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# Permanent Magnet Synchronous Machines under Demagnetization Fault Using Finite Element Analysis-Diagnosis Methods

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*Abstract— Over the last few decades, permanent magnet synchronous machine (PMSM) fault diagnosis has been a crucial topic in research. In particular, the exponential increase in use of permanent magnets has led to the demagnetization fault in PMSM. In this paper, a model using 2D finite element method (FEM) is presented under healthy and faulty conditions to study defects due to the demagnetization in PMSM. The magnets will be considered as small elements to study three types of default which are total defective magnet, symmetrical and asymmetrical default. This lead to the visualization of different measures in the air gap. In the present article also, we focused on the methods of fault diagnosis that have of late been applied to PMSM under demagnetization. A plethora of published studies have dealt with the problem of fault diagnosis. Signal-Based Fault Diagnosis Method has been chosen as the most simple and efficient method to be used in the future work.*

**Keywords:** Permanent magnet synchronous motor, demagnetization fault, finite element method, demagnetization fault, fault detection, diagnosis.

## 1. NOMENCLATURE

CWT: Continuous Wavelet Transform
DTFT: Discrete Time Fourier Transform
DWT: Discrete Wavelet Transform
FDD: Fault Detection and Diagnosis
FEMM: Finite Element Method Magnetics
FFT: Fast Fourier Transformation
FRM: Field Reconstruction Method
HHT: Hilbert Huang Transform
ZSVC: Zero Sequence Voltage Component
DMF : Demagnetization Fault

## 2. INTRODUCTION

Thanks to the combined advantage of its high efficiency, small size, high torque density and reliability, the PMSM has become a more and more attractive and viable option. PMSMs are hence growingly the motors of choice for traction motors of Electric Vehicles (EVs).

This brightly promising side notwithstanding, a PMSM or rather permanent magnets are likely to go into faulty conditions owing to its limited material lifespan, intermittent operations, and/or manufacturing defects. This default may introduce the disruption of the flux in the airgap, causing imbalances between the rotor and the stator magnetic fields, which generate vibrations.

Demagnetization fault represents a big challenge to PMSMs. As a matter of course, condition monitoring and detection systems have become indispensable for PMSM developing industries to enhance the motors' availability, to decrease their maintenance costs and to shorten both the downtime and the maintenance time of the detected process[2]. In order to determine the behavior of PMSM under fault conditions, we have proposed a model using a 2D FEM. This model is developed to characterize the phenomenon of demagnetization. Simulation results using the FEMM software helps significantly in the understanding of the effects of these defects on the PMSM performances.

This paper is organized as follows. In Section 3, a brief definition of the demagnetization fault and the modelling of the PMSM under healthy conditions are presented. Section 4 is deserved to show different simulation results under faulty conditions via the use of FEM. The concept of diagnosis procedure and different groups of FDD methods are mentioned in section 5. Several demagnetization detection and diagnosis methods are summarized. The conclusion and some prospects are given in the sixth and last section of the paper.

## 3. DEMAGNETIZATION FAULT IN PMSM

Electric motors are subject to different kinds of faults. These faults can be classified into electrical, mechanical and magnetic faults. Electrical faults include stator electrical faults such as stator winding open or short circuit. Mechanical faults are classified primarily in bearing faults, such as damage in rolling element bearing. Stator/rotor assembly faults takes part of mechanical faults. An oft-cited instance of this category is Rotor Eccentricity Fault (REF) [2] .The third kind of fault, which is the main subject of the article, is magnetic fault. Magnetic faults are a characteristic of PMSMs, and in particular refer to the demagnetization of the rotor magnets. These three kind of faults are correlated with each other. It means each fault may bring about the other fault.

Permanent magnets (PM) are among the most important components in PMSM. They generate rotor fluxes in the air gap. The PM can be demagnetized due to several conditions such as the temperature variation and negative directional electromagnetic flux of stator. The reversible demagnetization is not a serious problem, but the irreversible one is a very serious fault of PMSM. The PM's demagnetization faults occur partially or entirely in the rotor PM poles. Even if the partial demagnetization occurs, it can be expanded to entire demagnetization rotor PMs and winding turn's fault [3].

