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Model Prediction Current Control Strategy for PMSM Based on Current Error Limitation

Yuqing Wang [a], Fujun Deng [b]

School of Dalian Jiaotong University, Dalian 116028, China;

[a]1145831830@qq.com, [b]1356267940@qq.com

Abstract

The Vector Control strategy of Permanent Magnet Synchronous Motor (PMSM) has many shortcomings in practical application, such as slow speed response, large overshoot, large torque ripple and so on. In view of the above shortcomings, a Model Predictive Current Control (MPCC) strategy based on current error limitation was adopted. The discrete mathematical model of PMSM was constructed, and the predicted current values of d and q axes at the next time were calculated by using the MPCC strategy, and the predicted results under different control vectors were screened by using the current error limitation strategy. Because the output of the MPCC system has hysteresis, a compensation device is set to compensate the output power of the system. Simulation results show that the proposed algorithm can effectively reduce the speed error and torque error, narrow the fluctuation range of torque, and improve the stability of Permanent Magnet Synchronous Motor.

Keywords

Model Prediction Current Control, Permanent Magnet Synchronous Motor, Time-delay control.

1. Introduction

Vector Control (VC) and Direct Torque Control (DTC) are the inverter voltage vector control methods commonly used in PMSM today. Model Predictive Control (MPC) algorithm has the advantages of simple principle, stable output result and simple design structure, so it is widely used in motor control technology, vehicle automatic driving technology, artificial intelligence technology and other fields. The Model Current Predictive Control (MPCC) developed on the MPC strategy has many advantages[1]. Different from VC and DTC, MPCC adopts the method of on- line adjustment in the process of selecting the maximum current vector, which is more accurate and efficient in vector selection and simpler and more flexible in electrical structure design.

In recent years, there are many effective research results on the MPC strategy of PMSM. Literature [2] puts forward a control method of MPCC on the control method of PMSM model predictive control, which can eliminate the dynamic coupling of d axis and q axis and improve the dynamic response of current. On the basis of high-power PMSM, literature [3] proposes an improved MPCC strategy based on three-level inverter, which can reasonably select the switching vector and voltage sequence and reduce the switching loss, but the calculation amount of this method is large and the model calculation time is long. Literature [4] introduces the best effective vector time to improve the traditional MPCC strategy. First, the effective vector is determined by the vector region, and then the best effective time is selected by calculation. This method has a certain improvement in the tracking accuracy of the current, and has a certain effect on the suppression of current distortion. In literature [5], the control performance of the two control cycles in MPCC is regarded as a whole, and the same voltage vector is selected as the optimal voltage vector of the two control cycles. This method effectively reduces the switching frequency and reduces the complexity of calculation.

In view of the disadvantages of the traditional vector control of PMSM such as large speed error and large torque fluctuation, this paper adopts an improved control strategy[6] based on the traditional MPCC on the basis of the discrete model of permanent magnet synchronous motor Δi_{max} , introduces the maximum error coefficient, and uses this value to select the best switching state of the inverter. The simulation results show that compared with the traditional vector control strategy, this method can effectively reduce the error of output speed and narrow the fluctuation range of torque[7 - 12].

2. Mathematical Model of Permanent Magnet Synchronous Motor

Regardless of the core saturation of the motor stator, eddy current loss and hysteresis loss of the motor stator, damping on the rotor and permanent magnet, and taking the induced electromotive force waveform in the phase winding as a sine wave, the voltage equation of PMSM in the synchronous rotating coordinate system is as follows:

$$u_d = Ri_d + L_d \frac{di_d}{dt} - L_d i_d \omega_e \tag{1}$$

$$u_q = Ri_q + L_q \frac{di_q}{dt} + L_d i_d \omega_e + \psi_f \omega_e \tag{2}$$

Where: u_d and u_q respectively are the d and q axis voltages; i_d and i_q are respectively d and q axis current; ψ_f is the flux linkage of permanent magnet; L_s is the stator inductance; ω_e is the electric angular velocity of the rotor at the current time; R is the stator resistance.

