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Field-Oriented Control of Stepper Motor with Model Predictive Current Control

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Abstract. Hybrid stepper motors (HSMs) have a wide range of applications. However, conventional open-loop control is difficult to meet the demand for higher accuracy. The development of control theory and electronic technology makes the application of advanced control techniques possible, including model predictive control (MPC). In this paper, a stepper motor current loop predictive model has been constructed, and then the design of q-axis current regulator has been implemented by feedback correction and rolling optimization, which has been applied to the field-oriented control (FOC) of stepper motor and verified by simulation and experiments. The results indicate that the MPC regulator in this paper has good regulation effect and reduces the q-axis current ripples to a certain extent in the series control, which finally improves the control performance.

Keywords. Hybrid stepper motor, field-oriented control, model predictive control

1. Introduction

Hybrid stepper motors (HSMs) are widely used in industrial applications, such as 3D printers and robotic arms, due to their low cost, high reliability, and easy implementation of open-loop control [1, 2]. However, although some improved open-loop control methods have improved the smoothness of open-loop operation to some extent [3], open-loop control still has some drawbacks and cannot meet the demand for higher accuracy. Therefore, with reference to the control of synchronous motors, by applying field-oriented control (FOC) to regulate the flux and torque separately, the torque ripples can be reduced [4], and the efficiency, robustness and dynamic performance of stepper motors can be improved [5].

For the FOC algorithm, for improving the control performance to meet different complex occasions, in addition to the conventional proportional-integral (PI) control, various control strategies have been proposed by researchers, such as fuzzy control, sliding mode control (SMC) [1], robust control [6], and model predictive control (MPC) [7]. Deeply rooted in industrial applications, MPC has received significant attention due to its simple implementation [8], effective handling of nonlinearities and constraints, and excellent dynamic performance [9, 10].

In this paper, a q-axis current MPC regulator has been designed for stepper motor FOC. First, a predictive model has been built based on the voltage equation of the stepper motor. Second, the MPC regulator has been constructed by calculating the control value

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through feedback correction and rolling optimization. Finally, the feasibility of the regulator has been verified by simulation and experiment under different conditions.

2. Design of Current Loop Model Predictive Control

2.1. Current Loop Predictive Model of Stepper Motor

Predictive control first requires a suitable predictive model. Considering the accuracy of the predictive model and the simplicity of practical application, the voltage equation is selected as the predictive model for the stepper motor. Hybrid stepper motor is an electromechanical device that exhibits significant nonlinearity, making it challenging to accurately describe and determine its nonlinear parameters with precision. Therefore, the effects of leakage, saturation, hysteresis, and eddy currents are ignored to simplify the model. The model of stepper motor in the d-q coordinate system can be written in the following form:

$$\begin{cases} u_{\mathrm{d}} = R_{\mathrm{s}} i_{\mathrm{d}} + L_{\mathrm{d}} \dfrac{\mathrm{d}i_{\mathrm{d}}}{\mathrm{d}t} - L_{\mathrm{q}} i_{\mathrm{q}} \omega_{\mathrm{e}} \\ u_{\mathrm{q}} = R_{\mathrm{s}} i_{\mathrm{q}} + L_{\mathrm{q}} \dfrac{\mathrm{d}i_{\mathrm{q}}}{\mathrm{d}t} + L_{\mathrm{d}} i_{\mathrm{d}} \omega_{\mathrm{e}} + K_{\mathrm{e}} \omega_{\mathrm{r}} \end{cases} \tag{1}$$

where u_{d} and u_{q} are the voltages of d and q axes; R_s is the winding resistance; i_{d} and i_{q} are the currents of d and q axes; L_{d} and L_{q} are the inductances of d and q axes; ω_{e} is the rotational speed in its electrical form; ω_{r} is the mechanical rotational speed; K_{e} is back electromotive force coefficient.

To reduce the complexity of the MPC algorithm, the voltage equation of the stepper motor can be simplified to two separate single-input single-output (SISO) systems. Treating the cross-coupling term between d and q axes as a perturbation, the equation for current control is obtained as:

$$\begin{cases} u_{\mathrm{d}} = R_{\mathrm{s}} i_{\mathrm{d}} + L_{\mathrm{s}} \dfrac{\mathrm{d}i_{\mathrm{d}}}{\mathrm{d}t} \\ u_{\mathrm{q}} = R_{\mathrm{s}} i_{\mathrm{q}} + L_{\mathrm{s}} \dfrac{\mathrm{d}i_{\mathrm{q}}}{\mathrm{d}t} \end{cases} \tag{2}$$

