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Research paper

Preliminary studies of 12S-8P and 12S-14P Hybrid-Excited Flux Switching Machine with FEC in radial direction by using JMAG-designer software

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Abstract

In this paper, design analysis of Hybrid- Excited Flux Switching Machine (H-EFSM) with 12Slot-8Pole (12S-8P) and 12Slot-14Pole (12S-14P) topologies are presented. H-EFSM has been introduced in which the advantage of Permanent Magnet (PM) machines and DC Field Excitation Coil (FEC) synchronous machines is combined. H-EFSM design proposed less permanent magnet consumption, high to torque/power density and high efficiency. In recent, most of H-EFSM having FEC arranged in theta direction that affect in flux production which cause less flux generation and machines performances. Therefore, a design of 12S-8P and 12S-14P H-EFSM with FEC arranged in radial direction is proposed to prevent flux cancellation and produce high flux linkage. Performance analysis of 12S-8P and 12S-14 H-EFSM such as PM flux, induced voltage, cogging torque and flux distribution are investigated by 2-D Finite Element Analysis (2D-FEA). A design with 12S-14P configuration has achieved the higher torque and power with 220.15Nm and 92.45kW, respectively at maximum field and armature current density

Keywords: *2D-FEA; Flux cancellation; H-EFSM; Radial Direction; Theta direction.*

1. Introduction

Flux Switching Machines (FSMs) are a new class of electric machine which has potential to generate high torque and power density, applied in HEV [1]. The FSM concept has been established and reported in the mid-1950s. Throughout the most recent decade, numerous novel, arrangement and configurations have been designed for different applications and function, including electric vehicles, home appliance, industry and aerospace applications [2-3]. FSM can be categorized into three groups, which are permanent magnet (PM) FSM, Field-Excited (F-E) FSM and Hybrid-Excited (H-E) SFM as illustrated in Figure 1. Permanent magnet and field excitation winding are the main flux sources in PMFSM and F-EFSM, respectively for the motor to operate. However, in H-EFSM, it requires both permanent magnet and field excitation winding to generate the flux [4-5].
Overall in FSM design, the field excitation winding, armature winding or permanent magnets known as active parts are positioned on the stator while rotor only laminated steel. The concept of PM FSM based on the flux switching principle has been studied for quite a few years [6]. In general, this type of machines utilizes a salient rotor with PMs housed in the stator part. Although the PM material is high-priced, it exhibits a high torque density and efficiency. Furthermore, PM material used having their operating temperature which cause limitation in its application and accomplishment. At high speed operating region, the flux-weakening operation disturbing the performance of PM machines due to the fixed excitation of PM. Thus, to overcome the high cost in

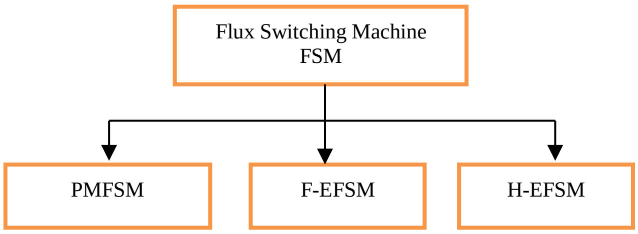


Fig. 1: Three classes of FSM

China development, the PMFSM can be replaced by F-EFSM by removing the PM part and replaced with the FEC.
With their own novelty, the structure of F-EFSM is quite identical to salient rotor reluctance machine. F-EFSM is formed when the principles of Switched-reluctance Motor and inductor generator [7] are combining together. Basically, F-EFSM involves exchanging the flux magnitude and direction of FEC with the armature coil winding and it is related to the changing rotor tooth position respectively. F-EFSM has the advantage of low cost, ease and performs variable flux, applicable for numerous application and accomplishment [6-7]. In addition, the structure of F-EFSM design is very simple and easy to develop because no PM used. In spite of F-EFSM advantages, a single-phase F-EFSM has issues relating to high cogging torque, low pull-up torque and rotating in one direction only. Moreover, both FEC and armature coil windings are overlapped to each other and resulting in high coil end length and high copper loss [6].

