Effects of Dynamic Eccentricity in Flux Switching Permanent Magnet Machines

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***Abstract*—This paper investigates the effect of rotating eccentricity fault on a 10/12 Flux Switching Permanent Magnet (FSPM) machine. Main characteristics of the studied machine such as air-gap flux density, magnetic force between rotor and stator and torque profile are calculated by using finite element analysis (FEA) which is the most accurate numerical method. Furthermore, Fourier analysis is performed in order to study the impacts of rotating eccentricity faults on magnetic force and torque profiles. In addition, the results of Fourier analysis of the machine in healthy condition are compared with the machine with 40% rotating eccentricity. This studies shows that the eccentricity has significant effects on FSPM characteristics which shows the importance of investigating the fault. To the best awareness of the authors, the effects of the rotating eccentricity on FSPM machines have not been studied before.**

***Keywords*— Eccentricity, Flux Switching Permanent Magnet Machines(FSPM), Finite Element Analysis (FEA), Fourier Analysis**

I. INTRODUCTION

Flux Switching Permanent Magnet (FSPM) Machines are one of the most attractive topologies of electrical machines which are very similar to Switched Reluctance Machines (SRMs) with embedded permanent magnet (PM) in stator structure [1]. In other words, FSPM machines are generated by combining of permanent magnet (PM) machines and SRMs [2]. Hence, the FSPM machines inherit both advantages of SRMs and RFPMs such as robust structure, high efficiency, high power and torque density, small size, low weight and fault tolerant ability [3]. These types of electrical machines are a suitable candidate for both low-speed and high-speed application such as starter-generator in aircraft [4], hybrid vehicles [5] and wind turbines [6]. Recently most literatures have been given especial attention on design optimization [7-8], enhance topology and performance analysis of FSPM machines [9].

In general, there are several kinds of faults that may happen in electrical machines which are due to electrical or mechanical reasons. Moreover, these faults usually deteriorate machine performance and cause much costs and damages. Bearing deficiency and eccentricity are the most common failures among electrical machines. In order to improve the electrical machines life time and prevent bearing fatigue, study about electrical machines under faulty condition is necessary. The first step is to learn more about the impacts of different faults and to know how to detect and diagnose the faults.

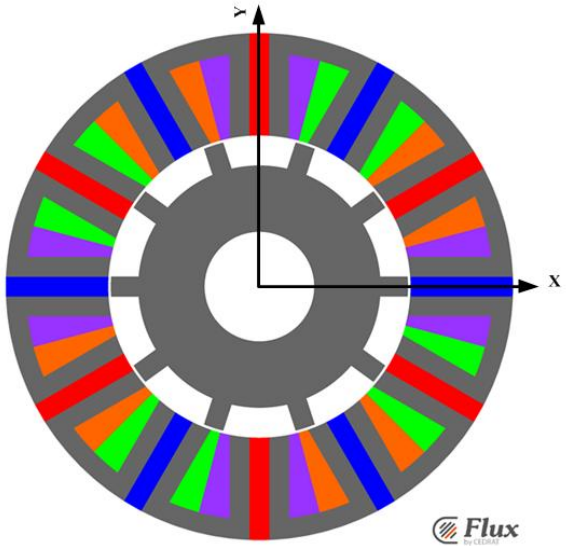

Fig. 1. Schematic of studied FSPM machine

The aim of this paper is to elaborate the influences of rotor dynamic eccentricity fault in FSPMs. For this purpose, a commonly used three phase 12/10 flux switching permanent magnet motor under rotating eccentricity fault at different values of dynamic eccentricity factor (DEF) is simulated using two-dimensional (2D) finite element analysis (FEA). The air-gap flux density of the machine has been obtained. Moreover, the magnetic force between rotor and stator of the machine and torque profile of the motor with 20% and 40% eccentricity are derived and compared with a healthy motor. In addition, harmonic contents of the magnetic force and the toque profile are indicated for both healthy and faulty motor.

II. MOTOR SPECIFICATIONS

The studied FSPM machine is a three-phase 12/10 stator/rotor pole motor. The 2D schematic of proposed FSPM machine is shown in Fig. 1. Furthermore, main geometric parameters of the machine are given in Table I.

