Current Delay Compensation Decoupling Control for Digital Control System of PMSM at High Speed

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Abstract

A current delay compensation decoupling control for digital control system of permanent magnet synchronous motor (PMSM) is presented. Unlike the previous complex analysis method of multiple-input multiple-output (MIMO) system, this paper simplifies the MIMO system of PMSM into analyzable single-input single-output (SISO) system. On this basis, the complex vector root locus analysis method is used to analyze the influence of the time delay of digital control system on PMSM control at high speed. Then a current control method with time delay compensation decoupling term is designed to compensate the magnitude and phase errors of voltage commands, which improves the stability and dynamic performance of current control at high speed. The proposed control method is easy to implement, and its good performance are illustrated through experimental results.

Keywords

Permanent Magnet Synchronous Motor; Current Delay Compensation Decoupling Control; MIMO System; SISO System; Complex Vector Root Locus Analysis.

1. Introduction

With the development of microprocessor and power electronics technology, closed-loop digital control system based on pulse width modulation (PWM) technology has been widely used in the field of permanent magnet synchronous motor (PMSM) control. However, in the digital control system of PMSM, due to the influence of the execution time of the control algorithm and PWM, the actual output voltage of the inverter will inevitably be delayed. Especially in the digital control system of high-power motor, the phase current is large. In order to ensure the reliable operation of power devices, the switching frequency of digital controller should not be set too high [1]. Therefore, when the motor runs at high speed, the time delay caused by low switching frequency accompanied by coordinate rotation will increase the coupling effect of the system [2]. The coupling effect caused by time delay will make the output voltage of the inverter have errors in amplitude and phase, thus making the motor in high speed state show poor dynamic and unstable phenomena [3].

Throughout the existing references, due to the small impact of time delay on current control at medium and low speed, few references have made corresponding practical solutions to the impact of time delay on current control of PMSM at high speed. Most of them are very complex and require a lot of algorithmic resources to implement [4, 5].

Accordingly, the influence of digital control system delay on the control system at high speed is analyzed in this paper, then a current control method with digital control system delay error

ISSN: 2414-1895 DOI: 10.6919/ICJE.202507_11(7).0003

compensation is proposed. The amplitude and phase angle error compensation of voltage command is realized, and the stability of current loop at high speed is guaranteed.

2. Establishment of Complex Vector Model for PMSM

In the scalar description mode, the equivalent model of PMSM in $\alpha\beta$ coordinate system is as follows:

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \begin{bmatrix} R+pL & 0 \\ 0 & R+pL \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} \tag{1}$$

where u_α and u_β are $\alpha\beta$ axis voltage respectively, i_α and i_β are $\alpha\beta$ axis current respectively, R and L are stator resistance and inductance respectively, e_α and e_β are $\alpha\beta$ axis back EMF respectively, and $e_\alpha = -\omega_e \psi_f \sin\theta_e$, $e_\beta = \omega_e \psi_f \cos\theta_e$, θ_e is rotor electrical angle, ω_e is rotor electrical angular velocity, ψ_f is rotor flux linkage, p is differential operator.

In the complex plane, the back EMF in $\alpha\beta$ coordinate system can be expressed as follows:

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \begin{bmatrix} -\omega_e \psi_f \sin\theta_e \\ \omega_e \psi_f \cos\theta_e \end{bmatrix} = -j\omega_e \psi_f e^{j\theta_e} \tag{2}$$

According to the above definition of complex vector, the mathematical equation of PMSM based on complex vector in $\alpha\beta$ static coordinate system is

$$u_{\alpha\beta} = Ri_{\alpha\beta} + Lpi_{\alpha\beta} - j\omega_e \psi_f e^{j\theta_e} \tag{3}$$

where $u_{\alpha\beta}$ is $\alpha\beta$ axis voltage, $i_{\alpha\beta}$ is $\alpha\beta$ axis current in the complex plane.

According to Park transformation, the transformation relations of current and voltage vectors in dq rotating coordinate and $\alpha\beta$ stationary coordinate are

$$\begin{cases} u_{dq} = u_{\alpha\beta} e^{-j\theta_e} \\ i_{\alpha\beta} = i_{dq} e^{j\theta_e} \end{cases} \tag{4}$$

where u_{dq} is dq axis voltage, i_{dq} is dq axis current.

