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Position Synchronous Timing Control Method of Multiple Permanent Magnet Servo Motors System

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Abstract. With the needs of production and life and the development of science and technology, Multiple permanent magnet servo motors (MPMSMs) system has been widely used in Computer Numerical Control (CNC) machine tools and intelligent robots. Since the traditional MPMSMs control cannot make the system converge the motor position angle to the desired position within the specified time, this paper designs the Position Synchronous Timing Control method of MPMSMs System. At the same time, the current controller introduces the deadbeat current predictive control. Since there is a one-beat delay between the actual digital system and the control algorithm, the deadbeat current predictive control is compensated by one beat. Compared with the traditional proportional integral (PI) controller, the position synchronization timing control of the MPMSMs system based on Terminal sliding mode control can realize the timing synchronization control of the MPMSM system, and improve the steady-state accuracy and dynamic response of the system.

Keywords: multiple permanent magnet servo motor, permanent magnet synchronous motor, sliding mode control, current predictive control, synchronous timing

1. Introduction

Motors are an indispensable power source in industrial manufacturing and daily life. High-end manufacturing equipment has high requirements for motor control performance. Permanent magnet synchronous motor (PMSM) have the advantages of high torque to inertia ratio, high power density, high efficiency, simple structure, etc., and is widely used in high-precision Computer Numerical Control (CNC) machine tools and intelligent robots and other servo drive fields[1]. With the rapid growth of science, technology and economy, the traditional single motor servo system can no longer meet the requirements of some modern automation equipment. In high-precision CNC machine tools, intelligent manufacturing robots and other applications, multiple motors often need to work together, which forces people to gradually study the servo control of Multiple permanent magnet servo motors (MPMSMs)[2-3].

The current control methods for MPMSMs mainly include non-coupling cooperative control methods and coupled cooperative control methods. Non-coupling cooperative control methods include master reference control, master-slave control and virtual electronic spindle control[4]. Coupling cooperative control methods include cross-coupling control and deviation coupling control. In some special places, high-precision PMSM position servo performance is required to meet the requirements of precise positioning of multiple motors, such as multi-degree-of-freedom manipulators, robots and other special occasions. Commonly used single-motor control strategies are also suitable for MPMSMs control. PMSM control mainly includes direct torque control and vector control. Direct torque control has a small amount of calculation and is easy to implement, but the control effect is not as good as vector control. The vector control of the traditional servo control system is mainly composed of a three-loop structure of position loop, speed loop and current loop. The current mainstream control theories include proportional integral derivative (PID), sliding mode control, predictive control and intelligent control.

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The sliding mode control algorithm is simple, small in calculation, and robust, and is widely used in the field of motor control[5-6]. But in ordinary sliding mode control, it cannot make the following error of the system converge to zero within a specified time, like PID control. In order to achieve the MPMSMs reaching the given position within the specified time, this article elaborates the terminal sliding mode (TSM) control in detail, combined with the deadbeat current predictive control, and designs the multi-motor servo system position synchronization timing control based on the TSM control[7-8]. Compared with the traditional PI control algorithm, it can set the time for the system to reach a given position, and make the position following error converge to zero within the specified time.

In this paper, TSM control is used to design the position controller of MPMSMs system, and the current controller adopts advanced deadbeat current predictive control. Based on the mathematical model of motor and sliding mode control theory, the simulation model of position synchronous timing control of MPMSMs system is established with the help of Matlab / Simulink.

2. MATHEMATICAL MODEL AND SERVO CONTROL PRINCIPLE OF MPMSMS SERVO SYSTEM

2.1. Mathematical Model of MPMSMs System

The MPMSMs system studied in this paper is shown in Fig. 1. The system adopts the parallel structure of multiple sub motors and their driving system. The sub motor adopts PMSM, and each sub motor has its own driver. Therefore, taking the mathematical model of j^{th} sub PMSM (j=1,2,...,n , n is the total number of motors) as an example, the control model of MPMSMs system is analyzed. The mathematical model of single sub PMSM is similar to synchronous motor with rotor excitation winding. Therefore, in order to simplify the mathematical model of PMSM, some factors with small influence are ignored.

