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Performance Analysis of 12Slot with Various Rotor Pole Numbers HE-FSM for HEV Application

Khalidah Rahimi, Zarafi Ahmad, Erwan Sulaiman, Enwelum Mbadiwe I,
Syed Muhammad Naufal Syed Othman
Research Center for Applied Electromagnetics (EMCenter), Faculty of Electrical and Electronic Engineering,
Universiti Tun Hussein Onn Malaysia, Batu Pahat, Malaysia.

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ABSTRACT

This paper presents performance analysis of 12Slot with various rotor pole numbers Hybrid Excitation Flux Switching Machine (HEFSM) for Hybrid Electric Vehicles (HEVs) application. HEFSM has carried out by combining the advantage of Permanent Magnet (PM) machines and DC Field Excitation Coil (FEC) synchronous machines. Previously, most of HEFSM structure having FEC windings in theta direction that create a problem of flux cancellation that will affect the performances of the machine. Thus, a design of 12Slot HEFSM with FEC wounded in radial direction is proposed to eliminate the flux cancellation effect. At first, armature coil arrangement test at no-load condition is conducted to analyze PM flux. Furthermore, induced voltage and cogging torque at open circuit condition are investigated based on 2D finite element analysis (FEA). Finally, torque and power performances are also examined at maximum FEC and armature current densities. The outcomes demonstrate that 12S-14P configuration has the highest PM flux linkage, torque, power and less distortion of back-emf waveform which are required to be used as a motor in HEVs. The highest torque and power achieved are 220.15Nm and 92.45kW, respectively.

Corresponding Author:

Siti Khalidah Rahimi
Research Center for Applied Electromagnetics (EMCenter),
Department of Electrical Power Engineering,
Universiti Tun Hussein Onn Malaysia.
P.O Box.86400 Parit Raja, Batu Pahat, Malaysia.
Email: sitikhalidah17@gmail.com

1. INTRODUCTION

In recent days, an interest for vehicles using electrical propulsion drive is rapidly increased to prevent the global warming and to save fossil fuel. From here on, Hybrid Electric Vehicles (HEVs) have been popularized by several automotive company and mostly favor Interior Permanent Magnet Synchronous Motors (IPMSM) to be utilize as a main traction motor. Moreover, current technology tends to employ high-speed machine and reduction gear to increase motor output power density [1]. Although the IPMSM has the capability to deliver high torque with high efficiency, it also has several disadvantages which affect the performance of the machine. In stator part, the three-phase armature windings are wound in distributed, windings, resulting in high coil end length and copper loss. Besides, PM bridges at the rotor are exposed to have higher mechanical stress. Therefore, there is a tendency to increase the weak point when the number of bridges are increased. On the other hand, with high number of bridges leads to high flux leakage between the adjacent PMs that will affect the machine performances. In addition, complex structure of IPMSM causes difficulty to perform design optimization [2].

Therefore, flux switching machines (FSMs) have been known to overcome the previous problems in IPMSM. FSM becoming more popular and well known research topic due to their advantages such as rotor robustness, easy cooling system, high torque and high power density capability. The FSM was introduced by C. Pollock in 1999 as a new class of electrical motors that can be defined as combination of the switched reluctance motor (SRM) and the inductor alternator [3]. In general, FSM can be specified into three main flux source, a fully permanent magnet (PM) source, DC field excitation(FE) source, and combination of both PM DC-FEC source or known as hybrid excitation (HE) source as shown in Figure 1.

PM-FSM can be operated further than the base speed in the flux weakening region by means of controlling the armature winding current [4]. Furthermore, PM-FSM are convenient in cooling machine with robust structure since the armature coil and PM located at the same active region. Thus, PM-FSM are able to operate at higher speed region compared to existing conventional PM machines [5-7]. However, this type of machine has some disadvantages such as high copper loss, high PM volume, low efficiency and high potential irreversible demagnetization of the PMs. Another single main flux source machine is the FE-FSM and the construction cost is lower compared to PM-FSM. HE-FSM is develop by combining the use of PM machines and DC-FEC synchronous machines. Since HE-FSM used a hybrid excitation flux source, the machine has a potential to produce a higher torque output and power density, improve flux weakening performance, increase efficiency and more flux variable capability. It have been studied by most researcher broadly over a decade [8-13].

