International Journal of
INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING
ISSN:2147-6799 www.ijisae.org Original Research Paper

Local Demagnetization Fault Diagnosis Method of Permanent Magnet Synchronous Motor Based on Transient Analysis of Stator Back EMF Attenuation

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Submitted:11/03/2024 **Revised**: 26/04/2024 **Accepted**: 03/05/2024

Abstract: Permanent magnet demagnetization can impair motor performance, causing torque fluctuations and efficiency drops, masking fault signatures. To address this, we propose a fault detection method based on stator back electromotive force (EMF) attenuation transients in permanent magnet synchronous motors. Our approach involves modeling the motor's mechanical and electrical systems, formulating voltage equations relating rotor and stator fluxes. We calculate the relationship between stator phase voltages during EMF attenuation, ignoring zero sequence effects, to analyze attenuation patterns. By observing the magnetic EMF from a demagnetization perspective and applying coordinate transformation, we extract the rotor's magnetic flux. Comparing observed flux with thresholds enables fault diagnosis. Experimental results demonstrate that our method achieves high accuracy (mean square error <1) and reliability (AUC near 1) in detecting local demagnetization faults in these motors.

Keywords: *permanent magnet synchronous motor; Stator; Back EMF attenuation; Local demagnetization; flux linkage*

1. Introduction

Permanent magnet synchronous motor (PMSM) has significant advantages in energy conversion efficiency, which can provide constant torque output over a wide speed range, reducing energy loss and lowering operating costs [1]. Because of its high efficiency and low noise characteristics, it also meets the current social needs for energy conservation and environmental protection. The PMSM performs well in applications requiring high-precision control and regulation, such as robotics, automation equipment, and other fields [2]. However, different permanent magnet materials have varying magnetic stability and thermal resistance, and some permanent magnet materials are more prone to demagnetization in high-temperature or strong magnetic field environments. Local demagnetization of the permanent magnet refers to the weakening or even loss of magnetic performance in local areas of the permanent magnet due to temperature rise, mechanical stress, and uneven distribution of the magnetic field during motor operation [3]. This phenomenon will not only reduce the electromagnetic torque and efficiency of the motor but also cause problems such as vibration, noise, and overheating, which will seriously affect the normal operation of the motor. Furthermore, it will accelerate the demagnetization process of the permanent magnet under the influence of harsh environments such as high temperature, high humidity, and high vibration. Additionally, the motor's operating mode is also a primary cause of demagnetization problems, such as overload, frequent starting and stopping, and high-speed operation [4]. This kind of local demagnetization problem has gradually become an important factor affecting the performance and reliability of the motor. Therefore, timely diagnosis of local demagnetization fault of permanent magnet synchronous motor, detection and solution of demagnetization fault can ensure that the motor operates in the best state and avoid adverse effects caused by performance degradation, which is of great significance to ensure motor performance and prolong service life.

In reference [5], aiming at the demagnetization problem of permanent magnet motor caused by insufficient heat dissipation and high temperature, an accurate model of the motor that can identify demagnetization fault is established. By changing the Fourier coefficient of permanent magnet magnetization to simulate demagnetization fault, the characteristics of the motor under various demagnetization conditions are effectively extracted, including radial air gap flux density, back EMF and torque. The corresponding relationship between demagnetization degree and fault characteristics is established, and the diagnosis of demagnetization fault is realized. However, the

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demagnetization of permanent magnet may be manifested by the reduction of the maximum magnetic flux of the magnetic core and the magnetization under the saturated magnetic field. These changes may be difficult to accurately identify solely based on Fourier coefficients. In order to further study the characteristics of permanent magnets under extreme operating conditions, reference [6] established a finite element simulation model for local non-uniform demagnetization faults in permanent magnet motors. This model successfully extracts demagnetization characteristics by analyzing no-load back electromotive force and load stator current data, combined with Hilbert Huang transform technology, providing an effective solution for monitoring local uneven demagnetization of permanent magnet motors and providing corresponding technical support. However, the feature quantity extracted based on no-load back EMF and load stator current may not fully reflect all the features of demagnetization fault, resulting in misjudgment or missed judgment. Reference [7] conducted in-depth research on local demagnetization faults in permanent magnet synchronous motors using a ring yoke type detection coil. Firstly, deploy a yoke coil on the stator side to capture signals containing demagnetization fault information. Subsequently, by analyzing the stator electromotive force induced by the coil, a zoning criterion for demagnetization signals was developed to accurately identify the types of demagnetization faults and achieve precise localization of local demagnetization faults. However, this method mainly depends on external signals and sensor data, such as current, voltage and temperature. Although these methods can reflect the running state of the motor to a certain extent, they are often unable to directly detect the changes in the magnetic properties of the permanent magnet, especially when the permanent magnet has local demagnetization, it is often difficult to accurately identify the fault.

In order to reduce the interference of changes in the magnetic properties of permanent magnets on the diagnosis of local demagnetization faults in permanent magnet synchronous motors, The new method was developed for diagnosing local demagnetization faults in permanent magnet synchronous motors based on the analysis of transient characteristics of stator back electromotive force attenuation.

