International Journal of Engineering Research and Technology.
ISSN 0974-3154 Volume 11, Number 10 (2018), pp. 1619-1632

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A Novel Switched Flux Permanent Magnet Machine with Eccentric Rotor Structure

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Abstract

Switched flux permanent magnet (SFPM) machine has gained popular attentions, as it possesses the advantages of simple rotor structure with salient iron poles and high efficiency. However, most permanent magnet machines suffer from torque ripple problem, due to the cogging torque that is an inherent feature of such machines. Hence, reduction of cogging torque for such machines has become of interesting, particularly for high-reliability applications such as automation and aerospace. In order to reduce cogging torque and consequently torque ripple, a new SFPM machine with eccentric rotor structure is introduced in this study. The proposed machine is compared with the conventional counterpart under the same conditions of design and optimization. It has been shown that the eccentric SFPM machine exhibits about 93.7% less cogging torque and 79.5% less torque ripple in comparison with the existing SFPM machine. On the other hand, the proposed machine has about 17% less electromagnetic torque compared to the conventional corresponding.

Keywords: Cogging torque, Eccentric rotor, Torque ripple, Switched flux permanent magnet machine.

1. INTRODUCTION

Since the development of high energy permanent magnet (PM) materials, PM machines, especially doubly salient permanent magnet (DSPM) machines have been receiving a considerable attention. This is because such topologies incorporate the merits of PM and reluctance machines. Switched flux permanent magnet (SFPM) machines may be considered as the most popular type of the DSPM machines, due to the advantage of flux focusing and high torque as well as efficiency densities. 12/10 SFPM machine was analysed and the influence of the rotor pole arc on the back-EMF waveform was investigated in [1]. It was shown that the machine has the advantage of sinusoidal back-EMF, and the harmonic content of the waveform can be reduced by an optimal rotor pole arc. On the other hand, a parametric optimization to maximize the average torque was addressed in [2], while in [3], the individual and global optimization of the main design parameters of the SFPM machine were compared. It was found that globally optimized machine has shown slightly higher average torque than the individually optimized corresponding. Feasible stator/rotor combinations of SFPM machine was discussed in [4]. It was revealed that the SFPM machine with rotor pole number close to the stator pole number can deliver the highest average torque. In addition, SFPM machines with all and alternative pole wound with different stator/rotor pole combinations were compared in [5]. It was noticed that stator/rotor combinations as well as winding configuration of SFPM machines have a significant effect on the machines performances. Furthermore, the method to determine the winding configuration for the design of high performance SFPM machine was illustrated in [9]. Three different winding layouts, i.e. single, double and multi-layers were discussed. It was found that the single-layer winding layout is the most suitable for high performance machine. As a promising candidate for high torque and low speed applications, a multi-tooth SFPM machine has been introduced in [6]. It was confirmed that with less amount of PM usage, the multi-tooth SFPM machine has lower torque ripple as well as higher torque density compared to the conventional counterpart at low current level, yet at high current level such configuration has shown lower torque density than that of the conventional machine due to the iron saturation. Additionally, SFPM machine with E-core construction was designed in [7], in which the optimal stator/rotor combination and main design parameters were determined. It was found that although the volume of the PM on the E-core SFPM topology is less compared to the conventional SFPM, the former has higher torque density than the later. Furthermore, the effect of the slot opening on the performance of the optimal stator/rotor combination of the SFPM machine has been investigated in [8]. It was stated that such parameter has a remarkable effect on the machine performance, consequently, a new topology with large slot opening named as C-core SFPM machine was developed and compared to the conventional SFPM topology. It has been observed that the new configuration has about 40% higher back-EMF and average torque compared to that in conventional machine. In order to improve the performance of the exiting SFPM machine, sandwiched SFPM machine was designed in [10], in which two PMs with opposite polarities are located in one stator pole instead of one PM. It was revealed that the torque density can be improved with sandwiched SFPM topology compared to the conventional SFPM topology. In [11], to reduce the leakage flux on the back-iron of the stator, outer and inner rotor SFPM machines with radial and circumference PM in which radial PMs were placed on the stator back-iron . It was concluded that the outer rotor topology delivers higher torque and better magnetic utilization compared to the conventional SFPM counterpart. Furthermore, low rotor mass and reduction in the rotor iron loss was achieved by a modular rotor SFPM [12].

One of the inherent demerits of permanent magnet (PM) machines is cogging torque, which is caused by the interaction between stator iron poles and rotor permanent magnet poles. Such torque has no contribution to the output torque, yet it results in torque ripple and consequently vibration and speed pulsation. Although SFPM machine has no PM on the rotor, cogging torque is caused by the doubly salient of its stator and rotor [13]. As cogging torque is presented in SFPM machine, and negatively affecting on its performance, various approaches have been proposed to minimize the cogging torque of SFPM machines. The influence of rotor tooth shape on the cogging torque of the SFPM machine was discussed in [14], in which four rotor tooth shapes were designed and compared. Although SFPM machine with combination of notched and stepped rotor teeth shape shows about 31% less cogging torque and about 1.6% less desirable output torque, the manufacturing cost would be raised due to the complexity of the rotor structure. On the other hand, SFPM machine with shorter PM was investigated in [15], and about 50% reduction was achieved in the cogging torque with such structure, but the useful torque was reduced by 25%.

