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Deadbeat Control of Permanent Magnet Synchronous Motorized Spindle Based on Improved Parameter Identification Algorithm

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ABSTRACT: A deadbeat control method based on an improved parameter identification algorithm is proposed to improve the control accuracy and rapidity of permanent magnet synchronous motorized spindle (PMSMS). Firstly, based on the mathematical model of PMSMS and Euler discretization formula, the current prediction equation is established. Secondly, the deadbeat control logic is described; the deadbeat control model is established; and the influence of parameters on the system stability is analyzed. Thirdly, in order to improve the parameter robustness of deadbeat control, an improved adaptive parameter identification algorithm is proposed, which combines the least mean square algorithm and recursive least square algorithm. Based on the voltage equation, the inductance and flux linkage parameters are identified, and then a more accurate parameter identification effect is achieved. Finally, the proposed algorithm is verified by experiments on the experimental platform. Experimental results show that the proposed algorithm has better control accuracy, faster response speed, and stronger stability than vector control method and traditional deadbeat control method.

1. INTRODUCTION

Permanent magnet synchronous motorized spindle (PMSMS) has been widely used in computer numerical control (CNC) machining centers now, because it has the advantages of high power density, low calorific value, and high control accuracy [1, 2]. When using CNC machining center, grinding is an essential step to realize precision machining. Accurate speed control and fast dynamic performance are very important for realizing high precision machining [3, 4]. In order to realize high precision control of PMSMS, many control methods have been applied, such as vector control [5], direct torque control [6], model predictive control [7], and deadbeat control [8, 9]. These methods all have their own advantages and disadvantages, and vector control and deadbeat control have both control accuracy, rapidity, and algorithm convenience. However, in practical application, vector control needs many adjustment parameters, and these parameters are closely related to operating conditions. The current loop with deadbeat control directly cancels the proportional-integral (PI) operation process, which not only reduces the complexity of adjusting multiple parameters, but also effectively improves the dynamic response speed of the system.

The advantages of deadbeat control make it a research hotspot of high performance control of PMSMS, and many scholars have studied it. In [10], a reduced-order model based on singular perturbation theory is proposed, and an enhanced model predictive control strategy is designed to achieve excellent rapidity and stability of PMSM. In [11], a dead-time predictive current control method considering parameter mismatch is proposed to enhance the robustness of the traditional dead-time predictive current control method by constructing an extended voltage model. In [12], a robust dead-time predictive current control method for PMSM based on full-parameter identification is proposed. This method innovatively combines deadbeat control method with high frequency current injection method to observe the inductance, flux linkage, and resistance of PMSM on-line, and realizes robust control of deadbeat algorithm of PMSM. In [13], an improved dead-time predictive current control strategy is proposed to improve the control performance of PMSM in the face of concentrated disturbances by using a composite integral sliding mode observer. Although the proposed control strategy improves the performance, the complex integral sliding mode observer may increase the structural complexity of the control system, and the simulation results are mainly aimed at specific load variations and parameter mismatches, and the effectiveness of the strategy may need to be further verified for a wider range of operating conditions and more complex disturbances.

The above research focuses on deadbeat control, but these methods are highly sensitive to parameters, so improving the accuracy of parameters is beneficial for improving the performance of deadbeat control. The research of parameter accuracy is also one of the research focuses and has been widely studied at present. In [14], a comprehensive overview of PMSM online parameter estimation is provided, including key issues, latest technologies, and typical applications. This overview provides a detailed analysis of key issues in parameter estimation,

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particularly rank deficiency, and inverter nonlinearity. Various online parameter estimation modeling techniques are summarized and evaluated. In [15], the resistance and inductance of d-q axis of PMSM are identified by high frequency signal injection, and the flux linkage is identified on line. At the same time, in order to improve the recognition accuracy, a parameter sensitivity analysis based algorithm is proposed to detect the resistance and flux linkage. However, this paper does not discuss in detail the robustness of the algorithm under different operating conditions. By means of multi-frequency interference injection, the accuracy of parameter identification is not affected by the rotor position error and flux linkage error [16]. This method not only identifies the resistance and inductance, but also models and compensates the dead-time effect, which improves the accuracy of on-line parameter estimation. However, the proposed method may be more sensitive to noise and interference in practical applications, especially at low resistance values. In [17], an on-line parameter identification method based on high-frequency signal injection of virtual rotating axis is proposed, which considers cross-coupling and magnetic saturation, and improves the accuracy and robustness of parameter identification effectively. However, this method is sensitive to measurement noise and system non-ideality in practical application. In [18], a two-step method for off-line identification of flux linkage, inductance, and phase resistance of d-q axis is presented. However, this method requires a specific mode of operation for the motor and may not be suitable for all application scenarios. The above methods have effectively improved the accuracy of system parameters to a certain extent, but there are also some shortcomings.