Then the state equation for the q-axis can be written as:

$$\frac{\mathrm{d}i_{\mathrm{d}}}{\mathrm{d}t} = \frac{R_{\mathrm{s}}}{L_{\mathrm{s}}} i_{\mathrm{d}} + \frac{u_{\mathrm{d}}}{L_{\mathrm{s}}} \tag{3}$$

The equation of state is discretized according to the first-order Euler method to obtain the discrete form as:

$$i_{\mathrm{q}}(k+1) = \left(1 - \frac{R_{\mathrm{s}} T_{\mathrm{s}}}{L_{\mathrm{s}}}\right) i_{\mathrm{q}}(k) + \frac{T_{\mathrm{s}}}{L_{\mathrm{s}}} u_{\mathrm{q}}(k) = A i_{\mathrm{q}}(k) + B u_{\mathrm{q}}(k) \tag{4}$$

where T_{s} is the current sampling time.

After the predictive model is established, the future output of the system needs to be predicted by using the past and current information of the system. Let the prediction time domain be N_p. In the actual situation, the control value in the latter N_{p} cycles is unknown.

Therefore, it's assumed that the control value in the latter N_p cycles is kept constant as $u_q(k\text{-}1)$, then the a priori predicted value of the controlled object can be written as:

$$\begin{cases} i_{q0}(k+1|k) = Ai_q(k) + Bu_q(k-1) \\ i_{q0}(k+2|k) = Ai_{q0}(k+1|k) + Bu_q(k-1) \\ \quad\vdots \\ i_{q0}(k+N_p|k) = Ai_{q0}(k+N_p-1|k) + Bu_q(k-1) \end{cases} \tag{5}$$

Considering the variation of the control value, the actual control value is assumed to be as:

$$\begin{cases} u_q(k) = u_q(k-1) + \Delta u_q(k) \\ u_q(k+1) = u_q(k) + \Delta u_q(k+1) \\ \quad\vdots \\ u_q(k+N_p) = u_q(k+N_p-1) + \Delta u_q(k+N_p) \end{cases} \tag{6}$$

Then, after considering the change of the control value, the predicted value of the predictive model for the control object can be written as:

$$\boldsymbol{Y}_p = \boldsymbol{i}_{q0}(k) + \boldsymbol{\Phi U} \tag{7}$$

where:

$$\boldsymbol{\Phi} = \begin{bmatrix} B & 0 & \cdots & 0 \\ AB & B & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ A^{N_p-1}B & A^{N_p-2}B & \cdots & B \end{bmatrix} \tag{8}$$

$$\begin{cases} \boldsymbol{i}_{q0}(k) = [\, i_{q0}(k+1|k) \;\; i_{q0}(k+2|k) \;\; \cdots \;\; i_{q0}(k+N_p|k)\,]^{T} \\ \boldsymbol{Y}_p = [\, i_{qp}(k+1|k) \;\; i_{qp}(k+2|k) \;\; \cdots \;\; i_{qp}(k+N_p|k)\,]^{T} \\ \boldsymbol{U} = \Delta\boldsymbol{u}_q = [\, \Delta u_q(k) \;\; \Delta u_q(k+1) \;\; \cdots \;\; \Delta u_q(k+N_p-1)\,]^{T} \end{cases} \tag{9}$$

2.2. Feedback Correction of Prediction Deviations

In practical situations, due to the error factors of parameters, models, quantization, as well as load perturbations and nonlinearities, the algorithm will have certain deviations for the prediction of the control object. To eliminate such deviations, feedback correction is applied to correct the predicted value. First, the prediction deviation of the current step can be obtained based on the sampled and predicted values at the current moment as:

$$e(k) = i_q(k) - i_{qp}(k) \tag{10}$$

The prediction deviation exists in the prediction time domain, and the output value at the future time cannot be detected at the current sampling moment. Therefore, the prediction deviation in the prediction time domain N_p is assumed to be equal to the prediction deviation at the current step. The prediction deviation in the prediction time domain can be obtained as follows:

$$\boldsymbol{E} = \boldsymbol{h} \cdot e(k) \tag{11}$$

$$\boldsymbol{h} = [h \quad h \quad \cdots \quad h]^{\mathrm{T}} \tag{12}$$

where h is the feedback coefficient.

2.3. Rolling Optimization and Control Value Calculation

MPC algorithm performs an optimization calculation at each sampling moment by means of online rolling optimization, and the optimized performance metrics are only related to a finite time domain from that moment and in the future. This optimization time domain will move forward to the next sampling moment, and so on, for the purpose of rolling optimization. The optimization metrics in this paper are chosen as quadratic functions:

$$J = \sum_{i=1}^{N_{\mathrm{p}}} q_i [i_{\mathrm{qr}}(k+i) - i_{\mathrm{qp}}(k+i|k) - e(k+i)]^2 + \sum_{j=1}^{N_{\mathrm{c}}} r_j \Delta u_{\mathrm{q}}(k+j-1)^2 \tag{13}$$

where N_{p} is the prediction time domain, and N_{c} is the control time domain, and satisfies $N_{\mathrm{c}} \le N_{\mathrm{p}}$.

