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Finite-time synchronization control and parameter identification of uncertain permanent magnet synchronous motor ☆

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ABSTRACT

In this paper, the robust finite-time synchronization control and parameter identification problems for uncertain permanent magnet synchronous motor are discussed in detail. Based on finite-time control theory, by using adaptive control approach, a novel adaptive finite-time control scheme is proposed firstly. Then, a robust adaptive finite-time synchronization control method is developed depending on the terminal attractors with updating tuning parameters, which can not only guarantee the synchronization of permanent magnet synchronous motor with uncertain parameters in a shorter finite time, but also can guarantee these uncertain parameters to be identified effectively simultaneously. Finally, some simulation and comparison results are provided to demonstrate the effectiveness and usefulness of the developed results.

1. Introduction

Over the past few decades, chaos control and synchronization have been intensively studied in various fields as witnessed by a variety of publications [1–12], some useful control methods, such as fuzzy control [13–15], sliding mode control [16–18], etc., have been widely used. Among them, chaos control and synchronization in electrical machines has also been an active research topic, because electrical machines are directly used in various industrial applications in the low-medium power range with some superior features, such as compact size, high torque/weight ratio and absence of rotor losses.

Permanent magnet synchronous motor (PMSM), as a kind of complex nonlinear system, which has strong coupling and high dimension. It is found that with certain system parameters, PMSM can exist some interesting dynamic behaviors, such as violent oscillation of speed or torque, the instability of control performance and irregular electromagnetic noise, etc. In 1994, Hemati [19] discovered the chaos phenomena of the open-loop system of permanent magnet motor, Li et al. [20] deduced the universal model and discussed the bifurcation and chaos in PMSM. Actually speaking, the existence of chaotic behavior in PMSM is highly *undesirable* for its performance, in order to eliminate the chaos, chaos control in PMSM has attracted increasing consideration in recent years, various effective control strategies for chaotic PMSM have been presented. In [21], a kind of nonlinear feedback control method was proposed to control the chaos in PMSM. In [22], by using cascaded systems theory, the set-point control problem of PMSM was discussed via linear time-invariant control approach. In [23], the undesirable chaos in PMSM was controlled by using Lyapunov exponents placement. For the other related results, refer to [24,25] and the references therein.

It is worth pointing out that almost all the aforementioned results depend on the accurate information on the parameter and load torque values of PMSM, while in practical applications, PMSMs are subject to system parameter variations and external disturbances in most cases. Thus, most previous PMSM control methods cannot guarantee stability and convergence of speed error responses under inexact information on PMSM parameters, such as the stator resistance, the stator inductance, the rotor inertia, the viscous friction coefficient, the magnetic flux, etc. Considering these, in [26], by using the sliding mode control approach, an adaptive controller design method was proposed for a chaotic PMSM, which removes these restrictive assumptions where accurate information on the PMSM parameter and load torque values are available, thus it has robustness to model uncertainties.

However, although the aforementioned controller designing methods considered the robustness of the system, but did not

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consider the performance of system from the perspective of the optimal time. From the practical engineering point of view, it is more crucial to stabilize chaotic systems in a finite time, that is finite-time stability makes more sense in practice [27–31]. Therefore, it is of importance to consider chaos control in PMSM in an optimal finite time. In recent years, the finite-time stable control and synchronization of chaotic systems have also attracted numerous interest of many researchers [32–35]. In [36], by designing a nonlinear controller, the undesirable chaos in PMSM was controlled in finite time. In [37], an active finite-time stability controller was presented for chaotic PMSM with uncertain parameters. In [42], the authors further discussed finite-time chaos synchronization of PMSM. In [38], the adaptive finite-time stabilization problem was considered to eliminate the chaos in PMSM with uncertain parameters. Generally speaking, for the control and synchronization of PMSM, two important things should be taken into account, one is the practical value of the proposed algorithm, that is the control performance should be achieved in finite time, another one is the proposed algorithm that should be robust to uncertainties. However, to the best of the authors' knowledge, up to now, there are few results considering adaptive finite-time chaos control and synchronization of PMSM by using adaptive feedback control approach, and most of existing results chose to control the direct-axis current i_d firstly or controlling direct-axis current i_d, quadrature-axis current i_q and angular frequency ω together, which need a longer time to be convergent. Based on the above discussion, in this paper, based on finite-time control theory, by introducing into the terminal attractors with updating tuning parameters, different from most of existing results, through controlling the motor angular frequency firstly, novel finite-time chaos control and synchronization strategies will be developed, from which chaos control and robust synchronization of chaotic PMSM would be achieved in a shorter finite time, in addition the uncertain parameters could also be identified simultaneously.

