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Article

Robust Current Predictive Control-Based Equivalent Input Disturbance Approach for PMSM Drive

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Abstract: The implementation and experimental validation of current control strategy based on predictive control and equivalent input disturbance approach is discussed for permanent magnet synchronous motor (PMSM) control system in the paper. First, to realize the current decoupling control, the deadbeat predictive current control technique is adopted in the current loop of PMSM. Indeed, it is well known that the traditional deadbeat current control cannot completely reject the disturbance and realize the zero error current tracking control. Then, according to the model uncertainties and the parameter variations in the motor, an equivalent input disturbance approach is introduced to estimate the lump disturbance in the system, which will be used in the feed-forward compensation. Thus, a compound current controller is designed, and the proposed algorithm reduces the tracking error caused by the disturbance; the robustness of the drive system is improved effectively. Finally, simulation and experiment are accomplished on the control prototype, and the results show the effectiveness of the proposed current control algorithm.

Keywords: PMSM drive; current control; deadbeat predictive control; equivalent input disturbance

1. Introduction

Owning to the multiple advantages of high efficiency, high power density, and exceptional reliability, permanent magnet synchronous motor (PMSM) has been widely used in different applications [1], such as electric vehicle drive system, rail traffic, and robot. However, the main weakness of PMSM is the complex controller for its nonlinear and strong coupling characteristics. Therefore, the vector control strategy is employed for the practical applications in general. Consequently, a double closed-loop control method with the inner current loop and the out speed loop is formed. This paper mainly concentrates on solving the current control problem of PMSM in the face of different disturbance.

In general, the proportional plus integral (PI) current control method is popular for industrial applications and is not designed based on the mathematical model. The good performance of zero steady-state error and fixed switching frequency has promoted extensive industrial application. However, it may not meet the requirement in some special occasions, and the transient response may be limited. Meanwhile, it is a challenge for engineers to select the PI parameters by trial and error because of the large parameter uncertainties [2]. Thus, many approaches have been proposed for the motor drive system, such as, sliding mode variable structure control [3], feedback linearization control [4], finite-time control [5], predictive control [6], and passive control [7]. These methods may improve the performance of motor drive system in different aspects, such as good transient response, strong robustness, or lower torque ripple in the steady state.

Among these methods, predictive control, as an advanced control strategy, has been widely applied to the power electronics and drives [8,9]. Predictive control can achieve good tracking control and can be completed easily. For the current control of PMSM, predictive control methods mainly includes deadbeat predictive control [10,11] and model predictive control (MPC) [12–15]. In comparison, the requirement for high computational resources is one of the main drawbacks in a drive with MPC. Deadbeat predictive control, as one of the simplest and best-known predictive control methods, can obtain good tracking performance with less computational burden. In this method, the discrete time model is used to compute the reference voltage, and the zero-error can be achieved within one sampling time. Then, the voltage is translated to the corresponding switching configurations through pulse width modulation or the space vector PWM [16]. Thus, the deadbeat predictive control is characterized with fixed switching frequency, fast current dynamic response, and less computational burden.

It is worth emphasizing that the deadbeat predictive control is a model-based control technique, and the exact model is required. The sensitivity of deadbeat predictive control against uncertainties is a well-known disadvantage. If the motor parameters are known, the tuning problem is reduced to the selection of one parameter only in deadbeat predictive control. However, the PMSM drive system faces inevitable model uncertainties and parameter variations, as the values of stator resistance, stator inductance, and the rotor flux may change, along with the changes of the operation conditions. Influenced by system uncertainty, the motor current cannot track the reference value, which will affect the field-oriented control of the motor, then the performance of the control system will be degraded. Thus, the uncertainties inside the motor and outside disturbances are the main factors to reduce the system performances. Confronted with the problem of system uncertainty, effective methods include the disturbance estimation and attenuation method [17]. Meanwhile, it is proven that this technology has a different but complementary mechanism to widely used robust control and adaptive control [18]. In the work by the authors of [19], a generalized proportional integral observer method is proposed to estimate the time-varying disturbance for the speed current control of PMSM. In the work by the authors of [20], a generalized predictive current control method is proposed for the current control of PMSM, and a sliding mode compensation controller is designed to eliminate the disturbance. Meanwhile, several papers focusing on improving the robustness of deadbeat controller have been published. In the work by the authors of [21], a robust current controller is designed by using an additional integrator term in deadbeat control. In the work by the authors of [22], a robust deadbeat current control method is studied through calculating the switch signals applied in the next sampling period. In the work by the authors of [23], the parameter identification method is used to estimate the motor parameters in real time, and the robustness is improved, but this method depends on the identification precision of the model parameters, and the model still contains uncertainties due to unmodeled dynamics and disturbances. In the work by the authors of [24], a high-order sliding mode observer is designed for the estimation of disturbance in the current loop for PMSM. In [25–27], the disturbance observer or extended state observer is designed in the deadbeat current control for PMSM. In these methods, the system disturbance is estimated through the observer, then they are used for the feed-forward compensation control to improve the robustness.

In this paper, to enhance the robustness of deadbeat predictive control and improve the consequent system performance degradation for the uncertainties, a novel disturbance attenuation method based on equivalent-input-disturbance (EID) is proposed. EID is a signal on the input voltage that produces the same effect on the current output as actual disturbance does [28–30]. To the best of our knowledge, this method has not been used in the current control of PMSM at present. In this paper, we applied EID into the current control of PMSM, and it is used to deal with the disturbance in the drive system. Thus, a composite current controller by combining the deadbeat predictive control and EID approach is designed. The decoupled current control is completed by the deadbeat control. Then, according to the parameter variations and model uncertainties, EID is designed to eliminate the influence triggered by the uncertainties. In the EID, the lumped disturbance that consists of the model uncertainties and the parameter variations is regarded, and it is used to the feed-forward compensation control. The main contribution of the paper is the idea that the EID is introduced to estimate the disturbance in the current control for PMSM. Only the nominal motor parameters are needed in the controller. Meanwhile, the designed current controller is not complex and the parameters are convenient to be adjusted. Finally, the simulation and experimental verification on a speed current closed-loop control system of PMSM is completed, and the effectiveness is verified in different conditions. Meanwhile, the designed controller can also be used to the torque control of PMSM.