The sub-motor is a salient-pole PMSM, and it is assumed that the number of pole pairs (P_n), stator resistance (R), inductance (L_d , L_q), permanent magnet flux linkage (φ_f), moment of inertia (J) and damping coefficient (B) of all sub-motors are equal, according to the previous assumptions and the PMSM basic coordinate transformation formula, the voltage equation of the MPMSMs system in the synchronous rotating d-q coordinate system can be obtained as

$$\begin{cases} u_{dj} = Ri_{dj} + \dfrac{d\varphi_{dj}}{dt} - \omega_{ej}\varphi_{qj} \\ u_{qj} = Ri_{qj} + \dfrac{d\varphi_{qj}}{dt} - \omega_{ej}\varphi_{dj} \end{cases} \tag{1}$$

The stator flux is

$$\begin{cases} \varphi_{dj} = \varphi_f + L_d i_{dj} \\ \varphi_{dj} = L_q i_{qj} \end{cases} \tag{2}$$

The electromagnetic torque is

$$T_{ej} = \frac{3}{2}P_n\left[\varphi_{dj}i_{qj} - \varphi_{qj}i_{dj}\right] = \frac{3}{2}P_n\left[\varphi_f i_{qj} + (L_d - L_q)i_{dj}i_{qj}\right] \tag{3}$$

The equation of motion is expressed as

$$J\frac{d\omega_{mj}}{dt} = T_{ej} - T_{Lj} - B\omega_{mj} \tag{4}$$

In the above (1) ~ (4), j represents the j^{th} motor, u_{dj} , u_{qj} , i_{dj} , i_{qj} , φ_{dj} and φ_{qj} are the motor stator voltage, stator current and the stator flux respectively, ω_{ej} is the electrical angular velocity, ω_{mj} is the mechanical angular velocity of the motor, and T_{Lj} is the load torque.

2.2. MPMSMs Control System

The basic structure diagram of the MPMSMs control system based on vector control is shown in Fig. 1. As the most basic synchronization control, compared with other synchronization control strategies, parallel control has a simple structure, which can control multiple motors at the same time, and the given input signal of each motor is the same, the synchronization effect of the system is good, and the response speed is fast. Each motor unit is independent of each other. When a motor unit is interfered by the outside, it will not cause interference to other motor units, and there is no problem of a motor lagging behind, so it is widely used in industrial occasions.

Each motor unit in Fig. 1 adopts three closed-loop control schemes: position loop, speed loop and current loop. The actual position of the motor can be controlled by the position loop, and the actual speed of the motor can be controlled by the speed loop. The current loop is the core of the entire servo control system, which determines control system and has a decisive effect on the dynamic performance of the system, and its design is critical[9]. The output of the position controller is used as the given input of the speed controller, and the output of the speed controller is used as the given input of the current controller. The vector control strategy of $i_d=0$ is usually used in combination with SVPWM to realize the control of the MPMSMs system. The position loop of the traditional servo control system adopts proportional control, the speed loop and the current loop are use proportional integral (PI) control.

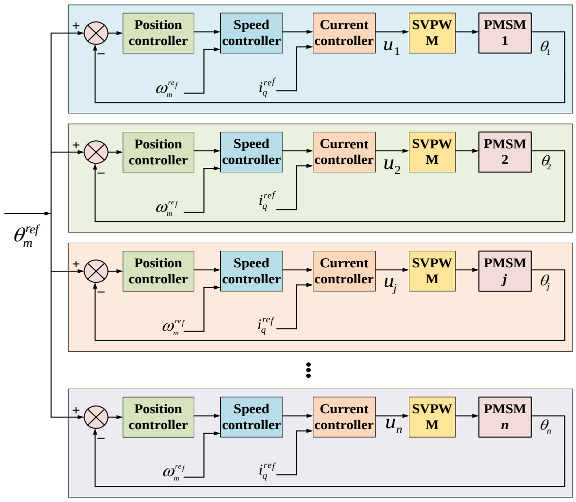


Fig. 1. Control block diagram of MPMSMs system

The reference current component of the d-axis of the motor is $i_{dj}^*=0$. In practical engineering applications, the q reference current component is

$$i_{qj}^* = \left(K_p + \frac{K_i}{s}\right)\left(\omega_{mj}^{ref} - \omega_{mj}\right) \tag{5}$$

where K_p and K_i are the proportional coefficient and differential coefficient of the PI controller, respectively.

