

Article

Improved Deadbeat Predictive Control Based Current Harmonic Suppression Strategy for IPMSM

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Abstract: When the interior permanent magnet synchronous motor (IPMSM) is running, there are abundant harmonics in the stator current. In order to achieve the suppression of current harmonics, the current harmonic extraction method and current harmonic controller are studied in this paper. Firstly, a simple and accurate method for extracting current harmonics is proposed by means of multiple synchronous rotating frame transformation (MSRFT). Secondly, an improved deadbeat predictive control (IDPC) based current harmonic controller is designed after analyzing the advantages and disadvantages of traditional current harmonic controllers. Thirdly, IDPC-based current harmonic suppression strategy is proposed by combining the proposed current harmonic extraction method and the proposed current harmonic controller. The proposed strategy can still effectively achieve current harmonic suppression when the motor runs at low speed, medium speed and high speed and the controller parameters are mismatched with the motor parameters. Finally, the feasibility and effectiveness of the proposed strategy are verified by simulation and experiments.

Keywords: interior permanent magnet synchronous motor (IPMSM); current harmonic suppression; multiple synchronous rotating frame transformation (MSRFT); deadbeat predictive control (DPC)



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1. Introduction

Interior permanent magnet synchronous motor (IPMSM) has the advantages of high-power density and wide operating speed range, and is widely used in electric vehicle drive systems [1]. In the actual operation process, non-ideal factors such as the dead-time effect of the inverter and the non-sinusoidal flux linkage of the permanent magnet will cause the motor stator current to contain rich harmonic content. This will cause unnecessary motor losses and affect the running quality of the motor [2]. Therefore, the suppression of stator current harmonics plays an important role in ensuring the stable operation of the drive.

The essence of the current harmonic suppression strategy is to accurately control the current harmonic components to 0. In order to achieve the control of the current harmonic components, it is necessary to extract the current harmonic components accurately and have a current harmonic controller with good performance.

In terms of current harmonic extraction, the multiple synchronous rotating frame transformation (MSRFT) method has received extensive attention in recent years [3–7]. This method transforms the stator current into a combination of DC quantities (current harmonics of specified frequency) and several AC quantities, and the first-order low-pass filter (FLPF) is used to extract the current harmonics. Since the FLPF cannot attenuate the signal to 0 at the cutoff frequency, it is difficult to eliminate high amplitude AC quantities in the current. In order to improve the extraction accuracy of current harmonics, second-order Butterworth filter and type II Chebyshev filter are used in [5] and [6], respectively, and a closed-loop extraction method with FLPF and PI controller in series is designed in [7]. The above methods all improve the extraction accuracy of current harmonics. However, they all increase the complexity of the algorithm. In addition, band-pass filter and adaptive filter based on least squares are used to extract current harmonics with the goal of extracting AC qualities [8–10].

In terms of current harmonic controllers, some current harmonic controllers based on proportional resonance controllers, repetitive controllers, and iterative learning controllers have been proposed [11–15]. The above controllers can achieve current harmonic suppression. However, the parameters of the controllers often need to be adjusted with the harmonic frequency. Due to the PI controller can control the DC qualities and avoid the influence of the frequency change, it is widely used in the current harmonic suppression [16–19]. The traditional PI based current harmonic controller usually subtracts the extracted current harmonic component from the reference value, and then the resulting value is input to the PI controller to generate the harmonic compensation voltage. The harmonic compensation voltage is injected into the dq axis voltages through the inverse MSTFT. However, PI controllers' parameters tuning is difficult as using multiple PI controllers. In order to solve this problem, some scholars replaced PI with deadbeat predictive control (DPC) and designed a current harmonic controller based on DPC. However, traditional DPC depends on the motor parameters and the model error and the position change of the rotor in one cycle cannot be ignored due to the high electrical frequency of the motor in the 5th and 7th synchronous rotating frames. This will lead to a static error between the current harmonic components and the reference value 0. Therefore, this scheme has difficulty effectively suppressing the current harmonics.

From above, two aspects have been studied in this paper: improving the detection accuracy of current harmonics, and improving the performance of current harmonic controllers. Firstly, the existing current harmonic extraction method based on MSRFT is improved by reconstructing the input current of the filter. This method has a simple structure and can achieve accurate extraction of current harmonics. Secondly, the improved deadbeat predictive control (IDPC) based current harmonic controller is established by improving the solution method of PMSM state equation and considering the effect of rotor position changes in one control cycle and applying the method of current static error elimination. Thirdly, IDPC-based current harmonic suppression strategy is proposed by combining the improved current harmonic extraction method and the IDPC-based current harmonic controller. Finally, the experimental results show that the proposed strategy can effectively suppress the current harmonics when the motor runs at low speed, medium speed and high speed and the controller parameters are mismatched with the motor parameters.

2. Mathematical Model of IPMSM Containing Harmonics

The three-phase windings of the IPMSM stator are usually star-connected. Under ideal circumstances, the windings are symmetrically distributed and the back EMF waveforms of the motor are half-wave symmetrical. Hence, the three-phase windings do not contain multiples of 3 and even harmonics. The three-phase currents can be expressed as:

$$\begin{cases} i_a = \sum I_n \cos(n\omega_e t + \theta_n) \\ i_b = \sum I_n \cos(n\omega_e t - \frac{2}{3}n\pi + \theta_n) \\ i_c = \sum I_n \cos(n\omega_e t + \frac{2}{3}n\pi + \theta_n) \end{cases} \quad (1)$$

where, $n = 1, 5, 7, 11, 13 \dots$, I_n is the amplitude of the n th harmonic current, θ_n is the initial phases of the n th harmonic current, and ω_e is the electrical angular velocity of the motor.

The transformation matrix from the abc frame to the dq axis frame can be expressed as:

$$\mathbf{T}_{abc}^{dq} = \frac{2}{3} \begin{bmatrix} \cos \omega_e t & \cos(\omega_e t - \frac{2\pi}{3}) & \cos(\omega_e t + \frac{2\pi}{3}) \\ -\sin \omega_e t & -\sin(\omega_e t - \frac{2\pi}{3}) & -\sin(\omega_e t + \frac{2\pi}{3}) \end{bmatrix} \quad (2)$$

By transforming (1) with (2), the IPMSM stator current in the dq axis frame can be expressed as:

$$\begin{cases} i_d = I_1 \cos \theta_1 + I_5 \cos(6\omega_e t + \theta_5) + I_7 \cos(6\omega_e t + \theta_7) + \dots \\ i_q = I_1 \sin \theta_1 - I_5 \sin(6\omega_e t + \theta_5) + I_7 \sin(6\omega_e t + \theta_7) + \dots \end{cases} \quad (3)$$

Typically, the permanent magnet flux linkage of the IPMSM contains a certain number of harmonics, which results in the presence of harmonics in the back EMF of the motor. In the dq axis frame, the permanent magnet flux linkage can be expressed as [10]:

$$\begin{cases} \psi_{fd} = \psi_{f1} + (\psi_{f5} + \psi_{f7}) \cos 6\omega_e t + (\psi_{f11} + \psi_{f13}) \cos 12\omega_e t + \dots \\ \psi_{fq} = (\psi_{f7} - \psi_{f5}) \sin 6\omega_e t + (\psi_{f13} - \psi_{f11}) \sin 12\omega_e t + \dots \end{cases} \quad (4)$$

where, ψ_{f1} , ψ_{f5} , ψ_{f7} , ψ_{f11} and ψ_{f13} are the fundamental, 5th, 7th, 11th and 13th harmonic components amplitudes of the rotor permanent magnet flux linkage, respectively.

In the dq axis frame, the voltage equation of IPMSM can be expressed as:

$$\begin{cases} u_d = Ri_d + \frac{d\psi_d}{dt} - \omega_e \psi_q \\ u_q = Ri_q + \frac{d\psi_q}{dt} + \omega_e \psi_d \\ \psi_d = L_d i_d + \psi_{fd} \\ \psi_q = L_q i_q + \psi_{fq} \end{cases} \quad (5)$$

where, R is the stator resistance of the motor; L_d and L_q are the d and q-axis inductances, respectively; and ψ_d and ψ_q are the dq axis flux linkages, respectively.

In this paper, the suppression of the 5th and 7th harmonic currents is mainly considered. Substitute (3) and (4) into (5), the IPMSM voltage equation containing the 5th and 7th harmonics can be expressed as:

$$\begin{cases} u_d = R[I_1 \cos \theta_1 + I_5 \cos(6\omega_e t + \theta_5) + I_7 \cos(6\omega_e t + \theta_7)] \\ \quad - 6\omega_e L_d [I_5 \sin(6\omega_e t + \theta_5) + I_7 \sin(6\omega_e t + \theta_7)] \\ \quad - \omega_e L_q [I_1 \sin \theta_1 - I_5 \sin(6\omega_e t + \theta_5) + I_7 \sin(6\omega_e t + \theta_7)] \\ \quad - \omega_e (5\psi_{f5} + 7\psi_{f7}) \sin 6\omega_e t \\ u_q = R[I_1 \sin \theta_1 - I_5 \sin(6\omega_e t + \theta_5) + I_7 \sin(6\omega_e t + \theta_7)] \\ \quad + 6\omega_e L_q [I_7 \cos(6\omega_e t + \theta_7) - I_5 \sin(6\omega_e t + \theta_5)] \\ \quad + \omega_e L_d [I_1 \cos \theta_1 + I_5 \cos(6\omega_e t + \theta_5) + I_7 \cos(6\omega_e t + \theta_7)] \\ \quad + \omega_e [\psi_{f1} + (7\psi_{f7} - 5\psi_{f5}) \cos 6\omega_e t] \end{cases} \quad (6)$$

From above, Equations (3)–(6) constitute the IPMSM mathematical model considering harmonics.