According to the above transformation relation, the transformation relation of complex vectors of differential quantities in rotating and stationary coordinate is

$$p(i_{\alpha\beta}) = p(i_{dq} e^{j\omega_e t}) = p(i_{dq}) e^{j\omega_e t} + j\omega_e i_{dq} e^{j\omega_e t} \tag{5}$$

By substituting equation (4) and (5) into equation (3), the mathematical equation of PMSM based on complex vector in dq coordinate system is

$$u_{dq} = Ri_{dq} + L(p + j\omega_e)i_{dq} - j\omega_e\psi_f \tag{6}$$

Through the above transformation, the mathematical model of PMSM is transformed from a multiple-input multiple-output (MIMO) system to a single-input single-output (SISO) system, and the mathematical model is shown in Figure 1. The difference between the expression forms of system model equations based on scalar and complex vectors makes a great difference when they are used to analyze system characteristics. The model equation based on complex vectors can halve the input and output of the system. It is convenient to design the controller and analyze the performance of the system using classical control theory, such as root locus method.

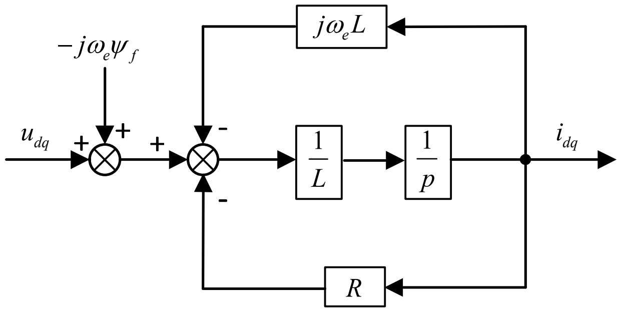

Figure 1. Mathematical model of PMSM based on complex vector

3. Complex Vector Root Locus Analysis of Digital Control System

According to the interruption mode of digital controller, the current sampling, algorithm execution and PWM output timing are analyzed, and then the source of digital control delay is pointed out. The influence of system time delay on current loop system is analyzed by modeling.

DSP digital controller uses timer counting method to realize the execution sequence of main interrupt. Taking the switching period T_s as example, the PWM duty cycle update sequence diagram of digital control system is shown in Figure 2.

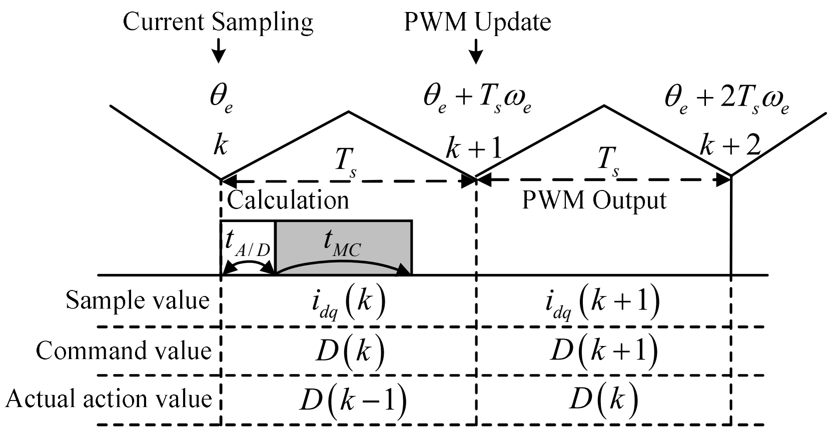

Figure 2. PWM duty cycle update sequence diagram of digital control system

In Figure 2, the digital controller samples the current at the beginning of each interruption, and obtained the current value $i_{dq}(k)$ after $t_{A/D}$ by A/D conversion. The current value is used for program calculation, then the duty cycle $D(k)$ of PWM at that time could be obtained after t_{MC}. However, the duty cycle $D(k)$ can only be updated when counter triangular waveform is at zero, so the actual effect of duty cycle $D(k)$ is completed between $k+1$ and $k+2$. The motor is still in operation during the period from the the sampling to the effective duty cycle, so there will be the error in the electrical angle used for rotating transformation. This error is related to the speed of the motor and the PWM cycle. For example, when the PWM switching frequency is 10kHz and the speed of 4 pole pairs PMSM is 8000rpm (i.e. the current frequency is about 533Hz), the electric angle error of each switching cycle is about 19.2°. The error of electric angle will lead to the error of phase and amplitude of output voltage, which will affect the stability of the whole current loop system.