In order to overcome drawbacks of both machines, an H-EFSM is introduced to replace previous two types of FSM by combining the benefits of both PM machines and DC FEC synchronous machines [8-10]. As such H-EFSM has the capability to reduce flux weakening, and improve torque, power density, efficiency with various flux capability. Besides, it has advantages in robust rotor structures suitable for high-speed application.

2. H-EFSM Topologies

Based on general equation, several H-EFSMs topologies have been designed and illustrated in Figure 2. Figure 2(a) depicts a H-EFSM with 6S-4P configuration, in which the armature coil, PM and DC-FEC are arranged in three different layers placed at the stator part. At the stator slot, the first or inner layer is the armature windings, the second or middle layer is the FECs, the PMs located at the outer layer [11-12]. Figure 2(b) shows a 12S-10P H-EFSM as proposed and discussed in [13-14]. PMs and FECs are arranged alternately to each other to form six north poles and six south poles. The 12 slots armature coils put in order at the first circumference with overlapping the PM as shown in Figure 2(b). Then, flux generated from magnetomotive force, mmf of the PMs and the FECs link with the armature coil alternately.
Three-phase 12S-10P H-EFSM with outer rotor configuration is also described as illustrated in Figure 2(c). The design is implemented based on a design in Figure 2(b), but different in rotor structure. All active part slots are in rectangle shape, means the machine has very simple structure with armature and field excitation coil being in concentrated winding [15]. In addition, FEC and armature coil in the machine are wounded to form non-overlapped winding in order to provide shorter end winding, then results in low copper losses.
Meanwhile, the H-EFSM shown in Figure 2(d) is a three phase 12S-10P H-EFSM with C-type of the stator. The FEC and PM placed on the stator are in rectangular shape which can make the proposed motor have a simple structure and easy to manufacture. All FECs and armature coils windings have arranged in counterclockwise direction. The design also has advantages in non-overlap winding and offers low copper loss. Nonetheless, the machine size significantly increased to employ high FEC slot, hence reduces output torque.
Previously in literature review, most HE-FSM configurations proposed the FEC and armature coil to be wounded in theta direction which results in cancellation of flux between PM and FEC. Therefore, this paper proposes new structure of H-EFSM with the FEC in radial direction to eliminate this drawback [15]. Hence, design and performance analysis is carried out for 12S-14P and 12S-16P of H-EFSM with FEC in radial polarity. Importantly, the research methodology, design specifications, design parameters of the proposed HE-FSM will be explained in this paper.

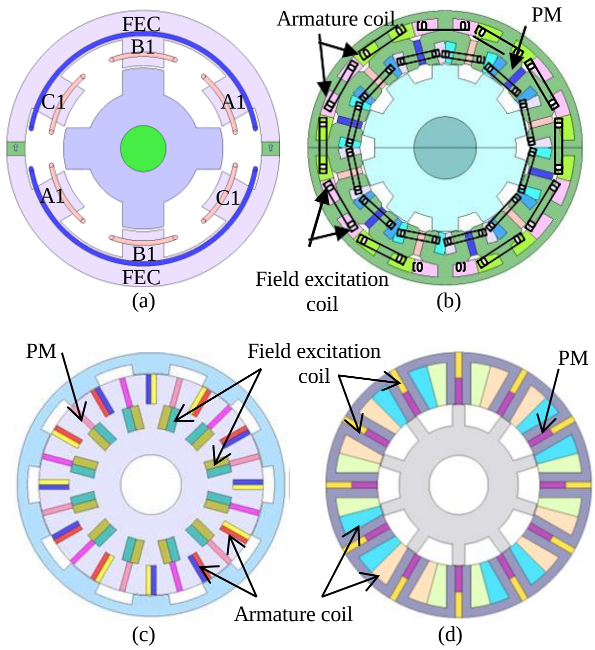


Fig. 2: Several H-EFSMs topology (a) 6S-4P (b) 12S-10P H-EFSM (c) 12S-10P with outer rotor (d) 12S-10P HEFSM with C-type stator

An analysis in no-load condition such as coil test analysis, U flux linkage by PM, back-emf, and cogging torque is examined. Furthermore, in load condition analysis such as output torque and power are also discussed. The comparison analysis for various pole designs presented focus on coil test and back-emf analysis. However, other simulations such as flux distribution, output torque and power performance are analyzed to find the optimal performances among them.

