Mode Recognition and Fault Positioning of Permanent Magnet Demagnetization for PMSM

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Abstract: This paper proposes a demagnetization fault detection, mode recognition, magnetic pole positioning, and degree evaluation method for permanent magnet synchronous motors. First, the analytical model of the single-coil no-load back electromotive force (EMF) of demagnetization fault for Permanent magnet synchronous motor (PMSM) arbitrary magnetic poles is established. In the analytical model, the single-coil no-load back EMF residual of the health state and the single magnetic pole sequential demagnetization fault are calculated and normalized. Model results are used as the fault sample database. Second, the energy interval database of the single-coil no-load back EMF residual with different numbers of magnetic pole demagnetization is established. Demagnetization fault detection and degree evaluation are performed by the real-time acquired amplitudes of the single-coil no-load back EMF residual. The number of demagnetization poles is determined by comparing the energy of the single-coil no-load back EMF residual with the energy interval database. Demagnetization mode recognition and magnetic pole positioning are realized by analyzing the correlation coefficients between normalized the single-coil no-load back EMF residual and the fault sample database. Finally, results of analysis of the finite element simulation validate the feasibility and effectiveness of the proposed method.

Keywords: Permanent magnet synchronous motor (PMSM); fault mode recognition; single-coil no-load back electromotive force (EMF); analytical model; correlation coefficient; fault sample database

1. Introduction

PMSM is widely used in electric vehicles, industrial robots, and aerospace fields, because of their high-power density, high efficiency, and ease of control [1]. Due to complex operating conditions, narrow installation space and poor heat dissipation environment, PMSM has a high probability of fault, which can be classified into three main categories: stator fault, rotor fault and bearing fault [2]. Stator fault include turn-to-turn short circuit, phase-to-phase short circuit, phase-to-neutral short circuit, and open circuit fault. Rotor fault include eccentricity and demagnetization fault. Bearing fault include outer race, inner race, and ball bearing fault. Permanent magnets are subjected to local demagnetization fault or uniform demagnetization fault because of the combined effects of armature reaction, the operating temperature rise and brittleness of sintered rare earth permanent magnet material [3–5]. When the permanent magnet has an irreversible demagnetization fault, the motor seriously heats up and the overload capacity will decline, thereby leading to performance degradation. In serious cases, the motor may go out of control and be scrapped. The diagnosis of the early demagnetization fault of the motor can improve the reliability of the motor operation, guide the maintenance, prolong the service life, and reduce sudden accidental shutdown. Therefore, studying
PMSM demagnetization fault detection, demagnetization mode recognition, magnetic pole positioning, and accurate evaluation of fault degree is of great significance.

In recent years, many scholars have performed many experiments on PMSM demagnetization fault. In [6,7], advanced signal processing technology is used to extract stator current harmonics from demagnetization fault, and the local demagnetization fault diagnosis of PMSM permanent magnet is realized. In [8], the demagnetization fault of PMSM is diagnosed by the harmonic characteristics of the back EMF. In [9], the index is obtained by analyzing the rotary radius of the cogging torque signal to diagnosis the uniform demagnetization fault of PMSM. In [10], a noninvasive approach to detect the uniform demagnetization for surface-mounted PMSM based on the acoustic noise analysis from a back propagation neural net-work (BPNN) model was presented. In [11], multi-sensor information, namely acoustic noise and torque, is used for demagnetization detection through the information fusion technique. In [12,13], through the establishment of flux observer of motor permanent magnet, the on-line detection of demagnetization fault and the evaluation of demagnetization degree are realized according to the size of observed flux chains.

In the field of demagnetization mode recognition [14,15], the change of PMSM electrical characteristics caused by the change of PMSM magnetic circuit state before and after demagnetization of permanent magnets is used as a diagnostic criterion for demagnetization fault of permanent magnets by high frequency signal injection. Demagnetization mode recognition and demagnetization degree evaluation are performed. However, this method needs to reasonably determine the amplitude and frequency of the injected high-frequency signal, which affects the accuracy of detection. In [16], direct acquisition of the inductive potential of stator tooth flux is performed by embedding the detecting coil on each stator tooth. The recognition of demagnetization mode and the evaluation of demagnetization degree are in accordance with the radar diagram of each coil’s inductive potential. However, this method increases the volume and cost of the motor by installing a number of detection coils during the motor manufacturing phase. In [17], the method of combining permanent magnet flux observation with the instantaneous frequency analysis of the stator current of Hilbert–Huang is used to realize the demagnetization fault diagnosis and mode recognition of PMSM. However, the harmonic of the power supply cannot be distinguished. Considering the combination of two analytical methods, the algorithm is complex, and computation is heavy. In order to realize the demagnetization magnetic pole positioning, a previous study [18] used the amplitude of the back EMF of the branch as the fault characteristic quantity and monitor the amplitude change of the back EMF on the multiple branches in parallel of the permanent magnet synchronous generator rotor. Demagnetization fault detection and demagnetization magnetic pole positioning were realized. However, this method is affected by the motor’s structure. In [19], the probabilistic neural network (PNN) classification algorithm is used to locate the magnetic pole demagnetization fault of the permanent magnet synchronous linear motor at different positions. However, this method requires a large number of sample data as training samples, which requires a lot of calculations.

