ISBN: 978-981-18-5852-9
WCSE 2022 Spring Event: 2022 9th International Conference on Industrial Engineering and Applications
doi: 10.18178/wcse.2022.04.134

A Predictive Control Method for Improving the Robustness of Permanent Magnet Synchronous Motor

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Abstract. The high-performance permanent magnet synchronous motor control system requires higher performance such as speed tracking ability and current response speed. To this end, this paper proposes a predictive control method for improving the robustness of permanent magnet synchronous motor. The outer loop adopts closed-loop rolling optimized rotational speed predictive control to improve the speed tracking capability. For the irreversible delay of one beat of the digital control system, the inner loop adopts Newton interpolation compensation deadbeat current predictive control enables the system to have stronger dynamic response capability. Then a reduced-order load observer is designed to improve the disturbance immunity of the system under load changes. Finally, the feasibility of the proposed control method is verified by simulation, and the steady-state accuracy and robustness of the proposed control method are higher than that of the traditional deadbeat current predictive control method.

Keywords: PMSM; double closed-loop predictive control; rolling optimization; Newton interpolation compensation; deadbeat current predictive control.

1. Introduction

Permanent magnet synchronous motor (PMSM) has the advantages of small size, compact structure and large coverage of high and low temperature. It is widely used in various fields, and the requirements for its control performance are becoming higher and higher. In the PMSM system, the performance of the entire control system is determined by the control properties of the current inner loop[1]. To improve the control performance of PMSM, scholars have extensively studied thecurrent loop control method[2-8].

At present, the control methods of PMSM current loop mainly include proportional integral (PI) control, hysteresis control, and predictive control. Among them, PI control has the advantages of high precision and fixed switching frequency, but its control effect is not ideal when applied to complex systems such as PMSM, such as nonlinear, strong coupling, and time-varying. Hysteresis control has the advantages of fast response and simple algorithm, but the switching frequency changes greatly, which is easy to cause high-order harmonics in the output current[1,2]. Compared with the above two control methods, predictive control has the advantages of faster response speed and higher tracking accuracy, which has attracted the attention of many scholars[3]. Among the current predictive control algorithms, the deadbeat predictive control algorithm is the most mature. Reference [4] quantitatively compares three current predictive control algorithms with PI control in various performance indicators, and finds that current predictive control is superior to PI control in terms of dynamic performance. Based on the traditional one-beat delay PMSM current predictive control. Reference [5] uses a robust current predictive control algorithm to improve the control performance in the case of model parameters mismatch. Reference [6], on the basis of reference [5], uses recursive least squares estimation to further optimize the robust current prediction algorithm, thereby reducing the error caused by the mismatch of model parameters and improving the robustness of the system. Reference [7] compensates the delay caused by calculating the basic vector based on the vector machine principle and the deadbeat

This research is supported by the National Science Foundation of China (No.52077064), Foundation of Key Laboratory of Science and Technology on Integrated Logistics Support (No. 6142003200203). (Corresponding author: Jinping Xie).

control principle. Reference [8] proposed a robust fault-tolerant predictive current control method which can eliminate motor parameter disturbance.

This paper proposes a double closed-loop prediction control method with strong speed tracking ability and dynamic response performance, combining the closed-loop rolling optimization speed prediction control of the outer ring with the Newton interpolation compensation no-beat current prediction control in the inner loop to solve the problem of poor speed tracking ability and inherent delay in the PMSM control system. To improve the load-disturbance ability of the system, the down-order load observer is designed. Finally, the superiority of the proposed method is verified by simulation.

2. MATHEMATICAL MODEL OF PMSM

The mathematical model of PMSM is similar to the mathematical model of synchronous motor with rotor excitation winding, so in order to simplify the mathematical model of permanent magnet synchronous motor[3-4]. some less influential factors are ignored, and the following assumptions are made:

(1) The stator winding is three-phase symmetrical, the leakage inductance of the stator winding is ignored, and the influence of external factors such as temperature is not considered;

(2) The induced electromotive force in the stator winding is a sine wave;

(3) Ignoring magnetic saturation, ignoring hysteresis loss and eddy current;

(4) Stator magnet damping and rotor damping windings are ignored;

(5) The magnetic field generated by the stator winding current is sinusoidally distributed, ignoring the higher harmonics of the magnetic field.