The above equation is expressed in the form of a matrix as:

$$\boldsymbol{J} = (\boldsymbol{Y}_{\mathrm{r}} - \boldsymbol{Y}_{\mathrm{p}} - \boldsymbol{E})^{\mathrm{T}} \boldsymbol{Q} (\boldsymbol{Y}_{\mathrm{r}} - \boldsymbol{Y}_{\mathrm{p}} - \boldsymbol{E}) + \boldsymbol{U}^{\mathrm{T}} \boldsymbol{R} \boldsymbol{U} \tag{14}$$

where $\boldsymbol{Q}$ is the deviation weighting coefficient matrix and $\boldsymbol{R}$ is the control increment weighting coefficient matrix.

The control sequence can be derived from the necessary condition of the extreme value theorem as:

$$\boldsymbol{U} = (\boldsymbol{\Phi}^{\mathrm{T}} \boldsymbol{Q} \boldsymbol{\Phi} + \boldsymbol{R})^{-1} \boldsymbol{\Phi}^{\mathrm{T}} \boldsymbol{Q} [\boldsymbol{Y}_{\mathrm{r}} - \boldsymbol{i}_{\mathrm{q0}}(k) - \boldsymbol{E}] \tag{15}$$

Using only the first element of the control sequence $\boldsymbol{U}$ as a real-time control input, the control value of the regulator output at the current moment is obtained as:

The real-time control input is determined only by the first element of the control sequence $\boldsymbol{U}$. The regulator output control value at the current moment is obtained as:

$$u_{\mathrm{q}}^*(k) = u_{\mathrm{q}}^*(k-1) + [1 \quad 0 \quad \cdots \quad 0]^{\mathrm{T}} \boldsymbol{U} \tag{16}$$

3. Simulation and Experiments

3.1. Simulation of Q-Axis Current Model Predictive Control

The block diagram of the stepper motor FOC system with q-axis current MPC regulator is shown in Figure 1. The microcontroller generates a two-phase SVPWM to control a dual H-bridge driver to drive the stepper motor. Control strategy of $i_{\mathrm{d}} = 0$ is adopted, and q-axis current is controlled by using the MPC regulator established in the previous section instead of the conventional PI regulator.

The parameters of the stepper motor for simulation and experiment are illustrated in Table 1.

The current response curve for a given q-axis current of 0.8 A is shown as below. As shown in Figure 2, the MPC regulator for q-axis current has a good regulation performance, allowing the q-axis current to track to the desired current value accurately and rapidly.

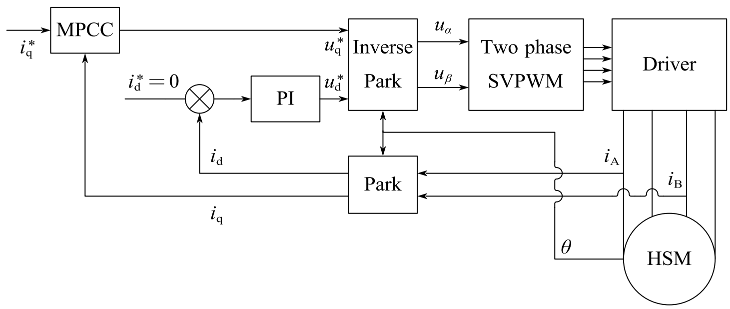


Figure 1. Block diagram of q-axis current MPC.

Table 1. Parameters of stepper motor.

Rated current	Resistance	Inductance	Inertia
1.5 A	2.5 Ω	2.7 mH	68 g·cm^2

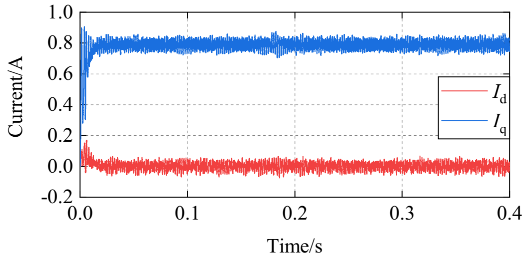


Figure 2. Simulation of d-q axis current response.