In this study, a novel SFPM machine with eccentric rotor pole will be investigated, using two dimensional finite element analysis (2D-FEA). The machine structure and operation principle is presented in section 2, while the optimal values of rotor parameters for the conventional and the proposed machines, in terms of the highest average torque and lowest torque ripple are determined in section 3. Furthermore, section 4 introduces a comparison between no-load and on-load performances of the proposed and conventional machines. Finally, a conclusion is given in section 5.

2. TOPOLOGY AND OPERATING PRINCIPLE

Cross-sections of the understudying machines, i.e. conventional and proposed machines, are depicted in Fig. 1. It is worth mentioning that both machines have the same stator. The stator accommodates both excitation sources. Each stator pole consists of two U-shape iron pieces and one PM, which is sandwiched between the iron pieces. It should be mentioned that the PMs for the neighbour stator poles have opposite polarity, and the windings are concentrated windings wounded around the stator poles. Furthermore, the rotors of both machines are passive, and they have neither windings nor PMs. On the other hand, the shapes of the rotors for the concerned machines are different, where the conventional SFPM machine has salient poles rotor, while the proposed SFPM machine possesses eccentric rotor pole type. Design parameters of the both machines are shown in Table 1.

The working principle of the SFPM topology can be explained by the switched flux principle, in which the flux linkage direction as well as amplitude are changed with the rotor position and the changing flux linkage results in induced back-EMF. When the armature windings are supplied by three-phase current, an electromagnetic torque will be produced, which results from the interaction between winding magneto-motive force (MMF) and air gap flux density that is provided by PM.

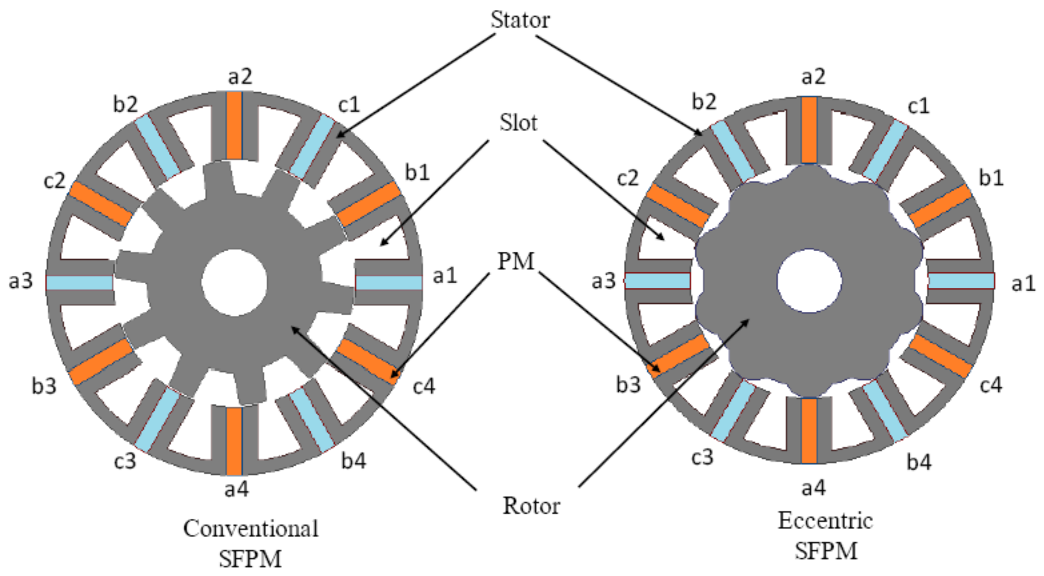


Fig. 1: Machines configurations.

Table 1: Design parameters for understudying machines.

Items	**Values**	**Units**
Phase number	3	-
Stator pole number	12	-
Rotor pole number	10	-
Air gap length	1	mm
Stator outer radius	200	mm
Stator inner radius	128.8	mm
Length in Z-direction	80	mm
Shaft radius	35	mm
Coils per phase	4	-
Turns per coils	56	-
speed	400	rpm
Current density	4	A/mm^2

3. INFLUENCE OF ROTOR PARAMETERS ON THE AVERAGE TORQUE AND TORQUE RIPPLE

As the aim of reducing torque ripple with a maximum average torque, parametric optimizations have been carried out for the rotors of both machines. Fig.2 shows the parameters that have been optimized. It should be noted that the eccentric-distance defined as the distance from the centre of the machine shaft to the eccentric centre.

