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Design of Model Predictive Control System for Permanent Magnet Synchronous Linear Motor Based on Adaptive Observer

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ABSTRACT

In order to improve the reliability of the permanent magnet synchronous linear motor control system and optimize the speed regulation performance of the permanent magnet synchronous linear motor, it is not only necessary to design a controller with good control performance, but also to obtain accurate speed information. However, the traditional current loop PI regulator is highly dependent on the motor parameters, and the installation and use of the speed mechanical sensor will increase the system cost and volume, and the use environment has relatively strict requirements. The current predictive control designed in this paper replaces the traditional current PI control, which can effectively suppress current ripple and improve current tracking performance. The design model refers to an adaptive system instead of a mechanical sensor to achieve accurate online speed recognition. Finally, the control system model established through the simulation environment verifies the superiority of the control strategy. The simulation results show that this control strategy can realize accurate online speed identification, effectively suppress current ripple and improve current tracking performance.

1. Introduction

In recent years, with the development of rare resources and the development of smelting technology, DC motors and AC asynchronous motors are gradually lagging behind the society and are being replaced by permanent magnet synchronous motors. With the continuous development of high-speed processing technology, precision manufacturing technology and numerical control technology and other advanced manufacturing technologies in today's society, permanent magnet synchronous motors are gradually evolving into the current development trend of numerical control equipment. Permanent magnet synchronous linear motor direct drive, as a new driving method widely used in high-precision industrial fields, can not only shorten the response time of the feed system to a large extent, but also improve the control accuracy of the control system [1-2].

High current bandwidth and strong robustness are gradually becoming the development trend of high-precision permanent magnet synchronous linear motor current closed-loop controllers [3]. At present, the main control strategies include hysteresis [4-5] control, PI control, and repetitive control [6] and predictive control [7-9] and other control methods. The model prediction algorithm uses the information in the control system to predict the increment of the control amount in the next few cycles without using the motor parameters, and the most suitable control value is obtained through the calculation of the optimized function [10]. Predictive control algorithms have been widely used in the field of motor control systems. Literature [11-12] applied predictive controllers designed based on motor mathematical models to the permanent magnet synchronous motor control system and asynchronous motor control system, so that the control performance of the control system was improved.

In the motor control system, in order to better reflect the control performance of the controller, the information that the control system feeds back to the controller must be fast and accurate. In order to simplify the volume of the motor control system, reduce installation costs and adapt to various harsh environments, the speed sensorless technology is introduced into the motor control system. Speed sensorless also overcomes the serious shortcomings of mechanical speed sensors, and opens up a new route for the current development of motor control [13]. In the speed sensorless technology, the cutting-edge controller technology is divided into

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the high-frequency signal injection method and the fundamental back-EMF observation method [14-17]. The adaptive observer is a control strategy designed on the basis of stability based on the voltage equation of the motor that can identify the parameters of the motor. The observer designed in the literature [18-19] adjusts the parameters of the estimated mathematical model to make the current difference between the adjustable and the reference model approach zero, keep the parameter estimates gradually converging, and keep it superior in the motor control system and the dynamic performance [17].

This paper designs a predictive current control strategy for permanent magnet synchronous linear motors with adaptive observers. The predictive current controller is designed by using the stator voltage equation to remove the cross-coupling electromotive force, replacing the traditional current controller, and improving the control performance of the motor control system. The reference model of the adaptive observer proposed in this paper is designed using the actual model of the motor, the adjustable model is designed using the estimated current model, and the motor speed can be estimated by designing an adaptive law based on the current difference between the reference model and the adjustable model. Finally, simulation software is used to verify the superiority of the proposed control strategy, and its effectiveness is verified by simulation and experiment.

