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Research Paper

Innovation of Flux Switching Machine: Design Variation Review

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Abstract : Flux switching machines (FSM) have advantages, including high torque density, low acoustic pollution, minimal vibration and high-speed potential. In addition, due to the PM's placement on the stator, the configuration also provides advantageous thermal management. However, it has been discovered that this machine tends to generate significant cogging torque, exhibit high leakage current, and possess a complex design for flux weakening capability. Numerous research efforts are dedicated to addressing these limitations, but there is a lack of comprehensive reviews specifically focused on the design variations of this type of machine. The objective of this study is to conduct a thorough analysis of the Permanent Magnet Flux Switching Machines (PMFSM), Field Excitation Flux Switching Machines (FEFSM), and Hybrid Excitation Flux Switching Machines (HEFSM), which employ field excitation in addition to permanent magnet operation. Subsequently, the review encompasses a variety of stator structures, rotor structures, and unique structures that employ distinct methodologies to mitigate the limitations of conventional FSM. This evaluation aims to pinpoint the prospective research topics and deficiencies the FSM should prioritize, particularly in industrial applications and transportation. Conclusively, the literature study indicates that PMFSM accounts for around 71% of the attention, whereas FEFSM and HEFSM each account for 14%.

Keywords: Field excitation, Electromagnetics, Flux switching machine, Finite element, Permanent magnet

1. Introduction

The Flux Switching Machine (FSM) provides numerous benefits over its competitors, including high torque density, low acoustic pollution, minimal vibration, ease of control and high-speed potential. Additionally, the FSM can function as a mechanical rotator, auxiliary power supply, or wind turbine [1-3]. Due to its stator excitation and absence of an active rotor component, this motor configuration is considered abhorrent for propulsion in electric vehicles. Compared to the Double Salient Permanent Magnet Motor (DPSM), the FSM exhibited a significant advantage in phase flux-linkage [4]. The inductor alternator with the switching reluctance motor is combined to create the FSM. In 1999, the beginning of the Permanent Magnet Flux Switching Machine (PMFSM) motor was presented to simplify motor design and power electronics control while achieving flux weakening capability, high torque density, and easy thermal management [5-6]. The automobile industry opted for switched reluctance motors, induction motors, and brushless DC motors to replace mechanically driven auxiliaries with electrically powered equipment in various applications such as heating, ventilation, steering systems, water pumps, and air conditioning. However, these motors require power electronic motor drives, which are comparatively costly [7].

In recent years, several novel FSM machine configurations have been created. These configurations offer sinusoidal back-electromotive force (EMF) and low speed at maximum torque, making them well-suited for demanding operating environments like aerospace, automotive, marine, and wind power implementations [8-12]. According to the source of their excitation, these machines have three types [13-17]: Hybrid Excitation Flux Switching Machine Permanent (HEFSM), Permanent Magnet Flux Switching Machines (PMFSM) and Field Excitation Flux Switching Machines (FEFSM) or Wound Field. This paper review primarily focuses on the latest advancements in the design of PMFSM, FEFSM, and HEFSM. This review delves into different facets, including slot-rotor poles, stator structure, rotor structure, and unique configurations. The main goal of this review is to pinpoint areas in which the PMFSM necessitates additional investigation and to implement successful techniques employed in one configuration to improve the performance of the PMFSM across different setups.

2. Permanent Magnet Flux Switching Machine

2.1. Ration stator slot-rotor pole

Analyzing the quantity of rotor poles and stator slots in a machine's design is crucial for enhancing performance. A recent study [18] examined the number of rotor-pole's impact on single-phase motor's properties. The findings revealed that the 4S-8P PMFSM configuration exhibited the most significant initial output torque of 2.47 Nm, exceptional alternative designs like 2S-8P, 8S-12P and 10S-15P achieved the torque values of 1.45 Nm, 1.66 Nm, and 1.72 Nm respectively. Another investigation [19] compared the straight rotor configuration of PMFSM of 6S-10P with the rotor structure PMFSM of 6S-8P, and it was found that the straight rotor structure produced higher magnetizing flux concentration.

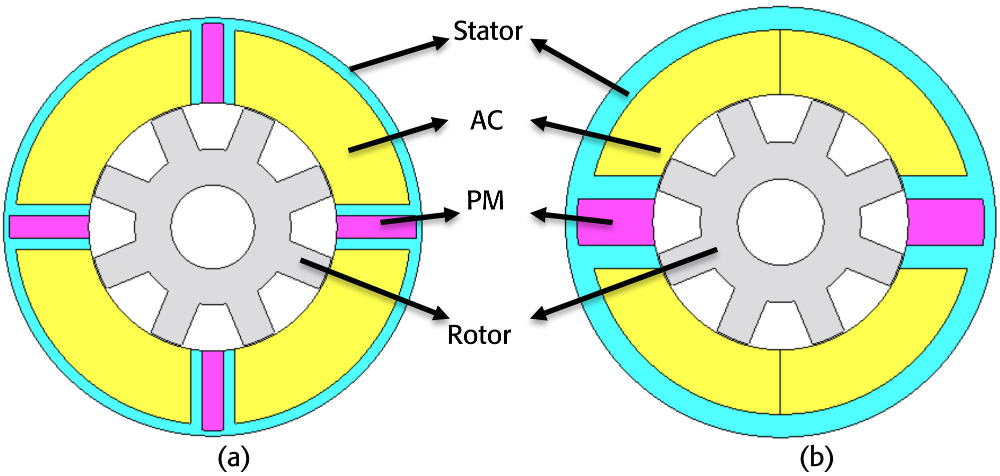


Figure 1. Configuration of PMFSM (a) 4S/8P (b) 2S/8P

In multiple articles, various additional stator-rotor combination topologies have also been presented [20-22]. Interestingly, odd numbers of rotors may reach torque capability and higher back emf compared to the 12S-10P configuration, but they have the disadvantage of unstable magnetic force [23]. Figure 1 displays the cross-sectional perspective of 4S/8P and 4S/8P configurations.

