Electromechanical Energy Conversion Systems (EECS),
Niroo Research Institute.
Vol. 1, Issue. 2. Spring 2021

Demagnetization Fault Diagnosis of FSPM Motor Based on Relief and SVM

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Abstract

Permanent magnet synchronous motors (PMSMs) have rencently attracted much attention of scientists due to high reliability, high efficiency, high density of power and torque. However, Permanent magnet (PM) motros suffer from irreversible demagnetization which is one of the most probable problems occurring in these motors. One of the recently developed permanent magnet synchronous motors, is the Flux Switching Permanent Magnet (FSPM) motor whose PM is placed on the stator. In this paper, a novel approach is proposed for the diagnosis of the demagnetization fault in a flux switching permanent magnet motor using electromagnetic torque. In this approach, the harmonic components of the electromagnetic torque are obtained, and then, ReliefF feature selection method is utilized to select the best-ranked harmonic component. The selected harmonic component is then applied to the Support Vector Machine (SVM) classifier to classify different states of the motor's PM. The proposed approach is validated by Finite Element Model (FEM) simulation.

Keywords: demagnetization; fault diagnosis; feature selection; machine learning.

1. INTRODUCTION

Nowadays, the use of permanent magnet motors has been growing due to their benefits compared with other types of electrical machines. One of the recently developed PM motors is the FSPM motor whose stator is placed on the stator instead of the rotor [1]. This results in some advantages, such as easy heat dissipation and robust structure [2]. However, in harsh environments, the probability of demagnetization of the PMs increases. Therefore, it is crucial to diagnose the demagnetization fault of the PM in the permanent magnet motor. In the literature, there are many investigations for the diagnosis of PM demagnetization in PMSMs [3]–[8]. In [3] and [4], an overview of the literature studied the diagnosis of demagnetization fault in permanent magnet machines is presented, specifically PMSM in [3]. They show that multiple signals are utilized for the detection of demagnetization, such as voltage, current, flux, torque, vibration, and etc. In [5], based on structural analysis of the motor inductance combined with the least square method to diagnose demagnetization fault on the PMSM. In [6], using vibration characteristics, the diagnosis of very slight demagnetization in interior PMSM is carried out. In [7] and [8], the demagnetization fault detection is performed using the electromagnetic torque analysis. According to the literature, there is no investigation of demagnetization fault detection in FSPM motors. However, in [9]–[12], the influence of the demagnetization on FSPM motors is studied.

Fault diagnosis of electrical machines has been a field of interest for scientists, according to the literature. Furthermore, machine learning approaches are widely used for fault detection purpose for many applications [13]–[15]. In the articles, for signal processing, some transformation and mathematic approaches are utilized, such as wavelet transform, Fast Fourier Transform (FFT), and statistical analyses. The obtained features by signal processing, are then employed to the classifiers such as k nearest neighbor, support vector machine, neural network, etc. However, in some cases using all of the obtained features may increase redundancy and decrease the classification accuracy. Therefore, in some articles to omit redundant features, feature selection methods are used [15].

In this paper, an approach is proposed for the diagnosis of demagnetization fault detection in FSPM motor using FFT as the signal processing method and SVM as the classifier. Therefore, the frequency harmonics of the electromagnetic torque of the FSPM motor are obtained. To select the best frequency, a filter feature selection method is utilized called ReliefF by which the harmonics are ranked, and the best-ranked harmonic is applied to the SVM. In order to compare the ranked harmonics and evaluate the performance of ReliefF.

This paper is structured as follows. In section II, a principle of demagnetization is presented. Then, the proposed approach is expressed where the algorithm of ReliefF is given. In the next section, the Finite Element Model (FEM) is utilized for evaluating the proposed fault detection approach, and finally, a conclusion of this work is presented.

2. PRINCIPLE OF DEMAGNETIZATION

One of the major problems of PM motors is the risk of demagnetization, which is caused by conditions such as strong magnetic field, high working temperature, self-demagnetization, high mechanical stress, or a combination of these factors [16]. This phenomenon affects motor performance characteristics such as power density, output torque [9]. Demagnetization of PMs can be partial or overall. In the first one, the PM is exposed to the uniform demagnetization field and all of the magnet regions have the same working point. The second one is partial demagnetization which is a common phenomenon in the PM motor. Because the armature reaction of the motor is not uniform so the regions of the magnet have a different working point [17].

There are two types of demagnetization, irreversible and reversible, in reversible demagnetization, the working point of the magnet is above the knee point and with removing the external magnetic field the magnet can recover its initial magnetic flux density. But in irreversible demagnetization, the working point of the magnet is below the knee point. In this condition with removing the external magnetic field magnet cannot recover its initial magnetic flux density and lose some of its magnetic properties. The return path of the magnet in the irreversible demagnetization is shown in Fig. 1 this path is known as recoil line which has the same slope of the B-H curve of the magnet at above the knee point. This feature is an intrinsic characteristic of the PM [18], [19].