2. Model predictive controller

In this paper, the voltage equation of the permanent magnet synchronous linear motor in the rotating coordinate system is simplified into two single-input single-output systems [12]. Regarding the cross-coupled electromotive force generated by the stator current in the d-axis and q-axis directions as disturbances, the obtained current control object equation is [13]:

$$\begin{cases} u_d = Ri_d + L\dfrac{d}{dt}i_d \\ u_q = Ri_q + L\dfrac{d}{dt}i_q \end{cases} \tag{1}$$

The cross-coupled electromotive force is:

$$\begin{cases} u_{dc} = -\omega_c L i_q \\ u_{qc} = \omega_c (L i_d + \psi_f) \end{cases} \tag{2}$$

Where R is the stator resistance, τ is the pole moment of the linear motor, υ is the speed of the motor running, u_d and u_q are the voltage components of the d-axis and q-axis, i_d and i_q are the current components of the d-axis and q-axis, L is The inductance components of the d-axis and q-axis, ψ_f is the stator flux linkage.

Formula (1) is expressed in the form of an equation of state:

$$\begin{cases} \dfrac{d}{dt}i_d = -\dfrac{Ri_d}{L} + \dfrac{u_d}{L} \\ \dfrac{d}{dt}i_q = -\dfrac{Ri_q}{L} + \dfrac{u_q}{L} \end{cases} \tag{3}$$

Taking the d-axis as an example, applying the first-order Euler method to discretize equation (4) into:

$$\begin{aligned} i_d(k+1) &= i_d(k) + \left[\frac{R}{L}i_d(k) + \frac{u_d}{L}\right]T_s \\ &= \left[1 + \frac{R}{L}T_s\right]i_d(k) + \frac{T_s}{L}u_d \\ &= Ai_d(k) + Bu_d \end{aligned} \tag{4}$$

where T_s is the sampling time.

The model predictive controller algorithm uses a three-step predictive method, and the implementation process of the algorithm is as follows:

A. Model Prediction

Assuming that the control quantity remains unchanged, both are $u(k)$, the state quantity of the next 2 cycles is predicted in the k-th period to obtain the predicted value of the controlled object, and then considering the change $\Delta u(k)$ of the controlled variable, the predicted value of the controlled object can be obtained [11]:

$$\begin{bmatrix} i_m(k+1|k) \\ i_m(k+2|k) \end{bmatrix} = \begin{bmatrix} i_0(k+\mathbf{1}|k) \\ i_0(k+\mathbf{2}|k) \end{bmatrix} + G\cdot\begin{bmatrix} \Delta u(k) \\ \Delta u(k+\mathbf{1}) \end{bmatrix} \tag{5}$$

In the expression, $G = \begin{bmatrix} B & \\ A\cdot B & B \end{bmatrix}$

B. Feedback Correction

In order to eliminate errors, ensure the accuracy of the predicted value and the robustness of the system [7]. Use feedback correction to correct the error of the predicted value. Assuming that the d-axis and q-axis current components of the k+1 cycle are $i_d(k+1)$ and $i_q(k+1)$ respectively, the correction error is:

$$e(k+1) = i_{d,q}(k+1) - i_m(k+1|k) \tag{6}$$

The corrected current prediction value is:

$$i_p = i_{d,q} + h\cdot e(k+1) \tag{7}$$

Where h is the feedback coefficient.

C. Rolling Optimization

In the current model predictive control of permanent magnet synchronous linear motors, it is assumed that the current given value in the two cycles after the k-th cycle is consistent with the current value:

$$i_r(k+2) = i_r(k+1) \tag{8}$$

In order to obtain the optimal control amount, an evaluation function can be used, which is:

$$\begin{aligned} J(k) = &\sum_{i=1}^{3} q_i\left[i_r(k+1) - i_m(k+i)\right]^2 + \sum_{j=1}^{3} r_j \\ &+\Delta u(k+j-1)^2 \end{aligned} \tag{9}$$

Among them, q_i and r_j are weighting coefficients, which respectively represent the suppression of tracking error and the change of control amount.