3. Improved Current Harmonic Suppression Strategy

3.1. Improved Current Harmonic Extraction Method

3.1.1. MSFRT

MSFRT is the basis of current harmonic extraction method. It can be seen from Equations (1) and (3) that when the fundamental wave angular velocity is used as the rotational speed of the synchronous rotating frame, the fundamental components of the three-phase currents are expressed as the DC quantities. In the same way, when the harmonic angular velocity of the specified frequency is used as the rotational speed of the synchronous

rotating frame, the harmonic components of the specified frequency in the three-phase currents will also be expressed as the DC quantities.

The rotation direction of the 5th synchronous rotating frame is opposite to that of the fundamental synchronous rotating frame. The transformation matrix of the fundamental synchronous rotating frame to the 5th synchronous rotating frame [7] can be expressed as:

$$T_{dq}^{dq5} = \begin{bmatrix} \cos 6\omega_e t & -\sin 6\omega_e t \\ \sin 6\omega_e t & \cos 6\omega_e t \end{bmatrix} \quad (7)$$

By transforming (3) with (7), the expression of the motor stator current in the 5th synchronous rotating frame can be expressed as:

$$\begin{cases} i_{d5} = I_5 \cos \theta_5 + I_1 \cos(6\omega_e t + \theta_1) + I_7 \cos(12\omega_e t + \theta_7) \\ i_{q5} = -I_5 \sin \theta_5 + I_1 \sin(6\omega_e t + \theta_1) + I_7 \sin(12\omega_e t + \theta_7) \end{cases} \quad (8)$$

The rotation direction of the 7th synchronous rotating frame is the same as that of the fundamental synchronous rotating frame. The transformation matrix of the fundamental synchronous rotating frame to the 7th synchronous frame can be obtained as:

$$T_{dq}^{dq7} = \begin{bmatrix} \cos 6\omega_e t & \sin 6\omega_e t \\ -\sin 6\omega_e t & \cos 6\omega_e t \end{bmatrix} \quad (9)$$

Similarly, by transforming (3) with (9), the expression of motor stator current in the 7th synchronous rotating frame can be written as:

$$\begin{cases} i_{d7} = I_7 \cos \theta_7 + I_1 \cos(6\omega_e t - \theta_1) + I_5 \cos(12\omega_e t + \theta_5) \\ i_{q7} = I_7 \sin \theta_7 - I_1 \sin(6\omega_e t - \theta_1) - I_5 \sin(12\omega_e t + \theta_5) \end{cases} \quad (10)$$

3.1.2. Harmonic Current Extraction Method

In order to achieve good current harmonic control, the extraction accuracy of current harmonics is particularly important. It can be known from (8) and (10) that the 5th harmonic component is DC quantity, and the fundamental component and other harmonic components are AC quantities in the 5th synchronous rotating frame. The 7th harmonic component is the DC quantity, and the fundamental component and other harmonic components are the AC quantities in the 7th synchronous rotating frame. The traditional current harmonic extraction method is shown in Figure 1. After the three-phase currents of the motor are transformed into the 5th and 7th synchronous rotating frames, the current harmonic components are extracted through FLPF. The extraction result can be expressed as:

$$\begin{cases} i_{d5h} = I_5 \cos \theta_5 \\ i_{q5h} = -I_5 \sin \theta_5 \end{cases} \quad (11)$$

$$\begin{cases} i_{d7h} = I_7 \cos \theta_7 \\ i_{q7h} = I_7 \sin \theta_7 \end{cases} \quad (12)$$

However, for a motor with a large current, the fundamental components of the three-phase currents are much larger than the harmonic component, and it appears as a high-amplitude six-fold frequency alternating current in the 5th and 7th synchronous rotating frames. Unfortunately, the FLPF does not attenuate the signal to 0 at the cutoff frequency, and the magnitude of the AC quantities in the filtered current are still non-negligible. This will reduce the extraction accuracy of current harmonics.

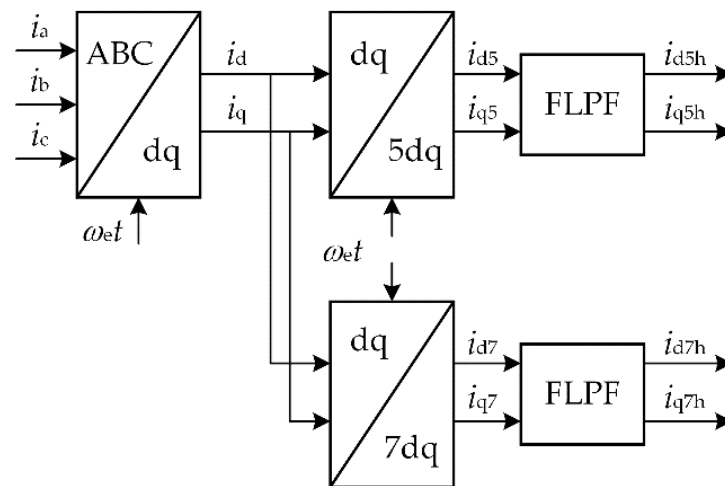


Figure 1. The block diagram of traditional method of current harmonic extraction.

In order to improve the extraction accuracy without increasing the complexity of the algorithm, the fundamental component is subtracted before the MSRFT of the dq axis currents in this paper. The fundamental component is considered as the dq axis currents reference value. As a result, the problem of high-amplitude alternating current under the 5th and 7th synchronous rotating frames can be avoided. Then, the extraction accuracy of current harmonics can be improved. The block diagram of the proposed method is shown in Figure 2.

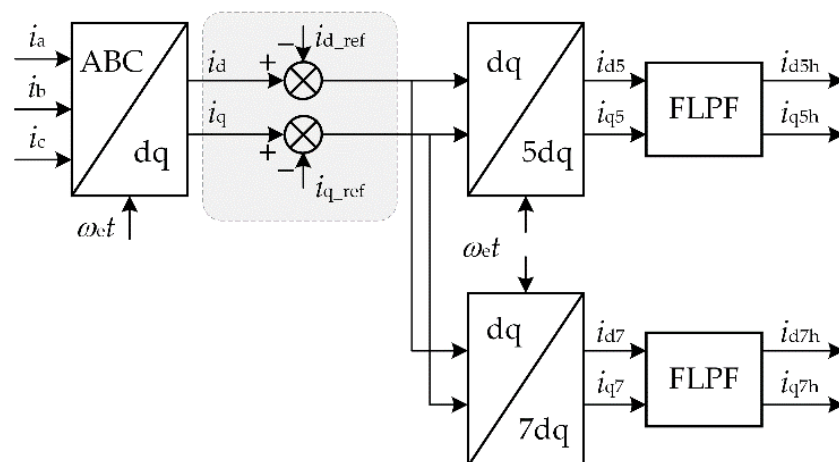


Figure 2. The block diagram of proposed method of current harmonic extraction.

3.2. Traditional Current Harmonic Controller

The current harmonic controller is the key to make the current harmonic components follow the current harmonic reference value. Traditional PI-based current harmonic controller generally makes the difference between the extracted 5th and 7th current harmonic components and the reference value 0, and then inputs the obtained values to the PI controllers to generate the harmonic compensation voltages. The harmonic compensation voltages are injected into the dq axis voltages through the inverse MSTFT. The block diagram of this method is shown in Figure 3. i_{d5h_ref} , i_{q5h_ref} , i_{d7h_ref} and i_{q7h_ref} represent the reference value of the 5th and 7th current harmonic dq axis components, respectively.

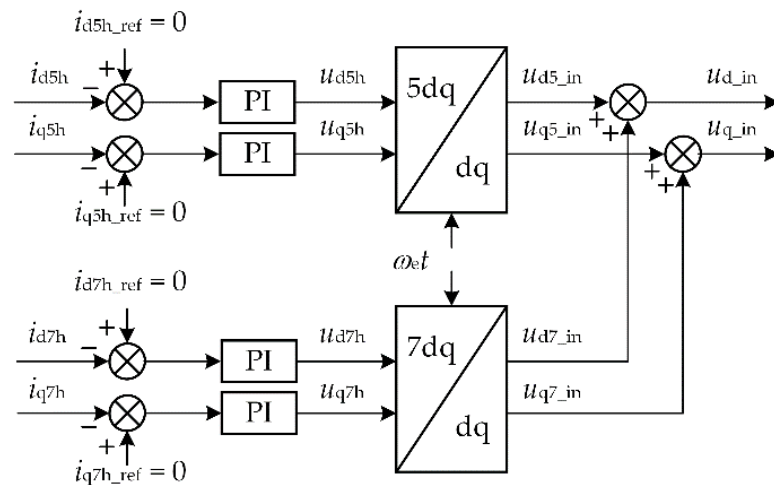


Figure 3. The block diagram of traditional current harmonic controller based on PI.

Where, the transformation matrices from the 5th and 7th synchronous rotating frames to the fundamental synchronous rotating frame are obtained by the inverse operation of Equations (7) and (9). The transformation matrices can be expressed as:

$$T_{dq5}^{dq} = (T_{dq5}^{dq})^{-1} = \begin{bmatrix} \cos 6\omega_e t & \sin 6\omega_e t \\ -\sin 6\omega_e t & \cos 6\omega_e t \end{bmatrix} \quad (13)$$

$$T_{dq7}^{dq} = (T_{dq7}^{dq})^{-1} = \begin{bmatrix} \cos 6\omega_e t & -\sin 6\omega_e t \\ \sin 6\omega_e t & \cos 6\omega_e t \end{bmatrix} \quad (14)$$

It can be seen from Figure 3 that this PI based current harmonic controller uses multiple PI, so the parameter tuning is complicated and the coupling effect between the dq axis is ignored. Which will affect the suppression effect of current harmonics. In order to avoid this problem, some scholars replace the PI controller with deadbeat predictive control (DPC). The control block diagram is shown in Figure 4.

