Model Predictive Current Control of Dual Inverter Fed Open-End Winding PMSM Based on Fast Vector Selection

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Abstract： Aiming at the problem of model predictive current for the dual two-level inverter needs to optimize the objective function of all 19 voltage vectors, which makes the calculation of optimization too large for practical application. A MPCC scheme for open-winding pmsm based on voltage vector preselection was proposed. First, the pre-selection of the voltage vector is performed by calculating the reference voltage vector using the deadbeat solution. And establish a voltage vector based objective function to achieve predictive current control and simplify the control algorithm. Next, the switching frequency constraint is introduced into the objective function to select the optimal switching state and reduce the average switching frequency. Finally, the simulation is verified and the effectiveness of the method is proved.

1. Introduction

The open-end winding permanent magnet synchronous motor (OEW-PMSM) can use two different power supplies, with multi-level features, flexible control modes and powerful fault tolerance.[1]. It has broad application prospects in the field of electric vehicles.

For getting good system performance, the high-performance control strategy of OEW-PMSM has always been a research hotspot. At present, DTC and FOC have been widely used. In DTC systems, good dynamic response is obtained, but torque ripple is usually large; in FOC systems, steady state performance is better than DTC, but the inverter has a higher switching frequency and a slower transient response.

In motor drive, MPC has received extensive attention owing to its simplicity and flexibility for multiple constraints [2]. Among them, FCS-MPC [3] uses the characteristics of the finite-switch state of the converter, and combines the system mathematical model to predict the future performance of the system. The objective function is constructed for online optimization, and the required switching state is directly selected. With no additional modulation technique, the parameters are easy to set, and the objective equation can be used to add other control objectives and deal with system constraints.

However, in a dual inverter driven permanent magnet synchronous motor drive system, more switching states and voltage vectors are involved, which adds the complexity of the prediction vector. There are more voltage vectors and multiple control constraints in [4] and [5]. In order to select the optimal voltage vector, more evaluation work on the objective function is required. Therefore, reducing calculation amount becomes an important issue in the new generation of permanent magnet synchronous motor systems. In addition, since some voltage vectors have several different switching states, the optimum voltage vector with the least switching loss must be considered.

In this paper, an improved MPC method is proposed for the problem of excessive selection of optimal switching vector selection and high switching frequency in the traditional dual-inverter feed system model predictive current control.

Firstly, mathematical modeling was carried out, and then an improved algorithm was proposed based on the traditional model of predictive current control, which including the calculation of no difference beat voltage, divided into sectors for voltage vector preselection. The optimal voltage vector can be obtained by a single comparison, which obviously reduces the computation of the program. In addition, in order to reduce the average switching frequency, the switching frequency constraint is introduced into the value function to select the optimal switching state. Finally, the correctness of the control strategy studied in this paper is verified by MATLAB, and the simulation results are given.

2. OEW- PMSM

2.1. Model of drive system

The structure of the open-winding PMSM system is shown in Fig.1, where Vdc1 = Vdc2.

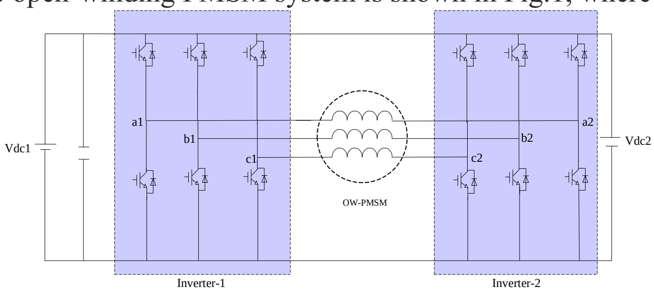


Fig. 1 OEW- PMSM system

In this paper, the rotor magnetic field orientation method is adopted. The voltage equation in the dq coordinate system may be expressed as:

$$\begin{cases} u_d = R_s i_d + L_d \dfrac{di_d}{dt} - w_e L_q i_q \\ u_q = R_s i_q + L_q \dfrac{di_q}{dt} + w_e L_d i_d + w_e \Psi_f \end{cases} \tag{1}$$

Where $u_d, u_q, i_d, i_q, L_d, L_q$ are the d- q axis components of the stator voltage, current, and inductance, respectively; ω_e is the rotor electrical speed; ψ_f is permanent magnet flux linkage; R_s is the stator resistance.

The torque can be expressed as:

$$T_e = \frac{3}{2} P_n \left[\Psi_f i_q + (L_d - L_q) i_d i_q \right] \tag{2}$$

Where P_n is the number of pole pairs.