When the system is in steady state, assume that the electrical angular speed of the motor ω_e and the ideal output voltage u_{dq}^* remain constant during the time delay. Let's define the ideal output voltage in the $\alpha\beta$ frame as $u_{\alpha\beta}^*$, and define the average actual output voltage (averaged over one sample) in the $\alpha\beta$ frame as $\overline{u}_{\alpha\beta}$. Then, the error relationship between the actual output voltage and the ideal output voltage of the digital control system is

$$f_{err} = \frac{u_{\alpha\beta}^*}{\overline{u}_{\alpha\beta}} = \frac{e^{j\theta_{e0}} u_{dq}^*}{\frac{1}{T_s}\int_{T_s}^{2T_s} u_{dq}^* e^{j(\omega_e \tau + \theta_{e0})} d\tau} = \frac{e^{j\theta_{e0}} u_{dq}^*}{K(\omega_e, T_s) e^{j(1.5\omega_e T_s + \theta_{e0})} u_{dq}^*} = \frac{e^{j(-1.5\omega_e T_s)}}{K(\omega_e, T_s)} \tag{7}$$

$$K(\omega_e, T_s) = \frac{2}{\omega_e T_s} \sin(\frac{\omega_e T_s}{2}) \tag{8}$$

where θ_{e0} is the initial rotor electrical angle. From the error expression, it can be seen that the output voltage error caused by the delay is essentially caused by the rotation coordinate transformation. It is shown in two aspects: first, the output amplitude of the voltage vector is multiplied by a coefficient $1/K(\omega_e, T_s)$, which is greater than 1; second, the voltage vector phase has a lag of $1.5\omega_e T_s$.

Considering the influence of digital controller delay on PMSM, the complex vector current control block diagram is established as shown in Figure 3.

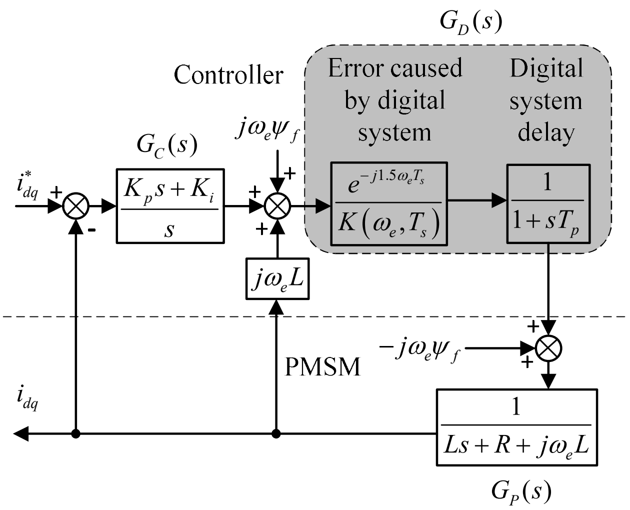

Figure 3. Complex vector current control block diagram considering the delay of digital control system

ISSN: 2414-1895 DOI: 10.6919/ICJE.202507_11(7).0003

In Figure 3, the digital system delay can be equivalent to the first order inertial link, and the time constant is $T_p = 1.5T_s$. K_p and K_i are the proportional and integral coefficient of PI controller respectively. $G_C(s)$, $G_D(s)$ and $G_P(s)$ are respectively the transfer function of PI controller, system delay and PMSM. From the control block diagram, it can be concluded that the current closed-loop transfer function in the rotating coordinate system is

$$\frac{i_{dq}}{i_{dq}^*} = \frac{G_C(s)G_D(s)G_P(s)}{1 + G_C(s)G_D(s)G_P(s) - (j\omega_e L)G_D(s)G_P(s)} \tag{9}$$

According to transfer function (9), the root locus of the closed-loop current transfer function without compensation for delay error is plotted when the current frequency is from 100Hz to 700Hz, as shown in Figure 4.