The components of the reference voltage vector on the d-axis and q-axis are:

$$u_{qj} = \left(K_p + \frac{K_i}{s}\right)\left(i_{qj}^* - i_{qj}\right) \tag{6}$$

$$u_{dj} = \left(K_p + \frac{K_i}{s}\right)\left(i_{dj}^* - i_{dj}\right) \tag{7}$$

The PI controller is used to decouple the d-axis and q-axis components i_{dj} and i_{qj} of the stator current. u_{dj} and u_{qj} are transformed by Park inverse to generate $u_{\alpha j}$ and $u_{\beta j}$, which are provided to the SVPWM module to output six PWM pulses to drive the power tube. Then, a quasi-circular rotating magnetic field is obtained to generate a three-phase sine wave voltage and current, and the motor is controlled.

3. THE BASIC PRINCIPLE OF SLIDING MODE VARIABLE STRUCTURE

Sliding mode variable structure is a control strategy in variable structure control, and it is a comprehensive method to solve nonlinear system problems. It has the advantages of low accuracy requirements for the mathematical model of the object, self-adaptation to internal perturbation, disturbance of the external environment and changes of system parameters, simple control algorithm, and easy engineering realization.

3.1. TSM Control

Sliding mode variable structure control system is a special kind of nonlinear system whose structure changes constantly during the control process. Sliding mode control uses the discontinuous control law to continuously change the structure of the system along a special hyperplane in the state space, forcing the system state to slide along this plane to the equilibrium point. Eventually, it gradually stabilized at the equilibrium point or within an allowable range.

In order to enable the position loop of the servo control system to reach a given position within a given time, TSM control is introduced.

For a second-order nonlinear system[10]:

$$\begin{cases} \dot{x} = x_1 \\ \dot{x}_1 = f(X,t) + \Delta f(X,t) + bu + d(t) \end{cases} \tag{8}$$

where $X = [x, x_1]$, and $|\Delta f(X,t)| \le F(X,t)$, $|d(t)| \le D$, The control goal is to design sliding mode law, so that the system state variables X can track instructions $X_d = [x_d, \dot{x}_d]$ within a specified time T.

(1) Design of sliding mode switching surface

Suppose the error vector is $E = X - X_d = [\varepsilon \ \ \dot{\varepsilon}]$, and the sliding mode function is designed as

$$s = C(E - Q) \tag{9}$$

where $C = [c, 1]$, $Q = [q(t) \ \ \dot{q}(t)]^T$, c is constant coefficient of sliding mode function. In order to achieve convergence at a specified time T, when t=T, $q(t)=0$, $\dot{q}(t)=0$, $\ddot{q}(t)=0$, the polynomial of the Terminal function constructed is [11-12]

$$q(t)=\begin{cases} \varepsilon(0)+\dot{\varepsilon}(0)t+\frac{1}{2}\ddot{\varepsilon}(0)t^2 \\ -\left(\frac{b_{00}}{(T)^3}\varepsilon(0)+\frac{b_{01}}{(T)^2}\dot{\varepsilon}(0)+\frac{b_{02}}{2T}\ddot{\varepsilon}(0)\right)t^2 \\ +\left(\frac{b_{10}}{(T)^4}\varepsilon(0)+\frac{b_{11}}{(T)^3}\dot{\varepsilon}(0)+\frac{b_{12}}{2(T)^2}\ddot{\varepsilon}(0)\right)t^4 \\ -\left(\frac{b_{20}}{(T)^5}\varepsilon(0)+\frac{b_{21}}{(T)^4}\dot{\varepsilon}(0)+\frac{b_{22}}{2(T)^3}\ddot{\varepsilon}(0)\right)t^5, 0 \le t \le T \\ 0, t > T \end{cases} \tag{10}$$

where $b_{ij}(i, j = 0,1,2)$ is the coefficient, which can be obtained by solving the equation.

