Numerical Study on the Influence of Non-uniform Demagnetization of Permanent Magnet Synchronous Motor

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Abstract: To study the influence of the non-uniform demagnetization of permanent magnets (PMs) on motor performance, this paper takes a two-phase four-pole Permanent Magnet Synchronous Motor (PMSM) as the research specimen. The influences of torque, phase current, back electromotive force (back-EMF), and radial magnetic density with different grades and types of demagnetization are analyzed. The simulation results show that as the degree of non-uniform demagnetization increases, the output torque and radial magnetic density gradually decrease, on the other hand, the phase current gradually increases. According to the change law of the amplitude of some harmonics of the back-EMF, it can be judged whether the motor has non-uniform demagnetization. This research conclusion can provide a theoretical basis for fault diagnosis of motor demagnetization.

1. Introduction
In recent years, Permanent Magnet Synchronous Motor (PMSM) has been widely used in high-speed trains, robots, electric vehicles (EV), other appliances by their remarkable advantages such as simple structure, stable operation, high efficiency, and diverse motor shapes. At the same time, the safety and stability of PMSM have received more and more attention [1-5].

At present, the research on motor demagnetization is mainly focusing on uniform demagnetization. ROSERO J, GRITLI Y, and FAIZ J studied the detection method of rotor demagnetization and judged whether the rotor is demagnetized by analyzing the amplitude of specific current harmonics, however, their detection methods have some limitations [6-9]. Wei D proposed an on-line monitoring method for local demagnetization faults of PMSM rotors based on a new detection coil. Through experiments, it is verified that the detection method can accurately determine the type of failure when the motor rotor has a small non-uniform demagnetization failure [10]. XueWei S established a permanent magnet synchronous linear motor model. Through the comparison of multiple characteristics of the multimodal graph and the PSO-LSSVM algorithm, a classification model for identifying the non-uniform demagnetization fault of PMSLM is established, and they claimed their recognition rate reaches 100%. However, there is a lack of comparison experiments with other failures [11]. CunXiang Y, CaiXia G, and NEJADI-KOTI H simulates the demagnetization of the motor by changing the flux linkage method for performance analysis. Unfortunately, only uniform demagnetization is considered in the models [12-15]. Besides simulation methods, an invasive experimental fault diagnosis method is proposed, the authors mentioned that method can classify the non-uniform demagnetization and the uniform demagnetization faults [16]. However, this method is not suitable for manufactured motors because the sensor must be installed in motor. Because most of the current researches focusing on the uniform demagnetization failure of the motor, the research needs to focus on the comprehensive study of the non-uniform
demagnetization failure.

To understand the influence of different grades and types of demagnetization, this paper proposed a Finite element method (FEM) to study the demagnetization fault through the analysis of the motor current, back-EMF, radial flux density, and output torque of different demagnetization models.

2. Non-uniform demagnetization model of PMSM

The magnetic strength of the permanent magnet mainly depends on the magnetic induction intensity $B$

$$B = -\mu_0 H_c + B_r$$  \(1\)

In Equation (1), $\mu_0$ is the vacuum permeability and its value is $4 \pi \times 10^{-7} \text{H/m}$, $H_c$ is the coercivity of the permanent magnetic material, $B_r$ is the residual magnetic induction.

From Equation (1), the demagnetization model of the motor can be obtained by reducing the coercive force and residual magnetic induction in an equal proportion.

When the motor has a non-uniform demagnetization failure, the amplitude of the motor's radial magnetic density will change. The expression of the radial magnetic density is shown in formula (2):

$$B_r = B_x \sin \phi + B_y \cos \phi$$  \(2\)

In the Equation, $B_x$ is the component of magnetic density along the X-axis; $B_y$ is the component of magnetic density along the Y-axis; $\phi$ is the angle between the radial magnetic density and the X-axis.

This paper takes a two-phase four-pole brushless DC motor as a case study. The main parameters of the motor are shown in Table. The distribution of the 4-level permanent magnets of the motor is shown in Figure 1(a). The distribution of magnetic field lines is shown in Figure 1(b). The single permanent magnet in this paper is permanent magnet No. 1. This paper simulates 10% to 70% of permanent magnet demagnetization failures.

| Parameter                        | Value   | Parameter                        | Value   |
|----------------------------------|---------|----------------------------------|---------|
| Outer diameter of stator /mm     | 120     | Number of pole pairs / pairs     | 2       |
| Stator inner diameter /mm        | 75      | Rated voltage /V                 | 220     |
| Rotor outer diameter /mm         | 67      | Rated speed /(r/min)             | 1500    |
| Rotor inner diameter /mm         | 27      | rated power /kW                  | 0.55    |
| Number of stator slots /Z        | 24      | Rated frequency /Hz              | 50      |
| Number of turns /Y               | 60      | Axial length /mm                 | 65      |

3. Results and discussions

3.1 The influence of non-uniform demagnetization fault on the output torque

After each demagnetization FEM model is built and the results are calculated, the output torques of a single permanent magnet (PM) demagnetized and all PMs uniform demagnetized 20%, 40%, and 60%
are shown in Figure 2 and Figure 3 respectively.

![Figure 2 Output torque of single permanent demagnetization](image)

![Figure 3 Output torque of permanent magnet magnet uniform demagnetization](image)

It can be seen from Figure 2 and Figure 3. As the degree of PM demagnetization intensifies, the amplitude of the output torque gradually decreases during the motor starting process, and the amplitude of the output torque increases when the motor is running stably. The amplitude change of the output torque can be used to judge whether the motor has a demagnetization fault on the single magnet or has uniform ones on all PMs.