### 3.1 Characteristics of the studied PMSM

our student machine is a synchronous motor with permanent magnets. it consists of four pairs of poles and six main teeth. Between two teeth main, an interposed tooth is added to improve the waveform and reduce leakage flow. Each phase winding is formed of two diametrically opposed coils whose winding is concentrated. That is, the turns of the coil are wound directly around a stator tooth [26] [27].

The following section presents the design of the surface mounted permanent magnet motor shown in figure 1. It is the simplest type of the PM machine design. Table I. shows the different parameters of the PMSM.

**TABLE I: Different parameters of PMSM**

| Designations | value |
|---|---|
| Stator exterior diameter (mm) | 185 |
| Stator interior diameter (mm) | 102 |
| Rotor exterior diameter (mm) | 80.6 |
| Core stack length (mm) | 250 |
| Magnet weight (Kg) | 2.71 |
| Permanent magnet height (mm) | 7.76 |
| Number of slots | 12 |
| Number of poles | 4 |
| Terminal current (A) | 63.57 |
| Shaft power (kW) | 21.63 |
| supply frequency (Hz) | 122 |
| Rotational speed (rpm) | 1836 |

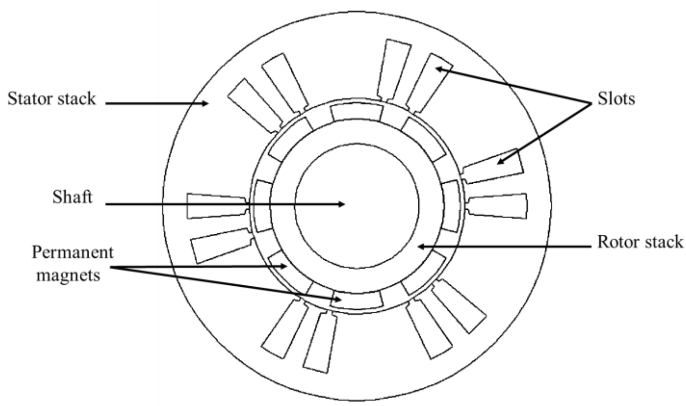



Figure 1: Geometry of the considered PMSM

There are several points that should be taken into account when designing a PM-machine. Essential criterions such as the choice of magnets, their arrangement and the protection against demagnetization (regarding overload and thermal capability) are discussed. In our case, we have chosen NdFe30 the material of the magnets [4]. The properties of the PM used here; the remanence Br, the coercivity Hc and the recoil permeability Mr, are shown in Table II and illustrated in figure 2 which represents the second quadrant of the hysteresis cycle called the demagnetization curve.

**TABLE II: The magnetic properties of NdFe30**

| Symbols | Magnitude |
|---|---|
| $B_R$ (T) | 1.1 |
| $H_C$ (A/m) | $-8.95x10^5$ |
| $M_R$ (H/m) | 1.044 |

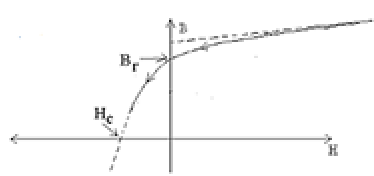



Figure 2: Demagnetization curve

3.2 PMSM structure under demagnetization fault

For PMSM, the main failure mode is magnet demagnetization, which produces a torque reduction. The DMF is defined as the decrease of the residual flux density of the PM [5].

The defect of a magnet may occur to armature reaction or fissure [1]. Demagnetization can be total that is all over the pole or partial on a certain region of the pole.
To study both situations, total or partial default, the magnet is considered to be composed of small elements showed in figure 3.

