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DEADBEAT PREDICTIVE CURRENT CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTORS WITH SUPER TWISTING SLIDING MODE OBSERVERS

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Abstract. *In order to solve the problem that traditional permanent magnet synchronous motor (PMSM) deadbeat predictive current control (DPCC) is sensitive to motor parameters, a deadbeat predictive current control method based on super-twisting sliding mode observer is proposed in this paper. Firstly, a prediction equation with a perturbed form is established considering the parameter perturbation of the current loop of the PMSM. Then, a second-order super-twisting sliding mode observer (STSMO) is constructed to estimate the parameter perturbation of the current loop to improve the robustness of the current loop. Finally, the proposed method is simulated and compared with the traditional method. The simulation results show that the proposed STSMO-based DPCC approach is able to perform satisfactory control and has a strong capability to reject parameter.*
Keywords: PMSM, Deadbeat predictive current control, Super-twisting sliding mode observer

1. **Introduction.** The current control technology based on model prediction shows great advantages in dealing with the optimization of complex constraints of nonlinear systems, so it is gradually attracting attention in the fields of power electronics and motor drives. Especially in recent years, with the rapid development of the digital signal processing speed of the main control chip, the model predictive control (MPC) technology is gradually being applied in the field of electric drive. At present, the current control technology based on MPC can be mainly divided into continuous control set model predictive control (CCS-MPC) and finite control set model predictive control (FCS-MPC) [1,2].

Through literature research and research on improving the robustness of model prediction parameters, domestic and foreign scholars have proposed many solutions, which can be roughly divided into the following three types. The first is model-free predictive control [3]. This method does not rely on the parameter model of the motor, and uses the current sampling value of the system for prediction. If the error of the current sensor is too large or there is large measurement noise in the surrounding environment, the reliability and stability of the system will be reduced. In [3], the current prediction is replaced by sampling the stator current twice in a control cycle and the current difference vector corresponding to the different switching states of the inverter, which does not require any motor model parameters, but increases the computational burden of the

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system. The second method is based on parameter identification [4]. This method eliminates the influence of parameter mismatch by online identification of motor parameters such as resistance, inductance, and flux linkage, and real-time update of model parameters. The third is interference estimation compensation. The basic idea is to estimate disturbance and uncertainty variables by designing an observation mechanism, and then use the estimated disturbance to achieve disturbance compensation [5,6].

In summary, this paper designs a deadbeat predictive current control (DPCC) scheme for permanent magnet synchronous motors based on super-twisted sliding mode observers. First, the current loop adopts deadbeat predictive current control, which can improve the control bandwidth and tracking accuracy. Second, in order to overcome the parameter mismatch problem in the current loop, a second-order super-twisting sliding mode observer (STSMO) is constructed, and the corresponding estimated value is compensated into the closed-loop control through a feedforward method. Finally, the experimental study is carried out on the MATLAB platform, and the experimental results show that the proposed control strategy can achieve fast dynamic response and excellent steady-state performance in the permanent magnet synchronous motor drive system with uncertain parameters.

2. **Modeling of PMSM with Uncertainties.** The stator current equation of the interior PMSM in the coordinate system is

$$\begin{cases} \dfrac{\mathrm{d}i_d}{\mathrm{d}t} = -\dfrac{Ri_d}{L_d} + \dfrac{\omega_e L_q i_q}{L_d} + \dfrac{u_d}{L_d} \\ \dfrac{\mathrm{d}i_q}{\mathrm{d}t} = -\dfrac{Ri_q}{L_q} - \dfrac{\omega_e L_d i_d}{L_q} + \dfrac{u_q}{L_q} - \dfrac{\omega_e \psi_f}{L_q} \end{cases} \tag{1}$$

The electromagnetic torque equation is

$$T_e = \frac{3}{2} P_n \left(\psi_f + (L_d - L_q)\, i_d\right) \cdot i_q \tag{2}$$

The equation of motion is

$$\frac{\mathrm{d}\omega_m}{\mathrm{d}t} = \frac{T_e}{J} - \frac{T_L}{J} - \frac{B\omega_m}{J} \tag{3}$$

where u_d, u_q; i_d, i_q are the stator voltage and stator current in the dq coordinate system, respectively. L_d, L_q is dq axis inductance respectively. R is the stator resistance; ω_e is the electrical angular velocity; ψ_f is the rotor permanent magnet flux linkage amplitude; T_e is the electromagnetic torque; P_n is the number of pole pairs; ω_m is the mechanical angular velocity; T_L is the load torque; B is the friction coefficient; J is the moment of inertia.

