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Initial Design Structure of E-Core HEFSM with Various Slot-Pole Combination for EV/HEVs

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***Abstract*—Research and developments on hybrid electric vehicle (HEV)which combined battery based electric motor and conventional internal combustion engine (ICE) have been intensively increased since the last decade due to their promising solution that can reduce green house effect and global warming. Several electric motors under serious consideration for HEV propulsion system at present are dc motor, induction motor (IM), interior permanent magnet synchronous motor (IPMSM) and switched reluctance motor (SRM). Although IPMSMs areconsidered to be one of the successful electric motor used in HEVs, several limitations such as distributed armature windings, un-control permanent magnet (PM) flux and higher rotor mechanical stress should be resolved. In this paper, design investigations of E-Core hybrid excitation flux switching motor (HEFSM) with various slot-pole combinations for hybrid electric vehicles (HEVs) applications are presented. With concentrated armature and field excitation coil (FEC) windings, variable flux capability and robust rotor structure, performances of 6S-4P, 6S-5P, 6S-7P and 6S-8P E-Core HEFSMssuch as flux lines, back-emf, cogging torque, flux distribution, instantaneous torque profile and torque versus speed characteristics are analyzed based on 2D Finite Element Analysis (2D-FEA). The initial design E-core HEFSM with 6S-8P topology has achieved the highest torque and power of 106.7Nm and 35.4kW, respectively.Further design improvements and optimizations will be conducted in future to increase their performances.**

Keywords—Hybrid Excitation Flux Switching Machine(HEFSM); Permanent Magnet (PM); Field-Excitation (FE)Coil; Hybrid Electric-Vehicle (HEV)

I. INTRODUCTION (*HEADING 1*)

An emphasis on green technology is greatly demanded of modern cities. The significant growth of today's cities has led to an increased use of transportation, resulting in increased urban pollution and other serious environmental problems that cause the greenhouse effect, which in turn leads to global warming. Gases produced by vehicle should be controlled and proactive measures should be taken to minimize these emissions [1-2]. In response to concern the environmental problem, Japan becomes the first country that commercialized hybrid electric vehicle in this world [3]. The automotive private industry such as Toyota and Honda has introduced hybrid cars, such as Toyota Prius and Honda Insight that minimize the use of combustion engines by integrating them with electric motors [4]. Such technology has a positive effect on the environment by reducing gas emission. The greatest challenge in research activities today is developing near zero-emission powered vehicles with optimum driving comfort. Electric vehicles powered by renewable energies offer a possible solution because they only emit natural byproducts and not exhaust fumes, which improve the air quality in cities and, thus the health of their populations [5]. In electrical machines, electric motors are used to transform one form of energy into another (electrical energy to mechanical energy). The main types of electric motors under serious consideration for HEVs and EVs at present are dc motor, induction motor (IM), permanent magnet synchronous motor (PMSM) and switched reluctance motor (SRM) [6-7]. Based on extensive review on up to date electric-propulsion systems, it is observed that investigations on cage IMs and PMSMs are highly dominant, whereas those on dc motors are decreasing but SRMs are gaining much interest [8-10].

Currently, an example of successfully developed electric motors for HEVs is interior permanent magnet synchronous motor (IPMSM) using rare-earth PM which has been employed mainly to increase the power density of the machines [11-13]. In spite of their good performances and well operated, IPMSMs installed in HEV, have some drawbacks such as (i) three-phase armature windings are wounded in the form of distributed windings which results in much copper loss and high coil end length (ii) mechanical stress of rotor depends on high number of PM bridges causes much flux leakage between PMs (iii) complex shape and structure which is are relatively difficult to perform design optimization (iv) constant flux from PM is difficult to control especially at light load high speed operating points [13-14]. In order to avoid such weakness, a new hybrid excitation flux switching motor (HEFSM) with concentrated armature windings, robust rotor structure suitable for high speed applications, much simpler shape, and controllability of PM flux by DC field excitation coil (FEC) is identified and selected as alternative candidate for HEV drive system [15-16]. In this paper, initial performances of 6S-4P, 6S-5P, 6S-7P and 6S-8P E-Core HEFSM in term of armature coil test, flux enhancing, flux distribution, flux linkage, torque profiles and power characteristics are analyzed and discussed.