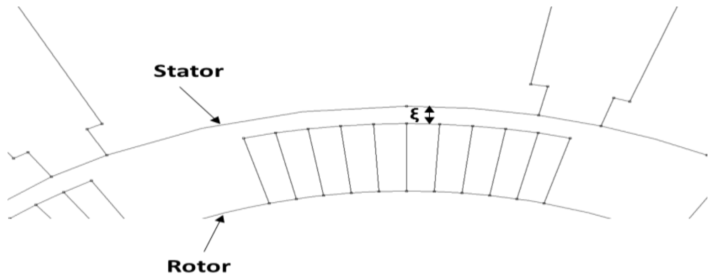
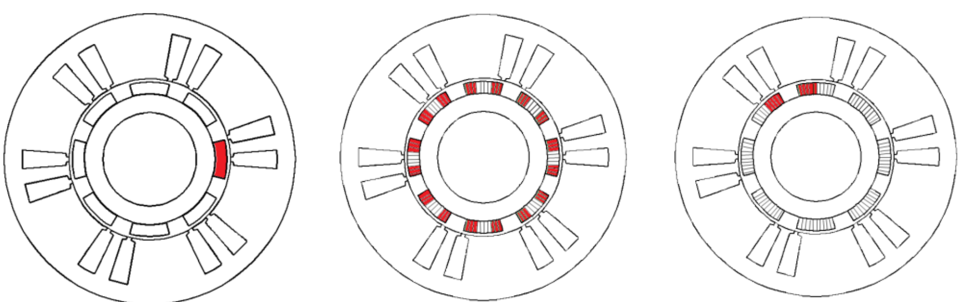



Figure 3: Geometry of the segmented magnet in the studied PMSM

A finite element simulation was conducted. Figure 4 shows the three considered defects due to demagnetization, respectively total (a), symmetric (b) and asymmetric (c). For total default, one magnet of eight is supposed to be totally defective. However, symmetrical default, six elements of each magnet was supposed to be demagnetized (each magnet is divided into ten elements). Concerning asymmetrical default, one-half of two magnets are defected. The residual induction of the unhealthy element of the magnet is less than its normal value.



(a)Total demagnetization default    (b) Symmetrical demagnetization default    © Asymmetrical demagnetization default

Figure 4: Types of demagnetization fault in PMSM

3.3 Electromagnetic force and torque calculation

The overall electromotive force of a phase is well proportional to the angular velocity Ω, to the number of turns per phase N and to the derivative of the flux with respect to the mechanical angle θ. It is given by the following equation

$$E = -N \frac{d\varphi}{d\theta} \Omega$$

The torque is estimated by the integration over a contour bounding the moving part. The electromagnetic torque is given as follows:

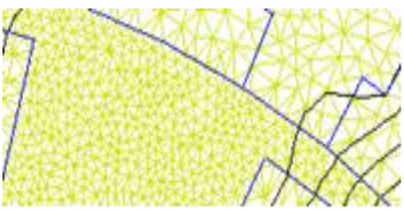
$$T = \frac{li}{\mu 0} \oint Bn\, Bt\ dl$$

Where, *li* is the stack length, $\mu_0$ is the permeability of the air, $B_n$ and $B_t$ *are* respectively the normal and tangential induction.

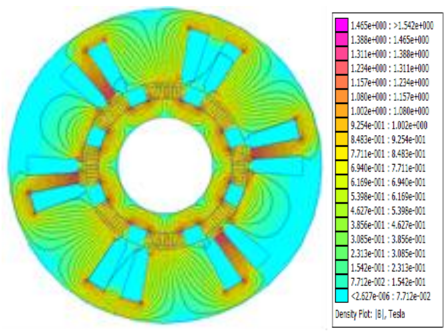
## 4. RESULTS OF FINITE ELEMENT ANALYSIS

### 4.1 PMSM structure under healthy conditions

The first step is to discretize the field of study into elements as shown in figure 5.a. These have a simple geometry. The size of the mesh influences the precision and computational time. The mesh in the air gap is very thin because of the importance of information at this level to know the accuracy of the distribution of the magnetic induction. The 2-D mesh of this motor consists of triangular elements with three nodes. Figure 5.b shows the magnetic field under healthy conditions.