3.2. Experiments in Different Situations

The stepper motor was first tested under no-load conditions by using an STM32F302R8 microcontroller as the main controller, with a carrier frequency and a current loop execution frequency of 10 kHz. q-axis current of 0.8 A was given by the microcontroller, and the response curve was measured and illustrated in Figure 3. The test results are in accordance with the simulation results, and the MPC regulator designed in this paper is capable of accurate regulation of the given current value.

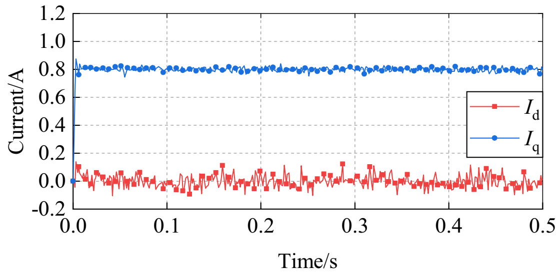


Figure 3. Current curve of d-q axis.

Under the no-load condition, a speed outer loop was introduced to the stepper motor control system to form a series control of the speed loop PI and current loop MPC. The measured speed response curves at different given speeds are shown in the following Figure 4. As shown in Figure 4, the MPC regulator in this paper is equally well suited as the conventional PI regulator for the series control of double closed-loop control and obtains an excellent regulation effect of both the speed outer loop and current inner loop.

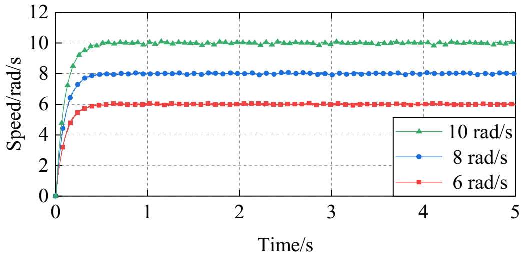
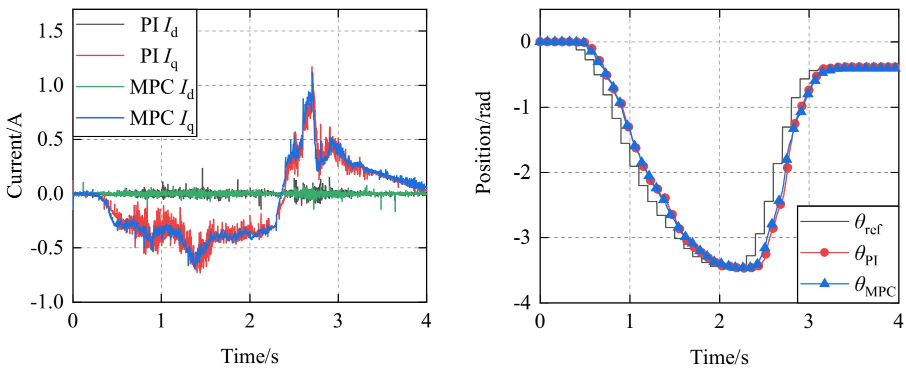


Figure 4. Speed curve with speed-loop control.

Based on the previous double closed-loop control system, a position outer loop was added, and the position loop acquired a proportional regulator to form a three-closed-loop series control system of position-velocity-current. On the test bench of the mechanical joint, the stepper motor was used to drive the joint through the gear reducer to move according to the given trajectory for testing. The microcontroller was used to give a reference trajectory to the position loop, and the current loop was compared and tested by conventional PI and MPC respectively. The position tracking curve and d-q axis current curve are obtained as shown in Figure 5. Both inner-loop control methods can achieve a good series control effect. Among them, the current ripples of q-axis during the motion with q-axis current MPC regulator are smaller, thus obtaining a more stable torque output, improving the smoothness of the outer-loop tracking and reducing the noise and vibration of the test bench during the experiment. During the position loop trajectory tracking, the offsets of the position points in the MPC regulator's curve with respect to the given trajectory are also slightly improved over the PI regulator.



(a) d-q axis current (b) position trajectory

Figure 5. Trajectory tracking curve.

4. Conclusion

In this paper, a q-axis current regulator for field-oriented control of stepper motor was established based on model predictive control. First, this paper established a predictive model of the current loop based on the voltage equation of the stepper motor, and then derived and obtained the control value through feedback correction and rolling optimization. Second, this paper established a simulation model of q-axis current MPC regulator and verified the regulation effect under a given q-axis current. Finally, the FOC control algorithm with q-axis MPC regulator was tested for a stepper motor under different conditions, and the following conclusions were obtained. The q-axis current MPC regulator designed in this paper is capable of fast and accurate current regulation and is suitable for use in a series closed-loop control system; with this current internal loop regulation method, the q-axis current pulsation can be reduced to obtain a more stable torque output, improve smoothness, and get better control effects.

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