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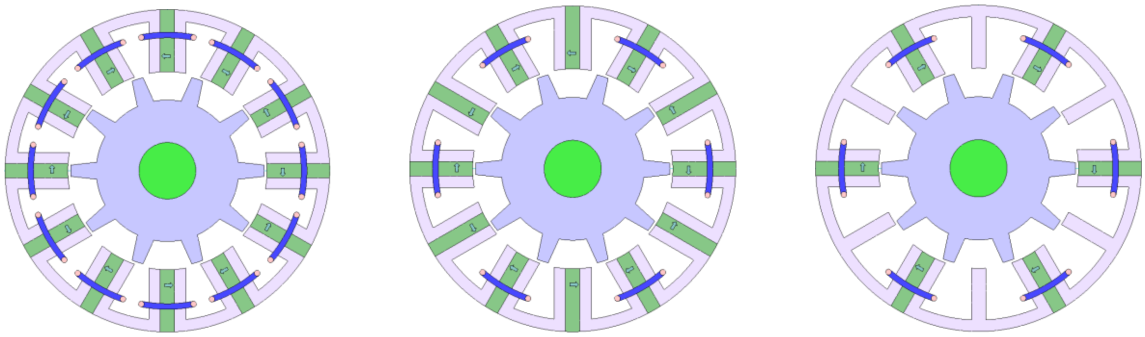

(a) (b) (c)

Fig. 1: Conventional and E-Core PMFSM (a) Conventional PMFSM with all pole wound. (b) Conventional PMFSM with alternative pole wound (c) E-Core PMFSM with alternate PM direction.

II. E-CORE HEFSMS TOPOLOGIES

HEFSMs are those which utilize primary excitation by PM as well as DC-FEC as secondary source. The goal behind using two excitation field sources is to combine advantages of PM excited machines and DC-FEC synchronous machines. DC-FEC is used to control excitation flux in the air-gap, which improves flux weakening capability. Hybrid excitation allows, by controlling excitation flux, the design of machines with a relatively low armature magnetic reaction and, at the same time, the extension of the speed operation range. Furthermore, it improves efficiency in the most frequently used operating zones of the traction motor. Machines with a relatively low armature magnetic reaction have better power factor, which implies a lower power rating for the power converters connected to them. Besides, hybrid excitation offers an additional degree of freedom and improves energy efficiency of the traction motors which have been researched extensively over many years [17].

The development of E-Core HEFSM starts with evolution of conventional 12S-10P permanent magnet flux switching machine (PMFSM) as shown in Fig. 1. In Fig. 1(a) the salient pole stator core consists of modular "U-shaped" laminated segments which are placed circumferentially between alternate polarities of magnetized PMs. The stator winding comprises concentrated armature coils wounded on a stator pole formed by two adjacent laminated segments and a magnet. As compared with conventional PM brushless machines [18], the slot area is reduced when the magnets are moved from the rotor to the stator, but when liquid cooling is employed, temperature rise of the magnets may be more easily managed since it is very difficult to dissipate the heat from rotor of conventional machine. PMFSM may have all poles wound or alternate poles wound as depicted in Fig. 1(a) and (b), respectively. It is obvious that in an alternate pole wound, the torque reduces considerably when PM in stator poles without coils are eliminated. In order to reduce the PM usage and, consequently, the cost, the stator poles without coils are replaced by corresponding stator teeth. However since the PM in the stator poles which carry coils are magnetized in the same direction, their magnetic field is "short circuited" via the stator back-yoke. Consequently, the circumferentially magnetized magnets of alternate polarity are employed as illustrates in **Fig. 1(c)**, which is designated as E-core PMFSM due to laminated "E-shape" segments employed in the stator. In contrast with conventional all pole wound PMFSM, the E-core PMFSM has the same rotor structure, less number of stator poles and half volume of PM. The magnet and its two adjacent stator teeth are defined as one stator pole [18-19].

A new structure of 6S-10P E-Core HEFSM is designed by employing additional DC-FEC on the middle stator teeth of the E-Core PMFSM with no magnet as shown in **Fig. 2**[10]. It sustains equivalent outer diameter as the corresponding E-Core PMFSM and exhibits a simpler 2D structure when compared with hybrid-excited PM machine developed from the conventional PMFSM. Since it also employs non overlap between DC-FEC and armature windings, the number of turns per phase of the E-Core HEFSM is maintained similar as that of the E-Core PMFSM. Moreover, the slot area in this machine is divided into two partitions, each for armature coil and DC-FEC windings, respectively. The total number of armature winding turns is equal to that of DC-FEC winding turns to ease the comparison of armature and field currents, because the slot areas for these two kinds of windings are equivalent. It is worth mentioning that, unlike the HEFSM developed from conventional PMFSM [20], the magnet field excited in the designed E-Core HEFSM remains similar as that in the conventional E-Core PMFSM. With additional DC-FEC employs in the designed motor, variable flux control capability can easily be applied to the E-Core HEFSM for various performances when compared with constant flux of PM in PMFSM.

