Predictive Control of Five-leg Inverter-Double Permanent Magnet Synchronous Motor System with Error Feedback Model

Chen Chen¹, Xiong Xiao²*, Qianli Sun¹, Minghua Peng¹, and Jianlei Wu¹

¹Ningbo Polytechnic, Ningbo 315000, China
²University of Science and Technology, Beijing 100089, China

*Corresponding author: 75540672@163.com

Abstract. In this paper, the five-leg inverter-dual permanent magnet synchronous motor system is taken as the research object. To solve the problem of large steady-state speed fluctuation when applying the traditional model predictive control strategy, based on the mathematical models of the five-leg inverter and the dual permanent magnet synchronous motor, the causes of the fluctuation are analyzed, and then an improved model predictive control algorithm with error feedback is proposed. The algorithm makes full use of the high-speed operation ability of modern digital processor, and introduces the prediction value of error feedback correction model, so that the rolling optimization is not only based on the model, but also makes full use of the actual value of the feedback state variables. At the same time, the second-order Euler discrete method is used to further improve the model progress. Simulation and experimental results show that the model predictive control strategy with error feedback can effectively improve the steady-state speed control performance of the system while maintaining the dynamic performance of the original system and the decoupling control effect of the two motors.

1. Introduction

In recent years, with the rapid development of electric vehicles, wind power generation, papermaking and other industrial fields, the application demand of multi-motor high-performance control has emerged. Double-motor system driven by five-leg inverter has been widely used in multi-motor control due to its advantages of simplified topology and reduced cost [1,2].

With the diversification of applications, the performance requirements of the five leg inverter driven dual motor system are higher and higher. After the traditional vector control method is used to improve the application system, there are some problems, such as performance defects, low utilization of DC bus, many parameters are not easy to set and so on [3–6].

In the 1970s, Model Predictive Control (MPC) was successfully applied in the fields of chemical industry, petroleum and other multivariable and low dynamic characteristics. With the continuous improvement of computer operation speed, it is possible to research and apply MPC in systems with high real-time requirements. Since 2007, MPC algorithm has been gradually applied to the fast time-varying systems such as permanent magnet synchronous motor, asynchronous motor and other inverter control. In reference [7], based on the traditional MPC algorithm, the control of PMSM is proposed.
Under the premise of satisfying the constraints, the control variables are predicted in multiple steps, and the optimal input is obtained for system control. In reference [8-10], based on the characteristics of limited switch state combination of inverter itself, considering all possible switch state combinations, one-step or two-step prediction of stator current is carried out, and finally the switch state satisfying the criterion function is selected as the input of inverter.

MPC can effectively improve the dynamic characteristics of the system on the premise of ensuring the stability of a single motor system [11,12], and can realize multi-objective optimization according to different application occasions. However, the application of MPC in multi-machine drive inverter control is relatively limited [13]. In this paper, an improved MPC method is proposed and applied to the transmission system with five-leg inverter driving two motors. First of all, this paper introduces the composition of the five leg inverter, and establishes the mathematical model of the inverter combined with its topology. At the same time, based on the complete decoupling of the stator current in the synchronous rotating coordinate system, the stator current is selected as the state variable, and the mathematical model of the dual permanent magnet synchronous motor in the d-q axis system is established. Secondly, through the analysis of the speed pulsation of motor control based on traditional MPC, error feedback is introduced to correct the predicted value of state variables. At the same time, combined with the requirements of actual control, combined with the discretization accuracy and calculation complexity, the second-order Euler discretization method is used to discretize the state equation of the dual motor, so that the prediction process can form a closed-loop system to improve the prediction control accuracy. Finally, the effectiveness of the proposed model predictive control strategy with error feedback is verified by simulation and experiment.

2. System Topology and Mathematical Model
The topology of the double-motor drive system based on the five-arm drive is shown in the figure, which mainly consists of DC power supply, five-arm inverter and two permanent magnet synchronous motors. Among them, the No.3 bridge arm of the five-leg arm inverter is a common bridge arm, so the five-bridge arm inverter can be divided into two groups of voltage type inverters: No.1, No.2 and No.3 bridge arms are inverter 1 driving M1, and No.3, No.4 and No.5 bridge arms are inverter 2 driving M2.

