ISA Transactions 58 (2015) 635–649

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Speed tracking and synchronization of multiple motors using ring coupling control and adaptive sliding mode control

Le-Bao Li [a,b], Ling-Ling Sun [b,*], Sheng-Zhou Zhang [a,b], Qing-Quan Yang [a,b]

[a] College of Electrical Engineering, Zhejiang University, Hangzhou 310027, China
[b] Key Laboratory of RF Circuits and Systems, Ministry of Education, Hangzhou Dianzi University, Hangzhou 310018, China

ARTICLE INFO

Article history:
Received 9 May 2015
Received in revised form
27 June 2015
Accepted 14 July 2015
Available online 5 August 2015
This paper was recommended for publication by Jeff Pieper.

Keywords:
Ring coupling control
Synchronization control
Permanent magnet synchronous motor
Adaptive sliding mode control

ABSTRACT

A new control approach for speed tracking and synchronization of multiple motors is developed, by incorporating an adaptive sliding mode control (ASMC) technique into a ring coupling synchronization control structure. This control approach can stabilize speed tracking of each motor and synchronize its motion with other motors' motion so that speed tracking errors and synchronization errors converge to zero. Moreover, an adaptive law is exploited to estimate the unknown bound of uncertainty, which is obtained in the sense of Lyapunov stability theorem to minimize the control effort and attenuate chattering. Performance comparisons with parallel control, relative coupling control and conventional PI control are investigated on a four-motor synchronization control system. Extensive simulation results show the effectiveness of the proposed control scheme.

1. Introduction

Permanent magnet synchronous motor (PMSM) drives play a vitally important role in high performance motion control fields [1,2]. In many industrial applications, in order to get better product quality, reduce contouring error and improve the system's safety, multiple motors must be controlled in a synchronous manner, including microelectronics, aerospace, solar cell, and flat panel manufacturing and inspection [3,4]. In the running process, multiple motors are arranged to track the desired trajectories while keeping their speed the same [5]. Although identical driving equipment would be selected at the design stage, synchronization performance of system may be deteriorated by system parameter variations and load torque perturbations [6]. Poor synchronization accuracy will lower the quality of work pieces or even result in unusable products [5,7]. Hence, good synchronization performance of multiple motors control system is very important in the field of modern manufacture.

The common synchronous control strategies used in multi-motor drive system are the parallel control, the master/slave control, the virtual-shaft control, the cross-coupling control, the relative coupling control and so on [4,8–10]. For the parallel control strategy, Ref. [10] points out that all motors can follow the reference signal completely, but synchronization performance becomes poor when a motor is disturbed. In the master/slave control method, slave motor lags behind its master, so there is a large synchronization error during the startup and shutdown periods [5]. In order to get the reference signal of motor, the system input needs passing through the virtual axis in the virtual-shaft control method, which makes motor's reference signal and the system input signal are not necessarily equal [11]. The cross-coupled control strategy is initially proposed and successfully applied to computer numerical control (CNC) biaxis motion control by Koren [5,12]. Nonetheless, Ref. [13] points out that there exist difficulties to extend this method for more than two motors. Many references had proved that the relative coupling control strategy had indeed better synchronization control performance over the last decades. However, Ref. [14] points out that with the increasing number of motor, the complexity of system control structure is also increasing. For reduction of the control complexity, researchers have proposed some new coupling synchronization control strategies for multiple motors in recent years, such as adjacent cross-coupling control [6] and ring coupling control strategy [15]. Considering an n-motor system, $3n$-controller needs to be designed in adjacent cross-coupling control system, but $2n$-controller needs to be developed in ring coupling control system [16]. So, these control strategies not merely ensure the synchronization performance of multi-motor control system but also simplify the control structure at the same time.

* Corresponding author. Tel.: +86 51786919167.
E-mail addresses: lilebao0305@gmail.com (L.-B. Li), sunll@hdu.edu.cn (L.-L. Sun), szzhang@zju.edu.cn (S.-Z. Zhang), 185594088@qq.com (Q.-Q. Yang).

http://dx.doi.org/10.1016/j.isatra.2015.07.010

To improve synchronization control precision of multiple motors, synchronous control algorithms are also further studied by researchers, such as adaptive feedforward control [17], H_∞ control [4], sliding mode control (SMC) [18], fuzzy control [19] and so on. When the system subjects to random disturbances and parameter variations, synchronization performance and stability of multiple motors control system become poor. So robustness of control system is an important aspect when choosing synchronization control algorithm of multiple motors. SMC has many attractive features such as: 1) it is robust to parameter variations and model uncertainties and insensitivity to external load disturbance; 2) it offers a fast dynamic response, and stable control system; 3) it can handle some nonlinear systems that are not stable by using linear controller; and, 4) it requires an easy hardware/software implementation [20–22]. Thus, SMC is suitable for multi-motor synchronization control system. Ref. [6] proposes an adjacent cross coupling control architecture incorporating a SMC method, which can make speed tracking errors and speed synchronization errors converge to zero. Ref. [16] has successfully combined the ring coupling control strategy with SMC in the synchronization control system of multiple motors, but it merely considers the speed change caused by the parameters uncertainties and the chattering is not eliminated. And the control effort cannot be minimized due to the lack of knowledge of lumped uncertainty among these studies. The assumption of known uncertainty bounds is necessary to design the proposed sliding mode control system [23]. In the previous works [24], a recurrent radial basis function network (RRBFN) uncertainty observer is designed to estimate the bound of lumped uncertainty. But, the disadvantages of the structure are complex network structure and inference mechanism. Therefore, to overcome the disadvantages of the aforementioned SMC, a new adaptive sliding mode controller (ASMC) is developed for multiple motors synchronization control system in this paper, which can minimize the control effort and attenuate chattering.

