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Static Eccentricity Fault Detection in Flux Switching Permanent Magnet Machines

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***Abstract*—This paper studies the effects of static eccentricity (SE) in Flux Switching Permanent Magnet (FSPM) Machines to propose a criterion for fault detection. SE is one of the most common mechanical faults in electrical machines on. In order to achieve this goal, the proposed machine is studied under different degrees of static eccentricity fault to analyze machine condition. Finite element modeling (FEM) as the most accurate numerical approach is used to obtain precise results. The magnetic flux distribution of rotor and stator are calculated. In addition, air-gap flux density as a parameter which has a direct impact on back-EMF is assessed by using finite element analysis (FEA). It is found that static eccentricity has noticeable influences on back-EMF of coils of the machine. Furthermore, Fourier analysis is performed in order to achieve appropriate index for the diagnosis process. The results are provided for the healthy machine and the machine with different values of SE and the proposed index has been derived for the fault detection process in the machine.**

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

I. INTRODUCTION

Permanent-magnet (PM) machines have been center of attention of researchers for a long time due to compact structures, high efficiency, high torque and power density [1]. PM machines can be categorized according to the PM locations in two groups, rotor PM machines and stator PM machines [2]. Among these two categories, stator PM machines have more robust structure in comparison with rotor PM machines. Moreover, these kinds of machines are cooled easily which reduces the risk of being demagnetized and PMs will not be exposed to the centrifugal forces of a rotating rotor [3]-[4].

Doubly salient PM (DSPM) machines are a one kind of stator PM machines which are very similar to switched reluctance machines (SRMs). DSPM machines are divided to two main types, Flux Switching Permanent Magnet (FSPM) machines and Flux Reversal Permanent Magnet (FRPM) machines [3]. FSPM machines have been the subject of extensive research during the last few years. FSPM machines were used as high frequency generator in military applications but by the time, they have been used in many other applications such as aerospace main propulsion and electric aircrafts [5], hybrid electric vehicles [6] and renewable energies as wind generator [7].

Most literatures which have presented researches over last years, have dealt with design aspects [8], and optimized design [4], performance analysis and topology improvement [9] in FSPM machines while the effects of electrical and mechanical faults as an inseparable parts of electrical machines analysis have not been studied before. Eccentricity is one of the mechanical faults which frequently occur in electrical machines. Eccentricity is also known as air-gap eccentricity occurs when there is a non-uniform air-gap between the rotor and stator. Eccentricity faults consist of three types, static eccentricity (SE), dynamic eccentricity (DE) and mixed eccentricity (ME) which is the combination of the static and dynamic eccentricity.

In the present study, a 10/12 flux switching permanent magnet machine under different degrees of SE faults is simulated by using two-dimensional (2D) finite element analysis (FEA). Magnetic flux distribution of different parts of machine is calculated. Moreover, back-EMF of all coils of the machine is acquired and compared for the healthy machine and the machine with different values of eccentricity. It is seen that static eccentricity has noticeable influences on back-EMF of coils of machine which can be utilized as a good criterion for SE fault detection.

II. STATIC ECCENTRICITY FAULTS

Eccentricity is one of the mechanical faults in electrical machines which is defined as non-uniformed air-gap between rotor and stator. These faults are categorized into three types SE, DE, and ME. In SE the rotation axis of rotor which is its symmetrical axis, is displaced with respect to the symmetrical axis of stator. In this case, the existed displacement is fixed and does not vary by time.

In [10], the Static Eccentricity Factor (SEF) is defined as follows:

$$SEF = \frac{r}{g} \times 100 \tag{1}$$

Where "r" is the offset between the rotor and the stator axes and "g" is the radial air-gap length in healthy condition.

Eccentricity faults are inevitable during the process of electric machine construction, even when the manufacturing precision is high. But it should have as less degree as possible. Usually, less than ten percent of relative eccentricity between the rotor and the stator is acceptable in manufacturing process.