(a) Finite element meshing of the PMSM




(b) Magnetic field of the PMSM

Figure 5: PMSM structure under healthy conditions

### 4.2 PMSM structure under total defective magnet

The following figure shows the magnetic field distribution for the motor under total defective magnet. We note the absence of magnetic field lines in the defective magnet.

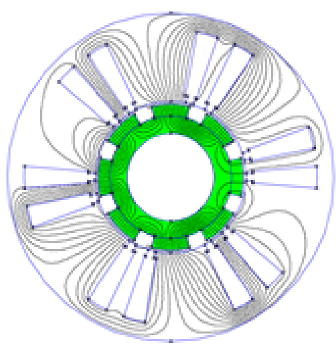


Figure 6: PMSM structure under total defective magnet

The simulation results has led to the determination of the variation of the magnetic potential vector A, the normal magnetic induction $B_n$, the flux density, the electromagnetic force EMF and cogging torque under healthy and faulty conditions.

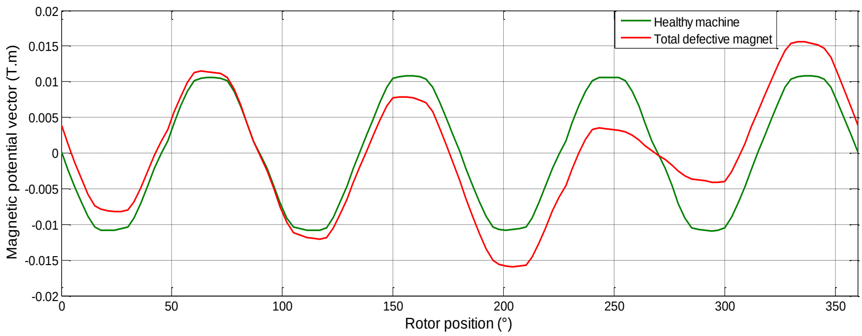



Figure 7: Magnetic potential vector for machine with and without default.

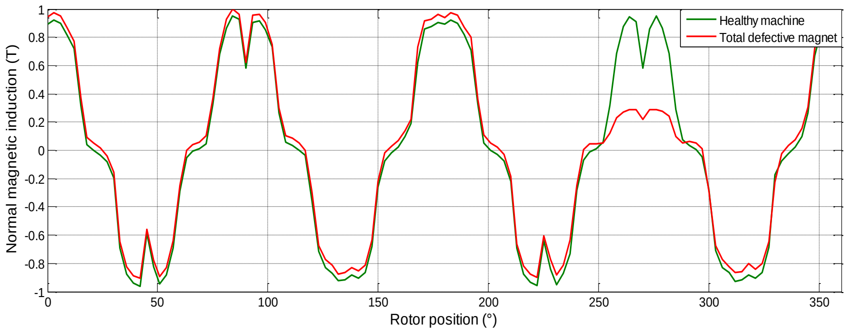



Figure 8: Normal magnetic induction with and without default.

Figure 7 and figure 8 show respectively the waveform of the magnetic vector potential and the normal component of the magnetic induction in the air gap in the healthy machine and in the presence of a total defective magnet. Note that in both cases the waveforms have a sinusoidal shape. Concerning the magnetic potential vector curve, its maximal value was unstable and the effect of the defective magnet is from 0 to 360 degrees.
It can be seen that the value of the normal component of the magnetic induction in the healthy machine is about 0.9 T and it is around 0.3 T in the area where the default is located.

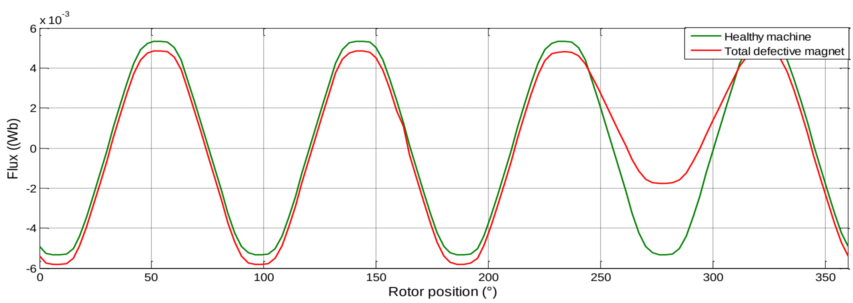



Figure 9: Flux density with and without default.