Because the response speed of the PMSM control system is very fast, the sampling period time selected is small enough, at this time, the value of the input variable of the system can be regarded as unchanged in one sampling period interval. Euler method is used for the first order discretization of the formula, and the prediction formula of d and q current values at the next moment can be approximately listed as follows:

$$i_d(k+1) = i_d(k) + \frac{T_s}{L_s}[u_d(k) - Ri_d(k) + E_d(k)] \tag{3}$$

$$i_q(k+1) = i_q(k) + \frac{T_s}{L_s}[u_q(k) - Ri_q(k) + E_q(k)] \tag{4}$$

Where: k is the current sampling time; *k+1* is the next sampling time; T_s is the sampling period; $i_d(k)$ and $i_q(k)$ are the current of d and q axis at time k respectively; $i_d(k+1)$ and $i_q(k+1)$ are the predicted current of d and q axis at specific *k+1* moment; $E_d(k)$ and $E_q(k)$ respectively are the d and q axis reverse electromotive force at k time; $E_d(k) = \omega_e(k)L_s i_q(k)$; $E_q(k) = -\omega_e(k)L_s i_d(k) - \omega_e(k)\psi_f$; $u_d(k)$ and $u_q(k)$ are respectively the d and q axis voltage at time k ; $\omega_e(k)$ is the electric angular velocity of the rotor at time k.

The torque equation of PMSM is:

$$T_e = \frac{3}{2} p_n i_q [i_d(L_d - L_q) + \psi_f] \tag{5}$$

3. MPCC Strategy Based on Current Error Qualification

3.1. Implementation Method of MPCC Strategy

MPCC structure consists of PI controller, coordinate transformation, space vector prediction and selection, inverter and so on.

The two-level three-phase inverter has 8 switching states according to the on-state of the upper and lower thyristors, and the 8 switching states respectively correspond to the 8 basic voltage vectors $u_0 - u_8$, see Fig. 1 .

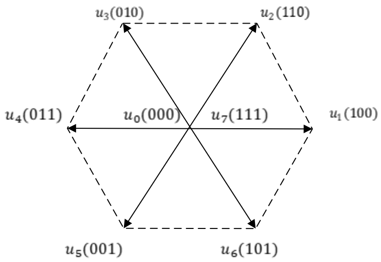

Fig. 1 8 voltage vectors of a two-level inverter

Since u_0 and u_8 is the same vector state, only 7 different voltage vectors need to be calculated when calculating. The MPCC strategy uses formula (3) and formula (4) to predict the current value of the d and q axes at the next time, and puts it into the calculation formula of the following cost function. By calculating the cost function corresponding to 7 different voltage vectors, the voltage vector with the smallest value is output to the inverter:

$$g = [i_d^* - i_d(k+1)]^2 + [i_q^* - i_q(k+1)]^2 \tag{6}$$

However, the inherent delay of the digital processor causes the voltage vector selected in the current control cycle to be applied only in the next cycle. Therefore, it is necessary to reduce the influence of delay on the control performance by delay compensation.

1)The current $i_d(k+1)$ and $i_q(k+1)$ at k+1 moment will be predicted according to the optimal voltage vector $u_d(k)$ and $u_q(k)$ of the last cycle determined by formula (1) and formula(2) .

2)With $i_d(k+1)$ and $i_q(k+1)$ as the initial condition, the current prediction formula after on e-beat delay compensation can be obtained. The formulas are as follows:

$$i_d(k+2) = i_d(k+1) + \frac{T_s}{L_s}[u_d(k+1) - Ri_d(k+1) + E_d(k+1)] \tag{7}$$

$$i_q(k+2) = i_q(k+1) + \frac{T_s}{L_s}[u_q(k+1) - Ri_q(k+1) + E_q(k+1)] \tag{8}$$

Where:$E_d(k+1) = \omega_e(k)L_s i_q(k+1)$; $E_q(k+1) = -\omega_e(k)L_s i_d(k+1) - \omega_e(k)\psi_f$

Therefore, the magnitude of each voltage vector value function can be evaluated by bringing the predicted current values of the 7 voltage vectors after delay compensation into the cost function shown below:

$$g = [i_d^* - i_d(k+2)]^2 + [i_q^* - i_q(k+2)]^2 \tag{9}$$

Where $i_d(k+2)$ and $i_q(k+2)$ predict the current of d and q axes at the next time after one-beat delay.

3)At this time, the optimal voltage vector will be applied to the PMSM in the next control cycle. The traditional MPCC control structure block diagram is shown in Fig. 2.