The remainder of this paper is organized as follows. The dynamic model of PMSM considering the disturbance is derived. The robust predictive current controller based on equivalent-input-disturbance is studied in Section 3. The simulation and experiment are demonstrated in Section 4, and the final part states the conclusions.

2. Mathematical Model of PMSM

The electromagnetic model of PMSM in d-q axes can be expressed as [1]

$$\begin{cases} L_d \frac{di_d}{dt} = -R_s i_d + n_p \omega L_q i_q + u_d + \xi_d \\ L_q \frac{di_q}{dt} = -R_s i_q - n_p \omega L_d i_d - n_p \omega \Phi + u_q + \xi_q \end{cases} \tag{1}$$

where L_d and L_q represent d-axes and q-axes stator inductances, respectively; i_d and i_q are the stator currents; u_d and u_q are the stator input voltages in dq-axes reference frame; R_s is the per-phase stator resistance; n_p is the number of pole pairs; ω is the mechanical angular speed; Φ is the rotor flux; and ξ_d and ξ_q represent the disturbance caused by the parameter variations and model uncertainties as

$$\begin{cases} \xi_d = -(\Delta R_s i_d - \Delta L_q n_p \omega i_q + \Delta L_d \frac{di_d}{dt} + \eta_d) \\ \xi_q = -(\Delta R_s i_q - \Delta L_d n_p \omega i_d + \Delta L_q \frac{di_q}{dt} + \Delta \Phi n_p \omega + \eta_q) \end{cases} \tag{2}$$

where η_d and η_q represent the model uncertainties.

$$\begin{aligned} &\Delta R_s = R_{st} - R_s, \Delta L_d = L_{dt} - L_d, \\ &\Delta L_q = L_{qt} - L_q, \Delta \Phi = \Phi_t - \Phi, \end{aligned} \tag{3}$$

in which R_s, L_d, L_q, and Φ denote the nominal parameter values, and R_{st}, L_{dt}, L_{qt}, and Φ_t denote the actual parameter values.

3. Current Control Scheme for PMSM

The control structure of PMSM control system with the proposed current control method is shown in Figure 1. The controller uses a cascade control structure including an out speed loop and two inner current loops. Here, the PI controller is used in the speed loop to realize the tracking control of motor speed, thus the q-axes reference current $i_q^* = k_p(\omega_r - \omega) + k_i \int_0^t (\omega_r - \omega)dt$, where ω_r is the reference speed. The reference current i_d^* is set to be zero. In this paper, a novel deadbeat predictive controller with equivalent-input-disturbance is used to solve the current control problem.

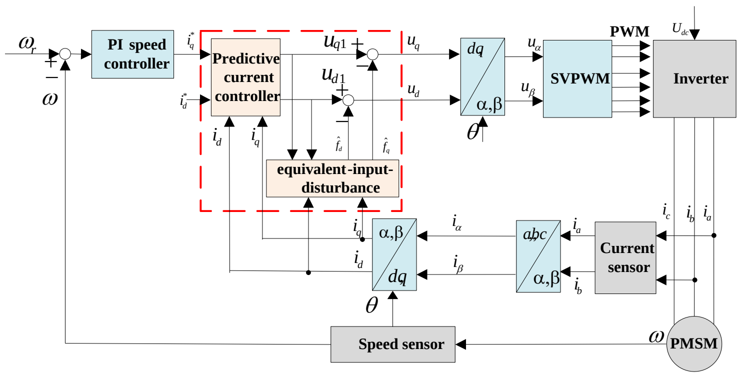


Figure 1. Block diagram of permanent magnet synchronous motor (PMSM) control system.

3.1. Deadbeat Predictive Current Controller for Pmsm

The model of the system (1) can be expressed as

$$\begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & 0 \\ 0 & -\frac{R_s}{L_q} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix} \begin{bmatrix} u_d \\ u_q \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix} \begin{bmatrix} f_d \\ f_q \end{bmatrix} \tag{4}$$

where $f_d = n_p \omega L_q i_q + \xi_d$ and $f_q = -n_p \omega L_d i_d - n_p \omega \Phi + \xi_q$ are considered as the lump disturbance, which include the disturbance and the back-electromotive force.

In the condition of ignoring the lump disturbance, the predictive model of (4) is expressed as a discrete-time form:

$$\begin{bmatrix} i_d(k+1) \\ i_q(k+1) \end{bmatrix} = \begin{bmatrix} 1 - \frac{R_s}{L_d} T_s & 0 \\ 0 & 1 - \frac{R_s}{L_q} T_s \end{bmatrix} \begin{bmatrix} i_d(k) \\ i_q(k) \end{bmatrix} + \begin{bmatrix} \frac{T_s}{L_d} & 0 \\ 0 & \frac{T_s}{L_q} \end{bmatrix} \begin{bmatrix} u_{d1}(k) \\ u_{q1}(k) \end{bmatrix} \tag{5}$$

where T_s is the sample time. u_{d1} and u_{q1} are the control input without considering the lump disturbance.

Define the state variable as $x(k) = \begin{bmatrix} x_1(k) & x_2(k) \end{bmatrix}^T = \begin{bmatrix} i_d(k) & i_q(k) \end{bmatrix}^T$, the input variable as $u_1(k) = \begin{bmatrix} u_{d1}(k) & u_{q1}(k) \end{bmatrix}^T$, and the output variable as $y(k) = \begin{bmatrix} y_1(k) & y_2(k) \end{bmatrix}^T = \begin{bmatrix} i_d(k) & i_q(k) \end{bmatrix}^T$.

The premise of deadbeat predictive current control is that the actual current $I(k)$ is sampled at the beginning of the $k-th$ carrier cycle, and the predicted value of current deviation vector $\Delta I(k)$ is obtained, then the reference voltage output is calculated [22]. For achieving the current control, the required input voltage $u_1(k)$ at the current time can be calculated through the sample current $x(k)$ at kT and $x(k+1)$ at $(k+1)T$. However, in a practical control system, the reference voltage $u_1(k)$ is not added to the inverter immediately at kT, and it is carried out at $(k+1)T$. Therefore, the sample current $x(k+1)$ just reaches the reference current $x^*(k) = \begin{bmatrix} i_d^* & i_q^* \end{bmatrix}^T$ at kT .

