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Review Article

Flux Switching Machines Topologies: State of the Art

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Abstract

The flux-switching machine (FSM) stands as an innovative form of brushless doubly salient permanent magnet machinery characterized by a stator flux possessing bipolar attributes. Distinguished by excitation and concentric windings nestled within the stator and a rotor design reminiscent of switched reluctance machines, the FSM presents a compelling array of advantages. Notably, it boasts a high-power capacity, remarkable torque density, and commendable efficiency, particularly at low rotational speeds. Its operational simplicity further enhances its appeal. This comprehensive paper delves into a meticulous evaluation and comparative analysis of various topologies inherent to the FSM. Through an in-depth exploration of its diverse structures and operational modalities, the study seeks to illuminate the nuanced differences between these topologies. By scrutinizing their respective functionalities, the paper aims to discern the unique strengths and potential limitations of each FSM topology. It provides insights crucial for optimizing the design, performance, and application of flux-switching machines across diverse industrial domains, thereby paving the way for enhanced efficiency and efficacy in electrical machinery systems.

Keywords: Flux Switching Machines, Permanent Magnet Machines, Axial Machines.

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1. INTRODUCTION

Various electric motors with unique features are created and manufactured for specific purposes. Researchers consistently strive to develop innovative designs to enhance the mechanical and electrical systems' functionality and increase their controllability. As electric motors are crucial tools in the industry, constructing machines that require lower maintenance costs, perform with maximum efficiency, and are controllable is a major objective across several sectors. Permanent Magnet (PM) motors are commonly used in electric vehicle applications and transportation systems. Despite their high initial cost compared to magnet-less motors, they offer superior performance. However, their sensitivity to temperature increase negatively affects their overall efficiency. The flux switching machine (FSM) is a type of brushless machine featuring doubly salient poles and bipolar flux. Its stator contains the excitation and concentric windings, while its rotor is comparable to that of a switched reluctance machine (SRM) [1-3]. Flux switching permanent magnet machines surpass other permanent magnet machines in several ways, such as high power and torque density, high efficiency, impressive flux attenuation, and effortless cooling. The cogging torque of flux switching machines is higher than other PM machines due to their structure with doubly salient poles and high flux density resulting from flux focusing. To meet the necessities of flux switching machines, they require sinusoidal back-EMF and low torque ripple, which are in comparison to conventional PM machines [4-7].

Reference [8] has used the segmental rotor structure to improve the no-load electromagnetic torque of the Flux-switching permanent magnet motor. Study [9] proposed a new modular E-Shaped Stator structure for hybrid excited flux switching motor (MHEFSM) with flux gaps, adding the fault-tolerant capability to the proposed motor. In [10] proposed a new air-foiled rotor structure for Flux Switching Permanent Magnet motor to perform compression functions. Reference [11] Proposed a Novel Flux Switching Magnetic Gear for High Speed Motor Drive System. In [12] a dual-mechanical-port flux-switching permanent magnet (DMP-FSPM) motor is studied for achieving high-efficiency design and optimization. Study [13] proposed a new axial dual-stator flux-switching permanent magnet (FSPM) machine with distributed winding for high-speed

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applications. Reference [14] proposed a new dual rotor counter-rotating permanent magnet flux switching generator that eliminates the need for slip rings and operates without brushes. study [15] used stator axial pairing structure for reduction of torque pulsation in flux switching motor. In [16] proposed PM segment shift technique for reduction of cogging torque in flux switching motor. Reference [17] proposed partitioned permanent magnet structure for performance improvement of flux switching permanent magnet motor.

This paper first evaluates PM machines, then categorizes them accordingly. Then the structure of FSM is presented, after that various topologies are introduced and compared. Finally, we conclude our paper in the conclusion section.

2. PERMANENT MAGNET MACHINES

PM machines can be categorized with respect to location of magnets on rotor or stator [1, 18]. Each category has several models. PM machines in which magnets are located on rotor are divided to radial flux permanent magnet machines (RFPM), axial flux permanent magnet machines (AFPM), transverse flux permanent magnet machines (TFPM). PM machines in which magnets are located on stator are divided to three groups including: doubly salient permanent magnet (DSPM), flux reversal permanent magnet (FRPM). This categorization is shown in Figure 1 [19-22].

