An Improved MPCC Method Based on the Predictive Delay Error Analysis for PMSM Speed Control System

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Abstract. Taking permanent magnet synchronous motor (PMSM) as the research object, the model predictive current control strategy (MPCC) was studied. In order to solve the shortcoming that the MPCC strategy depends on the motor prediction model, reduce the prediction error caused by MPCC and enhance the prediction accuracy of the system, an improved MPCC model was constructed by a two-step prediction method. At the same time, compared with the system based on Field-Oriented Control (FOC) and MPCC control and the system based on improved MPCC control, the proposed control strategy can make the PMSM run stably and efficiently, and reduce the torque ripple and the THD value of the three-phase stator resistance current. The simulation results show that the motor system controlled by the method can run stably, and then the correctness and effectiveness of the strategy are verified.

1. Introduction

PMSM has the advantages of simple structure, high efficiency, high power factor, small size and high torque current ratio. It is used in many fields such as transportation industry and industry. [1] In order to improve the efficiency of high-speed trains, sliding mode control (SMC) and model predictive control (MPC) are proposed to seek a comprehensive control scheme to enhance the system performance. Among them, MPC has been widely studied by domestic and foreign scholars for its high accuracy and performance.

The traditional MPCC strategy is divided into two parts: prediction and rolling optimization, and the predictive part has the problem of predictive control delay error. In the ideal state, the motor prediction part will be completed in an instant, that is, the current signal will be received, the prediction calculation will be carried out and the optimal switching quantity output will be completed at the same time. However, in the actual process, the prediction calculation will take some time, and the calculated voltage instruction will not be executed immediately, but will wait until the beginning of the next cycle to be sampled at the same time with the current signal. This will lead to control delay error, which will affect the accuracy and control performance of the MPCC system.

In order to solve the delay error problem in the MPCC, the model predictive current control strategy was adopted in Literature [2] to predict and optimize the delay error of the system. At the same time, the problems of parameter mismatch and model error in the traditional MPC were solved through feedback correction, and the robustness of the system was improved. In Literature [3], a novel PWM modulated model predictive control scheme was proposed by optimizing the voltage vector meter in DTC.
same time, the multi-step prediction of the adoption and control was carried out, and the PWM wave was calculated and output in advance. The results effectively suppressed the torque and flux pulsation. Literature [4] optimized the selection of the optimal vector. The traditional MPC requires multiple calculations using enumeration method, and the optimal voltage vector can be obtained after one calculation after improvement, effectively solving the motor delay error and control performance. Literature [5] improves PMSM current loop predictive control, reduces prediction error and MPC’s dependence on model parameters, and only uses one motor parameter to control the system, thus realizing efficient operation of current instructions and better dynamic control performance.

Based on permanent magnet synchronous motor MPC delay error problem, by two-step prediction method to construct a MPCC model, to improve its dynamic performance is verified by the simulation test, at the same time under the condition of considering load changes compared with SVPWM control of permanent magnet synchronous motor. The results show that the dynamic response of the improved MPCC is faster and the torque ripple is smaller, which verifies the feasibility of the strategy.

2. MPCC prediction optimization principle and mathematical model

2.1. PMSM mathematical model

The PMSM mathematical model in the three-phase static coordinate system is as follows. The three-phase winding voltage equation is shown in Equation 1.

\[
\begin{align*}
    u_a &= R_i a + d\psi_a / dt \\
    u_b &= R_i b + d\psi_b / dt \\
    u_c &= R_i c + d\psi_c / dt
\end{align*}
\]

(1)

The stator three-phase winding voltage is \( u_a, u_b, u_c \), the stator winding resistance value is \( R_i \), the rotor two-phase voltage is \( i_a, i_b, i_c \), and the stator two-phase flux linkage is \( \psi_a, \psi_b, \psi_c \).