Applying the forward Euler method to discretizing the model shown in (1), the discrete current model of PMSM can be expressed as

$$\begin{cases} i_d(k+1) = \left(1 - \dfrac{T_s R}{L_d}\right) i_d(k) + \dfrac{T_s \omega_e L_q}{L_d} i_q(k) + T_s \dfrac{u_d(k)}{L_d} \\ i_q(k+1) = \left(1 - \dfrac{T_s R}{L_q}\right) i_q(k) - \dfrac{T_s \omega_e L_d}{L_q} i_d(k) - \dfrac{T_s \omega_e \psi_f}{L_q} + T_s \dfrac{u_q(k)}{L_q} \end{cases} \tag{4}$$

where T_s is sampling period. In the traditional MPC method, according to the discrete prediction model formula (4), after one modulation period, the actual current vector is made to reach the reference current, and the stator voltage expression is as follows

$$\begin{cases} u_d(k) = \dfrac{L_d}{T_s}\left(i_d^*(k+1) - i_d(k)\right) + Ri_d(k) - \omega_e L_q i_q(k) \\ u_q(k) = \dfrac{L_q}{T_s}\left(i_q^*(k+1) - i_q(k)\right) + Ri_q(k) + \omega_e L_d i_d(k) + \omega_e \psi_f \end{cases} \tag{5}$$

The output stator voltage vector makes the actual current vector close to the expected value. From Equation (5), predictive control includes three parameters (stator resistance, stator inductance and permanent magnet link), which means that predictive current control is a model-based method. Therefore, the parameter accuracy of the prediction model is very important for the control performance of the PMSM system.

With motor operation or changes in external conditions, the parameters set in the controller may be different from the actual ones. The voltage equation with parametric uncertainty is expressed as

$$\begin{cases} u_d = Ri_d + L_d\dfrac{\mathrm{d}i_d}{\mathrm{d}t} - \omega_e L_q i_q + f_d \\ u_q = Ri_q + L_q\dfrac{\mathrm{d}i_q}{\mathrm{d}t} + \omega_e L_d i_d + \omega_e \psi_f + f_q \end{cases} \tag{6}$$

where f_d, f_q represent the parameter disturbances.

3. **Super-Twisting Sliding Mode Observer.** In order to achieve the purpose of parameter disturbance estimation and current prediction, a high-order sliding mode observer is designed with the following expressions:

$$\begin{cases} \dot{\hat{i}}_d = -\dfrac{Ri_d}{L_d} + \dfrac{\omega_e L_q i_q}{L_d} + \dfrac{u_d}{L_d} - \dfrac{\hat{f}_d}{L_d} - k_1 \left|e_d\right|^{1/2} \mathrm{sgn}(e_d) \\ \dot{\hat{f}}_d = L_d k_2 \mathrm{sgn}(e_d) \end{cases} \tag{7}$$

$$\begin{cases} \dot{\hat{i}}_q = -\dfrac{Ri_q}{L_q} - \dfrac{\omega_e L_d i_d}{L_q} - \dfrac{\omega_e \psi_f}{L_q} + \dfrac{u_q}{L_q} - \dfrac{\hat{f}_q}{L_q} - k_3 \left|e_q\right|^{1/2} \mathrm{sgn}(e_q) \\ \dot{\hat{f}}_q = L_q k_4 \mathrm{sgn}(e_q) \end{cases} \tag{8}$$

where $e_d = \hat{i}_d - i_d$, $e_q = \hat{i}_q - i_q$. Using Formula (7) and Formula (8) to subtract Formula (6) respectively, the error equation is

$$\begin{cases} \dot{e}_d = -k_1 |e_d|^{1/2} \mathrm{sgn}(e_d) + e_{f_d} \\ \dot{e}_{f_d} = -L_d k_2 \mathrm{sgn}(e_d) + F_d \end{cases} \tag{9}$$

$$\begin{cases} \dot{e}_q = -k_3 |e_q|^{1/2} \mathrm{sgn}(e_q) + e_{f_q} \\ \dot{e}_{f_q} = -L_q k_4 \mathrm{sgn}(e_q) + F_q \end{cases} \tag{10}$$

According to the parameter selection method in the [7], the appropriate observer gain is selected, and the observed current and disturbance errors can converge to zero in a limited time.