Considering the above-mentioned research progress and existing problems, the identification of local demagnetization and uniform demagnetization of PMSM and the location of demagnetization magnetic pole have become the key technologies to be solved in the field of demagnetization fault diagnostic. This paper presents a fault diagnostic method of PMSM demagnetization, which not only realizes demagnetization fault detection and degree evaluation, but also demagnetization fault mode recognition and fault magnetic pole positioning. Meanwhile, the method has less computation and is not affected by motor structure and parameters.

The paper is organized as follows: Section 2 introduces the structure and the parameters of PMSM. In Section 3, the single-coil no-load back EMF is established and compared to finite element simulation results. Section 4 presents the methods of demagnetization fault detection, mode recognition, fault magnetic pole positioning, and degree evaluation. Section 5 introduces the analysis of the finite element model (FEM) simulation results. A brief summary of this paper is presented in Section 6.
2. Structure and Parameters of PMSM

This paper focuses on demagnetization in a surface-mounted PMSM with 66 poles and 72 slots. Table 1 shows the parameters of the motor. The motor structure is shown in Figure 1. Note that stator uses fractional-slot concentrated teeth-separate winding, and each phase is composed of three branches in parallel. Each branch routes four coils in series. The magnetic pole adopts surface mounted equidistant distribution. The motor adopts NdFeB as the permanent magnet material. The simulation analysis of demagnetization fault of PMSM permanent magnet in varying degrees is realized by changing the coercivity (Hc) size.

Table 1. The key parameters of the PMSM.

| Items                        | Values | Unit |
|------------------------------|--------|------|
| Out diameter of stator       | 360    | mm   |
| Inner diameter of stator     | 300    | mm   |
| Air-gap length               | 1.2    | mm   |
| Wire diameter of winding     | 1.3    | mm   |
| Area of slot                 | 154    | mm²  |
| Thickness of PM              | 5.3    | mm   |
| Angle of PM                  | 5°     |      |
| Axial length                 | 150    | mm   |
| Rated power                  | 10     | kW   |
| Rated speed                  | 200    | r/min |
| Number of phases             | 3      |      |
| Number of coils              | 36     |      |
| Coil turn                    | 48     |      |
| Parallel-circuits per phase | 3      |      |
| Slot-Pole combination        | 72–66  |      |

![Figure 1. Structure of the PMSM: (a) structural representation of PMSM; (b) the rotor of PMSM.](image)

3. The Analytical Model of Single-Coil No-Load Back EMF of PMSM Demagnetization Fault

3.1. The Analytical Model of Single-Coil No-Load Back EMF

The analytical model of single slot no-load back EMF of demagnetization fault for arbitrary poles of PMSM under rated operation has been established in [20], which shows the single slot no-load back EMF and adjacent slot no-load back EMF of demagnetization fault for arbitrary poles of the prototype at any speed. The single-coil no-load back EMF is established in this paper, and the single-coil no-load back EMF residual is shown in Equations (1)–(4) (PMSM with the same winding connection law), as follows:

\[ e_1(t) = E_n \sin(2\pi ft) [1 - \sum_{i=1}^{2p} b_i \left( \frac{1}{2p} + \sum_{k=1}^{\infty} \frac{2}{ \pi k} \sin \left( \frac{k\pi}{2p} \right) \cos \left( \frac{k\pi ft}{p} - \frac{(2i-1)\pi}{2p} \right) \right)] \]  (1)
\[ e_2(t) = E_s \sin(2\pi ft - \frac{2\pi n}{Q}) \left[ 1 - \sum_{i=1}^{2p} \delta_i \left( \frac{1}{2p} + \sum_{k=1}^{\infty} \frac{2}{p} \sin\left(\frac{k\pi f t}{p} - \frac{(2i-1)k\pi}{2p} - \frac{2k\pi}{Q}\right) \right) \right] \]  