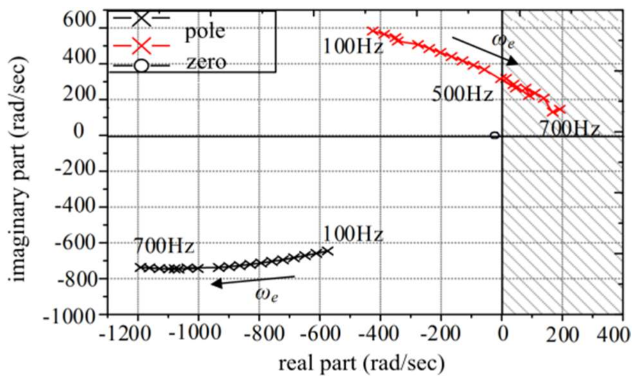

Figure 4. Root locus of the closed-loop current transfer function with delay error

As can be seen from Figure 4, under the fixed switching frequency and PI controller parameters, with the increase of motor speed, there exists a complex vector pole moving to the right side of S plane. The positive real part of the pole appears near the frequency at 500Hz. According to the classical control theory, the system will oscillate at this time. Therefore, the error caused by delay will lead to system coupling and deteriorate the stability of current controller.

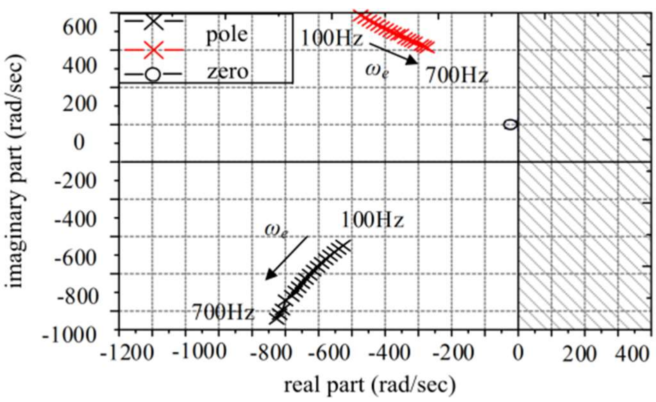

Figure 5. Root locus of the closed-loop current transfer function without delay error

If the error coupling term caused by the delay is eliminated by decoupling the control system, the stability of the system can be guaranteed theoretically. Therefore, assuming that there is no delay

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DOI: 10.6919/ICJE.202507_11(7).0003

error coupling term, the $G_D(s)$ term in the transfer function of the closed-loop system can be expressed as $G_D(s) = 1/(1+sT_p)$. The complex vector closed-loop transfer function can be obtained by introducing it into transfer function (9). According to the complex vector closed-loop transfer function, the closed-loop current root locus without delay error can be plotted as shown in Figure 5.

It can be seen from Figure 5 that with the increase of motor current frequency, complex vector pole are always in the left side of S plane, that is to say, the system has good stability in a wide speed range after decoupling the error coupling term.

According to the above comparative analysis, the running state of the motor has great influence on the stability of the system. From the transfer function and the complex vector root locus, it can be seen that the actual bandwidth of the current loop is not only controlled by the PI controller parameters, but also by the current frequency of the motor. From the pole distribution diagram of the closed-loop system, it can be seen that with the increase of the speed, the poles are no longer symmetrical with respect to the real axis of the complex vector coordinate system, which indicates that the coupling effect between the torque current component and the excitation current component of the permanent magnet synchronous motor is enhanced. Therefore, the parameters of PI controller should be designed according to the principle of minimum bandwidth, so as to ensure the effective tracking of small signal instructions, and avoid the saturation and overshoot of the controller when the large signal command is given.

4. Design of the Improved Current Controller with Time Delay Error Compensation

From the analysis in the previous section, it can be seen that compensating the coupling term caused by the delay can improve the stability of the current controller at high speed. The improved current controller with delay error compensation under complex vector system model is shown in Figure 6.