In practical digital systems, considering the one-step delay issue, the first order forward Euler discretization is employed to obtain Equations (11) and (12), shown as

$$\begin{cases} \hat{i}_d(k+1) = -\dfrac{T_s R}{L_d} i_d(k) + \dfrac{T_s \omega_e L_q}{L_d} i_q(k) + \dfrac{T_s}{L_d} u_d(k) - \dfrac{T_s}{L_d} \hat{f}_d(k) \\ \qquad - T_s k_1 \left|e_d\right|^{1/2} \mathrm{sgn}(e_d) + \hat{i}_d(k) \\ \hat{f}_d(k+1) = T_s L_d k_2 \mathrm{sgn}(e_d) + \hat{f}_d(k) \end{cases} \tag{11}$$

$$\begin{cases} \hat{i}_q(k+1) = -\dfrac{T_s R}{L_q} i_q(k) - \dfrac{T_s \omega_e L_d}{L_q} i_d(k) - \dfrac{T_s \omega_e \psi_f}{L_q} + \dfrac{T_s}{L_q} u_q(k) - \dfrac{T_s}{L_q} \hat{f}_q(k) \\ \qquad - T_s k_3 \left|e_q\right|^{1/2} \mathrm{sgn}(e_q) + \hat{i}_q(k) \\ \hat{f}_q(k+1) = T_s L_q k_4 \mathrm{sgn}(e_q) + \hat{f}_q(k) \end{cases} \tag{12}$$

Feed forward the parameter disturbance observed by STSMO to Equation (6), and obtain the given dq-axis voltage required by the current predictive control algorithm based on STSMO as

$$\begin{cases} U_d^* = u_d(k) + \hat{f}_d(k+1) \\ U_q^* = u_q(k) + \hat{f}_q(k+1) \end{cases} \tag{13}$$

The proposed control block diagram of the deadbeat prediction current system of PMSM based on STSMO is shown in Figure 1.

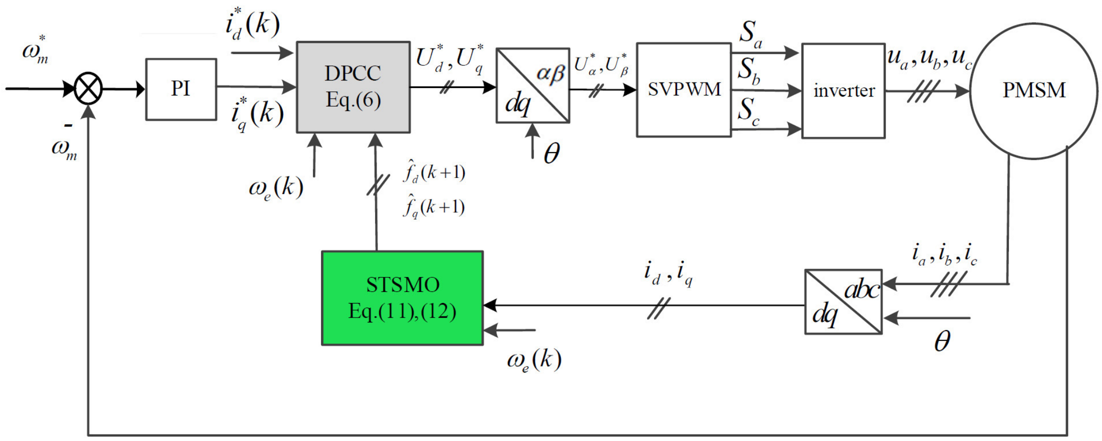


FIGURE 1. The control block diagram of the system

4. **Simulation Results.** In order to validate the effectiveness and robustness of the proposed dead beat predictive current control method based on STSMO, the two PMSM drive systems have been constructed in Matlab/Simulink platform. The first is PMSM drive employing conventional DPCC. The second is PMSM drive employing the STSMO based DPCC. The parameters of the PMSM are given in Table 1. The sampling period is 100 microseconds and the reference speed is set to 1500 r/min.

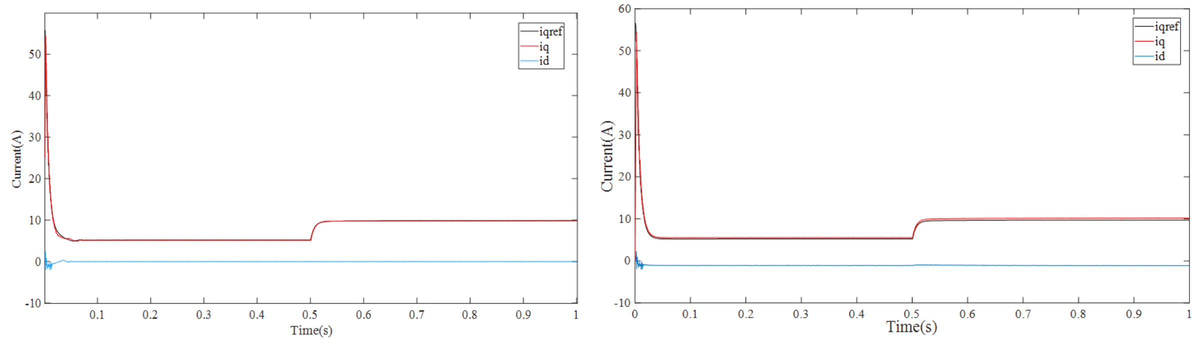
TABLE 1. Parameters of PMSM

Symbol	Value
R_s	0.602 Ω
L_d, L_q	9.32/14.14 mH
ψ_m	0.432 Wb
p	4
V_{dc}	530 V
J	0.007 Kg·m^2
B_m	0.008 Nms