Take the reference current $x^*(k)$ as the predictive current value at $(k+1)T$, thus $\begin{bmatrix} i_d(k+1) & i_q(k+1) \end{bmatrix} = \begin{bmatrix} i_d^* & i_q^* \end{bmatrix}$. According to Equation (5), the following can be calculated.

$$\begin{bmatrix} u_{d1}(k) \\ u_{q1}(k) \end{bmatrix} = \begin{bmatrix} \frac{T_s}{L_d} & 0 \\ 0 & \frac{T_s}{L_q} \end{bmatrix}^{-1} \left(\begin{bmatrix} i_d^*(k) \\ i_q^*(k) \end{bmatrix} - \begin{bmatrix} 1 - \frac{R_s}{L_d} T_s & 0 \\ 0 & 1 - \frac{R_s}{L_q} T_s \end{bmatrix} \begin{bmatrix} i_d(k) \\ i_q(k) \end{bmatrix} \right) \tag{6}$$

The control laws in (6) are the reference dq-axes voltage based on deadbeat predictive control. The designed controller can solve the deadbeat control problem in general without additional means of support, but the lump disturbance is ignored, and the current control results will be affected in the face of the strong disturbance.

3.2. Disturbance Observer Based on EID

To suppress the lump disturbance in the system and improve the robustness, an equivalent-input-disturbance approach combined with the deadbeat predictive controller is studied. EID approach is a simple disturbance attenuation method and it can be easily implemented in the digital controller because it does not require an inverse model of the plant or prior information on the disturbance. Usually, an EID-based control system includes a state observer, an EID estimator, and state feedback [29]. The structural diagram of EID is shown in Figure 2. Thus, the deadbeat predictive controller can be seen as the state feedback.

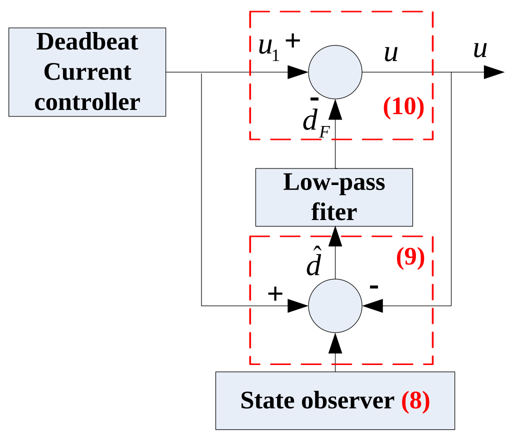


Figure 2. Structural diagram of equivalent-input-disturbance (EID).

Firstly, according to (4), the model can be described as

$$\begin{cases} \dot{x} = Ax + Bu + Bd \\ y = cx \end{cases} \tag{7}$$

where $A = \begin{bmatrix} -\frac{R_s}{L_d} & 0 \\ 0 & -\frac{R_s}{L_q} \end{bmatrix}$, $B = \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix}$, $C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $u = \begin{bmatrix} u_d & u_q \end{bmatrix}^T$ and $d = \begin{bmatrix} f_d & f_q \end{bmatrix}^T$.

The system is controllable and observable, and it has no zeros on the imaginary axis, which guarantees the internal stability of the motor system and allows the speed to track the reference value [31]. Assume the distubance d satisfies $\|d\|_\infty < d_M$, where d_M is an unknown positive real number.

The EID is estimated by making the best use of the state observer of the system. A full-order observer is used to estimate the EID, then a state observer is defined as

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + Bu_1 + L[y - \hat{y}] \\ \hat{y} = c\hat{x} \end{cases} \tag{8}$$

where $u_1 = \begin{bmatrix} u_{d1} & u_{q1} \end{bmatrix}^T$, L is the observer gain, and $\hat{x}$ is the reconstructed state of x.

According to the literatures [29,30], the estimator of EID is derived as

$$\hat{d} = B_1 LC[x - \hat{x}] + u_1 - u \tag{9}$$

where $B_1 = \left(B^T B\right)^{-1} B^T$.

As the output y contains a measurement noise, to depress the noise of the measured output current, a low-pass filter is used in the estimator of EID, thus $d_F = F(s)\hat{d}$, $F(s) = \frac{B_F}{s+A_F}$ is the low-pass filter.

Combing the deadbeat controller and the EID estimator, the final current controller of PMSM control system can be given as

$$u = u_1 - d_F \tag{10}$$

In the paper, the model of PMSM is represented as the linear model, which is shown in Equation (7). The stability of the motor drive system can be broken down into two independent parts: state feedback and the observer. First, the state feedback is designed by the deadbeat predictive control method. Then, according to the Theorem 1 in the work by the authors of [31], the conditions are satisfied for the motor system. Thus, the stability of the control system can be guaranteed.

Meanwhile, the following simulation and experiment in different conditions prove that the motor can run steadily.

4. Simulation and Experiment

The proposed current control method with deadbeat predictive control and equivalent input disturbance approach is implemented in simulation and dSPACE based experiment. The motor parameters used in the simulation and experiment are given in Table 1.

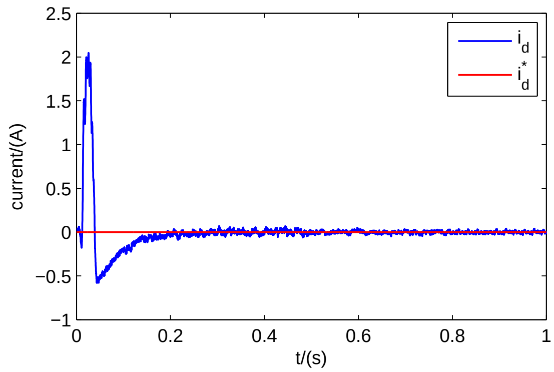
Table 1. Parameters of PMSM.