2. Design of diagnostic strategy for local demagnetization faults in permanent magnet synchronous motors

2.1. Mathematical model of PMSM

Because the local demagnetization fault of permanent magnet synchronous motor (PMSM) will destroy the symmetrical structure inside the motor, and the mathematical model of PMSM can accurately describe the electrical, magnetic and dynamic characteristics of the motor [8]. By building the model, the working principle of the motor, including electromagnetic relationship, current voltage relationship and dynamic response, provided the theoretical basis for the fault diagnosis.

In permanent magnet synchronous motor, the stator part drives the rotor to rotate through electromagnetic induction [9]. Permanent magnets are usually embedded in the rotor core, which provide the necessary magnetic field for the motor. In the natural coordinate system (such as A-B-C coordinate system), the calculation of electromagnetic torque and flux linkage of PMSM is relatively complex, but in the q -axis d -axis coordinate system, the dynamic equation of the motor can be simplified as a second-order differential equation group. By converting the physical quantities such as current and voltage of three-phase AC motor into the components in the q -axis d -axis coordinate system, the design and implementation of the control algorithm can be significantly simplified. Therefore, the establishment of PMSM mathematical model in the q -axis and d -axis coordinate system made the observation of the permanent magnet synchronous motor behavior better under the complexity and strong coupling of electromagnetic torque and flux caused by multiple variables involved in the natural coordinate system. It avoided the difficulty of flux analysis and unnecessary large amount of calculation, so as to achieve better results [10]. In the q -axis and d -axis coordinate system, the mathematical model of PMSM can be expressed as:

$$\begin{bmatrix} u_{sd} \\ u_{sq} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s & \square & \square & \square \\ \square & R_s & \square & \square \\ \square & \square & R_r & \square \\ \square & \square & \square & R_r \end{bmatrix} \times \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} + \omega_e \begin{bmatrix} -\psi_{sq} \\ \psi_{sd} \\ 0 \\ 0 \end{bmatrix} + p \begin{bmatrix} \psi_{sd} \\ \psi_{sq} \\ \psi_r \\ \omega_{slip}\psi_r \end{bmatrix} \quad (1)$$

In the formula, u_{sd} and u_{sq} represent the voltage values of the stator on the q -axis and d -axis coordinate systems, respectively; And R_s and R_r respectively represent the resistance values of the stator and rotor windings;i_{sd},i_{sq}, i_{rd}, and i_{rq} respectively represent the current of the stator on the d -axis, the current of the stator on the q -axis, the current of the rotor on the d -axis, and the current of the rotor on the q -axis in the q -d coordinate system; ψ_{sd}. ψ_{sq} represents the magnetic flux of the stator on the d and q axes, while ψ_r represents the magnetic flux of the rotor; ω_e represents the electrical angular velocity of the rotor magnetic flux; ω_{slip} represents the slip electric angular velocity between the rotor flux and stator; ψ_r is the electrical angular velocity of the rotor itself; And p is used as a differential operator.

The permanent magnet synchronous motor (PMSM) has a saturated iron core, a sinusoidal induced current, and no eddy current and hysteresis losses [11]. The three-phase voltage equations for the mechatronics, rotor and stator of PMSM are defined as:

$$\begin{cases} u_{abc(s)} = r_s i_{abc(s)} + p\lambda_{abc(s)} \\ \left(f_{abc(s)}\right)^T = [f_{as}, f_{bs}, f_{cs}] \end{cases} \quad (2)$$

Where, $u_{abc(s)}$ represents the combination of voltage, current and three-phase voltage of flux linkage; r_s is the electromotive force constant; $i_{abc(s)}$ represents the current parameters of ab, bc and cs; $\lambda_{abc(s)}$ represents the number of three-phase magnetic links; $\lambda_{abc(s)} = L_s i_{abc(s)} + \lambda_m$. L_s describes the mean short-circuit inductance and a specific parameter, respectively; λ_m specifically refers to the stator winding of permanent magnet synchronous motors; $\left(f_{abc(s)}\right)^T$ represents the differential difference in magnetic flux based on parameters ab, bc, and cs; And f_{as}, f_{bs}, and f_{cs} correspond to the voltage, current, and magnetic flux values of permanent magnet synchronous motors, respectively.