In order to improve the control accuracy and system rapidity of PMSMS, deadbeat control is adopted in this paper. At the same time, in order to improve the parameter robustness of deadbeat control, a parameter identification method based on improved adaptive algorithm is proposed to form a deadbeat control method based on improved parameter identification algorithm. Experimental results show that the proposed algorithm has better control accuracy, faster response speed, and stronger stability.

2. MATHEMATICAL MODEL OF PMSMS

The mathematical model of surface mounted PMSMS in rotating coordinate system is:

$$\begin{bmatrix} u_\mathrm{d} \\ u_\mathrm{q} \end{bmatrix} = \begin{bmatrix} R_\mathrm{s} & -\omega_\mathrm{e} L_\mathrm{s} \\ \omega_\mathrm{e} L_\mathrm{s} & R_\mathrm{s} \end{bmatrix} \begin{bmatrix} i_\mathrm{d} \\ i_\mathrm{q} \end{bmatrix} + L_\mathrm{s} \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} i_\mathrm{d} \\ i_\mathrm{q} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_\mathrm{e} \lambda_\mathrm{f} \end{bmatrix} \tag{1}$$

where u_d and u_q are the d-q axis voltages; i_d and i_q are the d-q axis currents; R_s is the stator resistance; L_s is the stator inductance; ω_e is the motor angular velocity; and λ_f is the permanent magnet flux.

Due to the sufficiently short interruption time in real-time control systems, Formula (1) can be discretized using a first-order forward Euler formula, and its discretized deadbeat current prediction model is:

$$\begin{bmatrix} u_\mathrm{d}(k) \\ u_\mathrm{q}(k) \end{bmatrix} = \begin{bmatrix} R_\mathrm{s} & -\omega_\mathrm{e} L_\mathrm{s} \\ \omega_\mathrm{e} L_\mathrm{s} & R_\mathrm{s} \end{bmatrix} \begin{bmatrix} i_\mathrm{d}(k) \\ i_\mathrm{q}(k) \end{bmatrix}$$

$$+ \begin{bmatrix} \frac{L_\mathrm{s}}{T_\mathrm{s}} & 0 \\ 0 & \frac{L_\mathrm{s}}{T_\mathrm{s}} \end{bmatrix} \begin{bmatrix} \Delta i_\mathrm{d}(k) \\ \Delta i_\mathrm{q}(k) \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_\mathrm{e} \lambda_\mathrm{f} \end{bmatrix} \tag{2}$$

where k stands for discrete quantity. Δi_dq is the current error value, and $\Delta i_\mathrm{dq} = i_\mathrm{dq}^* - i_\mathrm{dq}(k)$.

The controller samples the actual current vector $i_\mathrm{dq}(k)$ at time k and predicts the current vector $i_\mathrm{dq}(k+1)$ for the next beat based on the current reference voltage vector $u_\mathrm{dq}(k)$ calculated from the previous beat. The prediction equation is:

$$\begin{bmatrix} i_\mathrm{d}(k+1) \\ i_\mathrm{q}(k+1) \end{bmatrix} = \begin{bmatrix} 1 - \frac{R_\mathrm{s}}{L_\mathrm{s}} T_\mathrm{s} & \omega_\mathrm{e} T_\mathrm{s} \\ -\omega_\mathrm{e} T_\mathrm{s} & 1 - \frac{R_\mathrm{s}}{L_\mathrm{s}} T_\mathrm{s} \end{bmatrix} \begin{bmatrix} i_\mathrm{d}(k) \\ i_\mathrm{q}(k) \end{bmatrix}$$

$$+ \begin{bmatrix} \frac{T_\mathrm{s}}{L_\mathrm{s}} & 0 \\ 0 & \frac{T_\mathrm{s}}{L_\mathrm{s}} \end{bmatrix} \begin{bmatrix} u_\mathrm{d}(k) \\ u_\mathrm{q}(k) \end{bmatrix} - \begin{bmatrix} 0 \\ \frac{\omega_\mathrm{e} \lambda_\mathrm{f} T_\mathrm{s}}{L_\mathrm{s}} \end{bmatrix} \tag{3}$$