3. Operating Principle of H-EFSM

The operating principle of H-EFSM can be defined as in Figure3. The flux generated by active part in stator flows to the rotor poles and changes flux polarity as well as position of rotor. In order to make a one complete flux cycle, half of rotor poles receive the flux from the stator while another half of rotor poles deliver the flux to the stator. Theoretically, flux switching concept can be described when changing flux in the rotor poles and changing flux in the stator slot. From the figure, the blue line indicates the flux from FEC while red line marks the flux from PM.
As shown in Figure 3(a), both PM and DC FEC fluxes flow from stator to rotor pole. Then in Figure 3(b), the fluxes in rotor part return back to the stator. Since the directions of both PM and FEC fluxes are in the same polarity, both fluxes are added together and flow directly into the rotor. Thus, delivering more fluxes with a so called hybrid-excited flux [16]. Meanwhile, Figure 3(c) and 3(d), shows the FEC is in reverse polarity, only flux from PM flows into the rotor pole while the FEC flux moves around the stator slot which results in less flux generation [17].

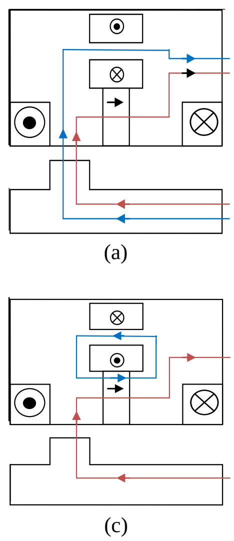


Fig. 3: The operating principle of H-EFSM (a) θe=0° - more excitation (b) θe=180° - more excitation (c) θe=0° - less excitation (d) θe=180° - less excitation

4. The Proposed Machine Design Specification and Restriction

Design study of 12S-14P and 12S-16P H-EFSM with FEC wounded in radial direction are examined. The design restrictions and specifications for the proposed machine are identical with IPMSM installed in hybrid electric vehicles as depicted in Table 1. The diameter of outer stator and stack length of machine are set to 269mm and 84mm, respectively. The electrical restrictions of to

Table 1: Proposed H-EFSM Design Specification

Description	Proposed H-EFSM
Max. DC-bus voltage inverter (V)	650
Max. inverter current (A_{rms})	360
Max. current density in armature winding, J_a (A_{rms}/mm^2)	30
Max. current density in excitation winding, J_e (A/mm^2)	30
Stator outer diameter (mm)	269
Motor stack length (mm)	84
Shaft radius (mm)	30
Air gap length (mm)	0.7
PM weight (kg)	1.3
Maximum speed (r/min)	20000
Maximum torque (Nm)	303
Maximum power (kW)	123

maximum DC bus voltage and maximum inverter current are fixed 650V and 360V, respectively. In addition, the weight of PM is fixed to 1.3kg, where PM material used is Neomax-35AH having coercive force at 20°C with circumferential anisotropic pattern and residual flux density of 932kA/m and 1.2T, respectively. Furthermore, electrical steel by using 35H210 material is used for the rotor and stator body of the machine. As a water jacket system is used as the cooling system of the machine, the limit of the current density is set to $30A/mm^2$ and $30A_{rms}/mm^2$ and for both DC FEC and armature winding, respectively. The proposed machine has simple structure in which all active parts are in rectangular shape and the armature and DC FEC winding are not overlap to each other which means reduce copper loss. The structure of rotor is robust and able? to rotate at high speed. because no PM is employed in it. The rotor consists of only stacked electromagnetic sheets and it is having high potential to elevate the maximum operating speed up to 12,000r/min. The proposed machine is targeted to generate the maximum output torque and power of 303Nm and 123KW, respectively.

The proposed H-EFSM design can be implemented by using two steps, the geometry editor and JMAG Designer. Basically, design parameters of the proposed machine are divided into two main parts which are the rotor and stator part. The design parameters for rotor parts can be divided into three parameters, which are the radius of rotor (R1), rotor pole length (R2), and rotor pole arc width (R3). Then, stator part is subdivided into three groups which are permanent magnet (PM), FEC slot, and armature coil slot. PM length is only parameter for PM as mark by R4. Then, the parameter involved in the FEC slot are FEC coil width (R5) and FEC coil height (R6). The parameters of armature coil slot are armature coil width and armature coil length, labelled by R7 and R8, respectively. The design parameters form R1 to R8 are shown in Figure 4 and the initial design parameters are listed in Table 2. Furthermore, a design of 12S-14P and 12S-16P H-EFSMs are illustrated in Figure 5.