Short circuit inductance is an important parameter of permanent magnet synchronous motor in case of fault. By calculating the mean value of short-circuit inductance, the electrical characteristics of permanent magnet synchronous motor in the state of local demagnetization fault can be more accurately described, which provides an important basis for fault diagnosis [12]. The change of the mean value of short-circuit inductance can reflect the change of internal winding structure and the development degree of fault. Therefore, it is necessary to calculate the mean value L_s of short-circuit inductance. The calculation formula is:

$$L_s = \begin{pmatrix} L_a - L_b 2n\theta_r & -\frac{1}{2}L_a - L_b\cos 2\left(n\theta_r - \frac{\pi}{3}\right) & -\frac{1}{2}L_a - L_b\cos 2\left(n\theta_r + \frac{\pi}{3}\right) \\ -\frac{1}{2}L_a - L_b\cos 2\left(n\theta_r - \frac{\pi}{3}\right) & L_a - L_b\cos 2\left(n\theta_r - \frac{\pi}{3}\right) & -\frac{1}{2}L_a - L_b\cos 2\left(n\theta_r + \pi\right) \\ -\frac{1}{2}L_a - L_b\cos 2\left(n\theta_r + \frac{\pi}{3}\right) & -\frac{1}{2}L_a - L_b\cos 2\left(n\theta_r + \pi\right) & L_a - L_b\cos 2\left(n\theta_r + \frac{2\pi}{3}\right) \end{pmatrix} \quad (3)$$

Where, L_a is the mean value of winding inductance of permanent magnet synchronous motor; L_b refers to the voltage amplitude change caused by the uneven air gap in the permanent magnet synchronous motor; θ_r represents the angular position variable of the winding rotor; n is the magnetic number of the motor.

It can be seen from formula (3) that the distribution of stator winding λ_m of permanent magnet synchronous motor will affect the change of inductance to a certain extent. In the stable state, stator winding λ_m belongs to sinusoidal distribution, and its distribution can be expressed as follows:

$$\lambda_m = K_e \begin{pmatrix} \sin n\,\theta_r \\ \sin\left(n\theta_r - \frac{\pi}{3}\right) \\ \sin\left(n\theta_r + \frac{2\pi}{3}\right) \end{pmatrix} \quad (4)$$

Where K_e is the sine distribution coefficient.

A lower voltage may cause the motor to fail to start or reach the rated speed, while a higher voltage may cause damage or overheating to the motor and related components [13]. Therefore, the constant voltage of permanent magnet synchronous motor will be affected by many factors, such as power grid fluctuation, motor load change, control system adjustment and so on, and the voltage at both ends of the motor may fluctuate or change slightly. After a long accumulation, the error will become larger and larger. Based on this, the voltage periodic state error change is obtained, as shown in formula (5):

$$\begin{cases} u_q = r_s i_q + n\lambda_q \frac{d\theta_r}{dt} + \frac{d\lambda_q}{dt} \\ u_d = r_s i_d + n\lambda_d \frac{d\theta_r}{dt} + \frac{d\lambda_d}{dt} \end{cases} \quad (5)$$

Where, λ_q and λ_d respectively represent the output torque of the q -axis and d -axis rotors; u_q,u_d represents the constant voltage value of the rotor of axis q and axis d respectively; r_s is the torque radius; i_q and i_d represent the output torque of the permanent magnet synchronous motor after being converted to the q -axis and d -axis, respectively. i_q and i_d can be merged for calculation, and the specific calculation formula is:

$$T\left(i_d, i_q\right) = \frac{3n}{2}\left[K_e i_q + \left(L_d - L_q\right) i_q i_d\right] \quad (6)$$

Where, L_d and L_q represent the mean value of the motor winding inductance of the rotor in axis q and axis d.

The magnetic flux composition of each phase winding of the stator includes the three-phase winding current, magnetic field strength, and the current position of the rotor. The equation is as follows:

$$\begin{bmatrix} \varphi_A \\ \varphi_B \\ \varphi_C \end{bmatrix} = i_A \begin{bmatrix} L_{AA} \\ L_{BA} \\ L_{CA} \end{bmatrix} + i_B \begin{bmatrix} M_{AB} \\ M_{BB} \\ M_{CB} \end{bmatrix} + i_C \begin{bmatrix} M_{AC} \\ M_{BC} \\ M_{CC} \end{bmatrix} + \begin{bmatrix} \varphi_{fA} \\ \varphi_{fB} \\ \varphi_{fC} \end{bmatrix} \quad (7)$$

Where, L_{AB}, L_{BB} and L_{CC} respectively represent mutual inductance of each phase winding of ABC; $M_{AB} = M_{BA}$. $M_{BC} = M_{CB}$ and $M_{CA} = M_{AC}$ respectively represent mutual inductance of corresponding two-phase windings; φ_{fA}. φ_{fB}

and φ_{fC} respectively represent the flux linkage of the rotor permanent magnet in each phase winding resistance of ABC; φ_f represents the flux linkage close to the maximum turn chain in the stator winding.

2.2. Transient analysis of stator back EMF attenuation

During the operation of PMSM, the motor may experience transient process due to the change of external conditions (such as power fluctuation, load mutation, etc.) or the switching of motor control strategy (such as start, stop, speed regulation, etc.). These transient processes will lead to rapid changes in the current, voltage, torque and other parameters of the motor, which will affect the stability and performance of the motor. Therefore, through the transient analysis of stator back EMF attenuation, these transient processes can be described more accurately, and the corresponding control strategy can be formulated to optimize the performance of the motor.