Figure 1. Topology diagram of a five-bridge arm voltage inverter.
Assuming that the switching devices are all ideal models, the switching states of the five bridge arms of the inverter can be expressed as:

\[
S_x = \begin{cases} 
1, & \text{No. } x \text{ upper bridge arm switch on} \\
0, & \text{No. } x \text{ lower bridge arm switch on} 
\end{cases}
\]  

(1)

Among them \(x = 1, 2, 3, 4, 5\)

Based on the negative pole of DC bus voltage, the voltage of any bridge arm can be expressed as:

\[
V_x = S_x V_{dc}, \quad x = 1, 2, 3, 4, 5
\]  

(2)

Where \(V_{dc}\) is the DC bus voltage, then the line voltage of the inverter is:

\[
V_{xy} = V_x - V_y = V_{dc} (S_x - S_y)
\]  

(3)

Where \(x, y \in \{1, 2, 3, 4, 5\}\) and \(x \neq y\). The phase voltages of the two motors can be derived from (1):

\[
\begin{bmatrix}
V_{a1} \\
V_{b1} \\
V_{c1}
\end{bmatrix} = \frac{1}{3} V_{dc} \begin{bmatrix}
2 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
S_1 \\
S_2 \\
S_3
\end{bmatrix}
\]  

(4)

\[
\begin{bmatrix}
V_{a2} \\
V_{b2} \\
V_{c2}
\end{bmatrix} = \frac{1}{3} V_{dc} \begin{bmatrix}
2 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
S_4 \\
S_5 \\
S_6
\end{bmatrix}
\]  

(5)

Write the above formula in the static \((\alpha-\beta)\) coordinate system:

\[
\begin{bmatrix}
V_{\alpha 1} \\
V_{\alpha 2} \\
V_{\beta 1} \\
V_{\beta 2}
\end{bmatrix} = \frac{2}{3} V_{dc} \begin{bmatrix}
1 & -\frac{1}{2} & -\frac{1}{2} & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & \frac{1}{2} & \frac{1}{2} \\
0 & \sqrt{3} & -\sqrt{3} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix} \begin{bmatrix}
V_{a1} \\
V_{b1} \\
V_{a2} \\
V_{b2}
\end{bmatrix}
\]  

(6)

In this paper, the synchronous coordinate axis system oriented by rotor magnetic field is adopted, so the control input of the system is transformed to the d-q axis system:

\[
\begin{bmatrix}
V_{\alpha 1} \\
V_{\alpha 2} \\
V_{\beta 1} \\
V_{\beta 2}
\end{bmatrix} = \begin{bmatrix}
\cos \theta_1 & 0 & \sin \theta_1 & 0 \\
0 & \cos \theta_2 & 0 & \sin \theta_2 \\
-\sin \theta_1 & 0 & \cos \theta_1 & 0 \\
0 & -\sin \theta_2 & 0 & \cos \theta_2
\end{bmatrix} \begin{bmatrix}
V_{\alpha 1} \\
V_{\alpha 2} \\
V_{\beta 1} \\
V_{\beta 2}
\end{bmatrix}
\]  

(7)
Where $\theta_1$ and $\theta_2$ are angles respectively representing rotor flux linkage of the motor 1 and the motor 2.

Under the vector control strategy of rotor magnetic field orientation, the electromagnetic torque of the motor is proportional to the Q-axis current, and permanent magnet synchronization can be equivalent to a "DC motor" with relatively simple control. Therefore, the synchronous coordinate system of rotor magnetic field orientation is also adopted in this paper, and the d-q axis current is selected as the state variable.

The state space expression of the two permanent magnet synchronous motors is:

$$\begin{align*}
\dot{X} &= AX + BU \\
Y &= CX
\end{align*}$$ (8)

Among them

$$X = \begin{bmatrix} I_{d1} & I_{q1} & I_{d2} & I_{q2} \end{bmatrix}^T, U = \begin{bmatrix} V_{d1} & V_{d2} & V_{q1} & V_{q2} & \omega_1 & \omega_2 \end{bmatrix}^T$$ (9)

$$A = \begin{bmatrix}
-\frac{R_1}{L_{s1}} & 0 & p_1\omega_1 & 0 \\
0 & -\frac{R_2}{L_{s2}} & 0 & p_2\omega_2 \\
-p_1\omega_1 & 0 & -\frac{R_1}{L_{s1}} & 0 \\
0 & -p_2\omega_2 & 0 & -\frac{R_2}{L_{s2}}
\end{bmatrix}, C = \begin{bmatrix} 1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}$$ (10)

$$B = \begin{bmatrix}
\frac{1}{L_{s1}} & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{L_{s2}} & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{1}{L_{s1}} & 0 & -\frac{\psi_{pm1}}{L_{s1}} & 0 \\
0 & 0 & 0 & \frac{1}{L_{s2}} & 0 & -\frac{\psi_{pm2}}{L_{s2}}
\end{bmatrix}$$ (11)

Where $R_i$ is the stator resistance, $L_{si}$ is the stator inductance, $P_i$ is the pole number of the motor, $\omega_i$ is the mechanical angular velocity of the motor rotor, and $\psi_{pmi}$ is the permanent magnet linkage. The above-mentioned parameter $i = 1,2$ represents the motor 1 and the motor 2 respectively.