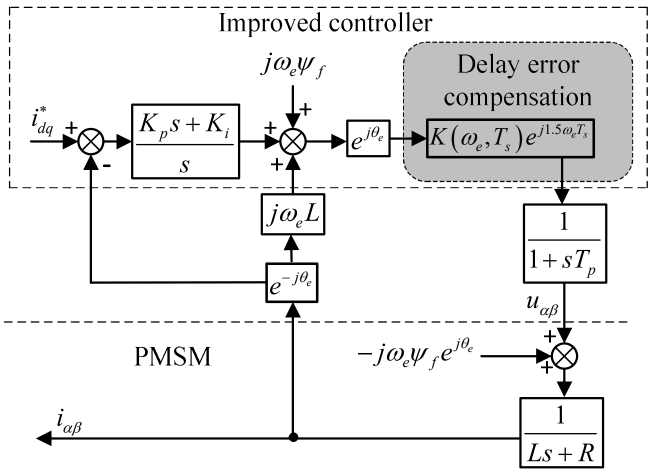

Figure 6. Complex vector control block diagram of improved current controller with delay error compensation

The improved current controller adds a delay error compensation term after the conventional PI controller to eliminate the system coupling caused by full digital control. Through the complex vector model, the design method of the control system can be obtained intuitively. However, the control system in practical application is built in scalar model, so the controller design method shown in Figure 6 should be equivalent to that of scalar control system, as shown in Figure 7. In the figure, i_d^* and i_q^* are the reference currents of dq axis in scalar model, i_d and i_q are the real currents of dq axis in scalar model.

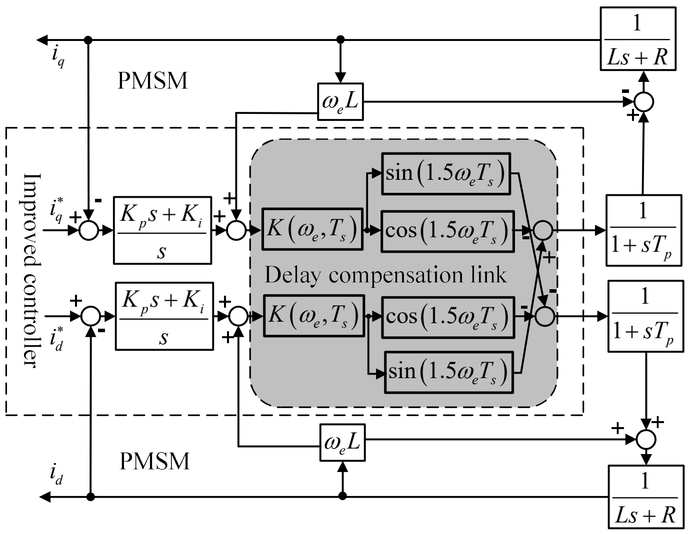

Figure 7. Scalar control block diagram of improved current controller with delay error compensation

5. Experiment Results

To validate the effectiveness of the proposed current control method, experimental tests were carried out on a 2.2 kW PMSM test bench. Motor parameters are listed in Table 1. The double motor tow loading mode is used to provide load torque through a coaxially connected load motor (running in constant torque control mode). In the experimental tests, the developed algorithm is implemented on a 32-bit floating point DSP TMS320F28377, and the PWM frequency and current sampling frequency are given 10kHz.

Table 1. Motor parameters

Parameters	Units	Values
Rated power	kW	2.2
Rated voltage	V	220
Rated speed	rpm	4500
Rated torque	N.m	4.7
Rated current	A	10.5
Stator resistance	Ω	0.89
Inductance of dq axis	mH	2.5
Number of pole pairs		4
EMF constant	V/krpm	15