(2)

\[ e_c(t) = e_1(t) - e_2(t) = E_s \left[ \sin(2\pi ft) \left( 1 - \sum_{i=1}^{2p} \delta_i \left( \frac{1}{2p} + \sum_{k=1}^{\infty} \frac{2}{p} \sin\left(\frac{k\pi f t}{p} - \frac{(2i-1)k\pi}{2p} \right) \right) \right) \right] \]

\[ - \sin(2\pi ft - \frac{2\pi n}{Q}) \left( \frac{1}{2p} + \sum_{k=1}^{\infty} \frac{2}{p} \sin\left(\frac{k\pi f t}{p} - \frac{(2i-1)k\pi}{2p} - \frac{2k\pi}{Q}\right) \right) \]  

(3)

\[ e_{\text{residual}}(t) = e_{\text{health}}(t) - e_c(t) = \sum_{i=1}^{2p} \delta_i E_s \sin(2\pi ft) \right( \frac{1}{2p} + \sum_{k=1}^{\infty} \frac{2}{p} \sin\left(\frac{k\pi f t}{p} - \frac{(2i-1)k\pi}{2p} \right) \right) \]

\[ - \sin(2\pi ft - \frac{2\pi n}{Q}) \left( \frac{1}{2p} + \sum_{k=1}^{\infty} \frac{2}{p} \sin\left(\frac{k\pi f t}{p} - \frac{(2i-1)k\pi}{2p} - \frac{2k\pi}{Q}\right) \right) \]  

(4)

where \( p \) is the number of pole pairs, \( f \) is the supply frequency, \( Q \) is the number of stator slots, \( E_s \) is the peak of the no-load fundamental back EMF of a single slot, \( i \) is the serial number of the magnetic poles of the motor, \( \delta_i \) is the degree of demagnetization of the corresponding numbered pole, and \( \delta_i = 0 \) under the healthy state. \( e_{\text{health}} \) is the single-coil no-load back EMF under the healthy state.

### 3.2. The Comparison of Simulation Results Between the Analytical Model and the FEM

Using the established analytical model to calculate the single-coil no-load back EMF at rated speed and 100 r/min speeds, we determined that 75%, 50%, and 25% of irreversible demagnetization occur at the Pole 1 and 75%, 50%, and 25% of irreversible demagnetization occurs respectively at the Pole 1 and 2 at the same time. The comparison of simulation results between the analytical model and the FEM is shown in Figure 2. The single-coil no-load back EMF in the diagram has been normalized. There is a certain error between the simulation results of the analytical model and the FEM. This is due to the existence of harmonic components in the single-coil no-load back EMF in the motor, but the analytical model only takes into account the fundamental components of the single-coil no-load back EMF in the PMSM. Moreover, under different degrees of demagnetization fault, more changes in the harmonic components of single-coil no-load back EMF are observed with increasing demagnetization degree. However, the FEM simulation results are basically in agreement with analytical model results, which verified the correctness of the analytical model.

![Figure 2. Cont.](image-url)
4. The Methods of Demagnetization Fault Detection, Mode Recognition, Magnetic Pole Positioning, and Degree Evaluation

4.1. The Method of Demagnetization Fault Diagnosis

The PMSM demagnetization fault diagnosis method is shown in Figure 3. First, the fault sample database of the single pole demagnetization fault sample database is established. Second, any coil is designated as the detecting coil of the motor to be diagnosed, and the single-coil no-load back EMF residual ($e_{\text{residual}}$) is obtained by the Equation (5). Then, demagnetization fault detection is realized by comparing the $e_{\text{residual}}$ energy. The $e_{\text{residual}}$ is normalized to obtain $e_{\text{norm}}$. Demagnetization mode recognition and magnetic pole positioning is realized by the results of correlation coefficient analysis among the $e_{\text{norm}}$ and the fault sample database. Finally, the degree of demagnetization is evaluated according to the amplitudes of $e_{\text{residual}}$.

$$e_{\text{residual}} = e_{\text{health}} - e_c$$

where $e_{\text{health}}$ is the single-coil no-load back EMF under the healthy state, $e_c$ is the single-coil no-load back EMF obtained in real time.