III. FIINITE ELEMENT SIMULATION

To study eccentricity in FSPM machines, it is vital to model the machine as precise as possible. Analytical procedures always are convoluted to calculate machine performance even for the simplified machine in a normal condition. Therefore, for modeling eccentricity in an FSPM machine which needs the high accurate details, analytical

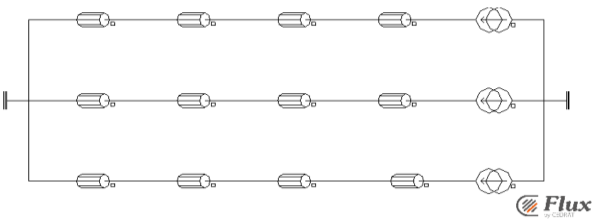

Fig. 2. Circuit diagram of proposed FSPM machine

methods are not preferred. Use of FEA can be a good solution which is precise enough to overcome this issue. The FSPM machine is modeled accurately in CEDRAT Flux package in order to study and analysis rotating eccentricity. The machine has concentrated winding which all coils are connected in series and supplied by three-phase sinusoidal current source. Fig. 2 shows the circuit diagram which is coupled to magnetic model of the machine.

In order to model eccentricity, two different coordinate systems are defined for each of rotor and stator. Stator coordination system is fixed and rotor coordinate system is shifted from the stator coordinate system along positive direction of x-axis in order to produce eccentricity. As a result, dynamic eccentricity is generated by turning the rotor around the stator axis with constant velocity. Then, a sensitivity analysis is performed for different degree of eccentricity to investigate the influence of rotating eccentricity in the FSPM machine.

TABLE I. MAJOR PARAMETERS OF FSPM MACHINE

Quantity	Value
Stator pole numbers (N_s)	12
Rotor pole numbers (N_r)	10
Outer diameter of stator (D_{so})	90mm
Active axial length (L_{st})	25mm
Air-gap length (g)	0.5mm
Rotor pole width (L_{pr})	4mm
Outer diameter of rotor (D_{or})	55mm
PM thickness (L_{PM})	3.6mm
Stator tooth width (L_{st})	3.6mm
Stator back iron thickness (y)	3.6mm
Number of turns per phase (N_{ph})	72
Rated current (I_a)	14A
Speed (N_s)	400rpm

IV. DYNAMIC ECCENTRICITY IN FSPM MACHINES

Asymmetric air gap in electric motors is known as eccentricity. Eccentricity consists of three types, static eccentricity, dynamic eccentricity which is known as rotating or rotor eccentricity, and a combination of these two kinds which is named mixed eccentricity.

In Dynamic eccentricity, the rotor rotates around stator axis with an offset as shown in Fig. 3 which causes the minimum air-gap between rotor and stator rotates by the rotor. These kinds of faults cause high unbalance electromagnetic force which consequently causes shaft bending and bearing fatigue.

In this paper DEF is defined as follows:

$$DEF = \frac{r}{g} \times 100 \quad (1)$$

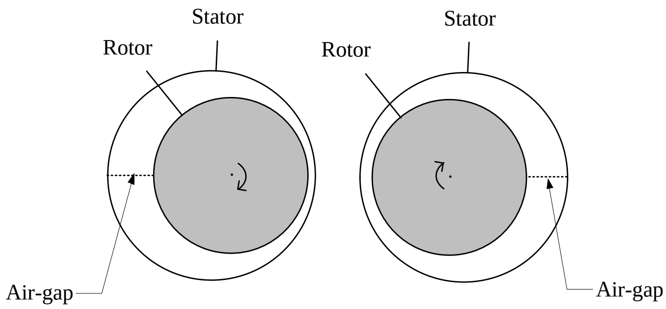

Fig. 3. Schematic representation of dynamic eccentricity

Where “r” is the offset between the rotation axis and the rotor axis and “g” is the radial air-gap length in healthy condition.