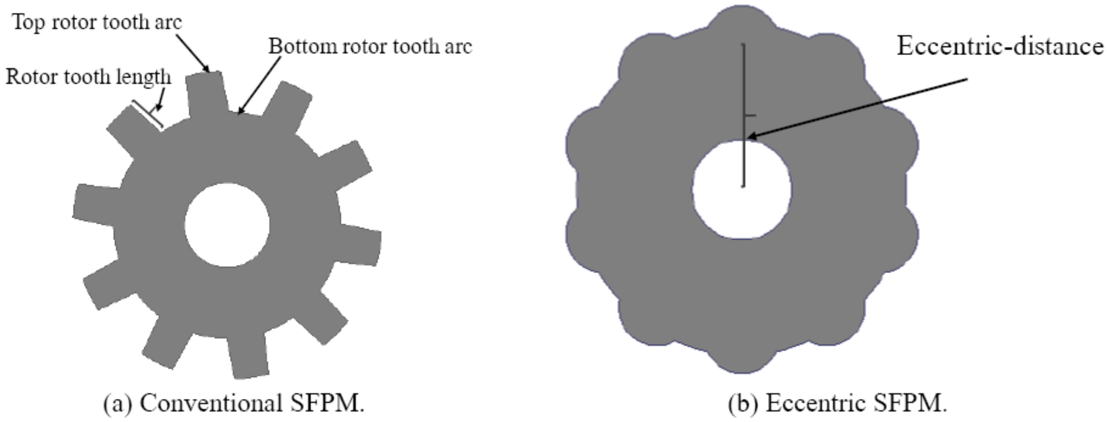


Fig. 2: Optimized parameters.

For the conventional SFPM machine, top rotor tooth arc and bottom rotor tooth arc are varied from (4-15 degrees) in step of 1, while rotor tooth length is changed from (20-4 mm) in step of 1. On the other hand, the effect of the eccentric distance on average torque and the torque ripple of the eccentric rotor machine has been investigated by changing the eccentric-distance from (85-105 mm) with step of 1. Fig. 3 presents the changes in average torque and the torque ripple with top rotor tooth arc. The average torque increases as the value of the top rotor tooth arc increased from (4-8 degrees). Then, it significantly decreases when the top rotor tooth arc goes above 8 degrees, while the torque ripple fluctuates with the changing of such parameter. It should be mentioned that the optimal value of top rotor tooth arc in which average torque will be at maximum with the lowest torque ripple can be found in 8 degrees. Furthermore, the average torque and torque ripple variations against the bottom rotor tooth arc are depicted in Fig. 4. Obviously, changing the bottom rotor tooth arc from (4-12 degrees) results in increasing the average torque, until reach the optimal value. In contrast, torque ripple increases as the bottom rotor tooth arc changes from (4 to 7 degrees). After that, it decrease when this parameter is increased. The optimal value for maximum average torque and minimum torque ripple is 12 degrees. Additionally, Fig. 5 illustrates the variations of both average torque and torque ripple with rotor tooth length. It can be clearly noted that both average torque and torque ripple are slightly changing with changing such parameter. Maximum output torque with the lowest torque ripple is obtained with 34 mm rotor tooth length. On the other hand, Fig. 6 shows the changes in average torque and torque ripple with the eccentric-distance. The optimal eccentric-distance value in terms of the highest average torque and the lowest torque ripple can be obtained in 101 mm.

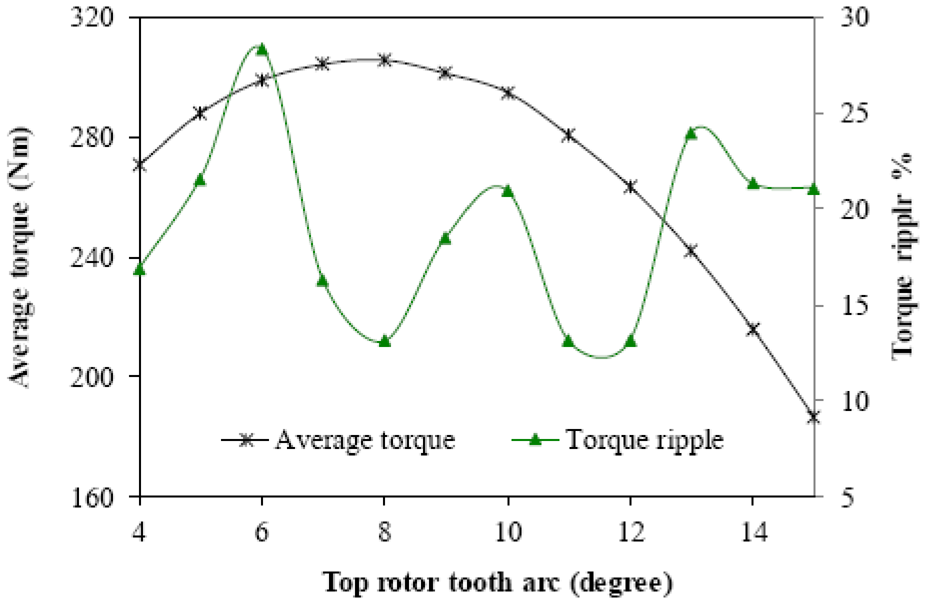


Fig. 3: Average torque and torque ripple variations with top rotor tooth arc.