The rest of this paper is arranged as follows. In Section 2, the chaotic PMSM model is presented and some useful lemmas are provided. In Section 3, the novel adaptive finite-time chaos control and robust synchronization strategies are proposed, by which the robustly adaptive synchronization could be realized in a shorter finite time, and the uncertain parameters could also be identified effectively. In Section 4, an illustrative example is provided to illustrate the effectiveness and usefulness of the developed results. At last, this paper completes with a conclusion.

Notations: The notations used in this paper are fairly standard. R^n denotes the n-dimensional Euclidean space, when the size is not relevant or can be determined from the context, the subscripts n or $m \times n$ will be omitted. $A > 0$ means A is a positive definite matrix. $\min\{\ldots\}$ denotes the minimum element in the group. A^{-1} denotes the inverse of matrix A. The notation $\|\cdot\|$ refers to the Euclidean norm.

2. Model description

Without loss of generality, the dimensionless mathematical model of PMSM is considered [20]

$$\begin{cases} \dfrac{di_d}{dt} = -i_d + i_q\omega + \tilde{u}_d, \\ \dfrac{di_q}{dt} = -i_q - i_d\omega + \gamma\omega + \tilde{u}_q, \\ \dfrac{d\omega}{dt} = \sigma(i_q - \omega) - \tilde{T}_L, \end{cases} \tag{1}$$

where i_d, i_q and ω are the state variables denoting the direct-axis and quadrature-axis currents and angular frequency of the motor, respectively. $\tilde{u}_d$ and $\tilde{u}_q$ are the direct-axis and quadrature-axis stator voltage components, respectively, $\tilde{T}_L$ is the load torque. σ and γ are two positive scalars denoting the system operating parameters.

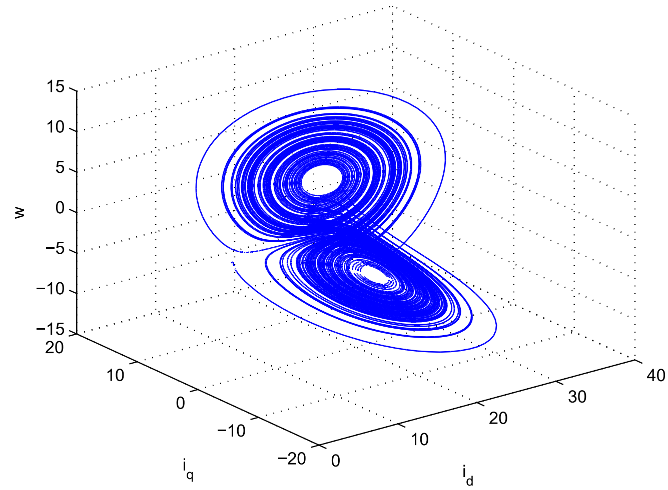

Fig. 1. Chaotic attractor in (x, y, z)-space.

After an operating period, the external inputs of the systems are supposed to be zero, that is $\tilde{u}_d = \tilde{u}_q = \tilde{T}_L = 0$, then the unforced system can be described by

$$\begin{cases} \dfrac{di_d}{dt} = -i_d + i_q\omega, \\ \dfrac{di_q}{dt} = -i_q - i_d\omega + \gamma\omega, \\ \dfrac{d\omega}{dt} = \sigma(i_q - \omega). \end{cases} \tag{2}$$

It is known that the PMSM model with non-smooth air-gap (2) is a nonlinear system with a strong coupling, if choosing some specific parameters and working conditions, this nonlinear system can exist a complex chaotic behavior [20]. For example, if given $\sigma = 5.46, \gamma = 25$ and the initial condition $(i_d(0), i_q(0), \omega(0)) = (5, 1, -1)$, the chaotic behavior can be found in Fig. 1.

The main purpose of this paper is to eliminate the chaos in PMSM by using the adaptive finite-time controller in advance, then discuss the robust finite-time synchronization and parameter identification problems. The following definition and lemma are introduced in advance, which will be used in the proof of main results.

Definition 1. [39] Consider the following nonlinear dynamic system

$$\dot{x} = f(x), \tag{3}$$

where $x \in R^n$ is the system state, f is a smooth nonlinear function. If there exists a constant $t^* > 0$ (t^* may depend on the initial condition $x(0)$), such that

$$\lim_{t \to t^*} \|x(t)\| = 0,$$

and $\|x(t)\| \equiv 0$, if $t \geq t^*$, then system (3) is called stable in finite time.

Lemma 1. *[40] If there exists a positive-definite function V(t) satisfies*

$$\dot{V}(t) \leq -cV^{\beta}(t), \ \forall t \geq t_0, \quad V(t_0) \leq 0,$$

where $c > 0$ and $0 < \beta < 1$ are two constants. Then for any initial time t_0, $V(t)$ satisfies

$$V^{1-\beta}(t) \leq V^{1-\beta}(t_0) - c(1-\beta)(t - t_0), \quad t_0 \leq t \leq t_1,$$