A Novel Hybrid Excited Flux-Switching Brushless AC Machines for EV/HEV Applications

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Abstract-**A novel E-core hybrid excited flux-switching PM (FSPM) brushless machine is proposed based on an E-core FSPM machine which has significantly less magnet and higher torque density than those of a conventional FSPM machine. The proposed machine has a simple structure. The main flux path of DC excitation does not affect the magnet excitation since it is not through the magnets. The combination of the stator and rotor pole numbers of proposed machine is optimized, and the flux enhancing and weakening capabilities are investigated by 2-D finite element analyses.**

I. INTRODUCTION

In order to easily adjust the main flux, which is fixed in permanent magnet (PM) machines, hybrid excited machines were developed to improve the starting/low speed torque and high speed flux-weakening capabilities which are required for electric vehicle (EV) and hybrid EV (HEV) applications [1]-[3]. Since hybrid excited machines with the excitation coils on the rotor require slip-rings to supply the DC excitation current [4], the machines with the excitation coils on the stator are much more convenient. However, the conventional hybrid excited machines, such as consequent pole topology [5], have a complicated 3-D structure, and, therefore, are difficult to analyze and manufacture.

The PM machines having magnets on the stator were investigated recently and the corresponding hybrid excited PM machines were introduced and analyzed. By way of example, the hybrid excited doubly-salient PM machine was proposed in [6], [7], Fig. 1(a). However, in addition to its inherent relatively low torque density, it has long end winding for the field windings which over-lap with the armature windings.

As another kind of machine having magnets on the stator, a flux-switching PM (FSPM) machine [8], [9] exhibits similar torque density to that of a fractional-slot PM machine with non-overlapping windings [10], which is much higher than that of the double-salient PM machine [11]. Hence, the hybrid excited FSPM machine employing non-overlapping field and armature windings was proposed in [12], Fig. 1(b). However, the outer diameter of the machine is significantly enlarged for the field winding, which significantly reduces the torque density. In addition, the magnets in the FSPM machine can be partially replaced by the DC excitation windings and consequently several hybrid excited topologies were developed [13], [14], although they have overlapping armature and field windings, albeit with significantly reduce torque capability.

The foregoing hybrid excited machines having magnets on the stator also suffer from one of the following demerits.

- The DC excitation field is in series with the field excited by magnets, which limits the flux adjusting capability due to low permeability of magnets, Fig. 1(a);
- The flux path of DC excitation significantly reduces the main flux excited by magnets and even short-circuits the magnet flux, Fig. 1(b);
- The torque density may be significantly reduced.

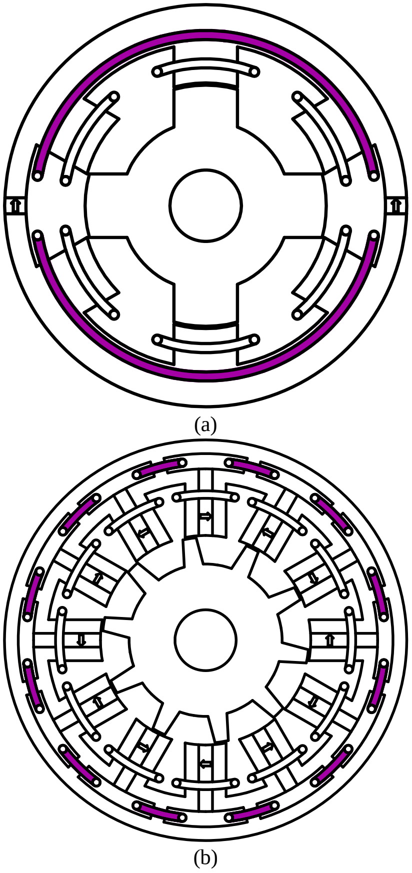
(a)

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Fig. 1. Existing hybrid excited machines having magnets on stator. (a) Doubly-salient machine. (b) Flux-switching machine.