3. Model Predictive Control with Error Feedback

3.1. Improved Model Predictive Control
MPC algorithm is based on the mathematical model of multi-motor system. However, due to the existence of nonlinearity, model mismatch, interference and other factors in the actual system, the prediction based on the invariant model cannot completely conform to the actual situation. The MPC algorithm, which is traditionally applied to motor control, only relies on the motor model to predict the state quantity at the future time, and does not correct the prediction error. Then the model predictive
control at this time is only a simple open loop prediction, and its rolling optimization is not based on feedback correction. This open-loop model predictive control will lead to the wrong switch state combination at some time, and the speed fluctuation of the steady-state operation of the motor is inevitable.

This requires the use of additional forecasting means to optimize the shortcomings of model forecasting. As we all know, feedback plays an irreplaceable role in overcoming the influence of disturbance and uncertainty and obtaining the closed-loop stability. Therefore, in the traditional MPC algorithm applied to motor control, feedback correction is introduced to correct the error value in the actual prediction process. That is, based on the prediction output of the model, the prediction value is constantly modified according to the actual output of the system, and then new optimization is carried out. This feedback correction method makes rolling optimization not only based on the model but also using feedback information to form closed-loop optimization.

The structural block diagram of the model predictive control system based on current feedback is shown in Figure 2.

![Figure 2. Block diagram of improved MPC control strategy.](image)

The improved MPC algorithm adds an error feedback module based on the traditional algorithm. According to the definition, $e(k+1)$ is the difference between the actual state variable value and the predicted value at the time of $K+1$:

$$e(k+1) = X(k+1) - X_m(k+1|k)$$ (12)

Where $x(k+1)$ represents the feedback value of the $k+1$th cycle system, and $x_m(k+1|k)$ represents the predicted value of the $k+1$th cycle. Since $x(k+1)$ is not available, $e(k)$ is used to approximate $e(k+1)$, that is:

$$e(k) = X(k) - X_m(k|k-1)$$ (13)

The error is added to the prediction output of the model to obtain the closed-loop prediction output of the system. The predicted value of the state variable at time $k+1$ after correction is:

$$X^n(k+1) = X_m(k+1|k) - h_p e(k)$$ (14)
As mentioned above, the d-axis and q-axis currents of the two motors are state variables, so equation (14) can be expanded and expressed as:

\[
\begin{bmatrix}
I_{d1}^p (k + 1) \\
I_{d2}^p (k + 1) \\
I_{q1}^p (k + 1) \\
I_{q2}^p (k + 1)
\end{bmatrix} =
\begin{bmatrix}
I_{d1}^m (k + 1 | k) \\
I_{d2}^m (k + 1 | k) \\
I_{q1}^m (k + 1 | k) \\
I_{q2}^m (k + 1 | k)
\end{bmatrix} + h_p
\begin{bmatrix}
I_{d1}^p (k) - I_{d1}^p (k) \\
I_{d2}^p (k) - I_{d2}^p (k) \\
I_{q1}^p (k) - I_{q1}^p (k) \\
I_{q2}^p (k) - I_{q2}^p (k)
\end{bmatrix}
\] (15)

Where \( a a a \) is the current prediction value corrected by feedback, \( d d d \) is the current prediction value obtained according to the discrete model, and \( f f f \) is the current feedback value of the k-th cycle. Where \( I = 1 \) and \( 2 \) respectively represent motor 1 and motor 2. \( X c \) can be \( d \) and \( q \) represent d-axis component and q-axis component.

Among them, \( I_{d1}^p (k + 1) \) is the current prediction value corrected by feedback, \( I_{d1}^m (k + 1 | k) \) is the current prediction value obtained according to the discrete model, and \( I_{d1}^p (k) \) is the current feedback value of the k-th cycle. Where \( i=1,2 \), respectively representing motor 1 and motor 2. \( x \) can take \( d \) and \( q \) to represent d-axis component and q-axis component.

3.2. Improved Discretization Algorithm

MPC is a model-based control algorithm, so the accuracy of system modeling directly affects the control effect of MPC. In reference [16], the first-order Euler method is used to discretize the continuous expression and predict the state value at the next moment. The calculation amount is greatly reduced, but the accuracy of the first-order Euler method is limited, which will affect the predictive control effect.