Figure 2 illustrates several HE-FSMs topologies that have been designed. Figure 2(a) illustrates a 6S-4P HE-FSM, where the armature coil, DC-FEC and PM arranged uniformly in three different circumference located at the stator. The first circumference or the inner layer located at the stator is the armature windings, FECs located at the middle layer while the PMs located at the outer layer of stator [14]. In this design, DC-FECs have long end winding and overlaps the armature windings are resulting in higher copper loss. FEC winding is introduced in order to reduce PM length with both stator and rotor laminations remain unchanged in Figure 2(b).

Meanwhile, 12S-10P HE-FSM with E-core stator has been developed as shown in Figure 2(c) [15]. DC-FECs are kept at the same diameter and placed at the middle teeth of E-core stator. In addition, the design has also no overlap winding between FECs and armature coils. The slot area divided into left and right which employed for the armature windings and the other side for the DC-FEC winding. Unlike previous design in Figure 2(c), the volume of magnet remains equivalent as the existing E-core PM-FSM [16]. Figure 2(d) shows the original 12S-10P HE-FSM as proposed and discussed in [17]. The proposed 12S-10P HE-FSM composed of 12 PMs and 12 FECs and each of them are uniformly distributed in the midst of each armature coil. PMs and FECs are arranged interval with six north poles intercepted with the six south pole. As illustrated in Figure 2(d), the 12 slots armature coils are arranged in the inner layer with overlapping the PM. Hence, flux generated by the magnetomotive force, mmf of the PMs and the FECs link with the armature coil alternately.

From the previous design of HE-FSM, the armature coil and FEC are arranged in theta direction and leads to a flux cancellation between PM flux and FEC flux. Based on previous topologies, a new design of HE-FSM is proposed with the arrangement of DC-FEC in radial direction to overcome flux cancellation. The comparison between theta direction and radial direction is depicts in Figure 3(a) and Figure 3(b), respectively [18]. Henceforth, design and performance analysis is carried out for several rotor pole numbers of HE-FSM with DC-FEC in radial polarity such as 12S-8P, 12S-10P, 12S-14P, and 12S-16P. Design methodology, parameter and restriction of the motor will be discussed in this paper. No-load analysis such as coil test, PM flux linkage, induced voltage, and cogging torque is examined. In addition, load analysis such as torque and power are also discussed.

