An Improved Deadbeat Predictive Current Control of PMSM Drives Based on the Ultra-local Model

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Abstract: Deadbeat predictive current control (DPCC) has been widely applied in permanent magnet synchronous motor (PMSM) drives due to its fast dynamic response and good steady-state performance. However, the control accuracy of DPCC is dependent on the machine parameters' accuracy. In practical applications, the machine parameters may vary with working conditions due to temperature, saturation, skin effect, and so on. As a result, the performance of DPCC may degrade when there are parameter mismatches between the actual value and the one used in the controller. To solve the problem of parameter dependence for DPCC, this study proposes an improved model-free predictive current control method for PMSM drives. The accurate model of the PMSM is replaced by a first-order ultra-local model. This model is dynamically updated by online estimation of the gain of the input voltage and the other parts describing the system dynamics. After obtaining this ultra-local model from the information on the measured stator currents and applied stator voltages in past control periods, the reference voltage value can be calculated based on the principle of DPCC, which is subsequently synthesized by space vector modulation (SVM). This method is compared with conventional DPCC and field-oriented control (FOC), and its superiority is verified by the presented experimental results.

Keywords: Deadbeat control, current control, robustness, PMSM drives

1 Introduction

A permanent magnet synchronous motor (PMSM) has the outstanding advantages of high efficiency and power density. It is a type of motor that has been widely applied in various fields in recent years [1]. The traditional high-performance PMSM control methods are field-oriented control (FOC) [2] and direct torque control (DTC) [3-4]. FOC has a wide range of speed regulations and good steady-state performance, but incorrect proportional integral (PI) gains can easily lead to overshoot and oscillation of the system. Additionally, the current loop's bandwidth limits the system's dynamic performance [5]. The DTC structure is simple and has a fast dynamic response. However, due to the large torque ripple and the variable switching frequency, its application is limited in high-performance control [6].

In recent years, model predictive control (MPC) has been widely studied in variable speed drives because of its simple principle, quick response, and ability to consider nonlinear constraints of the system [7-10]. According to the different control objectives, MPC is divided into predictive torque control (PTC) [11-13] and predictive current control (PCC) [14-15] methods. The traditional finite control set MPC uses a cost function to uniquely determine the output voltage vector by predicting the current for each switching state. However, there are relatively high steady ripples due to applying one voltage vector during one control period. When there are parameter mismatches, the performance will be further degraded. Moreover, the computation burden is high due to evaluating each converter voltage vector, especially for applying multistep prediction or multilevel converter [16].

Deadbeat predictive current control (DPCC) is a predictive current control method that incorporates space vector modulation (SVM) [17-18]. This method obtains the reference voltage value based on the principle of deadbeat current control and converts the

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voltage reference value into a switching state by using SVPWM. DPCC can realize fast dynamic response of current tracking. However, this method is sensitive to parameter variation. During the running process of the motor, the temperature of the motor increases with the running time, and the motor parameters become mismatched. This will lead to an increase in stator current harmonics and may even affect the stability of the system [19-23].

To address the aforementioned problems, numerous methods have been proposed in Refs. [24-29]. These methods are based on online identification. The scheme of online parameter identification includes recursive least-squares identification [24-25, 30], inductance estimation based on the observed disturbance voltage [31] or a model reference adaptive system [26, 32], affine projection algorithms [27-28], and fuzzy control algorithms [29]. However, these online identification methods are usually complex and require a high computation power. Another method is based on sliding mode control [33-35]. In Ref. [35], an adaptive integral sliding-mode predictive control is proposed using the self-regulation control method and the sliding-mode function. However, these methods require a large amount of calculation, and the performance depends on the design and adjustment of the controller parameters, which increases the design work of the controller.

Model-free control (MFC) tackles the problem of parameter robustness in another way [36]. The original MFC method was proposed by Michel Fliess in 2009 based on an ultra-local model. MFC depends only on the input and output data of the controlled system to set up the ultra-local model and its controller. It is a good solution to solve the problems of load disturbance and parametric variation. To date, MFC has been used in the current control of PMSM drive systems with parametric uncertainties [14]. Another model-free predictive current control (MFPCC) method is proposed in Ref. [37]. It is proposed by calculating the current difference, which requires sampling the current twice per control period. The stored current differences are updated online and used for the current prediction of MPC without using any machine parameters. However, measuring the stator current twice during one control period increases the hardware requirements. In addition, this method has the problem of stagnant current difference updating (SCDU), which makes the stator current distortion severe and affects the steady-state performance [20]. Moreover, this algorithm is based on single-vector model predictive current control (MPCC), and the steady-state ripples are much higher than that of SVM-based DPCC. In Ref. [14], the extended state observer (ESO) based on the ultra-local model of the PMSM is proposed to observe the lumped disturbance of the system. However, it still needs to tune one parameter, ω_0 (bandwidth of ESO). Furthermore, the gain of the input voltage is assumed to be roughly known and requires some tuning [38]. In Ref. [39], the current prediction error in the past control periods is used to compensate for the parameter mismatches when predicting the future current. Although good steady-state performance and strong robustness are achieved, the method is still computationally intensive.

This study proposes a modified DPCC method for the current control of PMSMs, which can achieve strong robustness against parameter mismatches with simple calculation. By replacing the accurate machine model with an ultra-local model, the current prediction and reference voltage calculation processes are simplified. However, different from Ref. [14], the gain of input voltage and the lumped disturbance are estimated online by using the information of stator voltages and currents in the past control periods rather than an ESO. The principle is very simple and straightforward, and the computational burden is much lower. The proposed DPCC is compared with traditional DPCC and FOC with the same sampling and switching frequencies, and the experimental results confirm the effectiveness of the proposed method.

2 Model of the PMSM drive system

The mathematical model of a surface-type PMSM (SPMSM) in a stationary $\alpha\beta$ frame can be expressed using complex vector as follows [6]

$$\boldsymbol{u}_s=R_s\boldsymbol{i}_s+\frac{\mathrm{d}\boldsymbol{\psi}_s}{\mathrm{d}t} \tag{1}$$

$$\boldsymbol{\psi}_s=L_s\boldsymbol{i}_s+\boldsymbol{\psi}_r \tag{2}$$

where $\boldsymbol{\psi}_r = \psi_f \cdot \exp(\mathrm{j}\theta_e)$ is the rotor flux vector; $\boldsymbol{u}_s$ and $\boldsymbol{i}_s$ are the stator voltage and current vectors, respectively; R_s, L_s, and ψ_f are the nominal parameters of the stator resistance, stator inductance and permanent magnet flux, respectively; $\boldsymbol{\psi}_s$ is stator flux vector; and θ_e is the electric rotor angle.

