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# Investigation of the Effect of Eccentricity in Flux Switching Permanent Magnet Machines

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***Abstract*—This paper studies a 10/12 Flux Switching Permanent Magnet (FSPM) machine under static eccentricity fault to assess the performance of the machine under different operating conditions. Two-dimensional finite element method (FEM) is used to model the complicated structure of the machine in order to obtain accurate results. Furthermore, finite element analysis (FEA) is used to obtain air-gap flux density, machine's torque and the force between stator and rotor under different degrees of static eccentricity. Furthermore, Fourier analysis is performed to study magnetic force and torque profiles. To the best awareness of the authors, the effects of the eccentricity of FSPM machines have not been studied previously.**

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

## I. INTRODUCTION

Permanent-magnet (PM) brushless machines have been extensively used for several applications because of their high efficiency and high torque/power density [1]. Stator-PM machines include Doubly Salient PM (DSPM) machine, Flux Reversal PM (FRPM) machine, and Flux Switching Permanent Magnet (FSPM) machines. In this kind of machines, PMs can be cooled simply and the PMs will not be exposed to the centrifugal forces of a rotating rotor [2]-[5]. FSPM machines have complicated structure in comparison with other stator-PM machines. This type of machines is used as one of high frequency inductor generators [6], [7]. Furthermore, FSPM machines are used in aerospace applications [8], high-speed applications [9], wind turbine application [10] and hybrid electric vehicles [11]. Over the last few years, several publications have concentrated their interest to design, analysis, and improve the FSPM structure in order to attain the desired requirements [12]-[16]. Moreover, some literatures have been done to improve the performance of FSPM machines especially reducing cogging torque [17]-[19] and back-EMF harmonics [20].

Generally, there are numerous types of fault which may occur in electrical machines which are categorized into two main groups according to their causes, external faults and internal faults. Furthermore, these faults are consisted in electrical faults and mechanical faults. Among these deficiencies, bearing faults and eccentricity faults are the most common failures in electrical machines. Static or dynamic

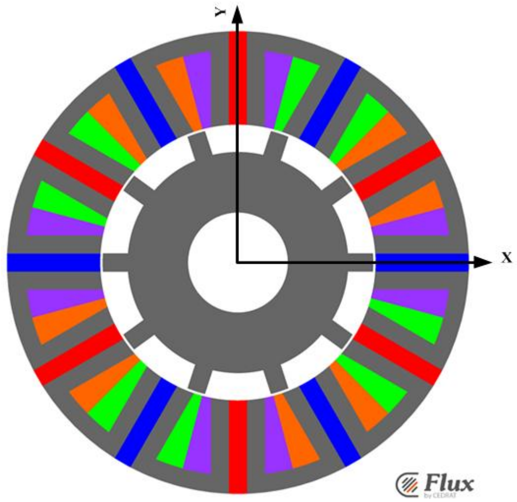



Fig. 1. Schematic of proposed FSPM machine

eccentricity faults are among the mechanical faults that are due to manufacturing imprecision of mechanical parts such as unbalanced mass, bearing deficiency, misalignment and excessive tolerances which cause a vibration and ultrasound noise [21]. There is no literature discussing the effects of the eccentricity on an FSPM and this paper is the first step in such an analysis for FSPM.

In this paper, a three phase 12/10 flux switching permanent magnet motor under static eccentricity fault is simulated at different percentage of static eccentricity using two-dimensional (2D) finite element analysis (FEA). Flux density distribution of the machine is calculated and the output torque is acquired. In addition, the force between rotor and stator of the machine and torque profile with 40% eccentricity is derived and compared with a faultless motor.

## II. MOTOR SPECIFICATIONS

The proposed FSPM machine is a three-phase 12/10 stator/rotor pole motor, as shown in Fig. 1. Major parameters of the machine are given in Table I.