2.2. Configuration of the Rotor

In the past few years, there has been an increasing trend towards using wheel motors in the context of electric vehicles (EVs) due to their ability to offer more space and direct wheel control. The outer-rotor configuration for permanent magnet flux switching motors (PMFSM) was created in 2010 [24]. Since then, more studies have been conducted on this structure's working principle and performance with different stator slot rotor pole ratios and sizes, using finite element software and laboratory experiments [25-29]. Nevertheless, despite its notable characteristics, the assembly of the outer rotor structure can pose challenges due to the need for substantial adjustments to the control mechanisms. For example, in [30], forced oil cooling is extensively employed to augment the heat transfer generated by the rotor. Cooling a rotor is typically more challenging than cooling a stator, particularly in vacuum settings, due to the air gap surrounding the rotor acting as an insulating medium. The stator and rotor immersion in oil effectively cools the motor. Next, [31] discussed the cooling system using the hollow shaft method. Its benefit is that it effectively cools the permanent magnet synchronous machine's (PMSM) rotor at high speed. Findings indicate that this approach effectively mitigates the rise in rotor temperature even when rotor losses occur. Additionally, the outer rotor bearing holds greater importance compared to the inner rotor, resulting in an increased friction area and presenting difficulties in effectively cooling the machine's internal components. Conversely, dual-rotor structures have also been studied [31-33], where several topologies have been reported, but to date, research has been restricted to both rotors rotating identically in orientation. Generally, the dual-rotor configuration improves PM utilization and efficiency, and more advanced structures employ an axial field, resulting in a shorter axial length, greater torque density and improved heat released [34-35]. However, to achieve rotation in the opposite direction, it might be necessary to use a separate stator. Recent studies propose using a double rotor configuration in co-axial magnetic gear applications[36-38]. Figures 2 and 3 visually depict the dual-rotor configuration of PMFSM from a cross-sectional perspective.

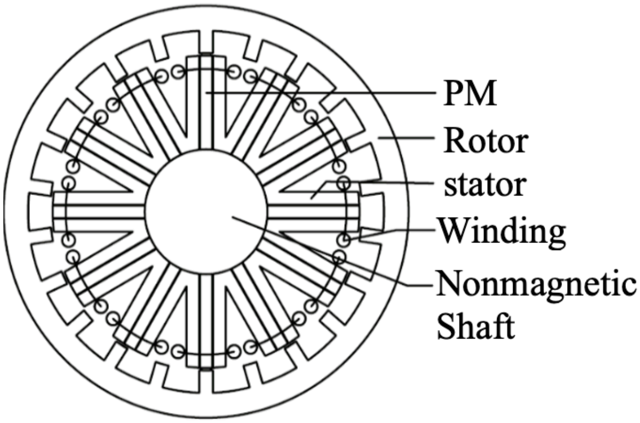


Figure 2. Outer-rotor PMFSM

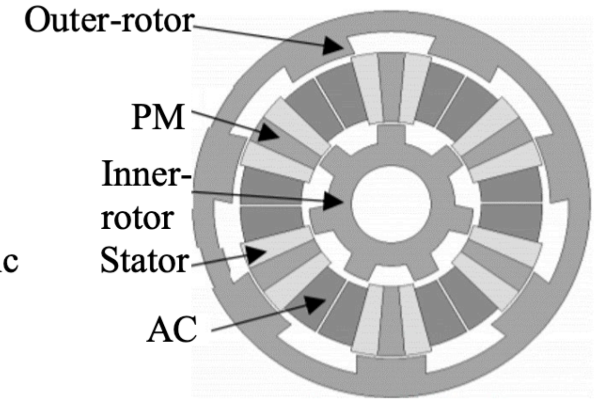


Figure 3. Dual rotor structure PMFSM.

2.3. Configuration of the Stator

It has been found that the Partitioned Stator (PS) PMFSM, also called a dual-stator machine, has been discovered to possess improved torque density because it effectively uses the available space by incorporating two stators [39]. Conversely, the Permanent Magnet (PM) is typically positioned inside the stator [39-42]. Table 1 compares the partitioned stator flux-switching permanent magnet (PA-FSPM), partitioned stator flux-switching hybrid excitation (PS-FSHE) and flux adjuster. The vast space within the inner stator allows for using a ferrite magnet with equivalent flux performance, replacing the need for rare earth magnets. However, the larger size of the motor limits its application in smaller spaces and increases manufacturing costs. Moreover, the losses of the stator core are also heightened in the PSPMFSM. Figure 4 depicts the partial structure of the PSPMFSM.