Literature [17] used Gloria-Hamilton to discretize the system, and an accurate discrete model can be obtained:

\[ X (k + 1) = \Phi X (k) + HU (k) \] (16)

Where: \( X (k) \) is the state variable of the kth cycle; \( X (k + 1) \) is the predicted value of the state variable of the k+1th cycle; \( \Phi \) is the state matrix index, expressed as:

\[
\begin{align*}
\Phi &= e^{\Delta T} \\
H &= \int_{0}^{T} e^{\Delta T} dt \cdot B
\end{align*}
\] (17)

Equation (17) has high on-line computational complexity and is not suitable for real-time control. However, if the continuous expression is discretized by the first-order Euler method and the state value at the next moment is predicted, the calculation amount is much smaller, but the precision of the first-order Euler discretization method is limited, which affects the predictive control effect. Considering the accuracy and calculation amount, this paper adopts the following form of second-order Euler discrete method to predict the state variables at the next moment:

\[
\begin{align*}
X_p (k + 1) &= X (k) + T_e \left[ AX (k) + BU (k) \right] \\
X (k + 1) &= X_p (k + 1) + \frac{T_e}{2} A [X_p (k + 1) - X (k)]
\end{align*}
\] (18)
In the formula: $T_c$ is the control period; $x_p(k+1)$ is the correction variable. The state matrices $A$, $B$ are consistent with formula (8) in section 2.2. After improving the MPC algorithm and the discretization method, the improved algorithm implementation flow chart is shown in Figure 4.

![Flow Chart](image)

**Figure 3.** Improved MPC algorithm flow chart.

4. Simulation and Analysis

4.1. Simulation condition

In order to verify the effectiveness of the proposed model prediction algorithm, a five-arm inverter drive system simulation model was established on the Matlab/Simulink platform. The simulation parameters are shown in the following table.
Table 1. Simulation and experimental parameters.

| Parameter | Numerical | Numerical | Numerical |
|-----------|-----------|-----------|-----------|
| $U_N/V$   | 380       | $f_N/Hz$  | 50        |
| $R_s/\Omega$ | 1.3      | $n/(r/min)$ | 1500     |
| $L_d/mH$  | 6.35      | $T_N/(N \cdot m)$ | 15     |
| $L_q/mH$  | 6.35      | $P$       | 4         |
| $\phi$    | 0.201     | $J/(kg \cdot m^2)$ | 0.0008 |
| $Ts/us$   | 40        |           |           |

4.2. Steady state characteristic simulation

As shown in Figure 4, when the load torque is set to 2Nm, the motor 1 speed setting value is 100 rad/s, and the motor 2 speed setting value is 70 rad/s.

Observe its speed waveform, and the speed of the two motors reaches the set value after 0.03 s. The overshoot $\sigma_1$ of motor 1 is about 3.23%, the overshoot $\sigma_2$ of motor is about 1.83%, and the steady-state error of motor speed is zero. This shows that the two motors can track different speed settings at this time, and the speed response of the motors is rapid.

In order to compare the steady-state characteristics of the proposed algorithm and the traditional MPC algorithm, the following experiments are further designed in this paper: when the motor is in steady-state operation, the control algorithm of the system is switched from the traditional MPC algorithm to the improved MPC algorithm at 0.2 s.

Figure 4. Speed waveform of motor 1, 2.
Figures 5a and 5b are speed curves of the motor 1 and the motor 2, wherein the red curve is a speed setting value and the blue curve is a speed feedback value. After observing the Q-axis current and speed waveform of the motor and switching to MPC with error feedback, the torque ripple of the motor is obviously suppressed.

In order to quantify the degree of motor speed ripple, this paper uses the speed ripple factor (SRF). By definition, the ripple coefficient is:

\[ SRF = \frac{\omega_{pp}}{\omega_{ave}} \times 100\% \]  (19)

Where: \( \omega_{pp} \) is the peak-to-peak value of speed fluctuation, \( \omega_{ave} \) is the average speed.

Analysis and calculation of the speed feedback values under the two controllers according to equation (19) show that after adding feedback error, SRF of motor 1 is reduced from 0.13% to 0.01%, and SRF value of motor 2 is reduced from 0.28 to 0.02%.
4.3. Dynamic characteristic simulation

In order to investigate the dynamic performance of the improved MPC algorithm and the anti-interference ability of the system, this paper designs dynamic simulation of sudden change of rotational speed and sudden change of torque. Initially, the given rotation speed of the motor 1 is 40 rad/s and the given rotation speed of the motor 2 is 30 rad/s; At 1s, the speed setting of the motor changes abruptly from 30 rad/s to -30 rad/s.