## III. FIINITE ELEMENT SIMULATION

In order to study eccentricity in FSPM machines, it is essential to use an accurate modeling of all machine details such as geometry and non-linear properties of the magnetic materials. Analytical methods are complicated when precise evaluation of saturation effects is needed.

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 |

This issue can be overcome by using FEA which can apply precise numerical approach. The finite element model of the FSPM machine is created in CEDRAT Flux package in order to study and analysis static eccentricity. Fig. 1 shows the schematic of proposed FSPM machine. The machine has concentrated winding with twelve coils which have star connection. The coils of each phase are connected in series and supplied by three-phase sinusoidal current waveforms as it is shown in Fig. 2. The circuit is coupled to magnetic domain in this study. Two different coordinate systems are defined for each of rotor and stator. Stator coordinate system is fixed and rotor coordinate system varies along positive direction of x-axis in order to generate eccentricity and the rotor rotates around globalist own coordinate system.

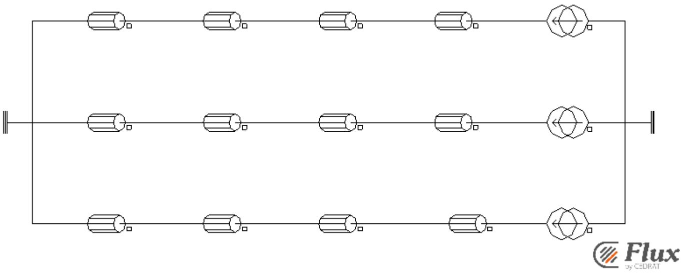



Fig. 2. Circuit diagram of proposed FSPM machine

## IV. STATIC ECCENTRICITY IN FSPM MACHINES

Bearing faults are the most regular sources of failure in electric machines that causes ball fatigue which is the main result of machine vibration. These vibrations in the air-gap are considered as non-uniform air-gap which is called eccentricity. Therefore, it can conclude that bearing faults change the air-gap balance like eccentricity faults.

When there is a non-uniform air-gap between rotor and stator, the axis of stator, the axis of rotor and rotation axis of rotor are misaligned. Eccentricity can be categorized into three types, static eccentricity, dynamic eccentricity and mixed eccentricity. In the static eccentricity, the rotor rotates around its own symmetrical axis, but the axis does not coincide with the stator center as shown in Fig. 3.

In [22], [23] the definition of Static Eccentricity Factor (SEF) is proposed which can be defined as follows:

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

Where “r” is the offset between the rotor and the stator axes and “g” is the radial air-gap length in faultless condition.

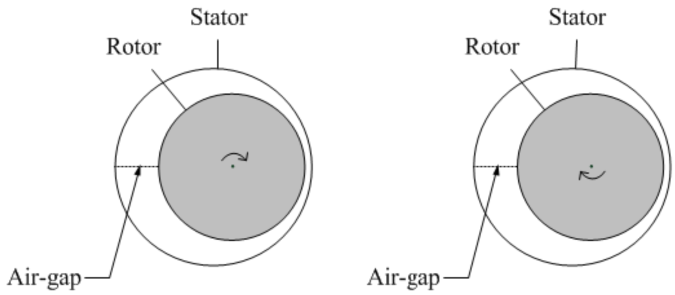



Fig. 3. Schematic representation of static eccentricity

## V. EFFECT OF ECCENTRICITY ON THE FLUX DENSITY

### A. *Flux Density Distribution*

Flux density distribution of the faultless motor and the motor with 40% static eccentricity are illustrated in Figs. 4 and Fig. 5 respectively. As mentioned in part III, the static eccentricity has happened along x-axis. It is observed that by decreasing the air-gap length in right side of the machine, machine’s reluctance in x-direction and consequently amplitude of magnetic flux density growths to 2.911 T in hotspots. However, on the opposite side, the air-gap length of the machine goes up and consequently reluctance and amplitude of magnetic flux density declines to 2.21 Tesla. So, it can be concluded that the static eccentricity causes asymmetric magnetic flux density distribution and harmonic components in the air-gap field.