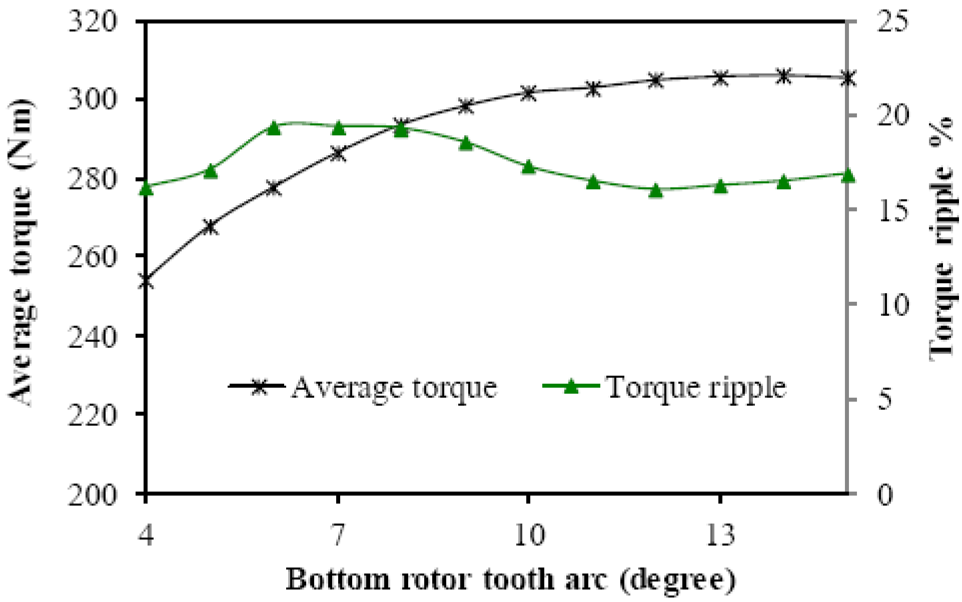


Fig. 4: Average torque and torque ripple variations with bottom rotor tooth arc.

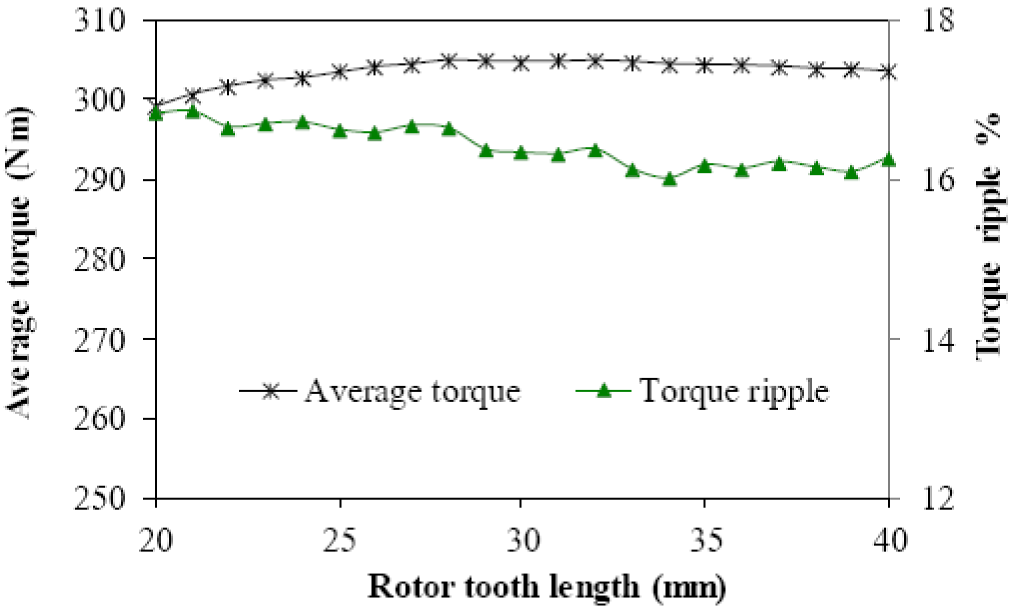


Fig. 5: Average torque and torque ripple variations with rotor tooth length.