When the stator power supply is disconnected, the electromotive force in the stator begins to decay. This is because the stator winding loses the electrical energy provided by the external power supply, while the rotor will still maintain a certain speed due to inertia, thus continuing to generate a magnetic field [14]. The magnitude of rotor flux linkage is directly related to the strength of rotor magnetic field. At the moment of disconnecting the stator power supply, the value of the rotor flux linkage depends on the interaction state between the magnetic field generated by the stator current and the rotor magnetic field before disconnecting.

Let T_r denote rotor inertia, and the formula can be obtained by combining the voltage relationship:

$$0 = R_r\psi_r/L + p\psi_r = \psi_r/T_r + p\psi_r \tag{8}$$

The formula to obtain the attenuation law of rotor flux linkage can be expressed as:

$$\psi_r(t) = \psi_{r0}e - t/T_r \tag{9}$$

In the formula, ψ_{r0} represents the initial value of the rotor magnetic flux at the beginning of stator electromotive force attenuation.

When the stator power supply is disconnected, the stator magnetic field will also weaken rapidly due to the rapid attenuation of the stator current to 0. However, due to the inertia of the rotor, its speed will not change immediately, so the rotor magnetic field still maintains a certain strength. Then the voltage equation becomes:

$$\left.\begin{array}{l} u_{sd} = p\psi_{sd} \\ u_{sq} = \omega_e\psi_{sd} \\ 0 = R_r i_{rd} + p\psi_r \\ 0 = R_r i_{rq} + \omega_{slip}\psi_r \end{array}\right\} \tag{10}$$

During the attenuation of stator back EMF, the relationship between stator phase voltage and stator voltage in axis q and axis d can be expressed by formula (11):

$$e_s^2 = u_{sd}^2 + u_{sq}^2 \tag{11}$$

Since the zero-sequence component has little impact on the motor performance in the star connection method, its impact can be ignored in many cases to simplify the analysis and calculation [15]. At the same time, the three-phase winding is symmetrically distributed in spatial layout, with electrical angles spaced at 120 ° intervals, these magnetic fields will form a closed loop, and their synthetic air gap magnetic field is zero, which means that it will not generate effective electromagnetic force or torque in the air gap, so it will not have a direct impact on the movement of the rotor [16]. The stator voltage during attenuation can be obtained without considering the influence of zero sequence component. The calculation formula is as follows:

$$e_s^2 = k^2\left(\frac{1}{T_r^2} + \omega_r^2\right)e^{-\frac{2t}{T_r}} \tag{12}$$

Where, k is the attenuation time function, which can be obtained through $k = (\psi_{r0}L_m/L_r)$, and L_r is the rotor inductance; L_m is excitation inductance.

The measured stator voltage is drawn using the envelope method, which usually involves the peak or valley value on the connection curve. The attenuation process of stator back EMF can reflect the state change of permanent magnet synchronous motor after power failure and the change of its internal magnetic field. After the motor is powered off, the magnetic field will gradually weaken, resulting in the reduction of back EMF [17]. By observing the shape, amplitude and attenuation speed of the back EMF waveform, the variation law and trend of the internal magnetic field of the motor can be understood. Make preliminary judgment on the health status, operation status and fault condition of the motor. The waveform of stator back EMF attenuation process is shown in Fig.1.

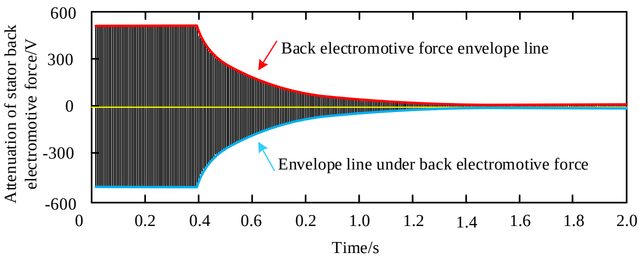

Fig. 1 Waveform of stator back electromotive force attenuation process

After power failure, the internal magnetic field and current of PMSM will gradually decay, resulting in the attenuation of stator voltage. The rotor time constant is usually used to describe the rate of conversion between electromagnetic energy and mechanical energy in a motor. After the motor is powered off, the rotor time constant determines the speed of electromagnetic energy attenuation, and then affects the attenuation speed of stator voltage. Generally speaking, the greater the rotor time constant is, the slower the electromagnetic energy decays and the slower the stator voltage decays; On the contrary, the smaller the rotor time constant is, the faster the stator voltage decays.

2.3. Analysis of magnetomotive force under demagnetization fault

The analysis of magnetomotive force of PMSM under demagnetization fault needs to consider the influence of the change of permanent magnet magnetic field strength on magnetomotive force. When the demagnetization fault occurs in PMSM, the weakening or disappearance of the magnetism of the permanent magnet is a key change. This change has a profound impact on the magnetic field distribution inside PMSM, which is directly related to the magnetomotive force and overall performance of PMSM [18]. Permanent magnet is the key part to generate the main magnetic field in PMSM. When the permanent magnet is demagnetized, its magnetism weakens or disappears, resulting in a reduction in the strength of the main magnetic field [19]. With the decrease of the main magnetic field strength, the magnetic field distribution in PMSM will change. The originally uniformly distributed magnetic field may become uneven, and even the loss of magnetic field may occur in some areas. This uneven magnetic field distribution will directly affect the magnetomotive force of the motor.