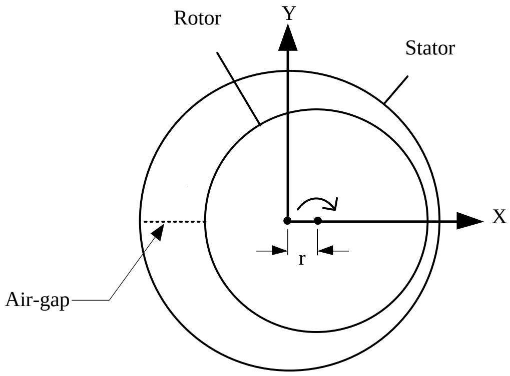

Fig. 1. Schematic representation of SE

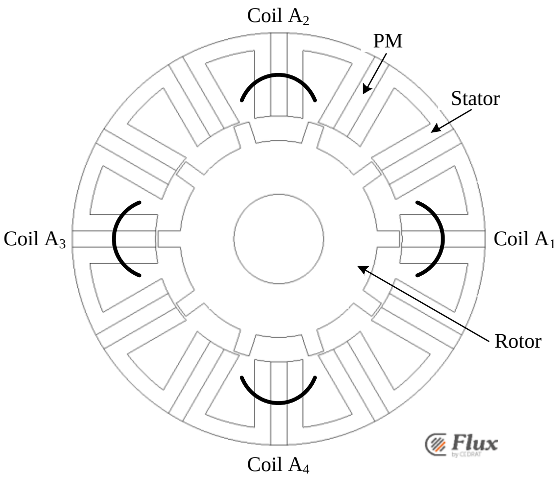

Fig. 2. Schematic of proposed 12/10 FSPM machine

III. Specifications of Studied Machine

In order to investigate the effects of SE on FSPM machines, a three-phase 12/10 stator/rotor pole machine as shown in Fig. 2, is modeled using FEM to acquire precise results. The studied model has concentrated winding which are connected in series and has star connection. This kind of winding has short end-winding and consequently less copper losses. Furthermore, each phase is connected to an extreme large resistance in order to calculate the back-EMF of machine. Major parameters of the machine are given in Table I.

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

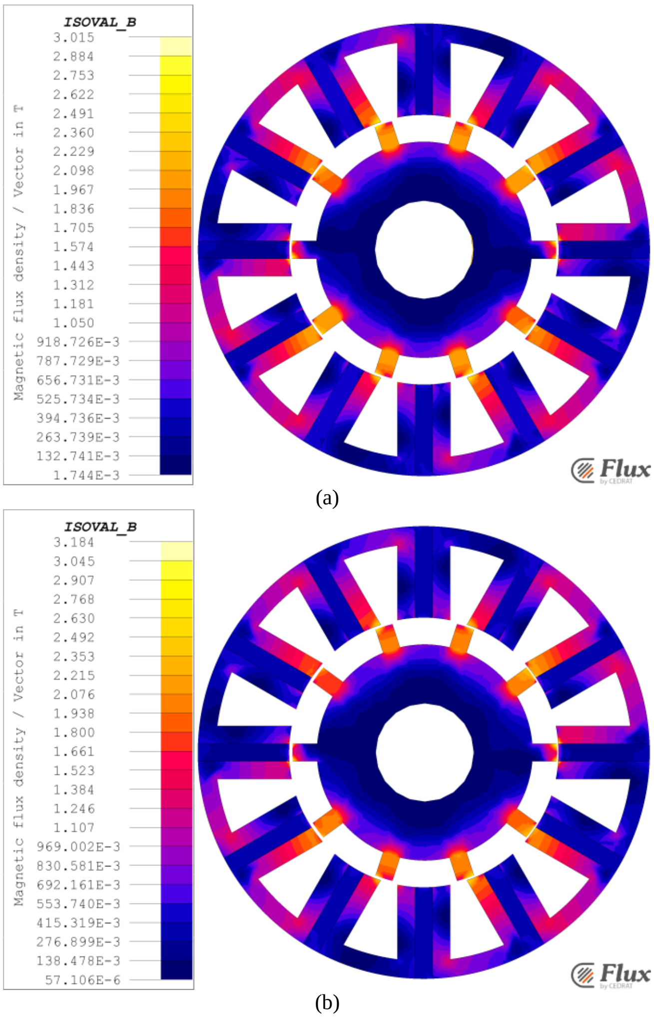

Fig. 3. Magnetic flux disturbution of FSPM machine: a) Healthy machine b) Machine with SEF=40%

IV. Effect of Eccentricity on the Magnetic Filed

A. Effect of eccentricity on the magnetic flux distribution

The study of magnetic flux distribution can be an appropriate approach to acquire reliable information about machine vibration and noise. Magnetic flux distribution of the healthy motor and the motor with 40% SE are illustrated in Figs. 3 (a) and Fig. 3 (b), respectively. By comparing the magnetic flux of the machine it is observed that the magnetic flux at right side where the air-gap has the smallest length is elevated while on the opposite side where the air-gap has the maximum length the magnetic flux density is reduced. So, it is concluded that SE causes an unbalanced magnetic flux distribution which can produce noise and vibration.