3. DEADBEAT CONTROL AND PARAMETER IDENTIFICATION ALGORITHM

3.1. Deadbeat Control Algorithm and Stability Analysis

The traditional PI controller's control concept for current loop is to use the difference between the current command value i_dq^* and the actual value i_dq to adjust and generate a reference voltage vector, thereby changing the current output and achieving the goal of following the command value. Unlike this method, the current prediction based control method utilizes the mathematical model of PMSMS to establish the relationship between the reference voltage vector and current output, calculates the current prediction value one beat in advance, and uses it to guide the generation of the optimal reference voltage vector. In practical systems, the timing of current loop control is shown in Fig. 1. According to Fig. 1, the voltage equation at the k time is shown in (2), and because the current loop bandwidth is greater than the speed loop bandwidth, the motor speed can be considered constant over a control period. The PMSMS mathematical model with k time discretization is shown in (2). Because the bandwidth of speed loop is much smaller than that of current loop, the effect of speed variation can be ignored in a control cycle.

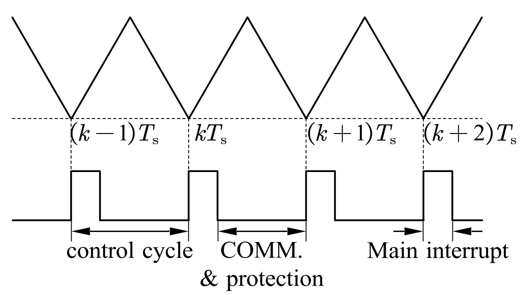

FIGURE 1. Diagram of current loop control timing.

The predicted next current is shown in (3). Based on the predicted current and reference current, the optimal reference voltage vector $u_\mathrm{dq}(k+1)$ can be calculated to achieve a current error of 0, that is:

$$\begin{bmatrix} u_d(k+1) \\ u_q(k+1) \end{bmatrix} = \begin{bmatrix} R_s & -\omega_e L_s \\ \omega_e L_s & R_s \end{bmatrix} \begin{bmatrix} i_d(k+1) \\ i_q(k+1) \end{bmatrix} + \begin{bmatrix} \frac{L_s}{T_s} & 0 \\ 0 & \frac{L_s}{T_s} \end{bmatrix} \begin{bmatrix} \Delta i_d(k+1) \\ \Delta i_q(k+1) \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_e \lambda_f \end{bmatrix} \quad (4)$$

In order to analyze the influence of parameter variation on deadbeat control, Formula (2) is introduced into Formula (3), and the actual values of R_{s0}, L_{s0}, and λ_{f0} are used to calculate:

$$L_{s0} \begin{bmatrix} i_d(k+1) \\ i_q(k+1) \end{bmatrix} - L_s \begin{bmatrix} i_d^*(k) \\ i_q^*(k) \end{bmatrix} = \begin{bmatrix} \Delta R_s T_s - \Delta L_s & -\Delta L_s \omega_e T_s \\ \Delta L_s \omega_e T_s & \Delta R_s T_s - \Delta L_s \end{bmatrix} \begin{bmatrix} i_d(k) \\ i_q(k) \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_e \Delta\lambda_f T_s \end{bmatrix} \quad (5)$$

where $\Delta R_s = R_{s0} - R_s$, $\Delta L_s = L_{s0} - L_s$, $\Delta\lambda_f = \lambda_{f0} - \lambda_f$.