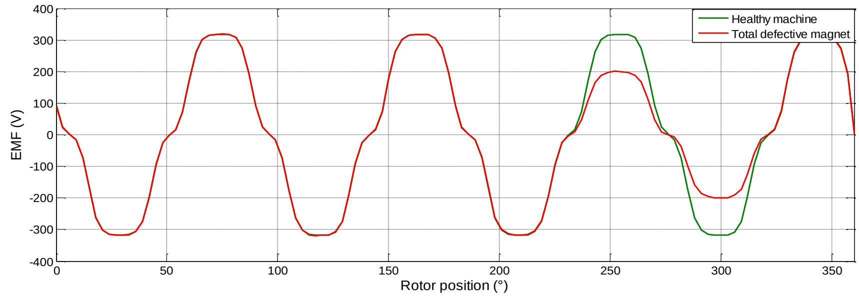



Figure 10: Electromagnetic force with and without default.

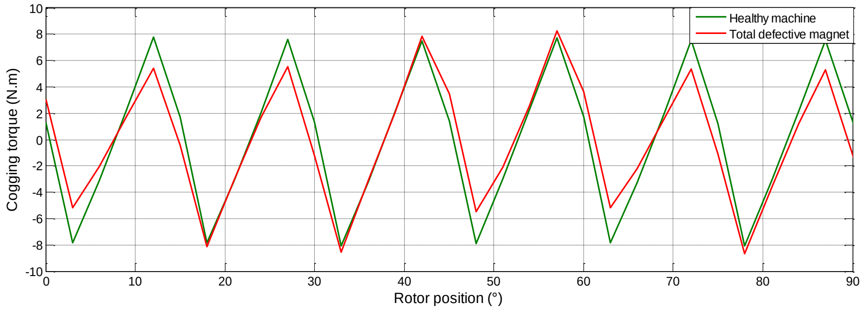



Figure 11: Cogging torque with and without default.

Figure 9, 10 and figure 11 show the flux density, the electromagnetic force and the torque in the healthy machine and in the presence of default, respectively. By comparing the curves, we can state that the maximal value of each curve in the healthy case has decreased significantly with the presence of a default (flux density from $5x10^{-3}$ Wb in a healthy machine to $2x10^{-3}$ Wb with total defective magnet, EMF from 325 V to 200 V and cogging torque from 8 N.m to 5 N.m).

4.3 PMSM structure under symmetrical and asymmetrical default

The following figures show the magnetic field distribution for the permanent magnet machine under symmetrical and asymmetrical default. The residual induction of the unhealthy element of the magnet is less than its normal value.

For Symmetrical default (Figure 12), six elements of each magnet was supposed to be demagnetized. It is clear that the dispersion of the magnetic field is more concentrated in the healthy areas of the magnet (4 elements in each magnet). On the other hand, it is negligible in the extremities where the defect occurs. Concerning asymmetrical default (Figure 13), one-half of two magnets are defected. We can notice that the magnetic field dispersion of the unhealthy element of the magnet is less than its normal one.

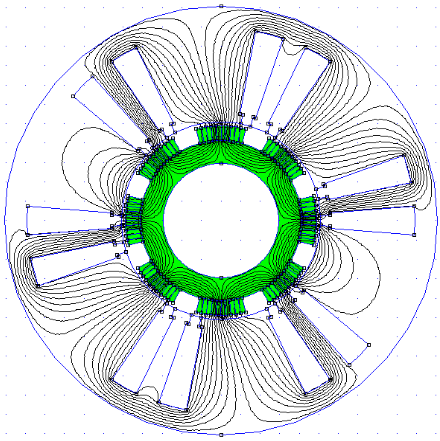


Figure 12: PMSM structure under symmetrical fault .