Also, the effect of temperature on the demagnetization of the NdFeB magnet is in Fig. 1. As shown in Fig. 1, with increasing the temperature (from T_1 to T_2) the amount of knee point go higher and the risk of irreversible demagnetization is increased.

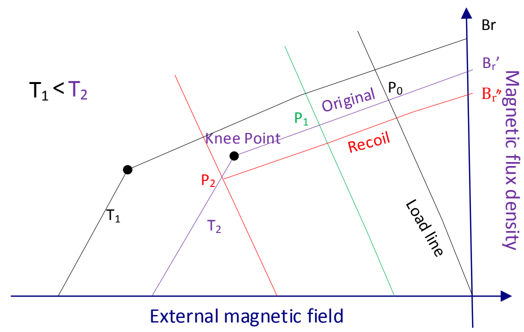

Fig. 1. The influenced factors on demagnetization [18]

3. The proposed approach

To detect the demagnetization fault in an FSPM motor, first the electromagnetic torque of the motor is obtained. Then, using fast Fourier analysis, 20 harmonic components of the electromagnetic torque are derived which are for 700 *Hz*, 1400 *Hz*, 2100 *Hz*, … , 14000 *Hz*. After that, using ReliefF method, a filter feature selection approach, the 20 harmonic components are ranked. The best-ranked harmonics is applied to the SVM classifier and the classification performance is evaluated. The classes are chosen as healthy state of the machine, 20% demagnetization of a PM, 40% demagnetization of a PM, and 80% demagnetization of a PM. In Fig. 2, an overview of the proposed fault detection approach is presented. In the following the ReliefF method is expressed.

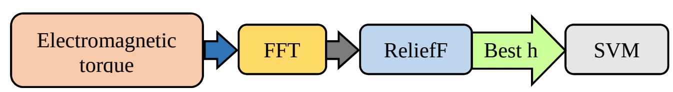

Fig. 2. The overview of the proposed approach

A. ReliefF

ReliefF is an extension of Relief which is proposed in [20]. the idea of Relief is to detect the features which are statistically relevant to the target concept for two-class classification problems [21]. Therefore, for an instance which is selected randomly, Relief searches for each instance's two nearest neighbors: one from the same class (nearest hit) and the other from a different class (nearest miss). ReliefF, however, can deal with multi-class and incomplete problems[22]. Similar to Relief algorithm, ReliefF selects a random instance R_i, and it searches for k nearest hits H_j and for k nearest misses $M_j(C)$ for each different class C. Then, ReliefF averages their contribution for updating the quality estimation $W[F]$ for all features F, that include wavelet and statistical features. The ReliefF algorithm is as Fig. 3 [23].

Start
Set the initial weights to zero.
for i:=1 **to** m **do**
begin
Select a random instance R_i
Find k nearest hits.
For each class $C \neq Class\left(R_i\right)$ find k nearest misses.
for F:=1 **to** #all_ features **do**

$$W\left[F\right]:=W\left[F\right]-\sum_{j=1}^{k}\frac{\operatorname{diff}\left(F,R_i,H_j\right)}{m\times k}+\sum_{C\neq Class(R_i)}\sum_{j=1}^{k}\left[\frac{P(C)}{1-P(Class(R_i))}\frac{diff\ (F,R_i,M_j(C))}{m\times k}\right]$$

end

Fig. 3. The Pseudocode for ReliefF [23]

4. Simulation validation

In order to validate the proposed approach, the FEM of the FSPM is simulated for different conditions. The studied cases of the PM of the FSPM, are healthy state, 20% demagnetization of one PM, 40% demagnetization of one PM, and 80% demagnetization of one PM. The flux density distribution of the FSPM motor under healthy condition is shown in Fig. 4. For one load condition and considering one of the PMs, the simulation results of electromagnetic torque is shown in Fig. 5 for the mentioned case studies. The FFT of the obtained electromagnetic torque from FEM is derived and then are applied to ReliefF. The harmonic components for each state construct a 20 component set which comprises harmonic components of 700 *Hz*, 1400 *Hz*, 2100 *Hz*, … , 14000 *Hz*. These components are ranked by ReliefF and result is presented in Table I where the calculated weight and the order of harmonic components are given.

