Retraction

Retracted: Fault Diagnosis Method of Rotor Magnetic Field Local Demagnetization in Permanent Magnet Synchronous Motor Model Predictive Current Control System

Security and Communication Networks

This article has been retracted by Hindawi, as publisher, following an investigation undertaken by the publisher [1]. This investigation has uncovered evidence of systematic manipulation of the publication and peer-review process. We cannot, therefore, vouch for the reliability or integrity of this article.

Please note that this notice is intended solely to alert readers that the peer-review process of this article has been compromised.

Wiley and Hindawi regret that the usual quality checks did not identify these issues before publication and have since put additional measures in place to safeguard research integrity.

We wish to credit our Research Integrity and Research Publishing teams and anonymous and named external researchers and research integrity experts for contributing to this investigation.

The corresponding author, as the representative of all authors, has been given the opportunity to register their agreement or disagreement to this retraction. We have kept a record of any response received.

References

[1] T. Chen and B. Chen, "Fault Diagnosis Method of Rotor Magnetic Field Local Demagnetization in Permanent Magnet Synchronous Motor Model Predictive Current Control System," *Security and Communication Networks*, vol. 2022, Article ID 9344484, 13 pages, 2022.

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Research Article

Fault Diagnosis Method of Rotor Magnetic Field Local Demagnetization in Permanent Magnet Synchronous Motor Model Predictive Current Control System

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In order to realize the reliable diagnosis of the rotor magnetic field local demagnetization fault of permanent magnet synchronous motor (PMSM) model predictive current control system, based on the establishment of the mathematical model of PMSM considering local demagnetization of rotor magnetic field and the simulation model of its model predictive current control system, a diagnosis method combining the adaptive signal extraction algorithm and Hilbert transform is proposed in this study. This method is first based on the adaptive signal extraction algorithm to extract the fault characteristic harmonics of rotor magnetic field local demagnetization fault in PMSM model predictive current control system under stationary and nonstationary operating conditions, and then, we use Hilbert transform to realize the time-frequency transformation of the extracted fault characteristic harmonics. Based on solving the problem that the weak fault characteristic signal near the fundamental wave component existing in the Hilbert–Huang transform is difficult to effectively decompose, the reliable diagnosis of the rotor magnetic field local demagnetization fault of the PMSM model predictive current control system is realized with the calculation amount less than Hilbert–Huang transform. The simulation and experimental results show that the proposed method is accurate and useful.

1. Introduction

Due to the fact that PMSM has the advantages of high-power density and achieving high-performance control easily, it has been widely used in electric vehicles, new energy power generation, and other fields. However, the above-mentioned fields are mostly limited by installation space, limited heat dissipation conditions, and complex motor operating conditions, it's easy to have a stronger armature reaction and high working temperature, resulting in local demagnetization fault or uniform demagnetization fault of PMSM rotor magnetic field, which affects the torque control accuracy and operational reliability of its drive system [1].

The PMSM rotor magnetic field demagnetization fault diagnosis mainly includes three basic methods: model-driven, data-driven, and high-frequency signal injection.

The artificial intelligence algorithm represented by the evolutionary algorithm is a typical representative of the model-driven method, because of its strong nonlinear processing ability, this kind of algorithm has certain advantages in the PMSM rotor magnetic field demagnetization fault diagnosis [2, 3]. However, how to reduce the amount of calculation is still an urgent problem to be solved. Another type of model-driven PMSM rotor magnetic field demagnetization fault diagnosis method is to use dynamic data processing technology to construct a rotor flux linkage observer and realize the rotor magnetic field demagnetization fault diagnosis according to the observation results. Algorithms such as luenberger observer [4], least squares method [5], extended Kalman filter [6, 7], and model reference adaptive algorithm [8] have been used to design PMSM rotor flux linkage observers, but these algorithms are

difficult to achieve a reasonable balance between the PMSM rotor flux linkage identification accuracy and identification speed due to the influence of factors such as the measurement noise, the change of motor parameters, the lack of rank of the identification model, and the difficulty in determining the adaptive rate to ensure the simultaneous convergence of multiple parameters [9]. The data-driven fault diagnosis method takes voltage, current, vibration, and noise as the analysis objects, and uses Fast Fourier Transform (FFT), Wavelet Transform (WT), and Hilbert-Huang Transform (HHT) to realize fault characteristics extraction, and then to achieve PMSM rotor magnetic field local demagnetization fault diagnosis. Fast Fourier transform, as a frequency domain analysis method that is easy to realize digitally, has been widely used in the field of PMSM rotor magnetic field local demagnetization fault diagnosis [10, 11], but it is a global transform, which is difficult to adapt to the nonstationary operating conditions of PMSM drive system. As time-frequency transform tools, wavelet transform and Hilbert–Huang transform can realize the analysis and extraction of fault characteristic signals in the nonstationary state [12, 13, 14]. However, the localization ability of wavelet transform depends on the localization property of the selected wavelet base in the time domain and frequency domain, and the wavelet basis function that takes into account the global optimum and the local optimum is difficult to reasonably determine. Hilbert–Huang transform consists of two parts: empirical mode decomposition (EMD) and Hilbert transform. It generates the required adaptive basis function through the signal itself and has better local adaptability and intuitive decomposition results when dealing with nonstationary signals. However, it is difficult to effectively decompose the weak fault characteristic signals near the fundamental wave. The high-frequency signal injection method [15, 16] takes the change of the PMSM magnetic circuit state before and after the rotor magnetic field demagnetization as the fault diagnosis criterion, which is suitable for the diagnosis and fault mode identification of both local and uniform rotor magnetic field demagnetization faults. It is necessary to superimpose the high-frequency current that varies with the degree of demagnetization, and the online diagnosis of the demagnetization fault of the rotor magnetic field cannot be realized. In a study [17], the fractal dimension was introduced into the PMSM rotor magnetic field local demagnetization fault diagnosis, and the Choi-Williams distribution in time-frequency analysis was used to extract the fault characteristic signal, the box dimension was calculated for it, and the rotor magnetic field local demagnetization fault of PMSM was determined according to the calculation results, but the calculation results of the box dimension are easily affected by the harmonics of the inverter, and the fault judgment threshold is difficult to reasonably determine.

Finite control set model predictive control (FCS-MPC) has the advantages of simple structure and good dynamic operation and is widely used in the PMSM drive and control system [18, 19, 20, 21]. FCS-MPC is a control algorithm that predicts the future state of the controlled system based on its current state and mathematical model [18]. The FCS-MPC

includes model predictive current control (MPCC) and model predictive torque control (MPTC), MPTC algorithm usually needs to determine the appropriate weight coefficient to construct the objective function [18, 19, 20], but the determination of the weight coefficient lacks effective theoretical support, and it relies on a large number of simulation and experimental data for continuous adjustment, the debugging process is complicated. In contrast, MPCC is simple to implement, the control variable can be directly measured, when constructing the objective function, only dimensionally consistent variables are included, so the weight coefficient design problem is avoided [21], and can realize high-performance PMSM drive system current control, which is beneficial to meet the requirements of PMSM drive system for wide speed regulation range, good dynamic characteristics, fast current response, and high-power density requirements [22].

There have been some studies on the diagnosis methods of PMSM rotor magnetic field local demagnetization fault based on conventional control strategies such as vector control and direct torque control in the existing literatures [2–17], but insufficient attention has been paid to the diagnosis methods of PMSM rotor magnetic field local demagnetization fault based on model predictive current control strategy. This paper proposes a fault diagnosis method for rotor magnetic field local demagnetization fault in the PMSM model predictive current control system by combining the adaptive signal extraction algorithm and Hilbert transform. First, the PMSM mathematical model considering local demagnetization fault of rotor magnetic field and the simulation model of its model predictive current control system is established. Then, based on the adaptive signal extraction algorithm, the characteristic harmonics of the rotor magnetic field local demagnetization fault of the PMSM model predictive current control system are extracted under steady and nonstationary operating conditions. And then, the Hilbert transform is used to realize the time-frequency transformation of the extracted rotor magnetic field local demagnetization fault characteristic signal, the instantaneous frequency of the extracted fault characteristic signal is obtained, and it can be used for fault diagnosis. Based on solving the problem that the weak fault characteristic signal near the fundamental wave is difficult to decompose effectively in Hilbert–Huang transform, the ability of fault characteristic signals to characterize local demagnetization fault of PMSM rotor magnetic field is improved and the reliable diagnosis of rotor magnetic field local demagnetization fault of PMSM model predictive current control system is realized.