### B. *Air-gap Flux Density*

The air-gap flux density is one of the crucial features in electrical machines because every change in this characteristic will affect other characteristics of motor. On the other hand, the air-gap flux density shows the machine condition. Thus, by monitoring air-gap flux density it is possible to foresee and diagnosis. This characteristic in static eccentricity which is non-uniform air-gap length should be analyzed. Air-gap flux density in the radial direction is computed using 2D-FEM. Fig. 6 shows the normal component of air-gap flux density computed by 2D-FEM simulation for both faultless motor and motor with SEF=40%.

By comparing the results it can be concluded that static eccentricity has high impact on air-gap flux density of the motor. At the right side of the machine where the air-gap has the smallest length, the air-gap flux density has the peak values and on the other side where the air-gap has the maximum length, the air-gap flux density has the minimum value. This happens because the flux path reluctance is depended on air-gap length and thus varying small value of air-gap has a great impact on the value of air-gap flux density. In Fig. 7 maximum value of air-gap flux density for various values of SEF is shown. It can be seen that the static eccentricity lead to increase the maximum air-gap flux density.

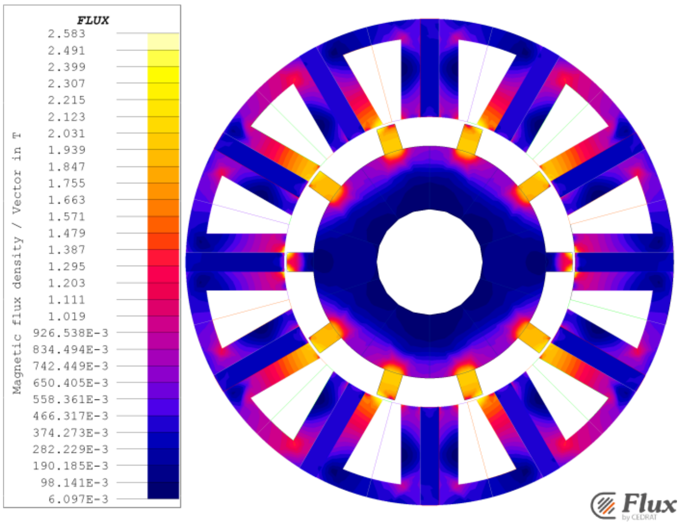



Fig. 4. Flux disturbution of FSPM motor with SEF=0%

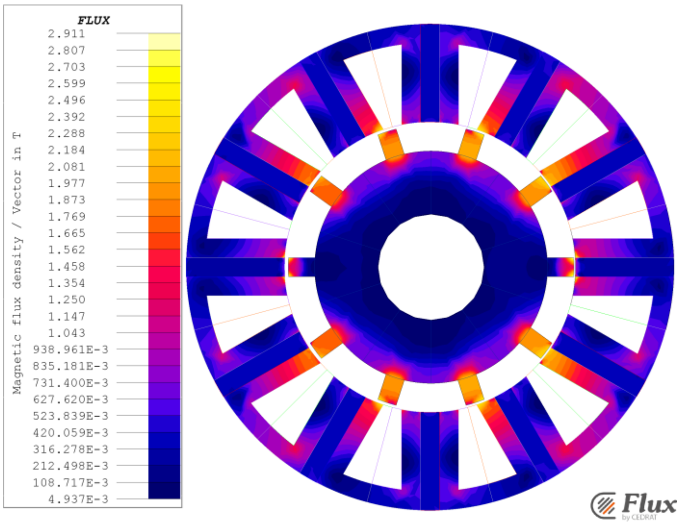



Fig. 5. Flux disturbution of FSPM motor with SEF=40%

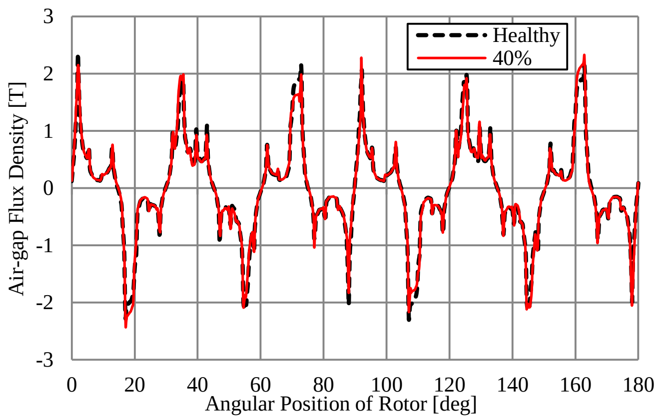



Fig. 6. Air-gap flux density of the faultless and motor with 40% eccentricity

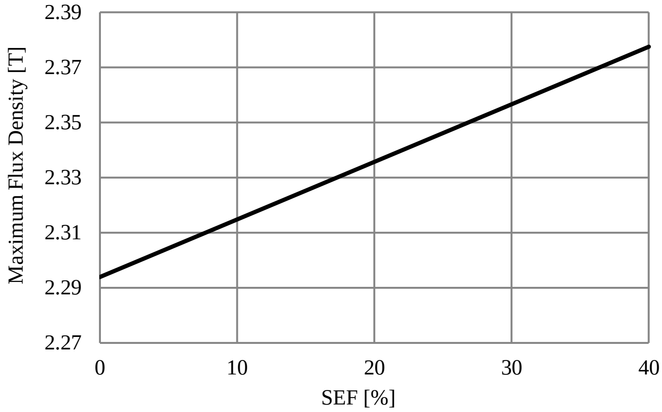



Fig. 7. Maximum air-gap flux density versus different values of SEF