Use the solution of $\partial J(k)/\partial \Delta u(k)=0$ to obtain the increments $\Delta u_d(k+1)$ and $\Delta u_q(k+1)$ of the optimal control quantity of the cycle to calculate the optimal control quantity [11]:

$$\begin{cases} u_d(k+1)=u_d(k)+\Delta u_d(k+1) \\ u_q(k+1)=u_q(k)+\Delta u_q(k+1) \end{cases} \tag{10}$$

The cross-coupling electromotive force of formula (2) is used as the feed forward compensation term and superimposed into formula (14):

$$\begin{cases} u^*_d(k+1)=u_d(k+1)+u_{dc}(k+1) \\ u^*_q(k+1)=u_q(k+1)+u_{qc}(k+1) \end{cases} \tag{11}$$

The actual control quantity of the system at k+1 time is $u^*_{d,q}(k+1)$, and in the next forecast period [14], the newly calculated optimal control quantity $u^*_{d,q}(k+2)$ is obtained.

Take the d-axis as an example, the block diagram of the current prediction controller designed is shown in Fig. 1.

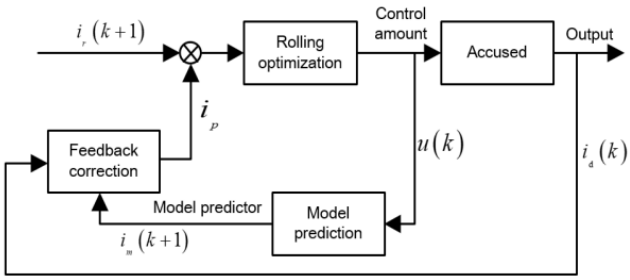

Fig.1. Block diagram of current model predictive controller

3. Model reference adaptive system

The current equation in the rotating coordinate system of the permanent magnet synchronous linear motor can be expressed as the following form:

$$\begin{cases} \dfrac{d}{dt}i'_d=-\dfrac{R}{L}i'_d+\omega_c\cdot i'_q+\dfrac{1}{L}u'_d \\ \dfrac{d}{dt}i'_q=-\dfrac{R}{L}i'_q-\omega_c\cdot i'_d+\dfrac{1}{L}u'_q \end{cases} \tag{12}$$

In the expression,

$$\begin{cases} i'_d=\dfrac{(Li_d+\psi_f)}{L},\ i'_q=i_q, \\ u'_d=u_d+\dfrac{R}{L}\psi_f,\ u'_q=u_d, \end{cases}$$

Express (12) in the form of estimated value:

$$\begin{cases} \dfrac{d}{dt}\hat{i}'_d=-\dfrac{R}{L}\hat{i}'_d+\hat{\omega}_c\cdot\hat{i}'_q+\dfrac{1}{L}u'_d \\ \dfrac{d}{dt}\hat{i}'_d=-\dfrac{R}{L}\hat{i}'_d-\hat{\omega}_c\cdot\hat{i}'_d+\dfrac{1}{L}u'_q \end{cases} \tag{13}$$

Regard formula (12) as the reference model of the model-reference adaptive system, and formula (13) as the adjustable model of the model-reference adaptive system [15]. Define the generalized error as: $e=i'-\hat{i}'$, and formula (12) minus formula (13) is:

$$\frac{d}{dt}e=C_m e-w \tag{14}$$

In the expression,

$$e=\begin{bmatrix} i'_d-\hat{i}'_d \\ i'_q-\hat{i}'_q \end{bmatrix},$$

$$J=\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix},$$

$$C_m=\begin{bmatrix} -\dfrac{R}{L} & \omega_c \\ -\omega_c & -\dfrac{R}{L} \end{bmatrix},$$

$$\boldsymbol{\omega}=\boldsymbol{J}(\boldsymbol{\omega}_c-\hat{\boldsymbol{\omega}}_c)\hat{\boldsymbol{i}}_d,$$

According to Popov's superstability theory [16], if the system made stable, the nonlinear time-varying feedback link must satisfy the following inequality:

$$\eta(0,t_1)=\int_0^{t_1}V^TWdt\geq-\gamma_0^2(t_1\geq 0, 0\leq\gamma_0\leq\infty) \tag{15}$$