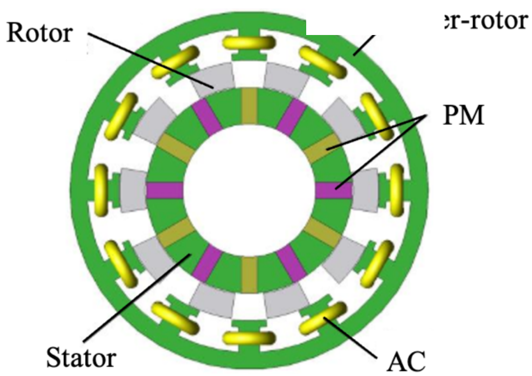


Figure 4. Dual-stator structure of PMFSM

References [43] and [44] explain the advantages of a segmented stator, including its ability to endure various stator winding faults. The segmented stator permanent magnet flux switching motor's construction from separate stator parts, with non-magnetic material replacing the gap between sections at an angle α. If an electrical problem exists in a particular stator section, the electric motor is expected to operate, but the torque value is reduced.

Table 1: Comparison of the partitioned stator

Item	PS-FSPM	PS-FSHE	FA-PS-FSPM	Prius
Cost-effectiveness	Medium	Low	Medium	High
Power- torque density	High	Low	Medium	Medium
Operating range	Narrow	Medium	High	Narrow
Flux-regulation	Low	Medium	High	Low
Thermal dissipation	Good	Medium	Good	Poor
Efficiency	High	Medium	High	High

2.4. Summary of PMFSM

Table 2 shows the performance comparison of different PMFSMs. All the performance is extracted from the reference discussed in the PMFSM section.

Table 2: Comparison of the various PMFSM

Types of motor	12S-12P	12S-8P	12S-22P	8S-12P	10S-15P	6S-10P	6S-8P	PS-FSHE 12S-10P	FA-PS-FSPM 12S-10P
Year	2015		2016	2016		2017		2019	
Author	M.Jenal and E.Sulaiman		Z.Xiang, L.Quan and X.Zhu	M.Jenal, E.Sulaiman, H.A.Soomro, S.M.N. Syed Naufal		R.Kumar, E.Sulaiman, H.A. Soomro, S.H.A Musavi, G.Kumar, I.A.Sohu		SM.N.S.Othman, N.Lassim, E.I.Mbadiwe, M.F.Omar, E.Sulaiman	
Rotor structure	segmental	Salient	salient	Straight rotor	Spanned rotor	Salient		Salient	
Stator structure	Salient		Partitioned	salient		V-shape		Segmental	
Rotor	Inner		Outer	Inner		Outer		Inner	
Stator diameter (mm)	150		269	150		80		132	
Rotor diameter (mm)	89.7		193.4	89.7		100		92.4	
Stack length (mm)	70		83.56	70		20		80	
Flux linkage (Wb)	21.04	15.25	0.09	0.06	1.88	7.8	9.0	N/a	0.034
Cogging torque (Nm)	13.33	21.11	3.2	1.12	3.00	1.75	4.94	27.5	231
Back-emf(V)	35.68	23.93	205.2	5.20	18.40	13.6	1.52	N/a	65.98
Torque (Nm)	9.50	25.54	19.39	1.5	1.65	6.22	0.22	342	222.30
Power (W)	2.93	8.11	4.13k	312.40	402.7	N/a	N/a	377	243.63
Speed (rpm)	N/a	N/a	2406.55	1805.4	2327.4	N/a	N/a	N/a	N/a
Efficiency (%)	N/a	N/a	94.08	N/a	N/a	N/a	N/a	87	N/a

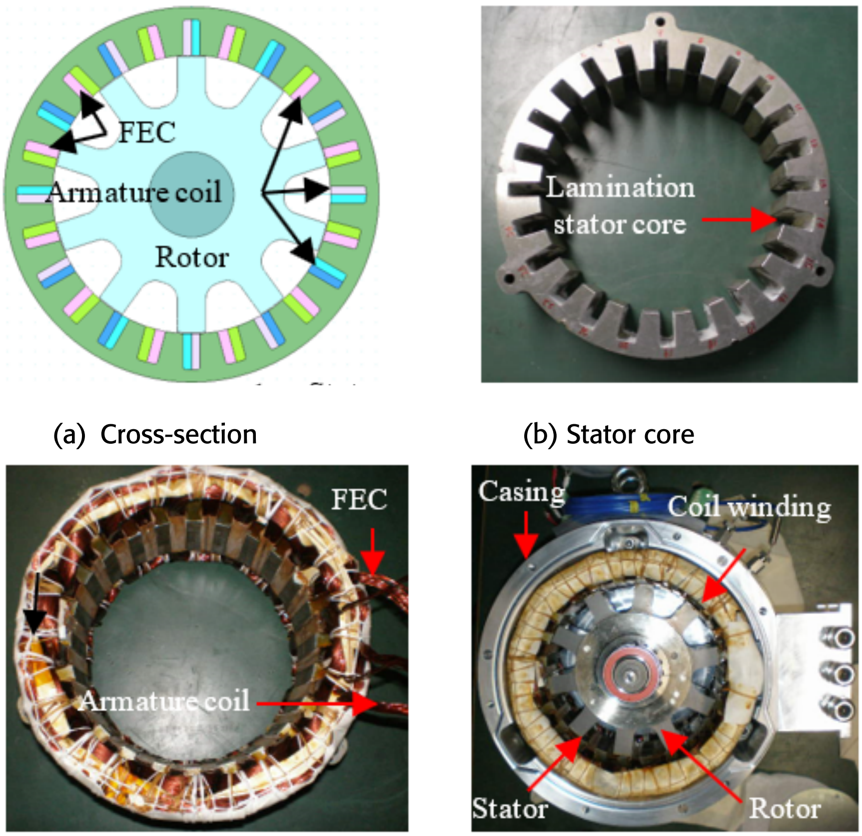
3. Field Excitation Flux Switching Machine (FEFSM)