Description	Value	Unit
rated speed	3000	r/min
rated torque	2.3	N·m
resistance	4.8	Ω
d-axes inductance	19.5	mH
q-axes inductance	27.5	mH
rotor flux	0.15	Wb

4.1. Simulation and Analysis

The simulation is completed in the speed control system of PMSM. The double closed-loop vector control method is used for the speed and current control, the out loop is the speed loop, and the inner loop is the current loop. The motor reference speed is given as $\omega_r = 1000$ r/min, and the load torque 1 N·m is added on the motor. The PI controller is adopted in the speed loop. In order to verify the merit of the proposed method, in the current loop, both PI current controller and proposed current control method have been completed, respectively. The parameters of speed loop are consistent with each other in both methods. In addition, to validate the current tracking performance of the proposed control method while the motor has parameter perturbation, the values of rotor–flux linkage, armature resistance, and dq-axes inductance are changed to 80%, 200%, and 150% of the normal values at $t = 0.5$ s, respectively. Figure 3 shows the motor response waveform based on PI control. Figure 3a,b shows the dq-axes current waveform.

The motor speed response curve is shown in Figure 3c. The simulation results based on the proposed current control method are shown in Figure 4.



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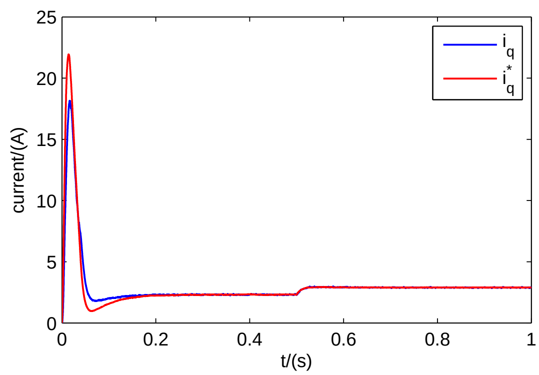

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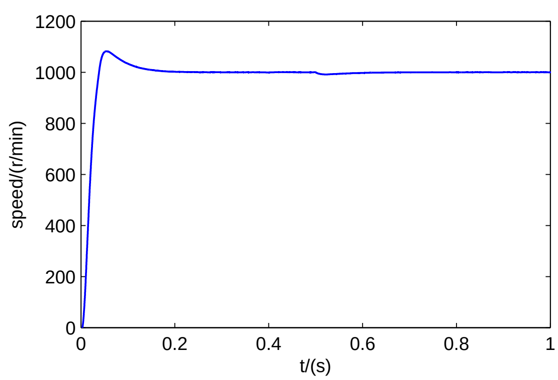


(**c**)

Figure 3. Simulation results with proportional plus integral (PI) control: (**a**) d-axes current; (**b**) q-axes current; and (**c**) speed response.

As shown in Figures 3 and 4, compared with the PI control, the proposed predictive current control method has better current control performance with a faster current response and smaller current fluctuation. When the motor parameters are changed, the results show that the parameter variations has little influence to the current control performance, and the proposed method in this paper still has precise current tracking and antidisturbance performance. Meanwhile, the control system has the good speed tracking performance.

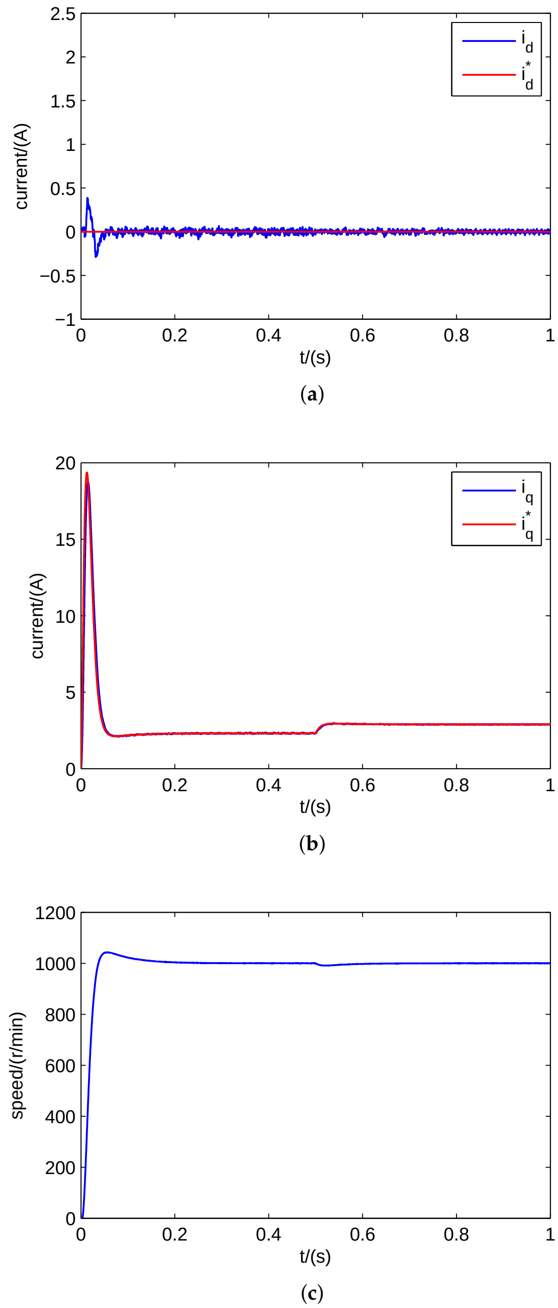
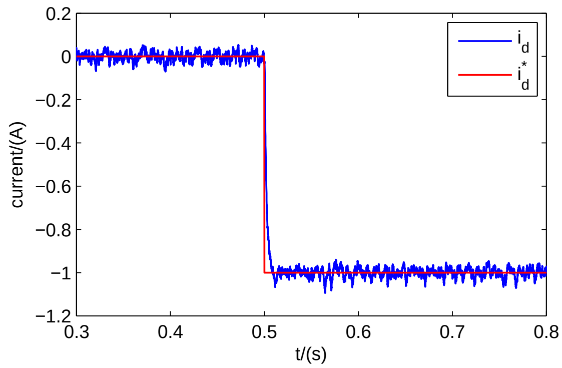


Figure 4. Simulation results with the proposed method: (**a**) d-axes current; (**b**) q-axes current; and (**c**) speed response.

To verify the effectiveness of the proposed method under the change of reference current, the d-axes reference current is changed from 0 to −1A at t = 0.5 s, and Figure 5 shows the current and speed response waveform. As shown in the figures, the dq-axes current varies with the change of the reference current, and the controller also good current tracking performance. Meanwhile, the motor speed has a small fluctuation, and it can be stable for a short period of time.