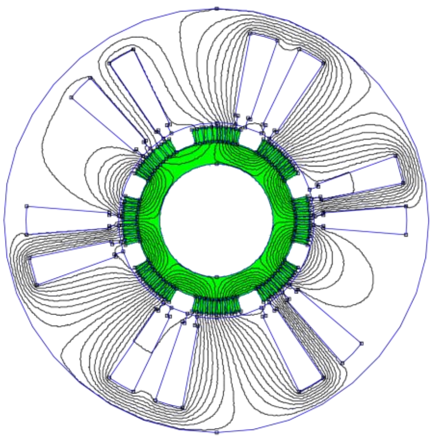


Figure 13: PMSM structure under asymmetrical fault.

The simulation results has led to the determination of the variation of the magnetic potential vector A, the normal magnetic induction $B_n$, flux density, the electromagnetic force EMF, and cogging torque under healthy and faulty conditions.

Figure 14 and figure 15 show respectively the waveform of the magnetic vector potential and the normal component of the magnetic induction in the air gap in the healthy machine and in the presence of a symmetrical and asymmetrical default. Note that in the three cases the waveforms have a sinusoidal shape.
Concerning symmetrical default, the maximal value of the magnetic potential vector it decreased from 0.011 T.m to 0.006 T.m from 0 to 360 degrees .However, in the area of asymmetrical default, the maximal value of the magnetic potential vector changes from –0.011 T.m to -0.004 T.m.

It can be seen that the value of the normal component of the magnetic induction in the healthy machine is about 0.9 T and it is around 0.6 T in areas where the symmetrical default is present and 0.3 T in the case of asymmetrical default.

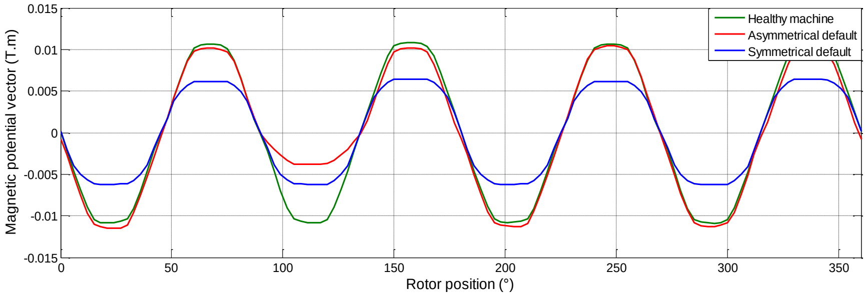



Figure 14: Magnetic potential vector with and without symmetrical and asymmetrical default

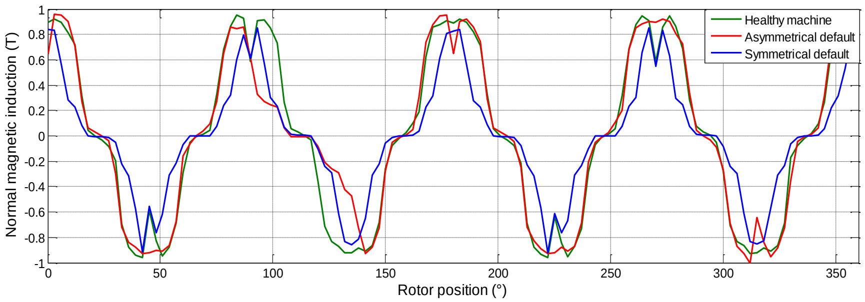



Figure 15: Normal magnetic induction with and without symmetrical and asymmetrical default

Figure 16, 17 and figure 18 give respectively the flux density ,the electromagnetic force and the torque in the healthy machine and in the presence of symmetrical and asymmetrical default. By comparing the curves, we can state that the maximal value of each curve in the healthy case has decreased significantly with the presence of a default.