III. OPERATING PRINCIPLE OF E-CORE HEFSM

The operating principle of E-Core HEFSM is similar with conventional flux switching machine (FSM) in which the flux

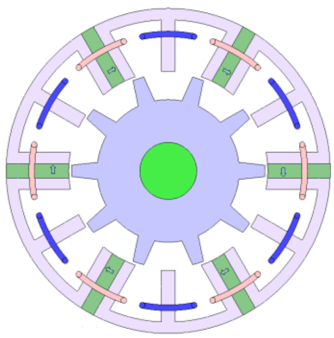

Fig. 2: E-Core HEFSM

flows from the stator to the rotor switches its polarity following the rotation of rotor. At one instant, half of rotor poles receive the flux from the stator while another half of rotor poles bring the flux to the stator to make a complete flux cycle. The operating principle and definition of flux switching can be described either by changing flux in the stator or changing flux in the rotor. Fig. 3 illustrates the operating principle of E-Core HEFSM in three different conditions. In Fig. 3(a), both fluxes of PM and DC-FEC flow from stator to rotor pole P2 and return back to the stator by rotor pole P1. At this stage, it is obvious that rotor pole P2 received the flux from stator. Meanwhile, in Fig. 3(b), when the rotor moves to the left side approximately half electric cycles, both fluxes from stator flow to rotor pole P3 in between DC-FEC winding of right side. It is clear that the stator flux switches its polarity through rotor pole P3 as receiving flux while rotor pole P2 brings the flux back to the stator to form a complete flux cycle. Finally, Fig. 3(c) depicts the condition where rotor pole P3 is in similar condition of rotor pole P2 in Fig. 3(a) to form one electric cycle. The flux from stator flows through stator teeth between PM and armature coil to rotor pole P3 while rotor pole P2 brings the flux to the stator, simultaneously. Since the direction of both PM and FEC fluxes are in the same polarity, both fluxes are combined and move together into the rotor, hence producing more fluxes with a so

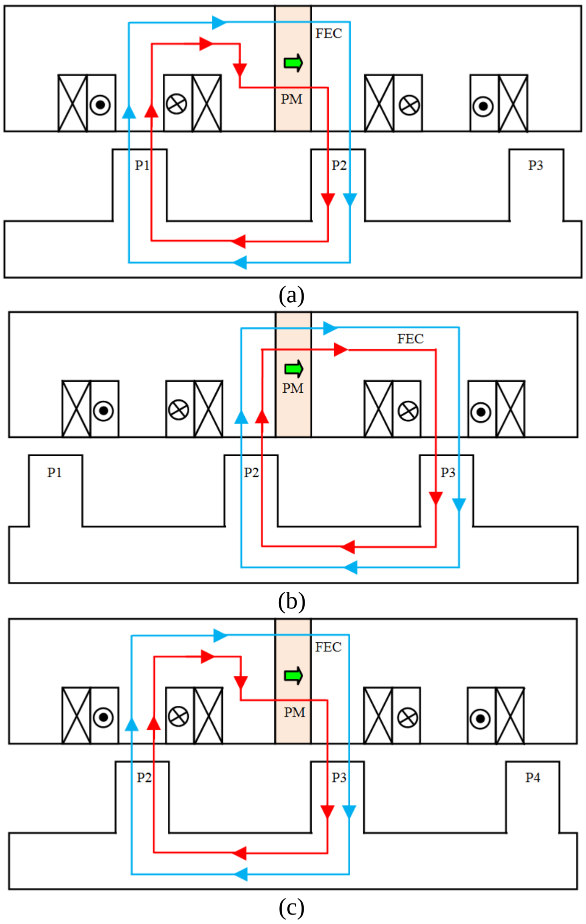

Fig. 3: Principle operation of E-Core HEFSM (a) flux from stator via P2 and P1 (b) flux from stator via P3 and P2 (c) flux from stator via P3 and P2 for one electric cycle

called hybrid excitation flux [21-23].