B. Effect of air-gap flux density

Air-gap flux density is one the most important parameters of electrical machines which has a direct impact on machine characteristics. By very small varying of this feature, machine behavior may change. Furthermore, the best way of monitoring and diagnosing the machine condition is analyzing the air-gap flux density by using special sensors. But as the process of putting sensors is invasive, the back-EMF of the machine has been used for fault detection purpose in this paper. Fig. 4 indicates the normal component of air-gap flux density in the healthy machine and the machine with 40% SE which is computed by using 2D-FEM.

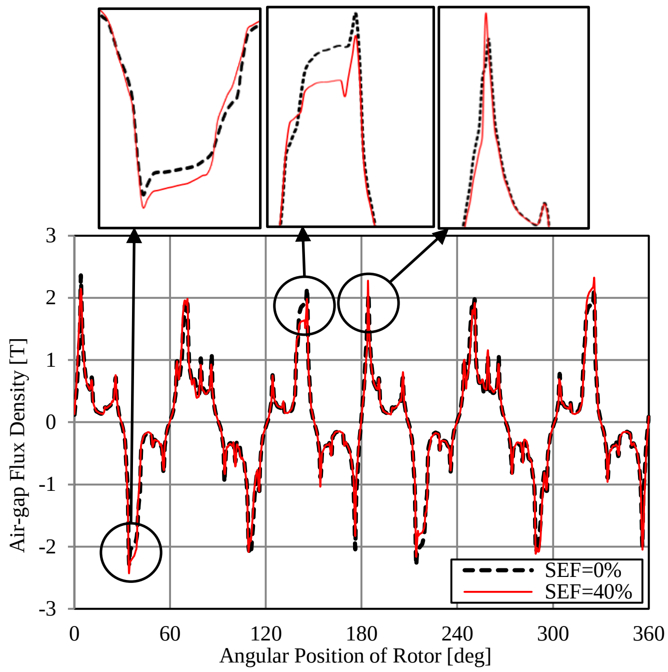

Fig. 4. Air-gap flux density of the healthy and motor with 40% eccentricity

It is observed that in the healthy machine the air-gap flux density is symmetric because the entire air-gap length between rotor and stator is uniformed while in the machine with SEF=40% where the air-gap length in the right side of the machine decreases, and the rotor becomes close to stator, the amount of air-gap flux density increases due to declining the value of air-gap reluctance and at the opposite, the amount of air-gap flux density has an decrement due to growing the value of air-gap reluctance.

V. Effect of Eccentricity on Back-EMF

The peak value of the induced voltage in PM machines can be expressed as [1]:

$$e_{ph} = K_e N_{ph} B_g \frac{\omega}{p} D_{out} l_{st} \quad (1)$$

Where "K_e" is the EMF factor which incorporates winding distribution factor, "N_{ph}" is the number of coil turns in series per phase winding, "B_g" is air-gap flux density, "ω" is angular speed, "p" is number of machine pole pair, "D_{out}" and "l_{st}" are the outer diameter of the rotor and stack length of the machine, respectively.

Back-EMF holds complete information from both mechanical and electrical parts of electric machines. Hence, a detailed observation of the Back-EMF can be carried out to detect the faults which could happen in electrical machines. In the healthy machine, the waveforms of the induced voltage of all the coils which belong to one phase have equal amplitudes and same profile. Regarding to the aim of this paper which is to propose a strict criterion for fault diagnosis in FSPM machines by analyzing this characteristic, FEA is carried out in order to investigate the influences of SE on back-EMF of all the coils which are belong to phase A.