2.2. Voltage Vectors of Dual Inverters

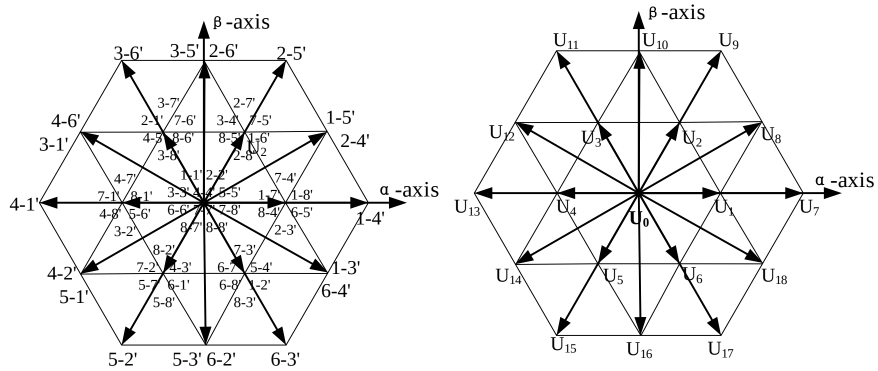
The stator voltage can be expressed as:

$$\begin{cases} u_a = V_{a1} - V_{a2} \\ u_b = V_{b1} - V_{b2} \\ u_c = V_{c1} - V_{c2} \end{cases} \tag{3}$$

The voltage vector can be defined as:

$$V_s = \frac{2}{3}\left(u_a + u_b e^{j\frac{2\pi}{3}} + u_c e^{j\frac{4\pi}{3}} \right) \tag{4}$$

In the OEW-PMSM system, each inverter can generate eight switching states. Therefore, there are a total of 64 voltage switching states and 19 voltage vectors. The distribution of all switching states and voltage vectors is shown in fig.2.



(a) (b)

Fig. 2 Space voltage vector plane for dual two-level inverters: (a) all switching states; (b) all different voltage vectors

3. Proposed method

3.1. The basic control algorithm

Based on (1), the stator current can be expressed as

$$\begin{cases} \dfrac{di_d}{dt} = -\dfrac{R_s}{L_d} i_d + \dfrac{L_q}{L_d}\omega_e i_q + \dfrac{1}{L_d} u_d \\ \dfrac{di_q}{dt} = -\dfrac{R_s}{L_q} i_q - \dfrac{L_q}{L_q}\omega_e i_d + \dfrac{1}{L_d} u_d - \omega_e \dfrac{\Psi_f}{L_q} \end{cases} \tag{5}$$

Although the traditional first-order forward Euler discrete method is relatively simple, the accuracy is poor[6]. To improve prediction accuracy without significantly increasing computational complexity, In this paper, the second order Euler discrete method is used to discretize equation (5).

$$\begin{cases} i_{dp}{}^{k+1} = i_d{}^k + \dfrac{T_s\left(u_d{}^k - R_s i_d{}^k - E_d{}^k\right)}{L_d} \\ i_{qp}{}^{k+1} = i_q{}^k + \dfrac{T_s\left(u_q{}^k - R_s i_q{}^k - E_q{}^k\right)}{L_q} \\ i_d{}^{k+1} = i_{dp}{}^{k+1} + \dfrac{T_s(-R_s)(i_{dp}{}^{k+1} - i_d{}^k)}{2L_d} \\ i_q{}^{k+1} = i_{qp}{}^{k+1} + \dfrac{T_s(-R_s)(i_{qp}{}^{k+1} - i_q{}^k)}{2L_q} \end{cases} \tag{6}$$

Where $i_{dp}{}^{k+1}$ and $i_{qp}{}^{k+1}$ are the predictive correction current; $E_d{}^k$ and $E_q{}^k$ are the d-q axis components of the counter electromotive force can be expressed as:

$$\begin{cases} E_d{}^k = -\omega_e L_q i_q{}^k \\ E_q{}^k = \omega_e\left(L_d i_d{}^k + \psi_f\right) \end{cases} \tag{7}$$

The voltage components in d- q axis can be expressed as:

$$\begin{bmatrix} u_d{}^k \\ u_q{}^k \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \bullet \begin{bmatrix} real(V_s) \\ \mathrm{imag}(V_s) \end{bmatrix} \tag{8}$$

To minimize the current vector tracking error as the control target, the objective function is constructed as:

$$g = \left|i_d{}^{k+1} - i_d{}^{ref}\right| + \left|i_q{}^{k+1} - i_q{}^{ref}\right| \tag{9}$$

3.2. Reduce calculation time

For the dual inverter feed system, each time the optimal voltage vector is selected, 19 current predictions are required, and the target function values need to be sorted, resulting in a large amount of computation. In order to achieve a good control effect in the actual project, the selected control period is relatively small, so the requirements for the digital controller are high, which makes the application of the method in engineering practice constrained. To this end, this paper proposes a fast algorithm based on partition judgment. The candidate voltage vector is determined based on the sector in which the deadbeat voltage vector is located. Only a comparison is needed to select the final optimal voltage vector, which reduces the amount of calculation.