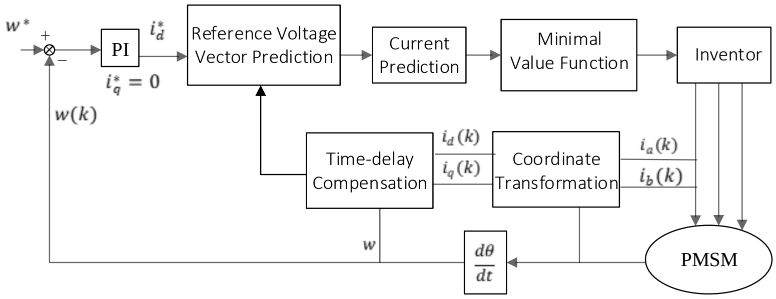

Fig. 2 Traditional MPCC control structure block diagram

3.2. MPCC Implementation Method Based on Current Error Limitation

The basic principle of MPCC strategy with current error limitation is similar to the traditional MPCC strategy. The difference between these two is that the current error limitation strategy replaces the calculation formula of cost function, and the voltage vector with the minimum current error calculation value is selected as the optimal voltage vector and output to the inverter.

On the basis of the calculated stator flux and stator current, the predicted current value is compared with the current value of the previous moment, the error value is calculated, and the expression of the maximum allowed current vector error is set as follows:

$$\Delta i = i_{1s}^*(k) - i_{1s}(k+1) \tag{10}$$

The vector $i_{1s}^*(k)$ is the final value of the stator current vector at the moment k, and the value is the center of the circle and Δi is the circle's radius, as shown in Fig 3(a). If the deviation between the given value and the predicted value of the current is less than or equal to it, it is considered that the current error conforms to the limiting strategy. Otherwise, as shown in Fig. 3(b), it is considered that the current error does not meet the limiting strategy.

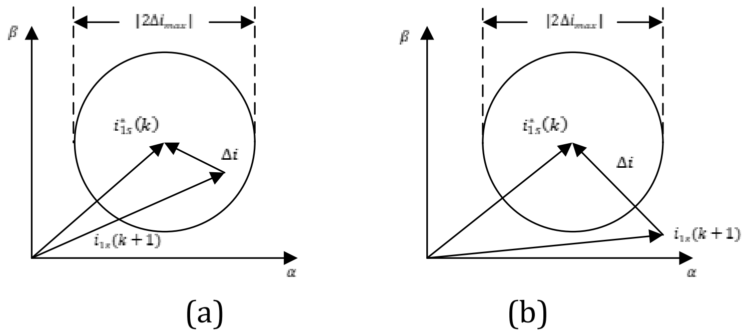

Fig. 3 Schematic diagram of current error limitation

1) Calculate the d and q axis voltage at time k according to formula (1) and formula(2).

2) According to formula (3) and formula(4), the predicted current value $i_{1s}(k+1)$ corresponding to 7 different voltage vectors at the next moment k+1 is calculated.

3) Substitute$i_{1s}(k+1)$ into formula (10), compare with the current value i_{1s}^* of the previous time, calculate the corresponding current error, and optimize it with the current error limiting strategy.

4. Delay Compensation

In the actual control system, due to the delay of the motor system, the voltage vector acting at the current moment cannot be output at the current moment, but is output at the next moment. This kind of delay will affect the dynamic and static performance of the motor, so it is necessary to design additional delay compensation when designing.

1) The predicted value of d and q axis current at time *k+1* is obtained from formula(3) and formula (4) .

2) The state variable at time *k+2* is obtained from formula(7) and formula(8). At this time, the equivalent current and voltage in the equation are the predicted value of the circuit at time *k+1*.

3) The formula(10) is rewritten into the formula (11), at this time, the formula (11) is the formula after considering the current error delay of one beat.

$$\Delta i = i_{1s}^{*}(k) - i_{1s}(k+2) \tag{11}$$

4) According to formula (11), take its minimum voltage vector Δi as the optimal switching state of the inverter.

After considering the delay, the MPCC control structure block diagram based on the current error limitation strategy is shown in Fig. 4 below:

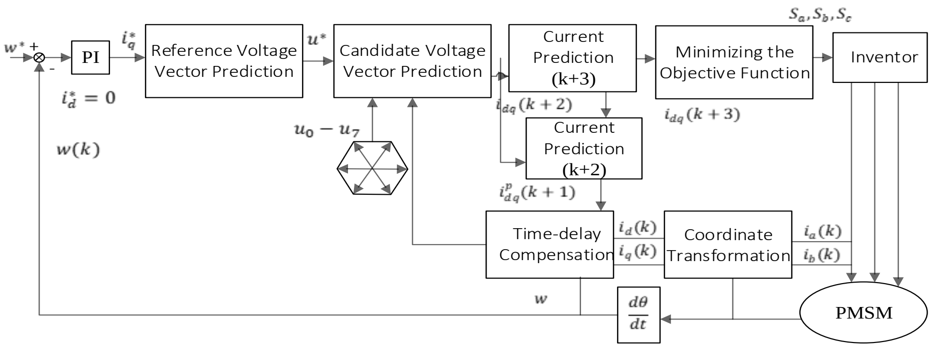

Fig. 4 MPCC control structure block diagram based on current error limitation strategy