IV. Design Restriction and Specification

In this paper, design study and flux interaction analysis between DC-FEC and armature coil of 6S-4P, 6S-5P, 6S-7P and 6S-8P E-Core HEFSM are investigated. The main geometrical dimensions of the designed E-Core HEFSM are identical with IPMSM used in conventional HEV in which the stator outer diameter and stack length are set to 132mm and 70mm, respectively. Fig. 4 shows the motor with initial dimension of main machine parts including air gap, stator outer and inner diameter, rotor outer and inner diameter and shaft diameter. The design restrictions and target specifications of the E-Core HEFSM are listed in Table 1 including the available and estimated specifications of the E-Core HEFSM for the same characteristic with IPMSM used HEV [9]. The electrical restrictions related with the inverter such as maximum 650V DC bus voltage and maximum 360V inverter current are set to be much severe. Assuming that only a water-jacket system is employed as the cooling system of the machine, the limit of the current density is set to $30A_{rms}/mm^2$and $30A/mm^2$for both armature winding and DC-FEC respectively. In addition, the weight of PM is limited to maximum of 1kg where Neomax35AH having coercive force at 20°C and residual flux density of 932kA/m and 1.2T, respectively is used as PM material while the electrical steel 35H210 is used for the stator and rotor body. The rotor structure is mechanically robust to rotate at high speed because it consists of only stacked electromagnetic sheets and hence, it is highly possible to elevate the target maximum operating speed up to 12,400r/min while keeping enough rotor mechanical strength. The target maximum torque and power are 333Nm and 123KW respectively, determined from a realization of comparable with the present IPMSM.

The relationship between the number of rotor pole and stator slot for the three phase structure are used to find the attainable numbers of slot and pole that can be express as:

$$n_r = n_s\left(1 \pm \frac{k}{2q}\right) \tag{1}$$

where n_r is the rotor poles number, n_s is the stator slot number, q is the number of phases and k is the natural entity. In this study,

TABLE 1. E-Core HEFSM design specifications and limitations

Items	IPMSM	HESFM
Maximum DC voltage (V)	650	650
Maximum current (A_{rms})	360	360
Maximum J_a (A_{rms}/mm^2)[a]	31	30
Maximum J_e (A/mm^2)[b]	NA	30
Stator diameter (mm)	264	264
Machine length (mm)	70	70
Diameter of shaft (mm)	60	60
Air-gap (mm)	0.8	0.8
PMvolume (kg)	1.1	<1.0
Max. speed (r/min)	12,400	12,400
Max. torque (Nm)	333	>333
Max. power (kW)	123	> 123
Power density (kW/kg)	3.5	> 3.5

J_a is current density in armature coil
J_e is current density in FE Coil

the selected number of stator and rotor slot is 6 and 4, 5, 7 and 8 correspondingly. In this proposed motor, the motor rotation through $1/n_r$ of a revolution, the flux linkage of armature has one periodic cycle and thus, the frequency of back-emf induced in the armature coil is n_r times of the mechanical rotational frequency.