The inverse solution of Popov's integral inequality can get the adaptive law [17], and the result is:

$$\hat{\omega}_c=\int_0^t K_i\left(\hat{i}'_d\hat{i}'_q-\hat{i}'_d\hat{i}'_q\right)d\tau+K_p\left(\hat{i}'_d\hat{i}'_q-\hat{i}'_d\hat{i}'_q\right) \tag{16}$$

Integrating the estimated speed $\hat{w}_c$ obtained in equation (16) can obtain the estimated rotor position $\hat{\theta}$:

$$\hat{\theta}=\int\hat{\omega}_c d\tau \tag{17}$$

The model reference adaptive system block diagram is shown in Fig.2 [18].

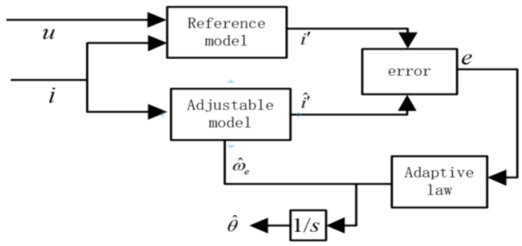

Fig.2. Model reference adaptive system block diagram

4. Simulation Results And Analysis

The designed model reference adaptive observer and current predictive controller are applied to the vector control system of permanent magnet synchronous linear motor, and the above-mentioned control system is simulated through the simulation environment to verify the effectiveness and superiority of the proposed control strategy.

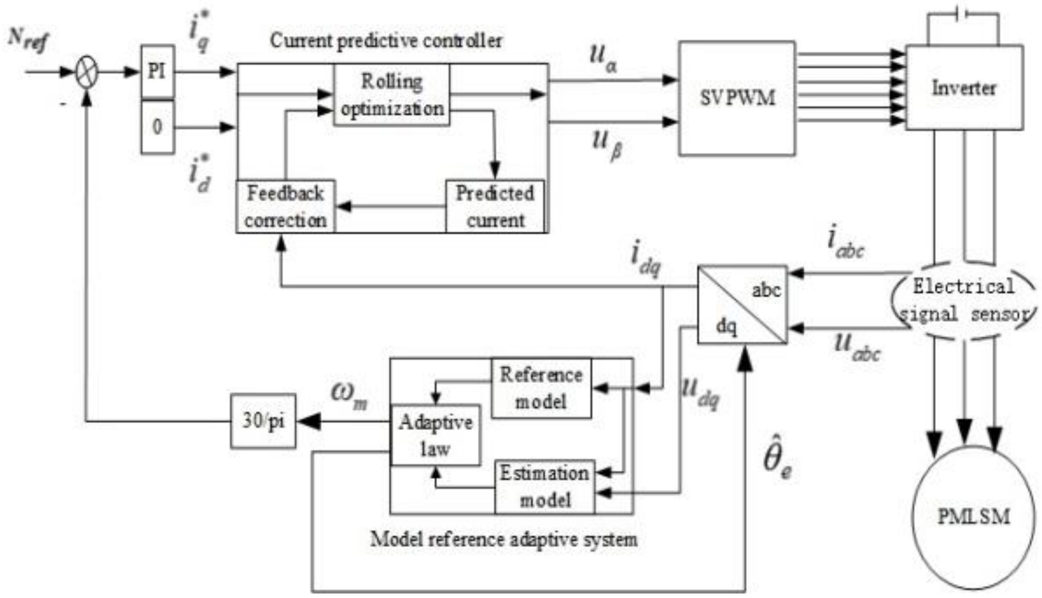

Fig. 3. Permanent magnet synchronous linear motor control system r

Table.1. Permanent Magnet Synchronous Linear Motor Parameters

Parameter	Value
Polar Logarithm	4
Polar Distance	0.019m
Primary Inductance	0.0013H
Primary Resistance	2Ω
Flux Linkage	0.1827Wb
Mover Mass	0.8kg

A. Load Unchanged, Change Speed

Fig. 4 and Fig. 5 respectively show the speed waveform of the motor in the case of MPC-MRAS and the running speed wave of the motor in the case of the traditional PI and sliding mode algorithm. When the load torque is 10N, during the acceleration and deceleration of the motor, it can be found from Fig. 4 and Fig. 5 that the control system can accurately identify the operating speed of the motor. Compared with the traditional PI and sliding film control strategy, the motor running speed fluctuates after the set speed is changed in the case of MPC-MARS, and the motor running speed is stable.