Concerning symmetrical default, flux density decrease from $5x10^{-3}$ Wb in a healthy machine to $3x10^{-3}$ Wb with defective magnet, EMF from 325 V to 300 V and cogging torque from 8 N.m to 6 N.m during 360 degrees.

For asymmetrical default, flux density decrease from $5x10^{-3}$ Wb in a healthy machine to $2.75x10^{-3}$ Wb with defective magnet, EMF from 325 V to 200 V and cogging torque from 8 N.m to 7 N.m when the default occur.

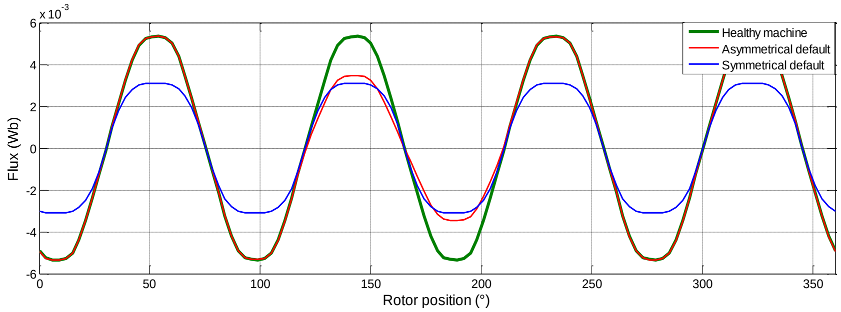



Figure 16: Flux density with and without symmetrical and asymmetrical default

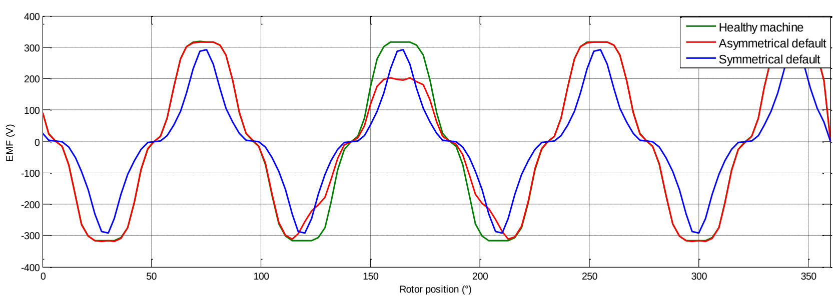



Figure 17: Electromagnetic force with and without symmetrical and asymmetrical default

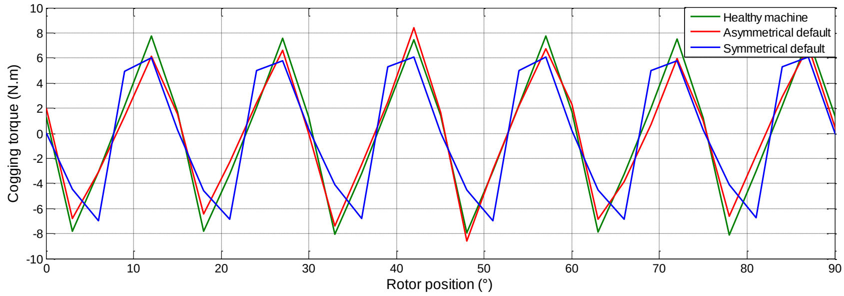



Figure 18: Cogging torque with and without symmetrical and asymmetrical default

## 5. FAULT DETECTION AND DIAGNOSIS METHODS IN PMSM

Failure in PMSMs means any incident giving rise to abnormal behavior by the motor which might lead to its short- or long-term damage. To remedy these defects, a good diagnosis tool is required to avoid the harmful, sometimes devastating, consequences of these defects. Many research endeavors have been undertaken to achieve adequate PMSM fault detection and diagnosis [6]. The good functioning of the FDD system is paramount to good decision making.