V. EFFECT OF ECCENTRICITY ON THE FLUX DENSITY

A. Flux Density Distribution

Flux density distribution of the motor with DEF=0%, DEF=20% and DEF=40% are shown in Fig. 4, Fig. 5, respectively. It is observed that by increasing DEF which means decreasing the air-gap length in positive direction of x-axis, the air-gap reluctance is declined and consequently the maximum value of magnetic flux density rises to 2.96 Tesla at hotspots. However, on the left side, the air-gap length increases which causes rising the air-gap reluctance and consequently decrement in magnetic flux density to 2.19 Tesla. In other words, the magnetic flux density of the healthy motor is symmetrical but according to Figure 5, which illustrates the asymmetrical condition, the flux density distribution of the machine is not uniform which may cause uneven forces between rotor and stator. This may lead to bearings fatigue.

B. Air-gap Flux Density

The air-gap flux density is one of the major features of electrical machines. There is a lot of information which can be obtained from this feature because it is affected by any change in machine structure. Therefore, by checking air-gap flux density, it is possible to recognize and consequently predict the machine condition. Furthermore, by knowing the machine condition, it is possible to diagnose if there is any problem. So, this feature should be analyzed carefully in dynamic eccentricity.

The normal component of air-gap flux density which is air-gap flux density in the radial direction is computed by using 2D-FEM simulation for the healthy motor and the motor with 40% rotating eccentricity, as shown in Fig. 6. It can be seen that the dynamic eccentricity has great influence on air-gap flux density of the motor. The maximum value of the air-gap flux density is obtained in the right side where the air-gap length has the lowest length while the minimum value of the air-gap flux density is obtained in the opposite side where the air-gap length has the greatest length. Moreover, for detailed studying, the maximum value of air-gap flux density for different values of DEF is illustrated in Fig. 7. It is observed that the rotating eccentricity leads to grow the maximum air-gap flux density.