The stator current model of the motor can be obtained from Eq. (1) and Eq. (2) as

$$\frac{\mathrm{d}\boldsymbol{i}_s}{\mathrm{d}t}=\boldsymbol{u}_s - \boldsymbol{R}_s\boldsymbol{i}_s - \boldsymbol{e} \tag{3}$$

where $\boldsymbol{e}=\mathrm{j}\omega\boldsymbol{\psi}_r$ is the back electromotive force (EMF).

In the original MFC, Eq. (3) can be written as a first-order ultra-local model, and it is expressed as follows [14]

$$\frac{\mathrm{d}\boldsymbol{i}_s}{\mathrm{d}t} = \boldsymbol{F} + \alpha\boldsymbol{u}_s \tag{4}$$

where $\boldsymbol{F}$ is the unknown part, and α is the gain of the input value.

According to Ref. [14], the control law of MFC is obtained as [14]

$$\boldsymbol{u}_s^{ref} = \left(-\hat{\boldsymbol{F}} + \frac{\mathrm{d}\boldsymbol{i}_s^{ref}}{\mathrm{d}t} + K_p\boldsymbol{e}\right)/\alpha \tag{5}$$

where $\hat{\boldsymbol{F}}$ is the estimated value of $\boldsymbol{F}$, $\boldsymbol{i}_s^{ref}$ is the reference current vector, $\boldsymbol{u}_s^{ref}$ is the reference voltage vector, $\boldsymbol{e} = \boldsymbol{i}_s^{ref} - \boldsymbol{i}_s$ is the current error, and K_p is the proportional gain.

The controller in Eq. (5) is called an intelligent P controller, and it can achieve robust tracking of the reference value. However, the estimation of $\hat{\boldsymbol{F}}$ is based on the differential algebra method [36], which is complicated. The gain α is assumed to be roughly known based on prior knowledge. More details regarding MFC can be found in Refs. [14, 36] and are not included here due to page limitations.

3 Conventional DPCC

According to Eq. (3), $\boldsymbol{i}_s$ at the next control period can be predicted using forward Euler discretization as

$$\boldsymbol{i}_s^{k+1}=\boldsymbol{i}_s^{k}+\frac{T_{sc}}{L_s}\left(\boldsymbol{u}_s^k - R_s\boldsymbol{i}_s^k - e^k\right) \tag{6}$$

where T_{sc} is the sampling period.

According to Eq. (6), the current prediction is parameter dependent. In practical applications, due to the influence of temperature, saturation and other factors, the parameters of the motor change and affect the current tracking accuracy, as shown in the experimental results.

To mitigate the influence of permanent magnet flux on the controller, the back EMF is estimated using the voltages and currents in the past control periods.

According to the Eq. (6), e^{k-1} is obtained as

$$e^{k-1} = \boldsymbol{u}_s^{k-1} - R_s\boldsymbol{i}_s^{k-1} - \frac{L_s}{T_{sc}}\left(\boldsymbol{i}_s^{k} - \boldsymbol{i}_s^{k-1}\right) \tag{7}$$

Similarly, e^{k-2} and e^{k-3} can be obtained as

$$e^{k-2} = \boldsymbol{u}_s^{k-2} - R_s\boldsymbol{i}_s^{k-2} - \frac{L_s}{T_{sc}}\left(\boldsymbol{i}_s^{k-1} - \boldsymbol{i}_s^{k-2}\right) \tag{8}$$

$$e^{k-3} = \boldsymbol{u}_s^{k-3} - R_s\boldsymbol{i}_s^{k-3} - \frac{L_s}{T_{sc}}\left(\boldsymbol{i}_s^{k-2} - \boldsymbol{i}_s^{k-3}\right) \tag{9}$$

As the sampling period is very short, the back EMF can be considered constant during several successive control periods. Hence, the back EMF can be obtained from the past three control periods as

$$e^{k} = \frac{e^{k-1} + e^{k-2} + e^{k-3}}{3} \tag{10}$$

By estimating the back EMF, the dependence on permanent magnet flux is alleviated. As a result, the robustness against permanent magnet flux variations is enhanced.

After predicting the stator current at k+1 instant, the reference voltage vector to eliminate the current at k+2 instant can be calculated as

$$\boldsymbol{u}_s^{k+1}=R_s\boldsymbol{i}_s^{k+1}+\frac{L_s}{T_{sc}}\left(\boldsymbol{i}_s^{ref}-\boldsymbol{i}_s^{k+1}\right)+e^k \tag{11}$$

where $\boldsymbol{i}_s^{ref}=\left(\boldsymbol{i}_d^{ref}+\mathrm{j}\cdot\boldsymbol{i}_q^{ref}\right)\cdot\exp(\mathrm{j}\theta_e)$, $\boldsymbol{i}_d^{ref}$ is zero to achieve the maximum torque per ampere (MTPA) operation, and $\boldsymbol{i}_q^{ref}$ is obtained from the outer speed loop using a PI controller.

4 Proposed DPCC

By estimating the back EMF, the parameter robustness of conventional DPCC is partially improved. However, it is still dependent on the inductance and stator resistance. To eliminate the parameter dependence of DPCC, this study proposes an improved DPCC based on the ultra-local model [36]. The control diagram is illustrated in Fig. 1.

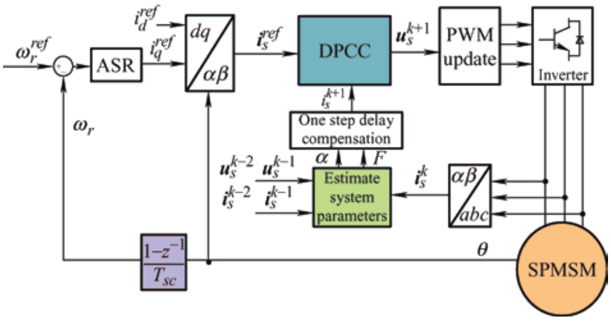


Fig. 1 Control diagram of the proposed DPCC

According to the ultra-local model in Eq. (4), the stator current at the k+1 instant can be predicted as

$$\boldsymbol{i}_s^{k+1}=\boldsymbol{i}_s^k+T_{sc}\left(\boldsymbol{F}+\alpha\boldsymbol{u}_s^k\right) \tag{12}$$

However, $\boldsymbol{F}$ and α are not readily known. In this study, they are estimated using the past stator currents and stator voltages.