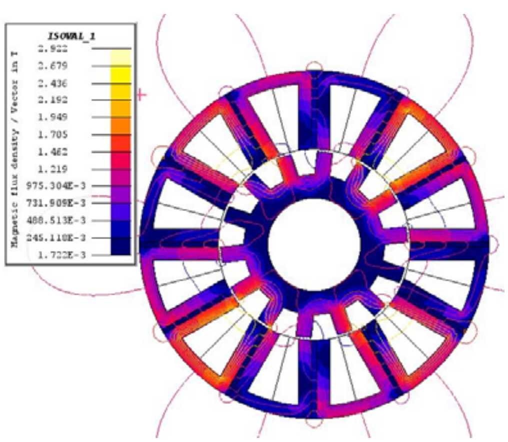

Fig. 4. The magnetic flux density distribution of FSPM motor

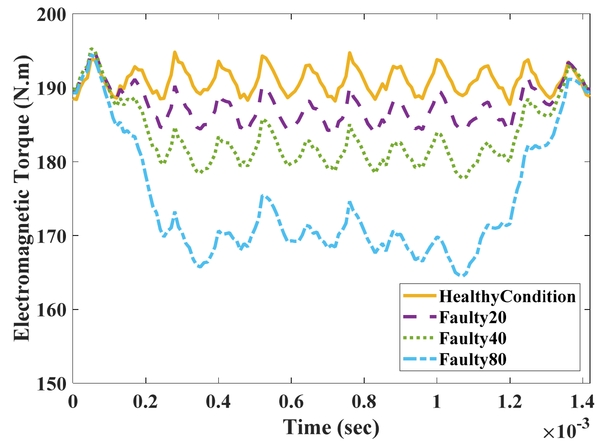

Fig. 5. The electromagnetic torque of the FSPM motor for four conditions of one PM of the motor including healthy state, 20% demagnetization, 40% demagnetization, and 80% percent demagnetization

The best harmonic component is the second component according to Table I. This component is applied to SVM, and the classification accuracy is obtained 100%. However, to evaluate the performance of ReliefF, the 10 best-ranked harmonic components by ReliefF are applied to SVM and their classification accuracy is shown in Fig. 6. According to this figure, besides second harmonic, first harmonic also results in the accuracy of 100%, and as rank increases, almost a descending accuracy can be seen. It means that ReliefF generally has a good performance. The confusion matrix for the third-rank and forth-rank harmonic are represented in Fig. 7 and Fig. 8 respectively.

TABLE 1. THE RANKED HARMONIC COMPONENTS USING RELIEFF

Rank	Harmonic	Weight	Rank	Harmonic	Weight
1	2	0.188	1	20	0.070
2	1	0.183	2	18	0.067
3	4	0.176	3	11	0.045
4	3	0.169	4	10	0.031
5	12	0.167	5	16	0.027
6	8	0.156	6	13	0.027
7	7	0.140	7	19	0.023
8	6	0.131	8	14	0.023
9	9	0.100	9	15	0.016
10	5	0.093	10	17	0.005

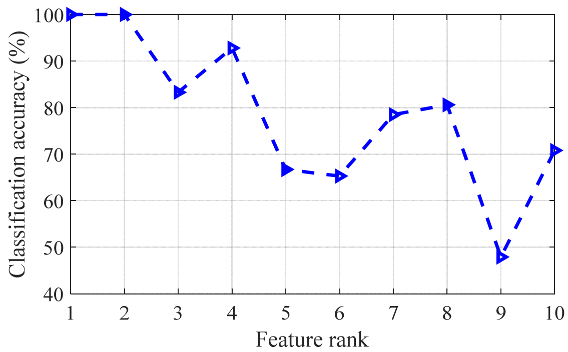

Fig. 6. The classification accuracy for 10 best-ranked harmonic components

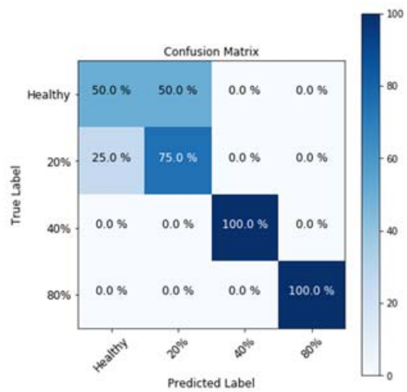

Fig. 7. Confusion martrix for classification of the third-rank harmonic

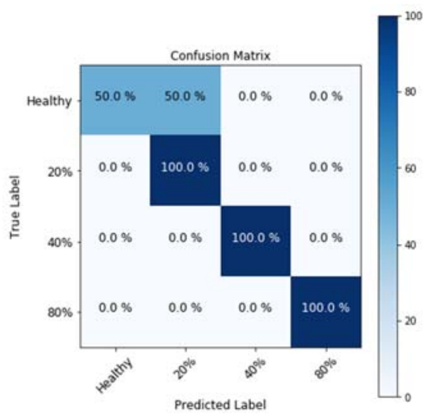

Fig. 8. Confusion martrix for classification of the forth-rank harmonic

5. Conclusion

In this paper, an approach is proposed for demagnetization fault detection of FSPM motor based on ReliefF and SVM. In this approach, 20 harmonic components of the electromagnetic torque of the FSPM motor are obtained for different situations of the magnets. Then, they are applied to the ReliefF algorithm to be ranked whose best-rank is the second harmonic. In the second step of the proposed method, the best-ranked harmonic, the second harmonic with the frequency of 1500 *Hz*, is applied to SVM for classification. The classification accuracy becomes 100% by this harmonic component. To evaluate the performance of ReliefF, the classification accuracy for 10 best-rank harmonic components is also given which shows the appropriate performance of ReliefF for this application. The general approach is to show the influence of the demagnetization fault on the electromagnetic torque and its harmonic components. The results imply that the most significant effect of the demagnetization is on the second harmonic of the electromagnetic torque of the FSPM motor.

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