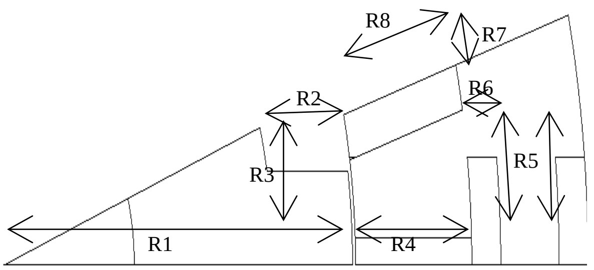
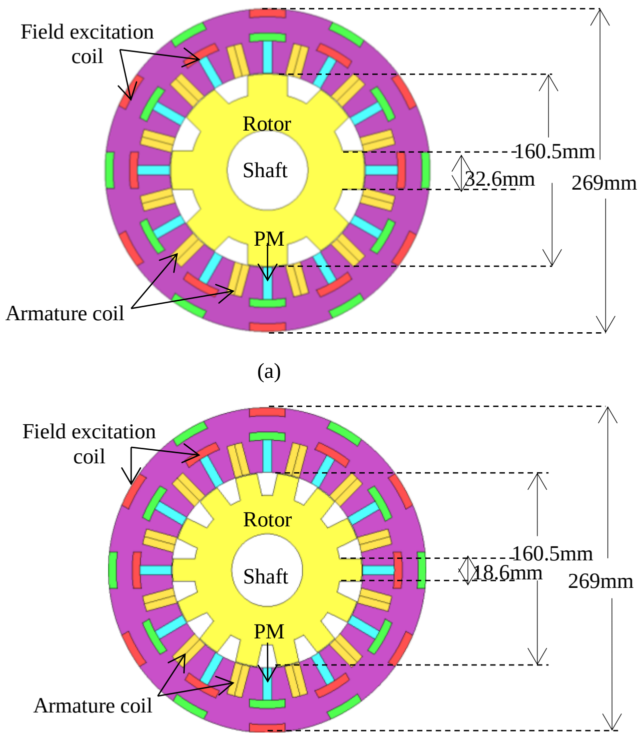


Fig. 4: Design parameters R1-R8

Table 2: Initial Design Parameters of Proposed H-EFSM

Items	12S-8P	12S-14P
Number of phase	3	3
Mechanical angle, θ (°)	22.5	12.86
Radius of rotor, R1 (mm)	80.25	80.25
Rotor pole length, R2 (mm)	20.2	20.2
Rotor pole width, R3 (mm)	16.33	9.33
PM length (mm), R4	26.775	26.775
FEC width (mm), R5	29.98	29.98
FEC height (mm), R6	6.67	6.67
Armature coil width (mm), R7	6.46	6.46
Armature coil length (mm), R8	26.75	26.75
No. of turns of armature coil	7	7
No. of turns of FEC	60	60



(b)

Fig. 5: Proposed HE-FSM design (a) 12S-14P (b) 12S-16P

4. Performance Analysis of Proposed H-EFSM based on 2D-FEA

4.1. Coil test analysis

Coil test analysis is conducted for all twelve armature coils separately to verify the operating principle of H-EFSM. Under no-load condition, coil arrangement test analysis is examined with current density of DC-FEC is set to 0A/mm2 as well as armature coil with $0A_{rms}/mm^2$, while PM is kept at 1.3kg. Each armature coil slot is investigated to form twelve flux linkages with base speed of 1200r/min. The flux source comes from the PM only while DC-FEC current is set at 0A. Then, each flux linkage is defined according to their position to form the conventional three phase as U, V, and W.