Recently, Neodymium (Nd) and Dysprosium (Dy) prices, necessary rare-earth materials used in PMSM and IPMSM, have experienced a significant increase due to yearly consumption and cost factors. This price surge has resulted in supply shortages and security concerns [45]. One possible way to tackle this issue is to substitute the permanent magnet (PM) excitation in traditional PMSM and IPMSM rotors with field excitation coils (FEC). This creates the field excitation-flux-switching machine (FEFSM) motor. The fundamental concept of the FEFSM is to alter the orientation of the magnetic flux linked to the armature winding based on the rotor's location. FEFSMs offer several benefits, including simple construction, the absence of permanent magnets, and a straightforward controller circuit. Numerous topologies of FEFSM have been extensively researched and printed [45-47].

Figures 5,6 and 7 display several three-phase FEFSMs with various combinations of winding arrangement and slot-poles. Based on the figures, different rotor structures and coil winding techniques have been developed to achieve optimal performance of FEFSMs. There are two types of three-phases FEFSM rotor structures: salient and segmental. The coil winding configuration is divided into overlap and non-overlap [48-51]. The three-phase Field Excitation Flux Switching Machine (FEFSM) is introduced, with different FEFSM designs utilizing overlap windings with both even and odd rotor pole numbers. Various designs of even rotor-pole number three-phase fractional-slot concentrated winding permanent magnet synchronous machines (FEFSMs) and overlapping windings have been suggested and recorded [52-55].

In 2012, Sulaiman et al. proposed 24S-10P for hybrid electric vehicle (HEV) applications [56]. The motor depicted in Figure 5(a) comprises 24 stator slots, with 12 slots dedicated to FEC coils and another 12 slots for armature coils. Additionally, there are 10 salient poles positioned on the inner part of the motor. Figure 5(b) illustrates the stator core assembly, which consists of 200 units of 35H210 electromagnetic steels with a stack length of 70 mm. In addition, Figure 5(c) displays the windings of armature coils and FECs overlapping in the 24 stator slots. Figure 5(d) illustrates that the entire assembly comprises a rotor core. The structural constraints and restrictions of the 24S-10P FEFSM were readily available, as were the anticipated value of the IPMSM [57]. From the results, at the based speed of 5,585 rpm, torque of 210.4 Nm is achieved, while the corresponding power is 123 kW. In open circuit conditions, the proposed motor has produced back-emf and torque ripple of 295 V and 6.4%, respectively. The motor efficiency at the highest torque operating point is achieved at 93%, and when high-speed operating, efficiency is slightly degraded to 91.5% owing to the escalation in iron loss [57]. However, the 24S-10P FEFSM has a low torque density because of the high volume of stator and rotor, thus resulting in high motor weight.

To achieve an additional enhancement in the torque density of a 24S-10P, the 12S-5P and 9S-5P FEFSMs with an odd number of rotor poles were proposed by Zhou [58]. Both 12S-5P and 9S-5P FEFSMs maintain a 90 mm outer stator diameter, but 9S-5P has much shorter end windings and less weight. Therefore, the 9S-5P motor has produced better efficiency and torque density performances. Figure 6(a) illustrates the 9S-5P FEFSM three-phase motor configuration, which features a prominent rotor and overlapping windings. The diagram illustrates that the 9S-5P FEFSM has an outer rotor diameter of 49.5 mm and a stack length of 25 mm. The torque and power output were quantified as 0.9 Nm and 37.7 W, respectively. Nevertheless, the motor under consideration has produced a substantial cogging torque of 0.2 Nm, which accounts for 22.2% of the average torque. Additionally, a significant torque ripple of 20% requires development.

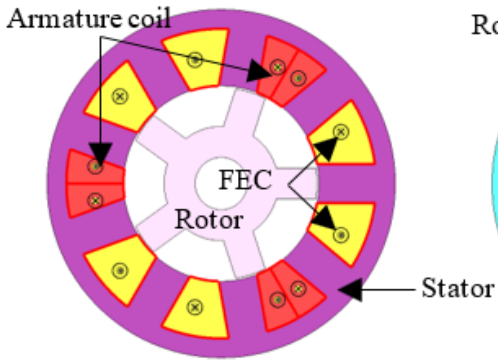


(a) Cross-section (b) Stator core

(c) Winding configuration (d) Stator and rotor assembly

Figure 5. 24S-10 configuration of salient rotor FEFSM [56]

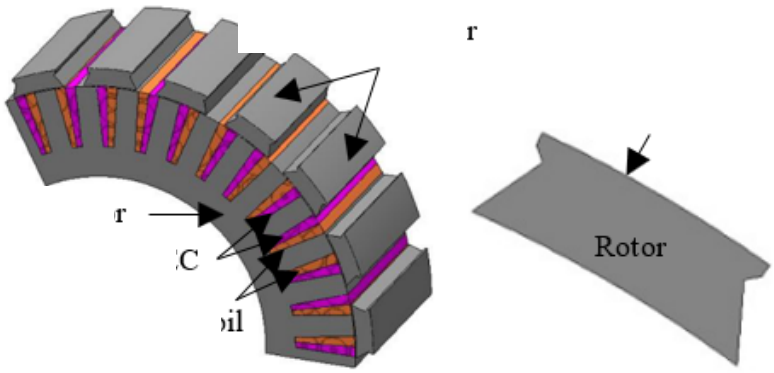
Nguyen et al. have presented three-phase outer-rotor 12S-7P salient rotor FEFSM and overlap windings for electric scooters [59]. The author alleged that outer-rotor FEFSM with odd rotor poles and 12 stator-slots combination can deliver high performance. Figure 6(b) displays the part of the projected motor. The diagram shows 6 armature stator slots and stator slots for FEC coils, respectively. The coil windings are wound over 2 stator teeth. The highest current density of 20 A/mm^2 and a speed of 500 rpm create a back-emf of 55 V and a flux linkage of 0.15 Wb for the FEC. At the same time, the outer rotor of 12S-7P can produce 18.75 Nm torque with the corresponding power of 981.7 W. In addition, FSMs that use odd rotor poles suffer from the disadvantages of noise and vibrations, which will shorten the bearing's life [60-62].