2. PMSM Modeling considering Rotor Magnetic Field Local Demagnetization Fault

The modeling idea of this study is as follows: First, establishing the PMSM finite element model with different demagnetization degrees of a single permanent magnet, and then performing the spectrum analysis and the flux linkage calculation of the no-load radial air gap flux density of permanent magnet. According to the analysis and calculation results, the flux linkage equation, the stator voltage equation, and the electromagnetic torque equation of PMSM

TABLE 1: The parameters of PMSM.

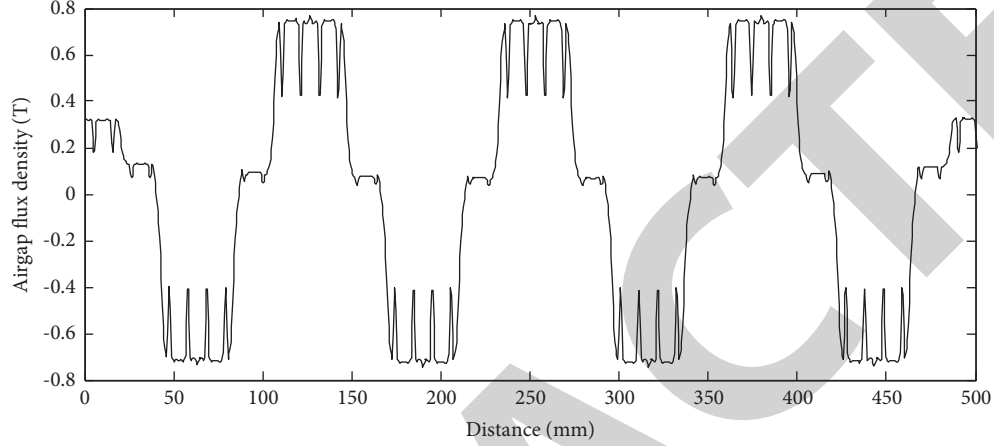| Parameters	Value	Parameters	Value
Pole pairs	4	Rated speed	900 rpm
Stator resistance	$0.0154\,\Omega$	d axis inductance	$L_d = 2.517\text{mH}$
Rotor flux linkage	0.1732 Wb	q axis inductance	$L_q = 5.99\text{mH}$

FIGURE 1: The no-load radial air gap flux density for 50% demagnetization of a single permanent magnet.

considering the local demagnetization of the rotor magnetic field are obtained, combined the above equation with the electromechanical motion equation of PMSM, the PMSM mathematical model with different local demagnetization degrees is established, which lay a foundation for establishing the simulation model of PMSM model predictive current control system considering the rotor magnetic field local demagnetization fault and studying the diagnosis method of local demagnetization fault. Table 1 shows the PMSM parameters, and Figure 1 shows the no-load radial air gap flux density for 50% demagnetization of a single permanent magnet. Figure 2(a) is the Fourier transform result of the no-load radial air gap flux density as shown in Figure 1, and Figure 2(b) is the Fourier transform result of the no-load radial air gap flux density in the permanent magnet healthy state.

The 4th harmonic in Figure 2 is the fundamental wave of the PMSM rotor no-load radial air gap flux density, the rest are integer or noninteger harmonics. As can be seen from Figure 2(a), when the rotor magnetic field is locally demagnetized, the k/p order noninteger harmonics of the air gap flux density increase significantly. Depending on this, the expression of the flux linkage in the stator armature winding generated by the fundamental wave and harmonics of the rotor air gap flux density can be obtained as [23]

$$\psi_v = \frac{2}{\pi}\left(l_{ef}\frac{\tau}{v}\right)B_v\left(NK_{\text{dpv}}\right). \tag{1}$$

In the formula, l_{ef} is the effective length of the armature core; τ is the pitch of the motor; B_v is the v-th harmonic amplitude of the rotor flux density; N is the number of series turns of armature winding of per phase; and K_{dpv} is winding

coefficient of the v-th harmonic. Taking phase A as an example, the flux linkage in the stator winding produced by the no-load radial air gap flux density can be expressed as

$$\psi_A = \psi_{1/4}\cos\left(\frac{\theta}{4}\right) + \psi_{2/4}\cos\left(\frac{2\theta}{4}\right) + \psi_{3/4}\cos\left(\frac{3\theta}{4}\right)$$
$$+ \psi_1\cos(\theta) + \cdots + \psi_{k/p}\cos\left(\frac{k\theta}{p}\right). \tag{2}$$

In order to take into account the modeling accuracy and model complexity of the PMSM rotor magnetic field local demagnetization fault, the study focuses on the noninteger harmonic flux linkage that can effectively describe the local demagnetization fault, and takes the noninteger air gap flux density characteristic harmonic to 7/4 times. At the same time, considering that the change of the integral air gap flux density harmonics is not obvious when the rotor magnetic field is local demagnetized, only the 5th and 7th harmonics with larger amplitudes are selected in the modeling process. Based on three-phase stator winding flux linkage, through constant amplitude coordinate transformation and simplification processing, the PMSM dq axis stator flux linkage equation shown in (3) can be obtained. Substitute (3) into (4) and (5), the stator voltage equation and electromagnetic torque equation considering the local demagnetization fault of the rotor magnetic field can be obtained. Combining the above-mentioned flux linkage equation, stator voltage equation, electronic torque equation with electromechanical motion equation, the PMSM mathematical model considering the rotor magnetic field local demagnetization fault is obtained, which lays a foundation for establishing the simulation model of PMSM model predictive current

control system considering the rotor magnetic field local demagnetization fault and implementing the research on

diagnosis method of rotor magnetic field local demagnetization fault.

$$
\left\{
\begin{aligned}
\psi_d &= \frac{1+\sqrt{3}}{3}\left(\psi_{3/4}+\psi_{5/4}\right)\cos(\theta/4)+\frac{2}{3}\left(\psi_{2/4}+\psi_{6/4}\right)\cos(2\theta/4)+\frac{1}{3}\left(\psi_{1/4}+\psi_{7/4}\right)\cos(3\theta/4)+\psi_1+ \\
&\quad \frac{1-\sqrt{3}}{3}\psi_{1/4}\cos(5\theta/4)-\frac{1}{3}\psi_{2/4}\cos(6\theta/4)+\frac{1-\sqrt{3}}{3}\psi_{3/4}\cos(7\theta/4)+\psi_2\cos(3\theta)+\frac{1}{3}\psi_{5/4}\cos(9\theta/4)+ \\
&\quad \frac{2}{3}\psi_{6/4}\cos(10\theta/4)+\frac{1+\sqrt{3}}{3}\psi_{7/4}\cos(11\theta/4)+\left(\psi_5+\psi_7\right)\cos(6\theta)+L_d i_d \\
\psi_q &= \frac{1+\sqrt{3}}{3}\left(\psi_{5/4}-\psi_{3/4}\right)\sin(\theta/4)+\frac{2}{3}\left(\psi_{6/4}-\psi_{2/4}\right)\sin(2\theta/4)+\frac{1}{3}\left(\psi_{7/4}-\psi_{1/4}\right)\sin(3\theta/4)+ \\
&\quad \frac{\sqrt{3}-1}{3}\psi_{1/4}\sin(5\theta/4)+\frac{1}{3}\psi_{2/4}\sin(6\theta/4)+\frac{\sqrt{3}-1}{3}\psi_{3/4}\sin(7\theta/4)-\psi_2\sin(3\theta)-\frac{1}{3}\psi_{5/4}\sin(9\theta/4)- \\
&\quad \frac{2}{3}\psi_{6/4}\sin(10\theta/4)-\frac{1+\sqrt{3}}{3}\psi_{7/4}\sin(11\theta/4)+\left(-\psi_5+\psi_7\right)\sin(6\theta),
\end{aligned}
\right. \tag{3}
$$