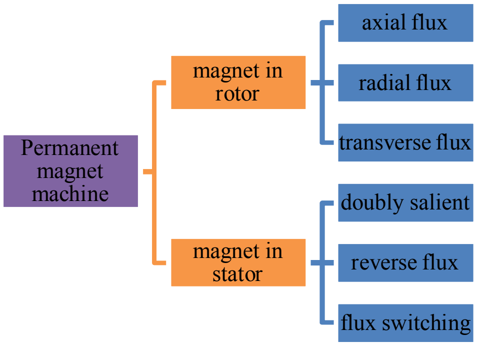


Fig. 1. Categorization of PM machines

A) **PM machines with Magnets in rotor**: such machines are the most widely used PMs in which instead of rotor excitation circuit, magnet is used inside the rotor. This change removes loss of rotor excitation circuit, resulting in high efficiency and power density. These machines are divided into two groups of radial flux and axial flux (Figure 2) [8, 13] which are designed with respect to number of layers of rotor and stator [9-12].

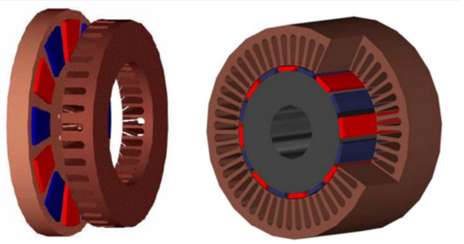
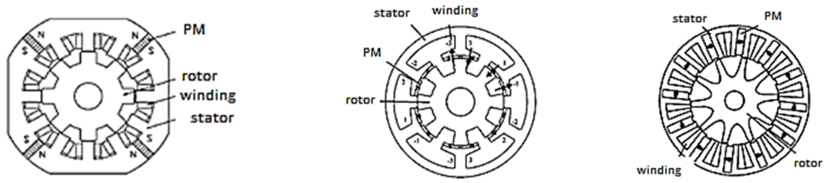

(a) (b)

Fig. 2. PM machines with magnet inside rotor a) radial flux, b) axial flux

Among advantages of these machines, high efficiency and torque density can be mentioned. However, magnet inside rotor requires protection against centrifugal force. To this end, holding sleeves which are made of stainless steel or non-metal fibers are used which reduce cooling capacity of the machine and limit power density of the machine [24].

B) Permanent Magnet Machines with Magnet in Stator: Since in these machines, inserting holding edge increases rotor volume and thermal loss, demagnetizes magnets and limits power density of the machine, machines with magnet on stator would be a suitable alternative which have found wide applications due to their high strength, high power density and high efficiency [13, 18]. Rach and Johnson proposed the first machine with magnet on stator in 1955 [25]. In general, there are three types of machines with magnet on stator called doubly salient machine (a combination of switched reluctance machines and machines with stator magnets), flux-reversal machine (with magnets on stator teeth and bipolar linkage flux) [26] and switched reluctance machine (magnets with ambient magnetization between stator teeth and bipolar linkage flux) [27] (Figure 3), where their operation principles are different. Apart from location of magnets in stator, resulting torque is mainly caused by magnets and reluctance torque can be ignored [4, 27-29].



(a) (b) (c)

Fig. 3. PM machines with magnet on stator a) doubly salient pole b) flux reversal c) flux switching

2.1.COMPARISON

Among PM machines with magnet on stator which are defined in the above, FSPM has higher torque and reliability. Thus, it is selected for comparison with PM machines with magnet on rotor. Advantages of using FSPM topology compared to the mentioned topologies are as follows [18, 30, 31]: a) since magnets are inside the stator, cooling the stator becomes easier as a result of which temperature increase in magnets becomes limited. b) since winding and magnet are magnetically in parallel, reaction of the armature at operating point of the magnet is negligible; thus, electric loading and torque of the FSPM are higher. Therefore, less demagnetization takes place as a result of armature reaction. c) since rotor is made of steel, FSPM machines are stronger.

However, in FSPM machines, excess rotor loss is created as a result of flux changes in magnet of the rotor which might result in lower efficiency of the machine. But for relatively low speed applications (like low-speed generators with speed lower than 1000rpm), iron loss is usually less than copper loss as a result of which their efficiency would not differ much. Table 1 compares performance of FSPM machine and permanent magnet rotor interior machines.

