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On-Line Detection of Harmonic Components in Magnet Defect Fault of Permanent Magnet Synchronous Motor through a Modified Prony's Method

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ABSTRACT

The use of permanent magnets in the structure of electric machines, in addition to simplifying design and construction by reducing losses, leads to increased efficiency in the motor. However, the magnetic material can be damaged by failure caused by faults such as short circuits in the electronic driver of the motor. Magnets containing samarium and neodymium are completely brittle and easy to crack. These elements are also very vulnerable due to their crystalline structure and grain texture. Magnet defect fault is one of the most common faults in permanent magnet machines. In this paper, a permanent magnet synchronous motor (PMSM) with a magnet defect fault is simulated using the finite element method. Moreover, Prony's method is modified by the matrix pencil method for the estimation of the component created in the stator current. The frequency spectrum of magnetic flux density and stator current in both faulty and healthy modes are extracted and fault detection is done through a modified Prony's method.

I. Introduction

The removal of the excitation coil and the use of a permanent magnet in synchronous motors increase efficiency and improve dynamic performance. By removing the brushes and slip rings, the copper losses of the field are reduced, which is the most important advantage of these motors. Permanent magnet synchronous motors (PMSM) are highly efficient due to low rotor losses and low magnetizing current. The simplicity of the motor design and construction and the high power-to-volume ratio are the main advantages of these motors [1].

Although due to the high price of permanent magnets, the price of these motors is higher than the dc excitation type, they are used in industrial applications such as pumps, compressors and centrifuges because of their advantages such as high efficiency, good power factor and low sensitivity to changes in voltage and frequency of supply [2]. Other uses for these motors include applications in medicine, aerospace, textile and petrochemical industries, and instrumentation. In addition to industrial applications, PMSMs are also widely employed in the military and telecommunications industries. Permanent magnet propulsion motors are extensively used in submarines [3].

Faults in electrical machines, whether mechanical, electrical, or magnetic, can lead to larger faults and sometimes irreparable damage if not detected in the early stages; therefore, knowing the types of faults and ways to detect them in every electric motor is essential. Electric motor faults sometimes occur due to inherent defects. These inherent defects may be due to impurities in the raw material in the machine, such as magnet impurities in permanent magnet machines. Moreover, structural defects of the machine which occur due to defects in the manufacture and production of parts, are among the inherent defects of the machine. Other inherent defects include physical asymmetries in the machine structure and winding insulation defects during construction. Each of these inherent defects increases the likelihood of other faults occurring in the machine. The occurrence of any fault in the magnet has significant effects on the output of the machine because the magnet is the most crucial component of the excitation part of the permanent magnet machine [4-6]. Faults in the magnet are considered magnetic faults. The frequency of these faults is less than mechanical and electrical faults, but their significance warrants special attention. The magnetic material can be damaged by failure caused by faults such as short circuits in the electronic driver of the motor. Magnets containing samarium and neodymium are completely brittle and easy to crack. These elements are very vulnerable due to their crystal structure and grain texture. The centrifugal force on the surface magnets and the increase in heat lead to damage and the breakage of these magnets [5].

In recent years, fault detection and preventive maintenance aimed at preventing major faults in motors have been considered by many researchers [7-10]. In general, there are two basic logics for diagnosing defects in electric machines; one is fault detection, which involves finding a fault in the machine, and the other is fault diagnosis, which indicates the type of fault created in the machine and its severity. So far, many destructive and non-destructive detection methods have been proposed to detect faults in electric machines. Non-destructive detection methods are based on simple and inexpensive measurements and do not require changing the structure of the motor. Motor current signature analysis and the analysis of the ac component of power signal are non-destructive fault detection methods [11-15]. Temperature analysis using sensors inside the motor is a destructive method of fault detection.

In [16], for the magnet defect analysis of PMSM, 7% of the magnet has been removed, which is a significant amount and its components have been obtained by using Discrete Fourier Transform (DFT). In practice, the crack created in the magnet is small and will has less effect on the amplitude of the components created in the induced voltage and stator current. To obtain the amplitude of these components, the DFT is not a suitable tool. Many harmonic estimation techniques have been identified and used in the field of signal processing of fault diagnosis.

One of these techniques is classical multiple signal classification (MUSIC)[17]. Although the MUSIC method is a powerful tool for high-resolution frequency detection, it has long computational time constraints from a short noisy data recording signal. It is also difficult to estimate the amplitude. To improve these major issues, a new method is proposed in [18]. This method uses a well-known approach, namely the estimation of signal parameters via rotation invariance technique (ESPRIT). ESPRIT results in more accurate frequency estimates than MUSIC. In this method, the corresponding amplitude of harmonic frequencies is obtained using least squares (LS). Despite the good results of the LS algorithm, amplitude/frequency tracking is still difficult for this method.