Figure 6 shows the three-phase generated flux linkages of PM for 12S- 8P and 12S-14P of H-EFSMs at zero rotor position. It is noticeable that a design with 12S-14P configuration has the higher amplitude of 0.012Wb. However, a design by 12S-8P topology produced only 0.011Wb of flux linkage. From the analysis, it is clearly demonstrated that different rotor pole number provides different magnetic flux amplitude due to different width of rotor tooth, in which flux easily flow to complete one electric cycle. A

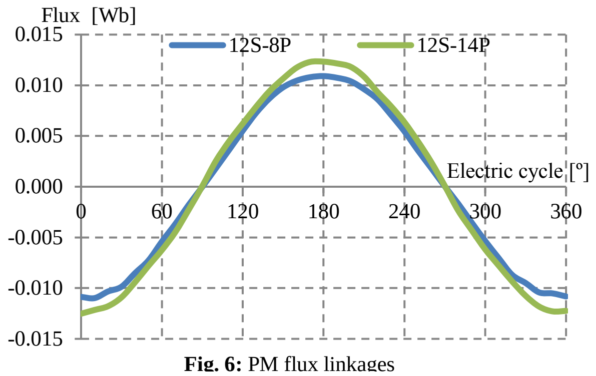


Fig. 6: PM flux linkages

design with 14-rotor pole has quite similar width between rotor tooth and stator tooth which easily allows the flux to complete its cycle and to flow from stator to rotor.

4.2. Induced voltage

The voltage with Je=0 means the induced voltage due to permanent magnet. The fundamentals of induced voltage generated by 12S-14P and 12S-16P are illustrated in Figure 7. The induced voltage of both H-EFSM is examined in open circuit condition at maximum current densities of armature and DC-FEC with the speed of 1200 r/min. As seen from the graph, a design with 12S-8P topology has the higher induced voltage of 36V compared to 12S-14P configuration with induced voltage of 34V. The value of induced voltage must be lower than 650V because more than voltage supply can interrupt motor operation as it is used for regenerative breaking to charge battery. In addition, the induced voltage waveform for 12S-8P topology has much distortion which affects large amount of torque pulsation and then results in less machine performance. In contrast, a design of 12S-14P H-EFSMs has less distortion which is good in practical application.

4.3. Cogging torque

Cogging torque known as unnecessary torque will affects machine performances by producing undesirable vibration and noise. The comparison of no-load PM cogging torque of proposed designs H-EFSM is illustrated in Figure 8. From the analysis, less amount of cogging torque with 9.4Nm peak-to-peak generated by 12S-14P H-EFSM. In contrast with 12S-14P design, H-EFSM with 12S-8P configuration produce the highest cogging torque with approximately 15Nm peak-to-peak which is lead the machine to produce high vibration and noise.

4.4. Flux distribution at maximum current densities

Flux distribution of every design should be taken as important

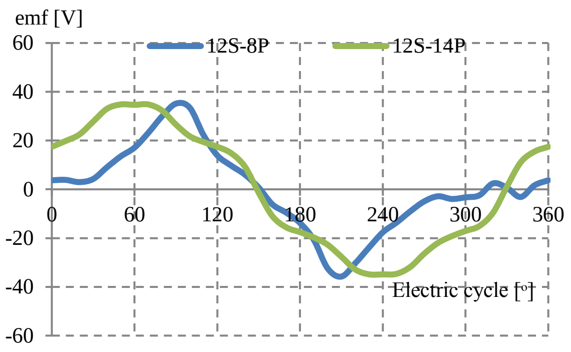


Fig. 7: Induced voltage for proposed H-EFSM

consideration because flux distribution will affect the performance of the machine. The flux characteristics at maximum current densities of armature and DC-FEC are investigated as shown in Figure 9. As seen in the figure, flux from the PM direction flows from stator slot to rotor while another flux flows around the DC-FEC pitch to make twelve complete flux cycles. Moreover, the room of stator slot between PM, DC-FEC and armature coil slots have limit space and effect on flux saturation in stator part. From the Figure 9(a) and 9(b) red colour plot shows the flux saturated takes place. Obviously, the machine design with 12S-8P topologies has high number of flux saturation if compared to another H-EFSM design. Higher number of flux saturation can reduce generated flux and affect machine performance especially in torque and power.