Therefore, this paper proposes a new hybrid excited FSPM machine to eliminate the foregoing disadvantages. It employs non-overlapping field and armature windings and also exhibits a simple structure. In the paper, the conventional FSPM machine is firstly presented, and its magnet material is halved while the torque density is improved in a developed E-core FSPM machine [15]. From the E-core FSPM machine, the proposed hybrid excited FSPM machine is developed in Section III. The combination of stator and rotor pole numbers

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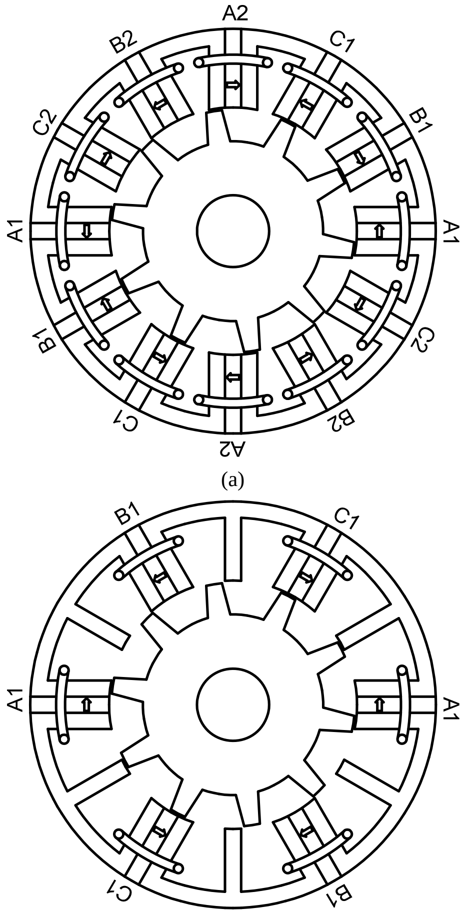
of the E-core hybrid excited FSPM machine is optimized and its electromagnetic performance is predicted by 2-D finite element (FE) analyses.

II. CONVENTIONAL AND E-CORE FSPM MACHINES

As compared in Fig. 2, the stator cores of the conventional and E-core FSPM machines comprise of laminated “U”- and “E”-shaped segments between which are sandwiched circumferentially magnetised magnets of alternate polarity, respectively. They have the same rotor which is similar to that of a switched reluctance machine. The number of stator poles in the E-core machine is half of that in the conventional machine, and hence the E-core machine exhibits significantly lower magnet usage. Fig. 3 shows the open-circuit field distribution of the E-core machine. The flux-linkage in Coil A1 varies from zero to maximum value when the rotor rotates a quarter of rotor pole-pitch, viz. from Figs. 3(a) to (b), and then the back-emf is induced.

The conventional and E-core machines were optimized respectively [15] and their design parameters are compared in the appendix. Both machines have the same stator outer diameter, active axial length, and the number of turns per phase due to similar slot area. Fig. 4 compares the 2-D FE predicted torque-current characteristics, and the E-core machine exhibits ~15% higher torque than that of the conventional machine at rated current.



(a)

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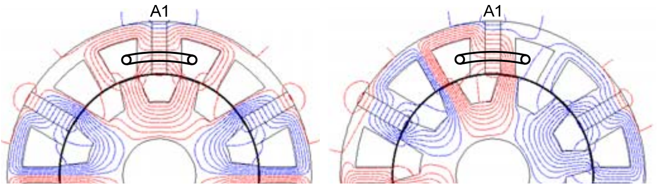
Fig. 2. Conventional and E-core FSPM machines. (a) 12/10 stator/rotor pole conventional machine. (b) 6/10 stator/rotor pole E-core machine.



(a) (b)

Fig. 3. Open-circuit field distribution of E-core FSPM machine. (a) Zero flux-linkage of coil A1, q-axis rotor position. (b) Positive maximum flux-linkage of coil A1, d-axis rotor position.