(2) Design of TSM controller

Suppose the error is $\varepsilon = x - x_d$, $\dot{\varepsilon} = \dot{x} - \dot{x}_d$, $\ddot{\varepsilon} = \ddot{x} - \ddot{x}_d$, and $\ddot{\varepsilon} = \ddot{x} - \ddot{x}_d = f(X,t) + \Delta f(X,t) + b(X,t)u + d(t) - \ddot{x}_d$, It can be obtained by formula 9:

$$\begin{aligned} \dot{s} &= C(\dot{E} - \dot{Q}) = C[\dot{\varepsilon} \ \ \ddot{\varepsilon}]^T - C[\dot{q} \ \ \ddot{q}]^T \\ &= \dot{\varepsilon} - \dot{q} + c(\ddot{\varepsilon} - \ddot{q}) \\ &= \dot{\varepsilon} - \dot{q} + c(f(X,t) + \Delta f(X,t) \\ &+ bu + d(t) - \ddot{x} - \ddot{q}) \end{aligned} \tag{11}$$

The Lyapunov function is designed as

$$Y = \frac{1}{2}s^2 \tag{12}$$

Then

$$\begin{aligned} \dot{s} &= \dot{\varepsilon} - \dot{q} + c(f(X,t) + \Delta f(X,t) \\ &+ bu + d(t) - \ddot{x} - \ddot{q}) \end{aligned} \tag{13}$$

The controller is designed as

$$u(t) = -\frac{1}{b}(\frac{1}{c}(\dot{\varepsilon} - \dot{q}) + f(X,t) \\ -\ddot{x}_d - \ddot{q} + \mu \operatorname{sgn}(s)) \tag{14}$$

where, the constant μ represents the speed at which the moving point of the system approaches the switching surface s=0, $\mu > 0$.

3.2. Design of Position Loop TSM Controller

In order to make MPMSMs reach a given position at the same time within the specified synchronization time T_m^{ref}, the traditional position loop controller needs to be improved [13]. In this paper, according to the design principle of TSM control, a position loop TSM controller is designed. According to (3) and (4), the following assumption is made:

$$\begin{cases} \dot{x}_{1j} = x_{2j} = \omega_{mj} \\ \dot{x}_{2j} = \dot{\omega}_{mj} = -\frac{B}{J} x_{2j} + \frac{3}{2J} P_n \varphi_f i_{qj} - \frac{1}{J} T_{Lj} \end{cases} \tag{15}$$

The expression of the error vector is

$$E_j = \begin{bmatrix} x_{1j} \\ x_{2j} \end{bmatrix} - \begin{bmatrix} x_{1d} \\ x_{2d} \end{bmatrix} = \begin{bmatrix} \theta_{mj} \\ \omega_{mj} \end{bmatrix} - \begin{bmatrix} \theta_m^{ref} \\ \omega_m^{ref} \end{bmatrix} = \begin{bmatrix} \varepsilon_j \\ \dot{\varepsilon}_j \end{bmatrix} \tag{16}$$

where, θ_{mj} is the real-time rotor position angle of the j^{th} motor, and the angular velocity is ω_{mj}, θ_m^{ref} is the reference position angle of control, and ω_m^{ref} is the reference angular velocity of control. According to the error vector and the synchronization time, the function expression of the sliding mode function is

$$s_j = B\left(E_j - Q_j\right) \tag{17}$$

where $B = \left[b, 1\right]$, $Q_j = \begin{bmatrix} q_j(t) \\ \dot{q}_j(t) \end{bmatrix}$. The function expression of the Terminal polynomial function is

$$q_j(t) = \begin{cases} \varepsilon_j(0) + \dot{\varepsilon}_j(0)t + \frac{1}{2}\ddot{\varepsilon}_j(0)t^2 \\ -\left(\frac{10}{(T_m^{ref})^3}\varepsilon_j(0) + \frac{6}{(T_m^{ref})^2}\dot{\varepsilon}_j(0) + \frac{3}{2T_m^{ref}}\ddot{\varepsilon}_j(0)\right)t^2 \\ +\left(\frac{15}{(T_m^{ref})^4}\varepsilon_j(0) + \frac{8}{(T_m^{ref})^3}\dot{\varepsilon}_j(0) + \frac{3}{2(T_m^{ref})^2}\ddot{\varepsilon}_j(0)\right)t^4 \\ -\left(\frac{6}{(T_m^{ref})^5}\varepsilon_j(0) + \frac{3}{(T_m^{ref})^4}\dot{\varepsilon}_j(0) + \frac{1}{2(T_m^{ref})^3}\ddot{\varepsilon}_j(0)\right)t^5 \\ ,0 \le t \le T_m^{ref} \\ 0, t > T_m^{ref} \end{cases} \tag{18}$$