Fig. 6 and Fig. 7 respectively show the motor d-axis current waveform and the error waveform of the d-axis current tracking in the case of MPC-MARS and the application of traditional PI and sliding mode.

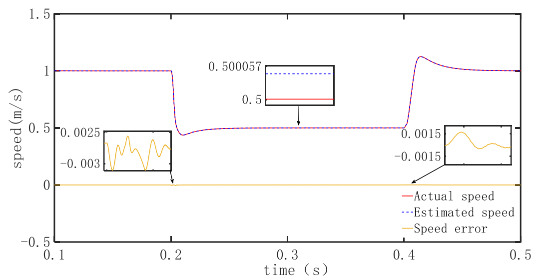

Fig.4. Speed in the case of MPC-MRAS

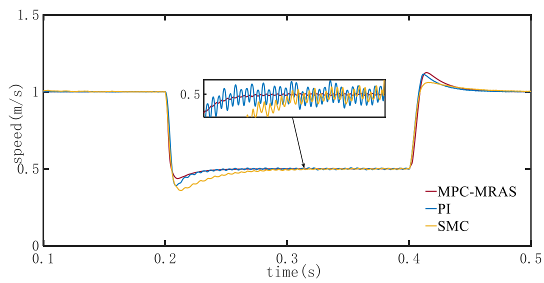

Fig.5. MPC-MRAS and PI, SMC speed

When the load torque is 10N, during the acceleration and deceleration of the motor, it is found from Fig. 6 and Fig. 7 that compared with the traditional PI and sliding film control strategy, the fluctuation of the d-axis current in the case of MPC-MARS is relatively small, and the current tracking accuracy is relatively high.

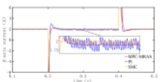

Fig.6. MPC-MRAS and PI, SMC current

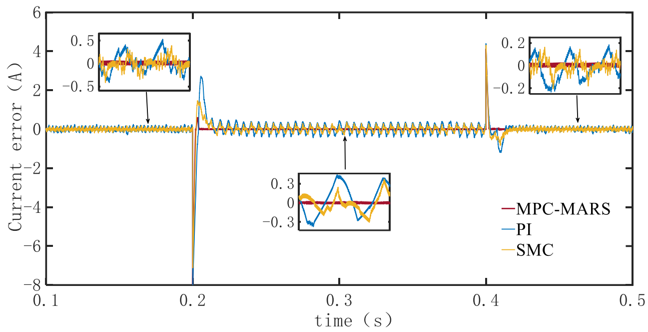

Fig.7. MPC-MRAS and PI, SMC current tracking error

B. Speed Unchanged, Change Load

Fig. 8 and Fig. 9 respectively show the speed waveform of the motor in the case of MPC-MRAS and the running speed wave of the motor in the case of PI and sliding mode algorithm. When the motor running speed is 1m/s, in the process of changing the load torque, it is found from the figure that the control system can not only accurately identify the motor running speed. Compared with the traditional PI and sliding mode control strategy, the load under the MPC-MARS The changed motor running speed fluctuates very little, and the motor running speed is stable.