$$
\left\{
\begin{aligned}
u_d &= R_s i_d + L_d di_d/dt - \omega_e L_d i_d - \omega_e \psi_q, \\
u_q &= R_s i_q + L_q di_q/dt - \omega_e L_q i_q + \omega_e \psi_d,
\end{aligned}
\right. \tag{4}
$$

$$
T_e = p\left(\psi_d i_q - \psi_q i_d\right). \tag{5}
$$

Here, θ is electrical angle between d axis and A phase winding axis, ψ_d, ψ_q, u_d, u_q, i_d, and i_q are d axis stator flux linkage, q axis stator flux linkage, d axis stator voltage, q axis stator voltage, d axis stator current and q axis stator current respectively, R_s, L_d, and L_q represent stator resistance, d axis stator inductance and q axis stator inductance respectively, ω_e is rotor electrical angular speed, and p is the pole pairs of the PMSM.

3. Model Predictive Current Control, Adaptive Signal Extraction, and Hilbert–Huang Transform Algorithm

3.1. Model Predictive Current Control Algorithm of PMSM

3.1.1. Prediction Model. Taking the stator current as a state variable, the PMSM current state equation can be obtained from formula (4) as

$$
\left\{
\begin{aligned}
\frac{di_d}{dt} &= \frac{R_s}{L_d}i_d + \omega_e \frac{L_q}{L_d}i_q + \frac{1}{L_d}u_q, \\
\frac{di_d}{dt} &= \frac{R_s}{L_q}i_q - \omega_e \frac{L_d}{L_q}i_d + \frac{1}{L_q}u_q - \frac{\omega_e}{L_q}\psi_f.
\end{aligned}
\right. \tag{6}
$$

If the sampling period T_s of the control system is short enough, the PMSM discrete-time model can be represented by a first-order Taylor series, which is approximately

$$
\left\{
\begin{aligned}
\frac{di_d}{dt} &= \frac{i_d(k+1)-i_d(k)}{T}, \\
\frac{di_q}{dt} &= \frac{i_q(k+1)-i_q(k)}{T_s}.
\end{aligned}
\right. \tag{7}
$$

Using (7) to discretize (6), the PMSM discrete current predictive model can be obtained as

$$
\left\{
\begin{aligned}
i_d^p(k+1) &= \left(1-\frac{T_s R_s}{L_d}\right)i_d(k)+T_s\frac{u_d(k)}{L_d}+T_s\omega_e(k)\frac{L_q}{L_d}i_q(k), \\
i_q^p(k+1) &= \left(1-\frac{T_s R_s}{L_q}\right)i_q(k)+T_s\frac{u_q(k)}{L_q}-T_s\omega_e(k)\frac{L_d}{L_q}i_d(k)-T_s\omega_e(k)\frac{\psi_f}{L_q}.
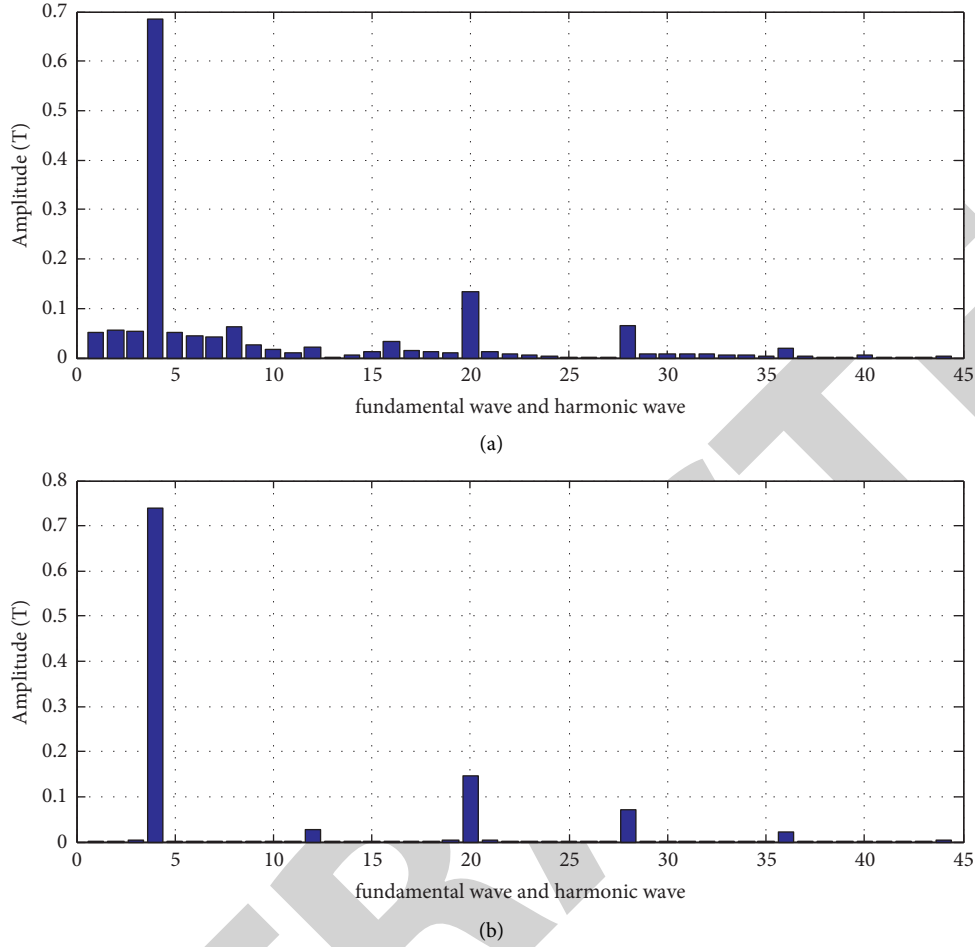\end{aligned}
\right. \tag{8}
$$

FIGURE 2: The fundamental wave and harmonic wave of no-load radial air gap flux density for 50% demagnetization of a single permanent magnet and healthy permanent magnet. (a)The fundamental wave and harmonic wave of no-load radial air gap flux density for 50% demagnetization of a single permanent magnet. (b)The fundamental wave and harmonic wave of no-load radial air gap flux density for healthy permanent magnet.

In the formula, T_s is the sampling time, $i_d^p(k+1)$ and $i_q^p(k+1)$ represent the $(k+1)$th d axis predictive current, and $(k+1)$th q axis predictive current, respectively.

3.1.2. Cost Function.

The three-phase PMSM drive system has 8 voltage vectors, including 6 nonzero voltage vectors and 2 zero-voltage vectors. In the model predictive current control algorithm, in order to make the actual stator current track the reference current with high performance, it is necessary to define a reasonable cost function, and the voltage vector with the minimum cost function is usually taken as the optimal voltage vector for the next sampling period of the PMSM drive system.

In this study, the cost function is defined as

$$g_i = \left[i_d^* - i_d^p(k+1)^2\right] + \left[i_q^* - i_q^p(k+1)^2\right] + g\left[i_d^p(k+1), i_q^p(k+1)\right]. \tag{9}$$

In the formula, $i = 0,1, \ldots, 7$; i_d^* and i_q^* represent d axis reference current and q axis reference current respectively, the last term is a nonlinear equation, its specific expression is

$$g\left[i_d^p(k+1), i_q^p(k+1)\right] = \begin{cases} \infty, \left|i_d^p(k+1) > i_{d\max}\right| \text{or} \left|i_q^p(k+1) > i_{q\max}\right|, \\ 0, \left|i_d^p(k+1) < i_{d\max}\right| \text{and} \left|i_q^p(k+1) < i_{q\max}\right|. \end{cases} \tag{10}$$

In the formula, $i_{d\max}$ and $i_{q\max}$ represent the limiting value of the d axis and q axis current, respectively. When the predictive current produced by a voltage vector exceeds the maximum allowable current, the cost function becomes infinite and the voltage vector cannot be used for the model predictive current control algorithm. When the predictive current is within the allowable range, only the first two terms are left in the cost function, and the optimal voltage vector that minimizes the cost function will be selected for the next control period of the PMSM drive system.

