Improved fast three-vector predictive current control of permanent magnet synchronous motor

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Abstract. In order to improve the steady-state performance of the traditional model predictive control and reduce the amount of calculation of the control algorithm, this paper proposes a new fast three-vector predictive current control algorithm, which uses the principle of deadbeat control of the dq-axis current to calculate the reference voltage vector, and obtains the reference voltage vector position through sector judgment, combined with the three-vector model predictive control algorithm, the optimal voltage vector is directly applied to the motor, without the need to predict the behavior of the system under the voltage vector, which greatly reduces the amount of calculation. At the same time, due to the introduction of three vectors, three functions are applied in one cycle. The voltage vector greatly improves the steady-state characteristics of the system. The simulation results show that the proposed new three-vector predictive current control algorithm can reduce the amount of calculation and improve the steady-state characteristics of the system.

1. Introduction

Permanent magnet synchronous motors are widely used in various fields because of their high efficiency and high power density [1]. There are mainly two traditional high-performance control schemes for permanent magnet synchronous motors, field-oriented control and direct torque control. In recent years, finite set model predictive control has also attracted more and more attention. This control method has the advantages of simple principle and easy handling of nonlinear constraints[2].

Model predictive control can be divided into predictive torque control and predictive current control. Predictive torque control usually takes electromagnetic torque and stator flux as the control variables. It is necessary to design appropriate weight coefficients when constructing the objective function. At this stage, there is no effective means to confirm the weight coefficient [3,4]. For predictive current control, the control variable is current, so the problem of total weight coefficients can be avoided. The traditional model predictive control algorithm needs to make 7 predictions, and bring them into the cost function for judgment. The amount of calculation is large .Literature [5] proposes to filter out some candidate vectors. This method cannot guarantee the global optimality of the selected vectors. Literature [6] proposed that the reference voltage is obtained through the principle of deadbeat current, and the position of the reference voltage is judged, and then the predicted current under the action of the filtered voltage vector and the zero voltage vector is brought into the cost function for judgment. This method still requires two calculations and judgments. Traditional model predictive control only selects an optimal voltage vector to act on the motor in a control cycle, resulting in poor steady-state performance of the control system. Literature [7] proposed a three-vector model predictive control scheme, which greatly improves the steady-state characteristics
of the system, but still requires 6 calculations and judgments, and the calculation amount of the
growth algorithm has not been significantly reduced. In order to improve the steady-state performance of
traditional model predictive control and reduce the amount of calculation of the control algorithm, this
paper proposes a new algorithm that does not require predictive judgment, greatly reduces the
complexity and calculation of the algorithm, and combines the three-vector model predictive
algorithm, which is effective Improve the steady-state performance of the system.

In order to verify the effectiveness of the algorithm, a simulation was performed in matlab. The
experimental results show that the algorithm proposed in this paper reduces the amount of calculation
and improves the steady-state performance compared with the traditional model prediction algorithm.

2. Mathematical Model of Permanent Magnet Synchronous Motor
In this paper, the built-in permanent magnet synchronous motor is selected as the object, and the
voltage mathematical model in the synchronous rotating coordinate system can be expressed as
\[
\begin{align*}
    u_d &= R_d i_d + L_d \frac{di_d}{dt} - \omega_L i_q \\
    u_q &= R_q i_q + L_q \frac{di_q}{dt} + \omega_L (L_d i_d + \phi_f) 
\end{align*}
\]

Among them, the flux linkage equation satisfies:
\[
\begin{align*}
    \phi_d &= L_d i_d + \phi_f \\
    \phi_q &= L_q i_q 
\end{align*}
\]

The torque equation is described as:
\[
T_e = \frac{3}{2} p_n [i_d (L_d - L_q) \phi_f] 
\]

In the formula: \( u_d, u_q, i_d, i_q, \phi_d, \phi_q \) are the d and q axis stator voltage, stator current and stator
flux linkage respectively; \( \omega_L \) is the electrical angular velocity; \( L_d \) and \( L_q \) are the d and q axis
inductances; \( R \) is the stator phase resistance; \( \phi_f \) is the permanent magnetic flux linkage; \( T_e \) is the
electromagnetic torque; \( p_n \) is the number of magnetic pole pairs.