Due to the short sampling time T_s, $\Delta R_s T_s$ is also small enough to be ignored, and the back electromotive force caused by magnetic flux deviation is treated as a disturbance term. Perform z-transform on (5) to obtain the closed-loop discrete transfer function of the actual current value and reference current value:

$$\frac{i_{dq}(z)}{i_{dq}^*(z)} = \frac{(L_s/L_{s0})\,z}{z - 1 + L_s/L_{s0}} \quad (6)$$

According to (6), a closed-loop pole of the discrete transfer function is $z = 1 - L_s/L_{s0}$, and according to the control theory, the closed-loop pole is located in the unit circle of the z plane. The system is in a stable state, so the stable interval of the system is:

$$0 < L_s < 2L_{s0} \quad (7)$$

Formula (7) shows that the deadbeat current prediction algorithm converges when the model parameters are less than 2 times of the real parameters, and when the model parameters are more than 2 times of the real parameters, the deadbeat current prediction algorithm will no longer converge, and the system will be in an unstable state. In order to prevent the control system from losing control, it is necessary to obtain accurate motor parameters, so it is necessary to use parameter identification algorithm to identify motor parameters.

3.2. Parameter Identification Algorithm

From Formula (1), it can be seen that the parameters included in the voltage equation mainly include stator resistance R_s, stator inductance L_s, and permanent magnet flux λ_f. The permanent magnet flux can be obtained by testing the back electromagnetic field (EMF) constant of the motor. The initial stator resistance and inductance can be measured by a multimeter and a digital bridge.

After the initial parameters are determined, the parameters can be updated dynamically by the adaptive algorithm. The parameter dynamic iteration algorithm can be updated by the adaptive algorithm shown in Fig. 2, which computes:

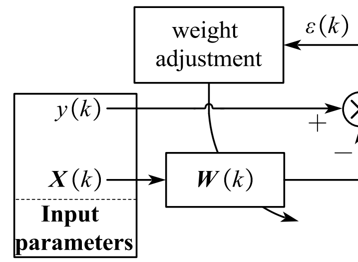

FIGURE 2. Diagram of parameter dynamic iteration algorithm.

$$\begin{cases} \varepsilon(k) = y(k) - W(k)X(k) \\ W(k+1) = W(k) + K(k)\varepsilon(k) \end{cases} \quad (8)$$

where $W(k)$ is the weight at k moment and represents the parameter L_s to be identified. $X(k)$ is the input variable at k moment, which represents the d-q axis current and motor speed. $Y(k)$ is the output value of the system at k moment, which represents the voltage variable of the d-q axis of the system. $\varepsilon(k)$ is the state error at k moment.

In order to achieve better control performance, $K(k)$ in the weight update formula is calculated using the least mean square (LMS) algorithm and recursive least square (RLS) algorithm, respectively. The $K(k)$ corresponding to the LMS algorithm is $K(k) = 2\mu X(k)$.

The $K(k)$ corresponding to the RLS algorithm is:

$$K(k) = P(k-1)X(k)\left[1 + X^T(k)P(k-1)X(k)\right]^{-1} \quad (9)$$

where $P(k-1)$ is the covariance matrix at time $(k-1)$.

The iterative process of covariance matrix is as follows:

$$P(k) = \left[1 + K(k)X^T(k)\right] P^{-1}(k-1) \quad (10)$$

After iteratively calculating the coefficient $K(k)$ using the LMS algorithm and RLS algorithm, the results $K(k)$ can be added to the (8), respectively, yielding two sets of results. LMS has the characteristics of simple calculation and high convergence precision. RLS algorithm has the advantages of fast convergence speed and long computation time. Considering the characteristics of LMS and RLS, the results of LMS and RLS are calculated by weighted coefficient method, and the required identification results are obtained. The identification process

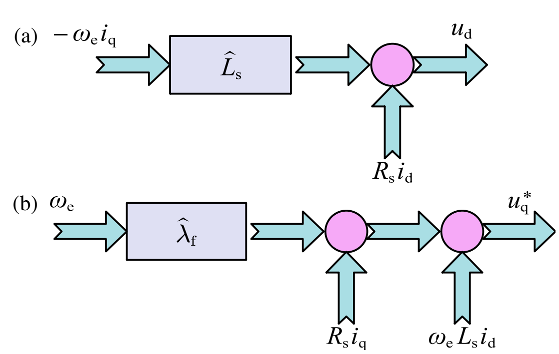

FIGURE 3. Diagram of parameters identification process.