## VI. EFFECT OF ECCENTRICITY ON MOTOR FORCE CHARACTERISTIC

Electrical machines eccentricity is an important consequence of bearing deterioration. Eccentricity disrupts the magnetic field and the balance between the magnetic forces of the machine and consequently resulting in unbalanced magnetic force. This unbalanced force places more loads on the bearing which can cause an increase in vibration at certain frequencies specified by the motor configuration [24].

The machine that is studied in this paper is a radial flux FSPM motor. Generally, when rotor and stator place in one centerline and the air-gap between the rotor and stator is uniformed, the resultant of acting forces between rotor and stator of radial flux machines is near zero. But, when there is an eccentricity fault, the resultant of acting forces between rotor and stator is not near to zero any more. FEM simulation shows that the magnetic force between the rotor and the stator is periodic and the period of this force can be expressed as follows:

$$\tau = \frac{2\pi}{N_r} rad = \frac{360}{N_r} deg \qquad (2)$$

Fig. 8 indicates the effect of the static eccentricity on the magnetic force of the faultless motor and the motor with 40% eccentricity. This magnetic force is the result of interaction between the air-gap flux density and stator and rotor teeth. The exact nature of the produced force waves is a function of motor dimensions and stator and rotor pole numbers combinations. Furthermore, it can be seen that the motor force is increased by increasing SEF.

Fig.9 (a) and Fig.9 (b) indicates the results of Fourier analysis of magnetic force performed for SEF=0% and SEF=40%, respectively. It is observed that the magnetic force between stator and rotor produces extra $1^{st}$, $2^{nd}$, $3^{rd}$, $4^{th}$ harmonics orders. For the machine with SEF=40% the amplitude of magnetic force content has a significant value in comparison with the machine with SEF=0% which leads to motor condition deterioration.