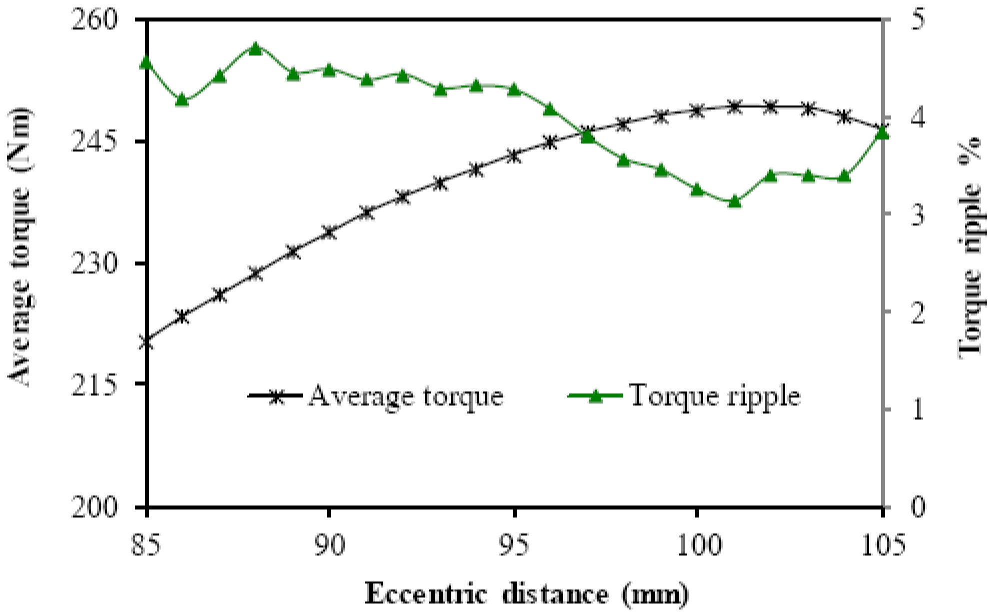
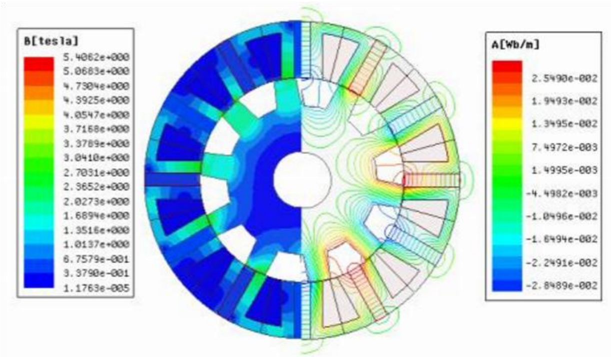


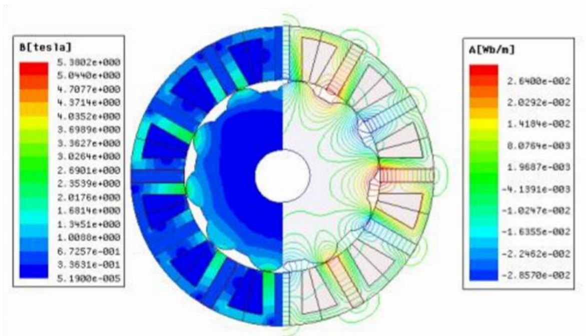
Fig. 6: Average torque and torque ripple variations with eccentric-distance.

4. COMPARISON OF BOTH MACHINES PERFORMANCES

No-load as well as load performances for both topologies are analysed and compared. Flux lines distributions and flux density at no-load condition are illustrated in Fig. 7. Furthermore, three-phase flux- linkages as well as back-EMFs for both machines are compared in Figs. 8 and 9, respectively. It can be seen that the conventional SFPM machine exhibits 16.67% higher flux linkage, consequently it possesses about 16.6% higher induced back-EMF compared to the proposed machine. Fig. 10 illustrates cogging torque waveforms for one electrical cycle for both machines. Apparently, the proposed topology has lower cogging torque in comparison to the conventional counterpart. The cogging torque of the proposed machine is about 93.8% lower than that of the conventional SFPM machine. On the other hand, electromagnetic torques for one electrical cycle of both machines are shown in Fig. 11. About 17% higher average torque can be achieved by the conventional SFPM machine compared to the proposed SFPM machine, due to higher flux-linkage and consequently higher back-EMF that can be obtained by the conventional SFPM machine. Furthermore, torque ripples for both machines are depicted in Fig. 12. It can be clearly seen that the eccentric SFPM machine delivers lower torque ripple compared to its counterpart. This is because of the former machine has lower cogging torque compared to the latter machine.

