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Research Article

İç ve Dış Rotorlu Akı Anahtarlamalı Sürekli Mıknatıslı Makinelerin Elektromanyetik Karakteristiklerine Göre Karşılaştırılması[**]

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Öz

Güncel teknoloji gelişmeleri elektrik makinaları alanındaki çalışmalara da yön vermektedir. O nedenle araştırmacılar geleneksel makinaların performans iyileştirmelerinin yanında yeni makina türleri üzerinde de çalışmaktadır. Akı anahtarlamalı sürekli mıknatıslı makineler de literatürde geliştirilen en yeni elektrik makine türlerinden birisidir. Çalışma prensibi ve makine tasarımı relüktans makinelere benzemektedir. Rotor tarafı relüktans makinelerle aynı yapıdadır. Ancak akı anahtarlamalı sürekli mıknatıslı makinelerde stator tarafında sargılar içinde, iki stator oluğu arasında gömülü mıknatıslar bulunmaktadır. Her ne kadar üretim aşamasında bazı zorlukları olsa da bu tasarımın getirmiş olduğu çeşitli avantajlar bulunmaktadır. Statordaki sürekli mıknatıs kutupları manyetik akının stator nüvesinden aktığı yolu destekleyici şekilde yönlendirilmiştir. Bu sayede zıt elektromotor kuvveti dalga şekli sinüs olarak meydana gelmektedir. Bu özellik de akı anahtarlamalı sürekli mıknatıslı makinaları bir adım öne çıkarmaktadır. Rotorda mıknatıs bulunmadığı için diğer (yüzey) mıknatıslı makinelere göre daha sağlam bir yapıdadır. Yüksek hız uygulamaları için uygundur. Bu makalede de akı anahtarlamalı sürekli mıknatıslı dört makine tasarımı elektromanyetik özellikleri bakımından karşılaştırılmaktadır. Sürekli mıknatıs hacimleri eşit alınan aynı oluk ve kutup sayısına sahip, iç rotorlu ve dış rotorlu dört makinenin statik elektromanyetik analizi yapılarak manyetik akı yoğunluğu karakteristikleri üç boyutlu sonlu elemanlar yöntemiyle değerlendirilmiştir. Karşılaştırmalar yapılırken özellikle makine boyutlarının da eşit olmasına dikkat edilmiştir. Tasarlanan dört tasarımdan ikisi karşılaştırma amacıyla gerçekleştirilirken, ikisi de incelenmek üzere geliştirilmiştir. Önerilen akı anahtarlamalı sürekli mıknatıslı makinalarda rotor tarafındaki dişlerin içerisine akı bariyeri denilen hava kanalları açılmıştır. Yapılan çalışmada bu hava kanallarının davranışı üç boyutlu sonlu elemanlar analizi verileri kullanılarak incelenmiştir. Sonuçta içerisinde hava kanalı bulunan tasarımların avatajları ve dezavantajları makine performansı açısından değerlendirilmiştir.

Anahtar Kelimeler: Akı anahtarlamalı makine, dış rotorlu elektrik makineleri, mıknatıslı motorlar, sonlu elemanlar analizi

Comparison of the inner and outer rotor flux switching permanent magnet machines in contrast to electromagnetic characteristics[*]

Abstract

Current technology developments also guide the works in the field of electrical machines. That's why researchers are working on new machine types as well as performance improvements of traditional machines. Flux-switching permanent magnet machines are also one of the novel electrical machine types developed in the literature. The working principle and machine design are similar to reluctance machines. The rotor side has the same structure as reluctance machines. However, in flux-switching permanent magnet machines, there are magnets embedded in the windings on the stator side between the two stator slots. Although there are some difficulties in the production process, there are several advantages brought by this design. The permanent magnet poles in the stator are guided to support the path through which the magnetic flux flows through the stator core. In this way, the opposite electromotive force waveform occurs as a sinusoidal. This feature put the flux-switching permanent magnet machines one step forward. Since there is no magnet in the rotor, it is more robust than other (surface) permanent magnet machines. It is convenient for high speed applications. In this article, four flux-switching permanent magnet machine designs are compared in terms of their electromagnetic properties. The magnetic flux density characteristics were evaluated by three-dimensional finite elements method by performing static electromagnetic analysis of four machines with inner rotor and outer rotor with the same number of slots and poles, whose permanent magnet volumes were taken equally. While making comparisons, it was especially paid attention to be equal to the machine dimensions. While two of the four designs designed were realized for comparison purposes, others were developed for investgation.

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In proposed flux-switching permanent magnet machines, air ducts called flux barriers are opened into the teeth on the rotor side. In this study, the behavior of these air ducts was analyzed using three dimensional finite element analysis data. As a result, the advantages and disadvantages of designs with air ducts were evaluated in terms of machine performance.