The current difference in the past two control periods can be measured, and they can also be calculated as

$$\Delta\boldsymbol{i}_s^k=\boldsymbol{i}_s^k-\boldsymbol{i}_s^{k-1}=T_{sc}\left(\alpha\boldsymbol{u}_s^{k-1}+\boldsymbol{F}^k\right) \tag{13}$$

$$\Delta\boldsymbol{i}_s^{k-1}=\boldsymbol{i}_s^{k-1}-\boldsymbol{i}_s^{k-2}=T_{sc}\left(\alpha\boldsymbol{u}_s^{k-2}+\boldsymbol{F}^{k-1}\right) \tag{14}$$

With a sufficiently high sampling frequency, $\boldsymbol{F}^k$ and $\boldsymbol{F}^{k-1}$ are assumed to be approximately equal, because the mechanical time constant is much larger than the electrical time constant.

According to Eq. (13) and Eq. (14), α can be obtained as

$$\alpha=\frac{\Delta\boldsymbol{i}_s^k-\Delta\boldsymbol{i}_s^{k-1}}{T_{sc}\left(\boldsymbol{u}_s^{k-1}-\boldsymbol{u}_s^{k-2}\right)} \tag{15}$$

Substituting Eq. (15) into Eq. (13), $\boldsymbol{F}$ can be obtained as

$$\boldsymbol{F}=\frac{\Delta\boldsymbol{i}_s^k}{T_{sc}}-\alpha\boldsymbol{u}_s^k \tag{16}$$

After obtaining α and $\boldsymbol{F}$ from Eq. (15) and Eq. (16), the current difference in the next two control periods can be obtained as

$$\Delta\boldsymbol{i}_s^{k+1}=\boldsymbol{i}_s^{k+1}-\boldsymbol{i}_s^k=T_{sc}\left(\alpha\boldsymbol{u}_s^k+\boldsymbol{F}^k\right) \tag{17}$$

$$\Delta\boldsymbol{i}_s^{k+2}=\boldsymbol{i}_s^{k+2}-\boldsymbol{i}_s^{k+1}=T_{sc}\left(\alpha\boldsymbol{u}_s^{k+1}+\boldsymbol{F}^{k+1}\right) \tag{18}$$

Summing Eq. (17) and Eq. (18), considering that $\boldsymbol{i}_s^{ref}=\boldsymbol{i}_s^{k+2}$ and $\boldsymbol{F}^k=\boldsymbol{F}^{k+1}$, the reference voltage vector can be calculated as

$$\boldsymbol{u}_s^{ref}=\boldsymbol{u}_s^{k+1}=\frac{(\boldsymbol{i}_s^{ref}-\boldsymbol{i}_s^k)/T_{sc}-2\boldsymbol{F}^k}{\alpha}-\boldsymbol{u}_s^k \tag{19}$$

It can be seen intuitively from Eq. (19) that the proposed method does not use any machine parameters. Both α and $\boldsymbol{F}$ are estimated and updated online. Hence, strong robustness against machine parameter variation is achieved.

As α and $\boldsymbol{F}$ are directly calculated from Eq. (15) and Eq. (16) rather than estimated from an observer, there may be irregular spikes in them due to the measurement noise in the stator current. Therefore, α and $\boldsymbol{F}$ need to be filtered to obtain more accurate and stable values, which helps to improve the stability of system. This study selects a first-order low-pass filter (LPF) for simplicity. For α, its true value is $1/L_s$, which does not change abruptly. Hence, the cut-off frequency can be low. In this study, the final cut-off frequency of the LPF for α is set to 25 Hz. The value of $\boldsymbol{F}$ may change dramatically in the dynamic process; hence, its cut-off frequency should not be too low. In general, the cut-off frequency of the LPF is a compromise between robustness and dynamic performance. The final cut-off frequency of the LPF for $\boldsymbol{F}$ is set to 1 000 Hz in this study.

5 Experimental results

To confirm the effectiveness of the proposed DPCC, experimental verification is carried out on the following experimental platform shown in Fig. 2. The main parameters of the machine are listed in Tab. 1. For comparison, conventional DPCC [18, 40], conventional FOC, and the proposed DPCC are implemented on a DSP TMS320F28335 SPMSM control platform. The sampling frequency is set to 10 kHz in this study. In the following figures of experimental results, the motor speed, reference and actual currents of the q-axis, and one-phase current are measured and displayed on a four-channel digital oscilloscope.

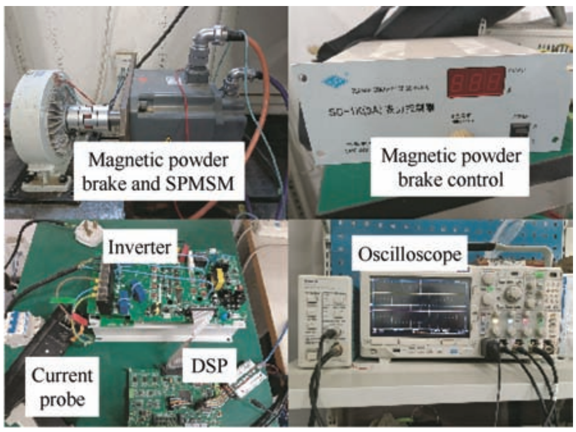
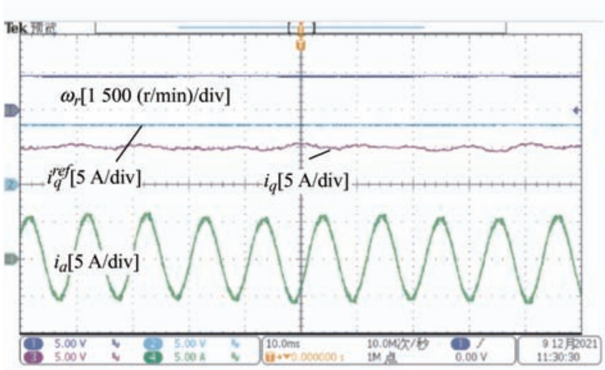