According to the above assumptions, the mathematical model of PMSM can be obtained [9-11]. The mathematical model in the synchronous rotating coordinate system can be expressed as:

$$\begin{cases} u_d = Ri_d + \dfrac{d\varphi_d}{dt} - \omega_e \varphi_q \\ u_q = Ri_q + \dfrac{d\varphi_q}{dt} - \omega_e \varphi_d \end{cases} \tag{1}$$

where u_d, u_q; i_d, i_q; φ_d, φ_q are the d-q axial component of the stator voltage, stator current and stator flux linkage respectively; R is the stator resistance. The stator flux linkage equation is:

$$\begin{cases} \varphi_d = \varphi_f + L_d i_d \\ \varphi_q = L_q i_q \end{cases} \tag{2}$$

where L_d, L_q are the d-q axial inductance component, φ_f is the flux linkage. The stator voltage can be expressed as:

$$\begin{cases} u_d = Ri_d + L_d \dfrac{di_d}{dt} - \omega_e L_q i_q \\ u_q = Ri_d + L_q \dfrac{di_q}{dt} - \omega_e (L_d i_d + \varphi_f) \end{cases} \tag{3}$$

The electromagnetic torque equation is:

$$\begin{aligned} T_e &= \frac{3}{2} p_n \left[\varphi_d i_q - \varphi_q i_d \right] \\ &= \frac{3}{2} p_n \left[\varphi_f i_q + (L_d - L_q) i_d i_q \right] \end{aligned} \tag{4}$$

where P_n is the polar logarithm. The mechanical equation of motion of the motor is:

$$J \frac{d\omega_m}{dt} = T_e - T_L - B\omega_m \tag{5}$$

where ω_m is the mechanical angular speed of the motor; J is the motor inertia; B is the damping coefficient; T_e is the electromagnetic torque; T_L is the load torque.

3. Double Closed-Loop Predictive Control System for PMSM

The PMSM double closed loop prediction control system designed in this paper has the overall control structure in Fig.1.

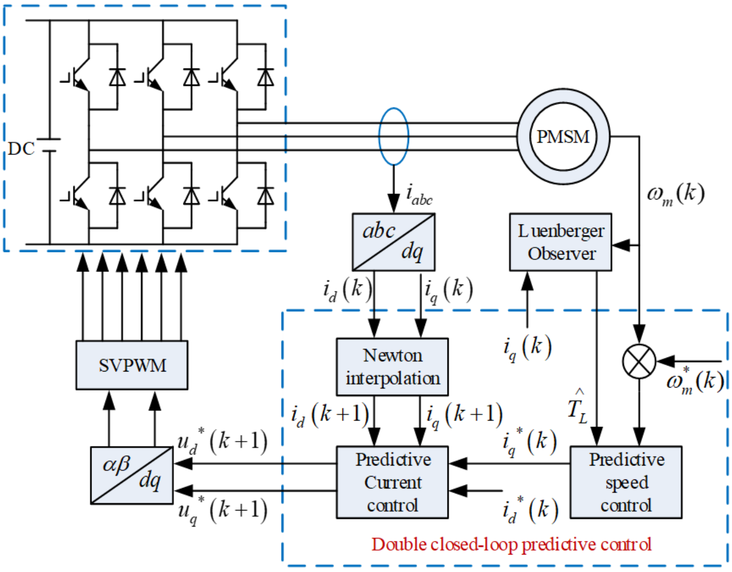


Fig. 1. Structural diagram of the double-closed-loop predictive control of PMSM

In Fig. 1, $i_d(k)$, $i_q(k)$, $\omega_m(k)$, $\omega^*_m(k)$ and $T_L(k)$ are the stator current, mechanical angular velocity, given mechanical angular velocity and load torque at the current sampling time of PMSM respectively. $i_d(k+1)$ and $i_q(k+1)$ are respectively the d-q axis component of stator current at the next time of PMSM, and $u_d(k+1)$, $u_q(k+1)$ are respectively the d-q axis component of stator voltage at the next time of PMSM.