The sliding mode reaching law adopted is $\dot{s}_j = -ksat(s_j)$, where

$$sat(s_j) = \begin{cases} 1 & s_j > \alpha \\ hs_j & |s_j| \le \alpha \\ -1 & s_j > \alpha \end{cases} \tag{19}$$

where, $sat(s_j)$ represents the symbolic saturation function, k is the saturation function coefficient, $h = 1/\vartriangle\alpha$, $\vartriangle\alpha$ is the boundary layer of the saturation function. Therefore, the output of the position loop TSM controller is

$$i_{qj}^*(t) = -\frac{2J}{3P_n\varphi_f}\left(\begin{array}{l} b\left(\dot{\varepsilon}_j-\dot{q}_j\right)+-\frac{B}{J}\omega_{mj} \\ -\dot{\theta}_{mj}^{ref}-\ddot{q}_j+ksat(s_j)\end{array}\right) \quad (20)$$

According to the above design, MPMSMs can reach a given position within a specified time, and the speed loop controller is omitted, which saves costs. The overall structure block diagram of the servo motor control system of the j^{th} station after improvement is shown in Fig. 2.

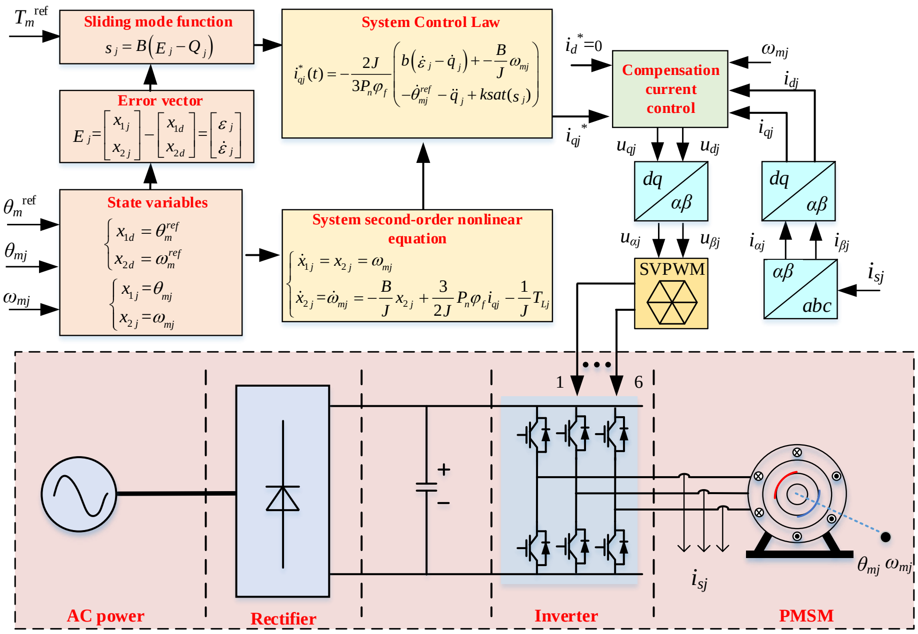


Fig 2. The structure block diagram of the position synchronization timing control of the motor servo system based on TSm control