3.2. Adaptive Signal Extraction Algorithm.

The adaptive signal extraction algorithm was proposed by Ziarani [24], Douglas et al. [25], and Barendse and Pilly [26] extended the algorithm to diagnosis of induction motor rotor broken bars and PMSM stator winding inter-turn short circuit faults,
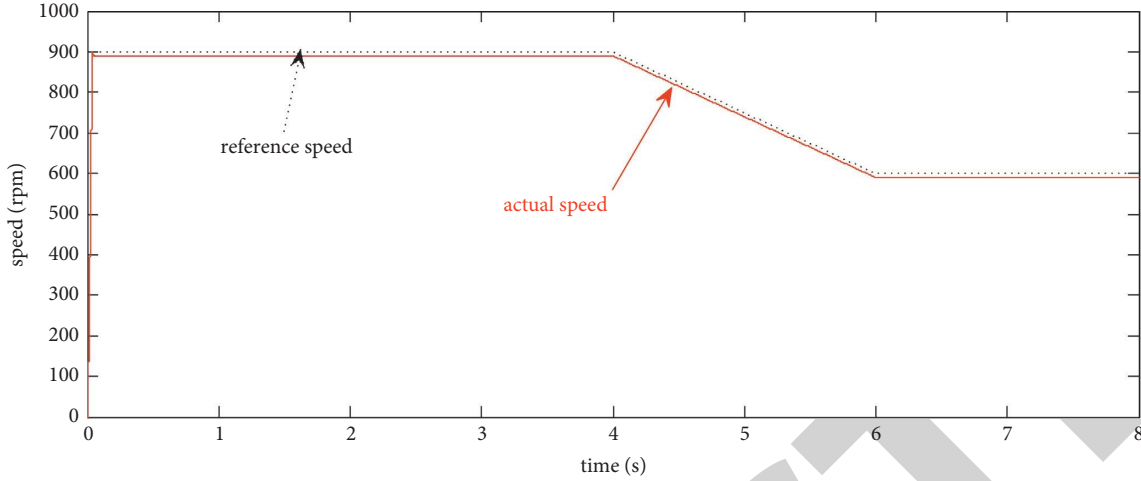
FIGURE 3: The reference speed and actual speed of the PMSM model predictive current control system.

respectively. This study applies it to fault diagnosis of PMSM rotor magnetic field local demagnetization, and gives the following derivation: Define $i(t)$ as PMSM stator current, which includes target extraction signal $i_o(t)$ and other signals $i_1(t)$, its expression is

$$i(t) = i_o(t) + i_1(t). \tag{11}$$

Assuming that the actual extracted signal of the stator current is $i_{ext}(t)$, the minimum square error criterion function of the $i(t)$ and $i_{ext}(t)$ can be minimized by the gradient descent method, and the cost function is defined as

$$J(t, \theta) = \frac{[i(t) - i_{ext}(t, \theta)]^2}{2} = \frac{1}{2}e^2(t, \theta), \tag{12}$$

where θ is the parameter vector representing the instantaneous values of the actual extracted signal amplitude $I(t)$, frequency $\omega(t)$ and phase $\phi(t)$. The gradient descent method provides an adjustment method to make the cost function converge to the minimum value point, and the adjustment process can be described by

$$\frac{d\theta}{dt} = -\mu \frac{\partial[J(t, \theta(t))]}{\partial \theta(t)}. \tag{13}$$

The convergence process of the cost function described by eq. (13) can generate a set of nonlinear differential equations representing the extraction process of the target extraction signal amplitude, frequency, and phase instantaneous value, and their expression is given as follows:

$$\frac{dI(t)}{dt} = \mu_1 e(t) \sin\phi(t), \tag{14}$$

$$\frac{d\omega(t)}{dt} = \mu_2 I(t) e(t) \cos\phi(t), \tag{15}$$

$$d\phi(t)dt = \mu_2 \mu_3 e(t) \cos\phi(t) + \omega(t), \tag{16}$$

$$i_{ext}(t) = I(t) \sin\phi, \tag{17}$$

where $I(t)$, $\omega(t)$ and $\phi(t)$ represent the instantaneous values of the actual extracted signal amplitude, frequency and phase, $e(t)$ is extraction error, μ_1, μ_2 and μ_3 are small positive constant, their size will determine the signal extraction accuracy and extraction speed. The adaptive extraction of the target extraction signal can be realized by solving the nonlinear differential equations (14)-(17).

3.3. Hilbert–Huang Transform. Literature research shows that, when the PMSM rotor magnetic field has a local demagnetization fault, the fault characteristic harmonics will be generated in the stator current [10, 11, 12, 13, 14], which is expressed as

$$f_{fault} = f_s \left(1 \pm \frac{k}{p}\right). \tag{18}$$

Here, f_{fault} is the fault characteristic harmonics, f_s is the fundamental frequency of the stator current, and p is the pole pairs of PMSM and k is a positive integer.

As a nonlinear and nonstationary signal processing method based on instantaneous frequency, the Hilbert–Huang transform has stronger adaptability and clearer physical meaning in processing nonstationary signals [27]. As an important part of the Hilbert–Huang transformation, empirical mode decomposition (EMD) can adaptively decompose nonstationary signals into a series of single component intrinsic mode functions with definite physical significance for instantaneous frequencies according to certain screening principles, then the instantaneous frequencies of each intrinsic mode function are obtained by Hilbert transform, and the time-frequency representation of the original signal is finally obtained. The extraction process of the intrinsic mode function is as follows:

(i) Obtain all extreme points of the original signal $x(t)$ and their upper and lower envelopes $e_{max}(t)$ and $e_{min}(t)$.

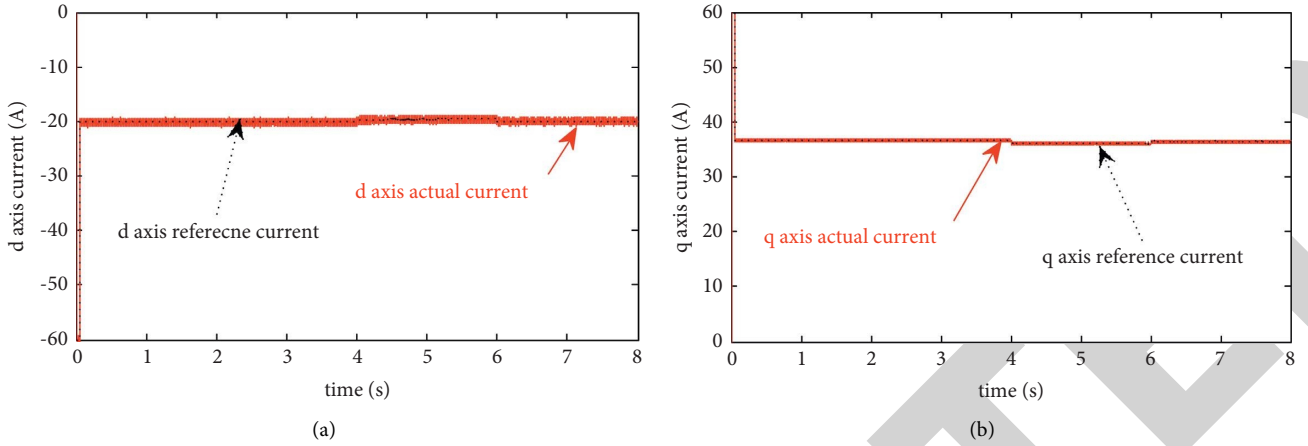(ii) Calculate the instantaneous envelope mean value, $m_1(t) = (e_{max}(t) + e_{min}(t))/2$.