Further simplifying equation (6)

$$\begin{cases} i_d{}^{k+1} = i_{d0}{}^k + \dfrac{T_s L_d - \dfrac{T_s{}^2 R_s}{2}}{L_d{}^2} u_d \\ i_q{}^{k+1} = i_{q0}{}^k + \dfrac{T_s L_q - \dfrac{T_s{}^2 R_s}{2}}{L_q{}^2} u_q \end{cases} \tag{10}$$

Where

$$\begin{cases} i_{d0}{}^{k}=\dfrac{L_d{}^2-L_dR_sT_s+0.5T_s{}^2R_s{}^2i_d{}^{k}+(0.5T_s{}^2R_s-T_sL_d)\mathrm{E_d}}{L_d{}^2} \\ i_{q0}{}^{k}=\dfrac{L_q{}^2-L_qR_sT_s+0.5T_s{}^2R_s{}^2i_q{}^{k}+(0.5T_s{}^2R_s-T_sL_q)\mathrm{E_q}}{L_q{}^2} \end{cases} \tag{11}$$

If $i_d{}^{k+1}=0$， $i_q{}^{k+1}=i_q{}^{ref}$ in (10)，the deadbeat reference voltage can be obtained as:

$$\begin{cases} u_d{}^{ref}=\dfrac{-i_{d0}{}^{k}L_d{}^2}{T_sL_d-0.5T_s{}^2R_s} \\ u_q{}^{ref}=\dfrac{(i_q{}^{ref}-i_{d0}{}^{k})L_d{}^2}{T_sL_q-0.5T_s{}^2R_s} \end{cases} \tag{12}$$

At this point, the objective function can be established as:

$$g=l_d\left|u_d{}^{ref}-u_{di}{}^{k+1}\right|+l_q\left|u_q{}^{ref}-u_{qi}{}^{k+1}\right| \tag{13}$$

Where $u_{di}{}^{k+1}$ and $u_{qi}{}^{k+1}$ are the preselected voltage vector.

$$\begin{cases} l_d=\left|\dfrac{T_s(L_d-0.5R_sT_s)}{L_d{}^2}\right| \\ l_q=\left|\dfrac{T_s(L_q-0.5R_sT_s)}{L_q{}^2}\right| \end{cases} \tag{14}$$

It is divided into 6 parts equally as shown in Fig.3.

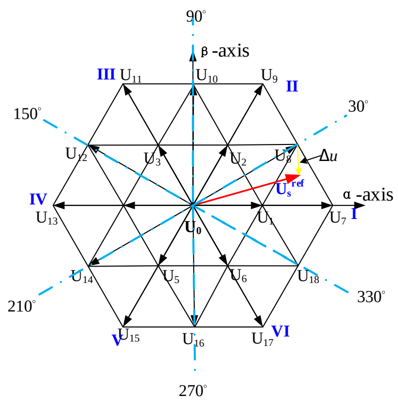


Fig. 3 voltage vector sector distribution

For a given deadbeat reference voltage:

$$V_{ref}=[V_a\ V_b\ V_c]^{\mathrm{T}} \tag{15}$$

In order to avoid determining the sector to which the V_{ref} is located, the method shown in Fig .4 is used to determine:

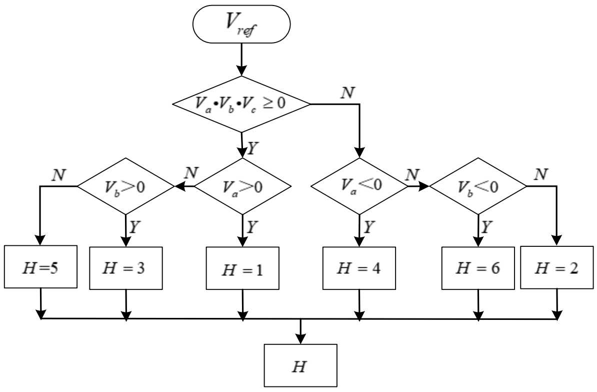


Fig.4 Sector judgment flow chart

It can be seen from (13) that the objective function has been minimized by minimizing the current error to a voltage error.

In Fig. 4, the deadbeat reference voltage vector falls in the first sector, and the voltage difference with the non-zero voltage vector u_8 is obviously the smallest, then

$$\Delta u = \left| u_s^{ref} - u_8 \right| \tag{16}$$

If the zero vector is taken as the selected voltage vector, the magnitude of the error is:

$$\Delta u_0 = \left| u_s^{ref} \right| \tag{17}$$

It is only necessary to compare the two to select the optimal voltage vector.