Because the self-inductance and mutual inductance of stator windings in the three-phase static coordinate system will change with the rotor position, the mathematical model is not conducive to the application, and the coordinate change is usually used to transform the equation into a synchronous rotating coordinate equation which is convenient for application. The state equation of PMSM in the synchronous rotation coordinate system is shown in Equation 2.

\[
\begin{bmatrix}
    \frac{d i_d}{dt} \\
    \frac{d i_q}{dt} \\
    \frac{d i_f}{dt}
\end{bmatrix} =
\begin{bmatrix}
    -\frac{R_i}{L_d} & \frac{\omega L_q}{L_d} & 0 \\
    \frac{-\omega L_q}{L_d} & -\frac{R_i}{L_q} & 0 \\
    0 & 0 & \frac{1}{L_q}
\end{bmatrix}
\begin{bmatrix}
    i_d \\
    i_q \\
    i_f
\end{bmatrix} +
\begin{bmatrix}
    0 \\
    0 \\
    \frac{-\omega \psi_f}{L_q}
\end{bmatrix}
\begin{bmatrix}
    u_d \\
    u_q \\
    u_f
\end{bmatrix}
\]

(2)

Where \( \omega \) is the rotor electric angular velocity, \( u_d, u_q \) is the stator voltage of D and Q axis, and \( \psi_f \) is the rotor permanent magnet flux. \( L_d, L_q \) discretizes the stator voltage state equation 2.2 with the forward Euler discretization method to obtain the PMSM discrete model, as shown in Equation 3.

\[
\begin{bmatrix}
    i_d(k+1) \\
    i_q(k+1) \\
    i_f(k+1)
\end{bmatrix} =
\begin{bmatrix}
    1 & -T \frac{R_i}{L_d} & 0 \\
    \frac{T \omega L_q}{L_d} & 1 & 0 \\
    \frac{T \omega L_q}{L_d} & \frac{T \omega L_q}{L_d} & 1 - \frac{T R_i}{L_q}
\end{bmatrix}
\begin{bmatrix}
    i_d(k) \\
    i_q(k) \\
    i_f(k)
\end{bmatrix} +
\begin{bmatrix}
    T \frac{R_i}{L_d} & 0 & 0 \\
    0 & T \frac{R_i}{L_q} & 0 \\
    0 & 0 & T \frac{R_i}{L_q}
\end{bmatrix}
\begin{bmatrix}
    u_d(k) \\
    u_q(k) \\
    u_f(k)
\end{bmatrix}
\]

(3)

In this paper, the error term of MPCC cost function is in the form of error square, and the value function plays an important role in the selection of switch sequence. Using the method of \( id=0 \), the difference between the predicted current value and the given value is calculated by using the constructed value function. The switch vector with the smallest difference value is selected to act its corresponding switch sequence on the inverter circuit, and then the motor is controlled. The value function relationship is shown in Formula 4 below.
\[
\min \{g_i\} = |i_d^*(k+1) - i_d(k+1)|^2 + |i_q^*(k+1) - i_q(k+1)|^2
\]  

(4)

The superscript * represents the reference value, and \(i(k)\) represents the value of the state variable \(i\) at the sampling moment.

3. Improved MPCC control of Prediction Error Analysis

The execution of the MPCC algorithm needs to occupy a certain proportion of time in each control cycle. The calculated voltage vector, whether applied immediately after the execution of the algorithm or at the beginning of the next control cycle, lags behind the data sampling time at the beginning of the control cycle, i.e., the control delay exists.

In order to solve the control error problem, this paper adopts the "two-step prediction" scheme to compensate the delay. Firstly, the sampling current \(i_d(k)\) and \(i_q(k)\) were used to calculate the predicted values of D-Q axis current \(i_d(k+1)\) and \(i_q(k+1)\) at time \(k+1\). Then, \(i_d(k+1)\) and \(i_q(k+1)\) were substituted into the prediction model to obtain the predicted values of D-Q axis current \(i_d(k+2)\) and \(i_q(k+2)\) corresponding to all possible voltage vectors at time \(k+2\), as shown in Equation 5.