There are broadly two directions for developing fault diagnosis system: using hardware redundancy or using analytical redundancy. Hardware redundancy uses multiplication of physical devices and an extra equipment to detect the fault and its location in the faulty system .The principal problem of this approach is the significant cost for the added equipment [7]. Analytical redundancy uses redundant functional relationships between variables of the system that does not need for extra equipment, instead. In the rest of this work, this paper reviews fault diagnosis methods based on analytical redundancy. Analytical redundancy also can be divided into two stages: The first stage is named qualitative method that includes Artificial Intelligence and the second one is quantitate method including model-based methods and signal-based methods.

### 5.1 Qualitative and Quantitative Methods

The qualitative methods consists exactly in Artificial Intelligence Techniques, which seek to imitate and acquire human-like reasoning capacities in different ways. In general, we find the following models that are used in the context of diagnosis: Artificial Neural Networks, Fuzzy Logic, Particle Swarm Optimization and so on.
The quantitative Methods includes Model-Based Fault Diagnosis and Signal-Based Fault Diagnosis.The central issue in model-based fault diagnosis is residual generation. Each residual generation method has associated a specific technique of computing the residual vector such as Parity Space Approach, Observer-Based Method and Parameter Estimation Technique.
Signal-Based Fault Diagnosis is based on the nature of the signal processing method. The first step in this approach consists in the modeling of signals by characterizing them in the frequency domain, determining their spectral content, their variance, etc. and obtained from stator currents, torque signals and the like. We consider four types of the most popular methods to complete this task, which are Frequency Domain Analysis such as FFT; Time Frequency Analysis such as WT, STFT, HHT; Analysis Based on Analytical Design; and

Analysis Based on Modelling Design such as FRM, Search Coil Design Based Analysis, Inverter Embedded Technique and Permeance Network Approach.

5.2 Demagnetization fault detection and diagnosis in PMSM

In the following, Table III summarizes different FDD methods concerning demagnetization faults.
Because of its characteristic simplicity and efficiency, the signal approach is widely used nowadays in diagnostics. This approach is based on the knowledge of a system's healthy behavior signatures which could be determined from such parameters as stator current and torque signal. It is then compared with the measured signals so as not to need a specific model. Moreover, with the development of variable speed applications, these methods are useful under non-stationary conditions. In future investigations, it would be interesting and rewarding to use Signal-Based Fault Diagnosis methods for fault detection and diagnosis.

**TABLE III : FDD methods concerning demagnetization faults**

| **FDD Methods** | | | **Reference** |
|---|---|---|---|
| **Model-Based Fault Diagnosis** | Least square method | | [8] |
| **Signal- Based Fault Diagnosis** | Frequency Domain Analysis | FFT | [9];[10];[11];[12];[13];[14] |
| | | DTFT | [15] |
| | Time Frequency Analysis | CWT | [9];[17];[15] |
| | | DWT | [9];[18];[17] |
| | | HHT | [18];[19];[20];[10] |
| | | ZSVC | [22];[23];[24] |
| | Analysis based on modelling design. | FRM | [25];[14] |
| | | Search coil design based analysis | [24] |
| | | Permeance network approach | [25] |

## 6. CONCLUSION

In this paper, a model based on the resolution of the electromagnetic equation vector using 2D finite element method is presented. This model is used to study the behavior PMSM under demagnetization fault. Simulation results have been driven by both FEA and FEMM. The simulation has permitted the determination of the magnetic potential vector, normal magnetic induction, flux density distribution in the air gap, electromagnetic force and hence the calculation of the cogging torque produced by the machine. In order to study different demagnetization modes, the magnetic poles are subdivided into small elements. Three types of defaults are considered total, symmetrical and asymmetrical faults. These defaults have a significant influence on the EMF, the Flux and the torque produced by the machine and hence on its performances.

Moreover, a study of the different methods of fault diagnosis was reviewed in the present paper. In particular, we explored recent methods which evinced a higher degree of simplicity and efficiency when applied to PMSMs under demagnetization fault. We elected to focus Signal-Based Fault diagnosis as the simplest, most popular and efficient FDD method. In future investigations, it would be interesting and rewarding to study the faults mentioned above and Signal-Based Fault Diagnosis methods implanted on Simulink model.

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