4. Current Loop Controller Design

The control of the PMSM stator current is essentially the control of the motor output torque, and the ability of system to control the motor current determines the motor torque response performance. Therefore, a current loop with fast following and high control accuracy is the key to the design of high-performance torque control system. The traditional PI controller has simple structure and is easy to implement, but its parameters are not easy to adjust and there are some phenomena such as integral saturation, which is not suitable for complex electromechanical systems. Compared with the traditional PI control, deadbeat current predictive control has faster dynamic response and better steady-state performance. For this reason, the current controller adopts deadbeat current predictive control in this paper. The current loop controller design for the servo motor is as follows. The discrete mathematical model of the j^{th} PMSM is

$$u_j(k) = B^{-1}[i_j(k+1) - M i_j(k) - \varphi] \quad (21)$$

where $M = \begin{bmatrix} 1-\frac{RT_S}{L_d} & \frac{T_sL_q}{L_d}\omega_{ej} \\ -\frac{T_sL_d}{L_q}\omega_{ej} & 1-\frac{RT_S}{L_q} \end{bmatrix}$, $B = \begin{bmatrix} \frac{T_S}{L_d} & 0 \\ 0 & \frac{T_S}{L_q} \end{bmatrix}$, $M = \begin{bmatrix} 0 \\ -\frac{T_s\omega_{ej}}{L_d}\varphi_f \end{bmatrix}$, $i_j(k) = [i_{dj}(k), i_{qj}(k)]^T$, T_s is the sampling period of the current loop. Because there is a one-beat delay between sampling and prediction calculation of the actual digital control system, the reference voltage $u_j(k)$ calculated at time kT_s is used at time $(k+1)T_s$. In order to eliminate the one-beat delay error, the control system uses the $u_j(k+1)$ control command at time $(k+1)T_s$. $u_j(k+1)$ can be expressed as

$$u_j(k+1) = B^{-1}[i_j(k+2) - M i_j(k+1) - \varphi] \quad (22)$$

Therefore, the control commands for the d-axis and q-axis of the deadbeat current predictive control at time $(k+1)T_s$ are

$$\begin{cases} u_{dj}(k+1) = \frac{L_d}{T_s} i_{dj}^*(k+2) + (R - \frac{L_d}{T_s}) i_{dj}(k+1) \\ -L_q \omega_{ej}(k+1) i_{qj}(k+1) \\ u_{qj}(k+1) = \frac{L_q}{T_s} i_{qj}^*(k+2) + L_d \omega_{ej}(k+1) i_{dj}(k+1) \\ +(R - \frac{L_q}{T_s}) i_{qj}(k+1) + \psi_f \omega_{ej}(k+1) \end{cases} \tag{23}$$

where, $\omega_{ej}(k+1)=\omega_{ej}(k)$, $i_{dj}^*(k+2)=i_{dj}^*(k)=0$, $i_{qj}^*(k+2)=i_{qj}^*(k)$.

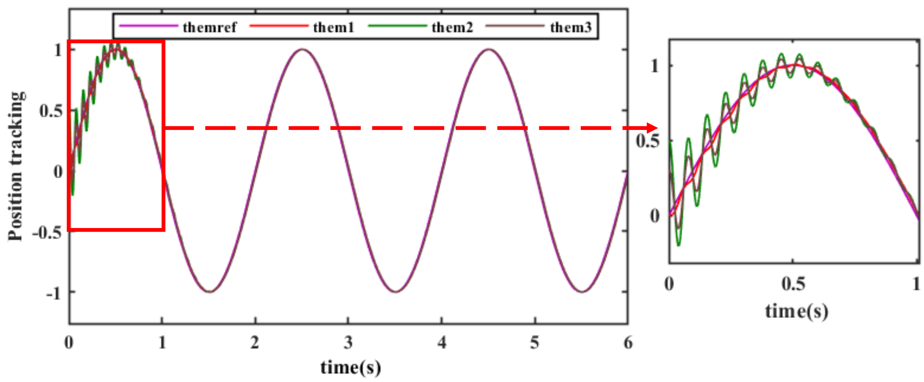
5. Comparison and Discussion of Simulation Result

This article has carried on the simulation verification to the position synchronization timing control of the improved MPMSMs system. The simulation parameters are the same as the three PMSMs, and the specific parameters are shown in Table I. The initial position angles of the three PMSMs are 0rad, 0.5rad, 0.3rad, given the desired position angle is $\theta_m^{ref}=1\sin(\pi t)$. In the figure, themref is θ_m^{ref}, them1, them2 and them3 are the actual mechanical position angles of the motor θ_1, θ_2 and θ_3, respectively. The errors e1, e2 and e3 are $\theta_m^{ref}-\theta_1$, $\theta_m^{ref}-\theta_2$ and $\theta_m^{ref}-\theta_3$, respectively.