The resistance becomes 2 times the nominal parameters, the inductance becomes 2 times the nominal parameters, and the flux linkage becomes 2 times the nominal parameters. In order to verify estimation accuracy of the designed STSMO, two systems employ the same DPCC. $k_1 = k_3 = 40000$, $k_2 = k_4 = 500000$.

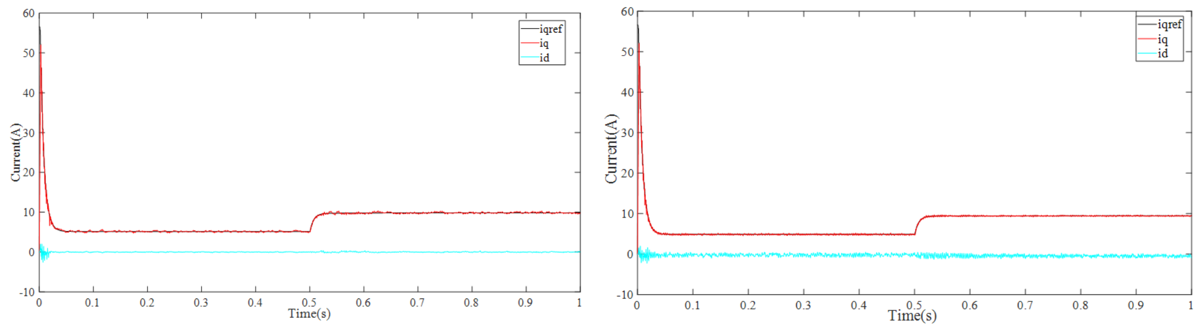
As can be seen in Figures 2 to 4, the system using STSMO has better noise immunity and tracking accuracy.

5. **Conclusions.** In this paper, a deadbeat predictive current control method based on a high-order sliding mode observer is proposed. The super-twisting sliding-mode observer designed in this paper can accurately estimate the disturbance when the resistance, inductance, and flux linkage parameters are perturbed and feed forward to the DPCC, which



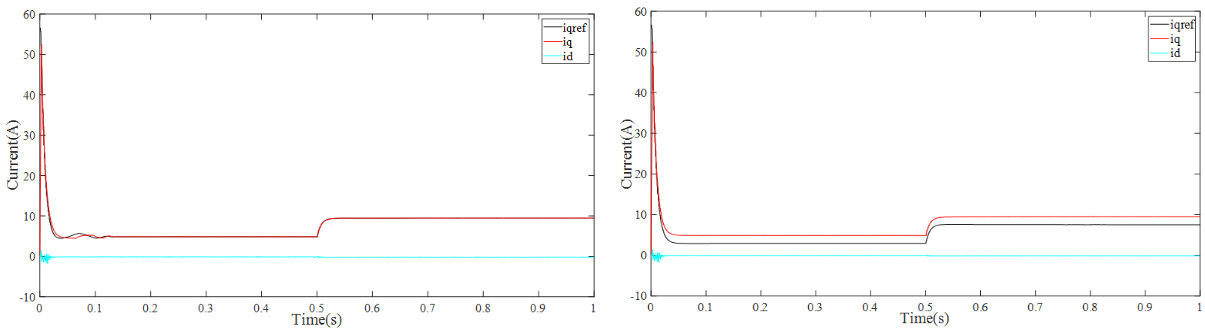
(a) (b)

Figure 2. The current responses under the perturbations of resistance: (a) Its response with DPCC + SCDO method; (b) its response with DPCC method



(a) (b)

Figure 3. The current responses under the perturbations of inductance: (a) Its response with DPCC + SCDO method; (b) its response with DPCC method



(a) (b)

Figure 4. The current responses under the perturbations of flux linkage: (a) Its response with DPCC + SCDO method; (b) its response with DPCC method

improves the robustness of the system. The simulation results show that, compared with the traditional control method, the control strategy can have better control performance under the condition of load and parameter changes.

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