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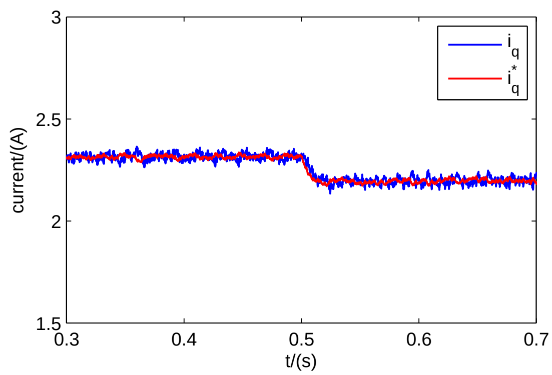

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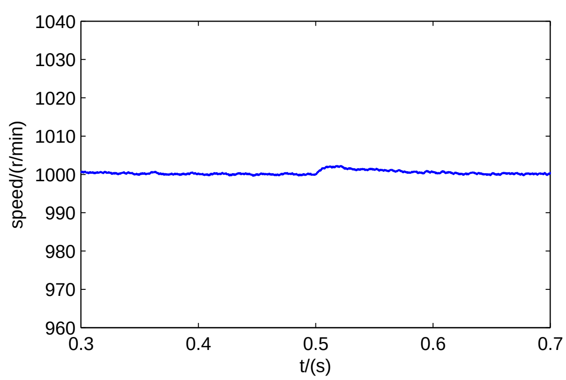


(**c**)

Figure 5. Simulation results with the proposed method when i_d^* is changed: (**a**) d-axes current, (**b**) q-axes current, and (**c**) speed response.

In addition, to test the performance of the controller with load disturbance, the reference speed is given as 1000 r/min, the load torque is changed from 1 N·m to 2 N·m at $t = 0.5$ s, and other parameters are fixed. The results are show in Figure 6. The figures reveal that with the increase of load torque, the q-axis current increases quickly to produce the same electromagnetic torque. Although the reference current has a variation with the change of load torque, the motor current can still track the reference value, and the robustness can be maintained in steady-state.

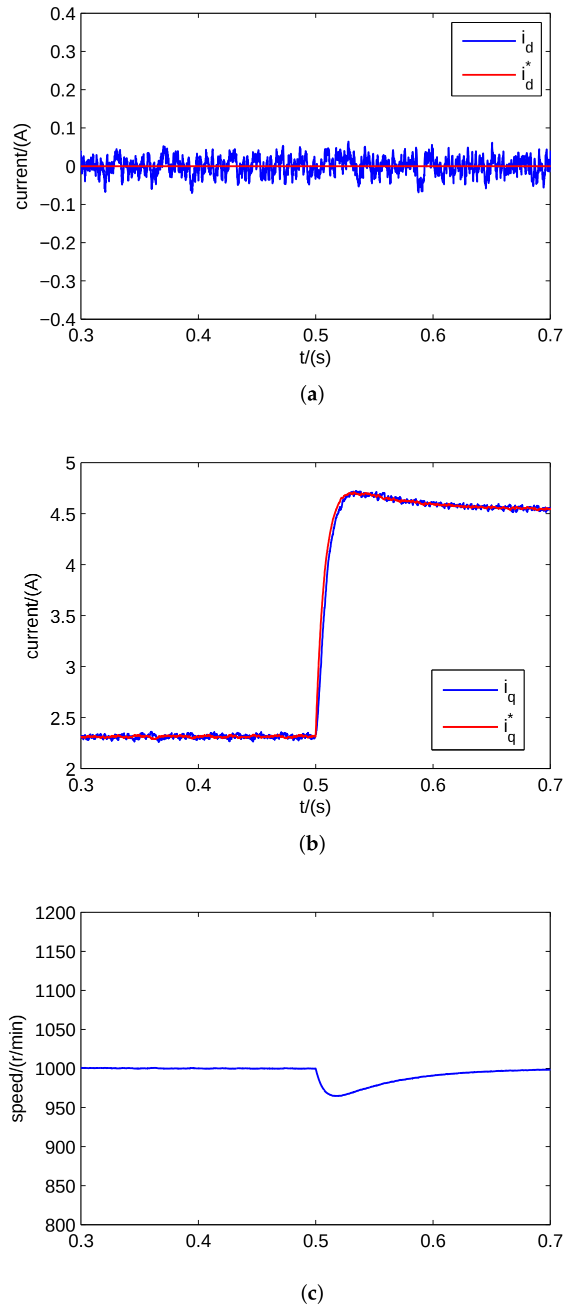
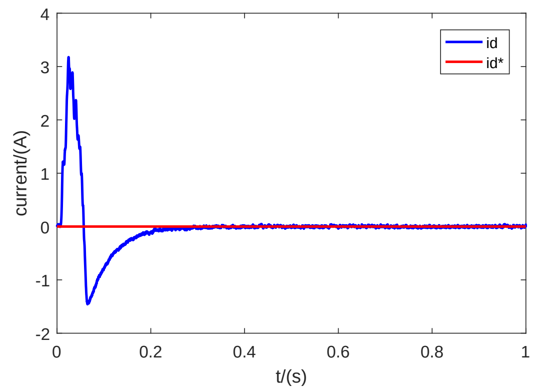


Figure 6. Simulation results with the proposed method when the load torque changed: (**a**) d-axes current, (**b**) q-axes current, and (**c**) speed response.

To better validate the advantage of the proposed current control method under parameter disturbance, three different comparative methods—PI current control, deadbeat predictive control without equivalent input disturbance approach, and the proposed method—have been used in the current loop controller of the drive system, respectively. The reference speed is also given as 1000 r/min, but the motor parameters are changed when the motor is started. The results based on three current control methods are shown in Figures 7–9. The speed loop has the same parameters as the PI control method.