Prony analysis (PA) is one of the best interesting techniques to estimate the harmonic frequencies of a signal. Prony's approach provides higher frequency resolution than other approaches due to its confidence in autoregressive analysis. In [19, 20], Prony’s method for the estimation of the frequencies of broken rotor faults of the induction motor has been presented. In this approach, the least squares algorithm is used for the estimation of the harmonic frequencies. As previously mentioned, amplitude/frequency tracking is still challenging for this method.

In our paper, to overcome these drawbacks, Prony's method is modified by using the matrix pencil method for the estimation of the component created in the stator current. When there is no fault in the motor, some inherent fault effects can be observed in the signals. By using this method, the possibility of mistaking the components caused by the fault with the components caused by other factors is minimized, because it is possible to estimate all frequency components with very high accuracy.

II. PRONY'S METHOD

A. *Prony’s method*

Prony's method is a technique for extracting sinusoidal signals or exponentials from temporal data by solving a set of linear equations. Assuming x (t) and N signals of the complex sample, Prony's method estimates the sampling data with the linear combination of the p complex exponential function [21].

$$x\left[n\right]=\sum_{k=1}^{p}h_k z_k^{\,n-1}$$

$$z_k=e^{(\alpha_k+j2\pi f_k)T_s}\quad h_k=A_K e^{j\phi_k} \tag{1}$$

where T_s is the sampling time, and $A_K, f_k, \phi_k, \alpha_k$ are amplitude, frequency, angle and the damping factor of the k^{th} components, respectively. The above equation is a complex nonlinear problem that can be solved using Prony’s method. In fact, Prony's method converts nonlinear problem estimation parameters into a linear system and calculates polynomial roots. For this objective, Prony's method forms a homogeneous linear differential equation with constant coefficients.

$$\sum_{k=0}^{p}a_k x\left[n-k\right]=0 \tag{2}$$

In the classical Prony's method, the number of the available data samples is considered to be equal to the number of the sample of the unknown model. However, in many practical cases N > 2p and, in this way, equation (2) should be modified. In this paper, the matrix pencil method is used to directly obtain z_k by solving a generalized eigenvalue problem.

B. Matrix pencil method

In this paper, to perform the matrix pencil method, a rectangular Hankel matrix Y is created from the signal x[n].

$$Y = \begin{bmatrix} x[1] & \cdots & x[p] & x[p+1] \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ x[N-p] & \cdots & x[N-1] & x[N] \end{bmatrix} \quad (3)$$

This matrix is used to construct matrices Y_2 and Y_1. Y_2 is created by eliminating the first column of Y, while Y_1 is formed by eliminating the last column of Y. It is more effective to obtain the values of z_k from the following phrase:

$$z_k = eigenvalues(Y_1^+ Y_2) \quad (4)$$

where $Y_1^+ 1$ is the Moore-Penrose pseudoinverse matrix of Y_1, defined as:

$$Y_1^+ = \left[Y_1^H Y_1\right]^{-1} Y_1^H \quad (5)$$

A polynomial with roots z_k can be created using the linear prediction parameters as follows:

$$F(z) = \sum_{k=0}^{p} a_k z^{(p-k)} \quad (6)$$

As a result, the frequency and the damping factor can be directly obtained from the roots z_k of (4):

$$a_k = \frac{ln|z_k|}{T_s}$$
$$f_k = \frac{1}{2\pi T_s} tan^{-1}\left[\frac{Im(z_k)}{Re(z_k)}\right] \quad (7)$$

III. SIMULATION RESULTS

There are several methods to model a PMSM, and the finite element method is one of the best. Using this method, first the study area is divided into a large number of smaller areas called meshes. Then the desired electromagnetic equations in each mesh are solved by numerical methods to finally obtain the distributed magnetic vector potential (A) in the whole area. With (A), the flux density distribution can be easily calculated. In order to analyze the fault of the defect magnet, using the two-dimensional finite element method, the model is divided into a number of finite elements and the following Maxwell equations are solved in each element [5]:

$$\nabla \times \left(\frac{1}{\mu} \nabla \times A\right) = J + \nabla \times H_C$$
$$\nabla \times E = -\frac{dB}{dt} \quad (8)$$

In this section, the simulation of a synchronous permanent magnet motor in Maxwell software is investigated. For this purpose, first a healthy motor is analyzed and then by adding cracks on the magnets, the simulation results are compared with the healthy motor results. Figure 1 displays the meshing in the Maxwell 2D model. The parameters of the simulated motor are given in Table 1.