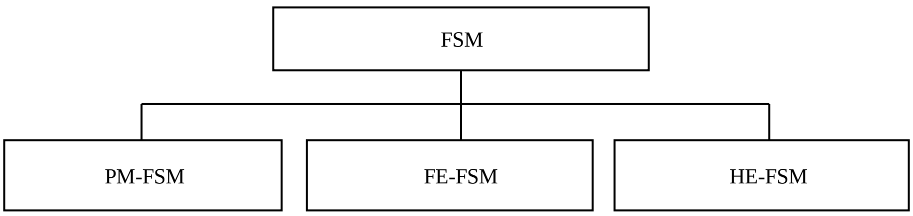
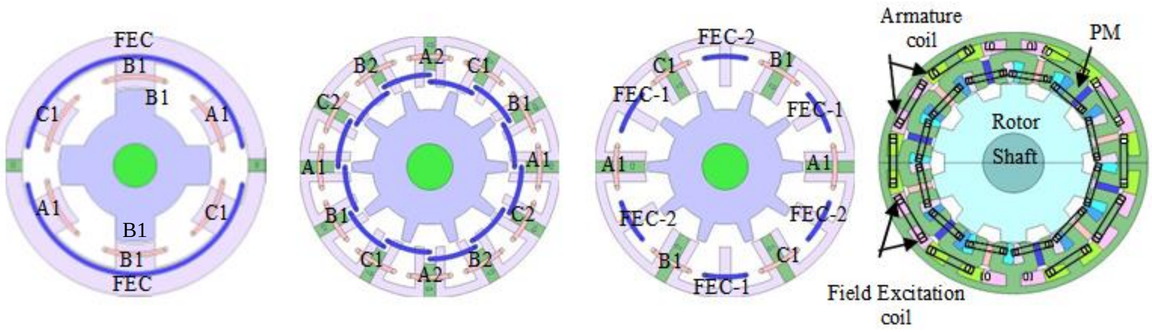
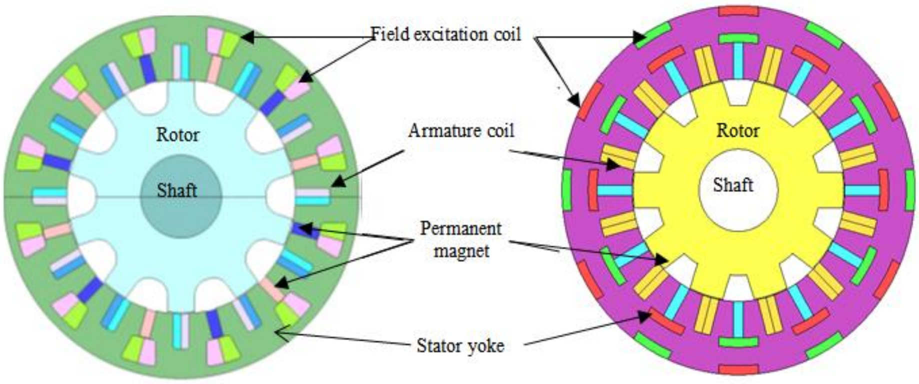


Figure 1. Three classes of FSM



(a) (b) (c) (d)

Figure 2. Several HEFSMs topology (a) 6S-4P (b) 12S-10P with separated C-core stator (c) 6S-10P E-core stator (d) 12S-10P HEFSM



(a) (b)

Figure 3. 12S-10P HE-FSM (a) theta direction (b) radial direction

2. RESEARCH METHOD

This section discusses the method use to design the proposed HEFSM using a 2-D Finite Element Analysis (FEA) software such as JMAG-Designer ver. 14.0. Besides, designing a new structure of various HE-FSM slot pole combination with FEC in radial direction, while considering the rotor pole width and mechanical angle, θ (°) is discussed.

2.1. Design Method and Specification

The design of the proposed HE-FSM implementation is specified into two steps, the geometry editor where drawing the stator, rotor, armature coil, PM and FEC takes place. It is then continued with JMAG-Designer where the condition setting and simulation are implemented. Generally, the proposed machine design can be categorised by two main parts which are the stator and rotor. The parameters involved for the rotor are the radius of rotor (P1), rotor pole length (P2), and rotor pole width (P3). For the stator part or known as active part will be occupied with the FEC slot, armature slot, and permanent magnet (PM). Parameter of PM length is represent by (P4), while the FEC parameters are FEC coil width and FEC coil height, (P5) and (P6) respectively. Subsequently, the armature coil parameters are the width (P7) and armature coil length (P8).

A maximum of 650V DC bus voltage and 360A of inverter current are set as electrical restrictions. It is assuming that a water cooling system is employed as the cooling system for the machine and current density for armature winding and FEC maximum is 30Arms/mm^2 and 30A/mm^2. General parameter such as outer machine diameter, the radius of shaft, the motor stack length, and the air gap width of the main part of the machine design being 269mm, 30mm, 84mm and 0.7mm, respectively. With this restrictions, the weight of the PM has been kept 1.3kg. Design parameter of the proposed design machine is shown in Figure 4.