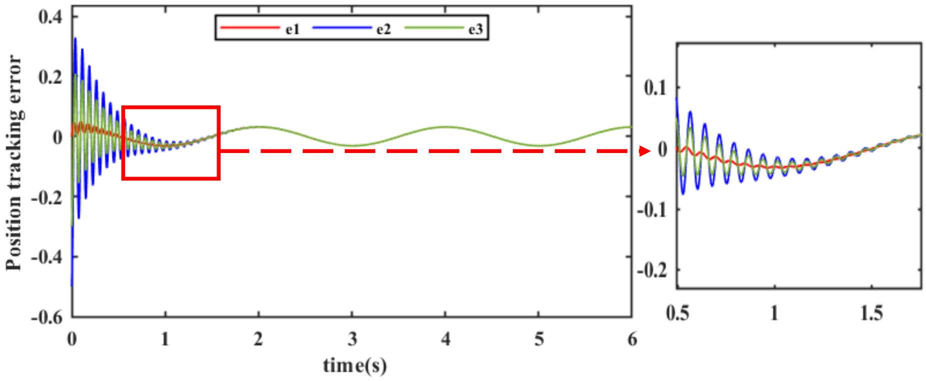
Fig. 3 shows the traditional position loop using a proportional controller and the speed loop and current using a PI controller. The position loop proportional parameter is 100, the speed loop PI parameter is Kp=0.14, Ki=7, the current loop PI parameter is Kp=13.2, Ki=200. Fig. 3 (a) shows the position following response of 3 PMSMs, and Fig. 3 (b) shows the position following error of 3 PMSMs. Although the system has high response speed and steady-state performance, and can achieve synchronous operation, it cannot set the time to reach a given position and synchronous operation, so it cannot meet the needs of some special occasions.

Table 1: Key Parameters of The Adopted PMSM

Parameter	Values
DC voltage	311 V
Stator resistance	0.958 Ω
Number of pole pairs	4
PM flux	0.1827 Wb
Rotational Inertia	0.003 kg.m2
Viscous friction coefficient	0.0008 Nm·s/rad
q-axis inductance	0.012 H
d-axis inductance	0.00525 H



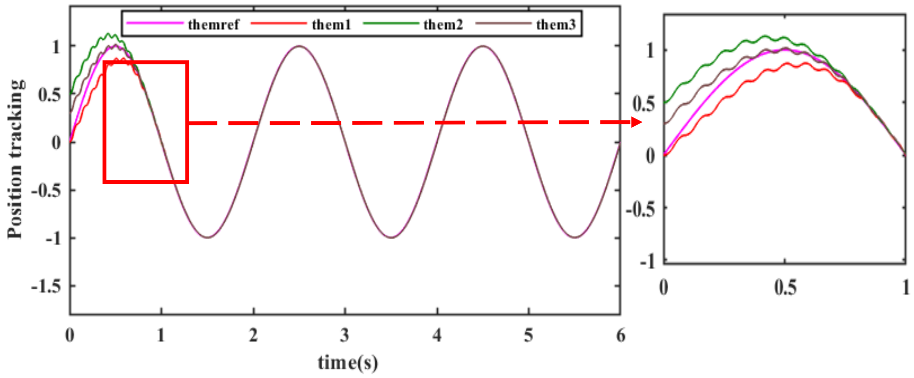
(a) Position following



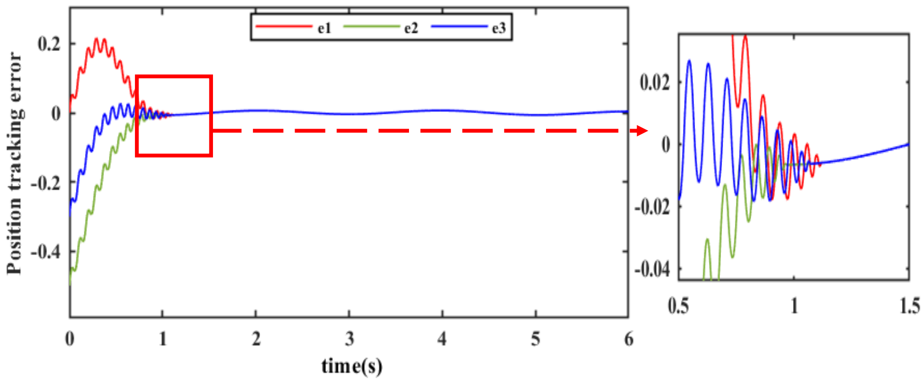
(b) Position following error

Fig. 3. Simulation results of traditional multi-motor servo system.