3.1. Closed-Loop Rolling Optimization Predictive Speed Control

The speed loop purpose is to make speed follow the given speed quickly and provide the reference current of the q-axis. On the basis of establishing the speed prediction model, this paper carries on the closed loop rolling optimization predictive speed control, and the control structure is shown in Fig.2.

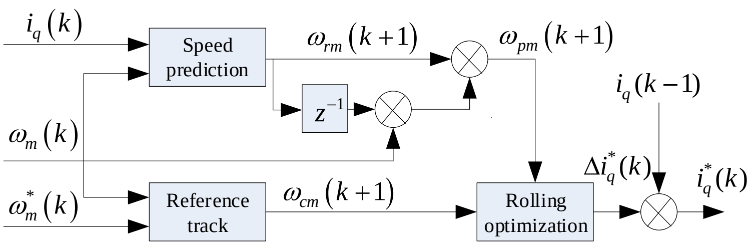


Fig. 2. Block diagram of P M S M speed ring prediction and control structure

In Fig. 2, $\omega_{rm}(k+1)$ and $\omega_{cm}(k+1)$ are the predicted angular velocity value and the output angular velocity value at the next time, $\omega_{pm}(k+1)$ is the predicted value after feedback compensation at the next time, $i_q(k-1)$ is the stator current at the previous time, $\Delta i^*_q(k)$ is the optimal control increment, and $i^*_q(k)$ is the given value of the q-axis component of the stator current output by the closed-loop rolling optimal predictive control.

Substituting (4) and (5), the forward Euler method is used to discretize the mechanical motion equation of the motor as:

$$\begin{aligned}\omega_m(k+1) &= \frac{1.5P_n\varphi_f T}{J} i_q(k) + \omega_m(k) \\ &- \frac{T}{J} T_L(k) - \frac{BT}{J}\omega_m(k)\end{aligned} \tag{6}$$

$$\omega_m(k) = \frac{1.5P_n\varphi_f T}{J} i_q(k-1) \\ +(1-\frac{BT}{J})\omega_m(k-1) - \frac{T}{J}T_L(k-1) \tag{7}$$

The mathematical model for the reduced speed loop prediction between (6) and (7) is:

$$\omega_m(k+1) = (2-\frac{BT}{J})\omega_m(k) - (1-\frac{BT}{J})\omega_m(k-1) \\ +\frac{1.5P_n\varphi_f T}{J}\Delta i_q(k) - \frac{T}{J}\Delta T_L(k) \tag{8}$$

The prediction model of the rotational speed ring without considering the load perturbation is:

$$\omega_m(k+1) = (2-\frac{BT}{J})\omega_m(k) - (1-\frac{BT}{J})\omega_m(k-1) \\ +\frac{1.5P_n\varphi_f T}{J}\Delta i_q(k) \tag{9}$$

Considering the error of the mechanical speed directly predicted by (9), the control strategy of rolling optimization and feedback correction is adopted. The rotational speed prediction error is [10,12]:

$$e(k) = \omega_m(k) - \omega_{rm}(k) \tag{10}$$

The closed-loop output after the feedback compensation is:

$$\omega_{pm}(k+1) = \omega_{rm}(k+1) + e(k) \tag{11}$$

The reference trajectory for the assumed velocity is:

$$\omega_{cm}(k+1) = \beta\omega_m(k) + (1-\beta)\omega_m^*(k) \tag{12}$$

where: β is the softening coefficient; $\omega^*{}_m(k)$ is the reference value of speed.