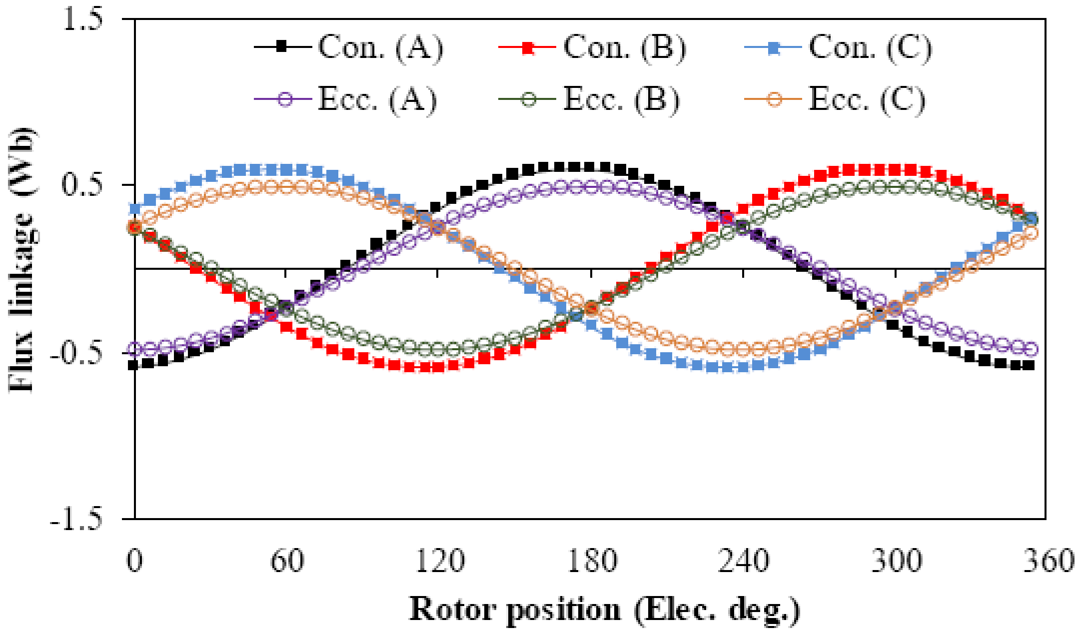


(a) Conventional machine.

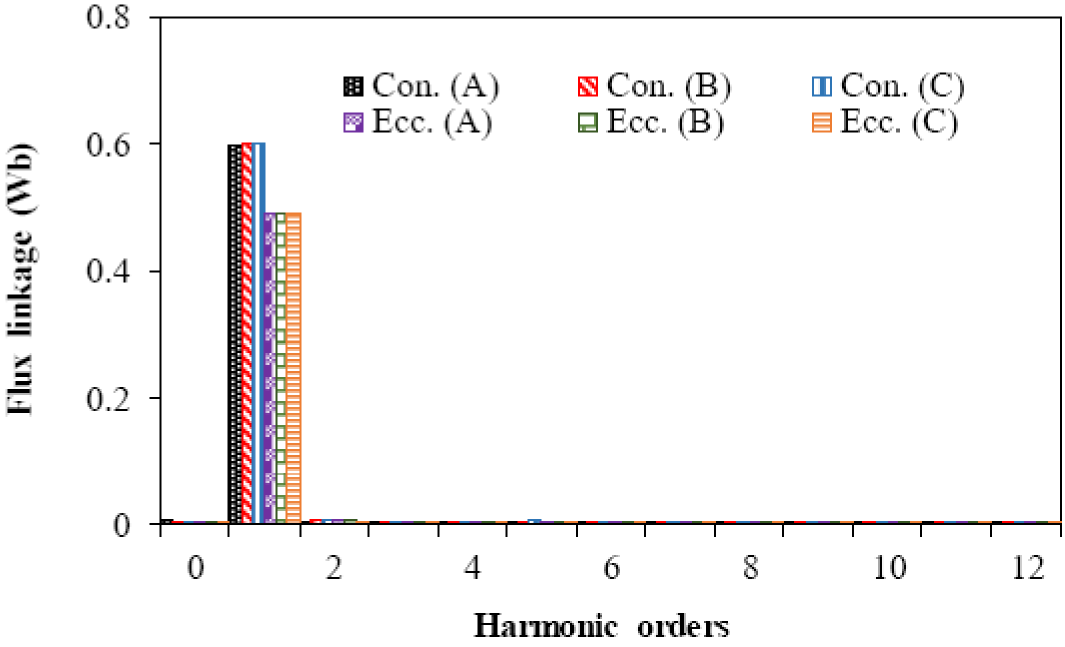


(b) Proposed machine.

Fig. 7: Flux-lines distribution and flux density.