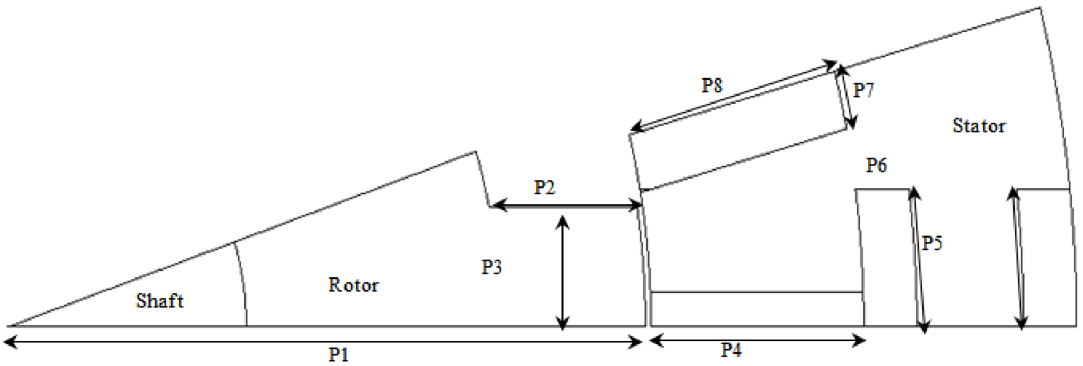


Figure 4. Design parameter defined as P1-P8

2.2. Design Structure of Proposed HE-FSM

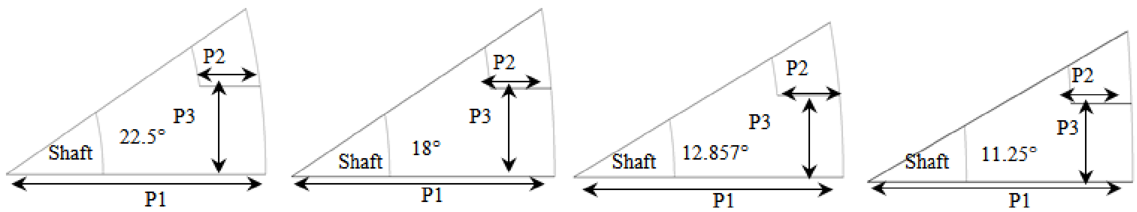
The impact of four different number of rotor pole with fixed number of stator pole of the proposed motor analysis is investigated to determine the best performances. Likewise, a possible rotor pole numbers can be defined as in (1)

$$N_r = N_s \left[1 \pm \frac{k}{2q}\right] \tag{1}$$

where N_r is the rotor pole number, N_s represent the number of slot, k is integer number from 1 to 5 and q is the phase. The 12Slot with 8, 10, 14 and 16Pole are selected for the further performance comparison. Table 1 shows design parameters of proposed HE-FSM. The initial rotor pole widths for 8, 10, 14 and 16 poles with 22.5°, 18º, 12.857° and 11.25° mechanical angle, respectively, are illustrated in Figure 5. Furthermore, a design of 12S-8P, 12S-10P, 12S-14P, 12S-16P HE-FSMs are shown in Figure 6. By using the same restriction and specification for all the proposed HE-FSMs, the performances are analyzed based on 2D-FEA for open circuit conditions which means no current supply in armature coil and also in load condition with maximum armature current (I_a) and DC-FEC current densities (I_e) of 30Arms/mm^2 and 30A/mm^2, respectively.

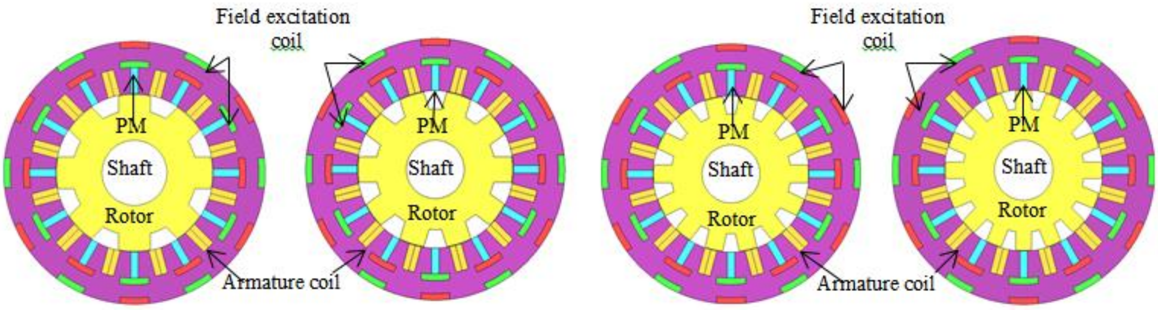
Table 1. Design parameter of various pole HE-FSM

