Speed Regulation System of Permanent Magnet Synchronous Motor Field Weakening Control Based on Model Predictive Control

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Abstract: The paper is based on the theoretical analysis of motor field weakening control, design field weakening control system based on voltage feedback. In this research, MPC control algorithm is introduced into speed loop. Under field weakening control strategy, the designed MPC controller is applied to motor control system. Finally, the simulation results show: under field weakening control, MPC controller has better robustness and stronger anti-interference ability than PI controller, which improves system stability.

1. Introduction
Permanent Magnet Synchronous Motor (PMSM) has attracted much attention in motor-related industries due to its small size, light weight and simple structure [1-2]. In recent years, as Model Predictive Control (MPC) has become more widely used in the field of control, MPC has also been fully applied in the field of motor control.

Predictive control is a new type of control algorithm derived from the needs of industrial control. Most of the control object models in industrial applications are nonlinear. Traditional control algorithms such as PID control can no longer meet the needs of control. However, the predictive control adopts the steps of feedback correction and online optimization, so it has high precision, strong robustness and not very high structural requirements on the control object model [3]. These characteristics appearing in predictive control can well solve a series of difficult problems caused by model nonlinearity.

This paper designs a motor speed loop controller based on model predictive control algorithm under the field weakening control strategy. Finally, the simulation results show that the constructed MPC controller has better dynamic characteristics, higher steady-state accuracy and stronger robustness than the traditional PI controller.

2. Basic theory of field weakening control
Field weakening control is a kind of vector control strategy. The use of field weakening control is to increase the speed of the motor. When PMSM armature voltage is at the limit voltage value, the speed of motor also reaches rated speed. The back electromotive force in the motor will also increase with the increase in speed. If the motor's speed exceeds the rated speed, the back electromotive force is still increasing at this time, and the armature voltage will not increase when it reaches the limit voltage.
When the back electromotive force is about to approach the limit voltage, the increase of motor speed will also stop, and finally stabilize at a certain value. In order to increase the motor speed above the rated speed, the back electromotive force must not exceed limit voltage, and the back electromotive force is directly proportional to the air gap flux in the motor, considering that the product of the motor speed and the air gap flux is not. Therefore, the method of reducing the magnetic flux can be considered to increase the speed of the motor [4]. Since the rotor part of the PMSM is composed of permanent magnets, the flux linkage of the air gap magnetic field is fixed, so the flux linkage cannot be directly reduced. You can change the direction of the stator current vector to produce excitation current of permanent magnet flux in the opposite direction can weaken the flux of the permanent magnet. This is the basic principle of the weakening control.

The weak magnetic module model is shown in figure 1. When vector sum of d-axis voltage and q-axis voltage is less than limit voltage, the field weakening module has no effect, and motor is still in vector(id=0) control mode. When vector sum of d-axis voltage and q-axis voltage is greater than limit voltage, difference between two passes through d-axis demagnetization current (- Idmax, 0) of PI regulator, and then redistributes q-axis current and d-axis current, it makes a part of q-axis current as the demagnetization current component, and at the same time reduce the size of its own current, so as to achieve the purpose of magnetic weakening and speed expansion.

3. Basic theory of MPC
There are many types of predictive control, but they all contain three links, which are composed of three links: predictive model, rolling optimization, and feedback correction. It is based on the information or data input and output in the past and the information or data input in the future to predict the information or data output in the future. Use the difference between the actual output of the system and the predicted output of the model to perform feedback correction. The reference trajectory is formed by the actual output value and the given expected value, and then the feedback corrected value is compared with the reference trajectory, and finally the selected performance is passed. The index function is optimized by rolling and the optimal solution is selected [5]. Predictive control is an optimization performed locally, and calculation optimization is performed every time a sampling is performed, so the calculation amount of predictive control is relatively large.

4. MPC Controller Design
Design process of model predictive controller is as follows:

4.1 Predictive model
PMSM mechanical motion equation:
\[ J \frac{d\omega}{dt} = T_e - B\omega - T_L \]  
(1)

In formula 1, \( \omega \) is actual speed of motor, \( T_e \), \( T_L \) are electromagnetic torque and load respectively, \( B \) is friction resistance coefficient, \( J \) is inertia moment. Without considering load rotation condition,
perform Laplace transform on formula 1 to get frequency domain model of system:

\[ G(s) = \frac{W(s)}{I_q(s)} = \frac{K}{Js + B} \]  

(2)

In formula 2, \( K = 1.5P_n\nu_f \).

Discretize model in formula 2, the zero-order holder is used to realized its discretization, and get the discrete Z transfer function:

\[ G(z) = Z\left[\frac{1 - e^{-Ts}}{s} \cdot \frac{K}{Js + B}\right] = \frac{az^{-1}}{1 + bz^{-1}} \]  

(3)

In formula 3, \( a = K(1 - e^{-TB/J}) / Bm, b = -e^{-TB/J}, T \) is PMSM speed loop sampling period.