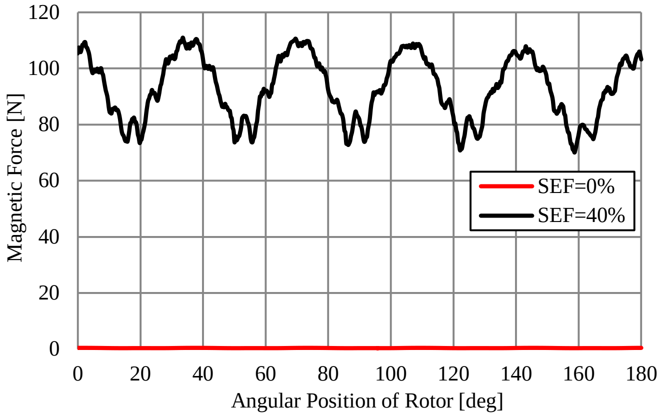
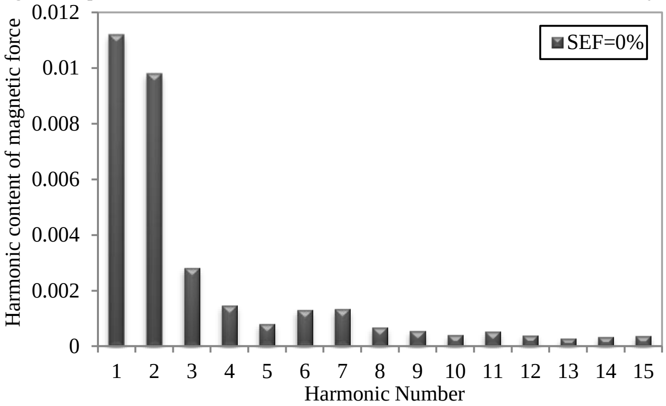
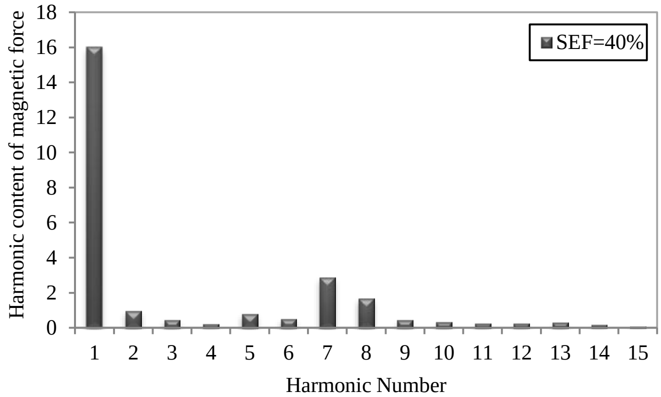



Fig. 8. A period of radial forces between rotor and stator at 40% eccentricity




(a)




(b)

Fig. 9. Harmonic of magnetic force between stator and rotor, a): SEF=0%, b): SEF=40%

Moreover, as it is indicated in Fig. 10, the mean value of magnetic force increases by increasing the SEF.

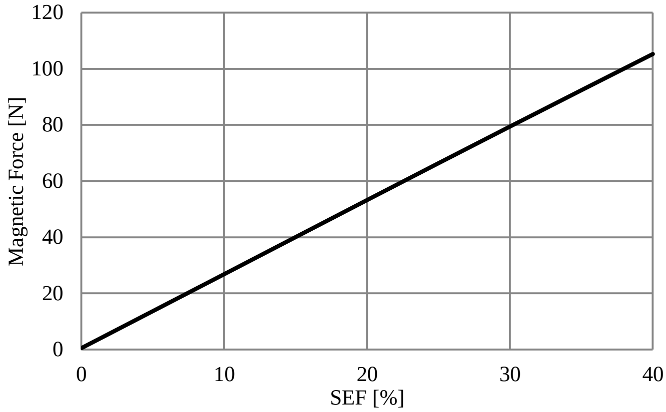



Fig. 10. Magnetic force versus different values of SEF

## VII. Effect of Eccentricity on Motor Torque Characteristic

As it was shown in section VI, static eccentricity increases the amount of forces between stator and rotor. This non-uniformed air-gap may cause an undesirable unbalanced torque and bearings defect [22]. Usually, the Maxwell stress tensor method is used to calculate the instantaneous torque of machines. In symmetric condition, vectorial sum of the radial components of the acting force is equal to zero and only tangential torque causes to produce torque. However, in asymmetric condition, the rotor is gravitated to stator, so the radial components of the acting force have not been in a balanced condition any more. Thus, it should be taken into account in calculation of torque [25].