Keywords: Flux switching machine, outer rotor machine, permanent magnet motors, finite element analysis, electric machinery.

1. Introduction

Electric machines have been one of the basic elements of the electrical system since the invention of electricity. Although it has more than a hundred years of history, today it is working on different and innovative electrical machines in response to the changing and increasing need. Flux-switching permanent magnet machines are one of the types of machines developed in this context. These machines are one of the most popular studying topics in this period when many products started to be electrified [1]. Due to technology trends such as energy efficiency, emission reductions, green energy, industry 4.0, the internet of things and electric vehicles, the interest in electrical machines is growing even more. As a result of the increasing interest, research and development activities in the field of electrical machinery are also intensifying.

As the needs for electrical machines increase, the requirements for high torque and power density also increase. Permanent magnet motors are generally recommended to meet high torque intensity with good efficiency [2]. However, studies show that flux-switching permanent magnet (FSPM) motors that can meet some needs such as high speed, robustness and protection from magnet demagnetization are more advantageous in many applications [2].

Z. Q. Zhu et al. proposed a general design aspects for the FSPM machine with various topologies. The power density of the topologies can be compared by the proposed equation. They obtained that the 3-phase 12-slot/10-pole machine can give higher power and power density than those of the 2-phase 8-slot/6-pole topology by ~11%. They provided an experimental study on the prototype motor that verify the proposition [3].

Cheng-Tsung Liu et al. studied the different winding topologies to illustrate the comparison of the performances. It was proved that the single layer winding topology is more convenient for the FSPM machine that need high average torque despite efficiency and torque ripple [4].

Ming Cheng et al. studied and compared the rotor PM and the stator PM flux switching machines under the same conditions. They used the sizing equation and electromagnetic torque production mechanism to make a comparison [5]. The effects and performance analysis of the winding types is given in many papers [6,7]. Slot and pole combinations are investigated by Ming Cheng et al. This study is validated by an experimental verification [8]. Outer rotor FSPM machine topology is preferably used for traction applications in many papers [9-15].

In this study, flux-switched permanent magnet machines are investigated. The outer rotor structure used in electric vehicles or motors with direct drive feature was compared with the inner rotor structures. However, the effect of the ducts opened in the rotor teeth on machines with both internal and external rotors has been electromagnetically examined. For that, three dimensional finite element analysis is used.

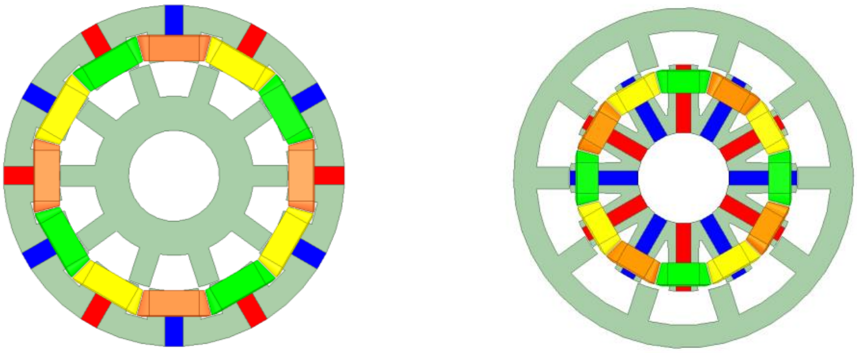
2. Flux Switching Machines

Flux-switching permanent magnet (FSPM) machines have been intensely studied for traction applications. Inner and outer FSPM machines have rigid structure because there are permanent magnets embedded on the stator and laminations have only steel on the rotor structure, as shown in Fig. 1. FSPM machines have not any magnets in the rotor side and have not the inclusion occurrence of rotating magnet parts. Due to that, FSPM machines are convenient for the robust applications, like the traction application.

Eddy-current loss exist highly in FSPM machines because of the cogging torque effect and much stator magnetomotive force harmonics [16]. So that, it is necessary to mitigate the eddy current loss of FSPM machines.

Wu et al. investigated a structure which is a 12 /10 FSPM topology with copper damping rings embedded into rotor laminations [17].

The eddy current produced in the copper damping rings coact with the magnetic fields of asynchronous harmonics to reduce eddy current loss. Nevertheless, based on other slot/pole combinations, the degree of eddy current loss mitigation is different. Changing the winding topology to the multilayer is a working study by [18] for surface permanent magnet machines to mitigate the low order stator MMF harmonics, and also, mitigating the rotor eddy current loss.