According to the optimal control theory, the performance index function can be selected as:

$$g = \lambda_1\left[\omega_{cm}(k+1) - \omega_{pm}(k+1)\right]^2 + \lambda_2\left[\Delta i_q(k)\right]^2 \tag{13}$$

where: λ_1 and λ_2 are weighting coefficients.

According to the optimization strategy $\partial g/\partial\Delta i_q(k)=0$, the optimal control increment $\Delta i^*{}_q(k)$ is solved, and the given current $i^*{}_q(k)$ can be expressed as:

$$i_q^*(k) = i_q^*(k-1) + \Delta i_q^*(k) \tag{14}$$

3.2. Current Ring Design

The role of the current loop is to speed up the dynamic regulation process of the system, so that the motor stator current is better close to a given current. In the traditional difference-free beat current prediction control, the mathematical model of (3) using the reverse difference transformation method is:

$$u_d(k) = (R-\frac{L_d}{T_s})i_d(k) + \frac{L_d}{T_s}i_d(k+1) \\ -\omega_e(k)L_q i_q(k) \tag{15}$$

$$u_q(k) = (R-\frac{L_q}{T_s})i_q(k) + \frac{L_q}{T_s}i_q(k+1) \\ +\omega_e(k)L_d i_d(k) + \omega_e(k)\varphi_f \tag{16}$$

where: T_s is the sampling time of the current ring.

The matrix is written in the form of:

$$\boldsymbol{u}(k) = \boldsymbol{B}^{-1}\left[\boldsymbol{i}(k+1) - \boldsymbol{Mi}(k) - \boldsymbol{\psi}\right] \tag{17}$$

where:

$$\boldsymbol{M}=\begin{bmatrix} 1-\frac{RT_S}{L_d} & \frac{T_s L_q}{L_d}\omega_e \\ -\frac{T_s L_d}{L_q}\omega_e & 1-\frac{RT_S}{L_q} \end{bmatrix} \tag{18}$$

$$\boldsymbol{B}=\begin{bmatrix} \frac{T_S}{L_d} & 0 \\ 0 & \frac{T_S}{L_d} \end{bmatrix} \qquad \boldsymbol{\psi}=\begin{bmatrix} 0 \\ -\frac{T_S\omega_e}{L_d}\varphi_f \end{bmatrix} \tag{19}$$

$$\begin{cases} \boldsymbol{i}(k)=\left[i_d(k),i_q(k)\right]^T \\ \boldsymbol{u}(k)=\left[u_d(k),u_q(k)\right]^T \end{cases} \tag{20}$$

When the system goes through a sampling period, the current reaches a given value, $i(k+1)=i^*(k)$, Through the deadbeat current predictive control principle, the reference voltage when the current reaches the given value can be calculated. In the sampling process of the actual digital control system, due to the one beat delay[8], Therefore, the reference voltage $u(k)$ calculated at time kT_s can only be used at time $(k+1)T_s$. In order to eliminate this delay, $u(k+1)$ is calculated at time kT_s to make the control system use voltage $u(k+1)$ at time $(k+1)T_s$. The calculation formula is as follows:

$$u(k+1)=\boldsymbol{B}^{-1}\left[i(k+2)-\boldsymbol{M}i(k+1)-\boldsymbol{\psi}\right] \tag{21}$$

Since the mechanical time constant of the system is much greater than the electrical time constant, it can be considered that the rotational speed is approximately constant over a control period, $\omega_e(k+1)\approx\omega_e(k)$. When the stator current reaches the given value at time $(k+2)T_s$, since $i(k-2)$, $i(k-1)$, $i(k)$ can be obtained by sampling, Newton interpolation method can be used to predict the current value $i'(k+1)$ of the next cycle.