The presented method of calculating the machine's torque is valid for doubly salient machines too. But, according to complex structure of FSPM machines, it is really difficult to calculate the machine's torque based on analytical methods. Hence FEA is used to obtain machine's torque. Fig. 11 shows the waveform of torque which is produced in faultless and faulty machine with SEF=40%. FEA is used in order to study this torque under different values of SEF. The machine in faultless condition has a little lower torque ripple in comparison with the machine with SEF=40%. Also by increasing the SEF the mean value of the machine torque is reduced which is indicated in Fig. 12.

Fourier analysis of torque profile is performed for both SEF=0% and SEF=40% and the results are shown in Fig. 13. As it can be seen there is an increment in the torque 7$^{th}$ harmonic order by increasing the SEF.

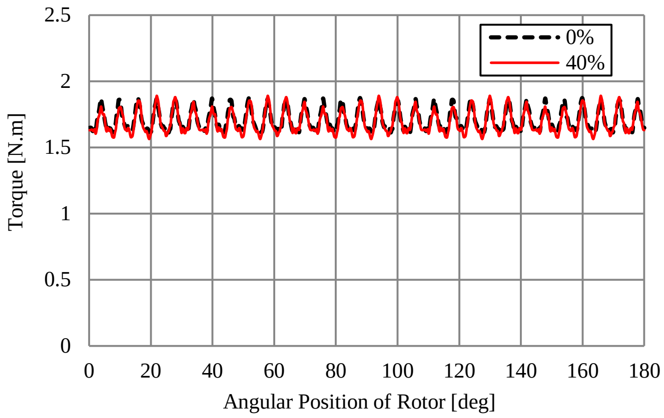



Fig. 11. Torque of the faultless and motor with SEF=40%

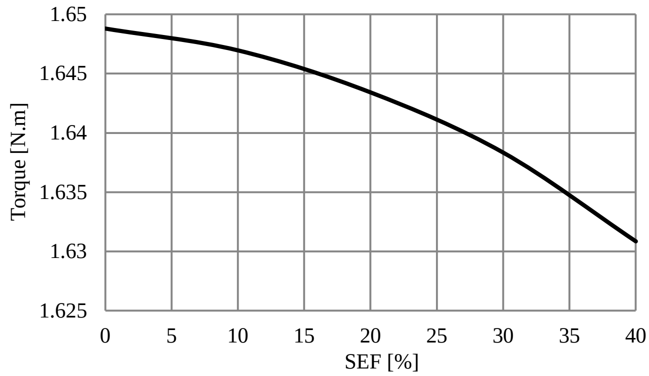



Fig. 12. Variation of fundamental torque with different values of SEF

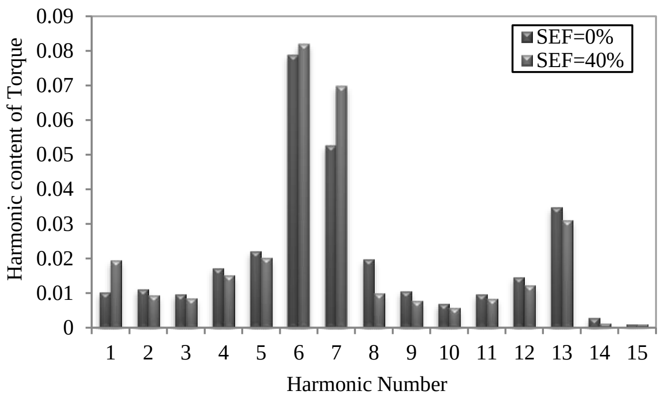



Fig. 13. Harmonic of torque in the faultless motor and motor with SEF=40%

## VIII. CONCLUTION

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

The results of FEM model show that static eccentricity deforms air-gap magnetic field and consequently leads to produce an unbalanced magnetic force between rotor and stator. Moreover, it is discovered that the produced magnetic force has a remarkable value. Furthermore, it is observed that the eccentricity does not vary the output torque profile significantly. Also, the machine torque has elevated 7th harmonic order which can be used for fault detection based on machine vibration analysis. Also magnetic force between rotor and stator is significantly elevated which leads to machine condition deterioration. These facts have not been studied before and the investigation can be useful for future studies.