4.2. Establishment of Demagnetization Fault Sample Database

First, the single-coil no-load back EMF under healthy state and demagnetization fault of different poles is obtained by the established analytical model. The single-coil no-load back EMF under healthy state and the successive demagnetization faults of the numbered poles are obtained. The Equation (6) is used to calculate the single-coil no-load back EMF residual of each numbered permanent magnets single pole demagnetization fault, which $a_1, a_2, \ldots, a_{2p}$ taken as the fault characteristic quantity. In Figure 4 shows the extraction process of the fault characteristic quantity during demagnetization of Pole 1, and the extraction process of the fault characteristic quantity of other numbered pole is the same as that of Pole 1.

$$a_i = e_{\text{health}} - e_i = 1, 2, 3 \cdots, 2p$$

where $e_i$ is the single-coil no-load back EMF under single pole demagnetization fault, $i$ is the numbered of the magnetic poles of the motor, $p$ is the number of pole pairs.
Whether the $e_{\text{residual}}$ amplitudes is greater than the threshold $(\text{Thr1})$?

Healthy state

The correlation coefficient $(k_1, k_2, \ldots, k_n)$ among the normalized $e_{\text{residual}}$ $(e_{\text{norm}})$ and the fault sample database

Whether $k_{\text{max}}$ is greater than the threshold $(\text{Thr2})$?

Uniform demagnetization fault

Local demagnetization fault

Demagnetization pole positioning by the energy of among $e_{\text{residual}}$ and $k_1, k_2, \ldots, k_n$

The demagnetization degree is evaluated according to the amplitudes of $e_{\text{residual}}$

The demagnetization degree is evaluated according to the amplitudes of $e_{\text{residual}}$

Figure 3. Diagnosis flow chart of demagnetization fault.

Figure 4. Extraction process of demagnetization fault eigenvector: (a) the waveform of single-coil no-load back EMF under healthy state and demagnetizing fault; (b) the waveform of $e_{\text{residual}}$ under demagnetizing fault.
To eliminate the influence of different demagnetization fault degrees on the fault characteristic quantity amplitude of permanent magnet and realize demagnetization fault mode recognition, the above mentioned fault characteristic quantity $a_1, a_2, \ldots, a_{2p}$ are normalized into $b_1, b_2, \ldots, b_{2p}$ which are stored in demagnetization fault sample database.

The waveform of fault characteristic quantity is shown in Figure 5. When demagnetization fault occurs at different numbered magnetic poles in turn, the waveform of the $e_{\text{norm}}$ of the latter pole will have a half-period that coincides with that of the former pole.

![Figure 5. Demagnetization fault characteristic quantity waveform.](image)

4.3. The Demagnetization Fault Detection and Mode Recognition

In order to achieve demagnetization fault detection, the comparison between the peak of $e_{\text{residual}}$ and the set threshold (Thr1) is adopted. Considering the influence of noise and modeling error and after undergoing many experiments and simulation analysis, the threshold of demagnetization fault detection in this prototype is set to 0.1 (Thr1 = 0.1). When the single-coil no-load back EMF residual is greater than Thr1, the motor to be diagnosed has a demagnetization fault. Otherwise, it is healthy.

The Equation (7) is used to calculate the correlation coefficients $(k_1, k_2, \ldots, k_{2p})$ between the $e_{\text{norm}}$ and fault sample characteristic quantity $(b_1, b_2, \ldots, b_{2p})$.

$$k_i = \frac{\text{Cov}(e_{\text{norm}}, b_i)}{\sqrt{D(e_{\text{norm}})} \sqrt{D(b_i)}} \quad i = 1, 2, 3, \ldots, 2p$$

(7)

where $\text{Cov}(e_{\text{norm}}, b_i)$ is the covariance of the normalized single-coil no-load back EMF residual $e_{\text{norm}}$ and fault sample database $b_i$ $(i = 1, 2, \ldots, 2p)$. $D(e_{\text{norm}})$ and $D(b_i)$ are the variances of normalized single-coil no-load back EMF residual ($e_{\text{norm}}$) and fault sample database $b_i$ $(i = 1, 2, \ldots, 2p)$ respectively.

Calculate the average of the correlation coefficients $(k_1, k_2, \ldots, k_{2p})$, and then calculate the absolute value of the difference between the correlation coefficients and the mean, and calculate the maximum value ($k_{\text{max}}$) of the absolute value. As shown in Equation (8).

$$k_{\text{max}} = \max \left| k_i - \frac{1}{2p} \sum_{i=1}^{2p} k_i / 2p \right| \quad i = 1, 2, 3, \ldots, 2p$$

(8)

where $k_i$ is the correlation coefficients between the $e_{\text{norm}}$ and the numbered characteristic quantity, $p$ is the number of pole pairs.