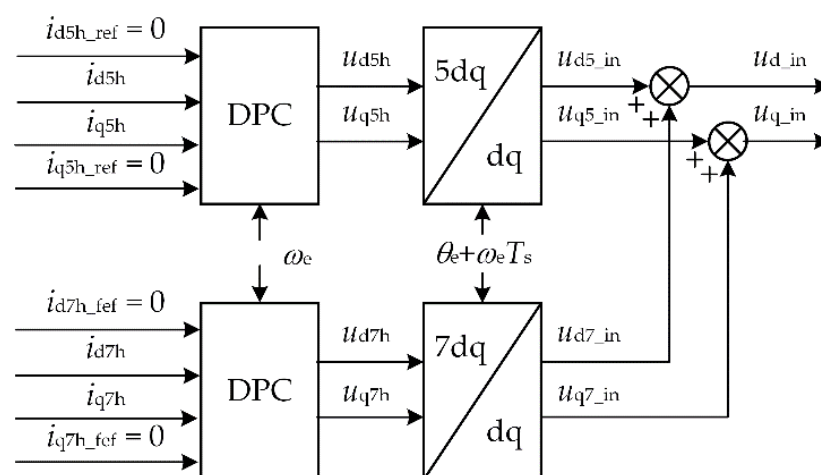


Figure 4. The block diagram of traditional current harmonic controller-based on DPC.

This strategy effectively avoids complex parameter tuning and is easier to implement digitally. However, this strategy depends on the motor parameters, and the model error caused by the rotor position variation within one control cycle cannot be ignored due to the higher electrical angular frequency of the motor in the 5th and 7th synchronous rotating frames. This will degrade the control performance of the current harmonic controller, and

lead to a static error between the current harmonic components and the reference value. Therefore, the current harmonics cannot be effectively suppressed.

3.3. Improved Current Harmonic Controller

3.3.1. Error Analysis of DPC

The model error analysis methods in the 5th and 7th synchronous rotating frame are the same. So, the traditional DPC model error in the 5th synchronous rotating frame is analyzed as an example in this section. In the 5th synchronous rotating frame, the DC voltage equation of IPMSM can be expressed as:

$$di_5/dt = A_5 i_5 + B u_5 + C_5 \quad (15)$$

$$\text{where, } i_5 = \begin{bmatrix} i_{d5h} \\ i_{q5h} \end{bmatrix}; u_5 = \begin{bmatrix} u_{d5h} \\ u_{q5h} \end{bmatrix}; A_5 = \begin{bmatrix} -R/L_d & -5\omega_e L_q/L_d \\ 5\omega_e L_d/L_q & -R/L_q \end{bmatrix}; B = \begin{bmatrix} 1/L_d & 0 \\ 0 & 1/L_q \end{bmatrix}; \\ C_5 = \begin{bmatrix} 0 \\ 5\omega_e \psi_{f5}/L_q \end{bmatrix}.$$

The control period of the system is T_s , and the motor speed is considered to be a constant value. Solving Equation (15), the solution in the k th control cycle can be expressed as:

$$\begin{cases} i_5(t) = i_{5m}(t) + i_{5n}(t) \\ i_{5m}(t) = e^{(t-kT_s)A_5} \cdot i_5(kT_s) + [e^{(t-kT_s)A_5} - I] A_5^{-1} C_5 \\ i_{5n}(t) = \int_{kT_s}^t e^{(t-\tau)A_5} \cdot B u_5(\tau) d\tau \end{cases} \quad (16)$$

where, i_{5m} is the free component matrix independent of the 5th harmonic compensation voltage matrix u_5 ; i_{5n} is the forced component matrix depend on the 5th harmonic compensation voltage matrix u_5 ; I is the unit matrix; and τ is the time constant.

In the k th control cycle, the harmonic compensation voltage matrix u can be expressed as:

$$\begin{cases} u_5(t) = F_5(t) u_5(kT_s) \\ F_5(t) = \begin{bmatrix} \cos 5\omega_e(t - kT_s) & -\sin 5\omega_e(t - kT_s) \\ \sin 5\omega_e(t - kT_s) & \cos 5\omega_e(t - kT_s) \end{bmatrix} \end{cases} \quad (17)$$

From Equations (16) and (17), it can be seen that the solution of Equation (15) is more complicated, which is not convenient for practical application. Since the matrix A_5 contains ω_e , the traditional DPC considers the value of $\omega_e T_s$ to be small, and (16) can be linearized. It can be considered that $e^{(t-kT_s)A} \approx (t - kT_s)A + I$ and $5\omega_e(t - kT_s) \approx 0$. The discrete form of (16) at the time of $(k + 1)T_s$ can be expressed as:

$$\begin{cases} i_5^{k+1} = i_{5m}^{k+1} + i_{5n}^{k+1} \\ i_{5m}^{k+1} = (A_5 T_s + I) i_5^k + C_5 T_s \\ i_{5n}^{k+1} = T_s B u_5^k \end{cases} \quad (18)$$

From Equation (18), the harmonic compensation voltage output by traditional DPC at the time of $(k + 1)T_s$ can be expressed as:

$$\begin{cases} u_{d5h}^{k+1} = R i_{d5h}^{k+1} + (L_d/T_s) (i_{d5h_ref} - i_{d5h}^{k+1}) + 5\omega_e \psi_{q5h}^{k+1} \\ u_{q5h}^{k+1} = R i_{q5h}^{k+1} + (L_q/T_s) (i_{q5h_ref} - i_{q5h}^{k+1}) - 5\omega_e \psi_{d5h}^{k+1} \end{cases} \quad (19)$$

where, $\psi_{d5h}^{k+1} = L_d i_{d5h}^{k+1} + \psi_{f5}$; $\psi_{q5h}^{k+1} = L_q i_{q5h}^{k+1}$.

However, in the 5th synchronous rotating frame, the electrical angular frequency $5\omega_e$ of the motor is very large, and $e^{(t-kT_s)A^5} \approx (t - kT_s)A^5 + I$ and $5\omega_e(t - kT_s) \approx 0$ are incorrect. Additionally, with the increase of the motor speed, the model error of the traditional DPC will gradually increase, which will cause the current harmonic components i_{d5h} and i_{q5h} to be unable to accurately track the given value.

3.3.2. Improved Deadbeat Predictive Control (IDPC)

In order to achieve accurate control of current harmonic components, an IDPC model suitable for the 5th and 7th synchronous rotating frames is proposed. Same as Section 3.1.1, the model error in the 5th synchronous rotating frame is analyzed as an example.

Since the resistive voltage drop of the IPMSM is small, the resistive voltage drop is ignored to simplify the calculation. The solution of the current harmonic free component matrix in Equation (16) can be expressed as:

$$\mathbf{i}_{5m}^{k+1} = \mathbf{A}_{m5} \mathbf{i}_5^k + \mathbf{C}_{m5} \quad (20)$$

$$\text{where, } \mathbf{A}_{m5} = \begin{bmatrix} \cos 5\omega_e T_s & -(L_q/L_d) \sin 5\omega_e T_s \\ (L_d/L_q) \sin 5\omega_e T_s & \cos 5\omega_e T_s \end{bmatrix}; \mathbf{C}_{m5} = \psi_{f5} \begin{bmatrix} [\cos(5\omega_e T_s) - 1]/L_d \\ \sin(5\omega_e T_s)/L_q \end{bmatrix}.$$

Due to the delay of the controller, the harmonic compensation voltage obtained in the k th control cycle acts on the motor side in the $(k + 1)$ th control cycle. If the angular frequency of the motor is too large, the angle error caused by the change of the rotor in one cycle will make the calculation of harmonic compensation voltage deviate. Thereby, the control effect of the current harmonics will be reduced. Considering the rotor variation in one cycle, the calculation formula of the current harmonic forced component matrix can be expressed as:

$$\mathbf{i}_{5n}^{k+1} = T_s \mathbf{B} \mathbf{F}_{50} \mathbf{u}_5^k \quad (21)$$

$$\text{where, } \mathbf{F}_{50} = \begin{bmatrix} \cos 5\omega_e T_s & -\sin 5\omega_e T_s \\ \sin 5\omega_e T_s & \cos 5\omega_e T_s \end{bmatrix}.$$

From Equations (20) and (21), the discrete form of Equation (16) at the time of $(k + 1)T_s$ can be expressed as:

$$\begin{cases} \mathbf{i}_5^{k+1} = \mathbf{i}_{5m}^{k+1} + \mathbf{i}_{5n}^{k+1} \\ \mathbf{i}_{5m}^{k+1} = \mathbf{A}_{m5} \mathbf{i}_5^k + \mathbf{C}_{m5} \\ \mathbf{i}_{5n}^{k+1} = T_s \mathbf{B} \mathbf{F}_{50} \mathbf{u}_5^k \end{cases} \quad (22)$$

From Equation (22), the harmonic compensation voltage output by IDPC at the time of $(k + 1)T_s$ can be expressed as:

$$\begin{cases} u_{dh5}^{k+1} = u_{dm5}^{k+1} \cos 5\omega_e T_s + u_{qm5}^{k+1} \sin 5\omega_e T_s \\ u_{qh5}^{k+1} = -u_{dm5}^{k+1} \sin 5\omega_e T_s + u_{qm5}^{k+1} \cos 5\omega_e T_s \\ u_{dm5}^{k+1} = (\psi_{dh5}^{\text{ref}} - \psi_{dh5}^{k+1} \cos 5\omega_e T_s + \psi_{qh5}^{k+1} \sin 5\omega_e T_s) / T_s \\ u_{qm5}^{k+1} = (\psi_{qh5}^{\text{ref}} - \psi_{dh5}^{k+1} \sin 5\omega_e T_s - \psi_{qh5}^{k+1} \cos 5\omega_e T_s) / T_s \\ \psi_{dh5}^{\text{ref}} = L_d i_{dh5_ref} + \psi_{f5} \\ \psi_{qh5}^{\text{ref}} = L_q i_{qh5_ref} \\ \psi_{dh5}^{k+1} = L_d i_{dh5}^{k+1} + \psi_{f5} \\ \psi_{qh5}^{k+1} = L_q i_{qh5}^{k+1} \end{cases} \quad (23)$$