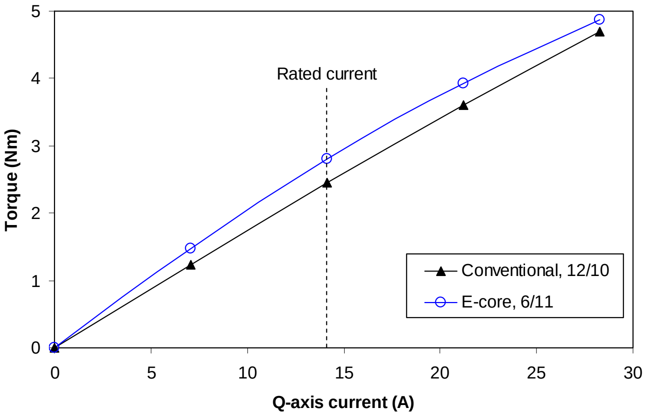


Fig. 4. Comparison of torque-current characteristics of optimized conventional and E-core FSPM machines.

III. PROPOSED E-CORE HYBRID EXCITED FSPM MACHINES

Since the E-core machine exhibits high torque density, a hybrid excited FSPM machine is proposed based on the E-core FSPM machine by employing DC excitation coils on the middle teeth of stator E-core which have no magnet, Fig. 5. It maintains the same outer diameter as the corresponding E-core machine and exhibits simpler 2-D structure than the hybrid excited PM machine developed from the conventional FSPM machine, Fig. 1(b). It also employs non-overlapping field and armature windings.

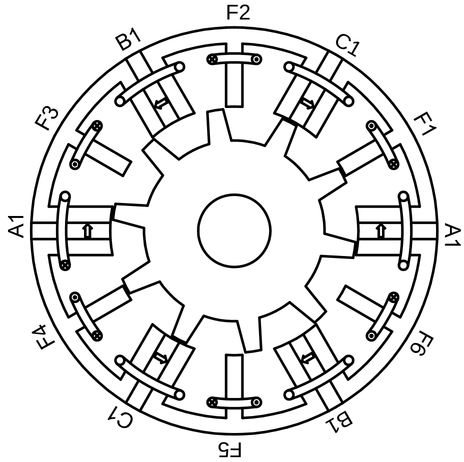


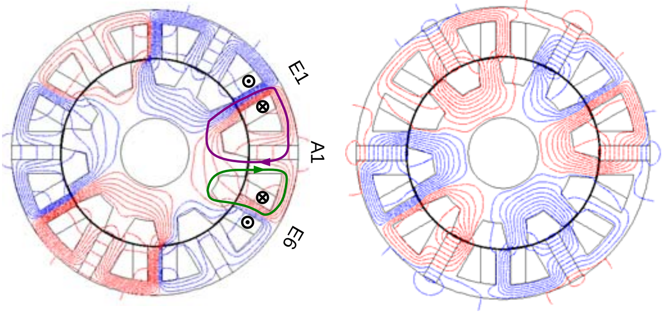
Fig. 5. Schematic of proposed E-core hybrid excited FSPM machine.

Since the E-core FSPM machines are optimized, the optimized parameters are employed for the E-core hybrid excited FSPM machine, the only difference being the DC excitation coils which are now employed. The number of turns per phase of the hybrid excited machine is maintained the same as that of the E-core machine. Half of the slot area is employed for the armature windings and another half is employed for the DC excitation windings. The total number of armature winding turns equals to that of DC excitation winding turns to ease the comparison of armature and field currents, since the slot area for these two kinds of windings are equal. The ratio of field to armature slot areas will be optimized later. Fig. 5 also shows the winding connections and the magnetization directions of magnets. It is worthy to mention that, unlikely the hybrid excited machines developed from the conventional FSPM machine [12] [13] [14], the magnet excited field in the E-core hybrid excited machine maintains the same as that in the conventional E-core FSPM machine.