## REFERENCES


[1] Yangsheng Chen; Haodong Yang; Ze Ying Han, "Investigation of electromagnetic vibration of permanent magnet brushless machines," in Electrical Machines and Systems, 2008. ICEMS 2008. International Conference on , vol., no., pp.621-626, 17-20 Oct. 2008

[2] Ming Cheng; Wei Hua; Jianzhong Zhang; Wenxiang Zhao, "Overview of Stator-Permanent Magnet Brushless Machines," in *Industrial Electronics, IEEE Transactions on* , vol.58, no.11, pp.5087-5101, Nov. 2011

[3] Chunhua Liu; Chau, K.T.; Jiang, J.Z.; Niu, S., "Comparison of Stator-Permanent-Magnet Brushless Machines," in *Magnetics, IEEE Transactions on*, vol.44, no.11, pp.4405-4408, Nov. 2008

[4] Yuefeng Liao; Liang, F.; Lipo, T.A., "A novel permanent magnet motor with doubly salient structure," in *Industry Applications Society Annual Meeting, 1992., Conference Record of the 1992 IEEE* , vol., no., pp.308-314 vol.1, 4-9 Oct. 1992

[5] Deodhar, R.P.; Andersson, S.; Boldea, I.; Miller, T.J.E., "The flux-reversal machine: a new brushless doubly-salient permanent-magnet machine," in *Industry Applications, IEEE Transactions on* , vol.33, no.4, pp.925-934, Jul/Aug 1997

[6] Rauch, S.E.; Johnson, L.J., "Design Principles of Flux-Switch Alternators," in *Power Apparatus and Systems, Part III. Transactions of the American Institute of Electrical Engineers* , vol.74, no.3, pp., Jan. 1955

[7] Zhu, Z.Q., "Switched flux permanent magnet machines — Innovation continues," in *Electrical Machines and Systems (ICEMS)*, 2011 International Conference on , vol., no., pp.1-10, 20-23 Aug. 2011

[8] Sanabria-Walter, C.; Polinder, H.; Ferreira, J.A., "High-Torque-Density High-Efficiency Flux-Switching PM Machine for Aerospace Applications," in *Emerging and Selected Topics in Power Electronics, IEEE Journal of* , vol.1, no.4, pp.327-336, Dec. 2013

[9] Thomas, A.S.; Zhu, Z.Q.; Jewell, G.W., "Comparison of flux switching and surface mounted permanent magnet generators for high-speed applications," in *Electrical Systems in Transportation, IET* , vol.1, no.3, pp.111-116, September 2011

[10] Akuru, U.B.; Kamper, M.J., "Comparative advantage of flux switching PM machines for medium-speed wind drives," in *Domestic Use of Energy (DUE), 2015 International Conference on the* , vol., no., pp.149-154, March 31 2015-April 1 2015

[11] Wei Hua; Gan Zhang; Ming Cheng, "Investigation and Design of a High-Power Flux-Switching Permanent Magnet Machine for Hybrid Electric Vehicles," in *Magnetics, IEEE Transactions on* , vol.51, no.3, pp.1-5, March 2015

[12] Zhu, Z.Q.; Chen, J.T., "Advanced Flux-Switching Permanent Magnet Brushless Machines," in *Magnetics, IEEE Transactions on* , vol.46, no.6, pp.1447-1453, June 2010

