ARTICLE IN PRESS

ISA Transactions ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

ISA Transactions

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

Research Article

Mean deviation coupling synchronous control for multiple motors via second-order adaptive sliding mode control

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ARTICLE INFO

Article history:
Received 8 November 2015
Received in revised form
3 January 2016
Accepted 20 January 2016

Keywords:
Mean deviation coupling
Synchronization control
Permanent magnet synchronous motor
Second-order adaptive sliding mode control
Synchronization error

ABSTRACT

A new mean deviation coupling synchronization control strategy is developed for multiple motor control systems, which can guarantee the synchronization performance of multiple motor control systems and reduce complexity of the control structure with the increasing number of motors. The mean deviation coupling synchronization control architecture combining second-order adaptive sliding mode control (SOASMC) approach is proposed, which can improve synchronization control precision of multiple motor control systems and make speed tracking errors, mean speed errors of each motor and speed synchronization errors converge to zero rapidly. The proposed control scheme is robustness to parameter variations and random external disturbances and can alleviate the chattering phenomena. Moreover, an adaptive law is employed to estimate the unknown bound of uncertainty, which is obtained in the sense of Lyapunov stability theorem to minimize the control effort. Performance comparisons with master–slave control, relative coupling control, ring coupling control, conventional PI control and SMC are investigated on a four-motor synchronization control system. Extensive comparative results are given to shown the good performance of the proposed control scheme.

1. Introduction

In many industrial applications, such as distributed paper-making, continuous rolling mills and manufacturing assembly [1], the load is often driven by two or more motors simultaneously. The motors can be designed to track the given trajectory and keep their speed the same during the running process [2]. It has been recognized that the synchronization performance of system may be degraded by some factors such as system parameter variations and external disturbances in the system, and the synchronization error will affect the quality of the work pieces and even lead to stop of the working process [3,4]. So, good synchronization performance of multiple motor control systems can be obtained while there are various uncertainties and perturbations, which has become a challenge due to the increasing demand for rapid response and high accuracy manufacture and inspection. Over the past few decades, several different synchronization control strategies for multiple motor drive systems have been proposed, which mainly consist of the master–slave control, the virtual-shaft control, the cross-coupling control, the relative coupling control, the adjacent cross-coupling control , ring coupling control and so on [1,5–13].

The master–slave control strategy has a simple control structure [14], which sets one motor as master and the other motors as slaves, and makes the slaves track the response of the master. The disturbances on the master will be conducted to the slaves, but the reverse is impossible [15]. In the virtual-shaft control strategy, the system input needs passing through the virtual axis to get the reference signal of motor, which results in the unequal between motor's reference signal and the system input signal [16,17]. Cross-coupling control strategy [6,10,18–20] utilizes the difference in speed response between two motors as an additional feedback tracking signal. But it is difficult to extend the method for more than two motors. To overcome this limitation, some improved synchronization control strategies have been presented, which include the relative coupling control, adjacent cross-coupling control and ring coupling control.

The relative coupling control has indeed better synchronization control performance , but when the number of motor is n ($n > 2$), n^2-controller needs to be designed [21]. Thus the complexity of system control structure is also increasing with the increasing number of motors [22]. In order to reduce complexity of multiple motor synchronization control systems, adjacent cross-coupling control strategy [1] and ring coupling control strategy [9] are proposed by some researchers. When the number of motor is n,

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http://dx.doi.org/10.1016/j.isatra.2016.01.015
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3n-controller needs to be devised in adjacent cross-coupling and 2n-controller in ring coupling control system [23]; hence, these control methods can reduce the control complexity. However, they just use the speed of adjacent motor as feedback compensation, which may result in the unequal response of all motors due to the conduction delay of the speed change [15]. Therefore, to overcome the disadvantages of the aforementioned multiple motor synchronization control strategies, a new multiple motors synchronization control strategy is developed, which can ensure the synchronization performance of multiple motors and reduce complexity of the control structure with the increasing number of motors.