A. *Combinations of Stator and Rotor Pole Numbers*

In order to obtain the optimized combination of stator and rotor pole numbers, the 10-, 11-, 13-, and 14-rotor pole and 6-stator pole E-core hybrid excited FSPM machines are investigated, since it is found that the optimized rotor pole number is close to twice of the stator pole numbers in the E-core machine [15]. The open-circuit field distributions of the machines excited only by the DC excitation current I_e or by magnets are shown in Fig. 6. The flux in coil A1 excited by the DC excitation current is significantly small relative to the total flux excited by the DC currents, especially in the 6/10 and 6/11 stator/rotor pole machines. It is mainly due to the flux-linkage of coil A1 excited by coils E1 and E6 being opposite. However, the permeance for excitation coil E6 in the 6/10 and 6/11 stator/rotor pole machines are much smaller than those in the 6/13 and 6/14 stator/rotor pole machines in which the rotor pole is almost aligned with coil E6 when the rotor is at d-axis. Hence, the 6/13 and 6/14 stator/rotor pole machines exhibit larger flux-linkage and back-emf excited only by the DC excitation currents than those of the 6/10 and 6/11 stator/rotor pole machine, Fig. 7. All the machines exhibit bipolar flux-linkage waveforms. It should be noted that the main flux excited by coil E6 is not through the magnets, while it is through magnets in existing hybrid excited machines, such as that shown in Fig. 1(a). In addition, the 6/10 and 6/14 stator/rotor pole machines have asymmetric back-emf waveforms, viz. with even order harmonics, while the back-emf waveform is symmetrical in the 6/11 and 6/13 stator/rotor pole machines. The 6/13 stator/rotor pole machine also exhibits the lowest harmonic contents relative to the fundament back-emf.

(I) I_e=30A, unmagnetized magnets **(II) I_e=0, magnetized magnets**



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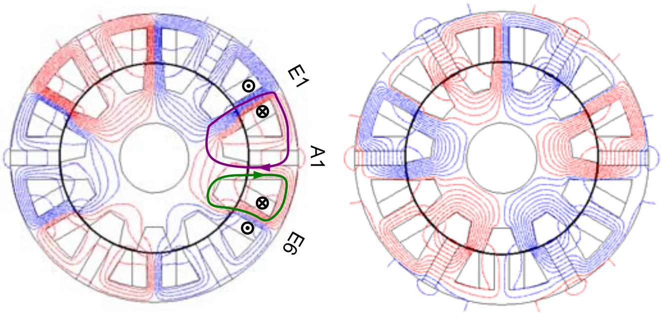

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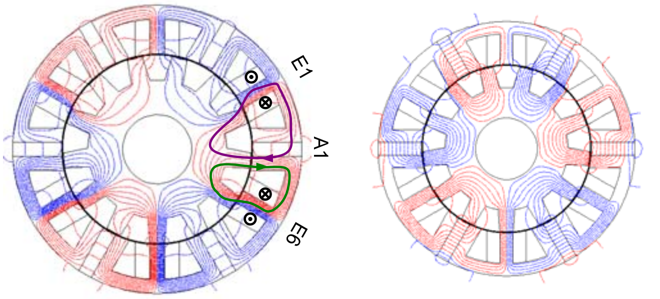

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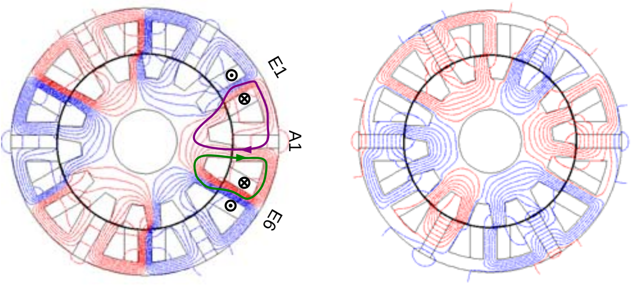
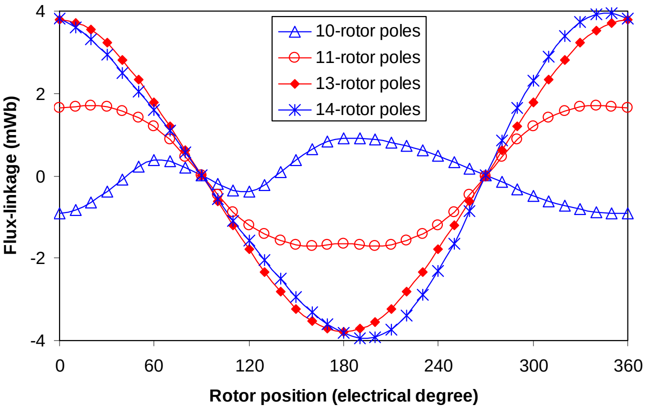


(d)

Fig. 6. Open-circuit field distribution of hybrid excited E-core FSPM machines excited only by DC excitation current or by magnets, rotor at d-axis. (a) 6/10 stator/rotor poles. (b) 6/11 stator/rotor poles. (c) 6/13 stator/rotor poles. (d) 6/14 stator/rotor poles.