Fig. 4 is the simulation result of the improved MPMSMs system at T_m^{ref} =1.0. It can be seen from Fig. 4 (a) that when the specified time is 1.0s, multiple motors can track the given desired position angle before 1.0s, and it has been running synchronously since then. Fig. 4 (b) shows that the following error quickly converges to zero at about 1.0s. Compared with the simulation results of the traditional MPMSMs system, the improved following error is smaller and there is almost no chattering. The simulation results of T_m^{ref} =3.0 and T_m^{ref} =5.0 are shown in Fig. 5. The following error is zero, and the following effect is good.

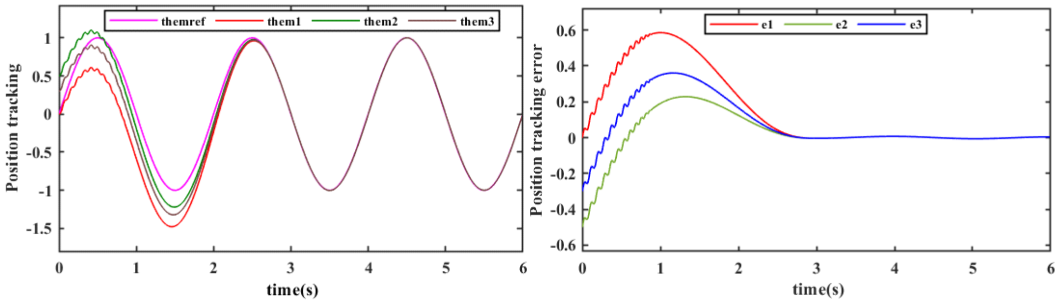


(a) Position following

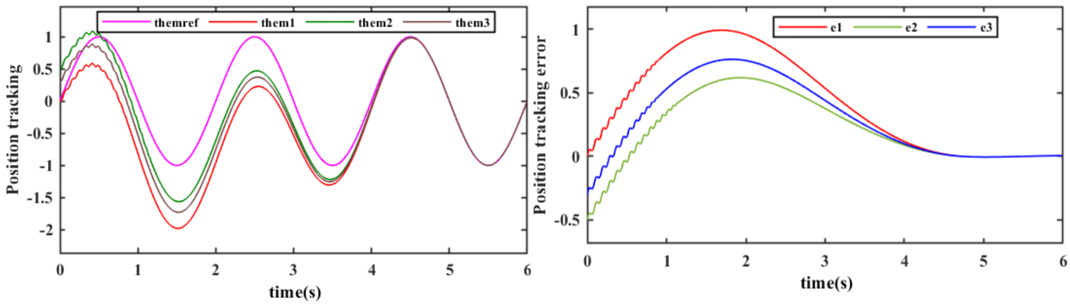


(b) Position following error

Fig 4. Improved simulation results of multi-motor servo system(T_m^{ref} =1.0)



(a) Position following (T_m^{ref} =3.0) (b) Position following error (T_m^{ref} =3.0)



(c) Position following (T_m^{ref} =5.0) (d) Position following error (T_m^{ref} =5.0)

Fig 5. Improved simulation results of multi-motor servo system (T_m^{ref} =3.0, T_m^{ref} =5.0)

6. Conclusion

Based on the PMSM vector control method, this article studies the synchronous timing control of the MPMSMs system. According to the TSM control principle, the position controller of the MPMSMs system is improved, and a current controller with compensation function is designed at the same time. Finally, a simulation comparison is carried out. The simulation indicate that the synchronous timing control of the MPMSMs system designed in this paper can make the MPMSMs reach a given position within a specified time and maintain synchronization, and the system has a good dynamic and steady state performance.

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