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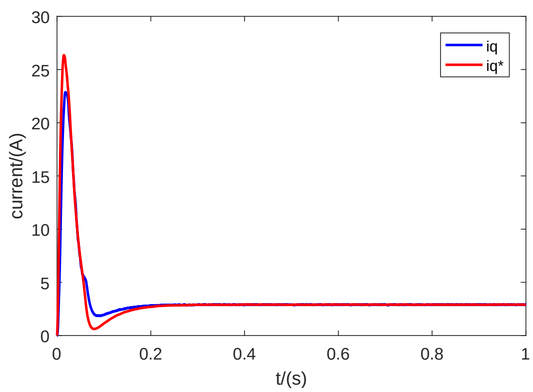

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Figure 7. Simulation results with PI control method under the parameter disturbance: (**a**) d-axes current and (**b**) q-axes current.

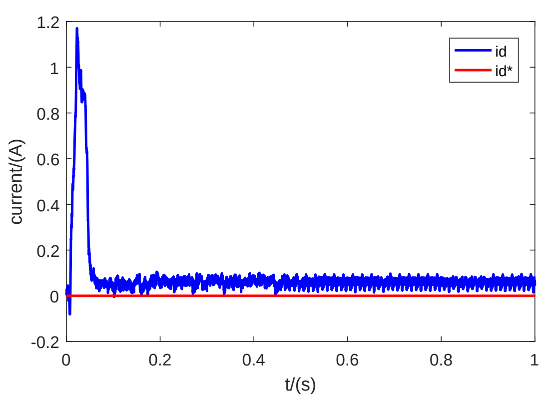

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Figure 8. *Cont*.

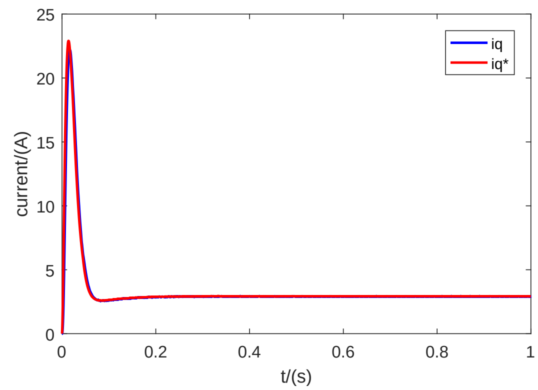

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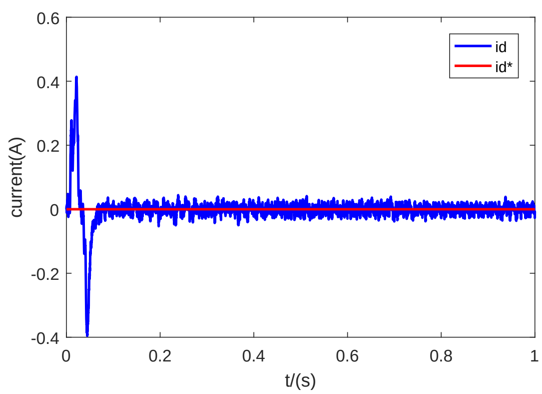
Figure 8. Simulation results with deadbeat control method under the parameter disturbance: (**a**) d-axes current and (**b**) q-axes current.



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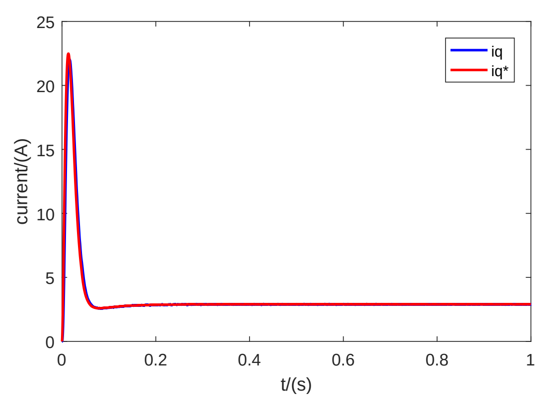


(**b**)

Figure 9. Simulation results with the proposed method under the parameter disturbance: (**a**) d-axes current and (**b**) q-axes current.

The results show that compared to the PI control, the proposed method has the smaller current fluctuation and the shorter settling time when the motor starts. Both methods have strong robustness for the parameter of disturbance. Although the deadbeat predictive current controller has the fast response, there is an obvious error between the output current and the reference values, and the dq-axes current cannot track the reference values accurately. The above results verify that the proposed method has better current control performance.

4.2. Experiment and Analysis

The experiment is implemented on a dSPACE-based PMSM control platform, as shown in Figure 10. The system includes an interior PMSM, a dynamometer, a converter based on IPM, and the dSPACE MicroAutoBox as the control board. MicroAutoBox is a rapid prototyping (RCP) system, and it is ideally suited as hardware for prototyping in the motor drive system. The current is measured by the Hall sensor and it is turned to the digital signal through ACMC module. The experiment is completed on a speed control system of PMSM based on a doubled closed-loop structure. The deadbeat predictive controller with EID is used in the current loop control. The parameters of the PMSM are given in Table 1. The sample time is chosen as $T_s = 0.1$ ms. The observer gain L is the main parameter to be adjusted in the controller. The larger the gain is, the faster the observer converges. However, in general, the gain, L, cannot be too large. Otherwise, the system will be too sensitive to the interference signal and the stability of the system will decrease. So the observer gain of $L = \begin{bmatrix} 100 & 0 \\ 0 & 100 \end{bmatrix}$ is chosen in the controller. The low-pass filter is chosen as $F(s) = \frac{200}{s+200}$.