The open-circuit field distributions of the 6/13 stator/rotor pole machine with weakening and enhancing DC excitation currents are compared in Fig. 8 when the rotor is at d-axis and magnets are magnetized. The flux through the stator E-core middle teeth and stator back-iron when the flux-weakening DC excitation current is applied is much larger than that when the flux-enhancing DC excitation current is applied, while the flux in the stator pole is smaller.



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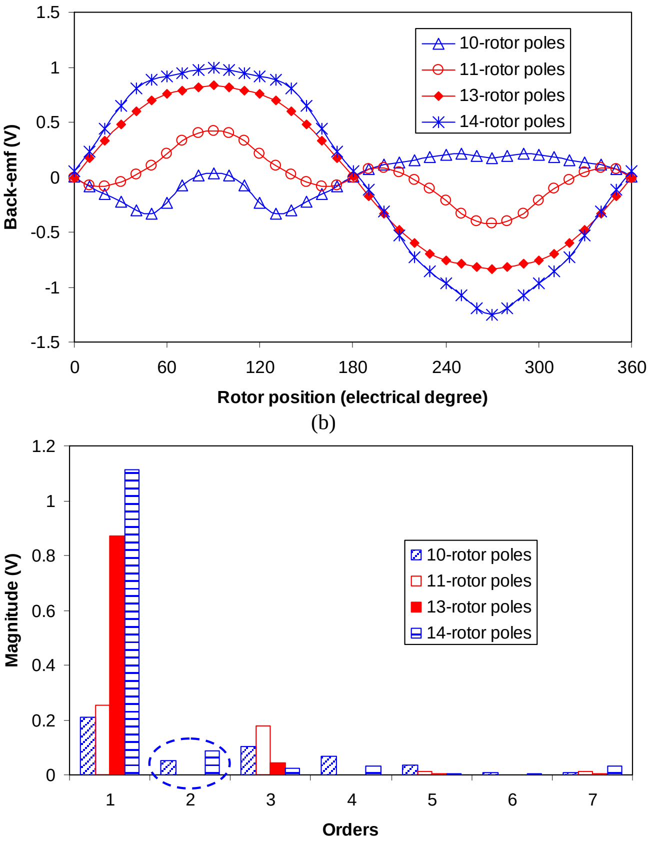
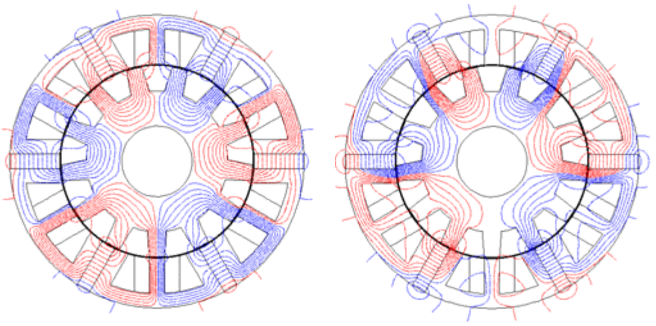


(b)

(c)