In this paper, a ring coupling adaptive sliding mode control (ASMC) system is proposed for the synchronization control of multiple PMSMs. In this approach, an adaptive law is developed to estimate the unknown bound of uncertainty which is obtained in the sense of Lyapunov stability theorem to minimize the control effort and attenuate chattering. The proposed synchronization control method in this study is to stabilize speed tracking errors and synchronization errors to zero. The organization of the present paper is as follows. The mathematical model of PMSM is introduced in Section 2. The adaptive sliding mode speed controller based on ring coupling control structure is designed and the associated stability analysis is presented in Section 3. Simulation results conducted on a four-motor system are given in Section 4. Section 5 gives the conclusion.

2. Mathematical model of PMSM

The mathematics model of a PMSM can be described in the rotor rotating reference frame as follows [25–27]:

$$\begin{cases} u_q = R_s i_q + \dot{\lambda}_q + \omega_e \lambda_d \\ u_d = R_s i_d + \dot{\lambda}_d - \omega_e \lambda_q \\ \lambda_q = L_q i_q \\ \lambda_d = L_d i_d + \psi_f \\ \omega_e = n_p \omega \end{cases} \tag{1}$$

where u_d and u_q are d-axis and q-axis stator voltages, respectively; i_d and i_q are d-axis and q-axis stator currents, respectively; R_s is stator resistance. λ_d and λ_q are d-axis and q-axis stator flux linkages, respectively; L_d and L_q are d-axis and q-axis inductances,

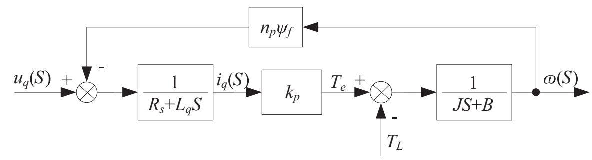

Fig. 1. Dynamic block diagram of PMSM.

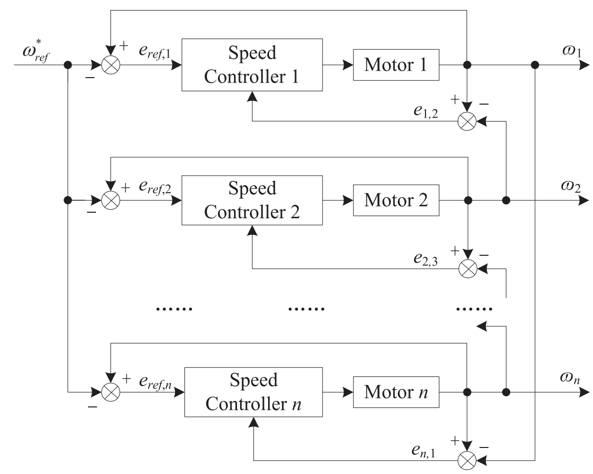

Fig. 2. Schematic diagram of ring coupling control strategy.

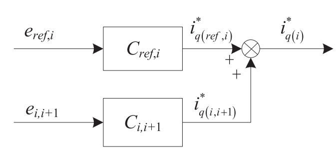

Fig. 3. Structure diagram of the speed controller.

respectively; ψ_f is rotor flux. ω_e is the rotor electrical angular velocity; ω is the rotor mechanical angular velocity; n_p is the number of pole pairs.

The equation of electromagnetic torque is described as

$$T_e = \frac{3n_p[\psi_f i_q + (L_d - L_q) i_q i_d]}{2} \tag{2}$$

Motor dynamics is presented as

$$J\dot{\omega}(t) + B\omega(t) = T_e - T_L \tag{3}$$

where T_e is the electromagnetic torque of motor; T_L is the load torque; J is moment of inertia; B is the viscous friction coefficient.

By using the field-oriented mechanism with $i_d = 0$ [25], we can have

$$\begin{aligned} T_e &= k_p i_q \\ k_p &= \tfrac{3n_p\psi_f}{2} \end{aligned} \tag{4}$$

So, the dynamic block diagram of PMSM is shown in Fig. 1. Substituting (4) into (3) yields

$$\dot{\omega}(t) = -\frac{B}{J}\omega(t) + \frac{k_p}{J} i_q(t) - \frac{T_L}{J} \tag{5}$$

The rotor mechanical motion equation of the ith-motor can be rewritten as

$$\dot{\omega}_i(t) = a_i \omega_i(t) + b_i i_{q(i)}(t) + c_i T_{L(i)} \tag{6}$$