Equations (22) and (23) are the IDPC mathematical model in the 5th synchronous rotating frame. Some factors such as the resistance voltage drop, non-ideal characteristics of inverter will cause the static error between the current harmonic component and the given value. Hence, current compensation is required necessarily. As an example, the current compensation scheme in the k th cycle is as follows:

Firstly, calculate the difference between the sampled actual values of the dq axis current harmonic components ($i_{d5h_rel}^k$ and $i_{q5h_rel}^k$) and the predicted values of the current harmonic components ($i_{d5h_pre0}^k$ and $i_{q5h_pre0}^k$) calculated by Equation (22) in the $(k - 1)$ th cycle. This difference comes from model error and parameter mismatch, which is input into FLPF to obtain compensation value (i_{d5hc} and i_{q5hc}). Then, the predicted value calculated by Equation (22) in the k th cycle is added to the compensation value as the final predicted value. The error of the predicted value at the time of $(k + 1)T_s$ (Δi_{d5h}^{k+1} and Δi_{q5h}^{k+1}) can be expressed as [20]:

$$\begin{cases} \Delta i_{d5h}^{k+1} = i_{d5h}^{k+1} - i_{d5h_pre0}^{k+1} - i_{d5hc} \\ \Delta i_{q5h}^{k+1} = i_{q5h}^{k+1} - i_{q5h_pre0}^{k+1} - i_{q5hc} \end{cases} \quad (24)$$

When the FLPF is stable, the error of the predicted value tends to 0. The tracking static error at this time is caused by the calculation of Equation (23), and its value can be expressed as:

$$\begin{cases} i_{d5h_ref}^k - i_{d5h}^k = i_{d5h}^k - i_{d5h_pre0}^k = i_{d5hc} \\ i_{q5h_ref}^k - i_{q5h}^k = i_{q5h}^k - i_{q5h_pre0}^k = i_{q5hc} \end{cases} \quad (25)$$

Finally, the value obtained by subtracting the compensation value from the given value of the current harmonic component is used as the given value in Equation (23), and the static error can be eliminated. In the k th control cycle, the IDPC block diagram in the 5th synchronous rotating frame including the current compensation scheme is shown in Figure 5.

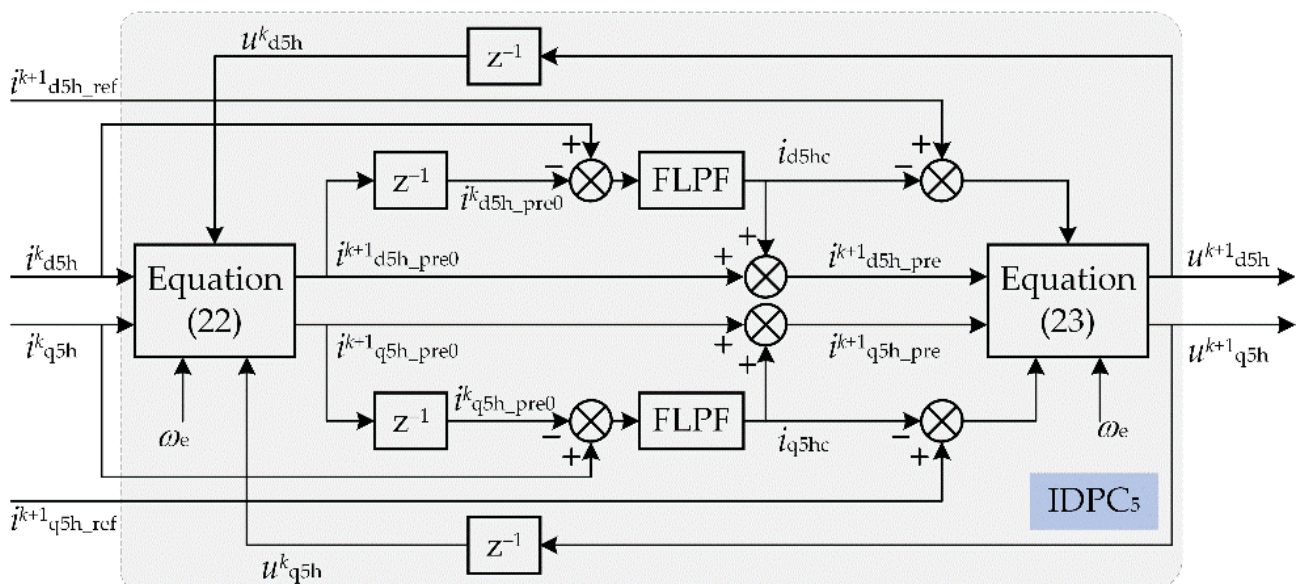


Figure 5. The block diagram of IDPC of the k th control cycle in the 5th synchronous rotating frame.

Similarly, in the k th control cycle, the IDPC mathematical model in the 7th synchronous rotating frame can be expressed as Equations (26) and (27), and the IDPC block diagram in the 7th synchronous rotating frame including the current compensation scheme is shown in Figure 6.

$$\begin{cases} i_7^{k+1} = i_{7m}^{k+1} + i_{7n}^{k+1} \\ i_{7m}^{k+1} = A_{m7} i_7^k + C_{m7} \\ i_{7n}^{k+1} = T_s B F_{70} u_7^k \end{cases} \quad (26)$$

where, i_{7m} is the free component matrix independent of the 7th harmonic compensation voltage matrix u_7 ; i_{7n} is the forced component matrix depend on the 7th harmonic compensation voltage

$$\text{matrix } u_7; i_7 = \begin{bmatrix} i_{d7h} \\ i_{q7h} \end{bmatrix}; u_7 = \begin{bmatrix} u_{d7h} \\ u_{q7h} \end{bmatrix}; A_{m7} = \begin{bmatrix} \cos 7\omega_e T_s & (L_q/L_d) \sin 7\omega_e T_s \\ -(L_d/L_q) \sin 7\omega_e T_s & \cos 7\omega_e T_s \end{bmatrix};$$

$$C_{m7} = \psi_{f7} \begin{bmatrix} [\cos(7\omega_e T_s) - 1]/L_d \\ -\sin(7\omega_e T_s)/L_q \end{bmatrix}; F_{50} = \begin{bmatrix} \cos 7\omega_e T_s & \sin 7\omega_e T_s \\ -\sin 7\omega_e T_s & \cos 7\omega_e T_s \end{bmatrix}.$$

$$\begin{cases} u_{dh7}^{k+1} = u_{dm7}^{k+1} \cos 7\omega_e T_s - u_{qm7}^{k+1} \sin 7\omega_e T_s \\ u_{qh7}^{k+1} = u_{dm7}^{k+1} \sin 7\omega_e T_s + u_{qm7}^{k+1} \cos 7\omega_e T_s \\ u_{dm7}^{k+1} = (\psi_{dh7}^{\text{ref}} - \psi_{dh7}^{k+1} \cos 7\omega_e T_s - \psi_{qh7}^{k+1} \sin 7\omega_e T_s) / T_s \\ u_{qm7}^{k+1} = (\psi_{dh7}^{\text{ref}} + \psi_{dh7}^{k+1} \sin 7\omega_e T_s - \psi_{qh7}^{k+1} \cos 7\omega_e T_s) / T_s \\ \psi_{dh7}^{\text{ref}} = L_d i_{dh7_ref} + \psi_{f7} \\ \psi_{qh7}^{\text{ref}} = L_q i_{qh7_ref} \\ \psi_{dh7}^{k+1} = L_d i_{dh7}^{k+1} + \psi_{f7} \\ \psi_{qh7}^{k+1} = L_q i_{qh7}^{k+1} \end{cases} \quad (27)$$

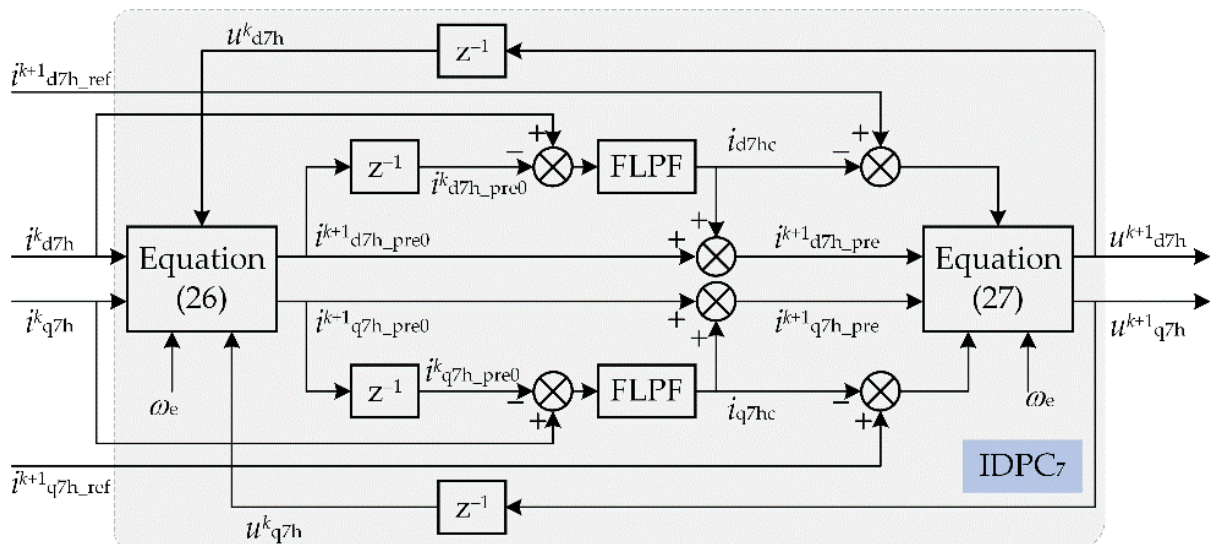


Figure 6. The block diagram of IDPC of the k th control cycle in the 7th synchronous rotating frame.