If Δu is greater than Δu_0, a non-zero voltage vector $u8$ is output, otherwise a zero vector is output.

This method is essentially the same as the traditional FCS-MPC, but the method avoids the calculation of 19 predicted currents, and only needs to make an optimal voltage vector based on the voltage tracking error.

3.3. Minimum switching loss

As shown in Fig. 2, there are redundant switching states which means that the determined optimal voltage vector can have several corresponding switching states. Since different switching states have an effect on the switching frequency, it is necessary to select an appropriate switching state to reduce the switching frequency. According to the principle of minimum switching loss, the number of switching of it in one control cycle is calculated as follows:

$$\begin{aligned} S = &\left| S_{a1}^{\ k+1} - S_{a1}^{\ k} \right| + \left| S_{b1}^{\ k+1} - S_{b1}^{\ k} \right| + \left| S_{c1}^{\ k+1} - S_{c1}^{\ k} \right| \\ &+ \left| S_{a2}^{\ k+1} - S_{a2}^{\ k} \right| \left| S_{b2}^{\ k+1} - S_{b2}^{\ k} \right| + \left| S_{c2}^{\ k+1} - S_{c2}^{\ k} \right| \end{aligned} \tag{18}$$

Where,Sx1(x=a, b, c)=0,1 is the INV1 switching state of U_{opt} ; Sx2(x=a, b, c)=0,1 is the INV2 switching state of U_{opt} ; “k+1” and “k” indicate the dual inverter switch state and current inverter switch state to be applied at the next moment.

3.4. Delay compensation

Considering the actual project, there is a beat delay between the actual output voltage of the digital controller and the command voltage. It is necessary to replace the predicted current $i_{dq}{}^{p}(k+1)$ of the next moment with $\mathrm{i_{dq}}^{k}$ to calculate the ideal voltage vector, and then use the improved algorithm to select the optimal voltage vector.

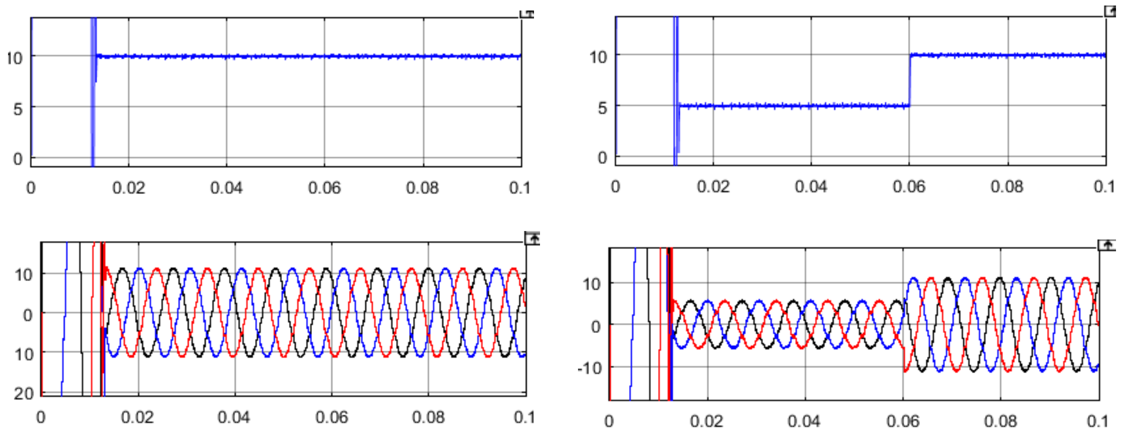
4. Simulink simulation

In order to verify the effectiveness of the algorithm, the improved algorithm is simulated in Matlab/Simulink environment. The parameters of the OW-PMSM used in the Table 1. The sampling frequency of the control system is 10khz.

Table 1. The parameters of the ow-pmsm

parameter	*value*
Stator resistance R_s	*2.375*Ω
Direct inductance L_d	*5.8mH*
Quadrature inductance L_q	*6.6mH*
DC bus voltage U_{dc}	*400V*
Permanent magnet flux linkage ψ_f	*0.1286wb*
number of pole-pairs P	*4*

4.1. Simulation waveform



(a) (b)

Fig.5 Simulation waveform:(a) Steady state operation
(b)Dynamic responses

4.2. Simulation results

First, it can be seen that the proposed MPCC produces good current and torque performance of the steady state performance in Fig. 5(a).

Second, it can be seen that the system has good anti-interference ability with sudden load from 5 Nm to 10 Nm at 0.06 s .The torque response time is short and the tracking time is short about the dynamic behavior in Fig. 5(b).

The fast vector selection MPCC method can indeed select the optimal voltage vector in a more convenient way, so it has higher practicability.

Acknowledgments

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