Suppose the Newton interpolation polynomials are as follows:

$$i(x)=C_0+C_1(x-x_0)+C_2(x-x_0)(x-x_1) \tag{22}$$

where: $x_0=k-2$, $x_1=k-1$, $x_2=k$, calculated by reasoning:

$$\begin{aligned} &C_0=i(x_0) \qquad C_1=\frac{i(x_1)-i(x_0)}{x_1-x_0} \\ &C_2=\frac{i(x_2)-i(x_0)}{(x_2-x_0)(x_2-x_1)}-\frac{i(x_1)-i(x_0)}{(x_2-x_1)(x_1-x_0)} \end{aligned} \tag{23}$$

Substituting C_0, C_1 and C_2 into (22) to obtain:

$$\begin{aligned} i(x)&=i(k-2)+\left[i(k-1)-i(k-2)\right](x-k+2) \\ &+\frac{i(k)-i(k-1)}{2}(x-k+2)(x-k+1) \end{aligned} \tag{24}$$

Let $x=k+1$, the current value of the next cycle predicted by Newton interpolation method is:

$$i'(k+1)=3i(k)-3i(k-1)+i(k-2) \tag{25}$$

3.3. Design of the Feedback Error Compensation of the Current Ring

It can be seen from (25) that the predicted current value is independent of the model parameters and only related to the current values of the past few cycles, which can reduce the secondary error caused by the mismatch of model parameters to a certain extent. Because Newton interpolation is an approximate estimation, the predicted value and the actual value still exist. Assume that the error is $\xi(k+1)$. In order to reduce the prediction error as much as possible, this paper uses the error feedback compensation method to make the current after compensation as follows:

$$i_p(k+1)=i'(k+1)+\xi(k+1) \tag{26}$$

To reduce the error, the error of each cycle is accumulated, and the current output after feedback compensation is:

$$i_p(k+1)=i'(k+1)+h\sum_{i=0}^{k}\xi(i) \tag{27}$$

where: h is the correction factor.

The reference voltage for the output of the current prediction controller is:

$$\begin{cases} u_d(k+1) = (R - \frac{L_d}{T_s}) i_{dp}(k+1) + \frac{L_d}{T_s} i_d^*(k) \\ \qquad - \omega_e(k) L_q i_{qp}(k+1) \\ u_q(k+1) = (R - \frac{L_q}{T_s}) i_{qp}(k+1) + \frac{L_q}{T_s} i_q^*(k) \\ \qquad + \omega_e(k) L_d i_{dp}(k+1) + \omega_e(k) \varphi_f \end{cases} \tag{28}$$

where: $i_{dp}(k+1)$, $i_{dq}(k+1)$ is the component of stator current on d-q axis predicted at time $(k+1)T_s$.

Since the maximum output voltage amplitude of the inverter is $2/3U_{dc}$, the DC bus voltage is U_{dc}. Since:

$$\sqrt{u_d(k+1)^2 + u_q(k+1)^2} > \frac{2}{3} U_{dc} \tag{29}$$

Then the reference voltage of the output of the current prediction controller needs to be adjusted to:

$$\begin{cases} u_d^*(k+1) = \frac{2}{3} U_{dc} \frac{u_d(k+1)}{\sqrt{u_d(k+1)^2 + u_q(k+1)^2}} \\ u_q^*(k+1) = \frac{2}{3} U_{dc} \frac{u_q(k+1)}{\sqrt{u_d(k+1)^2 + u_q(k+1)^2}} \end{cases} \tag{30}$$

3.4. Design of the Load Torque Observer

Considering the load disturbance, the dynamic change of the system. To improve the control performance of the motor, such as a descending order load torque observer is used. Let the equation of state of the system is:

$$\begin{aligned} \frac{d\hat{\boldsymbol{x}}}{dt} &= \boldsymbol{A}\hat{\boldsymbol{x}} + \boldsymbol{F}u + \boldsymbol{K}(y - \hat{y}) \\ \hat{y} &= \boldsymbol{C}\hat{\boldsymbol{x}} \end{aligned} \tag{31}$$