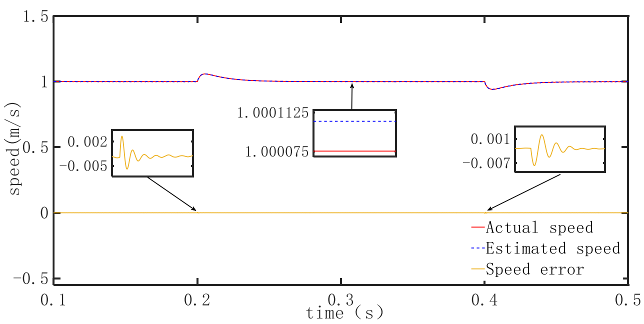

Fig.8. Speed in the case of MPC-MRAS

Fig. 10 and Fig. 11 show the d-axis current waveform of the motor in the case of MPC-MARS, PI and SMC, and the error waveform of the d-axis current tracking with traditional PI and SMC. When the motor running speed is 1m/s, it can be found from Fig. 10 and Fig. 11 that compared with the traditional PI and sliding mode control strategy, the tracking accuracy of the d-axis current in the case of MPC-MARS is higher, and the current fluctuates smaller.

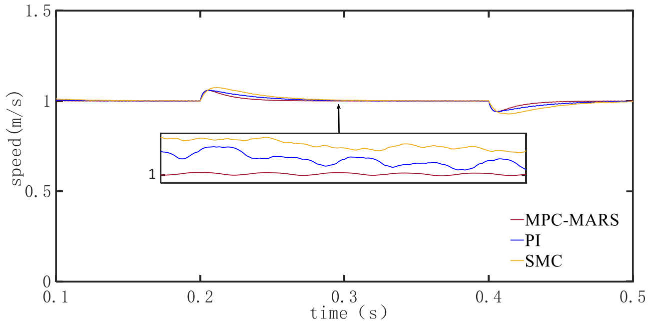

Fig.9. MPC-MRAS and PI, SMC speed

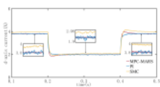

Fig.10. MPC-MRAS and PI, SMC current

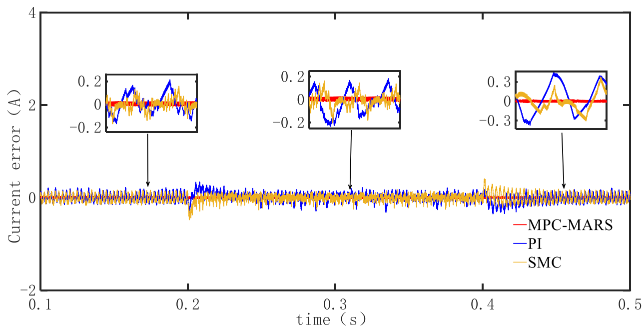

Fig.11. MPC-MRAS and PI, SMC current tracking error

C Experimental part

The experimental verification of this article is based on the STM32 development board and Matlab's automatic code generation tool. The use of STM32CubeMX software to generate the underlying configuration code improves work efficiency.

At light load, the given speed is 1m/s, the motor running speed is reduced to 0.5m/s in 0.2s, and the motor running speed is increased to 1m/s at 0.4s after the motor runs for 0.2s. The motor running speed waveform under the conditions of MPC-MRAS, PI and SMC. It can be found that during the motor running, MPC-MRAS is compared with the conditions of PI and SMC. After the set speed is changed, the motor speed under the condition of MPC-MRAS Relatively stable, while the motor speed fluctuates in the case of PI and SMC. The results of the tracking error estimated by the model reference adaptive system and the motor running speed during the motor running process. It can be found that the tracking error is very small, even if the absolute value of the tracking error is less than 0.006m/s at the time of speed regulation.

5. Conclusion

In order to achieve high-performance AC drive control, this paper designs a control strategy based on a speed sensorless Permanent magnet synchronous linear motor current prediction model. The experimental results show that the control strategy not only overcomes the defects caused by the use of mechanical sensors, but also replaces the traditional PI control with current predictive control, effectively reduces the control current and fluctuation effect, and improves the tracking accuracy of the control system.

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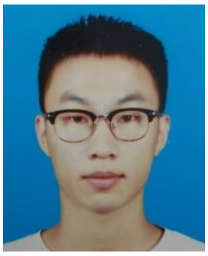

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