Magnetomotive force (MMF) is a physical quantity that describes the ability of the internal magnetic field of a motor to produce electromagnetic torque. It is related to the magnetic field strength and the length of the magnetic circuit. Due to the decrease of the main magnetic field intensity caused by demagnetization, the magnetomotive force will be reduced accordingly. The reduction of the magnetomotive force will further affect the performance and output of the motor. The reduced magnetomotive force means that the electromagnetic torque generated by the motor will also be reduced. In addition, the length of the magnetic circuit may increase due to demagnetization, which further increases the reluctance, reduces the efficiency of the motor and increases the temperature rise. Therefore, when PMSM has demagnetization fault, the weakening or disappearance of permanent magnet magnetism will directly lead to the change of magnetic field distribution in the motor, and then affect the magnetomotive force and overall performance of the motor [20]. By comparing the changes of magnetomotive force before and after demagnetization, it can help diagnose whether the demagnetization fault has occurred in PMSM.

The general calculation formula of magnetomotive force is:

$$F = N \times I \times B \times l \tag{13}$$

Where, F is the magnetomotive force; N represents the number of coils wound in PMSM; I represents current; B is the magnetic field strength generated by the permanent magnet and current; l is the path length of the magnetic field inside the motor.

In case of demagnetization fault, the magnetic field intensity generated by permanent magnet and current will change. Assuming that the magnetic field strength generated by the permanent magnet and current in the normal state is B_0, and the magnetic field strength after demagnetization of PMSM becomes B', the magnetomotive force under demagnetization fault can be expressed as:

$$F' = N \times I \times B' \times l \tag{14}$$

When the permanent magnet is demagnetized, the magnetic field intensity B generated by the permanent magnet and current will decrease. This will lead to the change of the magnetic field distribution in the PMSM, and then affect the magnetomotive force of the PMSM. As the magnetic field strength of the permanent magnet decreases, the magnetomotive force F' will also decrease accordingly. This will reduce the electromagnetic torque of PMSM, and then affect the output performance of PMSM. Demagnetization fault will lead to the performance degradation of PMSM, including the reduction of output power and efficiency. At the same time, the dynamic response and stability of the motor may also be affected due to the reduction of the magnetomotive force.

Given the symmetrical layout of the three-phase windings a, b, and c in the motor, once a permanent magnet experiences demagnetization failure, not only will the back electromotive force of the a-phase winding be affected, but also indirectly, through the magnetic field coupling effect inside the motor, it will have a certain degree of influence on the back electromotive force of the b-phase and c-phase windings, although this influence may be relatively limited. The back EMF of phase a winding is shown in Fig. 2.

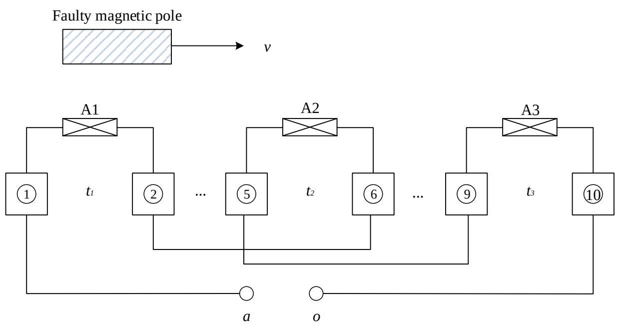

Fig. 2 Schematic diagram of the back electromotive force of phase A winding

If the demagnetization degree of the i permanent magnet is expressed as M_{Di}, the demagnetization range can be expressed as $0 \leq M_{Di} \leq 100\%$. If the demagnetization degree of the normally running permanent magnet is M_{Di} after demagnetization fault, the calculation process of the back EMF amplitude of the permanent magnet is as follows:

$$E_{mi} = E_{m0}(1 - M_{Di}) \tag{15}$$

E_{mi} represents the amplitude of the back electromotive force after a local demagnetization fault, and E_{m0} represents the amplitude of the back electromotive force of the permanent magnet under normal conditions. For permanent magnets that undergo local demagnetization, the amplitude E_{mi} of the generated back electromotive force should not exceed or be equivalent to the amplitude of a normal permanent magnet after normalization, denoted as $E_{mi} \leq 1$. This is because the amplitude of the normal permanent magnet has been set to the normalized maximum value of 1.