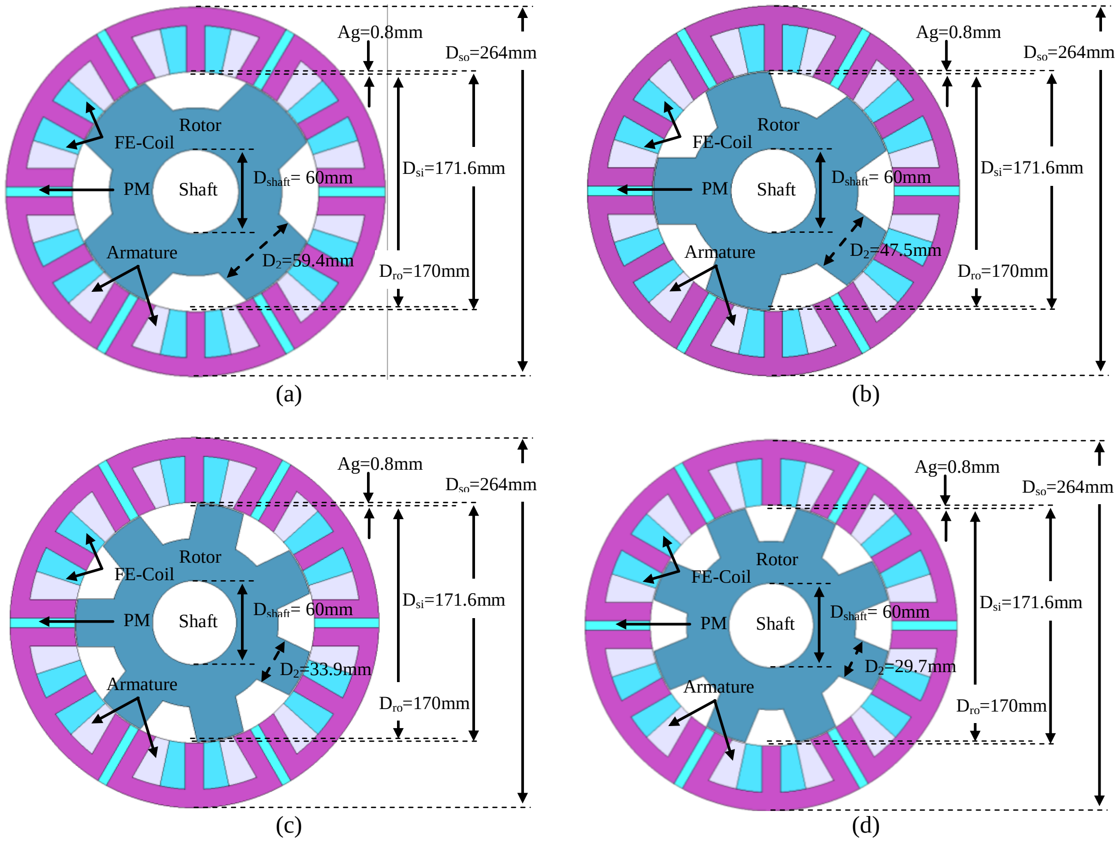

Fig. 4. Main machine dimension of proposed E-Core HEFSM (a) 6S-4P (b) 6S-5P (c) 6S-7P (d) 6S-8P

In general, the mechanical rotation frequency, f_m and the electrical frequency, f_e for the designed motor can be expressed as:

$$f_e = n_r f_m \tag{2}$$

where f_e, n_r and f_m is the is the electrical frequency, number of rotor poles and mechanical rotation frequency, respectively. The number of turns of armature coil and DC-FEC are defined from Equation 3 and 4, respectively while the filling factor of the motor, α is set at 0.5.

$$N_a = \frac{J_a \alpha S_a}{I_a} \tag{3}$$

$$N_e = \frac{J_e \alpha S_e}{I_e} \tag{4}$$

where *N*, *J*, α, *S* and *I* are number of turns, current density, filling factor, slot area and input current, respectively while the subscript "a" and "e" represent armature coil and DC-FEC, correspondingly. To ensure flux flow from stator to rotor equally without any flux leakage, the rotor teeth width of all designed E-Core HEFSMs is defined as:

$$\sum \text{Stator Tooth Width} = \sum \text{Rotor Tooth Width} \tag{5}$$

Basically, the design parameters of E-Core HEFSM are separated into two groups such as those related to rotor and stator structure. There are three groups that consist on the stator core design, such as the DC-FEC slot shape, armature slot shape, and PM. The rotor parameters consist of outer rotor radius (D1), rotor pole depth (D2) and rotor pole width angle (D3). PM width (D4) and the PM height (D5) are included in PM slot shape parameters while for the armature slot parameters consist of armature height and width, (D6) and (D7) correspondingly. Lastly, the DC-FEC parameters are DC-FEC height (D8) and DC-FEC width (D9).

V. Performances Prediction of Initial E-Core HEFSM Based on 2D-FEA

The performance predictions of the designed E-Core HEFSMs are conducted using commercial 2D-FEA package, JMAG-Studio ver.13.0, released by Japanese Research Institute. Primarily, the rotor, stator, armature coil, DC-FEC and PM of the proposed 6S-4P, 6S-5P, 6S-7P and 6S-8P E-Core HEFSMs are sketched in Geometry-Editor. Then, the area of armature coil, S_a and the area of DC-FEC, S_e are used to calculate optimum natural number of turns of armature coil, N_a and DC-FEC, N_e, respectively. Besides, the materials, conditions, circuits and properties of the machine are set in JMAG-Designer. Moreover, performance characteristics in open circuit and load conditions such as coil arrangement test, hybrid excited flux characteristics, induced voltage generated by PM, flux linkage, flux distribution, torque and power at various speed are analyzed in this design