(a) Inner-rotor 9S-5P (b) Outer-rotor 12S-7P

Figure 6. Three-phase, overlap windings with odd rotor poles FEFSM [56].

The study of three-phase FEFSM not only focused on an overlapping winding's inner rotor, but research has also been conducted and presented on the non-overlap winding of outer-rotor FEFSM and odd rotor pole [63]. Furthermore, the outer-rotor three-phase FEFSM with concentrated windings and even rotor poles were studied by Othman et al. [64]. Figure 7(a) illustrates the innovative configuration of a segmented FEFSM with concentrated windings presented by Galea et al. in 2012 [65]. The motor design consists of 36 stator slots and 21 segmental rotors with a dovetail shape, as shown in Figure 7(b). The author states that the segmental rotor, depicted in Figure 7(a), possesses favorable mechanical characteristics and yields exceptional motor performance. The machine being described has a diameter of 600 mm for its outer rotor and a length of 130 mm for its stack. The outer-rotor 36S-21P FEFSM has achieved the most considerable torque output of 2.81k Nm and a low torque ripple of 5.7%, as indicated by the findings. Furthermore, the maximum power output of 8.14 kW is achieved at a rotational speed of 28.6 rpm. Despite the motor's favorable torque and power capabilities, the drawbacks arise from its intricate design, which involves many slot-pole combinations and outer-rotor configurations. These challenges need to be addressed.



(a) Segmented FEFSM with concentrated winding (b) Dove-tail-shaped

Figure 7. Odd rotor pole, three-phase outer rotor 36S-21P (a) non-overlap windings FEFSM, (b) Dove-tail-shaped [64]

3.1. Summary of FEFSM

Table 3 shows the performance comparison of different FEFSM. All the performance is extracted from the reference discussed in the FEFSM section.

Table 3: Comparison of the various FEFSM

Types of motor	12S-8P	24S-10P	12S-14P	12S-6P	12S-9P	8S-4P	8S-6P	8S-10P

Year	2013		2014	2018		2019		
Author	E.Sulaiman, F.Khan, M.Z. Ahmad, M.Jenal, S.A.Zulkifli and A.A.Bakar		Z.A.Husin, E.Sulaiman, F.Khan and M.F.Omar	M.F1.Omar, E.Sulaiman, H.A. Soomro, L.I.Jusoh and F.Amin		B.Khan, F.Khan, N.Ahymad, G.Faraz, R.Ahmad and K.Naveed		
Rotor structure	Segmental		Salient	Segmental		Salient		
Stator structure	Salient		Salient	Salient		Salient		
Rotor	Inner		Inner	Inner		Inner		
Stator diameter (mm)	150		264	75		N/a		
Rotor diameter (mm)	90.6		N/a	44.5		N/a		
Stack length (mm)	N/a		70	N/a		N/a		
Flux linkage (Wb)	2.76	31.5	0.04	0.0412	0.031	0.32	0.12	0.1
Cogging torque (Nm)	N/a		18.5	3.4	1.03	3.38	0.02	0.5
Back-emf(V)	N/a		N/a	12.7	7.5	180	90	60
Torque (Nm)	0.31	21	43.04	0.77	0.55	1.6	1.3	1.1
Power (W)	N/a		5.41	0.26	0.23	N/a		
Speed (rpm)	N/a		N/a	N/a		N/a		
Efficiency (%)	N/a		N/a	N/a		N/a		

4. Hybrid Excitation Flux Switching Machine (HEFSM)

HEFSMs, also acknowledged as Hybrid Excitation Flux Switching Machines as advertised in Figure 8 [65-66], utilize two distinct sources of excitation flux. These machines have undergone thorough research and analysis over a considerable period and can deliver significant torque and power density. Additionally, they exhibit high efficiency and offer the flexibility of adjusting the flux as needed [67-70].

A 6S-4P arrangement of a HEFSM with three layers of PM, field winding, and armature winding inside the stator is depicted in Figure 8(a) [71]. Nevertheless, the extended end windings of this configuration result in heightened copper loss and diminished efficiency. Due to the low permeability of the PM, the field excitation coil (FEC) and PM are also connected in series, which limits the capacity to alter flux. A new 12S-10P HEFSM was proposed to address these issues in [66]. In this design, the permanent magnet (PM) is strategically placed near the center of the stator segments, allowing for ample space to accommodate a DC field excitation coil-(FEC), as illustrated in Figure 8(b). The DC FEC produces the presence of the flux path that can reduce the primary flux produced by the PM for higher torque generation.