To model SE, the rotation axis and the rotor axis is varied along the positive x-direction. Hence, the air-gap length in the right side reduces where coil A_1 is located is reduced while the air-gap length in the left side rises where coil A_3 is located and the air-gap length do not change for coil A_2 and A_4 as indicated in Fig. 2. FEM simulation is applied in order to calculate the back-EMF of coil A_1, A_2, A_3 and A_4. It is seen that the back-EMF of coil A_1 is increased due to increasing the air-gap flux density in the right side while the back-EMF of coil A_3 is declined due to decreasing the air-gap flux density in the left side and the back-EMF of coil A_2 and coil A_4 do not vary as expected according to equation 1. Furthermore, FEM results demonstrate that the growth of induced voltage of coil A_1 is the same as the drop of induced voltage of coil A_3. Thus, the induced voltage of phase A which can be expressed as equation 2, does not vary and affected by eccentricity:

$$V_A = E_{A1} + E_{A2} + E_{A3} + E_{A4} \quad (2)$$

where "E_{Ai}" is the induced voltage of coil A_i.

The effect of eccentricity on the induced voltage in coil 1 of phase A is illustrated in Fig. 5.Generally, it can be concluded that study of back-EMF of the coils of a phase is a proper measurement for fault detection because all coils are distributed in the machine. Also, it is discovered that the induced voltages of coil A_1 and coil A_2 are changed when SE is existed which can be appropriate criterions for fault detection. Moreover, air-gap length under coil A_1, A_2, A_3 and A_4 can be estimated sufficiently by measuring the amplitude of the induced voltages of coil A_1, A_2, A_3 and A_4. Also, it can be said that SE affects the induced voltage of at least two coils in any non-uniformity of air-gap length.

VI. Fourier Analysis of Back-EMF In Faulty FSPM

Most of the fault detection methods in power system are time domain based such as earth fault and impedance relays. However, electric machines fault detection techniques are frequency domain based, particularly the methods based on fast Fourier transforms (FFT) are very favorable among researchers. Generally, the machine current, flux, mechanical vibration, torque, and speed are analyzed by using FFT [11]. In order to discover more facts about the effects of SE on induced voltage, Fourier analysis is performed for induced voltage of coil A_1, A_2, A_3 and A_4 and the results are illustrated in Fig. 6. It is observed that in machine in faulty condition, the induced voltage harmonic contents for coil A_1 and A_3 are not equal in comparison with healthy condition because the air-gap under these two coils are not uniformed but on the other hands, the induced voltage harmonic contents for coil A_2 and A_4 are equal because the air-gap under these two coils does not change. Moreover, it can be seen that the 1st, 2nd, 3rd and 5th harmonic amplitude of coil A_1 is increased, and 1st, 2nd and 5th harmonic amplitude of coil A_3 is decreased. It should be noted that the harmonic amplitude of coil A_2 and A_4 do not have noticeable changes and they can be neglected. Also the variation of harmonic amplitude of coil A_1 and A_3 are plotted versus different SEFs as indicated in Fig. 7 and Fig. 8. It can be seen that 1st, 2nd, 3rd, 4th and 5th harmonic amplitude are grown

