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Robust finite-time chaos synchronization of uncertain permanent magnet synchronous motors ☆

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ABSTRACT

In this paper, a robust finite-time chaos synchronization scheme is proposed for two uncertain third-order permanent magnet synchronous motors (PMSMs). The whole synchronization error system is divided into two cascaded subsystems: a first-order subsystem and a second-order subsystem. For the first subsystem, we design a finite-time controller based on the finite-time Lyapunov stability theory. Then, according to the backstepping idea and the adding a power integrator technique, a second finite-time controller is constructed recursively for the second subsystem. No exogenous forces are required in the controllers design but only the direct-axis (d-axis) and the quadrature-axis (q-axis) stator voltages are used as manipulated variables. Comparative simulations are provided to show the effectiveness and superior performance of the proposed method.

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1. Introduction

Over the past decades, chaos control and synchronization have been intensively studied in various fields such as salt-water oscillators, semiconductor lasers, power electronics and secure communications [1–5]. In the field of power electronics, chaos phenomenon was firstly addressed in the motor drive systems by Kuroe and Hayashi in the late 1980s [6]. Since then, numerous research has been investigated to focus on the discovery and control of chaos in several types of motor drive systems, e.g., step motors, induction motor drives, DC motor drives, synchronous reluctance motor drives, switched reluctance motor drives and so on [7–11].

Due to the properties of higher efficiency, larger power density, and lower manufacturing cost, permanent magnet synchronous motor (PMSM) has been widely used in industrial applications. In [12,13], the PMSM systems with smooth-air-gap ($L_d = L_q$) and non-smooth-air-gap ($L_d \neq L_q$) were shown to behave in chaotic manners when system parameters were fallen into certain areas, respectively. Since the chaotic behavior has an effect on the stability of the motor system, the control and synchronization of the chaos in PMSM systems become important tasks and thus various control approaches have been proposed. In [14], a time delay feedback scheme was successfully implemented to control the chaos in PMSM. But it may not work when the desired target is other than the equilibrium or an unstable periodic orbit of the system. Wei et al. [15] developed an adaptive dynamic surface control of chaos in PMSM. Zhang and Ding [16] proposed an adaptive control to achieve the chaos synchronization in two PMSMs. The Lyapunov exponent control for the chaos in PMSM was investigated in [17–19]. However, the parametric uncertainties and external disturbances, which are usually encountered in practical situations, are not taken into account in most research works shown above.

To enhance the robustness of chaos control and synchronization in the PMSM, some robust methods are investigated [20–23]. In [20,21], robust linear and nonlinear feedback controls were implemented for the set-point control and tracking control of chaos in PMSM, respectively. Ahmad [22] developed a nonlinear sliding mode control to eliminate the chaotic oscillators in the PMSM and Yu et al. [23] proposed an adaptive fuzzy control for the chaotic PMSM with uncertain nonlinearities. In those approaches aforementioned, asymptotic stabilities of chaotic PMSM systems are guaranteed and thus the system states can converge to the desired trajectories or equilibriums as time goes to the infinity.

The concept of finite time stability (FTS) can date back to 1960s. It means that given a bound on the initial condition, the states will stay within a prescribed bound during a specified time interval. In [24,25], sufficient conditions for FTS and finite-time stabilization

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of continuous-time linear time-invariant systems were provided by using state feedback and output feedback, respectively. Recently, alternative definition of FTS was proposed by Bhat and Bernstein [26]. Different from the definition in [24,25], the finite time stability in [26] means the finite-time convergence of system responses based on the Lyapunov stability, and some relevant results are discussed in [27,28].

In contrast to the classical asymptotic stability, the finite-time stability requires that a control system be stable and the tracking errors tend to zero within a finite time. It was demonstrated that finite-time stable systems could own better robustness and disturbances rejection properties. Lately, some finite-time control approaches have been presented for stabilizing and synchronizing the chaotic systems, e.g., [29–34]. However, to the best of our knowledge, most of the existing finite-time controllers are mainly with complex structures and the same order with the chaotic systems. Thus, these methods aforementioned may not be used directly in the control and synchronization of chaotic PMSMs because they require an exogenous force to be an input to the differential equation of velocity. The accessible variable in the differential velocity equation is the external torque, which is difficult to be used as the manipulated variable [21]. In view of the above observation, it is a valuable and challenging work to investigate a finite-time chaos control and synchronization scheme for uncertain PMSM systems with simple controller structures.

Inspired by the previous work, this paper focuses on the robust finite-time chaos synchronization between two third-order PMSMs with two simple controllers in the presence of parametric uncertainties and external disturbances. The whole synchronization error system is divided into two cascaded subsystems and a novel virtual error variable is employed to transform the second-order error subsystem into a canonical form. Then, two continuous controllers are designed to achieve the finite-time convergence of both error subsystems based on the Lyapunov finite-time stability analysis by employing a power integrator.

The main contribution of this paper is that the proposed control law ensures that the finite-time chaos synchronization of two uncertain third-order PMSMs can be achieved in the presence of parametric uncertainties and external disturbances. The finite-time controllers are designed by only using the d-axis and the q-axis stator voltages as manipulated variables. They do not rely on an exogenous force to be an input to the differential equation of velocity, which can be applied in PMSM systems more effectively and conveniently.

The rest of the paper is organized as follows. Section 2 provides the descriptions of chaotic PMSM systems and the cascade synchronization error systems. In Section 3, finite-time controllers design is proposed and the finite-time stability of the closed-loop system is analyzed based on Lyapunov stability theory. Simulation results are shown in Section 4 and the conclusion is given in Section 5.