3. Traditional model predictive current control
The block diagram of the traditional permanent magnet synchronous motor model predictive current
control principle is shown in Figure 1. The speed outer loop generates the q-axis current reference
value through PI adjustment, and the d-axis current reference value is set to 0, and the predicted
current controller will track the d and q-axis reference currents.
In the rotating coordinate system, the state equation of the stator current can be described as:
\[
\begin{align*}
    \frac{di_d}{dt} &= u_d - R_d i_d - \omega L_d i_q \\
    \frac{di_q}{dt} &= u_q - R_q i_q - \omega_L (L_d i_d + \phi_f) 
\end{align*}
\]

Select the stator current as the state quantity, and use the first-order Euler discretization method to
discretize equation (4) to obtain:
\[
\begin{align*}
    i_d^{k+1} &= i_d^k + \frac{T}{L_d} (u_d^k - R_d i_d^k + \omega L_d i_q^k) \\
    i_q^{k+1} &= i_q^k + \frac{T}{L_q} (u_q^k - R_q i_q^k + \omega_L (L_d i_d^k + \phi_f)) 
\end{align*}
\]
In model predictive control, the value function is an evaluation index for online optimization, which is used to select the optimal voltage vector for the next sampling period. In this paper, $i_d$ and $i_q$ are selected as the control variables to realize the decoupling control of the current excitation component and the current torque component. The specific value function is defined as follows:

$$ g = |i_d^* - i_d^{k+1}| + |i_q^* - i_q^{k+1}| $$

In the prediction scheme, the discrete model of the motor will be responsible for predicting the stator currents corresponding to the seven different voltage vectors generated by the inverter. Select the voltage vector that can minimize the cost function and apply it to the entire sampling period.

![Figure 1](image1.png)

**Figure 1. Block diagram of traditional model predictive control**

### 4. New fast three-vector predictive current control

For traditional model predictive current control, the $d$ and $q$ axis currents under all voltage vectors need to be predicted in each control cycle, and the corresponding objective functions need to be compared cyclically, which requires a large amount of calculation. Predictive control itself hopes to shorten the control cycle and further improve the control performance. In addition, the traditional model predictive control only acts on one voltage vector in a control cycle. When the predicted current value after the optimal voltage vector is less than or greater than the given value, the control quantity will have large fluctuations and the steady-state performance of the system is poor.

In order to solve the above problems, this paper proposes a new fast three-vector predictive current control method. This method combines the deadbeat predictive current control algorithm and uses the principle of current deadbeat control to predict the reference voltage vector that should be applied in the next control cycle. Then by judging the sector where the reference voltage vector is located, using the three-vector model predictive control algorithm, Combine the adjacent effective voltage vector and the zero voltage vector of the sector where the reference voltage is located, and again use the principle of current deadbeat control between the alternating and direct axis current to calculate the action time of the two effective voltage vectors and the zero voltage vector, and combine the three voltage vectors. The optimal voltage vector is applied to the motor. This method directly eliminates the loop prediction current link of the model predictive control algorithm and the cost function comparison link, which greatly reduces the calculation time of the traditional model predictive control algorithm. In addition, due to the voltage vector of a control cycle It is composed of two effective voltages and one zero voltage, which will greatly improve the steady-state performance of the system.

In formula (5), set $i_d^{k+1} = i_d^* + i_d^{k+1}$ and $i_q^{k+1} = i_q^*$, the ideal voltage vector can be obtained:

$$
\begin{align*}
    u_d^* &= R_l i_d^* + L_d (i_d^* - i_d^{k+1}) / T_s + \omega_s L_l i_q^* \\
    u_q^* &= R_l i_q^* + L_q (i_q^* - i_q^{k+1}) / T_s + \omega_s (L_d i_d^* + \varphi_f)
\end{align*}
$$