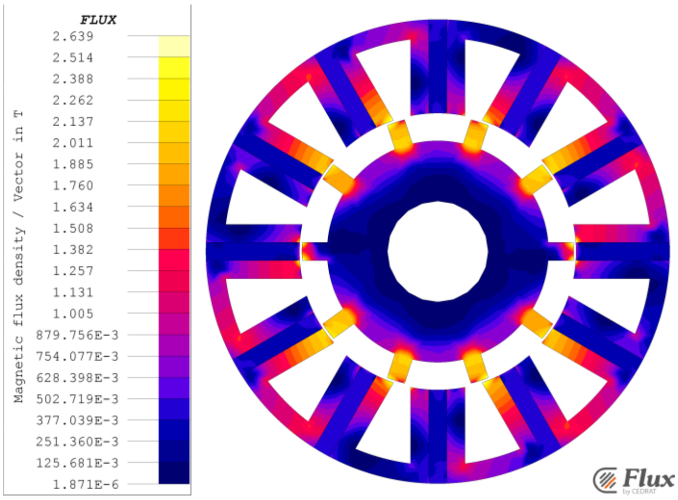

Fig. 4. Flux disturbution of FSPM motor with DEF=0%

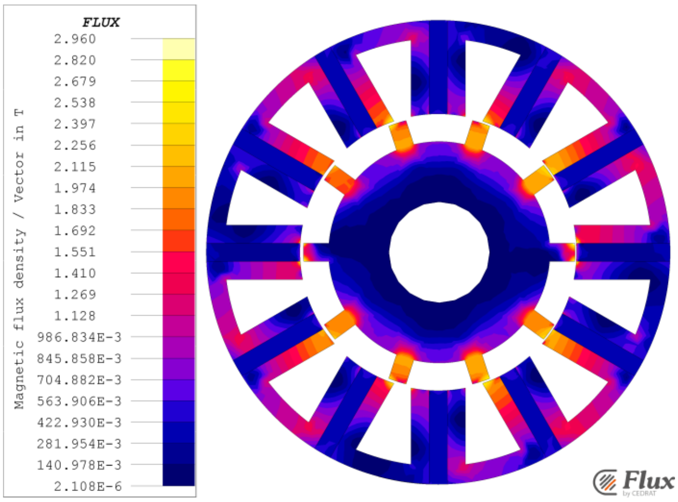

Fig. 5. Flux disturbution of FSPM motor with DEF=40%

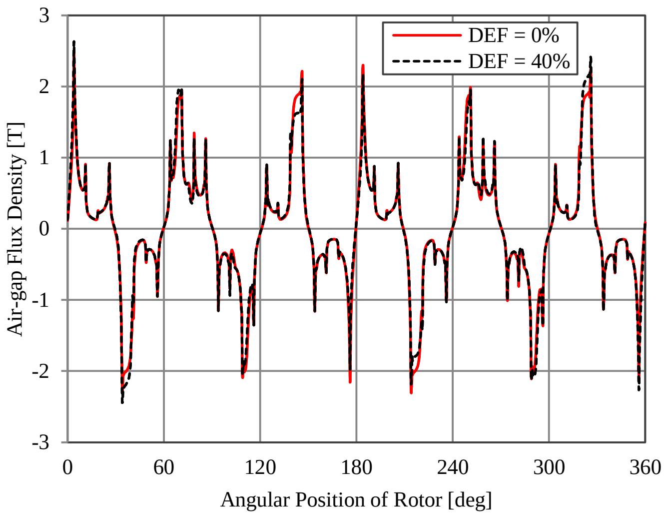

Fig. 6. Air-gap flux density of the healthy motor and motor with 40% eccentricity

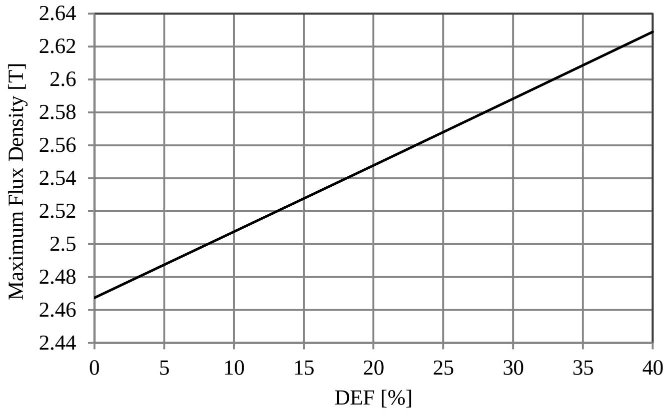

Fig. 7. Maximum air-gap flux density versus different values of DEF

VI. Effect of Eccentricity on Motor Force Characteristic

Eccentricity faults disturb the magnetic force between rotor and stator of the machine and lead to produce unbalanced magnetic force (UMF) in the machine. The UMF puts heavy loads on the bearing that can be the foundation of bearing weakness and consequently increasing vibration and noise, and finally makes fatigue and bending on the machine shaft [10]. Moreover, rotor eccentricity rises due to this unbalanced force that attempts to pull apart the rotor further away from the stator bore center. This unbalanced force is related to the motor rotating speed [11].

The studied machine in this paper is a radial flux FSPM motor which has cylindrical shape. In general, when rotor and stator have mutual centerline, the length of air-gap between the rotor and stator is symmetrical. However, when there is an eccentricity fault the length of air-gap between the rotor and stator is un-uniformed which causes to generate high value of acting forces between rotor and stator. In order to explore the effects of magnetic force between the rotor and the stator, FEM simulation is performed for the studied FSPM motor with DEF=0% and DEF 40%, and magnetic force between the rotor and the stator is calculated. Fig. 8 (a) and (b) show the influence of the rotating eccentricity on the magnetic force of the healthy motor and the motor with DEF= 40%, respectively. The results show that the magnetic force between the rotor and the stator has two components in X-direction (F_X) and Y-direction (F_Y) because in rotating eccentricity the minimum air-gap length rotates by rotor. It can be seen that both F_X and F_Y are periodic with the period of 360^o, and they have 90^o phase difference. Moreover, it can be observed that the motor force is increased significantly by increasing DEF.

Fig. 9 shows the distribution of magnetic force in the FSPM motor with DEF=0% and DEF=40%. By paying attention on the distribution of magnetic force in the faulty condition, it can be seen that the magnetic force contains harmonic number twelve which is equal to the number of stator poles. The main reason of these increments is the attraction of PMs which place in stator structure and the rotor teeth.