2. Problem statement and preliminaries

2.1. Chaotic model of PMSM

The dynamic model of PMSM on the d–q-axis described in [12] is given as

$$\begin{cases} \dfrac{di_d}{dt'} = \dfrac{1}{L_d}(u_d - Ri_d + \omega L_q i_q), \\ \dfrac{di_q}{dt'} = \dfrac{1}{L_q}(u_q - Ri_d - \omega L_d i_d - \omega\psi_r), \\ \dfrac{d\omega}{dt'} = \dfrac{1}{J}(n_p\psi_r i_q + n_p(L_d - L_q)i_d i_q - T_L - \beta\omega), \end{cases} \tag{1}$$

where i_d, i_q and u_d, u_q are the d-axis and q-axis stator currents and voltages, respectively; L_d, L_q are the d-axis and q-axis stator inductances and R corresponds to the stator resistance; J is the polar moment of inertia; β is the viscous friction constant; ψ_r is the rotor magnetic flux linking the stator and n_p is the number of pole-pairs; T_L represents the external load torque and ω corresponds to the rotor angular velocity.

By employing an affine transformation

$$(\tilde{\cdot}) = \lambda^{-1}(\cdot), \tag{2}$$

and a time-scaling transformation

$$t = \frac{R}{L_q}t', \tag{3}$$

where

$$\lambda = \begin{bmatrix} \tau k & 0 & 0 \\ 0 & k & 0 \\ 0 & 0 & \frac{R}{L_q} \end{bmatrix}, \quad \tau = \frac{L_d}{L_q}, \quad k = \frac{\beta R}{L_q n_p \psi_r},$$

$$\gamma = -\frac{\psi_r}{kL_q}, \ \sigma = \frac{\beta L_q}{RJ}, \ \varepsilon = \frac{n_p \tau L_q^2 k^2 (L_d - L_q)}{JR^2},$$

$\tilde{u}_d = \frac{u_d}{Rk}$, $\tilde{u}_q = \frac{u_q}{Rk}$ and $\tilde{T}_L = \frac{L_q^2 T_L}{JR^2}$, then system (1) can be transformed to the following form which is more suited for control-design purpose:

$$\begin{cases} \dfrac{d\tilde{i}_d}{dt} = -\tilde{i}_d + \tilde{\omega}\tilde{i}_q + \tilde{u}_d, \\ \dfrac{d\tilde{i}_q}{dt} = -\tilde{i}_q - \tilde{\omega}\tilde{i}_d + \gamma\tilde{\omega} + \tilde{u}_q, \\ \dfrac{d\tilde{\omega}}{dt} = \sigma(\tilde{i}_q - \tilde{\omega}) + \varepsilon\tilde{i}_d\tilde{i}_q - \tilde{T}_L, \end{cases} \tag{4}$$

where $\tilde{i}_d$, $\tilde{i}_q$ are the transformed d-axis and q-axis stator currents, respectively; $\tilde{\omega}$ is the transformed angle speed of the motor; $\tilde{u}_d$, $\tilde{u}_q$ are the transformed d-axis and q-axis stator voltages, respectively; $\tilde{T}_L$ is the transformed external load torque; σ and γ are system parameters.

The bifurcation and chaos phenomenon of system (4) are studied in the literatures [12–23]. It has been found that the PMSM experiences chaotic behavior when the initial conditions of system states and the operating parameters σ and γ fall in a certain area. For example, in the case of $\tilde{u}_d(0) = 0$, $\tilde{u}_q(0) = 0$, $\tilde{T}_L = 0$, $\sigma = 5.46$, $\gamma = 20$, $(\tilde{i}_d(0), \tilde{i}_q(0), \tilde{\omega}(0) = (20, 0.01, -5))$ or $(\tilde{i}_d(0), \tilde{i}_q(0), \tilde{\omega}(0) = (0.1, 0.1, 0.1)$, the system is chaotic. This case can be considered as that, after a period of operation, the external inputs of the system are removed. For more details on the bifurcation criterion and chaotic analysis, we refer to [12,13].

In this paper, we investigate the robust finite-time synchronization problem between the drive and response PMSMs with smooth air gap, *i.e.*, $L_d = L_q$ and $\varepsilon = 0$. For simplicity, let $x_1 = \tilde{i}_d$, $x_2 = \tilde{i}_q$ and $x_3 = \tilde{\omega}$, and the system (4) can be rewritten as

$$\begin{cases} \dot{x}_1 = -x_1 + x_2 x_3 + \tilde{u}_d, \\ \dot{x}_2 = -x_2 - x_1 x_3 + \gamma x_3 + \tilde{u}_q, \\ \dot{x}_3 = -\sigma(x_3 - x_2) - \tilde{T}_L. \end{cases} \tag{5}$$

By considering parametric uncertainties and external disturbances in the determined system (5), the following uncertain chaotic drive PMSM is obtained as

$$\begin{cases} \dot{x}_1 = -x_1 + x_2 x_3 + d_1, \\ \dot{x}_2 = -x_2 - x_1 x_3 + (\gamma + \Delta_1)x_3 + d_2, \\ \dot{x}_3 = -\sigma(x_3 - x_2), \end{cases} \tag{6}$$

where the initial conditions are set as $(x_1(0), x_2(0), x_3(0)) = (20, 0.01, -5)$ and $(\tilde{u}_d, \tilde{u}_q, \tilde{T}_L) = (0, 0, 0)$; $|\Delta_1| \le \Delta_{1m}$ denotes the bounded parametric uncertainty with Δ_{1m} being a positive constant; d_i, $i = 1, 2$ are bounded external disturbances, i.e., $|d_i| \le d_{im}$ with d_{im} positive constants.

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