5. Simulation Results

In order to verify the validity of the MPCC strategy proposed in this paper, the VC strategy and MPCC strategy models of PMSM were built by MATLAB/Simulink software. The PMSM parameters used in the simulation are shown in Table 1.

Table 1 PMSM simulate parameters

Parameters Names	Parameter Values
Rated voltage $\boldsymbol{V_{dc}}$/V	380
Polar logarithm p	4
Rated RPM $\boldsymbol{n_r}$/(r· $\boldsymbol{min^{-1}}$)	500
Stator phase resistance $\boldsymbol{R_s}/\Omega$	0.25
The d-q axis inductance L/H	0.0005
Permanent magnet flux$\boldsymbol{\Psi_f}$/ Wb	0.01325

The rated speed of the Permanent Magnet Synchronous Motor is required to be 500r/min. Fig. 5 and Fig. 6 are the simulation graphs of the motor speed response using traditional vector control and MPCC control respectively. It can be seen from the two figures that the speed of traditional vector control will rise to more than 530r/min and then drop to 500r/min during no-load operation. While MPCC control is more stable when the speed changes. In general, the MPCC strategy has better anti-interference for the control of the speed.

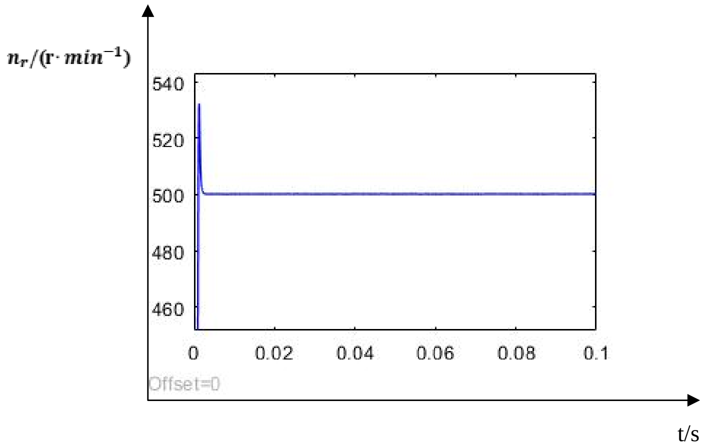

Fig. 5 Simulation diagram of speed response of traditional vector control

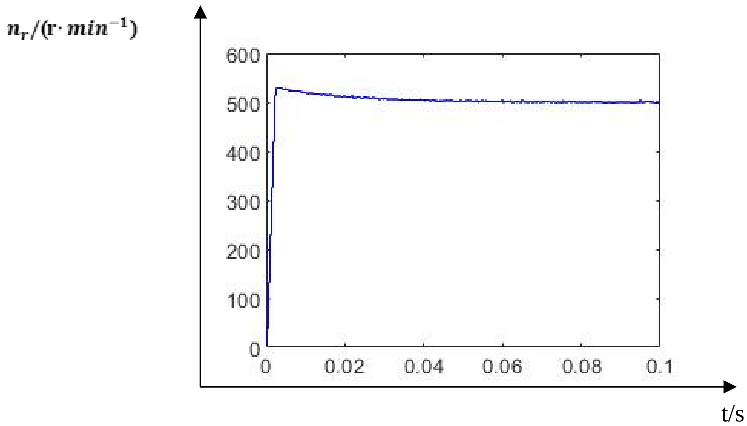

Fig. 6 Simulation diagram of speed response under MPCC contro

Fig. 7 and Fig. 8 are simulation diagrams of torque response using traditional vector control under no-load condition, and FIG. 9 and FIG. 10 are simulation diagrams of MPCC control torque response based on current error limitation respectively. As can be seen from Fig.7 and Fig.8, if the traditional vector control strategy is adopted, the output torque suddenly increases to 140r/min, and then suddenly decreases to 20r/min in the opposite direction, stabilizing to 0 at about 0.002s. Under MPCC control, the output torque only increases to about 0.8r/min, and also stabilizes to 0 at about 0.002s; The part between 0.01 and 0.02s is intercepted and enlarged, and it can be seen that the torque error fluctuates between ±0.5 in the traditional vector control and the MPCC control's torque error fluctuates between ±0.1. To sum up, the torque response of the motor under MPCC control is smaller, the error is smaller, and the fluctuation after stability is also smaller, so that the motor has a better torque response.