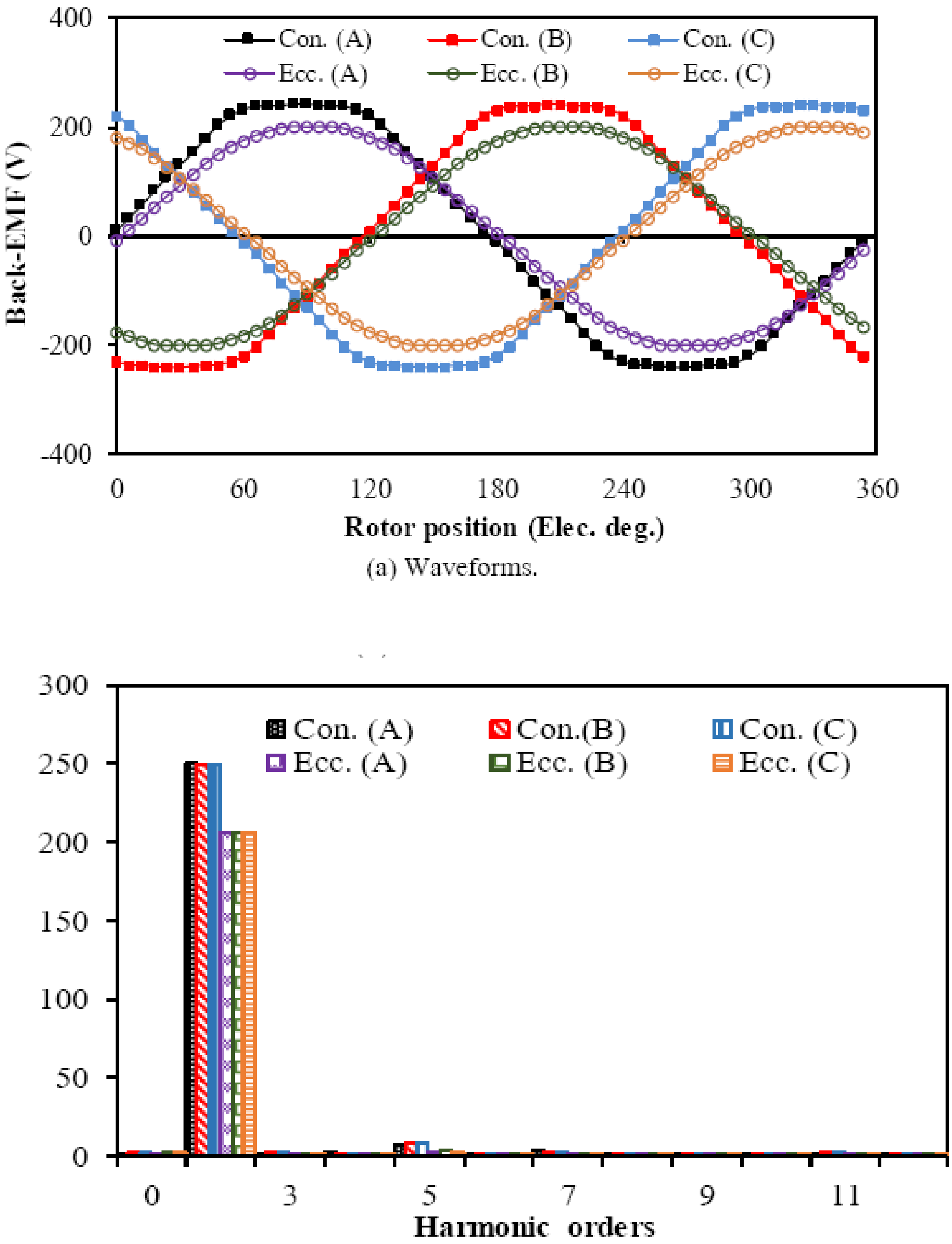


(a) Waveforms.



(b) FFT

Fig. 8 Three-phase flux linkage comparison.



(a) Waveforms.

(b) FFT.

Fig. 9: Three-phase back-EMF comparison.

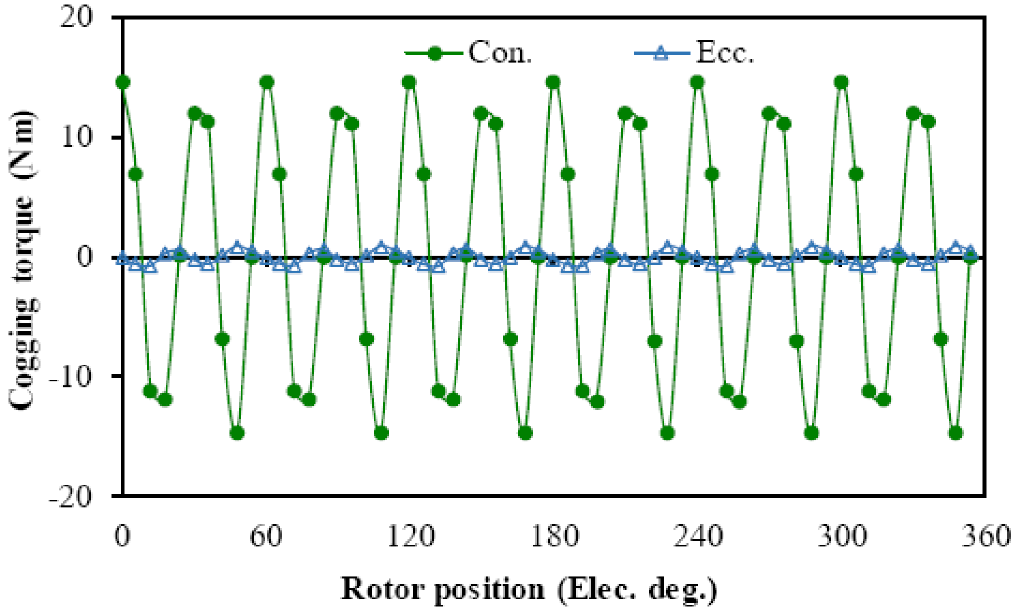


Fig. 10: Cogging torque comparison.