3.3.3. Improved Current Harmonic Controller

It can be seen from Figures 5 and 6 that when the filter is stable, the current harmonic component will track the given value without static error. If the given value is set to 0, the current harmonic suppression can be achieved. The block diagram of the current harmonic controller based on IDPC is shown in Figure 7.

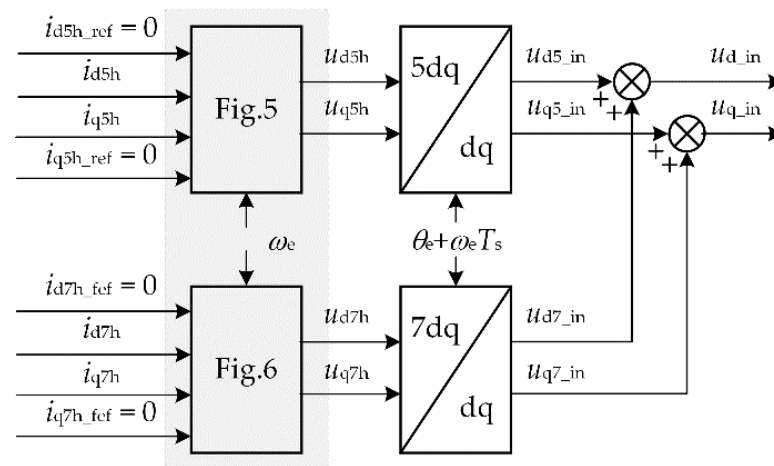


Figure 7. The block diagram of current harmonic controller based on IDPC.

3.4. Proposed Current Harmonic Suppression Strategy

The control block diagram of the proposed current harmonic suppression strategy is shown in Figure 8. Firstly, the sample values of three-phase currents are input to the current harmonic extraction module (Figure 2) to extract the current harmonic components (i_{d5h} , i_{q5h} , i_{d7h} and i_{q7h}). Secondly, the extracted current harmonic components are input into the current harmonic controller (Figure 7), which outputs the reference harmonic voltage compensation components (u_{d_in} and u_{q_in}). Finally, the u_{d_in} and u_{q_in} are injected into the dq axis voltages, respectively.

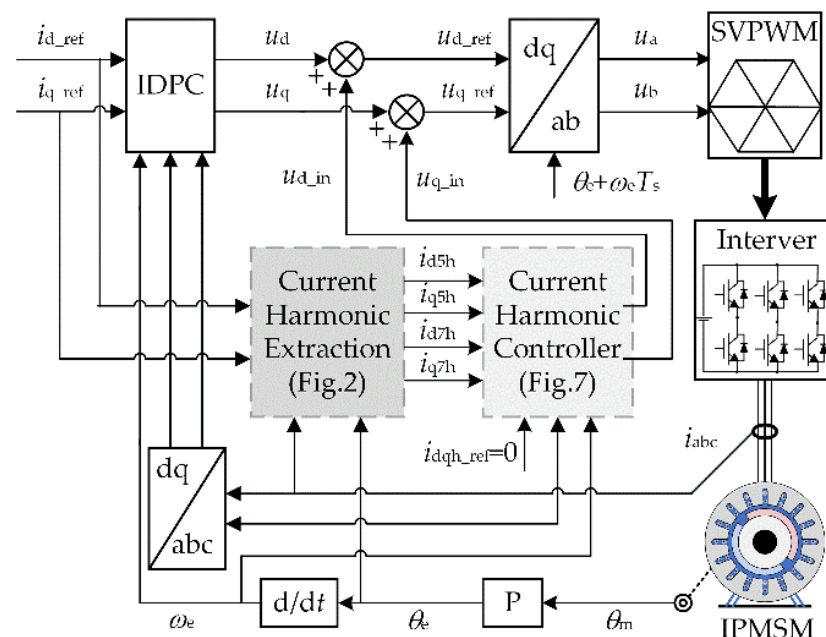


Figure 8. The block diagram of proposed current harmonic suppression strategy.

4. Simulation and Experimental Results

4.1. Simulation Results of IDPC Method

In order to verify the validity of the IDPC model, the IDPC model under the 5th synchronous rotating frame is taken as an example. Comparing the model errors of DPC and IDPC when the motor runs at different speeds by simulation. The model error of DPC is obtained by subtracting Equation (18) from (16), and the model error of IDPC is obtained by subtracting Equation (22) from (16). The motor parameters are shown in Table 1, and the sampling period is 100 μ s.

Table 1. The parameters of IPMSM.

Parameters	Symbol	Value
Rated voltage	U_N	320 V
Rated current	I_N	180 A
Rated speed	n	3000 rpm
Rated torque	T_N	72 Nm
Pole pairs	p	4
Stator resistance	R	0.03 Ω
D-axis inductance	L_d	0.1049 mH
Q-axis inductance	L_q	0.3453 mH
PM fundamental flux linkage	ψ_f	0.038749 Wb
PM 5th harmonic flux linkage	ψ_{f5}	0.0003771 Wb
PM 7th harmonic flux linkage	ψ_{f7}	0.0004135 Wb

Firstly, the error of the current harmonic free component (independent of the harmonic compensation voltage) is verified. Take the range of the 5th current harmonic dq axis components as ± 10 A. When the motor runs at 100 rpm (low speed), 1000 rpm (medium speed) and 2500 rpm (high speed), respectively, the errors of the free components in Equations (18) and (22) relative to the free components in Equation (16) are shown in Figure 9. In the figure, Δi_{5md_TRA} and Δi_{5mq_TRA} represent the dq axis free component error of DPC, and Δi_{5md_PRO} and Δi_{5mq_PRO} represent the dq axis free component error of IDPC.

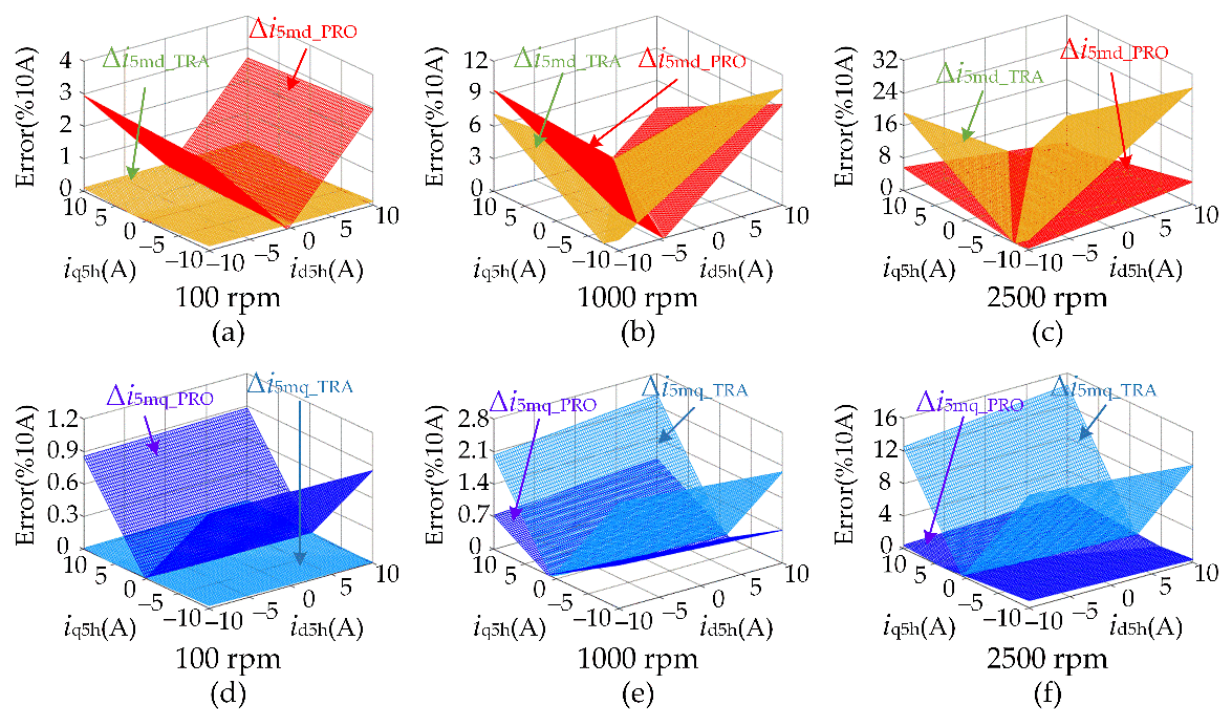


Figure 9. Errors of free components of DPC model and IDPC model at different motor speeds. (a) Free component of d-axis current harmonic at 100 rpm; (b) free component of d-axis current harmonic at 1000 rpm; (c) free component of d-axis current harmonic at 2500 rpm; (d) free component of q-axis current harmonic at 100 rpm; (e) free component of q-axis current harmonic at 1000 rpm; and (f) free component of q-axis current harmonic at 2500 rpm.