In order to verify the problem of time delay in digital control system, the q axis current of 9A is given to make the motor run at constant acceleration under no-load condition. The current controller uses the standard PI controller of Figure 6. The operation conditions of the system with no compensation for amplitude and phase, full compensation for amplitude and phase ($1/K(\omega_e,T_s)+1.5\omega_e T_s$), single compensation for phase ($1.5\omega_e T_s$) and incomplete compensation for phase ($\omega_e T_s$), are compared. Incomplete compensation for phase means using $e^{j\omega_e T_s}$ as rotation compensation. Under this condition, the stability of the current loop controller under different speed conditions is tested. Figure 8 shows the stability performance comparison of current controller with different degrees of time delay

ISSN: 2414-1895
DOI: 10.6919/ICJE.202507_11(7).0003

compensation at different speeds. Among them, Figure 8(a) is the waveform with no compensation. It can be seen from Figure 8(a) that, without time delay error compensation, with the increase of motor speed, the tracking performance of i_d and i_q decreases, and the output voltages of current regulator increase. Figure 8(b) is the waveform with full compensation. As can be seen from Figure 8(b), with the increase of motor speed, the tracking performance of i_d and i_q is still good, the output voltages of current regulator almost have no change, and the control system is stable. Compared with Figure 8(a) and Figure 8(b), it can be seen that the delay error compensation can effectively maintain the system stability under the condition of high speed. Figure 8(c) is the waveform with single compensation. It can be seen that the current tracking performance of the system is still good even with single compensation. Figure 8(d) is the waveform with incomplete compensation. Compared with Figure 8(c), the current tracking performance of the system is reduced, and the system stability is not as good as full compensation. Compared with Figure 8(c) and Figure 8(d), the phase delay factor has a great influence on the tracking performance of control system, and the controller can effectively reduce the system instability with the phase compensation $\omega_e T_s$.