A. Flux Path and Flux Linkage of PM at Open Circuit Condition, Back-emf and Cogging Torque

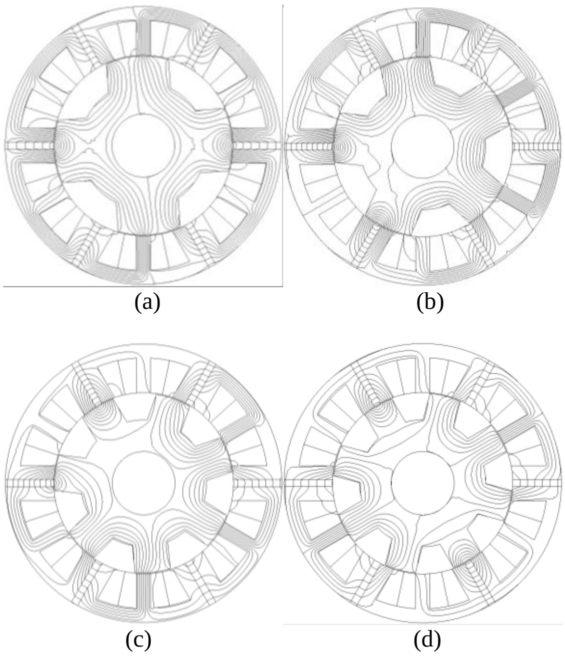

Fig. 5. Flux lines of various slot-pole combinations (a) 6S-4P (b) 6S-5P (c) 6S-7P (d) 6S-8P

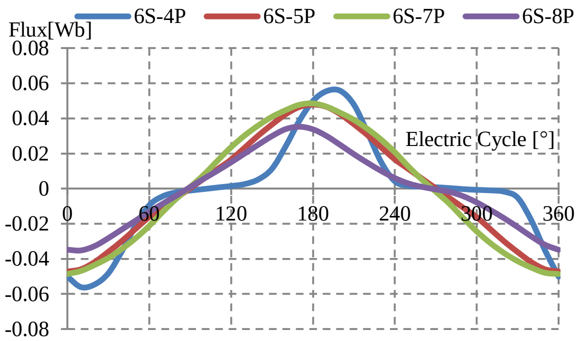

Fig. 6. Flux linkage of PM for each slot-pole combination

Under open circuit condition, the flux paths and flux distributions of PM only for 6S-4P, 6S-5P, 6S-7P and 6S-8P E-Core HEFSMs at zero degree rotor positionare compared as illustrated in Fig. 5 and Fig. 6, respectively. From Fig. 5, all flux lines flow from stator to rotor and return through adjacent rotor teeth to make a complete six flux cycles of PM in each design. In addition, most of the generated fluxes are distributed uniformly around the stator and rotor poles with average flux density of 2.8T. However, the fluxes generated are slightly saturated at rotor air gap and stator outer yoke with maximum magnetic flux density of approximately 3Tesla. Thus, from design point of view, the rotor air gap can be reduced to decrease the flux leakage, while the stator outer yoke width can be increased to reduce the flux saturation.

The generated PM flux linkages under coil test analysis are also compared as depicted in Fig. 6 for all designs. It is noticeable that 6S-4P design has the highest magnetic flux amplitude of 0.056Wb, while 6S-5P and 6S-7P designs have similar flux characteristics with flux amplitude of approximately 0.049Wb, and 6S-8P design has the lowest magnetic flux with approximately half of 6S-4P design. It is observed that increasing the rotor pole number results in low flux generation due to separation of flux in all rotor teeth. In addition, the flux characteristics of 6S-4P and 6S-8P designs are much distorted when compared with 6S-5P and 6S-7P designs due to fairly significant difference between slot-pole

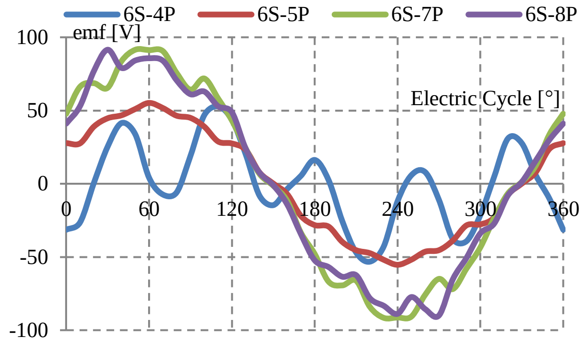

Fig. 7. Back-emf at various rotor pole configurations

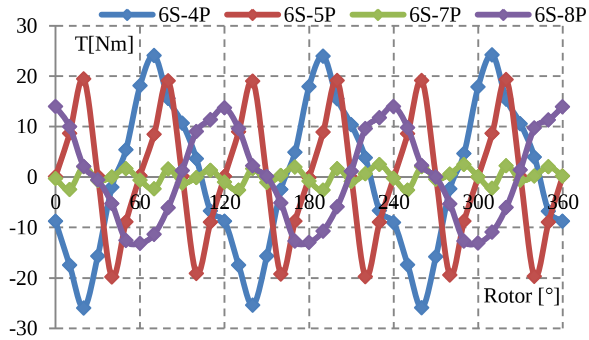

Fig. 8. Cogging torque of the initial design

combinations.