Items	Dimensions			
Number of phase	3			
No.of slots	12			
No. of pole	8	10	14	16
Mechanical angle, θ (°)	22.5	18	12.86	11.25
Radius of rotor (mm) , P1	80.25			
Rotor pole length (mm), P2	20.2			
Rotor pole width (mm), P3	16.33	13.06	9.33	8.16
PM length (mm), P4	26.775			
FEC width (mm), P5	29.98			
FEC height (mm), P6	6.67			
Armature coil width (mm), P7	6.46			
Armature coil length (mm), P8	26.775			
No. of turns of armature coil, Na	7			
No. of turns of FEC, Ne	60			



(a) (b) (c) (d)

Figure 5. Initial design of the rotor (a) 8 pole (b) 10 pole (c) 14 pole (d)16 pole



(a) (b) (c) (d)

Figure 6. Various pole of HE-FSM (a) 12S-8P (b) 12S-10P (c) 12S-14P (d) 12S-16

3. RESULTS AND ANALYSIS

3.1. Coil Test Analysis

Initially, a coil tests are investigate at all twelve armature coils respectively. Under no-load condition, the current density of DC-FEC and armature coil is set to 0A/mm^2, with the PM volume remain fixed. First of all, flux linkage is examined in each armature coil slot at 1200r/min base speed. The flux source comes from the PM only while DC-FEC current is set at 0A [19]. After that, analyzing continue to determine the position of each armature coil phase. The resulting flux linkage at each armature coil is compared and the three phase armature coil is defined according to conventional 120° phase shifted between all phases.

The comparison of three-phase generated PM flux linkages under coil test analysis of 12S-8P, 12S-10P, 12S- 14Pole and 12S-16P of HE-FSM designs are depicted in Figure 7. Obviously, 12S-14P HE-FSM design has the highest magnitude of flux linkage amplitude of 0.0123Wb followed by 12S-10P design with 0.012Wb. Then by 12S-8P design with the flux of 0.035Wb, and the lowest magnetic flux among the design is 0.0094Wb observed from 12S-16P topology. It is observed that different rotor pole number provides different flux amplitude, because of the different rotor tooth width which is used for flux to flow to complete one electrical cycle. For 12S-14Pdesign, the rotor tooth width is nearly equal to the stator tooth width which the flux can flow easily in the machine. In addition, flux generation of both designs is due to partition of flux in all rotor teeth.

3.2. Induced Voltage and Cogging Torque at Open Cicuit Analysis

The induced voltage of the proposed HE-FSM is examined at the speed of 1200 r/min, which is in an open circuit condition. The results aquired at various conditions of Je are shown in Figure 8. From the figure, it is clear that the highest induced voltage generated from the flux of PM is only is 39.11V for 12S-16P topology, while the lowest amplitude achieved by 12S-10P design with induced voltage of 23.70V. Unfortunately, the sinusoidal waveform of induced voltage produced by all design has some distortion. For 12S-16P and 12S-8P designs, the sinusoidal waveform of induced voltage has too much distortion, which means this topologies has a problem to give a better performance of the machine. This problem occurs because the flux generated in both machine configurations hard to through their path. In contrast 12S-10P and 12S-14P design have less distortion compared to others.

Figure 9 shows the PM cogging torque for one electric cycle of all design machines. It is observed that 12S-8P and 12S-14P topologies produce only three cycles of cogging torque while 12S-10P and 12S-14P design generate six cycle of cogging torque. From the figure, the lowest peak to peak value of cogging torque is 8.4Nm produced by 12S-14P configuration due to lower and smooth back-emf as in Figure 8. While the 12S-16P design gives the highest cogging torque compared to other designs, which undesirable because the larger value of cogging torque is lead to produce high vibration and noise.