Fig. 2 Experimental setup of two-level inverter-fed PMSM drive

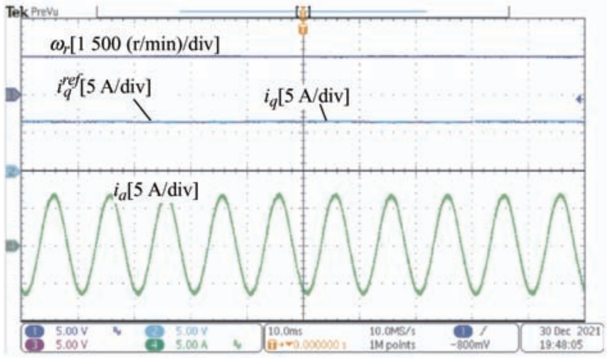
Tab. 1 Machine and control parameters

Parameter	Value
DC-bus voltage U_{dc}/V	540
Rated power P_N/kW	2.2
Rated voltage U_N/V	380
Rated frequency f/Hz	100
Rated torque T_N/(N • m)	14
Number of pole pairs N_p	4
Stator resistance R_s/Ω	2.34
Inductance of d-axis L_d/mH	19.36
Inductance of q-axis L_q/mH	19.37
Permanent magnet flux ψ_f/Wb	0.402
Control period T_{sc}/μs	100

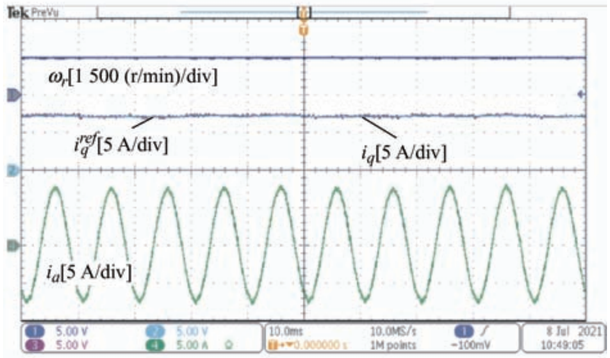
Fig. 3 shows the steady-state experimental results at a rated speed of 100 Hz for conventional DPCC with accurate parameters, conventional DPCC with mismatched parameters at 1.5R_s and 2R_s, FOC with mismatched parameters at 1.5R_s and 2R_s, and the proposed DPCC with mismatched parameters at 1.5R_s and 2R_s. It is seen from Fig. 3b that, when there are parameter mismatches in the conventional DPCC, both the speed and q-axis current cannot track the reference value, and the current harmonics are increased. In contrast, the proposed DPCC method does not use the motor parameters in the current prediction process and has good steady-state performance at rated speed, as shown in Fig. 3d. For FOC, there is no steady-state current error owing to the use of the PI controller; therefore, the steady-state performance of FOC is not affected by the parameter mismatches. Similar results can be seen at low and medium speeds, as shown in Figs. 4 and 5. The results confirm that the proposed DPCC method has evident advantages over the traditional DPCC method in the case of parameter mismatch.



(b) Conventional DPCC with mismatched parameters at 1.5R_s and 2R_s

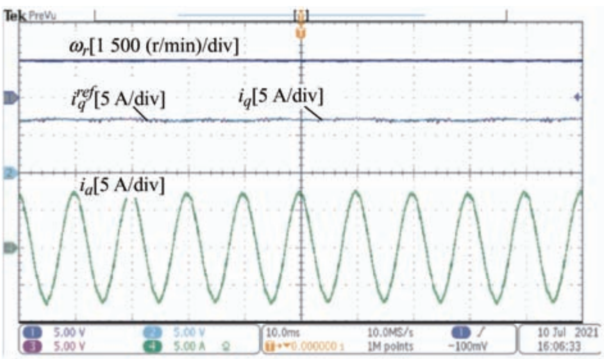


(c) FOC with mismatched parameters at 1.5R_s and 2R_s

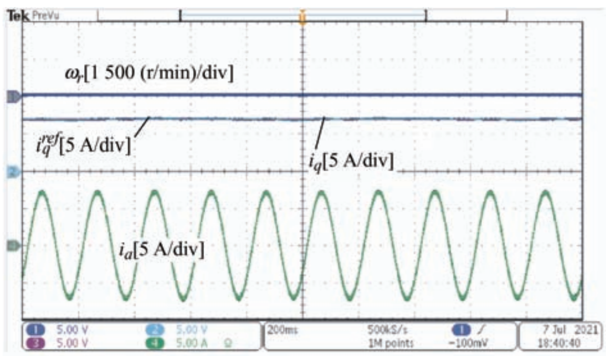


(d) Proposed DPCC with mismatched parameters at 1.5R_s and 2R_s

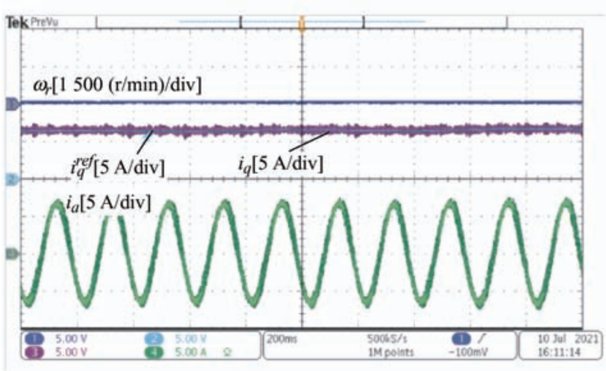
Fig. 3 Experimental results at 100% rated speed



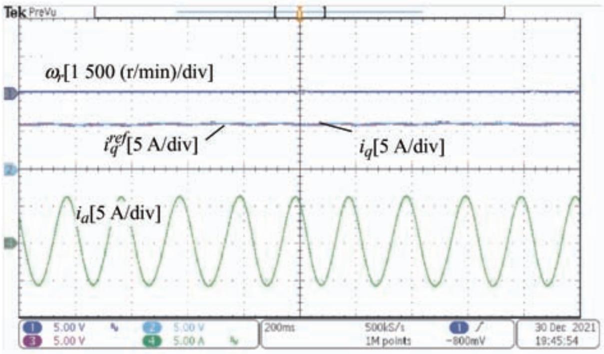
(a) Conventional DPCC with accurate parameters



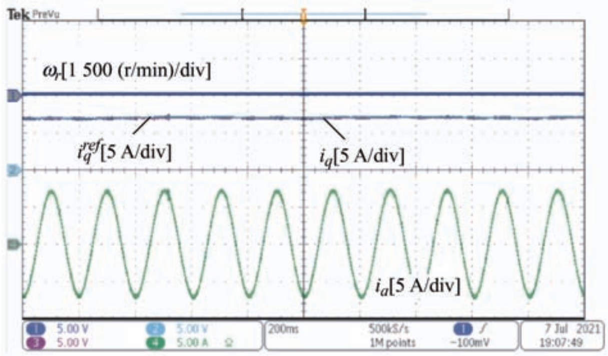
(a) Conventional DPCC with accurate parameters