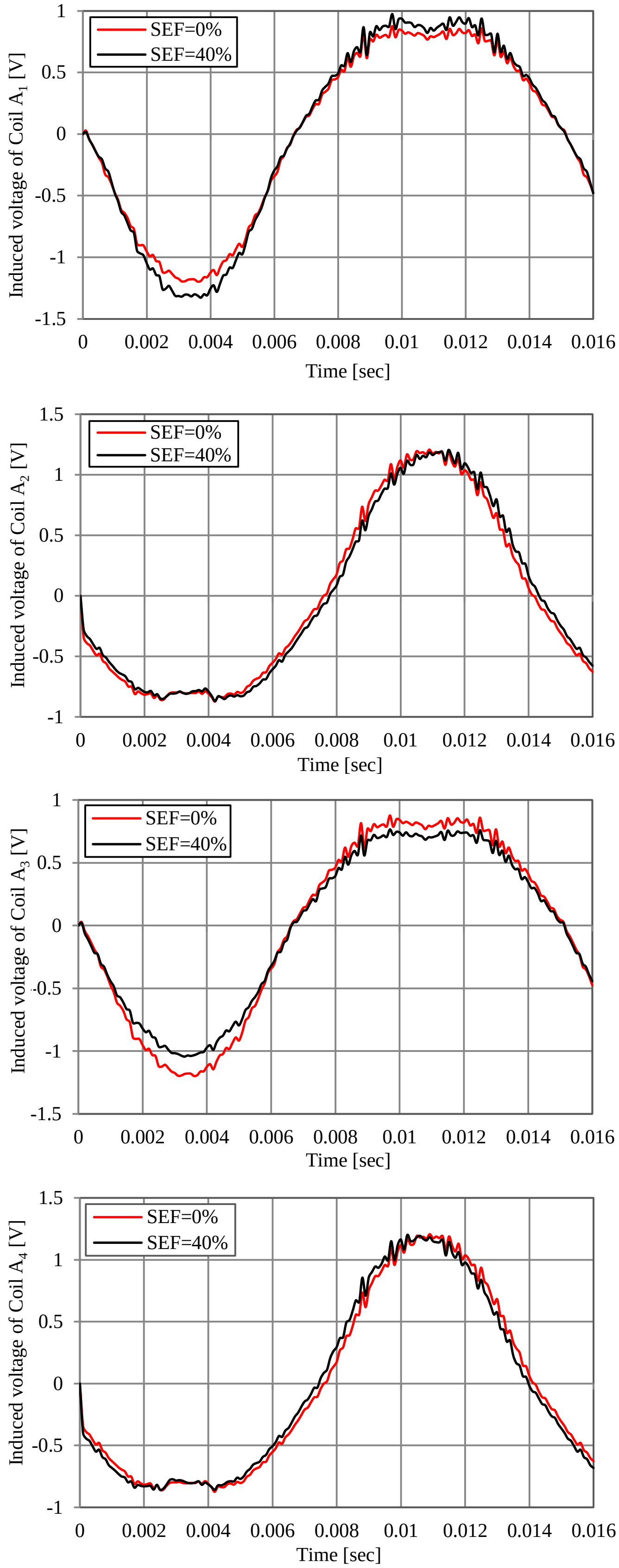

Fig. 5. Back-EMFs of four coils of phase A

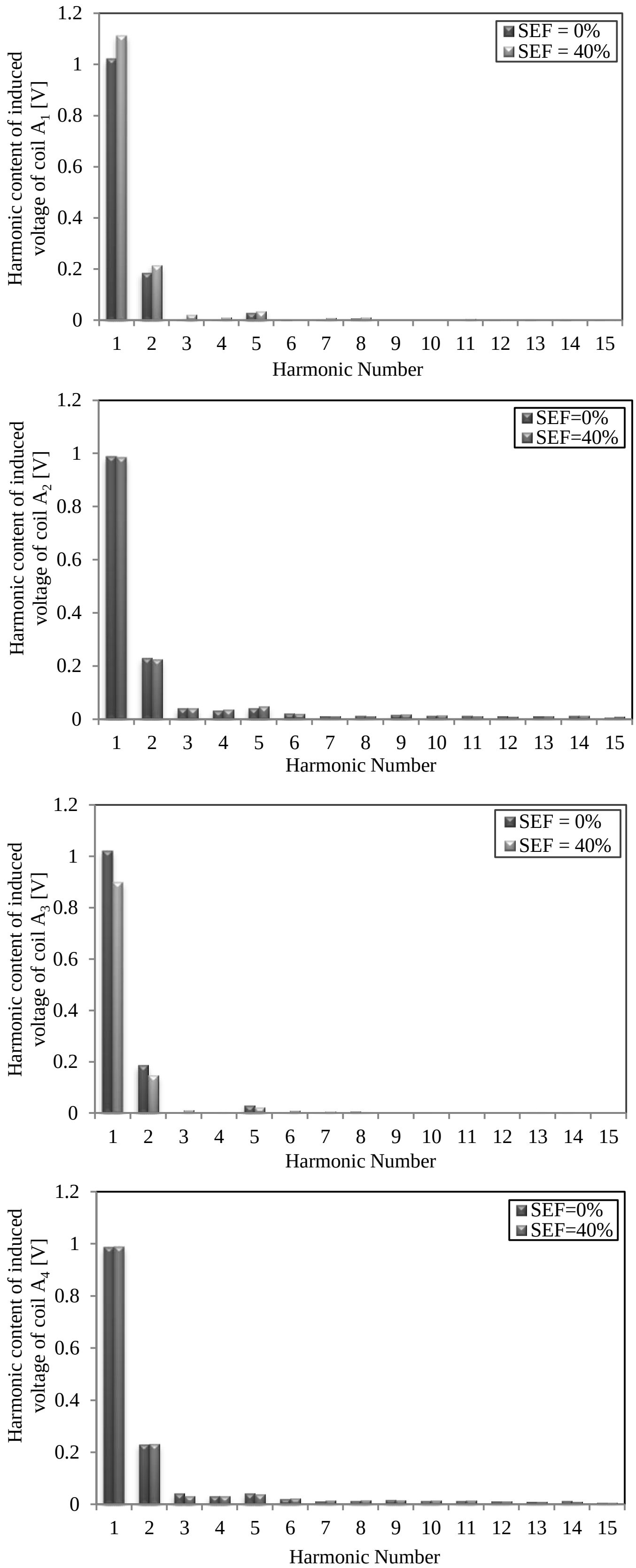

Fig. 6. Harmonic Content of induced voltages of four coils of phase A