2.4. Detection and diagnosis of demagnetization faults in permanent magnet synchronous motors

The electrical equation of PMSM in abc three-phase coordinate system mainly describes the relationship between the voltage, current and flux of the motor. These equations include voltage equation, flux equation and so on, which provide a basis for understanding the electromagnetic characteristics of the motor. By analyzing the parameters of voltage, current and flux in the electrical equation, we can deeply understand the electromagnetic characteristics of the motor, and then judge whether the demagnetization fault of the permanent magnet occurs. Parameters in the electrical equation (such as voltage, current, etc.) are used as input data. By collecting and analyzing these data, the feature information related to demagnetization fault can be extracted, and then accurate fault identification can be achieved. Let the electrical equation of PMSM for abc three phase be:

$$[V_{s,abc}] = [R_{sh}][i_{s,abc}] + \frac{d}{dt}[\lambda_{s,abc}] \tag{16}$$

$[\lambda_{s,abc}]$ represents the phase voltage of the stator winding; $[V_{s,abc}] = [V_a, V_b, V_c]^T$ represents a parameter related to voltage; $[R_{sh}]$ represents the phase resistance of the stator winding; $[R_{sh}] = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix}$ is an explanation or factor related to phase resistance; $[i_{s,abc}]$ represents the phase current of the stator winding; And $[i_{s,abc}] = [i_a, i_b, i_c]^T$ represents the magnetic flux of the stator winding.λ_{PM} is used to represent the amplitude of the flux linkage generated by the rotor permanent magnet. The flux linkage generated by the rotor permanent magnet can be expressed as:

$$[\lambda_{PM,abc}] = \lambda_{PM} \begin{bmatrix} \cos\theta \\ \cos\left(\theta - \frac{2}{3}\pi\right) \\ \cos\left(\theta + \frac{2}{3}\pi\right) \end{bmatrix} \tag{17}$$

Demagnetization fault refers to the phenomenon that the magnetism of permanent magnet is weakened due to long-time operation, high temperature, external magnetic field interference and other factors. The permanent magnet flux linkage can reflect the interaction between the magnetic field generated by the permanent magnet and the motor winding. When the demagnetization fault occurs, the magnetic field generated by the permanent magnet will be weakened, which will lead to the reduction of the permanent magnet flux linkage parameters. Since the reduction of permanent magnet flux linkage parameters is the direct manifestation of demagnetization fault, it is possible to determine whether demagnetization fault has occurred by monitoring PMSM permanent magnet flux linkage.

Sensors or data acquisition systems are used to monitor the parameters of permanent magnet flux linkage in real time. The parameters of permanent magnet flux linkage monitored in real time were compared with those of the normal operation of the motor. If the monitored parameters decrease significantly, it may indicate that the motor has demagnetization fault. In order to judge demagnetization fault more accurately, the flux linkage value of motor stator can be determined first. In permanent magnet motor control system, voltage model is widely used as the basis of fault detection module. The model calculates the flux linkage of the motor stator by integrating the input voltage and current values. As follows:

$$\begin{cases} e_\alpha = u_\alpha - Ri_\alpha \\ e_\beta = u_\beta - Ri_\beta \\ \Psi_\alpha = \int e_\alpha dt \\ \Psi_\beta = \int e_\beta dt \end{cases} \tag{18}$$

Where, e_α and e_β are the back EMF of PMSM stator; Ψ_α and Ψ_β represent the flux linkage value of PMSM stator.

According to the calculated flux linkage value of PMSM stator, it can be exchanged with the coordinates of q axis and d axis to obtain:

$$\begin{bmatrix} \Psi_d \\ \Psi_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \Psi_a \\ \Psi_b \end{bmatrix} \tag{19}$$

Considering that the rotor of PMSM (Permanent Magnet Synchronous Motor) uses permanent magnets and does not rely on stator current for excitation, the design of the control system is simplified and its complexity is reduced, L_d and L_d are ignored, and Ψ_d is directly equivalent to Ψ_f. The calculation formula is as follows:

$$\Psi_f = \Psi_d = L_d i_d \tag{20}$$

Where, L_d is the inductance component; L_d is the current of axis d.

When the PMSM is operated for the first time, the flux linkage is calculated by using the above calculation formula to obtain a value, which is used as the initial flux linkage value of the PMSM permanent magnet. The flux linkage value of PMSM is observed in real time through the flux linkage observation module and the observed value Ψ_g is obtained. Ψ_f flux linkage threshold Ψ_{max} is set as a marker to measure whether there is demagnetization fault. The flux linkage observed value Ψ_g is compared with the flux linkage threshold Ψ_{max}. when $\Psi_g \geq \Psi_{max}$, the demagnetization fault of PMSM is determined.

So far, based on the transient analysis of stator back EMF attenuation, the design of local demagnetization fault diagnosis method for permanent magnet synchronous motor is realized. The diagnosis process is shown in Fig. 3.