(b) Conventional DPCC with mismatched parameters at 1.5R_s and 2R_s

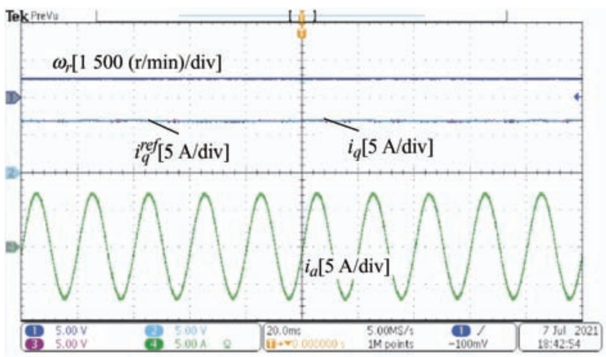


(c) FOC with mismatched parameters at 1.5R_s and 2R_s

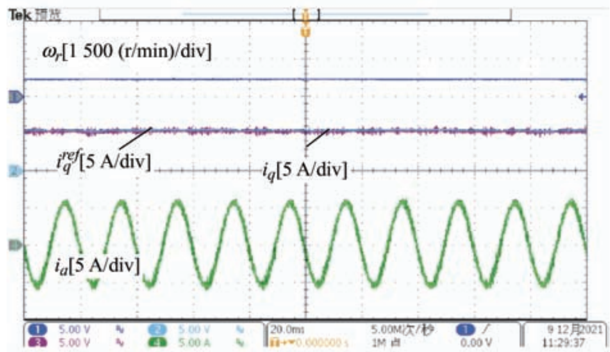


(d) Proposed DPCC with mismatched parameters at 1.5R_s and 2R_s

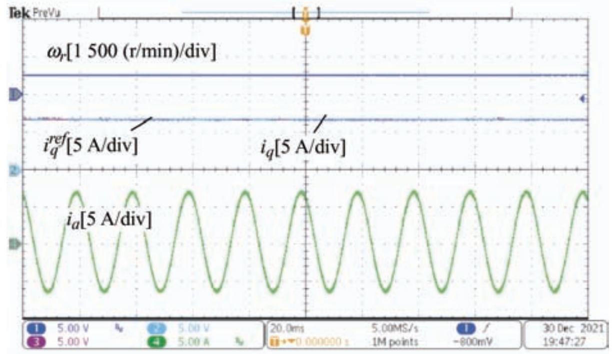
Fig. 4 Experimental results with 5% rated speed



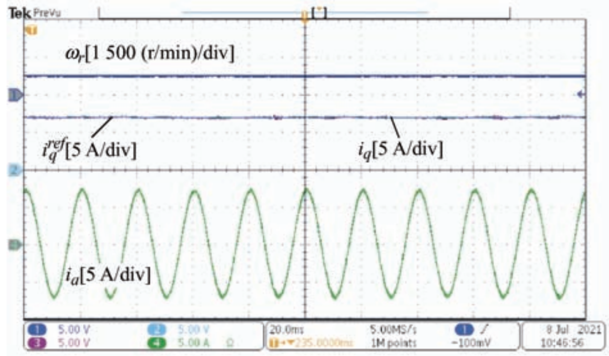
(a) Conventional DPCC with accurate parameters



(b) Conventional DPCC with mismatched parameters at 1.5R_s and 2R_s



(c) FOC with mismatched parameters at 1.5R_s and 2R_s



(d) Proposed DPCC with mismatched parameters at 1.5R_s and 2R_s

Fig. 5 Experimental results with 50% rated speed

Fig. 6 illustrates the current total harmonic distortions (THDs) of conventional DPCC with accurate/inaccurate machine parameters, FOC with mismatched parameters, and the proposed DPCC with mismatched parameters at different speeds. It can be seen that traditional DPCC has good performance in all speed ranges under the condition of accurate parameters. However, in the case of parameter mismatches, it has the highest current THD, especially at the 5% and 50% speeds. Conventional FOC with mismatched parameters has a lower current THD at medium and high speeds, but the harmonic content increases at low speeds. The proposed DPCC with mismatched parameters has a current THD similar to that of traditional DPCC with accurate machine parameters. As the proposed DPCC does not use any machine parameters, it avoids the influence of parameter variations on the system and improves the parameter robustness.

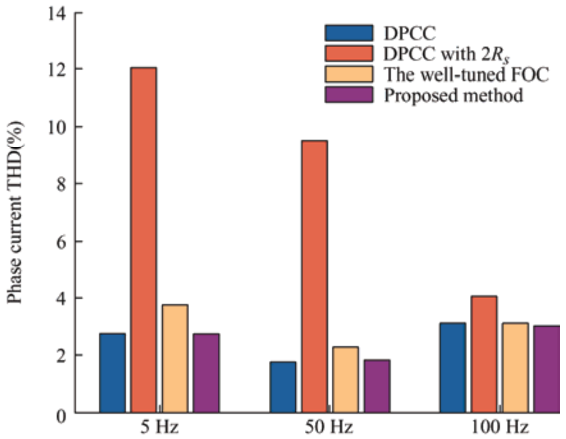
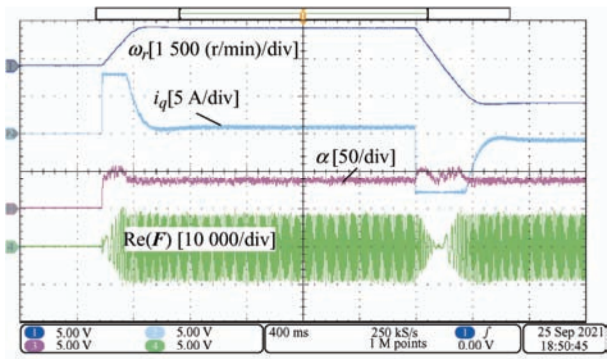
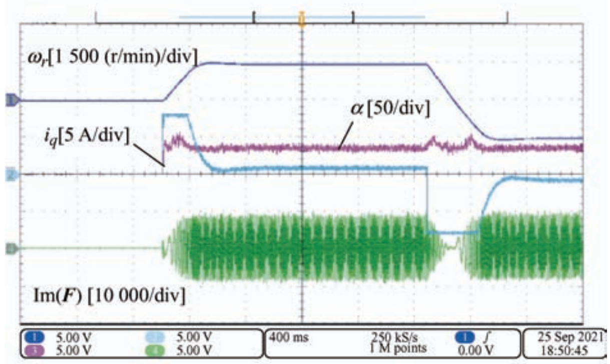