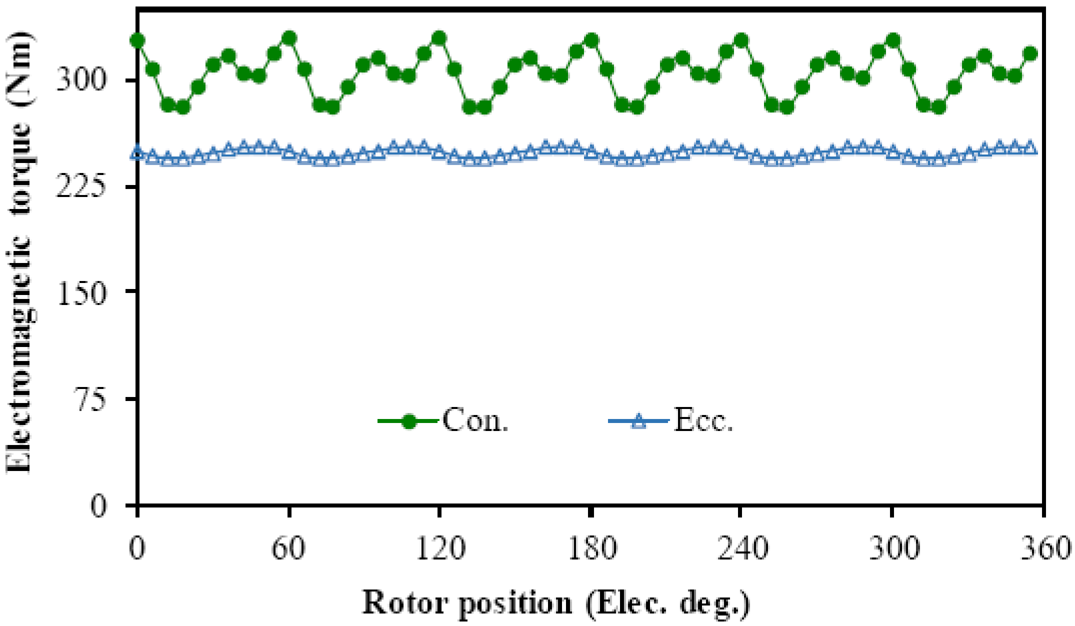


Fig. 11: Electromagnetic torque comparison.

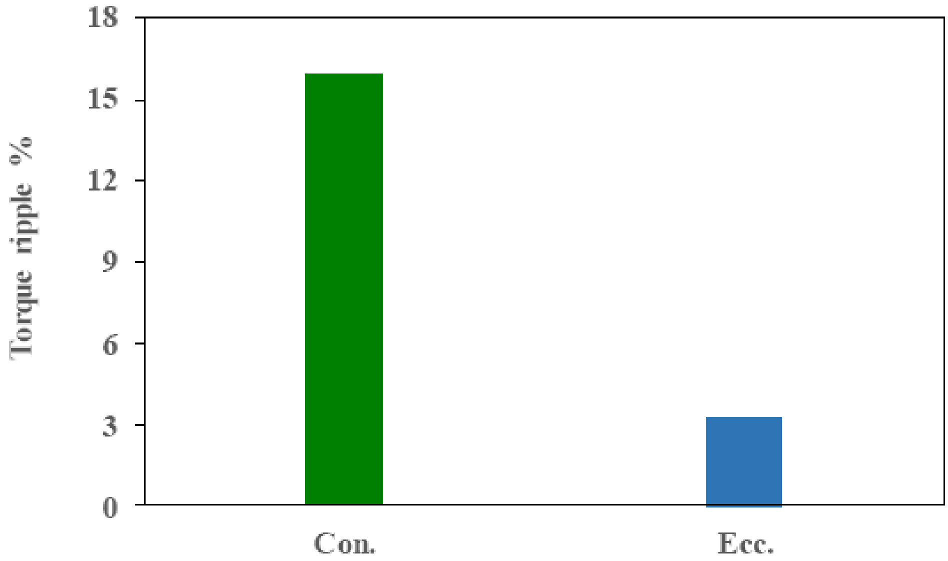


Fig. 12: Torque ripple comparison

5. CONCLUSION

A new SFPM machine with eccentric rotor structure is investigated in this study. Two dimensional finite element analysis (2D-FEA) has been utilized to design, optimise and analyse the proposed machine. A comparison between the proposed machine and the conventional counterpart was carried out, in order to evaluate the proposed machine performance. It must be mentioned that both machines have been designed and optimized with the same conditions for fair comparison. It has been revered that the cogging torque can be reduced by about 93.7% with eccentric rotor structure SFPM machine, and consequently resulted in less torque ripple about 79.5% of such topology compared to the conventional SFPM machine. Thereby, the proposed machine can be considered as a promising candidate for automation and aerospace applications.

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