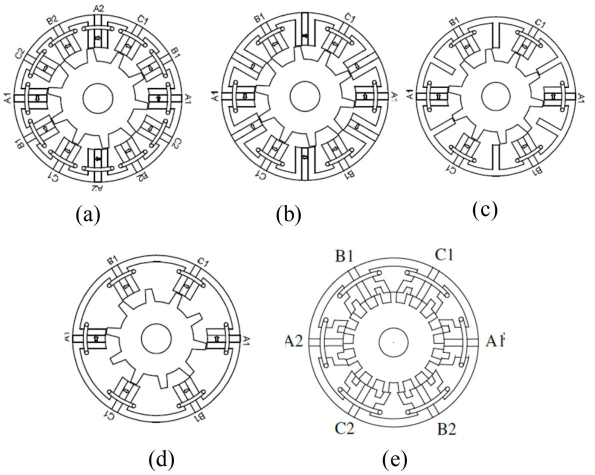
Table 1. Comparing Performance Of FSPM Machine And PM Machines With Magnet On Rotor

Machine Type	Torque density	Reliability	Cooling capacity	Efficiency
FSPM machine	Equal/Better	Better	Better	Less
PM rotor machine	Equal/Less	Less	Less	Better

3. STRUCTURE OF FLUX SWITCHING MACHINES

3.1.Basic STRUCTURES

Flux switching machines are brushless PM machines with high efficiency and torque density. Initial structure of these machines with U-shaped core is shown in Figure 4(a). Periodic structure is similar to the initial structure with the difference that windings are wrapped on decussate stator teeth on which no magnet is located (Figure 4(b)). In the structure with E-shaped core, magnet is not located on stator teeth on which winding is not wrapped (Figure 4(c)). In the structure with C-shaped core, teeth on which no magnet is located and no winding is wrapped, are removed (Figure 4(d)). In these structures, polarity of magnet on two adjacent teeth is different; rotors of all mentioned structure are strong, simple and similar to switched reluctance machine [5,7].



(a) (b) (c)

(d) (e)

Fig. 4. Structures of flux switching machines: a) complete winding b) periodic winding c) E-shaped core, d) multi-teeth

Machines with E and C-shaped core have a higher electromagnetic torque compared to two initial models and they have higher eddy current loss compared to two initial models due to larger slot span [25, 32]. Various structures of flux switching machines (Figure 5) including C-shaped model, E-shaped model and initial model can be constructed in two complete winding and periodic structures by combining stator/rotor poles of 14/6 and 13/6, 10/6 and 11/6, 10/12, 11/12, 13/12 and 14/12, respectively [33, 34]. In multi-teeth FSPM machines (Figure 4(e)), fewer magnets and windings and less core volume are required which reduce construction cost and required material. On the other hand, due to increase in number of stator teeth, more teeth are required for rotor, such that requirement to magnet is decreased to half compared to conventional FSPM machines, while slot area remains constant. But, when ratio of internal diameter to external diameter of the conventional FSPM and multi-teeth FSPM is the same, slot area of the stator is reduced. This structure generates higher torque compared to conventional FSPM if electric loading is low [6, 35].

3.2.MAGNET-LESS STRUCTURES

Excitation magnet in the stator among windings is one of the problems of flux switching machines, because windings are the most important heat generating element and as temperature of the stator increases, the magnet might become demagnetized. Initial samples of flux switching machines are radial flux machines which have shown to be superior [4, 5, 35] and have found their place in transportation systems [3, 36, 37].

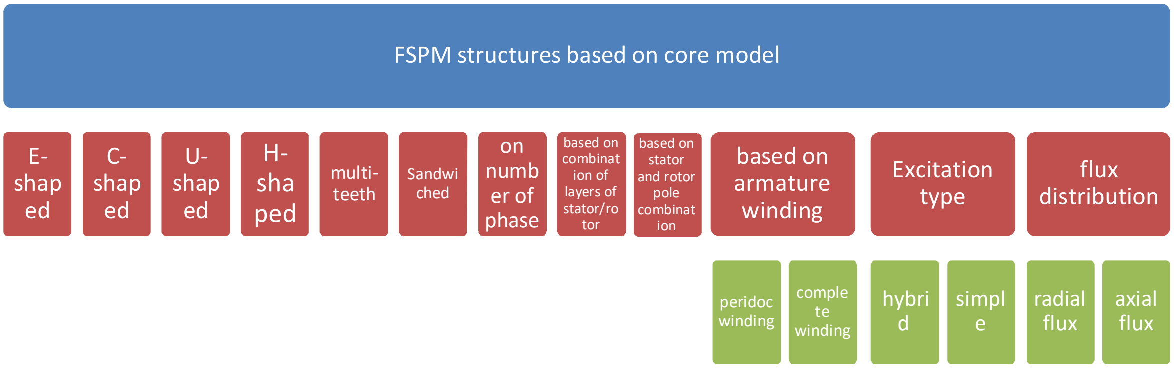


Fig. 5. Categorizing different FSPM structures based on core model

On the other hand, as mentioned, PM machines have high torque density and efficiency, but rare earth magnets like NdFeB are costly with limited sources and at specific ambient temperatures. In order to solve these problems, DC excitation winding is used instead of magnet. Comparing flux switching machine with DC excitation and conventional FSPM machine with the same number of poles (10/12) and the same external diameter and axial length, the generated torque is equal but using NdFeB magnet, the generated torque would be significantly lower than FSPM [38].