Fig. 6 Analysis of current THD for various control methods

In addition to the steady-state performance comparison, the dynamic performance is tested. Fig. 7 shows the estimated α and $\boldsymbol{F}$ during the dynamic process of the proposed method. The machine starts from a standstill to rated speed and then quickly runs to reverse rated speed. From top to bottom, the curves indicate the rotor speed, q-axis current, estimated α, and real/imaginary part of $\boldsymbol{F}$. It is observed that both α and $\boldsymbol{F}$ converge to the actual value quickly as soon as the machine starts and can still converge to the real α and $\boldsymbol{F}$ values in the dynamic process. Although there are some oscillations in the observed α during the dynamic process, the system is unaffected, and the machine runs stably. The results confirm that the proposed method can work effectively in both steady-state operation and dynamic processes without requiring any prior knowledge of system.



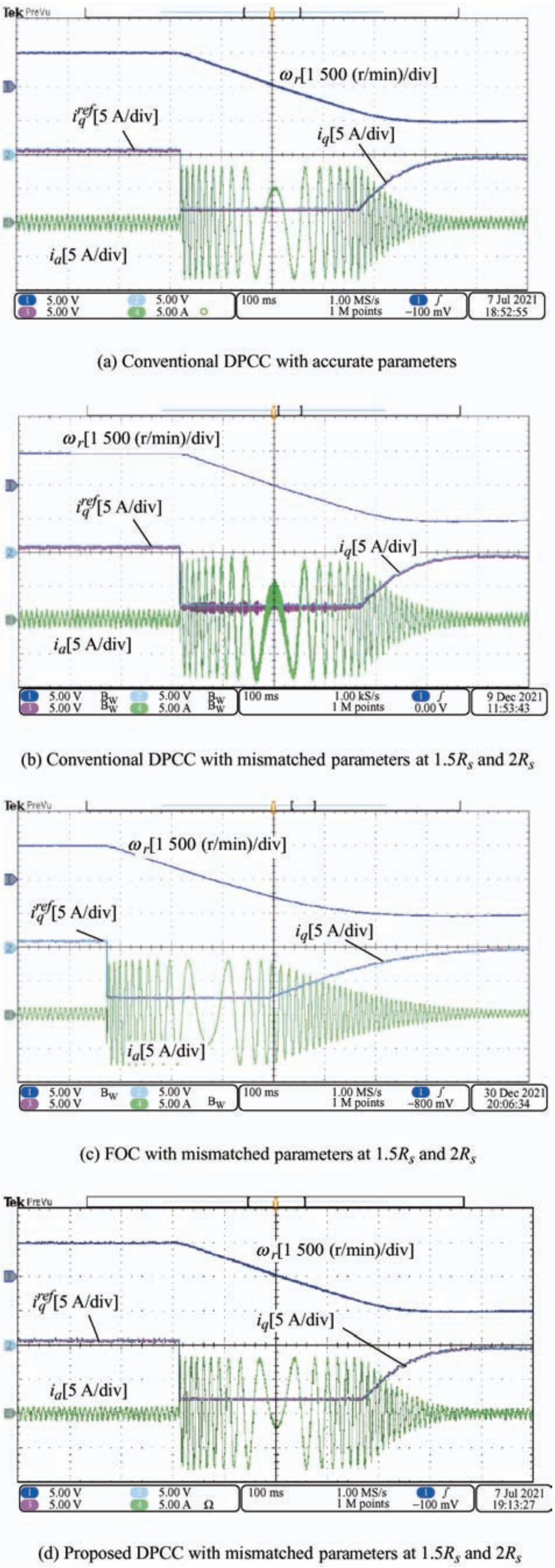
(a) α and real part of $\boldsymbol{F}$ during the dynamic process



(b) α and imaginary part of $\boldsymbol{F}$ during the dynamic process

Fig. 7 The rotor speed, q-axis current, and estimated α and $\boldsymbol{F}$ during the dynamic process of proposed method

Fig. 8 shows the dynamic responses of speed reversal at ±1 500 r/min for conventional DPCC with accurate parameters, conventional DPCC with mismatched parameters at $1.5R_s$ and $2R_s$, FOC with mismatched parameters at $1.5R_s$ and $2R_s$, and the proposed DPCC with mismatched parameters at $1.5R_s$ and $2R_s$. It is seen that the proposed method presents a quick response similar to that of traditional DPCC with accurate parameters. However, there are significant ripples in the q-axis current during the dynamic process when the used machine parameters in conventional DPCC are inaccurate. FOC with inaccurate machine parameters presents a steady-state performance similar to that of the proposed method, and the q-axis current is accurately tracked due to the use of the PI controller. However, its dynamic response is inferior to that of the proposed DPCC, which is mainly caused by the limited bandwidth of the current loop. Similar results are obtained under the condition of rated speed with sudden load change, as shown in Fig. 9. When the machine parameters are inaccurate, the motor speed does not reach the reference speed in conventional DPCC. In contrast, the parameter mismatches do not affect both FOC and the proposed DPCC. Compared to FOC, there is a smaller speed drop in the proposed DPCC, and the q-axis current increases much more rapidly. The results confirm that the proposed DPCC has a quick response similar to that of conventional DPCC and is not affected by the machine parameter variations.