In order to achieve demagnetization fault mode recognition, the comparison between the $k_{\text{max}}$ and the set threshold (Thr2) is adopted. After taking into account the modeling error and the existence of noise during signal acquisition, the threshold is set to 0.05 (Thr2 = 0.05). When the $k_{\text{max}}$ greater than the set threshold, the motor to be diagnosed has local demagnetization fault. Otherwise, it has the uniform demagnetization fault.
When the motor is under the uniform demagnetization fault condition, the correlation coefficients between the $e_{\text{norm}}$ and each sample characteristic quantity are shown in Table 2. The correlation coefficient is basically the same under the same degree of demagnetization. Calculate the size of $k_{\text{max}}$ in Table 2 by the Equation (8), which are 0.0065 and 0.0052 respectively. The $k_{\text{max}}$ is less than the Thr2.

Table 2. Correlation coefficients between the $e_{\text{norm}}$ of uniform demagnetization fault and fault sample database.

| Sample Characteristic Quantity Numbered | Uniform Demagnetization Fault Degree |
|----------------------------------------|--------------------------------------|
|                                        | Fault 25%   | Fault 75%   |
| 1                                      | 0.1748      | 0.1747      |
| 2                                      | 0.1749      | 0.1749      |
| 3                                      | 0.1749      | 0.1748      |
| 4                                      | 0.1746      | 0.1746      |
| 5                                      | 0.1749      | 0.1745      |
| 6                                      | 0.1741      | 0.1743      |
| 7                                      | 0.1740      | 0.1746      |
| 8                                      | 0.1742      | 0.1741      |
| ...                                    | ...         | ...         |
| $2p$                                   | 0.1747      | 0.1746      |

When the motor is under the local demagnetization fault condition, the correlation coefficients between the $e_{\text{norm}}$ and each sample characteristic quantity is shown in Table 3. The correlation coefficients are inconsistent under the same degree of demagnetization. Calculate the size of $k_{\text{max}}$ in Table 3 by the Equation (8), which are 0.0065 and 0.0052 respectively. The $k_{\text{max}}$ is much greater than the Thr2. Meanwhile, the correlation coefficient with the corresponding numbered fault sample is close to 1, and the correlation coefficient with the fault sample of the two numbered adjacent to the corresponding numbered fault sample is 0.5. This result is due to that the waveform of the $e_{\text{norm}}$ of a single pole demagnetization fault coincides with the waveform of the fault sample of the corresponding numbered, and with the waveform of the two adjacent numbered fault sample have a half cycle coincidence.

Table 3. Correlation coefficients between the $e_{\text{norm}}$ of single Pole 2 demagnetization fault and fault sample database.

| Sample Characteristic Quantity Numbered | Local Demagnetization Fault Degree |
|----------------------------------------|-----------------------------------|
|                                        | Fault 25%   | Fault 75%   |
| 1                                      | 0.5         | 0.5         |
| 2                                      | 1           | 1           |
| 3                                      | 0.5         | 0.5         |
| 4                                      | $-2.1972 \times 10^{-8}$          | $-2.1982 \times 10^{-8}$ |
| 5                                      | $9.9593 \times 10^{-11}$          | $9.9571 \times 10^{-11}$ |
| 6                                      | $1.1050 \times 10^{-10}$          | $1.1140 \times 10^{-10}$ |
| 7                                      | $1.1051 \times 10^{-10}$          | $1.1041 \times 10^{-10}$ |
| 8                                      | $9.8452 \times 10^{-11}$          | $9.8471 \times 10^{-11}$ |
| ...                                    | ...         | ...         |
| $2p$                                   | $1.1131 \times 10^{-10}$          | $1.1067 \times 10^{-10}$ |

4.4. Fault Magnetic Pole Positioning

First, the energy of the single-coil no-load back EMF residual with different numbers of magnetic poles demagnetization is calculated by the Equation (9), and the energy interval database corresponding to the single-coil no-load back EMF residual of different number of magnetic pole demagnetization is established. When one magnetic pole demagnetization, the energy interval is set to [500–1000]. When two magnetic poles are demagnetized, the energy interval is set to [1000–2000]. When three
magnetic poles are demagnetized, the energy interval is set to [2000–3500]. They are obtained after many experiments and simulation analyses.