3.3. STRUCTURES WITH HYBRID EXCITATION

These machines not only have a permanent magnet with high power density and reliability but their magnetic field is adjustable and flexible. Hybrid excitation machines are usually categorized based on location of excitation winding in the stator or rotor or based on magnetic circuit of magnet flux and DC winding flux which are either in series or in parallel [39]. However, external diameter is increased to locate DC field winding which reduces torque density, significantly. IN FSPM machine, some part of the magnet might be replaced by DC excitation winding as a result of which several hybrid excitation topologies (Figure 6(a, b)) are created [40-42] in which armature winding and field winding overlap and reduce torque capacity of the machine, significantly. A novel hybrid excitation FSPM machine based on E-shaped core is introduced in [43] to resolve the above shortcomings (Figure 6(c)) in which armature winding and field winding do not overlap and structure of the machine is simple. Compared to conventional FSPM, number of magnets in hybrid excitation FSPM is reduced to half and torque density is improved.

3.4.SANDWICHED STRUCTURES

In flux switching sandwiched permanent magnet machines, two or more magnets might be located on one stator tooth (Figure 7). This structure is suitable for using low-cost ferrite magnet. This structure has higher power density due to flux focusing effect [44-46].

3.5.VARIABLE FLUX STRUCTURES

Since flux of permanent magnet is not adjustable, load capacity at low speeds and machine performance at high speeds are limited which reduce efficiency of the machine. Thus, flux of permanent magnet needs to be adjusted [47]. This is usually done in vector control using positive or negative current of axis d. In addition, it is required to reduce current of axis q.

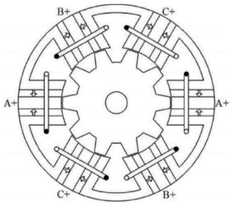
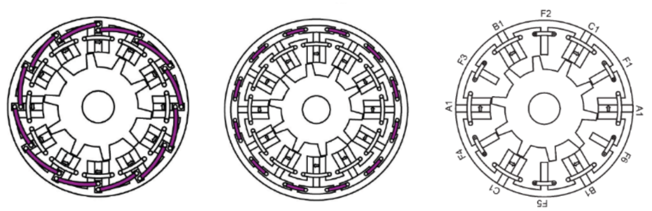


Fig.7. Flux switching sandwiched permanent magnet machine



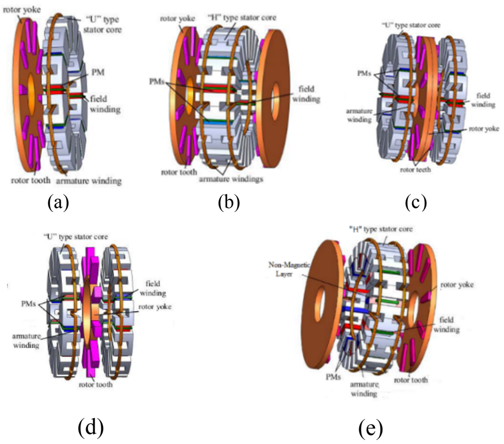
(a) (b) (c)

Fig. 6. Hybrid excitation flux switching machines a) hybrid excitation type 1, b) hybrid excitation type 2 and c) hybrid excitation with E-shaped core.

Variable flux machines in [39, 47] include hybrid excitation machine with winding and machines with mechanical adjustments. Advantage of these machines is performance with constant power (flux attenuation region), torque increase at low speeds, preventing increase in no-load back-EMF at high speeds, high efficiency performance in the whole torque-speed region. Among its disadvantages, complicated structure, probable torque reduction, limited flux increases due to magnetic saturation, requiring an additional DC source or additional mechanical devices for mechanical flux adjustment can be mentioned.