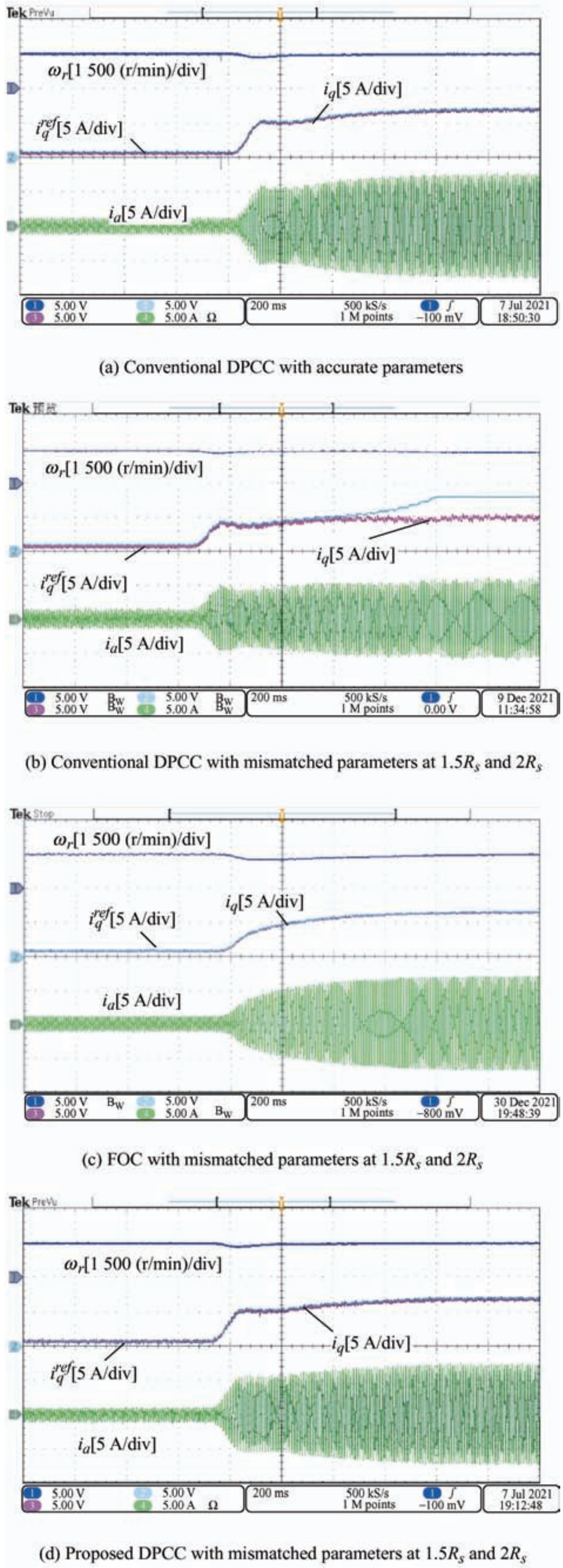
(a) Conventional DPCC with accurate parameters

(b) Conventional DPCC with mismatched parameters at $1.5R_s$ and $2R_s$

(c) FOC with mismatched parameters at $1.5R_s$ and $2R_s$

(d) Proposed DPCC with mismatched parameters at $1.5R_s$ and $2R_s$

Fig. 8 Experimental results during the dynamic process with −1 500 r/min to 1 500 r/min



(a) Conventional DPCC with accurate parameters

(b) Conventional DPCC with mismatched parameters at $1.5R_s$ and $2R_s$

(c) FOC with mismatched parameters at $1.5R_s$ and $2R_s$

(d) Proposed DPCC with mismatched parameters at $1.5R_s$ and $2R_s$

Fig. 9 Experimental results during the dynamic process with a sudden load at 1 500 r/min and the rated load

6 Conclusions

This study proposes a deadbeat predictive current control (DPCC) method for a PMSM drive system, which is an improvement over conventional DPCC. The two terms in the ultra-local model of the PMSM drive, α and $\boldsymbol{F}$, are estimated online by using the stator voltage vectors and current sample values from the last two control periods. Hence, the proposed method has good robustness because it does not require motor parameters. The proposed DPCC presents a steady-state performance similar to those of traditional DPCC with accurate machine parameters. However, when there are machine parameter mismatches, the performance of traditional DPCC degrades, while the proposed method is not affected. Moreover, the proposed DPCC presents a steady-state performance and parameter robustness similar to those of FOC, but the proposed DPCC offers a better dynamic response. The experimental results verify that the proposed DPCC has good steady-state performance, strong parameter robustness, and quick dynamic response without using any machine parameters.

References

[1] Yongchang Zhang, Hao Jiang, Haitao Yang. Model predictive control of PMSM drives based on general discrete space vector modulation. *IEEE Transactions on Energy Conversion*, 2021, 36(2): 1300-1307.

[2] D Casadei, F Profumo, G Serra, et al. FOC and DTC: Two viable schemes for induction motors torque control. *IEEE Transactions on Power Electronics*, 2002, 17(5): 779-787.

[3] L Zhong, M F Rahman, W Y Hu, et al. Analysis of direct torque control in permanent magnet synchronous motor drives. *IEEE Transactions on Power Electronics*, 1997, 12(3): 528-536.

[4] T Geyer, G Papafotiou, M Morari. Model predictive direct torque control—Part I: Concept, algorithm, and analysis. *IEEE Transactions on Industrial Electronics*, 2009, 56(6): 1894-1905.

[5] J Han. From PID to active disturbance rejection control. *IEEE Transactions on Industrial Electronics*, 2009, 56(3): 900-906.

[6] Y Zhang, J Zhu. Direct torque control of permanent magnet synchronous motor with reduced torque ripple and commutation frequency. *IEEE Transactions on Power Electronics*, 2011, 26(1): 235-248.

[7] Yongchang Zhang, Haitao Yang, Bo Xia. Model predictive torque control of induction motor drives with reduced torque ripple. *IET Electric Power Applications*, 2015, 9(9): 595-604.

[8] P Cortes, M P Kazmierkowski, R M Kennel, et al. Predictive control in power electronics and drives. *IEEE Transactions on Industrial Electronics*, 2008, 55(12): 4312-4324.

[9] F Morel, X Lin-Shi, J Retif, et al. A comparative study of predictive current control schemes for a permanent-magnet synchronous machine drive. *IEEE Transactions on Industrial Electronics*, 2009, 56(7): 2715-2728.

[10] S Vazquez, J Rodriguez, M Rivera, et al. Model predictive control for power converters and drives: Advances and trends. *IEEE Transactions on Industrial Electronics*, 2017, 64(2): 935-947.

[11] H Miranda, P Cortes, J I Yuz, et al. Predictive torque control of induction machines based on state-space models. *IEEE Transactions on Industrial Electronics*, 2009, 56(6): 1916-1924.

[12] Yongchang Zhang, Jianguo Zhu. A novel duty cycle control strategy to reduce both torque and flux ripples for DTC of permanent magnet synchronous motor drives with switching frequency reduction. *IEEE Transactions on Power Electronics*, 2011, 26(10): 3055-3067.