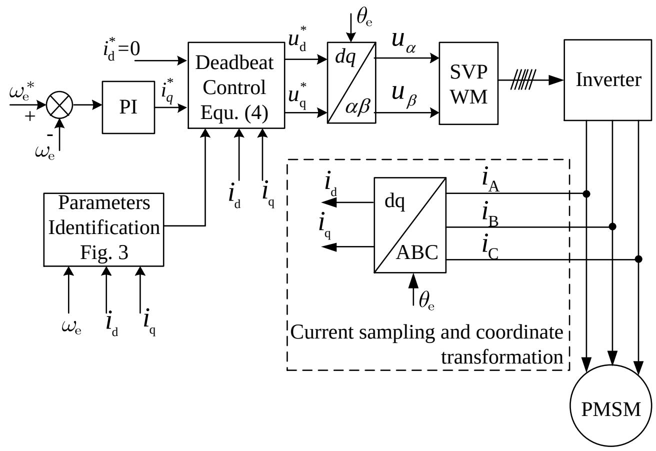

FIGURE 4. General diagram of system control.

of inductance is shown in Fig. 3(a). After the identification of inductance parameter is completed, the equation corresponding to the q-axis voltage can be used for flux linkage parameter identification. Since there is no flux linkage parameter in the d-axis voltage, the identification of flux linkage values in the q-axis voltage can achieve decoupling effect. The identification process is shown in Fig. 3(b).

3.3. The Proposed Parameter Identification Deadbeat Control Algorithm

Based on the deadbeat control method proposed in Section 3.1 and the parameter identification algorithm proposed in Section 3.2, an improved parameter identification deadbeat control algorithm is constructed. This algorithm uses LMS and RLS to jointly identify the required parameters. Firstly, the inductance parameter is identified through the d-axis voltage equation. Secondly, decoupling identification is achieved based on the flux linkage parameter in the q-axis voltage equation, which is not related to the d-axis voltage. Therefore, inductance parameter and flux linkage parameter can be identified simultaneously. After the identification is completed, apply the identified parameters to the deadbeat control algorithm. According to the system stability relationship shown in (7), when the coefficients meet the requirements, and the inductance parameter is more accurate, the system control accuracy is higher.

In addition, after the identification of inductance parameter and flux linkage parameter is completed, it can be used for the dynamic adjustment of the speed controller to further improve the control effect. The speed loop can be regarded as a third-order system or a typical second-order system [19]. According to the principle of minimizing the peak value of the closed-loop amplitude-frequency characteristic in the "oscillation index method", the designed proportional gain and integral gain are:

$$\begin{cases} K_p = \frac{\pi J}{300 n_p \lambda_f T_s} \\ K_i = \frac{\pi J}{6000 n_p \lambda_f T_s^2} \end{cases} \tag{11}$$

From Formula (11), it can be seen that the parameters of the speed loop controller are related to the parameters of the moment of inertia, the number of pole pairs, the permanent magnet flux linkage, and the interruption period of the controller. Therefore, the identified flux parameter can more accurately adjust the parameters of the speed controller and then achieve high-performance motor control. The overall control block diagram of the algorithm is shown in Fig. 4.

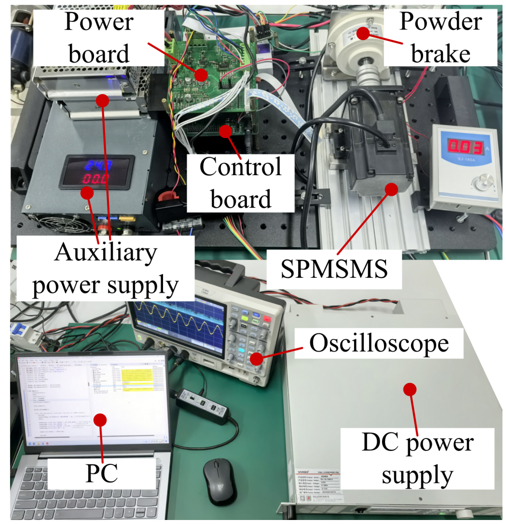

FIGURE 5. Schematic diagram of the experimental platform.