(7)
Transform the reference voltages $u_d^*$ and $u_q^*$ in the $dq$ coordinate system to $u_d^{**}$ and $u_q^{**}$ in the $\alpha\beta$ coordinate systems by inverse Park, and calculate the reference voltage vector position angle $\theta$ according to (7):

$$\theta = \arctan\left(\frac{u_{\beta}^*}{u_d^*}\right)$$  \hspace{1cm} (8)

According to the position angle $\theta$, determine the location of the reference voltage. For example, the reference voltage vector $u^*$ is located in the first sector. Therefore, the effective voltage vector $u_1$, $u_2$ and one of the two zero voltage vectors $u_0$ and $u_7$ are selected to synthesize the reference voltage $u^*$, and $f$ uses the $dq$ axis current non-beat tracking to calculate the action time of the three voltage vectors.

When the zero voltage vector is applied, the calculation formulas of the current slope of the orthogonal axis are

$$s_{d0} = \frac{di_d}{dt}\bigg|_{i_q=0} = \frac{1}{L_d}\left[-Ri_d + \omega_L i_q\right]$$

$$s_{q0} = \frac{di_q}{dt}\bigg|_{i_q=0} = \frac{1}{L_q}\left[-Ri_q - \omega_L i_d - \omega_L i_\varphi\right]$$  \hspace{1cm} (9)

From equation (8), when two effective reference voltage vectors $u_i$ and $u_j$ are acting, the current slope of $dq$ axis is

$$\begin{align*}
S_{d1} &= \frac{di_d}{dt}\bigg|_{i_q=0} = \frac{u_{d1}}{L_d}, S_{q1} = \frac{di_q}{dt}\bigg|_{i_q=0} = \frac{u_{q1}}{L_q} \\
S_{dj} &= \frac{di_d}{dt}\bigg|_{i_q=0} = \frac{u_{dj}}{L_d}, S_{qj} = \frac{di_q}{dt}\bigg|_{i_q=0} = \frac{u_{qj}}{L_q}
\end{align*}$$  \hspace{1cm} (10)

Where $u_{d1}$, $u_{q1}$, $u_{dj}$, and $u_{qj}$ are the voltage components of $u_i$ and $u_j$ on the $dq$ axis, respectively.

Use current deadbeat control, set $i_{d1} = i_{q1} = i_{qj}$

$$\begin{align*}
i_{d1}^{k+1} &= i_{d1} + s_{d1}t_i + s_{d0}t_j + s_{d0}t_z = i_d \\
i_{q1}^{k+1} &= i_{q1} + s_{q1}t_i + s_{q0}t_j + s_{q0}t_z = i_q
\end{align*}$$  \hspace{1cm} (11)

In the formula, $t_i$, $t_j$ are the action time of $u_i$, $u_j$ respectively; $t_z$ is the action time of the zero voltage vector. The sum of the action time of the three voltage vectors is

$$T_s = t_i + t_j + t_z$$  \hspace{1cm} (12)

Combining (8) ~ (11) can be solved

$$t_i = \frac{(i_{q1} - i_{d1})(s_{q0} - s_{q1}) + (i_{d1} - i_{q1})(s_{d0} - s_{d1})}{s_{q0}s_{d1} + s_{q1}s_{d0} + s_{d1}s_{d0} - s_{d0}s_{q1} - s_{q1}s_{d0} - s_{q0}s_{d1}} + T_s\left(s_{q0}s_{d1} - s_{q1}s_{d0}\right)$$

$$T_s\left(s_{q0}s_{d1} - s_{q1}s_{d0}\right)$$  \hspace{1cm} (13)
\[ t_j = \frac{(i_d^* - i_d^k)(s_{q0} - s_{qj}) + (i_q^* - i_q^k)(s_{d0} - s_{dq})}{s_{q0}s_{dq} + s_{qj}s_{d0} + s_{dq}s_{d0} - s_{dq}s_{dq} - s_{dq}s_{dq} - s_{dq}s_{dq}} + \]

\[ T_s \left( s_{q0}s_{d0} - s_{dq}s_{dq} \right) \]

\[ s_{q0}s_{dq} + s_{qj}s_{d0} + s_{dq}s_{d0} - s_{dq}s_{dq} - s_{dq}s_{dq} - s_{dq}s_{dq} \]

\[ t_z = T_s - t_i - t_j \] (15)