[13] Yuanlin Wang, Xiaocan Wang, Wei Xie, et al. Deadbeat model-predictive torque control with discrete space-vector modulation for PMSM drives. *IEEE Transactions on Industrial Electronics*, 2017, 64(5): 3537-3547.

[14] Yongchang Zhang, Jialin Jin, Lanlan Huang. Model-free predictive current control of PMSM drives based on extended state observer using ultralocal model. *IEEE Transactions on Industrial Electronics*, 2021, 68(2): 993-1003.

[15] Xiaoguang Zhang, Zhihao Zhao, Yu Cheng, et al. Robust model predictive current control based on inductance and flux linkage extraction algorithm. *IEEE Transactions on Vehicular Technology*, 2020, 69(12): 14893-14902.

[16] Huixian Liu, Shihua Li. Speed control for PMSM servo system using predictive functional control and extended state observer. *IEEE Transactions on Industrial Electronics*, 2012, 59(2): 1171-1183.

[17] S Bibian, H Jin. Time delay compensation of digital control for DC switchmode power supplies using prediction techniques. *IEEE Transactions on Power Electronics*, 2000, 15(5): 835-842.

[18] H T Moon, H S Kim, M J Youn. A discrete-time predictive current control for PMSM. *IEEE Transactions on Power Electronics*, 2003, 18(1): 464-472.

[19] T Sebastian. Temperature effects on torque production and efficiency of PM motors using NdFeB magnets. *IEEE Transactions on Industry Applications*, 1995, 31(2): 353-357.

[20] M Khalilzadeh, S Vaez-Zadeh, M S Eslahi. Parameter-free predictive control of IPM motor drives with direct selection of optimum inverter voltage vectors. *IEEE Transactions on Power Electronics*, 2021, 9(1): 327-334.

[21] F Tinazzi, P G Carlet, S Bolognani, et al. Motor parameter-free predictive current control of synchronous motors by recursive least-square self-commissioning model. *IEEE Transactions on Industrial Electronics*, 2020, 67(11): 9093-9100.

[22] J Yang, W H Chen, S Li, et al. Disturbance/uncertainty estimation and attenuation techniques in PMSM drives: A survey. *IEEE Transactions on Industrial Electronics*, 2017, 64(4): 3273-3285.

[23] Cheng Xu, Zaikun Han, Shuai Lu. Deadbeat predictive current control for permanent magnet synchronous machines with closed-form error compensation. *IEEE Transactions on Power Electronics*, 2020, 35(5): 5018-5030.

[24] Y Inoue, Y Kawaguchi, S Morimoto, et al. Performance improvement of sensorless IPMSM drives in a low-speed region using online parameter identification. *IEEE Transactions on Industry Applications*, 2011, 47(2): 798-804.

[25] Chengbo Yang, Bao Song, Yuanlong Xie, et al. Online parallel estimation of mechanical parameters for PMSM drives via a network of interconnected extended sliding-mode observers. *IEEE Transactions on Power Electronics*, 2021, 36(10): 11818-11834.

[26] Yu Yao, Yunkai Huang, Fei Peng, et al. An improved deadbeat predictive current control with online parameter identification for surface-mounted PMSMs. *IEEE Transactions on Industrial Electronics*, 2020, 67(12): 10145-10155.

[27] D Q Dang, M S Rafaq, H H Choi, et al. Online parameter estimation technique for adaptive control applications of interior PM synchronous motor drives. *IEEE Transactions on Industrial Electronics*, 2016, 63(3): 1438-1449.

[28] Y Abdel-Rady, I Mohamed, E F El-Saadany. An improved deadbeat current control scheme with a novel adaptive self-tuning load model for a three-phase PWM voltage-source inverter. *IEEE Transactions on Industrial Electronics*, 2007, 54(2): 747-759.

[29] N Jabbour, C Mademlis. Online parameters estimation and autotuning of a discrete-time model predictive speed controller for induction motor drives. *IEEE Transactions on Power Electronics*, 2019, 34(2): 1548-1559.

[30] S Kwak, U Moon, J Park. Predictive-control-based direct power control with an adaptive parameter identification technique for improved AFE performance. *IEEE Transactions on Power Electronics*, 2014, 29(11): 6178-6187.

[31] Xiaoguang Zhang, Liang Zhang, Yongchang Zhang. Model predictive current control for PMSM drives with parameter robustness improvement. *IEEE Transactions on Power Electronics*, 2019, 34(2): 1645-1657.

[32] M Mehreganfar, M H Saeedinia, S A Davari, et al. Sensorless predictive control of AFE rectifier with robust adaptive inductance estimation. *IEEE Transactions on Industrial Informatics*, 2019, 15(6): 3420-3431.

[33] A Bartoszewicz, K Adamiak. Discrete-time sliding-mode control with a desired switching variable generator. *IEEE Transactions on Automatic Control*, 2020, 65(4): 1807-1814.

[34] Bo Xu, Lei Zhang, Wei Ji. Improved non-singular fast terminal sliding mode control with disturbance observer for PMSM drives. *IEEE Transactions on Transportation Electrification*, 2021, 7(4): 2753-2762.

[35] Zheng Li, Fengxiang Wang, Dongliang Ke, et al. Robust continuous model predictive speed and current control for PMSM with adaptive integral sliding-mode approach. *IEEE Transactions on Power Electronics*, 2021, 36(12): 14398-14408.

[36] M Fliess, C Join. Model-free control. *International Journal of Control*, 2013, 86(12): 2228-2252.

[37] C Lin, T Liu, J Yu, et al. Model-free predictive current control for interior permanent-magnet synchronous motor drives based on current difference detection technique. *IEEE Transactions on Industrial Electronics*, 2014, 61(2): 667-681.

[38] Y Zhang, W Shen, H Yang, et al. An improved model-free predictive current control method for PMSM drives based

on extended control set and fast current difference updating. *2022 IEEE Energy Conversion Congress and Exposition (ECCE)*, October 09-13, 2022, Detroit, MI, USA. IEEE, 2022: 1-8.

[39] Yongchang Zhang, Tao Jiang. Robust predictive stator current control based on prediction error compensation for a doubly fed induction generator under nonideal grids. *IEEE Transactions on Industrial Electronics*, 2022, 69(5): 4398-4408.

[40] Y Zhang, D Xu, J Liu, et al. Performance improvement of model predictive current control of permanent magnet synchronous motor drives. *IEEE Transactions on Industry Applications*, 2017, 53(4): 3683-3695.

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