TABLE 1
PERMANENT MAGNET SYNCHRONOUS MOTOR PARAMETERS

Quantity	Name of Unit
Number of poles	4
Speed	1500
Voltage	220
Outer diameter of the stator	120mm
Outer diameter of the rotor	74mm
Rotor length	65mm

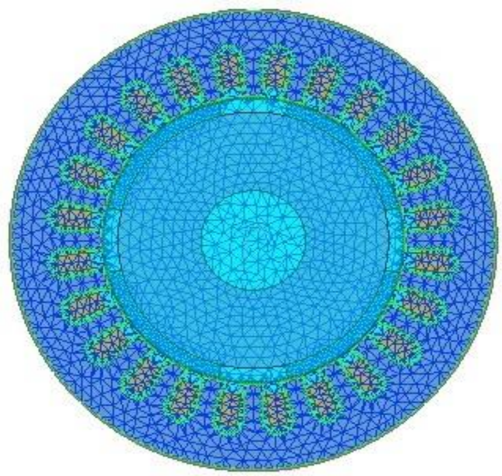

Fig. 1. Synchronous motor meshing in Maxwell.

The finite element (FE) method is used for analyzing the PMSM with a magnet defect. One crack is created, which is 0.049 mm wide along the magnet. (0.25% of the magnet is removed). Electrical and mechanical variables such as current, voltage, flux, and torque, are ideal waveforms for fault detection. Among these signals, stator current is a non-invasive fault detection procedure. In the case of a broken magnet, the unevenness of the air gap flux density causes a number of harmonics to flow through the stator windings. When a fault occurs in the magnet, they have a significant effect on the flux density. Figure 2 shows the flux density of one point in the air gap in the normal state (a) and the defect of the magnet (b).

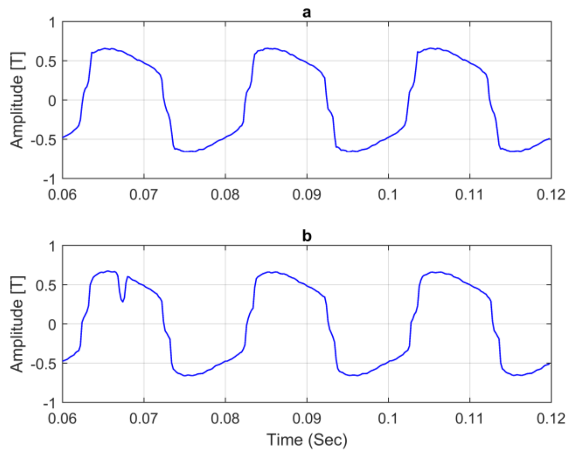

Fig. 2. The flux density of one point in the air gap in the normal state (a) and the defect of the magnet (b).

Using modified Prony's method, the frequency components of the flux density waveform have been estimated. Figure 3 shows the frequency spectrum of the flux density of one point in the air gap in the normal state (a) and the defect of the magnet (b).

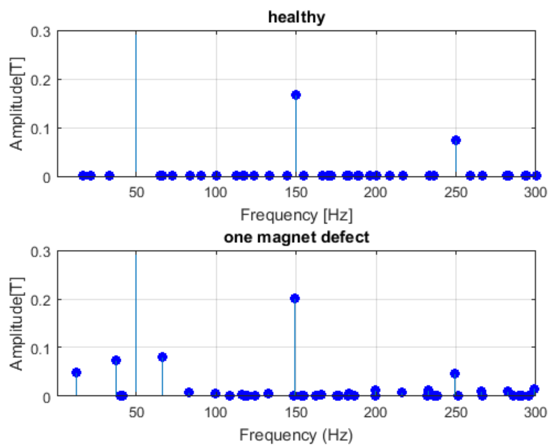

Fig. 3. The frequency spectrum of the flux density of one point in the air gap in the normal state (a) and the defect of the magnet (b).

After several simulations, it was found that the most effective harmonics in the flux density spectrum are the 0.25th, 0.5th and 0.75th harmonics. Other components are also affected, but not as much as these three harmonics. The behavior of these harmonics shows that they are more dependent on speed than torque. But, for these selected harmonics, which are located at the bottom of the main components, the number of slots has a greater impact on the components. As a result of this fault, the fourth and second harmonics had the greatest change compared to other harmonics. The effect of this fault on the sidebands of the second, third, and fourth harmonics is also significant.

Figure 4 depicts the frequency spectrum of the stator current waveform in the normal state (a) and the magnet defect (b).