![Speed waveforms of motors 1 and 2 when the speed changes suddenly](image1)

![A-phase waveform of the motor](image2)

![A phase waveform of the motor](image3)

**Figure 6.** (a) Speed waveforms of motors 1 and 2 when the speed changes suddenly, (b) A-phase waveform of the motor, (c) A phase waveform of the motor.

As shown in Figure 6(a), the forward and reverse switching process of the motor is stable, and the rotation speed can quickly reach the set value after the abrupt change command is issued for 0.02s s. The motor 1 fluctuates when the motor 2 performs speed adjustment, but the speed fluctuation is small and can finally stabilize at the set value. According to Figure 6(b), the forward and reverse dynamic transformation of the motor 2 does not affect the operation of the motor.

In addition, a sudden torque increase experiment has been carried out. As shown in the following figure, the torque setting value of motor 1 suddenly changed from 2Nm to 4Nm in 1s, and the torque setting of motor 2 remained unchanged throughout the experiment.
Figure 7. (a) Speed waveforms of motors 1 and 2 when the torque changes suddenly. (b) Phase A waveform of motor 1. (c) Phase A waveform of motor 2.

Looking at 7abc in Figure 7, the rotation speed of motor 1 decreases due to the increase of torque at 1s, and the motor can quickly re-track the upper set value after 0.05s; The motor 2 runs stably at the set rotational speed without any rotational speed pulsation.

5. Experiments and Analysis

5.1. Experimental system
This paper conducted an experimental study on a 15kW five-bridge inverter prototype. The experimental platform is shown in the following figure, including the main circuit, control circuit, sampling conditioning circuit, motor and its load. The control circuit uses 32-bit floating point DSP TMS320F28335. In addition, the control board is also extended through the RS232 serial port for internal variable observation of the motor, and the host computer communicates in real time. The parameters of the hardware system are consistent with the simulation parameters.
Figure 8. The experimental platform of 15kW five-bridge inverter prototype.

5.2. Steady state test
The load torque of the two motors is no load, the set value of the rotation speed of the motor 1 is 300r/min, and the rotation speed of the motor is set to 450r/min. The rotation speed output waveforms of the two motors are shown in Figure 9.

As the manual voltage regulator is used to regulate the DC bus voltage in this experiment, it will take some time for the DC bus voltage to reach the expected value. Therefore, the dynamic performance of speed response is poor. But the motor can finally track the set value.

In order to verify that the improved MPC algorithm can reduce torque ripple. When the motor runs in steady state for a certain period of time, the control algorithm of the system is switched to the improved MPC algorithm. As shown in Figure 10, the q-axis current waveform of the motor 1 is shown. The improved MPC algorithm significantly reduces the pulsation of the q-axis current.
Figure 10. Motor 1 q-axis current waveform.

5.3. Dynamic experiment

Figure 11 shows the motor state waveform with abrupt motor speed change, which is the motor current, speed and q-axis current from top to bottom. The given rotation speed of motor 1 is 100r/min, and it suddenly changes to 200 r/min at 20s; The initial set rotation speed of the motor 2 is 300r/min and remains unchanged throughout the process.

Observing the waveform diagram, the motor speed can quickly reach the set value after the sudden change instruction is issued for 0.8s; The state of the motor is not affected by the motor 1 and still maintains the original steady-state operation state.

In addition, in order to fully verify the dynamic performance of the algorithm, this paper also designs a load mutation experiment. The load of the motor 1 is unchanged, the load of the motor 2 changes from full load to 60%, and the running state of the motor is shown in the Figure 12.
The sudden change of load causes the rotation speed to increase. Observing the above figure shows that the torque of the motor 2 can quickly track the sudden change of load, and the motor will reach a stable state again after 0.8s; However, the motor 1 still operates normally and stably during this process.

6. Summary
In this paper, an improved model predictive control strategy is proposed to solve the problems of large computation and large speed fluctuation in the model predictive control strategy of the five-leg inverter-double permanent magnet synchronous motor system. On the one hand, the accuracy of the system model is improved by the second-order Euler discrete method; on the other hand, the prediction value of the model is corrected by introducing error feedback, so that the current prediction becomes a closed-loop process. Simulation and experimental results show that:

1) MPC has been successfully applied to the system. The five-leg inverter-driven dual permanent magnet synchronous motor system can operate stably and has good steady-state and dynamic characteristics.

2) By improving the algorithm, the improved MPC selects the appropriate switching vector, which suppresses the torque ripple of the motor in the system and improves the steady state of the motor.

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