It can be seen from Figure 9 that there are some current combinations at different speeds which make the error of the free component of the IDPC model larger than that of the DPC model. This phenomenon is caused by ignoring the resistive voltage drop when modeling, which further shows the necessity of current compensation. From Figure 9a–c, the errors of the d-axis current harmonic free component of the IDPC model increases a

little with rotating speed increasing, while the errors of the DPC model increases largely. From Figure 9d–f, the errors of the q-axis current harmonic free component of the IDPC model are less than 1%, while the errors of the DPC model are more than 1% and increases with rotating speed increasing. Therefore, the error of the free component of the IDPC model is smaller, and the model is established more accurately.

Secondly, the error of the current harmonic forced component (dependent of the harmonic compensation voltage) is verified. Take the range of the 5th harmonic compensation voltage dq axis components is set as ± 10 V. When the motor runs at 100 rpm, 1000 rpm and 2500 rpm, respectively, the error of the current harmonic forced component in Equations (18) and (22) relative to the forced components in Equation (16) are shown in Figure 10. In the figure, Δi_{5nd_TRA} and Δi_{5nq_TRA} represent the dq axis forced component error of DPC, and Δi_{5nd_PRO} and Δi_{5nq_PRO} represent the dq axis force component error of IDPC.

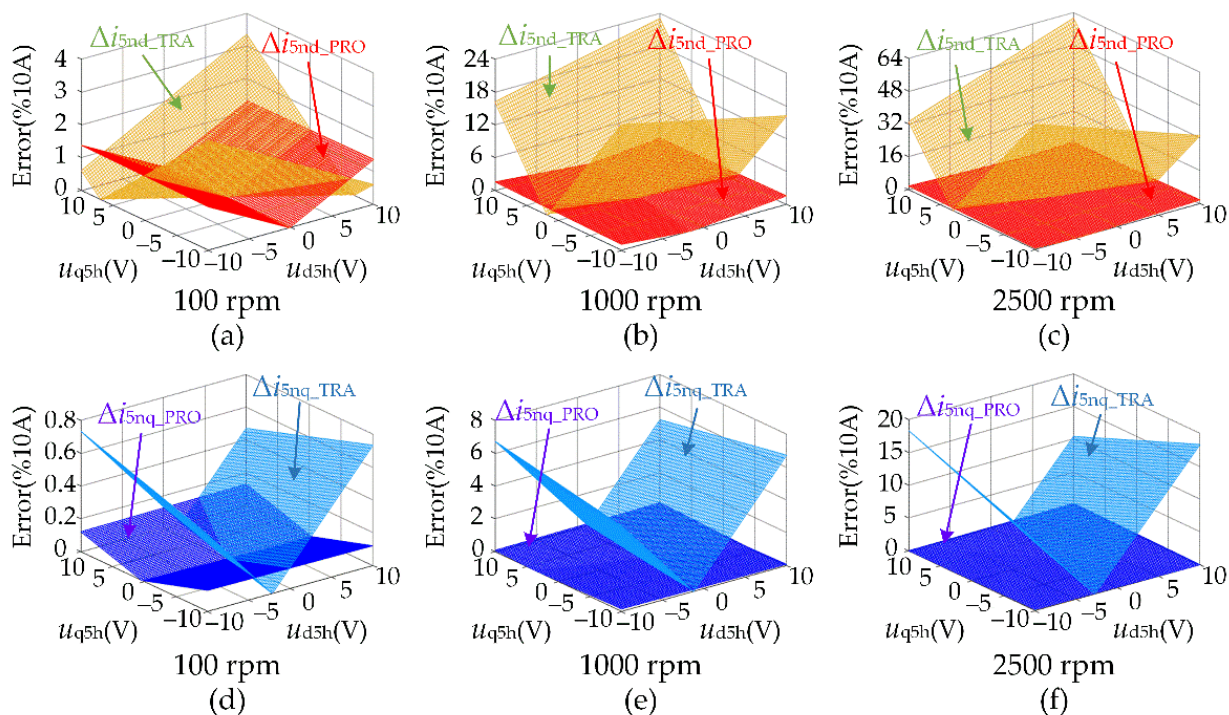


Figure 10. Errors of forced components of DPC model and IDPC model at different motor speeds. (a) Forced component of d-axis current harmonic at 100 rpm; (b) forced component of d-axis current harmonic at 1000 rpm; (c) forced component of d-axis current harmonic at 2500 rpm; (d) forced component of q-axis current harmonic at 100 rpm; (e) forced component of q-axis current harmonic at 1000 rpm; and (f) forced component of q-axis current harmonic at 2500 rpm.

It can be seen from Figure 10 that the errors of the current harmonic forced component of the IDPC model are less than 1.5%, while the errors of the DPC model are more than 1% and increases with rotating speed increasing. The results fully demonstrate the effect of rotor position changes within a control cycle and illustrate the importance of considering rotor position changes in modeling.

From above, compared with the DPC model, the current harmonic components can better track the reference current when the IDPC model is used. Therefore, the IDPC model is more accurate than the DPC model and is more suitable for the current harmonic suppression strategy.

4.2. Experimental Verification of the Proposed Strategy

In order to verify the feasibility and effectiveness of the proposed method, the experimental system shown in Figure 11 was built. The parameters of IPMSM are shown in Table 1. In the experimental system, the control unit adopts TMS320F28335. The sampling

frequency of the control system is 10 kHz, the control period is 100 μ s, and the dead time is set to 2.6 μ s. The load is provided by a dynamometer.

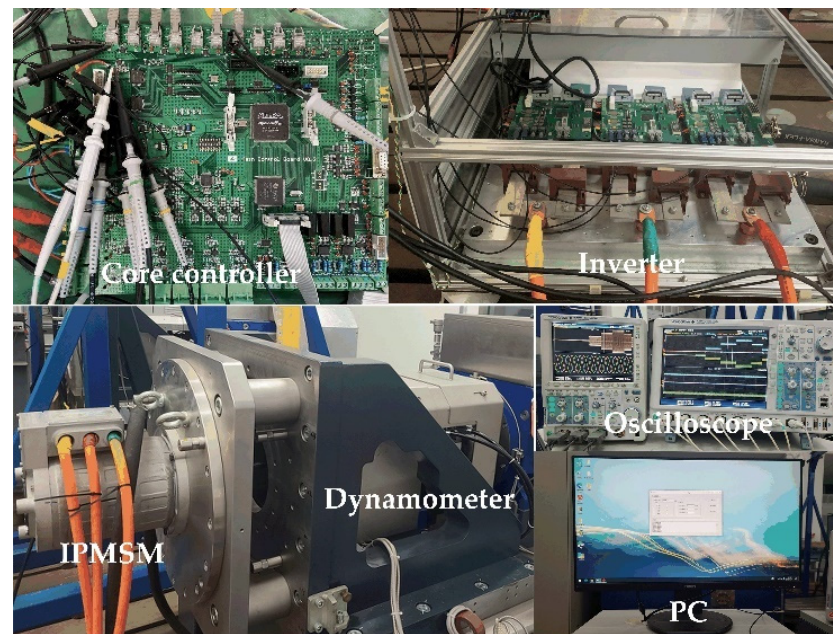


Figure 11. Diagram of experimental system.

4.2.1. Experimental Results of the Proposed Harmonic Extraction Method

When the motor speeds are 100 rpm, 1000 rpm and 2500 rpm, respectively, and the load torque suddenly changes from 0 Nm to 30 Nm, the waveforms of the 5th and 7th current harmonic components obtained by the traditional extraction strategy (Figure 1) and the proposed extraction strategy (Figure 2) are shown in Figures 12 and 13. The cutoff frequency of FLPF is 2 Hz. The fundamental current amplitude is 115 A when the load torque is 30 Nm.

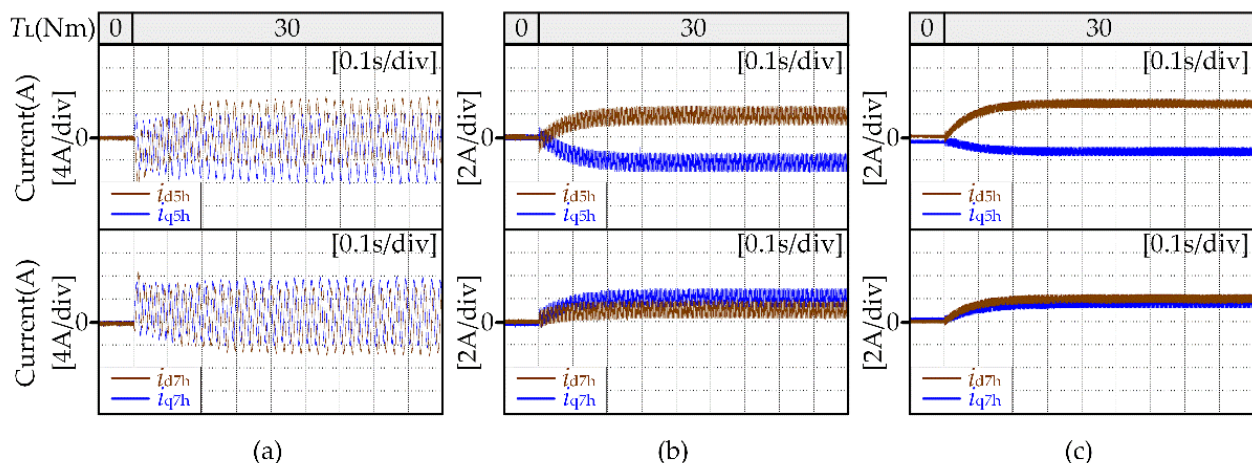


Figure 12. The 5th and 7th current harmonic components extracted by the traditional method when the load torque is 30 Nm. (a) 100 rpm; (b) 1000 rpm; and (c) 2500 rpm.