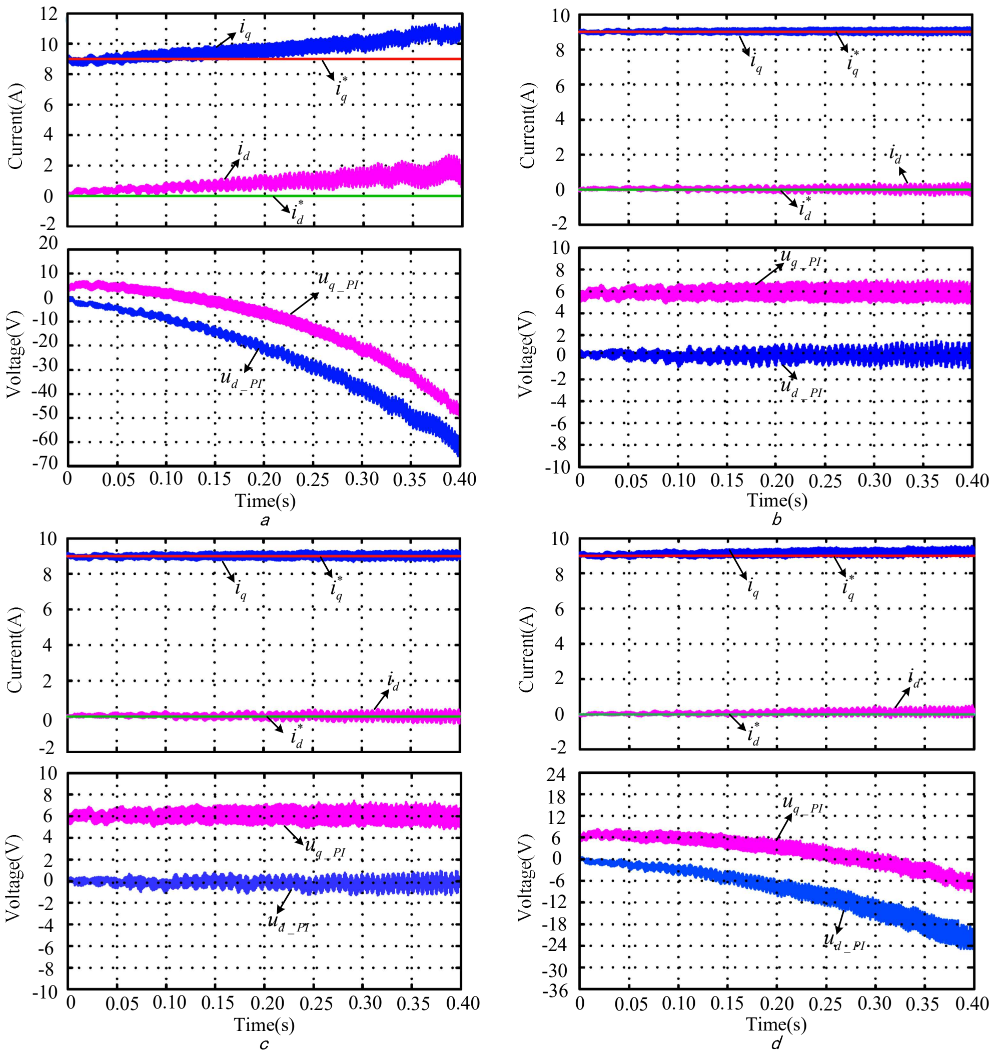

Figure 8. Stability performance comparison of current controller with different degrees of time delay compensation at different speeds

(a) No compensation, (b) Full compensation (Amplitude compensation ($1/K(\omega_e,T_s)$)+ Phase compensation ($1.5\omega_e T_s$)), (c) Single compensation for phase ($1.5\omega_e T_s$), (d) Incomplete compensation for phase ($\omega_e T_s$)

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DOI: 10.6919/ICJE.202507_11(7).0003

To further verify the effectiveness of the current controller with time delay error compensation, under no-load condition, the q axis current of 9A is given to make the motor run at constant speed. Given the -3A step signal with q axis current duration of 0.1s at 0.4s, stability and dynamic performance comparison of current controller before and after time delay compensation at different speeds are shown in Figure 9. Figure 9(a) shows the waveform before compensation (No compensation), and Figure 9(b) shows the waveform after compensation (Full compensation). It can be seen from Figure 9(a) that due to the influence of time delay coupling, the d axis current will fluctuate with the sudden change of q axis current during the current dynamic regulation process. In addition, the q axis current also has overshoot during the regulation process. When the motor speed reaches about 7600 rpm, the system is out of control, which is consistent with the root locus change trend in Figure 4, that is, positive real pole appears at the current frequency of about 500Hz, and the system is uncontrollable. Compared with Figure 9(b), the stability of the system is guaranteed after the delay compensation.