5.5. Torque and power performance

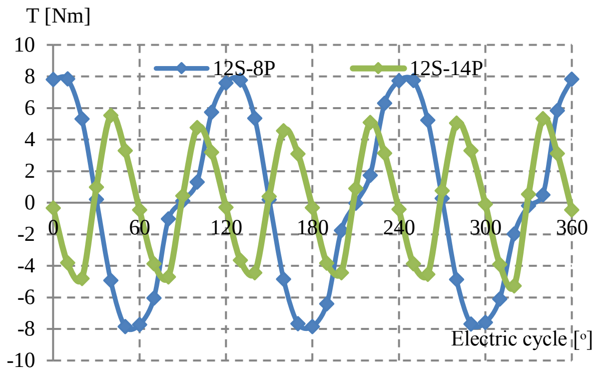


Fig. 8: Cogging torque

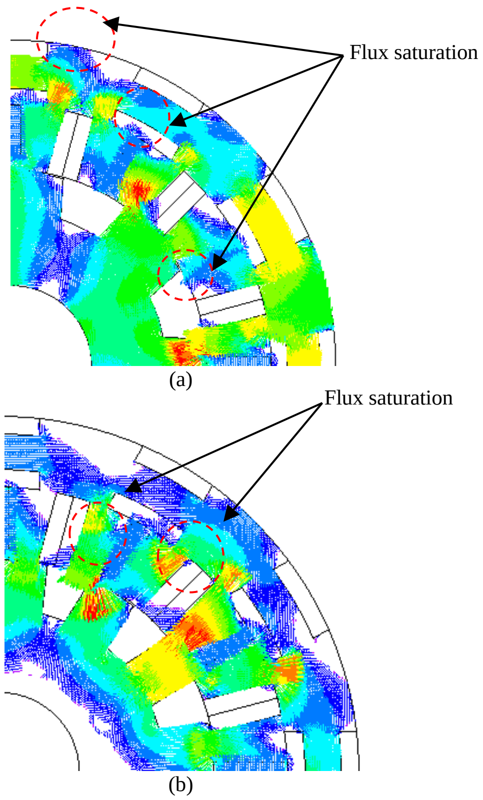


Fig. 9: Flux distribution at maximum Je, Ja (a) 12S-18P (b) 12S-14P

Finally, by set current density Je and Ja at maximum condition, the output torque and power are analysed as depicted in Figure 10 From the figure, it is shown that the maximum torque and power is 220. 2Nm and 92.5kW, respectively by 12S-14P configuration. Meanwhile, 12S-8P H-EFSM produces only 168Nm of output torque and 91kW of output power. Torque performance of 12S-8P configurations will be degraded due to high cogging torque. Based on analysis of magnetic flux density distribution as illustrated in

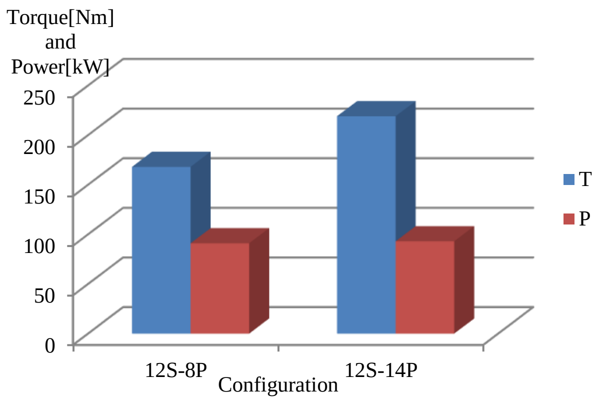


Fig. 10: Output torque and power

Figure 9, it is found that some of flux from DC-FEC and armature coil are cancelled, thus reducing the output torque of the machine.

5. Conclusion

Concisely, the design study and analysis comparison of 12S-8P and 12S-14P H-EFSMs with DC-FEC wounded in theta direction have been proposed and investigated based on 2D-FEA. The design parameter, dimension and material have been clearly explained. Coil test analysis at no-load condition has been analyzed in order to identify each flux characteristics. No-load analysis of the 12S-8P and 12S-14P H-EFSM designs such as induced voltage and cogging torque has also been investigated. A design with 12S-14P topology has produced higher output torque and power of 220.2Nm and 92.5kW, respectively, as a result it can be called as the best H-EFSM configuration. Hence, it has potential to be applied in a high- speed HEV.

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