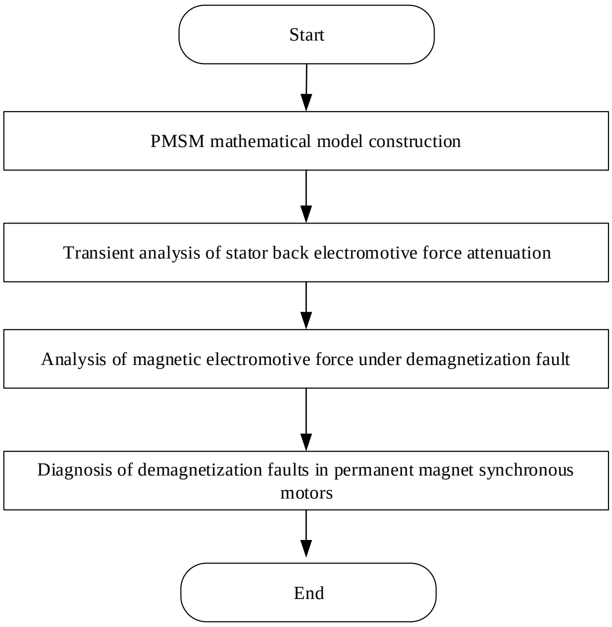

Fig. 3 Diagnosis process for local demagnetization faults in permanent magnet synchronous motors

3. Experiment

3.1. Experimental setup

In this experimental setup, HCP series htypg90s-8 low speed direct drive permanent magnet synchronous motor purchased by aeromagnetic motor manufacturing (Hubei) Co., Ltd. is selected as the core control object. The motor stands out in the field of motor with its excellent performance and integrated design, which provides a solid foundation for the experiment. Specific parameters are shown in Table 1.

Table 1 PMSM parameter description

Project	Parameter
Rated voltage/V	380
Synchronous/r·min	3000
Rated current/A	2.6
Rated frequency/Hz	200
Rated power/kW	1.5
Rated torque/N·m	4.8
Rated Efficiency/%	90.9
Rated power factor	0.96

Matlab 2019a simulation software is used to obtain the three-phase current of the rotor rotating for one cycle. The three-phase stator current under healthy state is shown in Figure 4.

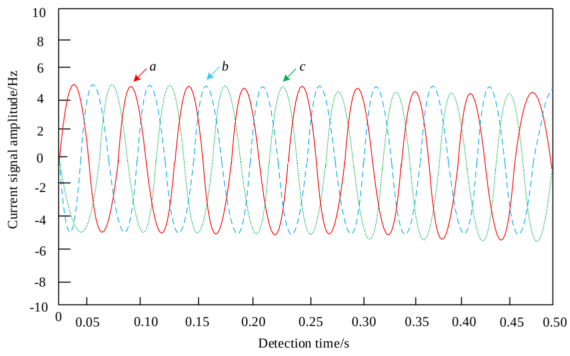

Fig. 4 Three phase stator current in healthy state

Using weak magnets to replace the original normal magnetic poles to simulate local demagnetization faults. Specifically, different levels of fault severity are displayed by demagnetizing 30% and 70% of a single magnetic pole. The weak magnet is shown in Fig. 5.

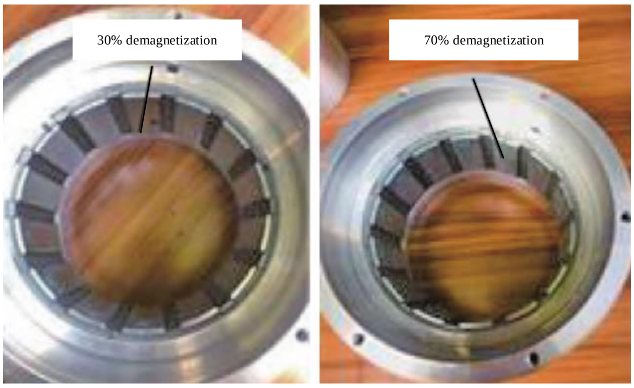

Fig. 5 Replacement of weak magnets

Through five experiments, the three-phase current of the rotor rotating for one cycle under 30% demagnetization fault of single pole and 70% demagnetization fault of single pole is counted, as shown in Fig. 6 and Fig. 7.

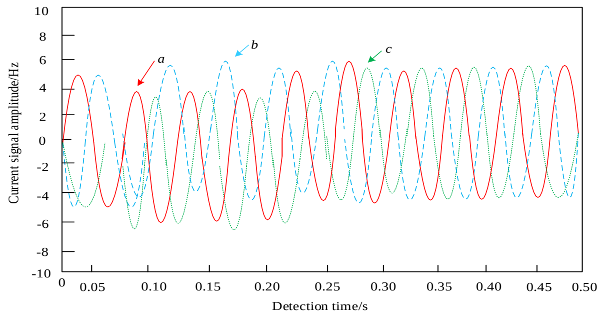

Fig. 6 Single pole 30% demagnetization fault three-phase current

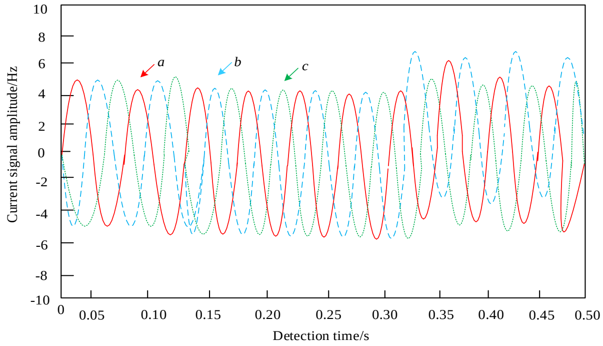

Fig. 7 Single pole 70% demagnetization fault three-phase current

3.2. Experimental results and analysis

3.2.1. Comparison of mean square error

The methods proposed in references [5], [6], and the transient analysis based on stator back electromotive force attenuation were applied to diagnose local demagnetization faults in permanent magnet synchronous motors. In order to evaluate the performance of different methods, the mean square error of the diagnostic results was calculated and the comparison results are listed in Table 2.