Fig. 7 and Fig.8 illustrate the comparisons of no-load induced voltage and cogging torque of all E-Core HEFSMs design, respectively where the induced voltage with J_e of 0A/mm^{2}represents the voltage generated due to PM flux only. At the speed of 1200r/min, the highest induced voltage amplitude of 91.58V is achieved for 6S-8P design, while the lowest induced voltage amplitude of 52.87V is achieved for 6S-4P design. It is noticeable that most of the induced voltage waveforms are distorted with large amount of cogging torque pulsation due to the fifth harmonic order that occurs in the initial flux itself. From Fig. 8, less amount of cogging torque with approximately 4Nm peak-to-peak for 6S-7P is produced due to slightly sinusoidal back-emf compared to other number of rotors. Since the peak-peak torque generated should generally not exceed 10% from the average torque to avoid high vibration and noise, further design refinement should be conducted to get the best performance of the machine.

B. DC-FEC and PM with DC-FEC Flux Linkages at various Je

The DC-FEC flux characteristics at various DC-FEC current densities, J_e for 6S-4P, 6S-5P, 6S-7P and 6S-8P E-Core HEFSMs are also investigated as illustrated in Fig. 9. From the plot, it is clear that initially the flux patterns for 6S-4P, 6S-5P and 6S-8P designs are increased with the increase in current density until J_e of 10A/mm^2. However, the flux generated starts to reduce when higher J_e is injected to the system. For all design configuration, flux linkage become constant at J_e of 25A/mm^2 due to saturation effect as clearly demonstrated in the plot. Furthermore, the flux linkage

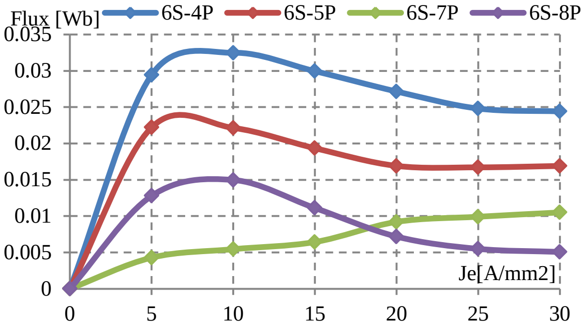

Fig. 9. DC-FEC flux linkage at various J_e

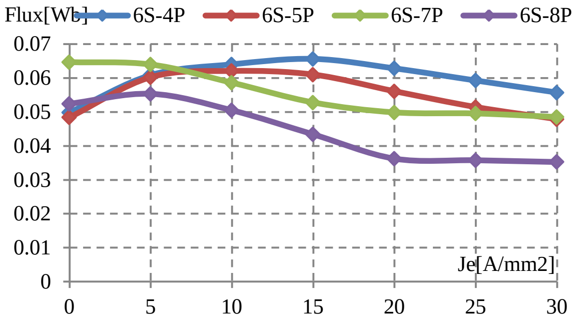

Fig. 10. PM and DC-FEC flux linkage at various J_e

combinations of both PM and DC-FEC at various DC-FEC current densities are also investigated as shown in Fig. 10. From the plot, 6S-4P and 6S-5P designs give similar flux characteristics in which the fluxes keep increasing until J_e of 15A/mm^2 and start to reduce when higher J_e is injected. In addition, at J_e of 0A/mm^2, although the flux generated from 6S-7P and 6S-8P designs are higher than 6S-4P and 6S-5P designs, it is evident that flux from DC-FEC cancelled all the PM flux and become saturated at J_e of 20A/mm^2.

C. Torque vs Je Characteristics at max. Ja

The torques characteristic at different J_e values is plotted in Fig. 11. From the graph, it is clear that higher J_e values at maximum J_a will enhance the torque for 6S-4P and 6S-5P designed. The graphs obviously illustrate that 6S-7P and 6S-8P give similar torque characteristic. The maximum torque of