The energy of the $e_{\text{residual}}$ obtained in real time is compared to the energy interval library to determine the number of demagnetization poles as $N_{\text{fault}}$. Then, the correlation coefficient ($k_1, k_2, \ldots, k_{2p}$) between the $e_{\text{residual}}$ and the fault sample database as are calculated. The numbered of first $N_{\text{fault}}$ maximum correlation coefficients is the numbered of the demagnetization fault magnetic pole.

$$E = \sum_{n=1}^{m} c^2(n)$$

where $m$ is the number of sampling points in a rotation period during which the motor operates. $n$ is the corresponding number of sampling points. $c(n)$ is the value of the $n$ sample point of the single-coil no-load back EMF residual signal.

4.5. Demagnetization Fault Degree Evaluation

Equations (1)–(4) indicate the presence of the linear relationship between the magnitude of the single-coil no-load back EMF and the degree of demagnetization of PMSM. Therefore, there is also a linear relationship between the amplitude of the $e_{\text{residual}}$ and the degree of demagnetization fault.

The $e_{\text{residual}}$ at different degrees of demagnetization of Pole 1 is shown in Figure 6. It can be seen that with an increasing demagnetization degree, the amplitude of the $e_{\text{residual}}$ increases. Therefore, the peak of the $e_{\text{residual}}$ with 100% demagnetization degree is the reference value, and the peak of the $e_{\text{residual}}$ obtained is divided by the reference value. When $(e_{\text{residual}}(t_{\text{peak}}) - e_{\text{residual}}(t_{\text{peak}} - 1)) * (e_{\text{residual}}(t_{\text{peak}}) - e_{\text{residual}}(t_{\text{peak}} + 1)) < 0$, the $e_{\text{residual}}(t_{\text{peak}})$ is the peak of the $e_{\text{residual}}$. The degree of demagnetization fault is shown in Equation (10), as shown below:

$$\delta = e_{\text{residual}}(t_{\text{peak}}) / e_{\text{residual}100\%}(t_{\text{peak}})$$

where $e_{\text{residual}100\%}$ is the $e_{\text{residual}}$ when demagnetization is 100%.

![Figure 6](image_url) The $e_{\text{residual}}$ waveform of different degree demagnetization fault.

5. Analysis of FEM Simulation Results

In order to verify the correctness of the proposed method, the finite element model is used to simulate the type and location of demagnetization faults of the first six poles. First, the coil A11 is designated as the detecting coil of the motor to be diagnosed, and the magnetic poles of the sample motor are numbered sequentially is shown in Figure 1b. Then, the A11 coil no-load back EMF is obtained by the finite element model, and the A11 $e_{\text{residual}}$ is obtained by the difference treatment between the A11 coil no-load back EMF and the A11 coil no-load back EMF under the healthy state.
5.1. Demagnetization Fault Detection and Mode Recognition

The $A_{11} e_{\text{residual}}$ in the healthy state, uniform demagnetization fault, and local demagnetization fault with 5% degree is shown in Figure 7. The $A_{11} e_{\text{residual}}$ is close to 0 in the healthy state, meanwhile, the $A_{11} e_{\text{residual}}$ is greater than the Thr1 in the case of weak demagnetization fault. Therefore, the amplitude of $A_{11} e_{\text{residual}}$ can be used as an index for detecting demagnetization fault.

![Figure 7](image)

Figure 7. $e_{\text{residual}}$ under healthy, uniform demagnetization fault, and local demagnetization fault.

The $A_{11} e_{\text{norm}}$ is obtained by normalization of $A_{11} e_{\text{residual}}$. Then, correlation coefficients $k_1$, $k_2$, ..., $k_6$ between $A_{11} e_{\text{norm}}$ and fault sample database $b_1$, $b_2$, ..., $b_6$ are calculated by the Equation (7). The correlation coefficients between the uniform demagnetization of varying degrees and the fault sample database are shown in Table 4. The correlation coefficients between $A_{11} e_{\text{norm}}$ and the fault sample are basically the same under the same demagnetization fault degree, and the $k_{\text{max}}$ is calculated by the Equation (8) to be less than the Thr2.