Where: $\boldsymbol{A} = \begin{bmatrix} -\frac{B}{J} & -\frac{1}{J} \\ 0 & 0 \end{bmatrix}$ $\boldsymbol{F} = \begin{bmatrix} \frac{1}{J} \\ 0 \end{bmatrix}$ $\hat{\boldsymbol{x}} = \begin{bmatrix} \hat{\omega}_m \\ \hat{T}_L \end{bmatrix}$ $\boldsymbol{C} = \begin{bmatrix} 1 & 0 \end{bmatrix}$ $\boldsymbol{K} = \begin{bmatrix} k_1 \\ k_2 \end{bmatrix}$ $\hat{T}_L$ is the observed value of T_L, $\boldsymbol{K}$ is the feedback gain matrix.

Suppose the expected poles of the observer are p_1 and p_2, the characteristic equation of the observer:

$$\begin{cases} k_1 = -p_1 - p_2 - \frac{B}{J} \\ k_2 = -p_1 p_2 J \end{cases} \tag{32}$$

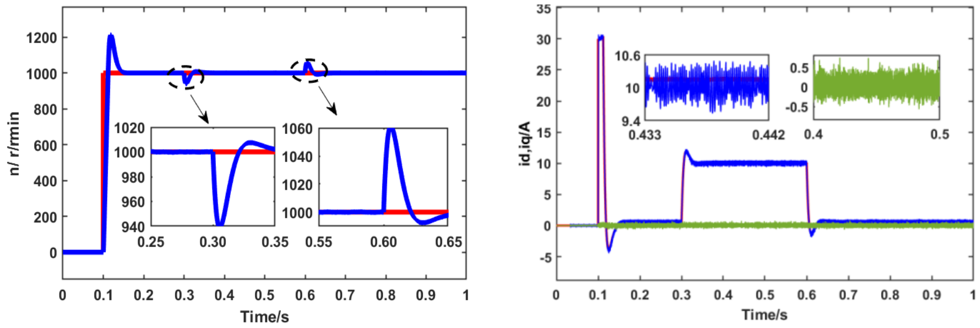
By discretizing the state equation, the observed values of speed and load torque can be obtained.

$$\begin{cases} \hat{\omega}_m(k+1) = (1 - k_1 T - \frac{BT}{J}) \hat{\omega}_m(k) + T k_1 \omega_m(k) \\ \qquad + \frac{1.5 P_n \varphi_f T}{J} i_q(k) - \frac{T}{J} \hat{T}_L(k) \\ \hat{T}_L(k+1) = \hat{T}_L(k) + T k_2 \left[\omega_m(k) - \hat{\omega}_m(k) \right] \end{cases} \tag{33}$$

The control strategy of i_d=0 and SVPWM are used to control PMSM, and the overall structure block diagram of the double closed-loop prediction control system with a load torque observer.

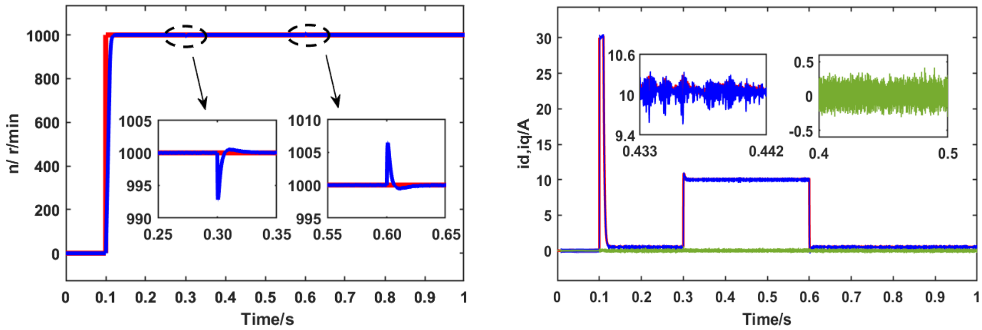
4. Simulation Verification

The prediction and control algorithm proposed in this paper is compared with the traditional prediction and control algorithm in the Matlab/Simulink environment. Some of the simulation parameters of PMSM are as follows: R=0.35Ω, P_n=8, L_d=L_q =8.5mH, J=0.007kg·m^2, φ_f=0.175Wb.