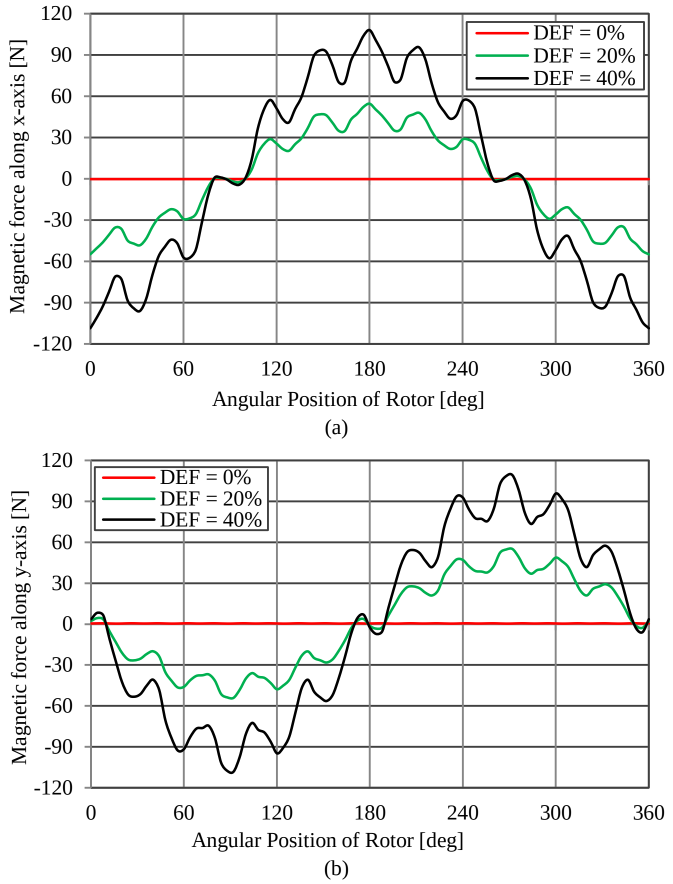

Fig. 8. A period of magnetic forces between rotor and stator, a): radial force along x-axis, b): radial force along y-axis

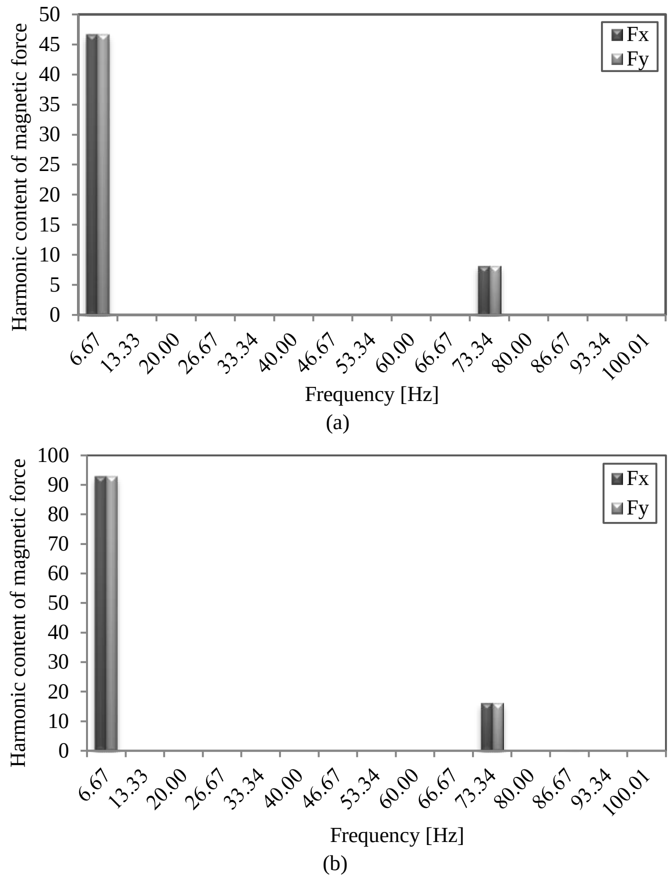

Fig. 10. Compare harmonic of F_X and F_Y, a): motor with DEF=20%, b): motor with DEF=40%