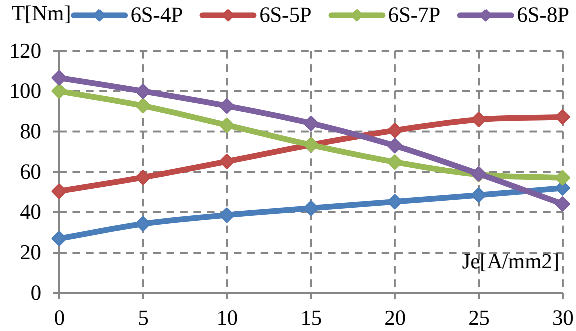

Fig. 11. Torque versus J_e at Max J_a

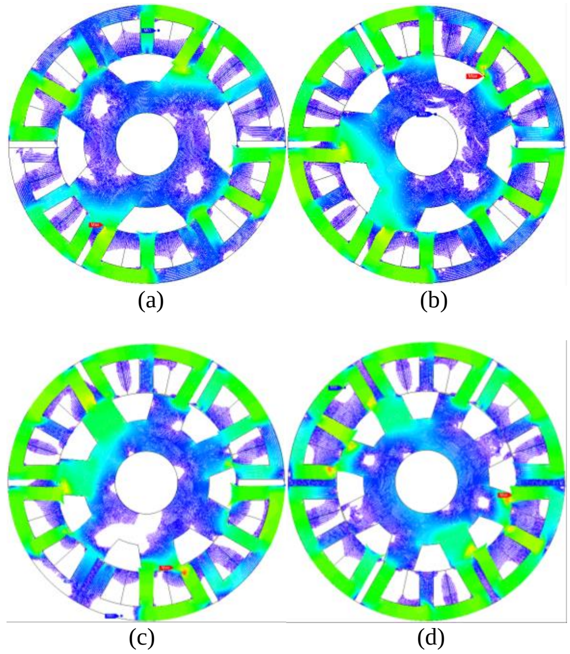

Fig. 12. Flux distribution of various slot-pole combination (a) 6S-4P (b) 6S-5P (c) 6S-7P (d) 6S-8P

106.65Nmfrom 6S-8P is achieved when J_a is set to 30A/mm^2 followed by 6S-7P with torque value of 100Nm. For both designs, when DC-FEC current density employed to the system, torque are automatically reduced. Based on examination of magnetic flux density distribution, it is found that, flux from J_e cancels the armature flux thus reducing the torque generation. From the plot, for design of 6S-4P and 6S-5P at J_a of 5A$_{rms}$/mm^2 until 30 A$_{rms}$/mm^2 it is noticeable that the average torque is increased with increasing J_e. The investigation of short circuit field distribution based on 2D-FEA for PM with maximum DC-FEC at maximum J_a of the initial design 6S-4P, 6S-5P, 6S-7P and 6S-8P E-Core HEFSMs are illustrated in Fig. 12 in which most the flux leak to the surrounding area in case of 6S-4P.

D. Torque vs Speed Characteristics

The torque versus speed curves of each E-Core HEFSM topology is plotted in Fig.13. It is clear that 6S-8P design has the highest maximum torque of 106.65Nm at based speed of 3171r/min, while the lowest torque characteristic of 52.22Nm at based speed 8103r/min is achieved for 6S-4P design. Since

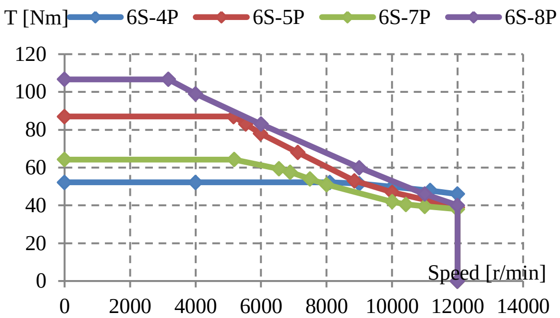

Fig. 13: Torque versus speed characteristics

TABLE II. PERFORMANCE COMPARISONS OF E-CORE HEFSMS

Items	6S-4P	6S-5P	6S-7P	6S-8P
Max. Speed (r/min)	12000	12000	12000	12000
Max. Torque (Nm)	52.22	87	64.27	106.65
Machine weight (kg)	27.7	27.66	27.63	27.62
Power (kW)	62.1	47	47.72	56.55
Torque density (Nm/kg)	1.885	3.145	2.326	3.861
Power density (kW/kg)	2.242	1.7	1.727	2.047

the initial torque in this initial design are far from the target performances of HEV, design optimization based on deterministic optimization method will be conducted in future. The performance comparisons of all design E-Core HEFSM are listed in Table 2.

VI. CONCLUSION

Design viability studies and performance investigation of 6S-4P, 6S-5P, 6S-7P and 6S-8P E-Core HEFSMs topologies are presented in this paper. The operating principle of DC-FEC, PM and armature windings placed on the stator has been analyzed for HEV applications. The performances of the E-Core HEFSM such as flux capability, torque and power versus speed curve have been examined. To prove the operating principle and to validate each coil phase, the coil arrangement test for this design has been examined. The machine has the advantages of easy manufacturing, low cost and copper loss due to less volume of PM and less FEC respectively. Finally, the proposed E-Core HEFSM is suitable for various applications with various performances.

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