Figure 4: The *dq* axis reference current and actual current of PMSM. model predictive current control system. (a) *d* axis reference current and actual current. (b) *q* axis reference current and actual current.
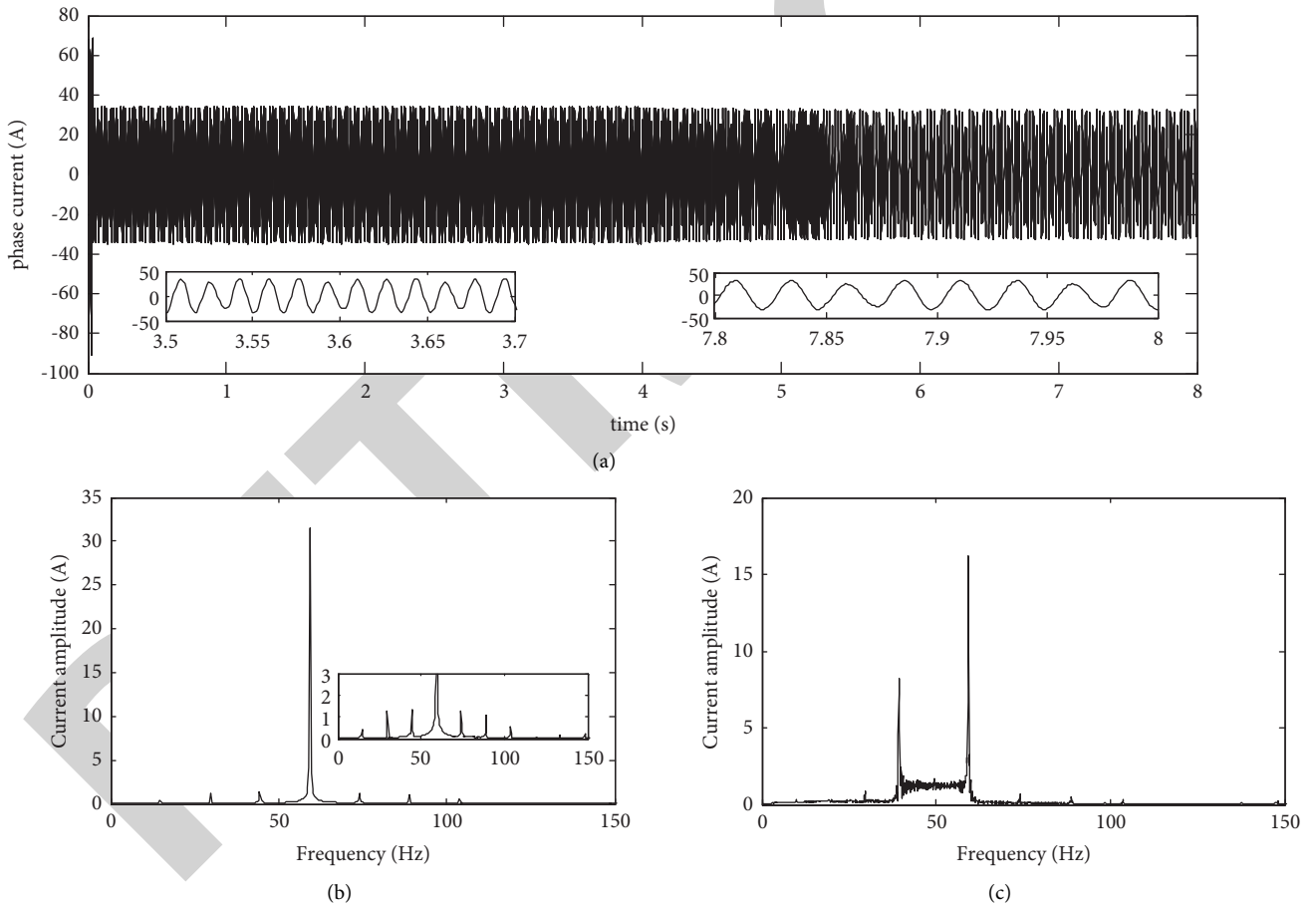

Figure 5: PMSM stator current and its Fourier spectrum at 50% demagnetization of a single permanent magnet. (a) Stator current. (b) Fourier spectrum of local steady-state current. (c) Fourier spectrum of the global current.

(iii) Calculate the difference between $x(t)$ and $m_1(t)$, let $h_{11}(t) = x(t) - m_1(t)$.

$h_{11}(t)$ generally does not satisfy the standard deviation condition described by eq. (19), it needs to be used as the original signal $x(t)$, and the above extraction process is repeated. It is assumed that after k times of decomposition, the obtained $h_{1k}(t)$ satisfies the standard deviation condition described in eq. (19), then the first intrinsic mode function $h_{1k}(t)$ is obtained and denoted as C_1.
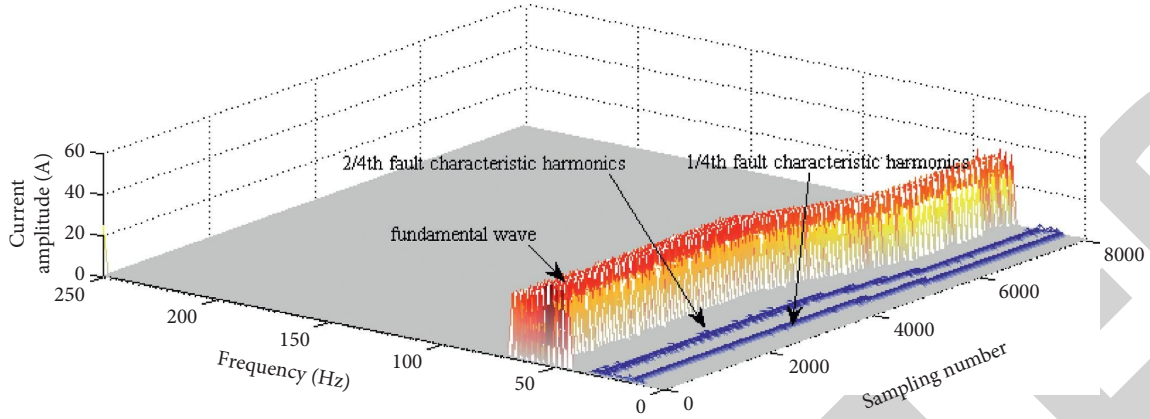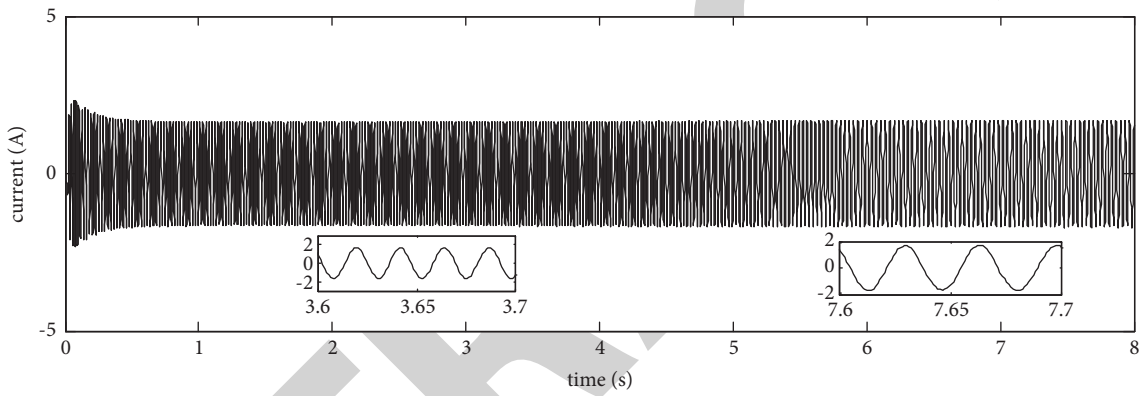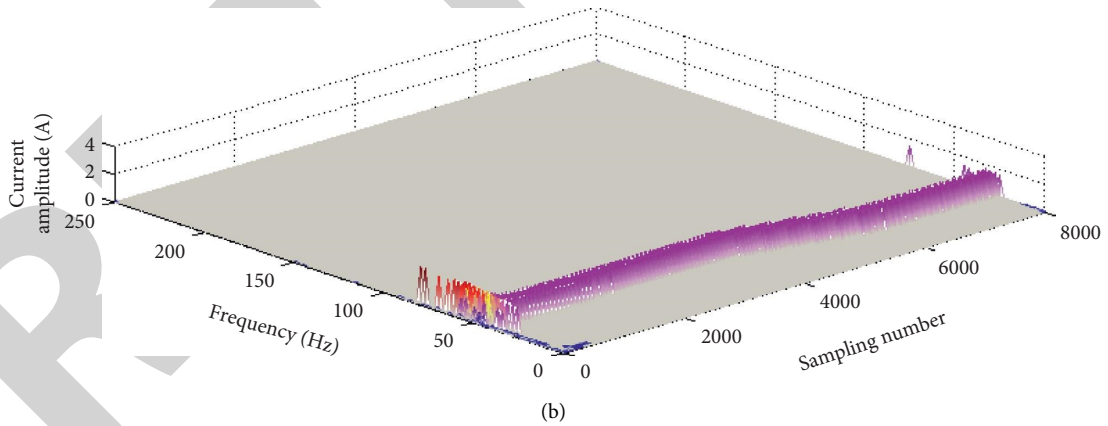
FIGURE 6: The three-dimensional time-frequency spectrum of stator phase current based on the Hilbert–Huang transform.