（a） （b）

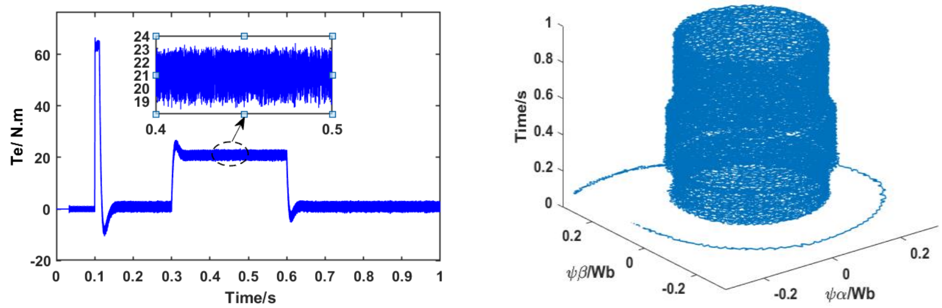
Fig. 3. Results of the traditional prediction and control simulation. (a) rotational speed (b) stator current



（a） （b）

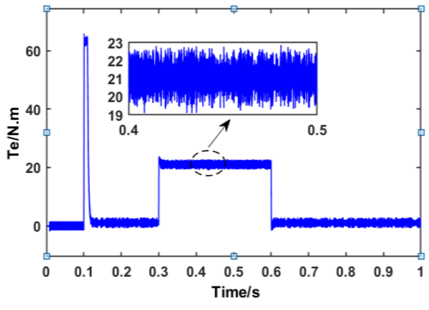
Fig.4. Simulation results of this paper. (a) rotational speed (b) stator current

Fig. 3 and Fig. 4 are the simulation results of the double closed-loop prediction control method and the traditional speed loop PI control and the single-beat delay prediction control current loop, respectively. A given speed reference value is 1000 r/min, with 20 N*m load at 0.3s and unloaded load at 0.6s. Compared with Fig. 3 and Fig. 4, we can see that the proposed method is fast dynamic response without overshoot, and can quickly return to stable state after mutation.



（a） （b）

Fig.5. Results of the traditional prediction and control simulation. (a) the electromagnetic torque (b) flux linkage



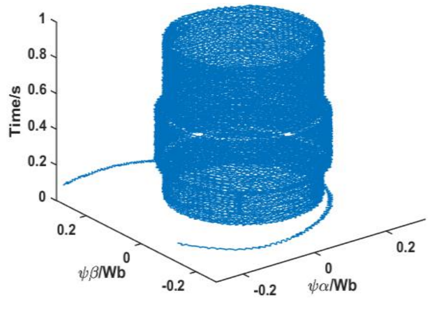


Fig.6. Simulation results of this paper. (a) the electromagnetic torque (b) flux linkage

Fig. 5 and Fig. 6 are the results of the electromagnetic torque and magnetic chain simulation of the conventional control method and the proposed method, respectively. As compared in Fig. 5 and Fig. 6, the electromagnetic torque fluctuations of the proposed method are significantly smaller than the conventional predictive control methods. Moreover, the magnetic chain of the two shows the proposed method is closer to the cylinder of the ideal control algorithm. Therefore,

The steady state accuracy of this method is higher than the traditional methods, tracking faster and without overshoot.

5. Conclusion

In this paper, a predictive control method for improving the robustness of PMSM is proposed. The drive control algorithm is improved from the speed loop and the current loop of the control system respectively. The speed adopts the closed-loop rolling optimization prediction control technique, the current loop use the Newton interpolation compensation no-difference current beat prediction control strategy, and the reduced-order load observer is combined to improve the disturbance resistance of the system under load changes. The simulation results show that the method improves the tracking performance, dynamic response and robustness of PMSM.

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