\[
\begin{bmatrix}
  i_d(k+2) \\
  i_q(k+2)
\end{bmatrix} =
\begin{bmatrix}
  1 - \frac{T_R}{L_d} & \frac{T \omega L_q}{L_d} \\
  -\frac{T \omega L_d}{L_q} & 1 - \frac{T_R}{L_q}
\end{bmatrix}
\begin{bmatrix}
  i_d(k+1) \\
  i_q(k+1)
\end{bmatrix} +
\begin{bmatrix}
  \frac{T}{L_d} & 0 \\
  0 & \frac{T}{L_q}
\end{bmatrix}
\begin{bmatrix}
  u_d(k+1) \\
  u_q(k+1)
\end{bmatrix} +
\begin{bmatrix}
  0 \\
  -\frac{T \omega L_q}{L_q}
\end{bmatrix}
\]  

(5)

Then rolling optimization is carried out according to the improved cost function, which is shown in Equation 6.

\[
g = |i_d^r(k+2) - i_d^e(k+2)|^2 + |i_q^r(k+2) - i_q^e(k+2)|^2
\]  

(6)

4. The simulation results

In order to verify the correctness and effectiveness of the proposed strategy, MATLAB was used for simulation research. PMSM motor parameters are shown in Table 1.

| Parameter                | Value       | Parameter                | Value       |
|--------------------------|-------------|--------------------------|-------------|
| magnetic pole number \(p\) | 4           | rated speed \(n\)       | 500 \(r \cdot \text{min}^{-1}\) |
| DC-link voltage \(U_{dc}\) | 540 V       | rotational inertia \(J\) | 0.0008 \(kg \cdot m^2\) |
| rated torque \(T_N\)     | 20 \(N \cdot m\) | stator resistance \(R_s\) | 2.875 \(\Omega\) |
| stator inductance \(L\)  | 0.0085 \(H\) | flux linkage \(\varphi_l\) | 0.175 \(Wb\) |
| viscous damping \(B_m\)  | 0.001 \(N \cdot m \cdot s\) |                          |             |

In this paper, two research schemes are presented: 1) Two PMSM systems based on MPCC control method and SVPWM control method are respectively constructed by using the speed regulator with the same PI parameters, and they are compared and analyzed. 2) The three systems (two-level system based on MPCC, two-level system based on SVPWM and control delay compensation system based on MPCC) are compared and analyzed.
4.1. Figures and results

Figure 1. Torque waveform

Figure 2. Q axis current

Figure 3. Speed waveform

The PMSM system starts without load and surges to 6N·m at 0.02 s. The load was reduced to 4N·m at 0.06s. As can be seen from Fig. 1 to Fig. 3, during no-load starting process and load torque sudden increase and decrease, the Q-axis current and torque waveform change under the control of MPCC strategy reflect a fast response speed and a small steady-state error.

Table 2 shows the comparison results of three-phase stator current value THD, where THD is sampling values of three current cycles within a period of 0.1 ~ 0.2s. Compared with the two-level system based on SVPWM and the two-level system based on prediction correction, the MPCC system can lower the three-phase THD value better.
### 5. Conclusion and prospect

In this paper, an improved MPCC control method based on a two-level inverter driving PMSM system is proposed to solve the problem of MPCC model predictive delay control. At the same time, compared with the two-level PMSM SVPWM system, the system has better stability, better performance, stronger anti-interference ability, and reduces the THD value of the three-phase current. In effect, it not only has the advantages of the traditional MPCC rapid response, but also effectively restrains the prediction error and improves the system control performance.

In this study, the two-step prediction method is used to conduct a preliminary study on the prediction error of MPCC, but the system has not completely eliminated the prediction error, and external error factors are not considered enough. In the next step, the observer design can be considered, and the error value can be obtained for direct feedback compensation and other improvements.

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| Systems      | Ia/\% | Ib/\% | Ic/\% |
|--------------|-------|-------|-------|
| MPCC         | 0.68  | 0.91  | 0.91  |
| SVPWM        | 1.05  | 1.21  | 1.21  |
| Improved MPCC| 18.4  | 19.6  | 19.4  |