### 3.2 The influence of non-uniform demagnetization failure on radial magnetic density

Using the same approach, the radial magnetic density of a single permanent magnet (PM) demagnetized and all PMs uniform demagnetized 20%, 40%, and 60% are shown in Figure 4 and Figure 5 respectively.

![Figure 4 Radial magnetic density of different degrees of non-uniform demagnetization](image)

![Figure 5 Radial magnetic density of different degrees of uniform demagnetization](image)

In Figure 4-5, it can be seen that as the non-uniform demagnetization of PM intensifies, the radial magnetic density at the demagnetized permanent magnet gradually decreases, and the radial magnetic density of two adjacent permanent magnets also decreases to varying degrees. When a single PM of the motor is demagnetized by 60%, the radial flux density has been reduced to 0.5T, which is reduced by 1/3. When the PMs are uniformly demagnetized by 60%, the radial magnetic density is already at a very low. It shows that the magnetic field has been severely distorted, which has affected the normal operation of the motor. Therefore, the radial magnetic density can be monitored online by the magnetic field sensor to determine the demagnetization status of the PM and improve the working efficiency of the motor.

### 3.3 The influence of non-uniform demagnetization fault on phase current

When the motor has a non-uniform demagnetization failure, it will affect the radial magnetic density. Moreover, it leads to increase the stator phase current sharply and damage the Insulated Gate Bipolar Transistor (IGBT).
Figure 6 The amplitude of Phase current of non-uniform demagnetization

Figure 7 The amplitude of the demagnetization phase current of all PMs

It can be seen from the figure 6-7 that as the degree of PM demagnetization intensifies, the phase current amplitude gradually increases, and the phase current amplitude increases more obviously during uniform demagnetization. The reason for the large surge in phase current is that the demagnetization of PMs will cause the back EMF to decay. According to the voltage balance equation, when the input voltage source remains unchanged, the decay of the back EMF will inevitably lead to increasing of the phase current.

The stator phase current in the Fast Fourier transform (FFT) domain with non-uniform and uniform demagnetization is shown in Figure 8 and Figure 9 respectively. The detailed information is listed in Table 2.

Figure 8 Harmonic amplitude of phase current of non-uniform demagnetization

Figure 9 Harmonic amplitude of phase current of uniform demagnetization

From Figure 8-9 and Table 2 we can see that as the degree of PM non-uniform demagnetization intensifies, the amplitudes of the fundamental wave and the 3rd harmonic gradually increase. As the degree of PM uniform demagnetization intensifies, the amplitudes of the 1/2th harmonic significant increase. This feature can be used to determine whether the motor has a uniform demagnetization failure.

Table 2 Harmonic amplitude of phase current of non-uniform demagnetization

| Demagnetization position | Degree of demagnetization | 1/2th harmonic | Fundamental wave | 3th harmonic |
|-------------------------|---------------------------|----------------|------------------|-------------|
| None                    | 0                         | 3.7212         | 5.7971           | 1.325       |
|                         | 10%                       | 3.5373         | 5.8017           | 1.5206      |
|                         | 20%                       | 3.9614         | 6.144            | 1.5452      |
|                         | 30%                       | 3.9833         | 6.3628           | 1.6704      |
|                         | 40%                       | 4.0321         | 6.6128           | 1.7911      |
|                         | 50%                       | 4.4174         | 7.1228           | 1.8972      |
|                         | 60%                       | 4.5346         | 7.4276           | 2.0464      |
|                         | 70%                       | 4.6054         | 7.7636           | 2.2602      |
| Single PM               | 10%                       | 4.2676         | 6.8102           | 1.7256      |
|                         | 20%                       | 4.8473         | 8.012            | 2.2693      |
|                         | 30%                       | 6.1618         | 9.6361           | 2.9203      |
|                         | 40%                       | 7.8593         | 11.3339          | 3.6395      |
|                         | 50%                       | 12.0099        | 11.9376          | 3.0631      |
|                         | 60%                       | 17.6409        | 12.9913          | 1.6203      |
|                         | 70%                       | 19.1618        | 13.7566          | 2.7834      |

All PMs
3.4 The influence of non-uniform demagnetization fault on back-EMF
The magnetic field generated by the PM will affect the back electromotive force of the motor. When the PM has a demagnetization failure, the back EMF will also attenuate. Fourier transform on the back-EMF with non-uniform and uniform demagnetization faults are shown in Figure 10 and Figure 11 respectively.

![Figure 10 Harmonic amplitude of Back-EMF of non-uniform demagnetization](image1)

![Figure 11 Harmonic amplitude of Back-EMF of uniform demagnetization](image2)

From Figure 10-11, as the degree of non-uniform demagnetization intensifies, the amplitude of the fundamental wave and the 3/2th harmonic gradually decrease, and the amplitude of the 3rd harmonic gradually increases. As the degree of uniform demagnetization intensifies, the amplitude of the fundamental wave dropped significantly. This feature can be used to determine whether the motor has a uniform demagnetization failure.

4. Conclusions and future works
In this paper, the FEM approach to study the model of 10%-70% demagnetization on a single PM and all PMs of PMSM is proposed. We can draw conclusions as follows:

Through the simulation of the non-uniform demagnetization of PMs, it is found that as the degree of demagnetization increases, the amplitude of the output torque, radial flux density, and back EMF of the motor will decrease. Moreover, the amplitude of the phase current will increase sharply and lead to damage to the IGBT of PMSM. It can be judged whether the motor has a uniform demagnetization fault through the change of the phase current and the harmonic amplitude of the back electromotive force. Furthermore, it can be used as an indicator to protect IGBT.

Future works: Using the simulation results obtained in this paper, we will develop algorithms to classify the uniform and non-uniform demagnetization faults of the motor online and offline.

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