Adding the concentrated field and armature depicted in Figure 8(c) produced a new extension of an E-Core HEFSM [67]. The armature winding and the field excitation coil (FEC) occupied the same slot area and had an equivalent number of turns. On the contrary, the PM was situated on the external top of the stator in this particular configuration. Consequently, the PM that produces flux acts as leakage flux and does not contribute to torque generation. Recently, a three-phase E-core HEFSM was analysed in [69] featuring non-overlapping windings, illustrated in Figure 8(d). The power-speed curve, torque, and flux capability were examined to assess the proposed motor's efficacy. The machine offers advantages such as lower cost and reduced copper usage. Nevertheless, the torque density might experience a decline as a result of the diminished PM volume.

HEFSMs equipped with active components on the stator face certain drawbacks, such as the challenging manufacturing and assembly process due to the segmented stator core. The presence of a salient rotor structure also results in increased rotor weight. Moreover, compared to PMFSMs, HEFSMs that utilize two excitation flux sources necessitate a complex control circuit for regulating the magnetic flux linkages in the Field Excitation Coil (FEC) and armature coil. Furthermore, the FEC and armature coil might reduce overall motor efficiency due to higher copper losses.

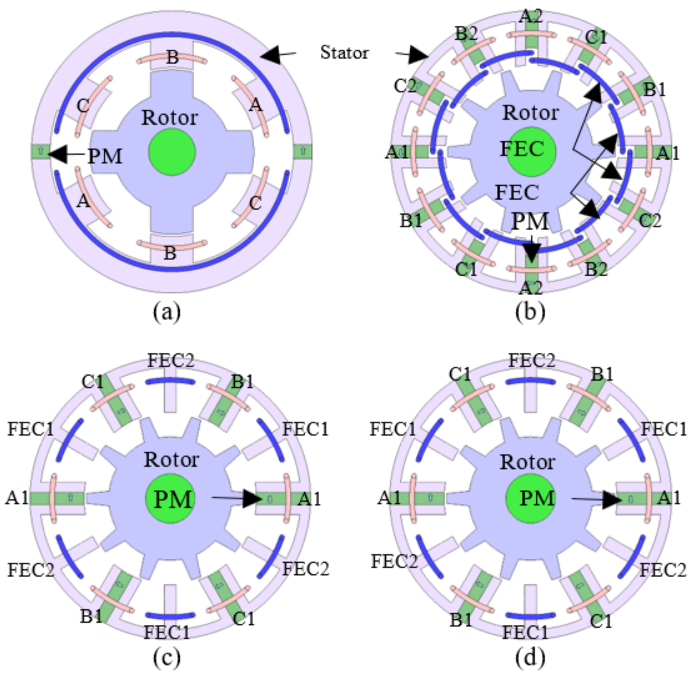


Fig. 8. HEFSM three-phase, (a) 6S 4P, (b) C-core12S-10P, (c) E core 12S-10P, and (d) E-core 6S-8P E core [65-69].

4.1. Design Extension and Customization

This portion of the text discusses how design can be customized and expanded for specific reasons. Using a segmented rotor has been proven effective in reducing the magnetic path length, as stated in reference [72]. Flux in the armature teeth and magnetic connections in the winding's armature can be generated using a segmented rotor in a single operation cycle. This design is commonly used in dissimilar types of machines [73-77]. The angle of each segment is established by the most minor separation required to avoid substantial flux transfer between adjacent segments. The number of segments employed determines the segment pitch. Figure 9 shows a partial view of a 6-pole and an 8-pole segmental rotor.

Most modern electrical machines use an anisotropic and circumferential flux distribution, with permanent magnets (PMs) placed tangential to the shaft, as seen in FSMs. Modifying the configuration of permanent magnets (PMs) around the stator circumference can alter the magnetic flux pattern. Various studies, referenced as [42], [78], [79], have explored the utilization of radial and circumferential flux. Recent advancements, cited in references [80-82], have significantly progressed the design of axial flux machines. These improvements entail the application of a dual rotor or dual stator arrangement in which magnetic flux is directed perpendicular to the stator and rotor's surface. However, designing and analyzing axial flux devices is more time-consuming due to the need for three-dimensional modelling. Additionally, as the complexity of the design increases, manufacturing the machine can become more challenging. Figure 10(a) illustrates a partial depiction of the design of magnets in an outspread and circumferential configuration. However, Figure 10(b) displays a three-dimensional depiction of an axial flux machine that showcases a dual stator. The flux path in an axial flux machine is unidirectional, and grain-oriented magnetic steels are used to achieve maximum efficiency.

Before this stage, the design's magnets were positioned directly from the inner to outer stator or along the inside of the stator diameter. A recent development has involved modifying the shape of the magnets to resemble the letter "V" to maximize output torque and improve magnet utilization. In conventional configuration, a pair of permanent magnets (PMs) are positioned within the stator [83]. When the machine has an outer-rotor arrangement, the V-shaped permanent magnet is visible on the outside of the machine [59]. A multi-tooth machine, known as another inventive stator core arrangement, was developed to enhance the torque value of the V-shaped permanent magnet. The multi-tooth machine demonstrates a higher average torque, lower inductance, and significantly less imbalanced magnetic force. It does so at the expense of a marginally increased cogging torque and undesirable total harmonic distortion [84]. In reference [85], a permanent magnet flux-switching synchronous machine (PMFSM) with radial segmentation was presented.