Carrying out difference equation in formula 3:

\[
\begin{align*}
\omega(k) &= a\omega(k-1) - b\omega(k-1) \\
\omega(k+1) &= a\omega(k) - b\omega(k)
\end{align*}
\]

(4)

In formula 4, \( \omega(k) \) is actual motor speed at time \( k \).

Subtract two formula in formula 4 to get the prediction model of motor speed.

\[ \omega_m(k+1) = (1-b)\omega(k) + b\omega(k-1) + a\Delta i_q(k) \]  

(5)

In formula 5, \( \Delta i_q(k) \) is PMSM q-axis current control increment at time \( k \).

4.2 Feedback Correction

In order to improve anti-interference ability of predictive control system, the error between the actual speed of motor model and the speed of predictive model is used to compensate output signal of the predictive model, the error between actual speed and predicted speed of motor at time \( k \).

\[ e(k) = \omega(k) - \omega_m(k) \]  

(6)

Closed-loop predictive output of predictive control system at time \( k \).

\[ \omega_m(k+1) = \omega_m(k+1) + e(k) \]  

(7)

4.3 Reference Trajectory

Take the form of first-order exponential change, and its expression is as follows:

\[ y_s(k+1) = \alpha\omega_s(k) + (1-\alpha)\omega_{ref}(k) \]  

(8)

In formula 8, \( \alpha, \omega_{ref}(k) \) respectively indicate softening coefficient and desired speed, and \( 0 < \alpha < 1 \).

4.4 Select optimized performance index

Predictive control selects performance index function:

\[ J = \min \left[ \sum_{i=1}^{H_2} \lambda_i [y_p(k+i) - y_s(k+i)]^2 + \sum_{i=1}^{m} \beta_i [\Delta u(k+i-1)]^2 \right] \]  

(9)

\( H_1, H_2 \) is the initial and final values of the time domain for the optimization, \( m \) is the maximum value of control horizon, \( y_p(k+i) \) is plant output reference value, \( y_s(k+i) \) is closed-loop predictive input at time \( (k+i), \Delta u(k+i-1) \) is system control increment, \( \lambda_i, \beta_i \) are weighting factor not less than 0, they indicate respectively inhibit degree of tracking error and control amount change.

Substitute the corresponding values in formula 7 and formula 8 into formula 9, obtain:

\[ J = \lambda\omega_p(K+1) - y_s(k+1) + \beta[\Delta i_q'(k)]^2 \]  

(10)

Differential derivation in formula 10, which is \( \partial J / \partial \Delta_i_q(k) = 0 \): obtain
\[ \Delta i_q^*(k) = -\frac{\lambda a}{\lambda a^2 + \beta}[(1-b)\omega(k) + b\omega(k-1) + e(k) - y_q(k + 1)] \]  

(11)

$q$-axis current given value in $k$ time:

\[ i_q^*(k) = i_q^*(k-1) + \Delta i_q^*(k) \]  

(12)

5. Results & Discussion

The simulation conditions are as follows: Rated voltage is 220V, given speed is 3000r/min, Load is $5N \cdot m$, motor speed, $d, q$-axis current response curve is shown from figure 3 to figure 5.

| Parameter                          | Value   | Unit |
|-----------------------------------|---------|------|
| Stator resistance                 | 0.958   | Ω    |
| $d$-axis inductance               | 6.1e-3  | H    |
| $q$-axis inductance               | 12e-3   | H    |
| Permanent magnets flux            | 0.1827  | Wb   |
| Number of pole pairs              | 4       |      |
| Moment of inertia                 | 0.003   | $kg \cdot m^2$ |

Table 1. Parameter of PMSM

Figure 3. Motor speed response curve
The motor speed response curve in figure 3, PI control is unstable in process of speed transition, PI controller has poor tracking performance, MPC controller has good tracking performance. Add load 0.5N·m at 0.4s, PI controller cannot recover to desired speed, MPC controller can recover quickly to the desired speed, MPC controller has higher control accuracy than PI controller under load conditions, good system dynamic performance. It can be seen from figure 4, PI control q-axis current has overshoot and party under no-load, but MPC controller does not. MPC control has a slight overshoot under load conditions, MPC controller response speed is fast, PI controller response speed is slow. It can be seen from figure 5, PI control d-axis current has overshoot and party under load conditions, MPC controller does not.

6. Conclusions
Aiming at the overshoot phenomenon and poor anti-interference ability of PI controller in field weakening control, this paper designs field weakening control system based on voltage feedback, and introduces designed MPC controller into motor control system. In speed loop, under field weakening control strategy, MPC controller is more robust than PI controller in term of speed. When no loading, q-axis current under PI control has overshoot, MPC does not. When loading, d-axis current under PI control has overshoot, MPC does not.

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