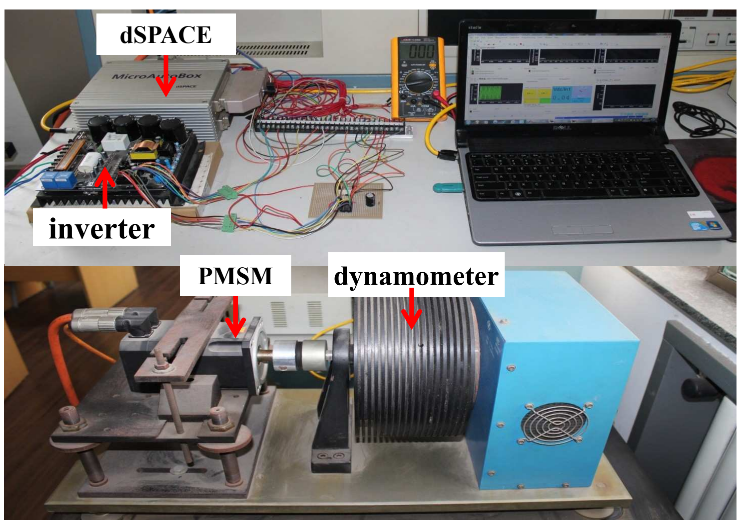
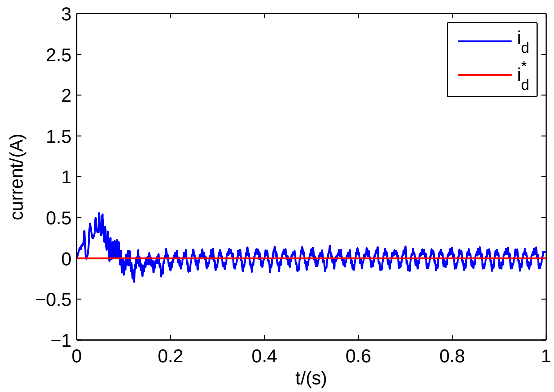
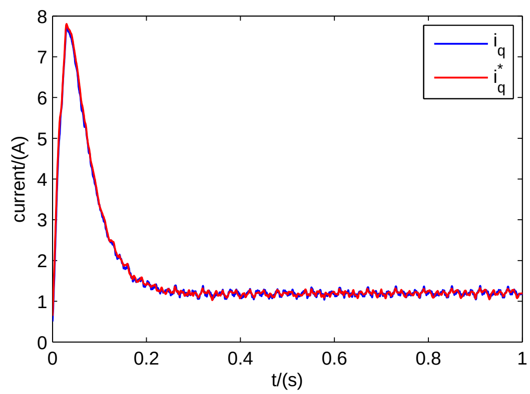


Figure 10. Experimental platform of PMSM drive system.

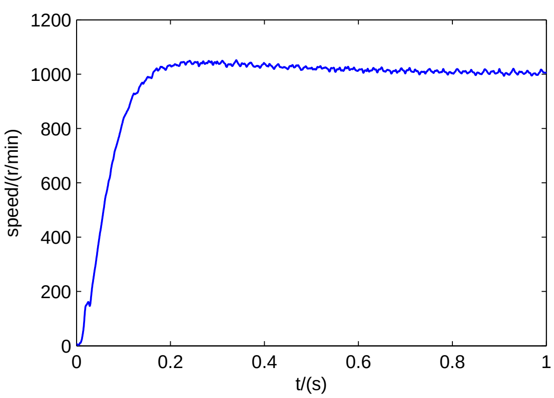
First, the motor starting speed is given as 1000 r/min. When the motor is stable, the reference speed is changed from 1000 r/min to 1500 r/min, and the experimental results are shown in Figures 11 and 12, which include the dq-axes current and speed response waveforms. As seen from Figures 11 and 12, when the motor is starting, the large starting current is produced, and the dq-axes current reaches to the reference current value soon. The designed current controller has the good tracking performance. The practical output current has a small fluctuation, which may be caused by the current harmonic, but the tracking performance is not affected. The motor speed can also arrive at the given value quickly.



(**a**)



(**b**)



(**c**)

Figure 11. Experimental results with the proposed method: (**a**) d-axes current; (**b**) q-axes current; and (**c**) speed response.

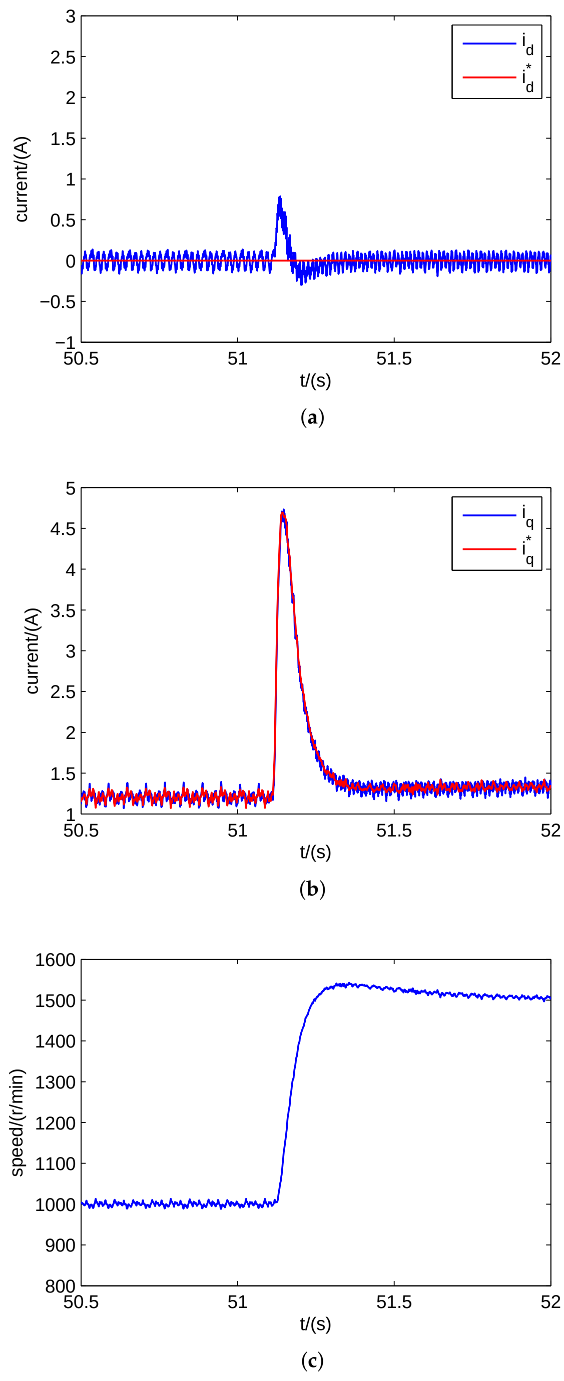
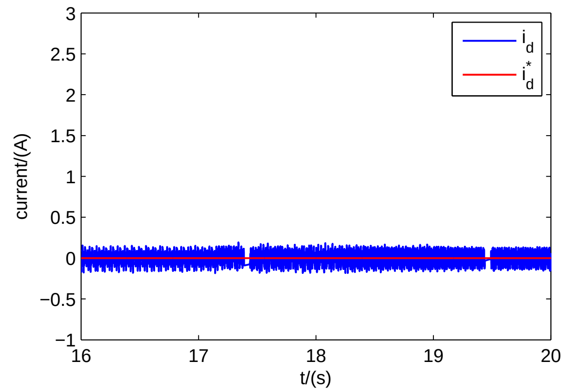
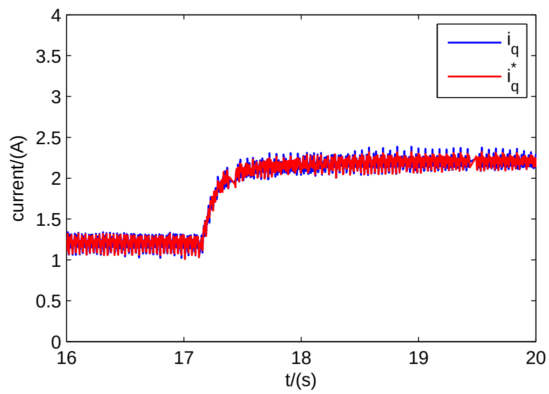