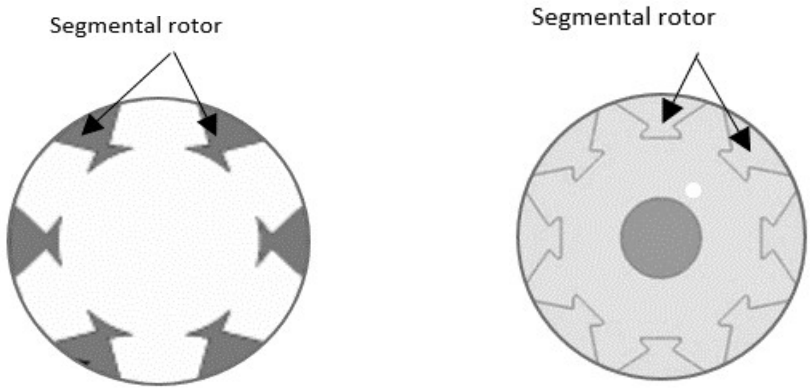


Figure 9. Segmental rotor (a) 6-rotor pole (b) 8-rotor pole

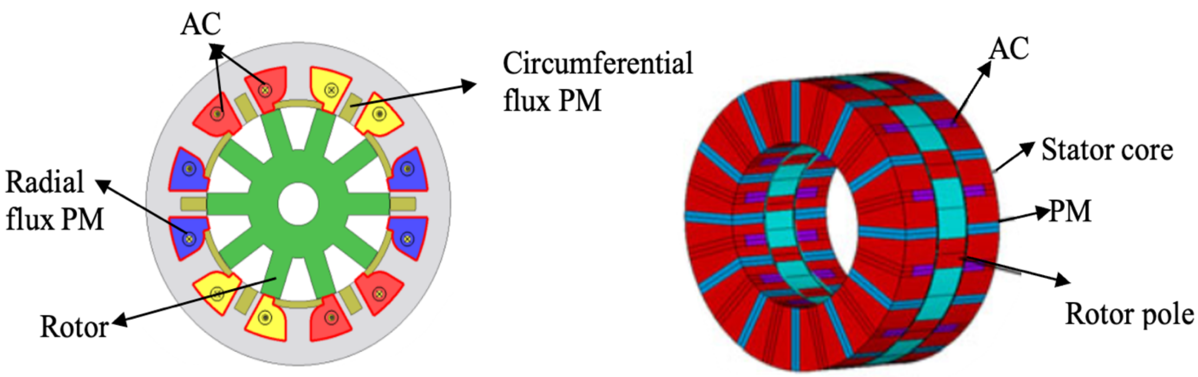


Figure 10. (a) Circumferential arrangement of the magnet(b) Double stator axial flux machine

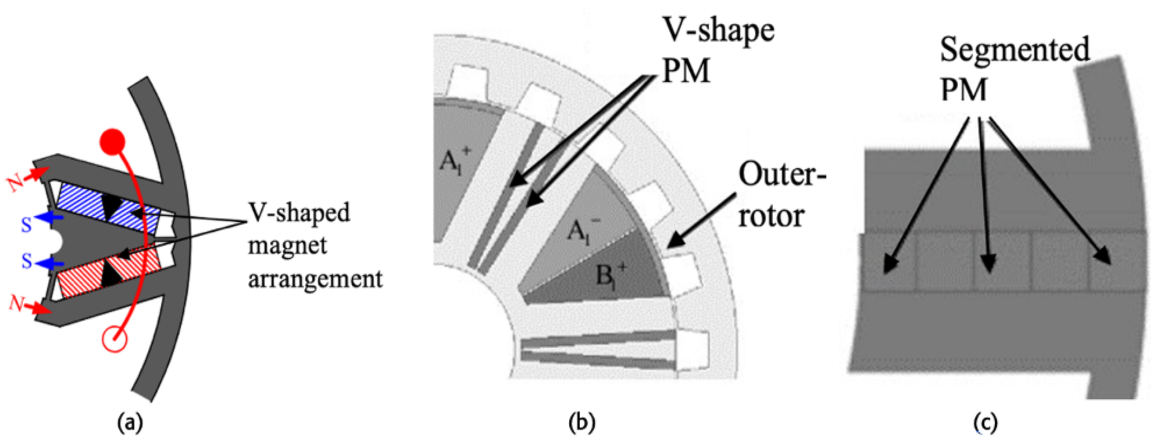


Figure 11. Magnet-V-shaped (a) rotor inner, (b) rotor-outer, (c) magnet-segmented

Researchers found dividing a rectangular magnet into five segments leads to a slight increase in torque production and a higher volume ratio of torque-to-magnet. In this design, smaller permanent magnets (PM) segments are positioned in the higher flux density region near the air gap. In comparison, more significant PM segments are suggested to be closer to the outer surface as the PM placement progresses. Figure 11 displays the V-shaped magnet design [86] and a cross-sectional representation of the segmented magnet. Moreover, Figure 12 depicts the multi-toothed machine.

The flux barrier (FB) method decreases the flux that escapes from the stator, specifically in C-type stators. There are six ways to arrange flux bridges on stator teeth, and the C2, C3, and C5 arrangements [87-88], which are positioned arrangements in the rotor at a greater distance from the stator teeth, produce superior maximum torque outcomes compared to alternative configurations. In addition to reducing flux leakage, FB can also lessen cogging torque and slightly reduce PM length, although it may also slightly lower the machine's average torque [89].