Table 2 Comparison of mean square error of diagnostic results using different methods

Demagnetization degree/%	Proposed method	Reference [5] Method	Reference [6] Method
30	0.78	2.61	3.54
40	0.72	2.53	3.50
50	0.65	2.51	3.48
60	0.72	2.48	3.46
70	0.65	2.46	3.45
80	0.66	2.46	3.43
90	0.63	2.48	3.43

It can be seen from the data in Table 2 that the results of different methods for diagnosis of local demagnetization fault of permanent magnet synchronous motor have different degrees of mean square error. Using the Reference [5] method to diagnose the local demagnetization fault of permanent magnet synchronous motor, the mean square error is 2.46~2.61;When using the method described in reference [6] to diagnose local demagnetization faults in permanent magnet synchronous motors, the mean square error range is between 3.43 and 3.54; By applying the method proposed in this article, the mean square error significantly decreased to 0.63 to 0.78 and remained below 1, which is much lower than the comparison method. This strongly proves the accuracy and reliability of the method in diagnosing local demagnetization faults in permanent magnet synchronous motors.

3.2.2. AUC Comparison

In order to further verify the effectiveness of this method for the diagnosis of local demagnetization fault of permanent magnet synchronous motor, taking the AUC value as the evaluation index, the methods in references [5] and [6], as well as the technique based on transient analysis of stator back electromotive force attenuation proposed in this paper, were used to diagnose local demagnetization faults in permanent magnet synchronous motors.. Calculate the AUC value of the diagnosis results of different methods, as shown in Fig. 8.

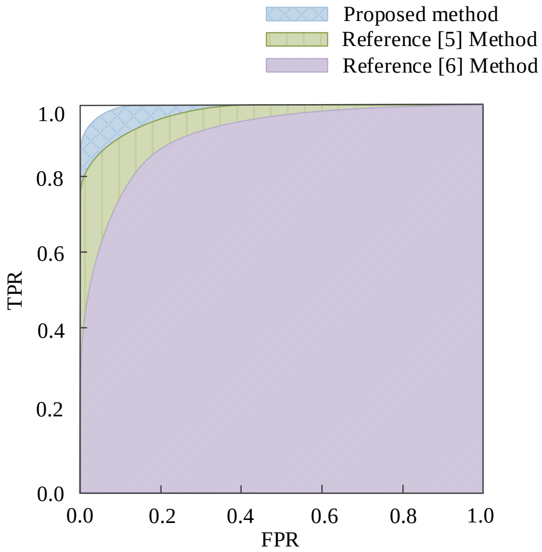

Fig. 8 Comparison of AUC values of diagnostic results using different methods

As shown in Figure 8, when the method proposed in this paper is applied to the diagnosis of local demagnetization faults in permanent magnet synchronous motors, the ROC curve is significantly close to the upper left corner, and the AUC value is close to 1. This highlights the accuracy of the proposed method in demagnetization fault diagnosis, which can achieve low false alarm rates while ensuring high recall rates.

4. Conclusion

During the operation of permanent magnet synchronous motor (PMSM), demagnetization fault is a problem that cannot be ignored. It may lead to motor performance degradation, energy consumption increases and even equipment damage. Therefore, ensuring accurate and rapid diagnosis of demagnetization faults in permanent magnet synchronous motors has crucial practical value. The local demagnetization fault diagnosis method of permanent magnet synchronous motor based on the transient analysis of stator back EMF attenuation proven effective. By constructing a mathematical model, analyzing the stator back EMF attenuation process and calculating the amplitude of permanent magnet back EMF, the accurate observation of permanent magnet flux linkage and the effective diagnosis of demagnetization fault are successfully realized. The experimental results show that the proposed method has high diagnostic accuracy and reliability, the mean square error is always kept at a low level, and the AUC value is close to the ideal value of 1, indicating that the method can accurately identify the demagnetization fault, and has certain advantages.

Looking forward to the future, we will continue to study the diagnosis technology of demagnetization fault of permanent magnet synchronous motor, further optimize the algorithm and improve the experimental verification. It is planned to apply this method to a wider range of motor fault diagnosis scenarios to meet the needs of different industries and fields for motor fault diagnosis, and provide a more comprehensive and efficient guarantee for the safe and stable operation of the motor.

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