Formulas (11) ~ (15) After calculating \( t_i, t_j, t_z \), we need to judge whether they are within the range of \( 0 \sim T_s \). If they are not within the range, cancel the corresponding voltage vector effect, which can be divided into the following situations:

- If \( t_z \) is not in the range, \( t_i \) and \( t_j \) both are in the range, then two effective vectors act on one cycle;
- If \( t_z \) is in the range and only \( t_i \) or \( t_j \) is in the range, then an effective vector and a zero voltage vector will act on a cycle;
- If \( t_z \) is not in the range and only \( t_i \) or \( t_j \) is in the range, then an effective vector acts on a cycle;

5. Simulation

In order to verify the correctness and effectiveness of the new fast three-vector predictive current control method proposed in this paper, Matlab/Simulink is used to build a simulation model of the traditional MPC and the new fast three-vector predictive current method and compare them. The sampling frequency of the system is set to 20KHz, the specific parameters are shown in Table 1, and the simulation results are shown in the figure. The three waveforms in Fig.2 and Fig.3 are the mechanical speed of phase A current and the electromagnetic torque. It can be seen from the figure that the new fast three-vector predictive current control method proposed in this paper is compared with the traditional MPC, the torque ripple are significantly reduced, and the steady-state performance is better.

| Table 1. Simulation parameters |
|-----------------|-----------------|-----------------|-----------------|
| **Parameter**   | **Value**       | **Parameter**   | **Value**       |
| \( U_{dc} / V \) | 311             | \( L_dL_m / mH \) | 5.25\|12 |
| \( n(r/\text{min}) \) | 1000           | \( \phi_f / Wb \) | 0.1827         |
| \( P_n \)      | 4               | \( J / (kg \cdot m^2) \) | 0.003          |
| \( R_s / \Omega \) | 0.958         | \( T_e / (N.m) \) | 3              |
6. Conclusion

Based on the three-vector model predictive control, combined with the deadbeat predictive current control method, a new type of fast three-vector predictive current control method is proposed. The method does not need to perform 7 online predictions, only need to use the dq-axis current deadbeat to get the reference voltage vector, and calculate the action time of each voltage vector, and then act on the permanent magnet synchronous motor. This method reduces the calculation amount and algorithm complexity of traditional model predictive control. Compared with the traditional deadbeat predictive control, the SVPWM modulation step is omitted, and the algorithm complexity is further reduced. Simulation and experiment show that the control algorithm proposed in this paper has good dynamic and steady-state performance.

References

[1] S. Kouro, P. Cortes, R. Vargas, U. Ammann and J. Rodriguez,(2009)Model Predictive Control—A Simple and Powerful Method to Control Power Converters[J].in IEEE Transactions on Industrial Electronics, vol. 56, no. 6, pp. 1826-1838.
[2] Rodriguez J, Kennel R, Espinoza J, et al. (2012) High performance control strategies for electrical drives: An experimental assessment[J]. IEEE Transactions on Industrial Electronics, 59(2): 812-820.
[3] Rojas CA, Rodriguez J, Villarroel F, et al. (2013) Predictive Torque and Flux Control Without Weighting Factors[J]. IEEE Transactions on Industrial Electronics, 60(2):681-690.
[4] Wang B, Wang Y, Guo W, et al. (2014,) Deadbeat direct torque control of permanent magnet synchronous motor based on reduced order stator flux observer[J]. Transactions of China Electrotechnical Society, 29(3):160-171. (Chinese).
[5] Niu F, Li K, Wang Y.(2015)Model predictive direct torque control for permanent magnet synchronous machines[J].Electric Machines and Control,19(12):60-67(Chinese).
[6] Zhang Y, Yang H, Wei X(2016) Model Predictive Control of Permanent Magnet Synchronous Motors [J]. Electric Machines and Control,31(6):66-73(Chinese)
[7] Xu Y, Wang J, Zhang B, Zhou Q.(2018) Three-Vector-Based Model Predictive Current Control for Permanent Magnet Synchronous Motor,[J]. Electric Machines and Control,33(5):980-987(Chinese)