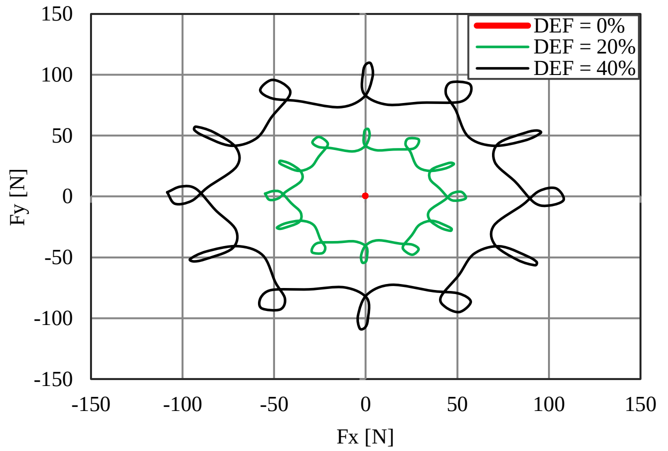

Fig. 9. Distribution of magnetic force versus different values of DEF

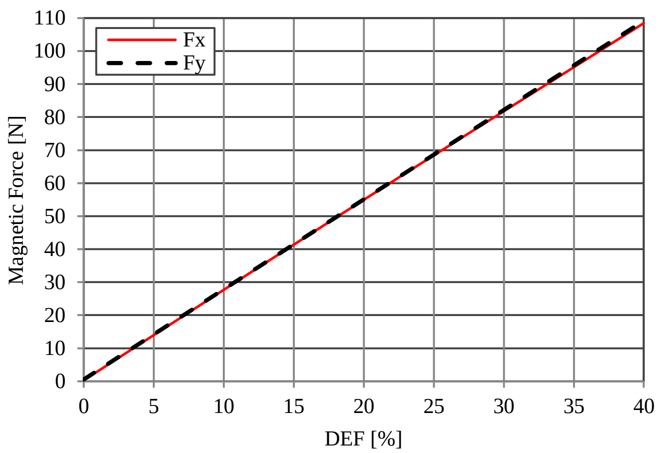

Fig. 11. Maximum magnetic force versus different values of DEF

In general, fast Fourier transforms (FFT) are very popular technique in fault detection studies. To have a closer inspection, harmonic analysis is performed for studying the magnetic force waveforms. Fig.10 (a) and (b) indicate the results of Fourier analysis of F_X and F_Y are performed for the healthy motor and the motor with DEF=20% and DEF=40%, respectively. By comparing the harmonic content of the magnetic force between stator and rotor it can be concluded magnetic force between stator and rotor it can be concluded that rotating eccentricity generate extra 6.667 Hz and 73.337Hz harmonics orders. In addition, F_X and F_Y has remarkable 1st harmonic content in comparison with 12th harmonic. Furthermore, Both F_X and FY have a remarkable value in comparison with the healthy motor which deteriorates the motor condition. Furthermore, as it is indicated in Fig. 11, the maximum value of magnetic force increases by increasing the DEF for both F_X and F_Y.