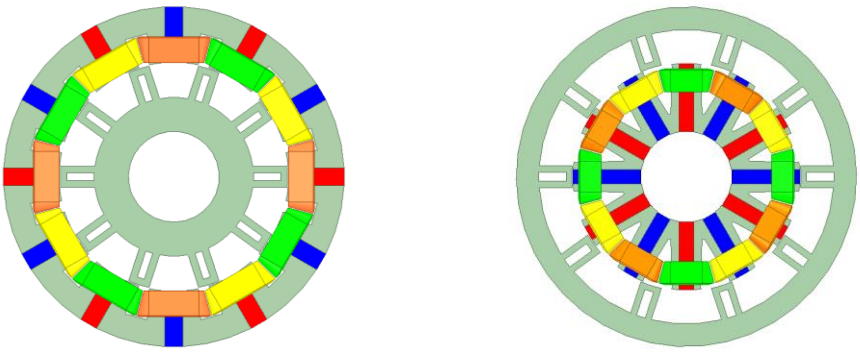
(a) (b)

Fig. 1 FSPM Machines a) Inner rotor 12-slot/10-pole FSPM machine topology b) Outer rotor 12-slot/10-pole FSPM machine topology

But, multilayer winding topology has difficulties on manufacturing. The magnetic flux barriers in the stator steel of a 12/10 permanent magnet machine [19], some harmonics of MMF is mitigated to have eddy current loss. But, stator flux barriers are not convenient for FSPM machines. Because it has effects on the path of critical flux lines come up with a torque reduction. Therefore the rotor flux barriers can be implemented to the FSPM machine to improve the performance. J. Mao et. al. is proposed to put the barriers at the inner side of the rotor yoke [20]. The proposed method works to mitigate the eddy current losses but the manufacturing of this structure reduces robustness, too.

2.1. Proposed Structure

Until now, the studies are investigated for improving the FSPM machines. But there is no proposition such as shown in figure 2. It illustrates the proposed flux barriers for the inner and outer machines. The main reason of this proposition is the getting more efficient motor by cancelling the eddy currents as written in the literature. All of the parameters are given in the tables below for the inner and the outer FSPM machines.



(a) (b)

Fig. 2 Outer rotor FSPM Machines a) Proposed inner rotor 12-slot/10-pole FSPM machine topology b) Proposed outer rotor 12-slot/10-pole FSPM machine topology

Magnet volumes of the all structures are the same. Also outer dimensions are kept same for the four machines. 12-slot/10-pole machine topology is chosen for this study due to the wide usage for academic studies.

Figure 3 gives the information of the steel used for the simulations. The steel saturates at nearly 1.5T.

Table 1. Inner Rotor FSPM machines parameters

Inner Rotor FSPM Machines Parameters	**Standard FSPM Motor**	**Proposed FSPM Motor**
Stator Inner Diameter	101	101
Stator Outer Diameter	150	150
Rotor Outer Diameter	100	100
Airgap Length	1	1
Axial Length	20	20
Slot/Pole Number	12/10	12/10
Steel Type	M250-35A	M250-35A
Steel Weight of the Rotor	1 p.u.	0.91 p.u.
Magnet Volume	$25x10^3$ mm^2	$25x10^3$ mm^2
Phase Number	3	3

Table 2. Outer Rotor FSPM machines parameters

Outer Rotor FSPM Machines Parameters	**Standard FSPM Motor**	**Proposed FSPM Motor**
Stator Inner Diameter	50	50
Stator Outer Diameter	100	100
Rotor Outer Diameter	150	150
Airgap Length	1	1
Axial Length	20	20
Slot/Pole Number	12/10	12/10
Steel Type	M250-35A	M250-35A
Steel Weight of the Rotor	1.5 p.u.	1.45 p.u
Magnet Volume	$25x10^3$ mm^2	$25x10^3$ mm^2
Phase Number	3	3

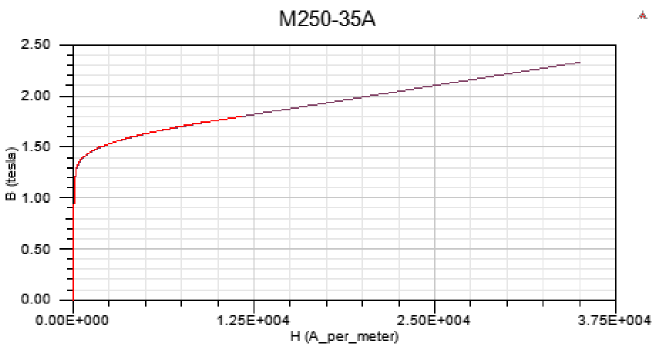
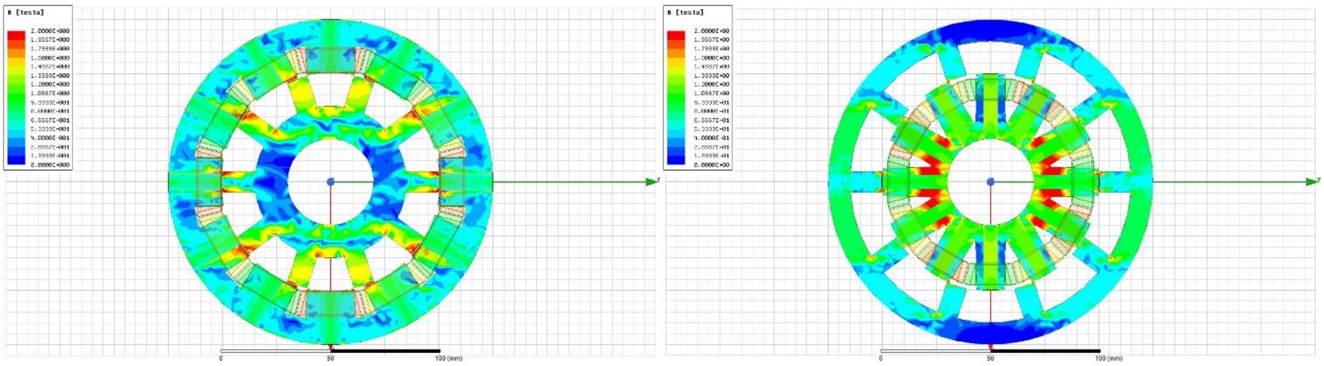