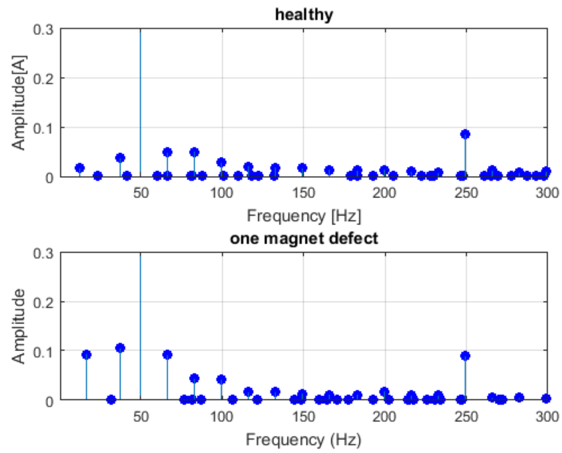

Fig. 4. The frequency spectrum of the the stator current in the normal state (a) and the defect of the magnet (b).

Simulations have been performed in different modes, and the results have shown that in the stator current spectrum, 0.25th and 0.5th harmonics had the most change compared to other harmonics. The effect of this fault on the sidebands of the second, third and fourth harmonics is also significant. Within this frequency range, the left sideband of the third harmonic is affected the most. The fourth and second harmonics can also be introduced as indicators of other faults due to significant changes in their harmonic amplitude during the fault; however these two components show similar behavior in other faults.

The harmonic behavior of the 0.5th harmonic also shows that it is highly dependent on speed. The changes in these two harmonics in the induced voltage are similar to the components in the stator current. The amplitude of these two components increases with increasing the gap and, in all cases, can be identified using these two components. Although the parameters of the motor, the shape of the stator winding, and the change in the load torque affect the current spectrum, according to the simulations performed in this study, the 0.25th and 0.5th harmonics are predominant components in the detection of magnet defect fault, and they are more trustworthy. Other components do not seem as reliable.

To compare Prony's method modified by the matrix pencil approach with the method presented in [21], the least squares and the matrix pencil methods along with the Prony's method have been used to estimate the waveform of the flux density of one point in the air gap under fault conditions. Figure 5 indicates the comparison of these two methods. As it is clear, modified Prony's method results in a considerably better estimate for the same p-values than the Prony's method based on the least squares algorithm.

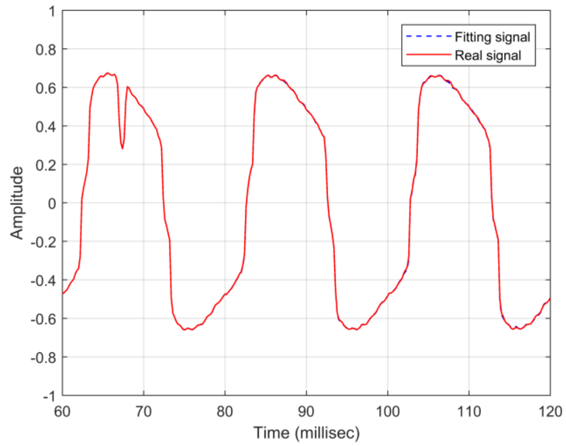

Fig. 5. The flux density of one point in the air gap estimated by modified Prony's method.

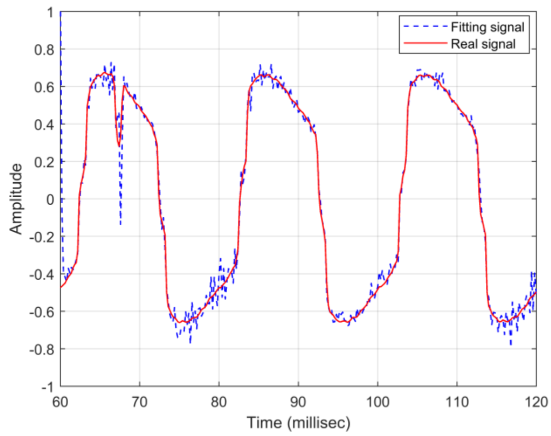

Fig. 6. The flux density of one point in the air gap estimated by the method presented in [21].

IV. Conclusions

According to the results obtained from the simulation in Maxwell software, creating cracks and fissures in the magnet can affect the performance of the motor. Using modified Prony’s method, the frequency components of the flux density and stator current have been estimated.

Simulations have been performed in different modes, and the results have shown that in the stator current spectrum, 0.25^{th} and 0.5^{th} harmonics had the greatest change compared to other harmonics. The effect of this fault on the sidebands of the second, third, and fourth harmonics is also significant. Within this frequency range, the left band of the third harmonic is affected the most. The second and fourth harmonics can also be introduced as indicators of other faults due to significant changes in their harmonic amplitude during the fault; however, these two components show similar behavior in other faults. Comparing the healthy model with the defective models, we conclude that although the parameters of the motor, the shape of the stator winding and the change in the load torque affect the current spectrum, according to the simulations performed in this study, the 0.25^{th} and 0.5^{th} harmonics are more dominant and reliable components in the detection of magnetic defect fault. Other components do not seem as reliable.

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