It can be seen from Figure 12 that the current harmonics extracted by the traditional method contain high-amplitude AC quantity, and the lower the motor speed, the higher the AC amplitude. This is because the high-amplitude fundamental current is expressed as a high-amplitude AC quantity with a frequency of 6 times in the 5th and 7th synchronous rotating frame, and the attenuation ability of the filter to the signal increases as the signal

frequency increases. The amplitude of the AC quantity in the filtered current cannot be ignored since the FLPF cannot attenuate the signal to zero.

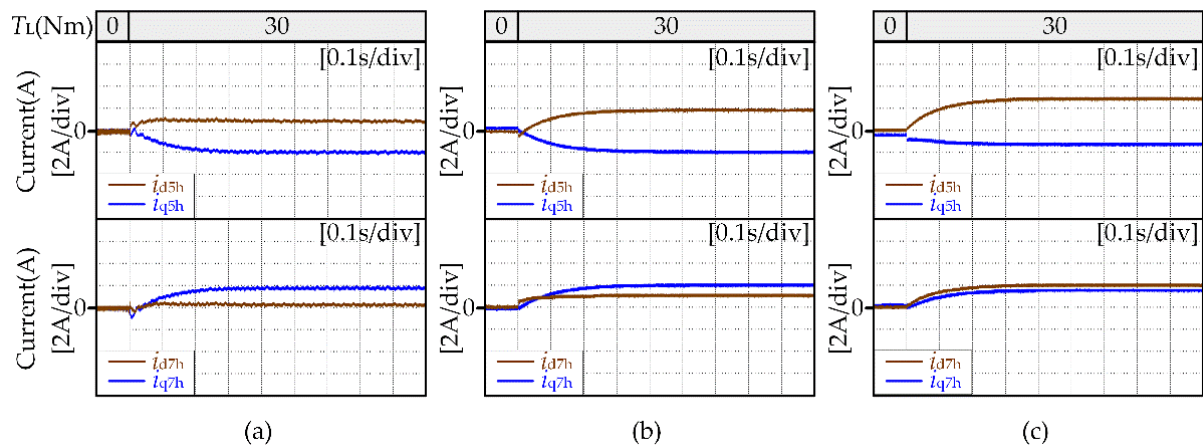


Figure 13. The 5th and 7th current harmonic components extracted by the proposed method when the load torque is 30 Nm. (a) 100 rpm; (b) 1000 rpm; and (c) 2500 rpm.

It can be seen from Figure 13 that the amplitude of the AC quantity contained in the current harmonic components extracted by the proposed method is small. This is because the proposed method eliminates the AC quantity with a frequency of 6 times in the current before filtering, which fundamentally solves the problem of high-amplitude AC quantity in the current after filtering. Therefore, the proposed method has higher current harmonic extraction accuracy.

4.2.2. Experimental Results of the Proposed Current Harmonic Suppression Strategy

When the motor speeds are 100 rpm, 1000 rpm, and 2500 rpm, respectively, and the load torque suddenly changes from 0 Nm to 20 Nm, then to 40 Nm and finally to 60 Nm. The waveforms of the 5th and 7th current harmonic components without applying the harmonic suppression strategy and applying the proposed current strategy (Figure 8) are shown in Figures 14 and 15. The cutoff frequency of FLPF in the current harmonic extraction strategy is 2 Hz, and the cutoff frequency of FLPF in IDPC is 25 Hz.

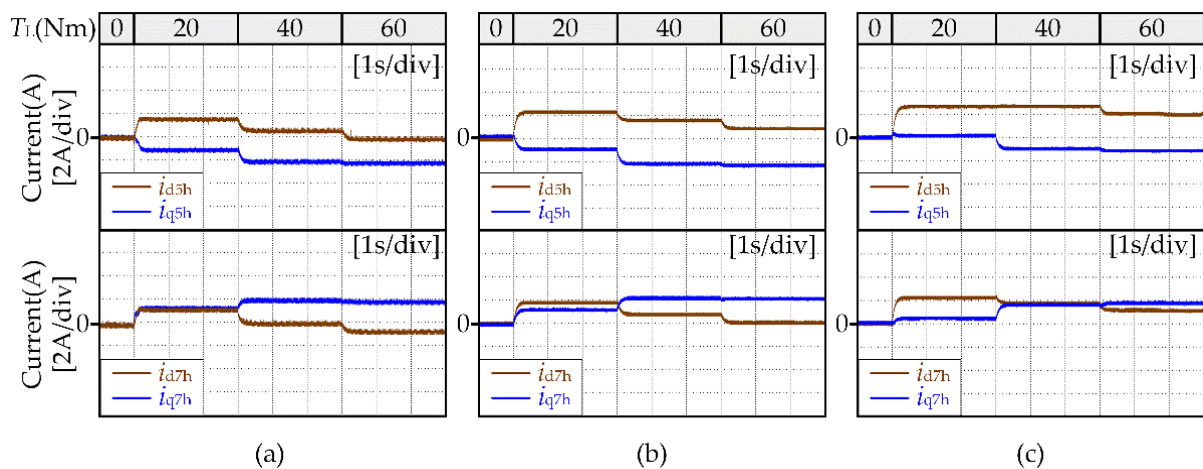


Figure 14. Waveforms of 5th and 7th current harmonic components without current harmonic suppression strategy applied. (a) 100 rpm; (b) 1000 rpm; and (c) 2500 rpm.

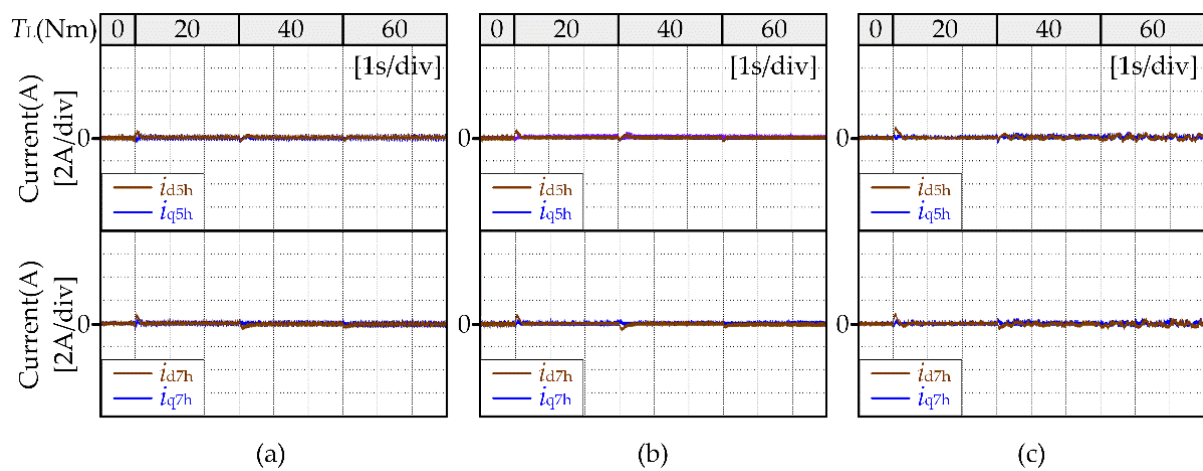


Figure 15. Waveforms of 5th and 7th current harmonic components with proposed current harmonic suppression strategy applied. (a) 100 rpm; (b) 1000 rpm; and (c) 2500 rpm.

It can be seen from Figure 14 that the 5th and 7th current harmonic components exist in the motor stator three-phase current at different speeds and different load torques without applying the current harmonic suppression strategy. It can be seen from Figure 15 that after applying the proposed current harmonic suppression strategy, the amplitudes of the 5th and 7th current harmonic components in the three-phase current are almost zero. Therefore, the proposed IDPC-based current harmonic controller can effectively control the current harmonic components to track the reference current value 0.

When the motor speeds are 100 rpm, 1000 rpm, and 2500 rpm, respectively, and the load torque is 40 Nm. The steady-state waveforms of phase A current and its Fast Fourier Transform (FFT) analysis results without applying the harmonic suppression strategy and applying the proposed current strategy are shown in Figures 16 and 17.

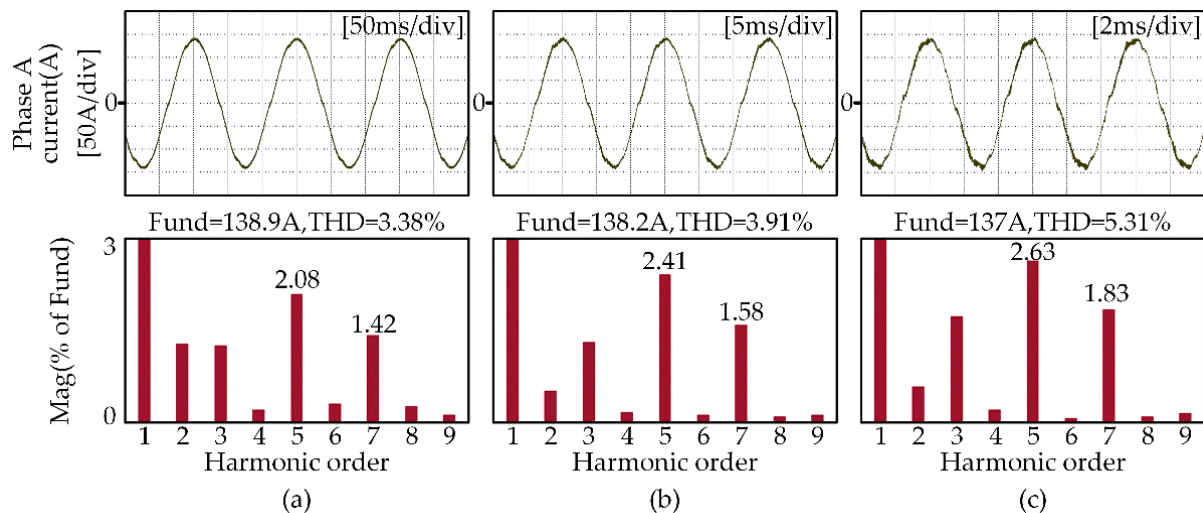


Figure 16. Waveforms of phase A current and its FFT analysis results without current harmonic suppression strategy applied. (a) 100 rpm; (b) 1000 rpm; and (c) 2500 rpm.