| Sample Characteristic Quantity Numbered | Uniform Demagnetization Fault Degree |
|----------------------------------------|--------------------------------------|
|                                        | Fault 12.5%  | Fault 25%  | Fault 50%  | Fault 75%  |
| 1                                      | 0.1952       | 0.1952     | 0.1952     | 0.1952     |
| 2                                      | 0.1952       | 0.1952     | 0.1952     | 0.1952     |
| 3                                      | 0.1954       | 0.1954     | 0.1954     | 0.1954     |
| 4                                      | 0.1951       | 0.1951     | 0.1951     | 0.1951     |
| 5                                      | 0.1951       | 0.1951     | 0.1951     | 0.1951     |
| 6                                      | 0.1954       | 0.1954     | 0.1954     | 0.1954     |

For single Pole 2 with varying degrees of demagnetization, the correlation coefficients between $A_{11} e_{\text{norm}}$ and fault sample database are shown in Table 5. Compared to uniform demagnetization fault, the correlation coefficients are very different under the same demagnetization fault degrees. They also differ under different demagnetization fault degrees. The correlation coefficients between $A_{11} e_{\text{norm}}$ of the demagnetization fault of different degrees of single Pole 2 and the fault sample of the corresponding number is close to 1, and the $k_{\text{max}}$ is calculated by the Equation (8) to be greater than the Thr2.
Table 5. Correlation coefficients between single pole 2 with different demagnetization degrees and fault sample database.

| Sample Characteristic Quantity Numbered | Local Demagnetization Fault Degree |
|----------------------------------------|------------------------------------|
|                                        | Fault 12.5% | Fault 25% | Fault 50% | Fault 75% |
| 1                                      | 0.4413      | 0.4492    | 0.4566    | 0.4613    |
| 2                                      | 0.9924      | 0.9958    | 0.9984    | 0.9996    |
| 3                                      | 0.4446      | 0.4474    | 0.4522    | 0.4567    |
| 4                                      | 0.0166      | 0.0187    | 0.0243    | 0.0289    |
| 5                                      | 0.0019      | 0.0005    | 0.0057    | 0.0104    |
| 6                                      | 0.0285      | 0.0299    | 0.0337    | 0.0373    |

By comparing uniform demagnetization fault and local demagnetization fault, the results of correlation coefficients between different demagnetization fault types and fault sample database are different. Thus, the demagnetization fault types can be distinguished according to this method.

5.2. Fault Magnetic Pole Positioning

According to Equation (9), the energy of the residual with different the number of demagnetization fault magnetic poles is shown in Table 6. When one magnetic pole demagnetization fault, the energy of the residual is in the energy interval [500–1000] that is set. When two magnetic poles demagnetization fault, the energy of the residual is in the energy interval [1000–2000] that is set. When three magnetic poles demagnetization fault, the energy of the residual is in the energy interval [2000–3500] that is set. Therefore, the number of demagnetization fault magnetic poles can be determined by comparing the magnitude of the residual energy with the energy interval library.

Table 6. The energy of the single-coil no-load back EMF residual with different numbers of demagnetization poles.

| One Pole Fault | Two Pole Fault | Three Pole Fault |
|----------------|----------------|------------------|
| Fault Pole     | Energy         | Fault Pole       | Energy         | Fault Pole | Energy         |
| 1              | 697            | 1, 2             | 1990           | 1, 2, 3    | 3276           |
| 2              | 699            | 1, 3             | 1433           | 1, 2, 4    | 2711           |
| 3              | 703            | 1, 4             | 1406           | 1, 3, 4    | 2700           |
| 4              | 699            | 1, 5             | 1458           | 1, 2, 5    | 2687           |
| 5              | 703            | 1, 6             | 1407           | 1, 3, 5    | 2273           |
| 6              | 699            | 2, 3             | 1995           | 2, 3, 4    | 3280           |

For the demagnetization fault with different numbers and positions, the correlation coefficient between the A11 residual and the fault sample database are listed in Table 7. When there is one magnetic pole demagnetization fault, and the numbered of the maximum correlation coefficient is the numbered of demagnetization fault magnetic pole. When there are two magnetic poles demagnetization fault, and the numbered of the first two maximum correlation coefficients are the numbered of demagnetization fault magnetic poles. When there are three magnetic poles demagnetization fault, the numbered of the first three maximum correlation coefficients is the numbered of demagnetization fault magnetic poles. The abovementioned results prove that this method can realize demagnetization fault magnetic pole positioning.
Table 7. Correlation coefficients between demagnetization fault and fault sample database.