(a)

(b)

FIGURE 7: The extracted 3/4 order harmonic current based on adaptive signal extraction algorithm and its three-dimensional time-frequency spectrum based on the Hilbert transform. (a) The extracted 3/4 order harmonic current based on adaptive signal extraction algorithm. (b) Three-dimensional time-frequency spectrum based on Hilbert transform.

$$sd = \sum_{}^{T} \left[h_1 (k - 1) - h_{1k} (t) \right]^2. \qquad (19)$$

In the formula, sd is usually taken as 0.2–0.3.

(iv) Let $r_1(t) = x(t) - h_{1k}(t)$, and let the $r_1(t)$ be the original signal $x(t)$, that is, $x(t) = r_1(t)$.

Repeat steps (1)–(4), until the $r_n(t)$ after n times of decomposition is smaller than the predetermined value or is a monotone function, EMD decomposition is completed, and a series of intrinsic mode functions with decreasing frequency components denoted $C_1, C_2, \ldots, C_n$ and a residual component r_n that no longer contains any frequency
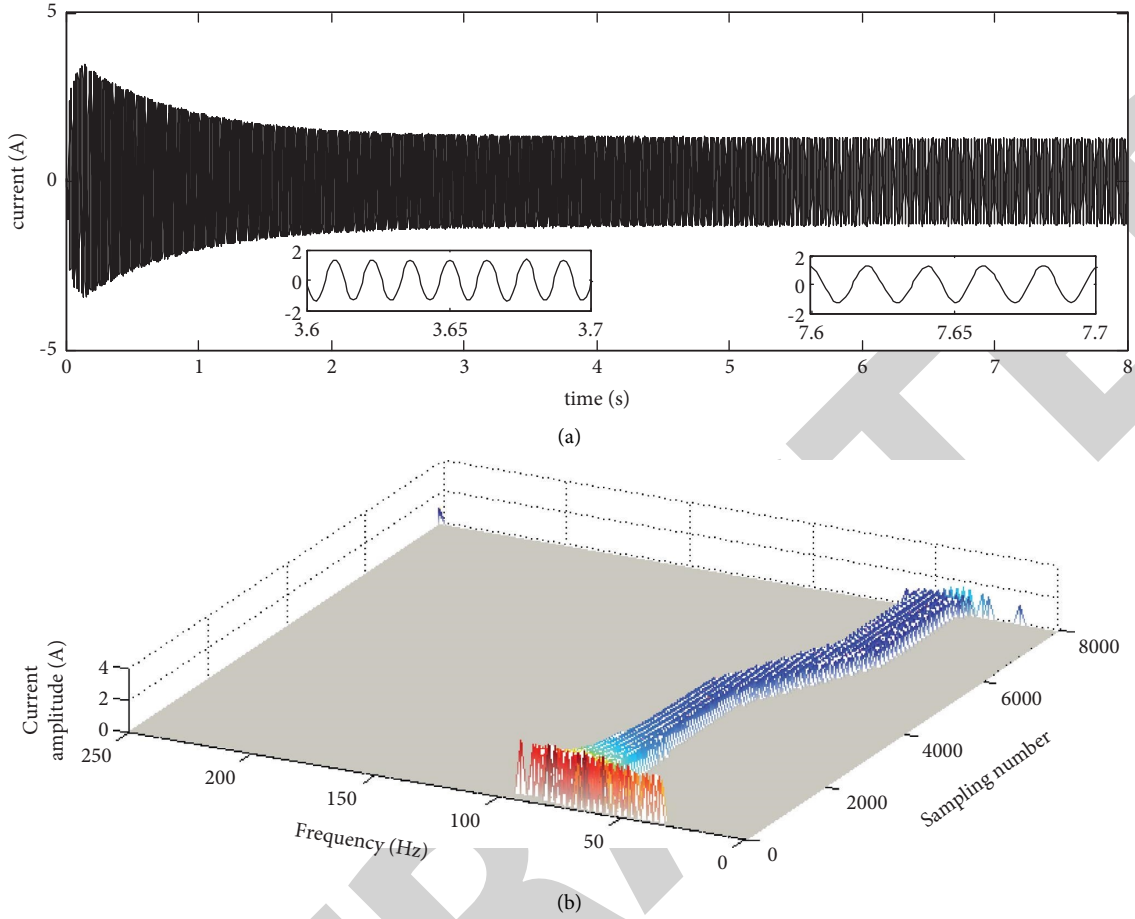
Figure 8: The extracted 5/4 order harmonic current based on adaptive signal extraction algorithm and its three-dimensional time-frequency spectrum based on Hilbert transform. (a) The extracted 5/4 order harmonic current based on adaptive signal extraction algorithm. (b) Three-dimensional time-frequency spectrum based on Hilbert transform.
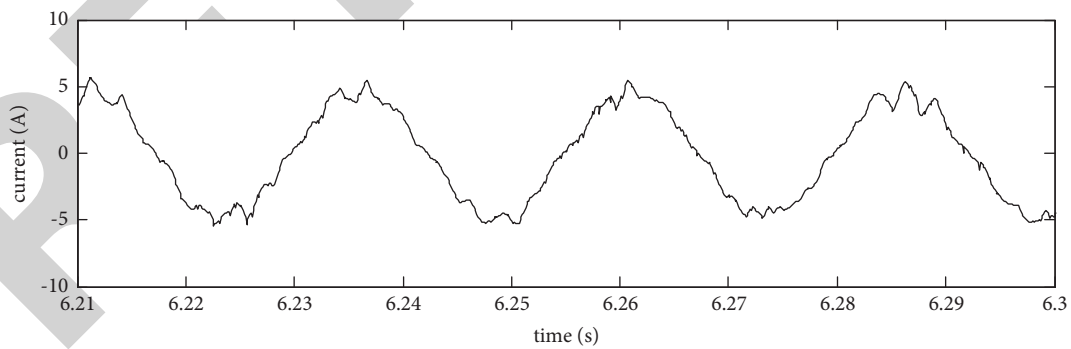

Figure 9: The measured stator current at the speed of 600 rpm.