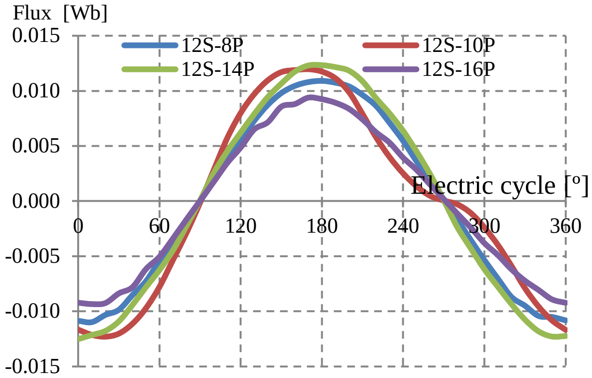


Figure 7. Three-phase generated PM flux linkages

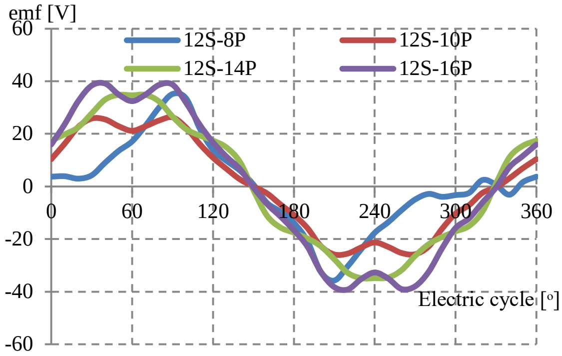


Figure 8. Induced voltage at various pole configurations

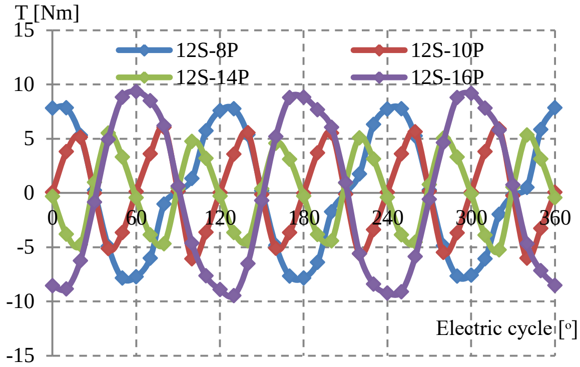
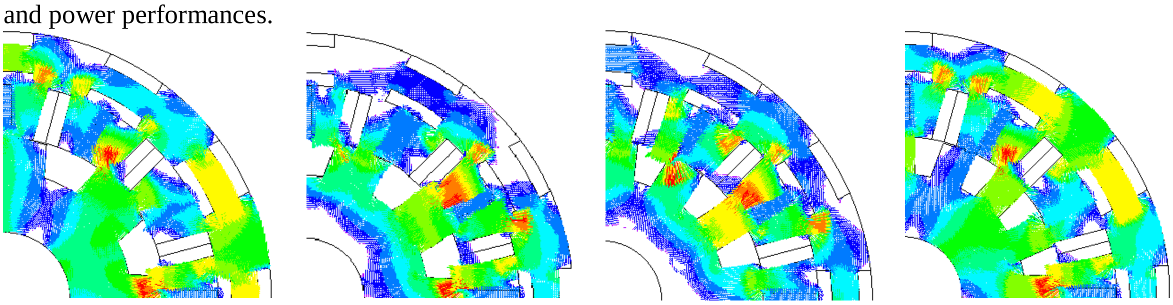


Figure 9. Cogging torque of the initial design at PM only

3.3. Flux Distribution at Maximum Current Densities

The flux distribution of initial design at open circuit condition is essential to take into consideration. This is because the flux distribution in each design will affect the performance of the machine [21]. The flux characteristics for 12S-8P, 12S-10P, 12S-14P and 12S-16P HE-FSMs are also investigated at maximum current densities of DC-FEC and armature , Ja as demonstrate in Figure 10. Form the figure, it shows that flux from the PM direction flows from stator to rotor and some flux flows around the DC-FEC pitch to form a total of 12 complete flux cycle. However, a large air gap results in higher air gap flux density, which lead to higher flux leakage and cancellation.