A typical multiple motors synchronization control scheme consists of a synchronization control strategy to calculate the errors and a control algorithm to improve synchronization control precision. Many control algorithms have been proposed, such as traditional PID control [24], adaptive feedforward control [14,25], H_∞ control [6], iterative learning control [26], sliding mode control (SMC) [2,8,11,27,28], fuzzy control [29], neural network control [30] and so on. When the system subjects to random disturbances, mismatched drive dynamics and parameters variation [31], the synchronization performance and stability of multiple motor control systems become poor. It is well known that SMC system is robust to parameter variations and model uncertainties and insensitivity to external disturbance once the system trajectory reaches and stays on the sliding surface [32–34]. Therefore, SMC is suitable for multiple motor synchronization control systems to improve synchronization control precision. In general, to guarantee the robustness of the SMC, a large switching control gain will be used. But, it often leads to chattering phenomena which are caused by the switching (sign) function [35]. To attenuate the chattering, the sign function in traditional SMC is often replaced by the saturation function. Although the chattering can be mitigated by using saturation function, good control performance cannot be guaranteed and an indefinite steady-state error is also caused by using the selection of the boundary layer [36,37]. Another method to eliminate chattering is to diminish the switching control gain; however, the robustness of the SMC becomes poor because it is not strong enough to cope with the uncertainties. To overcome the disadvantages of the traditional SMC, high-order sliding mode controls including the second-order sliding mode control (SOSMC), which not only maintain the advantages of the traditional SMC such as robustness and simplicity, but also alleviate the chattering phenomena, have been proposed in [33,36,38–41]. In addition, the selection of the upper bound of the uncertainty, which contains mechanical parameter variations and external disturbances, has a significant effect on the control performance. Unfortunately, the upper bound of uncertainty is difficult to know in advance in practical applications, and it is very difficult to implement the sliding mode control law practically [36]. Therefore, the assumption of known uncertainty bounds is necessary in the design the SOSMC. In this paper, an adaptive law is developed to estimate the unknown bound of uncertainty to design the SOSMC law, which can minimize the control effort. Thus, to improve the synchronization control precision of multiple motor control systems and ensure the robustness of the SMC to various system uncertainties and external disturbances, a new mean deviation coupling SOASMC scheme is presented for multiple motor synchronization control systems.

Considering the defects of many synchronization control strategy, the mean deviation coupling synchronization control structure of multiple motors is proposed, which can guarantee the synchronization performance of multiple motors and reduce complexity of the control structure with the increasing number of motors. Moreover, SOASMC is applied into mean deviation coupling control structure to improve speed tracking and synchronization control precision of multiple motor control systems. The organization of the present paper is as follows. The mathematical model of permanent magnet synchronous motor (PMSM) is introduced in Section 2. The second-order adaptive sliding mode speed controller based on mean deviation coupling control structure is designed and the associated stability analysis is presented in Section 3. Comparative studies conducted on a four-motor system are given in Section 4. Section 5 gives the conclusion.

2. The mathematical model of PMSM

PMSM has been chosen as plant. The dynamic model of PMSM under rotor field synchronous rotating d–q reference frame can be described as the following differential equations [42–44]

$$\dot{x}_{d,q} = Ax_{d,q} + Bu_{d,q} \tag{1}$$

where

$$A = \begin{bmatrix} -\frac{R_s}{L_d} & 0 & 0 & \frac{p\omega}{L_d} \\ 0 & -\frac{R_s}{L_q} & -\frac{p\omega}{L_q} & 0 \\ -R_s & 0 & 0 & p\omega \\ 0 & -R_s & -p\omega & 0 \end{bmatrix}, B = \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$x_{d,q} = \begin{bmatrix} i_d & i_q & \psi_d & \psi_q \end{bmatrix}^{\mathrm{T}}, u_{d,q} = \begin{bmatrix} u_d & u_q \end{bmatrix}^{\mathrm{T}}$$

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. L_d and L_q are d-axis and q-axis inductances, respectively;, ψ_d and ψ_q are d-axis and q-axis stator flux linkages, respectively; p is the number of pole pairs. ω is the rotor mechanical angular velocity.

The equation of electromagnetic torque is stated as

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

Motor dynamics is presented as

$$\dot{\omega}(t) = -\frac{B}{J}\omega(t) + \frac{1}{J}(T_e - T_{\mathrm{L}}) \tag{3}$$

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; ψ_f is rotor flux.

By using the field-oriented mechanism with $i_d = 0$ [43], we have

$$T_e = k_e i_q(t) \tag{4}$$

$$k_e = \frac{3}{2}p\psi_f \tag{5}$$

Substituting (4) and (5) into (3), the following result can be obtained:

$$\dot{\omega}(t) = -\frac{B}{J}\omega(t) + \frac{1}{J}k_e i_q(t) - \frac{1}{J}T_{\mathrm{L}} \tag{6}$$

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

$$\dot{\omega}_i(t) = -\frac{B_i}{J_i}\omega_i(t) + \frac{1}{J_i}k_{e(i)}i_{q(i)}(t) - \frac{1}{J_i}T_{\mathrm{L}(i)} \tag{7}$$

Set $x_i(t) = \omega_i(t)$, $u_{q(i)}(t) = i_{q(i)}(t)$, $a_i = k_{e(i)}/J_i$, $b_i = -1/J_i$, $c_i = -B_i/J_i$, Eq. (7) can be presented as follows

$$\dot{x}_i(t) = a_i u_{q(i)}(t) + b_i T_{\mathrm{L}(i)} + c_i x_i(t) \tag{8}$$

Please cite this article as: Li L, et al. Mean deviation coupling synchronous control for multiple motors via second-order adaptive sliding mode control. ISA Transactions (2016), http://dx.doi.org/10.1016/j.isatra.2016.01.015