| Sample Characteristic Quantity Numbered | Demagnetization Magnetic Pole Numbered |
|----------------------------------------|----------------------------------------|
|                                        | One Pole Fault                         |
|                                        | Two Pole Fault                         |
|                                        | Three Pole Fault                       |
| 1                                      | 2                                      |
| 2                                      | 3                                      |
| 3                                      | 4                                      |
| 4                                      | 5                                      |
| 5                                      | 6                                      |
| 6                                      | 1                                      |
| 7                                      | 2                                      |
| 8                                      | 3                                      |
| 9                                      | 4                                      |
| 10                                     | 5                                      |
| 11                                     | 6                                      |
| 12                                     | 7                                      |
| 13                                     | 8                                      |
| 14                                     | 9                                      |
| 15                                     | 10                                     |

5.3. Demagnetization Fault Degree Evaluation

The A11 coil no-load back EMF with degrees of uniform demagnetization is shown in Figure 8a. The amplitude of the A11 coil no-load back EMF increases with the degree of uniform demagnetization. The relationship between the degree of uniform demagnetization fault and the peak of the A11 \( e_{\text{residual}} \) is shown in Figure 9a. The peak of the A11 \( e_{\text{residual}} \) increases linearly with the degree of uniform demagnetization.

![Figure 8](image-url-8.png)

Figure 8. The single-coil no-load back EMF residual with different degrees of demagnetization fault: (a) uniform demagnetization fault; (b) single pole demagnetization fault.

![Figure 9](image-url-9.png)

Figure 9. The relationship between demagnetization degree and the peak of the single-coil no-load back EMF residual: (a) uniform demagnetization fault; (b) single pole demagnetization fault.

The degree of uniform demagnetization of calculated according to Equation (10) and the degree of demagnetization simulated by finite element model are as shown in Table 8. The degree of demagnetization fault calculated is basically consistent with the degree of demagnetization simulated by finite element model.
Table 8. Comparison of evaluation value and FEM results of uniform demagnetization.

| FEM Simulation Value | 0   | 25% | 50%  | 75%  | 100% |
|----------------------|-----|-----|------|------|------|
| evaluation value     | 0   | 25.01% | 50.00% | 74.99% | 100% |

The A11 coil no-load back EMF with different degrees of the single pole demagnetization is shown in Figure 8b. The residual amplitude of the A11 coil no-load back EMF of only increases in part of one rotating period, which is due to the fact that only when the demagnetization pole passes through the A11 coil, the amplitude of the A11 coil no-load back EMF demagnetization decrease, and the amplitude of the A11 coil no-load back EMF residuals will increase. Meanwhile, with increasing demagnetizing degree, the amplitude of A11 coil no-load back EMF residual is also increasing. The relationship between the degree of demagnetization of a single pole and the A11 $e_{\text{residual}}$ peak is shown in Figure 9b. The degree of demagnetization is linear with the A11 $e_{\text{residual}}$ maximum. With the increase of demagnetization degree, the peak of the A11 $e_{\text{residual}}$ increases linearly.

The degree of demagnetization of a single magnetic pole was calculated according to Equation (10) and the degree of demagnetization simulated by finite element model are as shown in Table 9. The degree of demagnetization fault calculated is basically consistent with the degree of demagnetization simulated by finite element model.

Table 9. Comparison of evaluation value and FEM results of single pole demagnetization fault.

| FEM Simulation Value | 0   | 25% | 50%  | 75%  | 100% |
|----------------------|-----|-----|------|------|------|
| evaluation value     | 0   | 25.02% | 50.03% | 74.97% | 100% |

6. Conclusions

This paper presents an analytical model of the single-coil no-load back EMF of demagnetization fault for PMSM arbitrary magnetic pole, as well as a diagnostic method of PMSM demagnetization fault. The method can not only realize the detection and degree evaluation of the demagnetization fault but also the recognition of the demagnetization mode and demagnetization magnetic pole positioning. The main conclusions are as follows:

1. The amplitude change of the single-coil no-load back EMF residual can realize the detection of demagnetization fault and the evaluation of demagnetization degree.
2. The demagnetization mode can be recognized by the correlation coefficient between the single-coil no-load back EMF residual and the demagnetization fault sample database.
3. The demagnetization fault energy interval database is established, and researchers realize the demagnetization magnetic pole positioning by the energy of the single-coil no-load back EMF residual and the correlation coefficient between the single-coil no-load back EMF residual and the fault sample database.

The study of the diagnostic method only extracted the single-coil back EMF residual under no load. Therefore, the extraction of single-coil back EMF residual under different loads will be studied in the future.

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