4. EXPERIMENT AND ANALYSIS

In order to verify the effectiveness of the proposed algorithm, the experimental platform as shown in Fig. 5 is set up for testing. The parameters of the tested prototype are shown in Table 1. The TMS320F28335 from Texas Instruments Corporation is used to develop the algorithm, and the PS21965 Intelligent Power Module from Mitsubishi Company is used to drive the motor. Three experiments are carried out on this hardware platform, which are vector control experiment, traditional deadbeat control experiment, and improved parameter identification deadbeat control experiment.

TABLE 1. Parameters of the prototype.

Parameters	Value
Stator resistance R_s (Ω)	1.6
Pole Pairs	4
Permanent magnet flux λ_f (Wb)	0.0825
Rated speed n_N (r/min)	3000
Rated power P (kW)	0.2
Rated voltage U (V)	220
Rated current I (A)	2.1
Rated torque T_e (N · m)	0.64

The stator resistance of the motor and the amplitude of the permanent magnet magnetic flux are obtained through multimeter and back electromotive force coefficient tests, respectively, as shown in Table 1. The stator inductance is identified using the parameter identification algorithm shown in Section 3.2, and the identification results are shown in Fig. 6. As

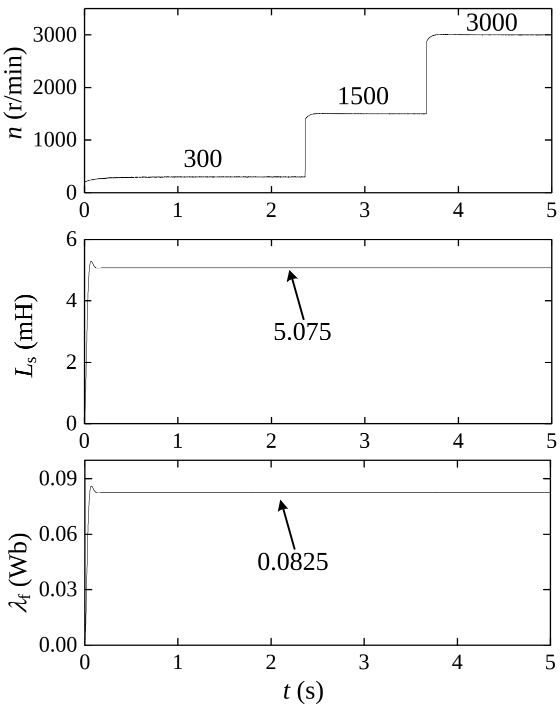

FIGURE 6. Waveforms of parameter identification results.

can be seen from Fig. 6, the stator inductance value is stable at 5.075 mH; the permanent magnet flux linkage value is stable at 0.0825 Wb; and the speed change has no obvious effect on the inductance identification result.

The speed waveform and d-q axis currents during vector control are shown in Fig. 7. From the figure, it can be seen that the motor starts at a speed of 1500 r/min and rises to 3000 r/min at 2 s, with a rise time of 0.32 s. However, at this time, there is a coupling phenomenon in the d-axis current, and the current fluctuation amplitude reaches 1.89 A. At 3 s, a sudden load of 0.64 N · m is applied, and after 0.80 s, the speed reaches the given value again.

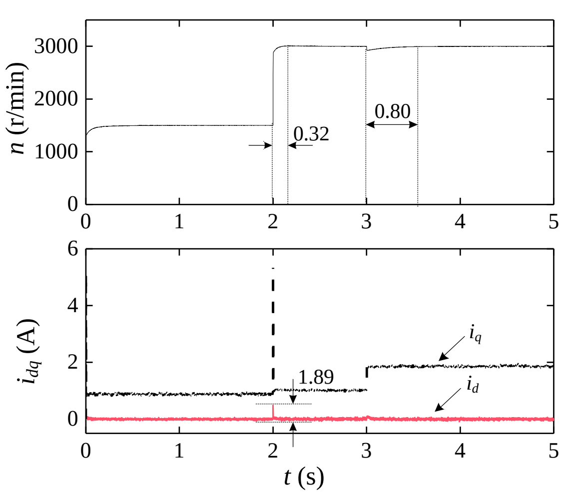

FIGURE 7. Waveforms of the vector control method.