[13] Zhu, Z.Q.; Pang, Y.; Howe, D.; Iwasaki, S.; Deodhar, R.; Pride, A., "Analysis of electromagnetic performance of flux-switching permanent-magnet Machines by nonlinear adaptive lumped parameter magnetic circuit model," in *Magnetics, IEEE Transactions on* , vol.41, no.11, pp.4277-4287, Nov. 2005

[14] Sulaiman, E.; Kosaka, T.; Matsui, N., "Design optimization of 12Slot-10Pole hybrid excitation flux switching synchronous machine with 0.4kg permanent magnet for hybrid electric vehicles," in *Power Electronics and ECCE Asia (ICPE & ECCE), 2011 IEEE 8th International Conference on* , vol., no., pp.1913-1920, May 30 2011-June 3 2011

[15] Jurca, F.N.; Martis, C., "Optimal design of a flux-switching permanent magnet machine for small power automotive applications," in *Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2014 International Symposium on* , vol., no., pp.439-443, 18-20 June 2014

[16] Chen, J.T.; Zhu, Z.Q., "Winding Configurations and Optimal Stator and Rotor Pole Combination of Flux-Switching PM Brushless AC Machines," in *Energy Conversion, IEEE Transactions on* , vol.25, no.2, pp.293-302, June 2010

[17] Zhu, Z.Q.; Thomas, A.S.; Chen, J.T.; Jewell, G.W., "Cogging Torque in Flux-Switching Permanent Magnet Machines," in *Magnetics, IEEE Transactions on* , vol.45, no.10, pp.4708-4711, Oct. 2009. doi: 10.1109/TMAG.2009.2022050

[18] Daohan Wang; Xiuhe Wang; Sang-Yong Jung, "Reduction on Cogging Torque in Flux-Switching Permanent Magnet Machine by Teeth Notching Schemes," in *Magnetics, IEEE Transactions on* , vol.48, no.11, pp.4228-4231, Nov. 2012

[19] Zhu, Z.Q.; Chen, J.T.; Pang, Y.; Howe, D.; Iwasaki, S.; Deodhar, R., "Analysis of a Novel Multi-Tooth Flux-Switching PM Brushless AC Machine for High Torque Direct-Drive Applications," in *Magnetics, IEEE Transactions on* , vol.44, no.11, pp.4313-4316, Nov. 2008

[20] Bobba, D.; Li, Y.; Sarlioglu, B., "Harmonic Analysis of Low Stator Slot and Rotor Pole Combination FSPM Machine Topology for High Speed," in *Magnetics, IEEE Transactions on* , vol.PP, no.99, pp.1-1

[21] Mirimani, S.M.; Vahedi, A.; Marignetti, F., "Effect of static eccentricity in back-EMF of Axial Flux Permanent Magnet Machines," in *Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2012 International Symposium on* , vol., no., pp.464-468, 20-22 June 2012

[22] Mirimani, S.M.; Vahedi, A.; Marignetti, F., "Effect of Inclined Static Eccentricity Fault in Single Stator-Single Rotor Axial Flux Permanent Magnet Machines," in *Magnetics, IEEE Transactions on*, vol.48, no.1, pp.143-149, Jan. 2012

[23] Mirimani, S.M.; Vahedi, A., "Effects of static eccentricity in axial flux permanent magnet machines," in *Power Electronic & Drive Systems & Technologies Conference (PEDSTC), 2010 1st* , vol., no., pp.311-315, 17-18 Feb. 2010

[24] Kim, U.; Lieu, D.K., "Effects of magnetically induced vibration force in brushless permanent-magnet motors," in *Magnetics, IEEE Transactions on* , vol.41, no.6, pp.2164-2172, June 2005

[25] Katsuyoshi, E; Kazurou, H; Yoshiyuki, I.; Yoshiyuki, T., "A calculation of torque in motors considering rotor eccentricity", Electrical Engineering in Japan, Volume 132, Issue 4, pages 53–61, September 20