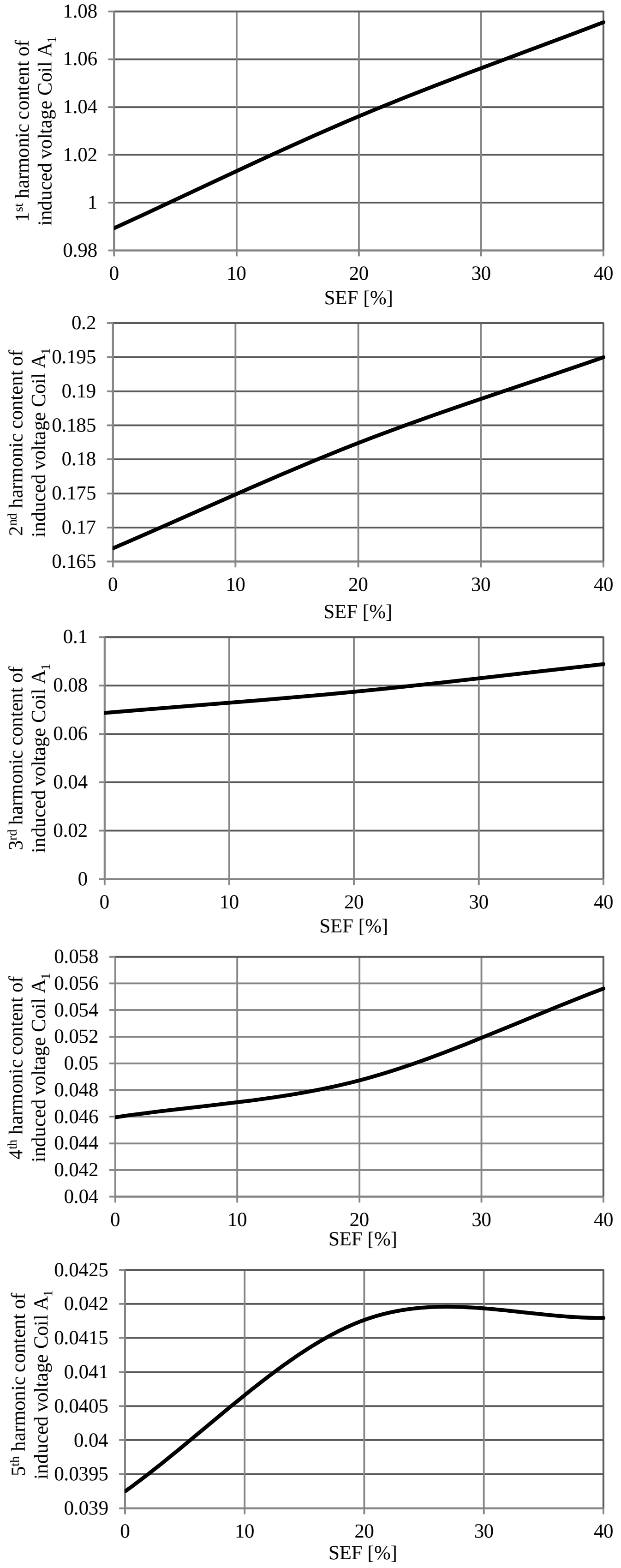

Fig. 7. Variation of first, second, third, fourth and fifth harmonic content of back-EMF of coils 1 calculated by FEM