Furthernore, the region between the DC-FEC and armature coil slots have high flux density in stator part and affect flux saturation. Generally, the flux distribution patterns for all designs are increased with the increase in current density. Based on the figure, it clearly shows that the machine design of 12S-8P and 12S-16P design have much flux saturation which reduces the flux generation and hence reduce the torque and power performances.



(a) (b) (c) (d)

Figure 10. Flux Distribution at maximum Je, Ja various pole of HE-FSM (a) 12S-8P (b) 12S-10P (c) 12S-14P (d) 12S-16P

3.4. Torque and Power Performances

The performances of the machine at load condition, especially, torque and power when Je and Ja at maximum, 30A/mm^2 and 30Arms/mm2, respectively is important to analyze. Finally, the current density Je and Ja are set at maximum condition to analyze the torque performance and power outputis shown in Figure 11 and Figure 12, respectively. The highest performance of torque and power output is 220.15Nm and 92.45kW, respectively, are achieved for 12S-14P design, while 12S-8P design gives only 168.2Nm, which is lower than the other design but the power is more than design with 12S-16P configuration.

However, the torque performance will be degraded for 12S-8P and 12S-16P designs due to higher cogging torque. Based on analysis of magnetic flux density distribution as illustrated in Figure 10, it is found that the flux from Je cancels the armature coil flux and thus reducing the torque performances.

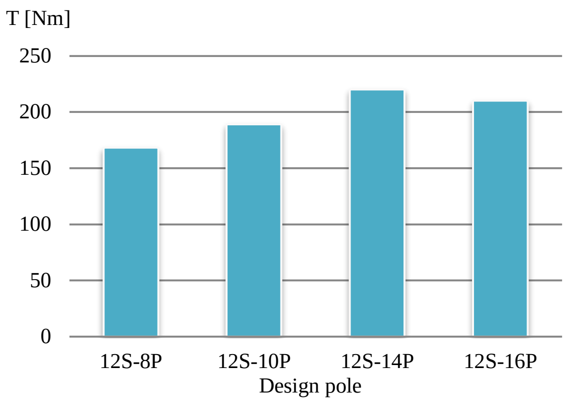


Figure 11. Maximum torque for various pole configurations

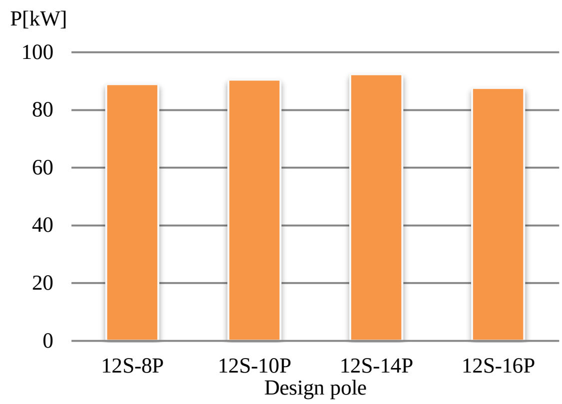


Figure 12. Maximum power for various pole configurations

4. CONCLUSION

In this paper, design studies and performance analysis of 12S- 8P, 12S-10P, 12S-14P, 12S-16P HE-FSMs for HEV application have been presented. To identify flux characteristics of each design, coil test analysis at no-load condition have been carried out. Several no-load analysis of the proposed motor such as induced voltage and cogging torque have also been investigated. The 2D-FEA carried out shows that the 12S-14P HE-FSM has highest torque and power performance of 220.15Nm and 92.45kW, respectively. From the result, 12S-14P HE-FSM with FEC in radial direction is the best configuration that can deliver high torque and power. Hence, it is potentially to be applied in a high- speed HEV.

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