Figure 12. Experimental results with the increase of reference speed: (**a**) d-axes current; (**b**) q-axes current; and (**c**) speed response.

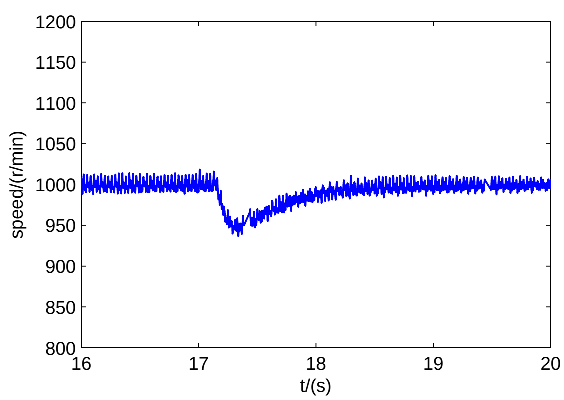
To further evaluate the performance of the proposed control method, the q-axe reference current is changed in the experiment. When the motor is working in 1000 r/min, the load torque disturbance is added to the motor at $t = 1$ s, and the experimental results are shown in Figure 13. We can see that the q-axes current changes with the increase of load torque, and it can converge to its reference value quickly. In this process, the d-axes current is not affected by the load disturbance, can stay at zero, and the robustness still can be maintained.



(**a**)



(**b**)



(**c**)

Figure 13. Experimental results with load disturbance: (**a**) d-axes current, (**b**) q-axes current, and (**c**) speed response.

To further verify the robustness of the proposed method with the parameters perturbation, the controller parameters are set mismatched with the real motor parameters. In comparison with the real values in the controller, the dq-axes inductances are set as two times of the rated values in the controller. The corresponding results are shown in Figure 14. Although the parameters are not consistent between the current controller and the motor, there is no large difference in the actual output current and the reference current. The experimental results prove the designed controller has excellent robustness for the disturbance.

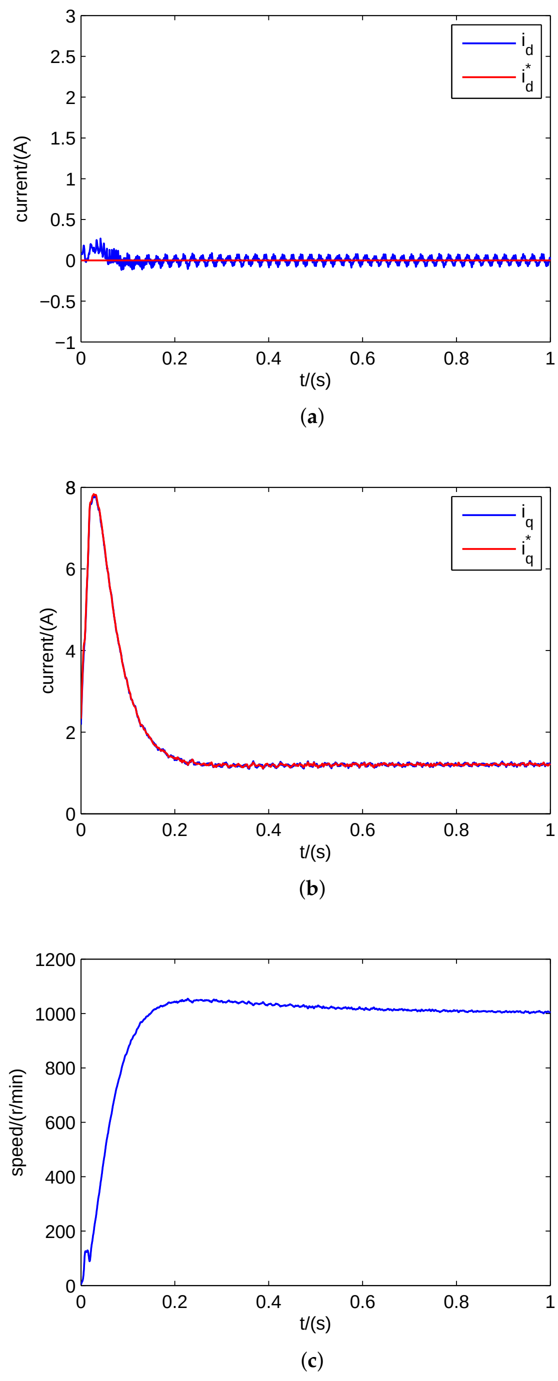


Figure 14. Experimental results with parameter variations: (**a**) d-axes current, (**b**) q-axes current, and (**c**) speed response.

5. Conclusions

In this paper, a novel current control method based on deadbeat predictive control and equivalent-input-disturbance theory has been proposed for PMSM drive. With the designed deadbeat controller, the current stabilizing control is achieved. According to the disturbance in the PMSM, we have designed an equivalent-input-disturbance estimator for the feed-forward compensation, and the robustness can be maintained under the disturbance. The simulation and experiment results have proved that the controller has good current tracking performance in different conditions. Meanwhile, the designed current controller is also suitable for torque control system of PMSM.

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