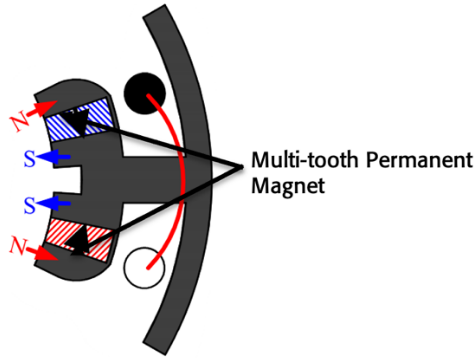


Figure 12. Cross-sectional view of multi-toothed machine

Table 4: Summary of design variation

Design variation				Motivation
Design extension and customization	PMFSM	FEFSM	HEFSM	
Segmental rotor	✓	✓	✓	Flux path
Modular rotor	✓	✓		Flux path
Segmental stator	✓	✓	✓	Fault-tolerant
Stator E, U, C shape	✓	✓	✓	Magnetic circuit arrangement
Multi-tooth	✓	✓		Advancement of V-shape
Segment magnet	✓		✓	Reducing flux leakage
Flux-bridge	✓			Flux weakening
Mechanical flux adjuster	✓		✓	Flux weakening
Flux adjuster		✓	✓	Flux weakening

A movable flux adjuster (FA) placed on the stator's outer cover can enhance the flux weakening capability, but it also increases the motor's size [90-91]. To tackle this problem, The FA is integrated into the interior stator of the PMFSM partitioned stator machine in order to address this issue. This arrangement enables the FA to occupy the same space as the PM, thereby decreasing the size of the machine while enhancing its power and torque densities. Another design improvement involves inserting an FB in the rotor yoke and teeth to reduce eddy-current loss and minimize eddy-current harmonics [92]. The cylindrical rotor structure, borrowed from the SRM and features ribs linking each rotor pole, is utilized to reduce loss in high-speed operation [93-95]. This loss reduces efficiency in SRM's high-speed and low-power sectors [96]. While the cylindrical rotor structure is rarely utilized in PMFSM, a comprehensive investigation was undertaken regarding HEFSM, which uses two distinct varieties of cylindrical rotor structures. The study found that the cylindrical rotor structure reduces windage loss by 35.4% compared to the salient rotor type, with a minor disadvantage in the highest torque [97-98]. Table 4 summarizes the design variation of PMFSM, HEFSM and FEFSM. Although most publications have focused on inner rotor designs, only a few have explored outer rotors.

4.2 Manufacturing Challenges

Its design often determines the intricacy of the manufacturing process for a Flux Switching Machine (FSM). It is essential to consider the rotor's manufacture to reduce the number of rotor losses. The more sophisticated and unique a design, the more complexity the manufacturer must deal with. Three points need to be highlighted here. Firstly, rotor structure. Frankly, the salient rotor structure is better than the segmented rotor structure. Based on Figure 10(a) and in [98], the salient rotor tooth has a rectangular shape, while the segmented rotor tooth produces various shapes. The segmented rotor has many shaped sides, complicating the design manufacturing process. On the other hand, the salient rotor has only one slot pole, even though it has many teeth. However, one tooth equals one slot pole for the segmented rotor, making manufacturing more expensive. However, the segmented rotors outperform the salient rotors in terms of flux linkage, torque, and power.

Apart from that, the positioning of permanent magnets also affects the manufacturing challenges. Essentially, this machine can be categorised into two main types: surface-mounted permanent (SPM) machines and internally mounted permanent-magnet (IPM) machines. In the context of Integrated Permanent Magnet (IPM) systems, the reluctance route experiences specific torque loads, which necessitates a reduction in the mass of the magnet in order to achieve the desired torque [99]. Additionally, when calculating the mass of the PM, the stator volume will change depending on the volume of PM needed. The manufacturer complexity will appear here due to the various sizes and shapes of the stator following the PM restriction. In addition, placing any non-passive components on the rotor could lead to challenges in effectively managing heat and thermal concerns [100]. Regarding sandwich PM shape, the machine is more complex than others. Usually, the sandwich PM shape comes with a double rotor or double stator. So, the cost of manufacturing will increase along with the difficulty of design.

Next, the last point that needs to be considered is the machine's winding. It is essential to consider the manufacturing process for the stator core and windings early on in the design of the machine. The method used determines the teeth geometry of the machine and whether it has tips or not. The various manufacturing procedures are given and further analysed in [101]. [102] provides a concise overview of the techniques employed in producing the stator core and windings for a Permanent Magnet Synchronous Motor (PMSM) with concentrated windings. Next, an appropriate number of winding layers should be selected after carefully considering the manufacturing process. The selection of the layers primarily depends on their application. Besides that, from the mechanical side, the machine also faced manufacturing challenges regarding the bearing, inner shaft, end coil and casing.

5. Conclusions

This research addresses this deficiency by examining the most recent design modifications in three Finite State Machines (FSMs) categories: the FEFSM, PMFSM and HEFSM, which combines permanent magnet and field excitation. The review encompasses the analysis of various armature slots, rotor poles, stator structures, rotor structures, and unique structures that employ different approaches to mitigate the drawbacks of conventional FSMs. The main objective of this analysis is to pinpoint possible research topics and gaps that necessitate greater attention in the development of FSM, specifically for industrial applications and transportation. Additionally, the paper emphasizes the design possibilities of incorporating different structures into one another to enhance the performance of FSMs. In conclusion, the literature review reveals that approximately 71% of the research on FSMs is focused on PMFSMs, while FEFSMs and HEFSMs each account for 14%. This highlights the dominant research emphasis on PMFSMs.

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Authors' Contributions

Therefore, each author contributed to the study's design conception, optimization, and analysis. All authors reviewed the results and approved the final version of the manuscript.

Competing Interests

The authors declare that they have no competing interests.

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