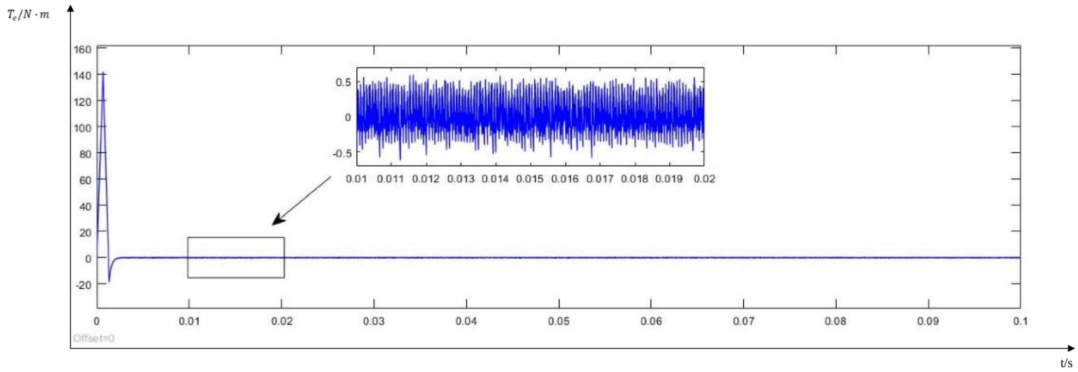

Fig. 7 Comparison diagram of torque response simulation under traditional vector control

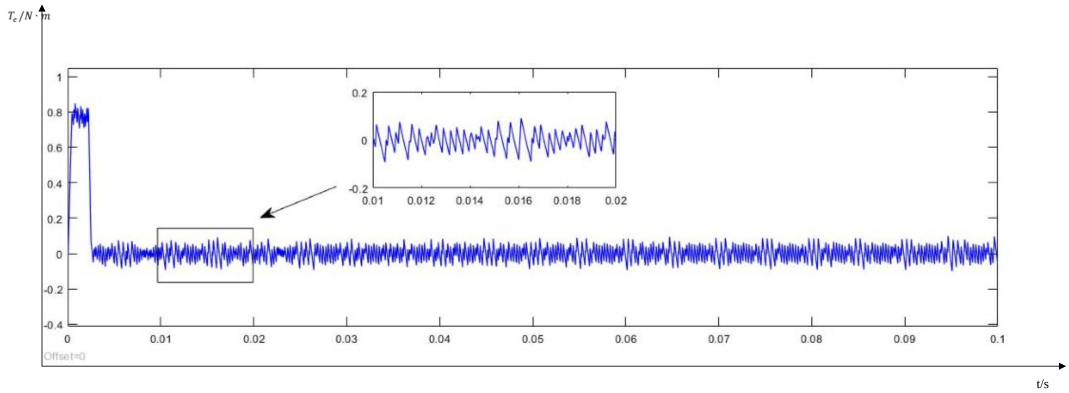

Fig. 8 Comparison simulation diagram of MPCC control torque response

6. Conclusion

In this paper, a model prediction current control algorithm based on current error limitation is adopted to solve the problem of excessive speed overshoot and large torque error in traditional vector control of PMSM. The algorithm analyzes the discrete mathematical model of PMSM, on the basis of which MPCC strategy is introduced to improve the control strategy of the motor. Because of the working principle of MPCC strategy, compared with the traditional vector control, this way does not need to carry out cumbersome coordinate transformation, can reduce the amount of calculation of the motor and improve the response speed of the motor. On this basis, this paper also introduces the current error limitation strategy, which replaces the value function in the traditional MPCC strategy with the current error limitation. By limiting the size of the current error and the rolling optimization of the vector voltage selection, this method not only solves the difficult problem of calculating the weight coefficient in the traditional model prediction algorithm. Moreover, the output speed and torque images are similar to those of the traditional MPCC. This method requires less computation and the motor response speed is faster. The simulation results show that compared with the traditional vector control mode, the MPCC strategy based on current error limitation has smaller output speed over jump, smaller torque error and smaller fluctuation, which can achieve better output speed and torque and make PMSM have better performance.

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