information are obtained. At this time, the decomposition formula of the original signal $x(t)$ can be expressed ast

$$x(t) = \sum_{i=1}^{n} C_i + r_n. \tag{20}$$

After obtaining a set of intrinsic mode functions of the original signal through EMD decomposition, the

instantaneous frequency of each intrinsic mode function can be calculated by using Hilbert transform, so as to obtain the time-frequency relationship of the original signal, namely, the instantaneous frequency. However, for the weak fault characteristic signals near the fundamental wave, it is difficult to realize effectively decompose due to the limitation of its own decomposition ability, this will inevitably limit its ability to characterize local demagnetization fault and reduce
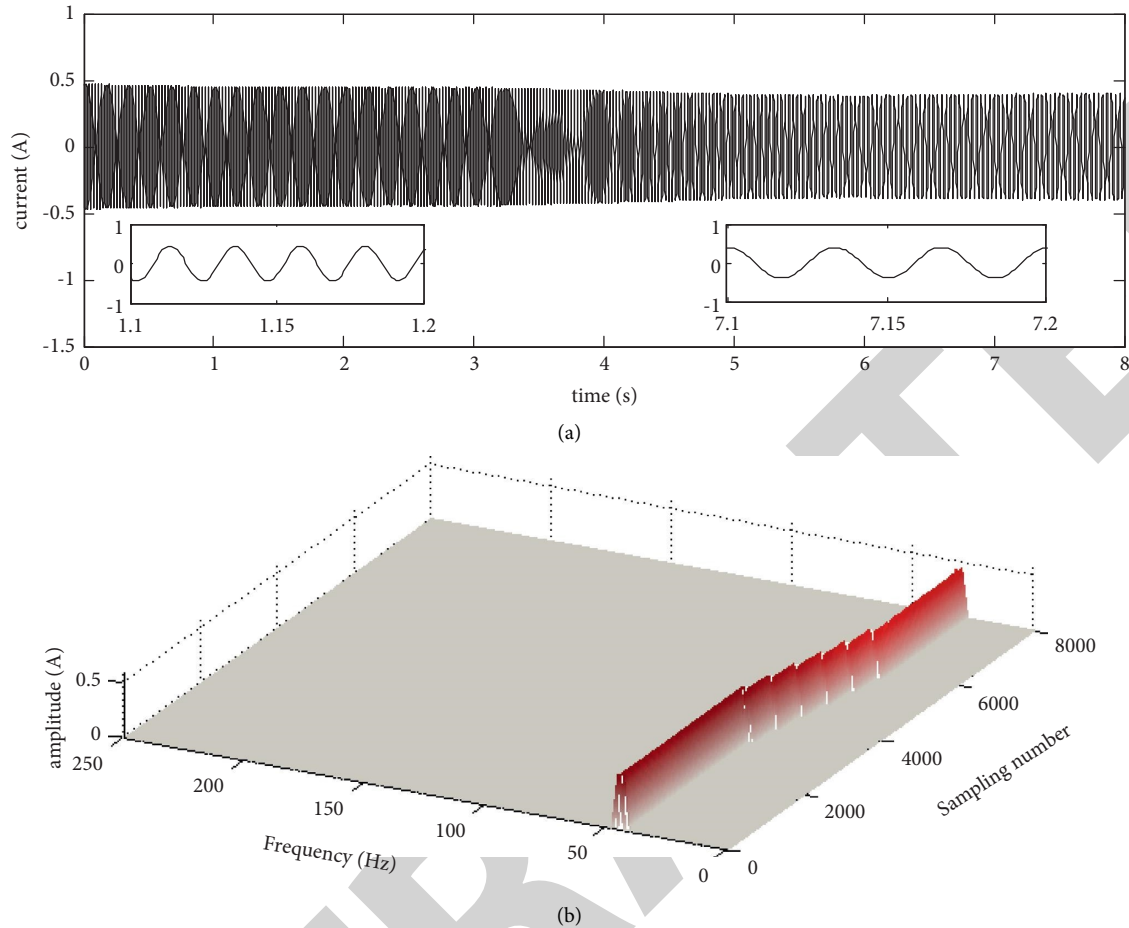
(a)

(b)

Figure 10: The 3/4 order fault characteristic harmonic current extracted from stator current based on adaptive signal extraction algorithm and its three-dimensional time-frequency spectrum based on Hilbert transform. (a) The 3/4 order fault characteristic harmonic current extracted from stator current. (b) Three-dimensional time-frequency spectrum.

the accuracy of fault diagnosis using this method. At the same time, the decomposition process of EMD is complicated and the calculation amount is relatively large.

4. Simulation Research

The PMSM parameters used for simulation are shown in Table 1. Based on the established PMSM mathematical model considering the local demagnetization fault of the rotor magnetic field, the simulation model of its model predictive current control system is established by using MATLAB/Simulink. The simulation step size and the discrete period of the model predictive current control algorithm are both set at 0.1 ms, and the current sampling frequency is set at 1 KHz. Figure 3 shows the reference speed and actual speed of the PMSM model predictive current control system when the rotor magnetic field is in healthy state, and Figure 4 shows its dq axis reference current and actual current. It can be seen from Figures 3 and 4 that the model predictive current control algorithm can realize fast, no overshoot tracking of PMSM speed and accurate control of dq axis current, and has high speed and current control performance. The PMSM model

predictive current control system operates under the conditions shown in the reference speed in Figure 3, and sets a single permanent magnet to lose its flux density by 50%. Figure 5(a) is the PMSM stator current waveform under the above fault state, Figures 5(b) and 5(c) are the Fourier spectrum of local steady-state current (1–4 seconds data in Figure 5(a)) and global current (1–8 seconds data in Figure 5(a)), respectively. It can be seen from Figure 5(b) that when the PMSM rotor magnetic field is locally demagnetized, the fault characteristic harmonics shown in (18) appear in the stator current (integer harmonics are not considered), and the Fourier transform can obtain the frequency domain representation of the fault characteristic signal under the steady-state operating condition of the PMSM drive system, which provides a basis for rotor magnetic field local demagnetization fault diagnosis. However, in the nonstationary operating condition of the PMSM drive system, the Fourier transform cannot obtain the correct frequency and current amplitude transformation results, as shown in Figure 5(c).

Figure 6 is the three-dimensional time-frequency spectrum of the current in Figure 5 obtained based on the Hilbert–Huang transform. It can be seen from Figure 6 that the Hilbert–Huang
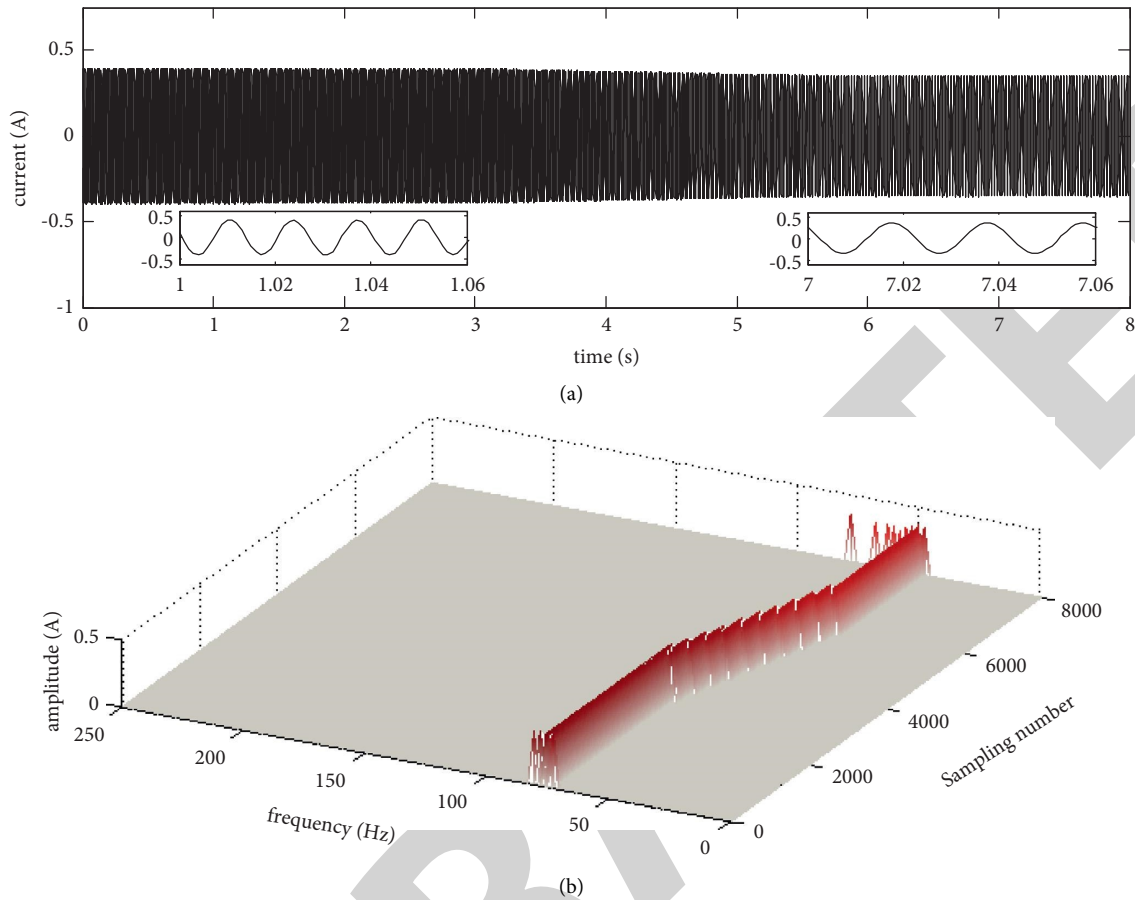
Figure 11: The 5/4 order fault characteristic harmonic current extracted from stator current based on adaptive signal extraction algorithm and its three-dimensional time-frequency spectrum based on Hilbert transform. (a) The 5/4 order fault characteristic harmonic current extracted from stator current. (b) Three-dimensional time-frequency spectrum.