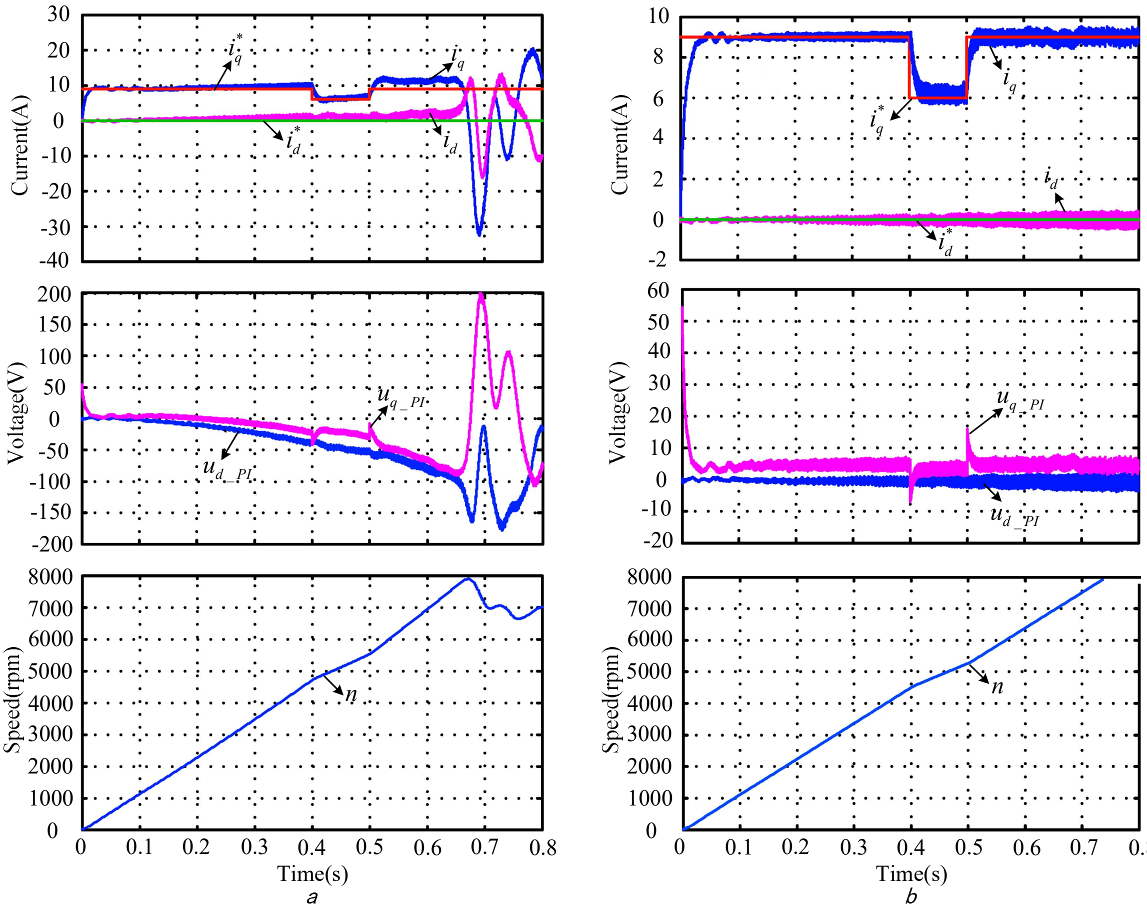

Figure 9. Stability and dynamic performance comparison of current controller before and after time delay compensation at different speeds

(a) Before compensation, (b) After compensation

6. Conclusion

This paper presents a current delay compensation decoupling control for digital control system of PMSM. In the Letter, the MIMO system of PMSM is simplified as an analytic SISO system by using the complex vector motor system description method. On this basis, a current control method with time delay compensation is designed to keep the motor still has good dynamic and stability at high speed. The problems of digital control system of PMSM are studied, and the factors affecting the stability of current loop controller are analyzed by complex vector root locus analysis method. On this basis, a current control method with delay error compensation of digital control system is proposed by complex vector root locus method. The amplitude and phase error compensation of voltage command is realized, and the current stability and dynamic performance at high speed are improved. The proposed current delay compensation decoupling control method requires low computational resources with low tuning effort since only the delay error compensation term is added to the current controller. The experimental results indicate that the new current control method provides better dynamics and stability than the traditional.

Acknowledgments

The authors thank the editor and anonymous reviewers for their valuable remarks and helpful suggestions. This study was supported by Provincial Research Platform Opening Fund of Yancheng Polytechnic College (YGKF2305).

References

[1] Miyama Y, Hazeyama M, Hanioka S, et al. PWM Carrier Harmonic Iron Loss Reduction Technique of Permanent-Magnet Motors for Electric Vehicles[J]. IEEE Transactions on Industry Applications, 2016, vol.52(4), 2865-2871.

[2] Zhao S, Huang X, Fang Y, et al. Compensation of DC-Link Voltage Fluctuation for Railway Traction PMSM in Multiple Low-Switching-Frequency Synchronous Space Vector Modulation Modes[J]. IEEE Transactions on Vehicular Technology, 2018, vol.67(1), 235-250.

[3] Hu W, Nian H, Zheng T. Torque Ripple Suppression Method With Reduced Switching Frequency for Open-Winding PMSM Drives With Common DC Bus[J]. IEEE Transactions on Industrial Electronics, 2019, vol.66(1), 674-684.

[4] Choi C. Analysis and Compensation of Time Delay Effects in Hardware-in-the-Loop Simulation for Automotive PMSM Drive System[J]. IEEE Transactions on Industrial Electronics, 2012, vol.59(9), 3403-3410.

[5] Wei D Q, Zhang B, Qiu D Y, et al. Effects of Current Time-Delayed Feedback on the Dynamics of a Permanent-Magnet Synchronous Motor[J]. IEEE Transactions on Circuits & Systems II Express Briefs, 2010, vol.57(6), 456-460.