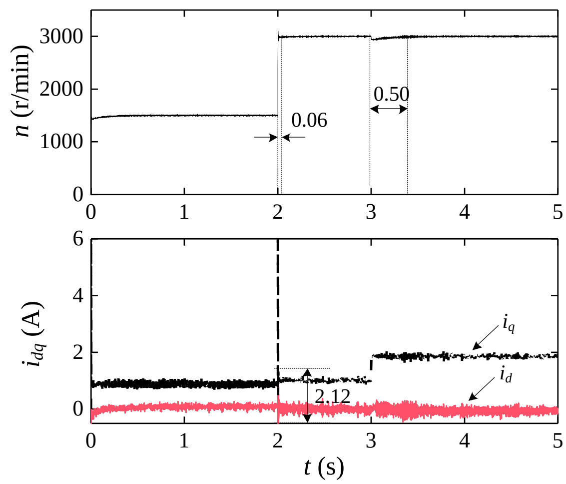

FIGURE 8. Waveforms of the traditional deadbeat control method.

The rotational speed waveform and d-q axis currents of traditional deadbeat control method are shown in Fig. 8. It can be seen from the figure that the starting speed is 1500 r/min; the speed changes to 3000 r/min at 2 s; the rising time is 0.06 s; but the current fluctuates greatly at this time; the amplitude of the current fluctuation in d-axis reaches 2.12 A; the amplitude of current fluctuation is always large in the following operation. When the load of 0.64 N · m is suddenly added at 3 s, and the motor speed reaches the given value again after 0.50 s.

Figure 9 shows the speed waveform and d-q axis currents waveform of the proposed algorithm. As can be seen from the figure, the starting speed is 1500 r/min, which changed abruptly to 3000 r/min at 2 s, with a rise time of 0.01 s. Compared with the vector control method in Fig. 7, the rise time of the speed mutation is significantly reduced to 96.88%, and the d-axis current has no obvious coupling phenomenon. Compared with the traditional DPCC method in Fig. 8, the speed rise time is also significantly reduced, reaching 83.33%, and the current fluctuation phenomenon is significantly improved. The motor speed reaches the given value again after 0.01 s. Compared with vec-

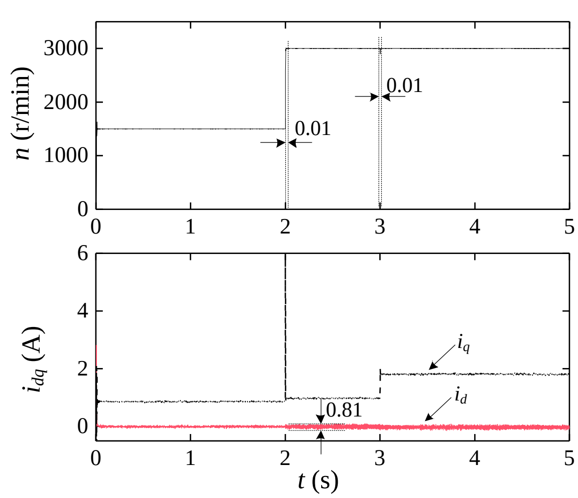

FIGURE 9. Waveforms of the proposed method.

tor control method and traditional DPCC method, the proposed method significantly improves the dynamic adjustment ability after load mutation and reduces the adjustment time by 98.75% and 98.00%, respectively. Therefore, the proposed method has better speed and current control effect than vector control and traditional DPCC method.

5. CONCLUSION

In this paper, a deadbeat control method based on improved parameter identification algorithm is proposed to improve the control accuracy and system rapidity of PMSMS. At the same time, parameter identification algorithm is used in the proposed method, so the proposed method is robust to parameters. Experimental results show that the proposed algorithm has better control accuracy, rapidity, and stability than the vector control method and traditional deadbeat control method.

Although the proposed method improves the above performance, the complexity of the corresponding control algorithm also increases, which requires a higher performance control chip. Next, we need to continue to optimize the simplicity of the algorithm, so that the proposed algorithm can be applied to low-performance control chips.

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