3.6. AXIAL FLUX STRUCTURES

Recent researches show high power capacity, high power density, high torque, high efficiency, simplicity and strength of flux switching machines [1, 36, 40, 48] specially in axial flux structures [49-52] compared to radial flux structures [51-53]. Since axial flux machines have characteristics of both field flux machines and flux switching machines, their radial flux has inherent superiorities like maximum torque density [49]. Hybrid excitation axial flux switching machine with partitioned stator is such that excitation winding is wrapped axially around the magnet (Figure 8). Considering studies in this context, a non-magnetic structure or layer (Figure 8(e)) is the most suitable design. In this structure, stator core is divided to internal and external sections using a non-magnetic layer. Under ideal conditions, magnet flux does not pass through a non-magnetic layer. Upper half of the stator core and filed are separate. In practice, a small part of flux might leak to the upper half. Since machine volume cannot be excessively large, leakage flux should be reduced to a specific value; in this machine, thickness of non-magnetic layer is the main factor which affects leakage flux [54]. Using a partitioned rotor instead of toothed rotor has many advantages; in partitioned rotor, using permanent magnet for excitation instead of DC coil increases torque density up to two times [55, 56].

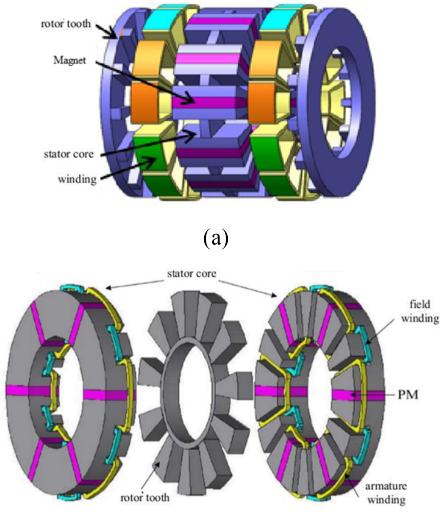


(a) (b) (c)

(d) (e)

Fig. 8. Axial flux switching machine with hybrid excitation with partitioned stator

In [57], an axial flux switching machine with hybrid excitation and E-shaped core is presented (Figure 9(a)). In [58], an axial flux switching machine with two rotors is presented (Figure 9(b)), in which angles of the two rotors are different so that cogging torque is reduced. In this structure, in order to obtain maximum torque, 12/13 combination of poles is considered. This structure has higher torque density and less cogging torque compared to the axial flux machine with 12/10 and 12/14 pole combination.



(a)

(b)

Fig. 9. Axial flux switching machine a) hybrid excitation with E-shaped core b) two rotors

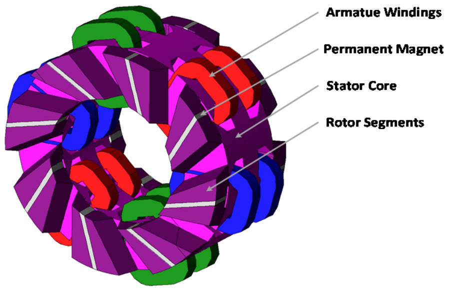


Fig. 10. The Rotor Excited Axial Flux-Switching Permanent Magnet Machine (RE-AFSPM)

In [59], a new structure of axial type FSM with segmented rotor has been introduced (Figure 10). The 12-pole stator has been installed between two 8-pole segmented rotors, and the excitation system has been connected to the rotor. This topology enhances the design of flux-switching permanent magnet machines. With this new topology, an increase in the torque density, the reduction the total harmonic distortion, simple construction, and the reduction of cogging torque have been achieved. The harmonic spectrum of the back electromagnetic force has also been improved. This topology provides an optimum power for the electric vehicles because of the short axial length and the high-power density along with the low vibration and noise due to lower torque ripple and cogging torque.

4. CONCLUSION

In conclusion, this paper delves into an extensive exploration of flux switching permanent magnet machines, unveiling their diverse topologies alongside the associated advantages and limitations. The scrutiny of key attributes ranging from their robust power and torque density to the efficiency of operations, sinusoidal back-EMF, and easily managed cooling systems provides a comprehensive understanding of their technological prowess. Categorizing these structures from varied viewpoints not only streamlines comprehension but also empowers decision-makers in selecting the most fitting design for specific applications. Whether it's the demanding realm of electric vehicles, the renewable energy landscape of wind turbines, the precision-driven requirements of industrial drives, or the exacting standards of the aerospace industry, these machines, with their amalgamation of high-power density, reliability, and the aforementioned defining features, present themselves as practical solutions. As we navigate towards a future driven by sustainable technologies and heightened efficiency, the significance of these flux switching machines becomes increasingly pronounced. Their pivotal role in diverse sectors underscores their potential to revolutionize and elevate the performance benchmarks across industries. Through this exploration, we not only grasp their present capabilities but also anticipate their ever-evolving role in shaping the technological landscape of tomorrow.

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