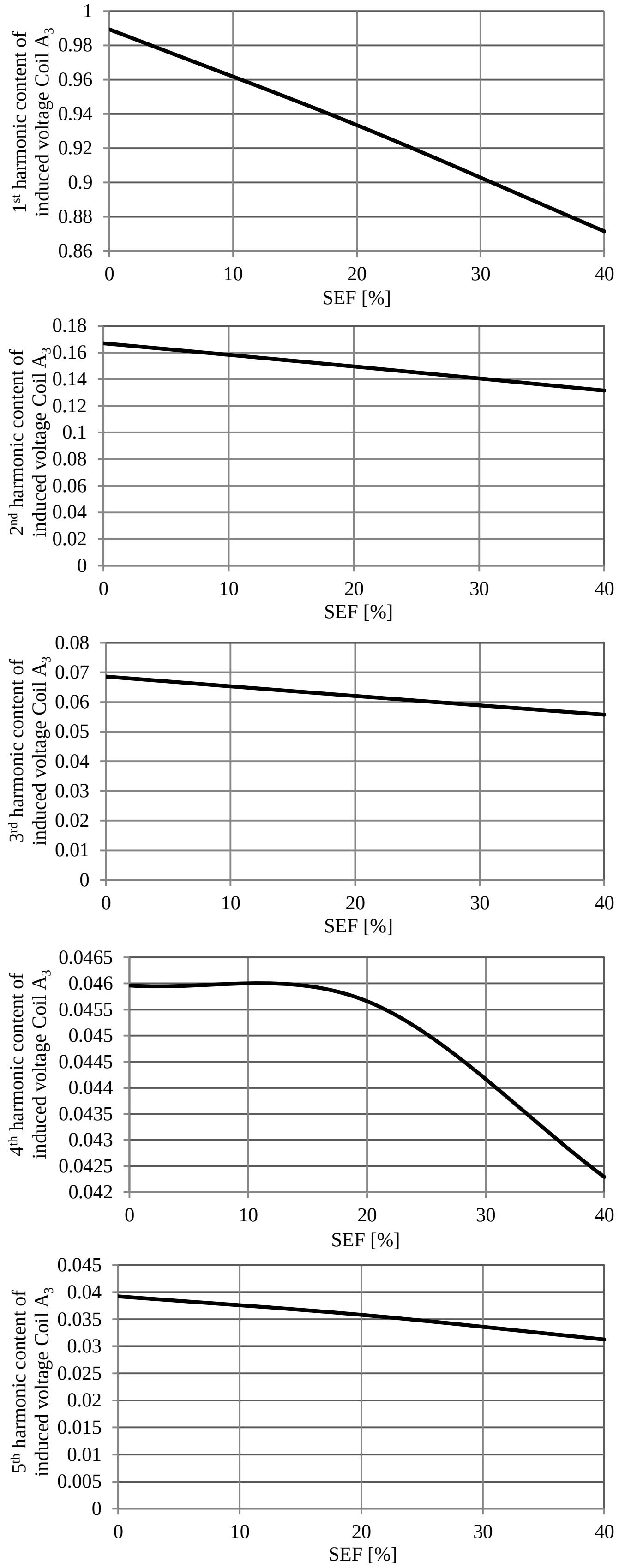

Fig. 8. Variation of first, second, third, fourth and fifth harmonic content of back-EMF of coils 3 calculated by FEM

up for coil A1 and they are dropping for coil A3. These trends can be used as index for SE fault detection in FSPMs.

VII. CONCLUTION

The effect of SE on back-EMF of an FSPM machine has been studied through 2D-FEA which is the most accurate numerical method. The results of FEM model shows that SE disturbs air-gap flux density and consequently induced voltage of the machine coils. Furthermore, by measuring the terminal voltage of machine phases, it is observed that SE does not affect the phase voltage but the individual coils are affected by the SE. In addition, harmonic analysis is performed to investigate the effects of eccentricity on back-EMF of coils which is an appropriate technique for fault detection. It is shown that the proposed method is straightforward for the SE fault detection in FSPMs. To the best knowledge of the authors, this has not been studied till now and it can be a useful approach for future investigations.

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