Fig. 3. B-H curve of the steel grade of M250-35A

2.2. Analysis

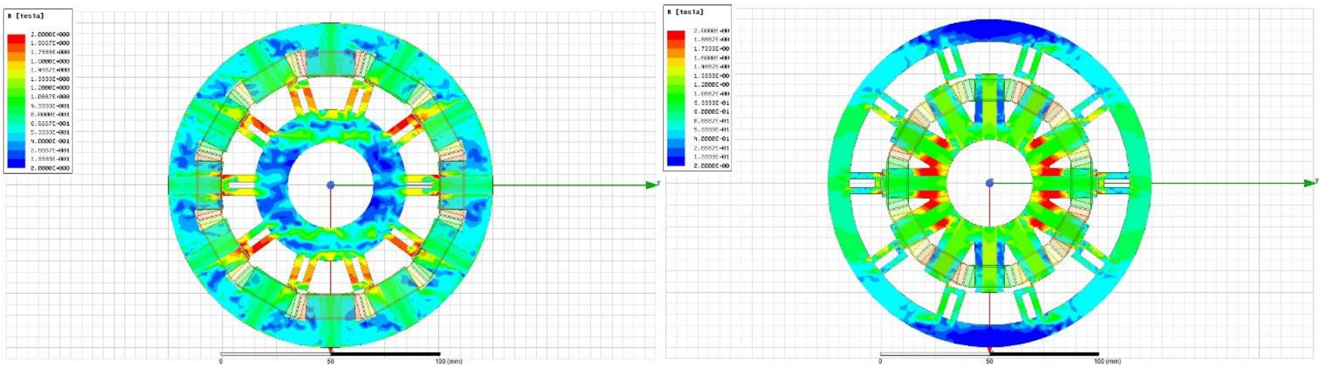
Electromagnetic analysis has been performed for the four three dimensionally designed FSPM machines. The results of the simulations are illustrated in the figure 4 and figure 5. The simulations are performed by using the finite element analysis with the meshes.

Figure 4 shows the standard structures of the FSPM machines. Figure 5 illustrates the simulation results for the proposed structures of the FSPM machines. Before starting the simulation, the mesh density needs to be checked. The air gap and flux paths need to have much more mesh nodes. Electromagnetic characteristics of the electric machines give many information such as thermal characteristics, efficiency, saturation points, flux path, etc.



(a) (b)

Fig. 4 Electromagnetic analysis of the FSPM machines a) Inner rotor 12-slot/10-pole FSPM machine topology b) Outer rotor 12-slot/10-pole FSPM machine topology



(a) (b)

Fig. 5 Electromagnetic analysis of the proposed FSPM Machines a) Proposed inner rotor 12-slot/10-pole FSPM machine topology b) Proposed outer rotor 12-slot/10-pole FSPM machine topology

3. Results and Conclusion

The electromagnetic simulations illustrates statical situation of the machines. 3D finite element analysis usually give more accurate results than 2D simulations for the electric machines. As given in the figures of the simulation results electromagnetic situation of the designed FSPM machines are taken. Results show that, proposed structures' electromagnetic characteristics are in the limits of the M250-35A steel not to get saturated. There are a few partially saturated points nevertheless they do not cut the flux path. Also these proposed flux barriers causes to mitigate the eddy currents on the rotor side. So this allows to get higher performance.

As seen from the results the best performance is taken from the inner rotor proposed FSPM machine in the Figure 5(a).

The proposed FSPM machines are promising structure for the future studies. The flux barriers have more impacts than their electromagnetic characteristics. Therefore this proposed structure is the basement of the further projects.

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