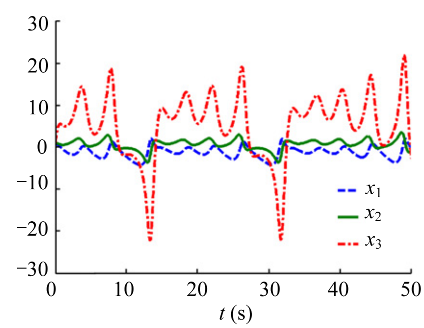

Fig. 4. Time response of the state variables.

The purpose of the control is to make the system state variable $x = [x_1, x_2, x_3]^T$ follow a time-varying state variable $x_d = [x_{d1}, x_{d2}, x_{d3}]^T$. Thus, the tracking errors can be described as:

$$e = x - x_d \tag{6}$$

Then, the errors dynamical system can be written as:

$$\dot{e} = \dot{x} - \dot{x}_d = \boldsymbol{A}x + \boldsymbol{B}g + \boldsymbol{B}d + \boldsymbol{B}u - \dot{x}_d \tag{7}$$

At the same time, the time-varying PI sliding surface can be defined as $S = S(e, t)$:

$$\boldsymbol{S} = \boldsymbol{K}e - \int_0^t \boldsymbol{K}(\boldsymbol{A} - \boldsymbol{BL})e(\tau)d\tau \tag{8}$$

where the additional matrix is $\boldsymbol{K} \in R^{3\times3}$ and $\det(\boldsymbol{KB}) \neq 0$. In order to facilitate the calculation, we set $\boldsymbol{K} = diag(1, 1, 1)$; so the additional matrix $L \in R^{3\times3}$ and $\boldsymbol{A} - \boldsymbol{BL}$ must be a negative definite matrix, and $S = \dot{S} = 0$ must be met in the sliding mode.

To satisfy the sliding conditions, the control strategy can be designed as follows:

$$\boldsymbol{u} = -[g + \boldsymbol{L}e] - (\boldsymbol{KB})^{-1}[\boldsymbol{KA}x_d - \boldsymbol{K}\dot{x}_d] - (\boldsymbol{KB})^{-1}[\varepsilon + \|\boldsymbol{KB}g\|]sign(S) \tag{9}$$