transform can accurately decompose the current fundamental wave, the 1/4th and the 2/4th fault characteristic harmonic in stationary and nonstationary states of the PMSM drive system and obtain their instantaneous frequencies, which can be used as the basis for the diagnosis of rotor magnetic field local demagnetization fault of PMSM model predictive current control system, but it is limited by its decomposition ability, the 3/4th, 5/4th, 6/4th, and 7/4th fault characteristic harmonics close to the fundamental frequency are annihilated by the larger fundamental current and cannot be effectively decomposed, which reduces the reliability of characterizing the rotor magnetic field local demagnetization fault by fault characteristic harmonics.

In order to obtain the noninteger fault characteristic harmonics annihilated by the fundamental current, an adaptive signal extraction algorithm is introduced in this study to achieve the effective extraction of the target fault characteristic harmonics, and then the time-frequency transformation of the extracted fault characteristic signal is realized based on Hilbert transform to obtain its instantaneous frequency. Figures 7 and 8 show the 3/4th and the 5/4th fault characteristic harmonics and their three-dimensional time-frequency spectrum obtained based on the proposed method in this paper, the 6/4th and 7/4th fault

characteristic harmonics and their time-frequency spectrum are no longer given due to the limitation of this paper workload. It can be seen from Figures 7(a) and 8(a) that the adaptive signal extraction algorithm can accurately extract the target fault characteristic harmonics; the time-frequency spectrum of the extracted fault characteristic signal based on Hilbert transform is shown in Figures 7(b) and 8(b); as shown in Figures 7(b) and 8(b), the reliability of fault characteristic harmonics in characterizing local demagnetization fault of PMSM rotor magnetic field can be significantly improved, which lays a foundation for reliable diagnosis of PMSM rotor magnetic field local demagnetization fault. Meanwhile, this method has much less computation than Hilbert–Huang transform, which is convenient for online implementation.

5. Experimental Verifications

In order to realize the experimental verifications of the proposed method, an experimental plat of PMSM model predictive current control system was built, which mainly includes a control and drive unit, power conversion unit, signal detection and conditioning unit, protection and loading unit, etc. The system debugging interface was

designed based on the control desk to realize the online adjustment of control parameters and real-time display and storage of measurement data. The main control unit was built with dSPACE standard component system, the program code generation and loading of the PMSM model predictive current control system was completed and the SVPWM signal was generated to drive the inverter. The experimental system is loaded with an AC dynamometer, and the PMSM parameters are as follows: rated voltage is 380 V, stator resistance is 0.28 Ω, dq-axis stator inductance is 1.273 mH, rotor flux linkage is 0.1278 Wb, and the number of pole pairs is 4.

The fault injection method is used to implement the experimental verification of the proposed diagnosis method for rotor magnetic field local demagnetization fault in the PMSM model predictive current control system. The 3/4th and 5/4th fault characteristic harmonics of the fundamental current are injected through the host computer, and the amplitude of the injected harmonics is the same as the amplitude ratio of the characteristic harmonics and the fundamental current obtained in the simulation study. The system control period and the discrete period of the model predictive current control algorithm are set at 0.1 ms, the current sampling frequency is set at 1 KHz, and the load torque is set at 3.0 Nm. Taking the dynamic running state of the PMSM model predictive current control system to verify the correctness and feasibility of the proposed fault diagnosis method, that is, the PMSM speed starts to fall from 900 rpm at the third second of the experimental data, and enters the steady state of 600 rpm at the fifth second. Figure 9 is the measured current waveform when the speed drops to 600 rpm, Figure 10 is the 3/4 order fault characteristic harmonic current extracted from stator current 9 based on adaptive signal extraction algorithm and its three-dimensional time-frequency spectrum based on Hilbert transform, and Figure 11 is the 5/4 order fault characteristic harmonic current extracted from stator current based on adaptive signal extraction algorithm and its three-dimensional time-frequency spectrum based on Hilbert transform. It can be seen from Figures 10(a) and 11(a) that the adaptive signal extraction algorithm can realize the accurate extraction of the characteristic harmonics of the rotor magnetic field local demagnetization fault in the PMSM model predictive current control system. The time-frequency spectrum of the extracted fault characteristic signal, as shown in Figures 10(b) and 11(b), can be used as a reliable basis for the rotor magnetic field local demagnetization fault diagnosis of the PMSM model predictive current control system, which greatly improves the ability of the fault characteristic signals to characterize the local demagnetization fault of the PMSM rotor magnetic field, the experimental results agree with the simulation results. Due to the heavy workload, the experiment verification of extraction and time-frequency transformation of other fault characteristic harmonics are not repeated in this study.

6. Conclusion

On the basis of establishing the PMSM mathematical model considering the rotor magnetic field local demagnetization fault, and the simulation model of its model predictive current control system, a diagnosis method of rotor magnetic field local demagnetization fault in PMSM model predictive current control system is proposed in this study, the accuracy and effectiveness of the proposed method are verified by simulation and experiments, and the following conclusions are drawn:

(i) The established PMSM mathematical model considering the rotor magnetic field local demagnetization fault can realize the accurate characterization of the abovementioned fault, which lays a foundation for establishing the simulation model of its model predictive current control system and implementing research on the diagnosis method of the local demagnetization fault.

(ii) The PMSM drive system based on the model predictive current control algorithm can realize high-performance control of speed and current, which is beneficial to meet the system control requirements of wide speed regulation range, good dynamic characteristics, fast current response, and high-power density.

(iii) The adaptive signal extraction algorithm can realize the effective extraction of the fault characteristic signal of the rotor magnetic field local demagnetization fault in the PMSM model predictive current control system under the stationary and nonstationary operating conditions, and effectively solve the problem existing in the Hilbert-Huang transform that the weak fault characteristic signal nearby fundamental wave component is difficult to be decomposed, which greatly improves the diagnosis reliability of the PMSM rotor magnetic field local demagnetization fault. And this algorithm has much less computation than the EMD algorithm, which is convenient for online implementation.

Data Availability

The experimental data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declared that they have no conflicts of interest regarding this work.

Acknowledgments

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