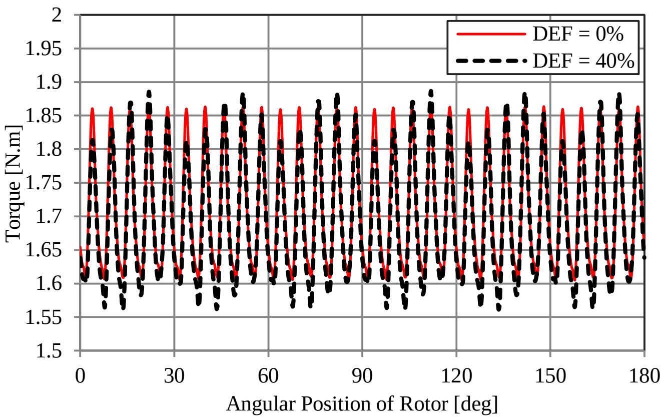

Fig. 12. Torque of the healthy motor and motor with DEF=20% and DEF=40%

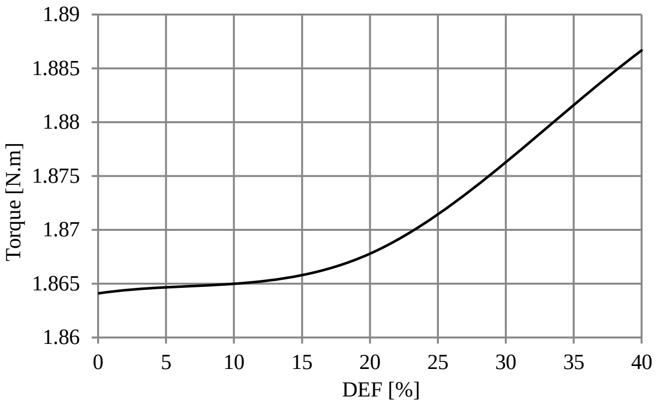

Fig. 13. Variation of fundamental torque with different values of SEF

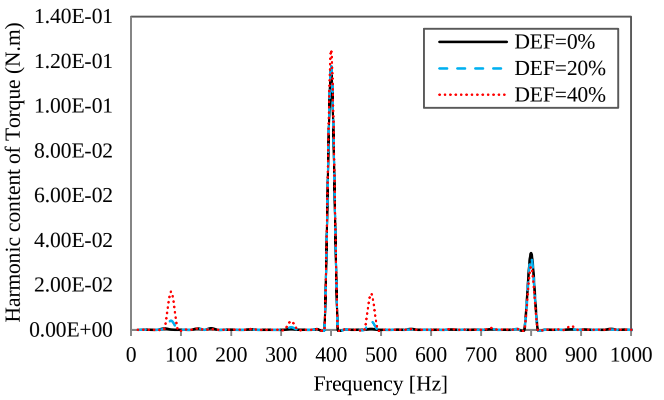

Fig. 14. Harmonic of torque in the healthy motor and motor with SEF=40%

VII. Effect of Eccentricity on Motor Torque Characteristic

Generally, all kinds of eccentricities cause the air-gap to be un-uniformed and consequently generating an undesirable unbalanced magnetic force between stator and rotor as described in last section and in addition changing the torque profile.

Usually, the calculation of machine torque is based on the Maxwell stress tensor method which calculates both radial components and tangential components of acting torque. In symmetrical condition, the tangential component is approximately zero. However, in eccentric condition, the machine is not balanced anymore, and rotor becomes closer to stator which leads to produce tangential component [12]. Thus, calculating the machine torque according to analytical methods is extremely difficult and time-consuming. So, FEA is preferred to be used to attain machine torque.

Fig. 12 indicates the machine torque profile which is produced in the motor in healthy condition and the motor with 40% rotating eccentricity. It is observed that the torque ripple is increased in faulty condition. Moreover, by paying more attention to Fig. 12 it can be seen that the torque waveform in faulty condition is modulated on a signal which has very little amplitude. This can be used for the fault detection purposes using vibration analysis of the machine, Moreover, as illustrated in Fig. 13, the mean value of the machine torque is a little increased in the motor with DEF=40% in comparison with the healthy motor which is negligible.

Fourier analysis of the output torque of machine is carried out for the healthy motor and the motor under 40% rotating eccentricity and the results are indicated in Fig. 14. It is observed that a rise is happened in the sideband frequencies which are 320 Hz and 480 Hz.by growing the DEF.

VIII. Conclution

The effect of rotating eccentricity on an FSPM motor has been studied through 2D-FEA. Use of this precise modeling makes it possible to attain required characteristics.

The obtained results by FEA demonstrate that rotating eccentricity distorts air-gap magnetic flux which causes to produce unbalanced magnetic force between rotor and stator in both X-direction and Y-direction. Furthermore, it is exposed that both F_X and F_Y dramatically does up by increasing the degree of rotating eccentricity. Moreover, it is observed that the eccentricity does not change the output torque profile significantly. Also, the machine torque has elevated 320 Hz and 480 Hz harmonics which can be used for fault detection based on machine vibration analysis. These facts have not been studied before and the investigation can be useful for future studies.

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