It can be seen from Figures 16a and 17a that when the motor runs at 100 rpm, the amplitude of the 5th and 7th current harmonic components decreases from 2.08% and 1.42% of the fundamental amplitude to 0.14% and 0.21%, and the Total Harmonic Distortion (THD) value decreases from 3.38% to 2.08%. It can be seen from Figures 16b and 17b that when the motor runs at 1000 rpm, the amplitude of the 5th and 7th current harmonic components decreases from 2.41% and 1.58% of the fundamental amplitude to 0.24% and 0.18%, and the THD value decreases from 3.91% to 2.86%. It can be seen from Figures 16c and 17c

that when the motor runs at 2500 rpm, the amplitude of the 5th and 7th current harmonic components decreases from 2.63% and 1.83% of the fundamental amplitude to 0.36% and 0.28%, and the THD value decreases from 5.31% to 4.27%.

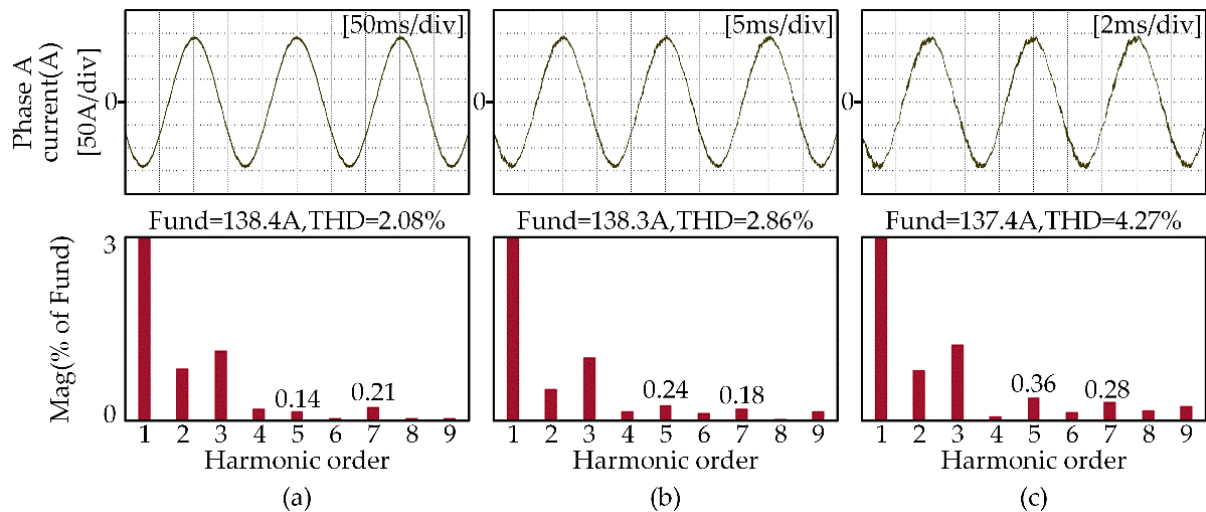


Figure 17. Waveforms of phase A current and its FFT analysis results with proposed current harmonic suppression strategy applied. (a) 100 rpm; (b) 1000 rpm; and (c) 2500 rpm.

From above, the proposed strategies can effectively suppress current harmonics when the motor runs at low speed, medium speed and high speed.

4.2.3. Robustness Experimental of the Proposed Current Harmonic Suppression Strategy

Since some control algorithms in the proposed strategy use motor parameters (L_d , L_q , ψ_{f5} and ψ_{f7}), it is necessary to verify the robustness of the proposed strategy to changes in motor parameters. When the motor speeds are 100 rpm, 1000 rpm, and 2500 rpm, respectively, and the load torque is 40 Nm, the motor parameters used in the controller are set to 0.8 times and 1.2 times the nominal value at the same time. The steady-state waveforms of the 5th and 7th current harmonic components when the parameter mismatch is 0.8 times are shown in Figure 18, and the steady-state waveforms of the 5th and 7th current harmonic components when the parameter mismatch is 1.2 times are shown in Figure 19.

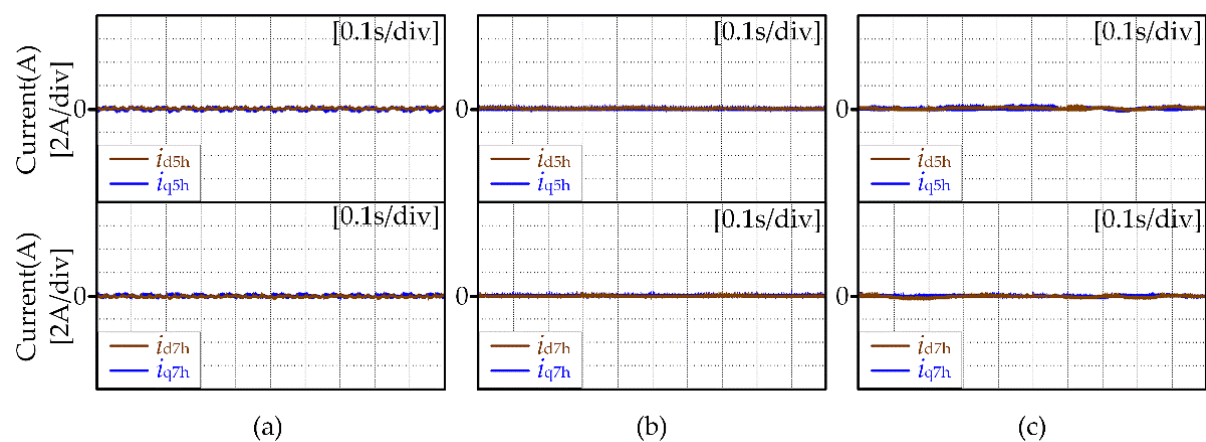


Figure 18. The steady-state waveform diagram of the 5th and 7th current harmonic components when the motor parameters change by 0.8 times. (a) 100 rpm; (b) 1000 rpm; and (c) 2500 rpm.

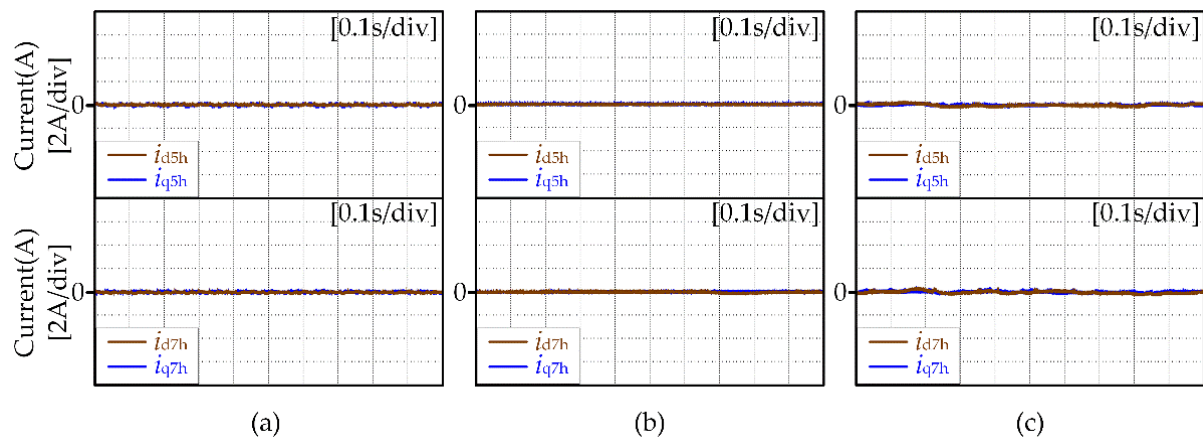


Figure 19. The steady-state waveform diagram of the 5th and 7th current harmonic components when the motor parameters change by 1.2 times. (a) 100 rpm; (b) 1000 rpm; and (c) 2500 rpm.

It can be seen from Figures 18 and 19 that the proposed strategy can still control the amplitude of the 5th and 7th current harmonic components to zero when the motor parameters used in the controller change by 0.8 times or 1.2 times at the same time. This is because the current compensation scheme in IDPC eliminates the current steady-state error caused by motor parameter changes. From above, the proposed strategy has strong robustness to motor parameter changes.

5. Conclusions

Two aspects of current harmonic extraction method and current harmonic controller of IPMSM are studied in this paper. The work content is mainly reflected in the following aspects:

1. The existing current harmonic extraction method based on MSRFT is improved by reconstructing the input current of the filter. The improved method has a simple structure and can achieve accurate extraction of current harmonics.
2. The reason why the DPC based current harmonic controller is difficult to effectively control the current harmonic components is analyzed when the motor speed is high. Additionally, the IDPC based current harmonic controller is proposed by improving the solution method of PMSM state equation and considering the effect of rotor position changes in one control cycle and applying the method of current static error elimination. The proposed controller can effectively control the current harmonic components when the motor speed is high and has strong robustness to motor parameter changes.
3. IDPC-based current harmonic suppression strategy is proposed by combining the improved current harmonic extraction method and the IDPC-based current harmonic controller. The experimental results show that the proposed strategy can effectively suppress the 5th and 7th current harmonics when the motor runs at low speed, medium speed and high speed and the controller parameters are mismatched with the motor parameters.

Only the suppression of the 5th and 7th current harmonics is described in this paper, but the proposed method is also applicable to suppress current harmonics of other frequencies.

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