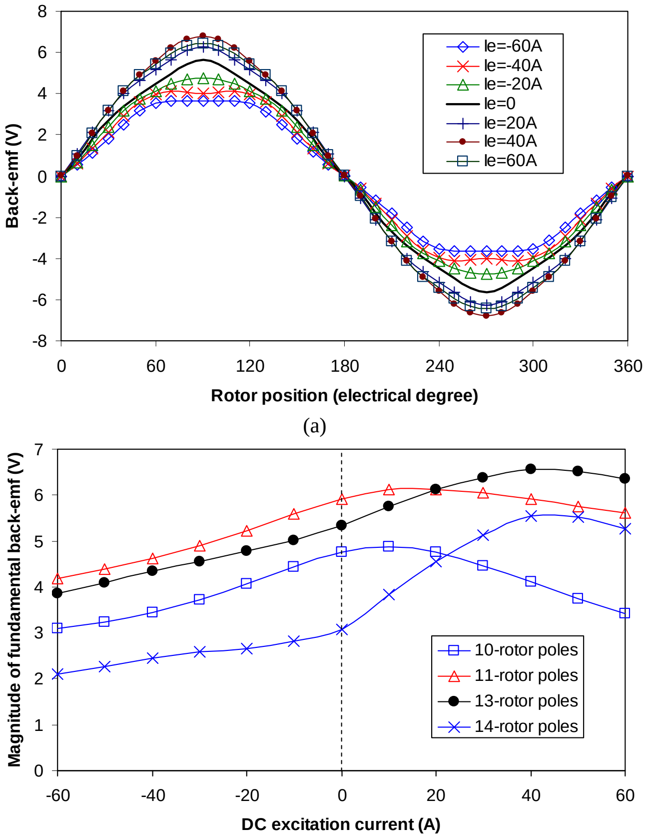
Fig. 7. Back-emf waveforms of hybrid excited FSPM machines excited only by DC excitation current (10A), 400rpm. (a) Phase flux-linkage waveforms. (b) Phase back-emf waveforms. (c) Spectra of phase back-emfs.

Furthermore, Fig. 9(a) shows the back-emf waveforms of the 6/13 stator/rotor pole machine with different DC excitation currents and the variation of fundamental back-emf magnitude with DC excitation current are summarised in Fig. 9(b). The 6/11 stator/rotor pole machine exhibits the largest back-emf when the DC excitation current = 0, while the smallest back-emf is obtained by the 6/14 stator/rotor pole machine, which is consistent with the analyzed result for E-core FSPM machines [15]. The 6/10, 6/11, and 6/13 stator/rotor pole machines exhibit similar flux-weakening capability by employing DC excitation current, which is higher than that of the 6/14 stator/rotor pole machine. However, the 6/14 stator/rotor pole machine obtains the highest flux-enhancing capability which is negligible in the 6/10 and 6/11 stator/rotor pole machine. The 6/13 stator/rotor pole machine exhibits slightly lower flux-enhancing capability than that of the 6/14 stator/rotor pole machine. In addition, the 6/13 stator/rotor pole machine obtains the largest back-emf when flux-enhancing DC excitation current is employed. It is worthy to mention that it is much easier to weaken the PM flux linkage by the DC excitation coil, and usually much more difficult to enhance the PM flux-linkage due to saturation of the magnetic circuit (depending on the saturation level of magnetic circuit on open-circuit), as likely to be the general case in all hybrid excited PM machines [1], [2], and [12]. Nevertheless, overall, the 6/13 stator/rotor pole machine is optimum for hybrid excitation operating.



(a) (b)

Fig. 8. Open-circuit field distribution of 6/13 stator/rotor pole machine, rotor at d-axis. (a) DC excitation current=-30A(flux weakening). (b) DC excitation current=30A (flux enhancing).



(a)

Fig. 9. Variation of fundamental back-emfs with DC excitation current in 6-stator pole hybrid excited E-core FSPM machines. (a) back-emf waveforms of 6/13 stator/rotor pole machine. (b) Variation of fundamental back-emf magnitude with DC excitation current.

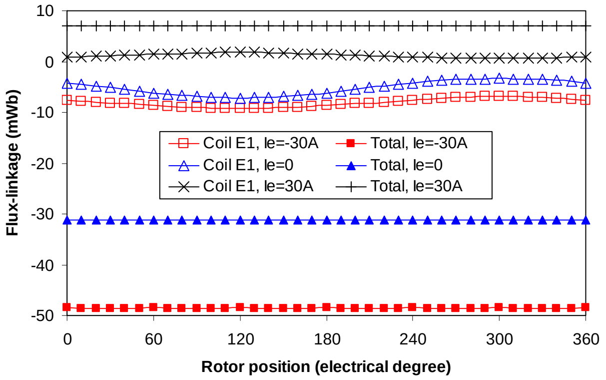
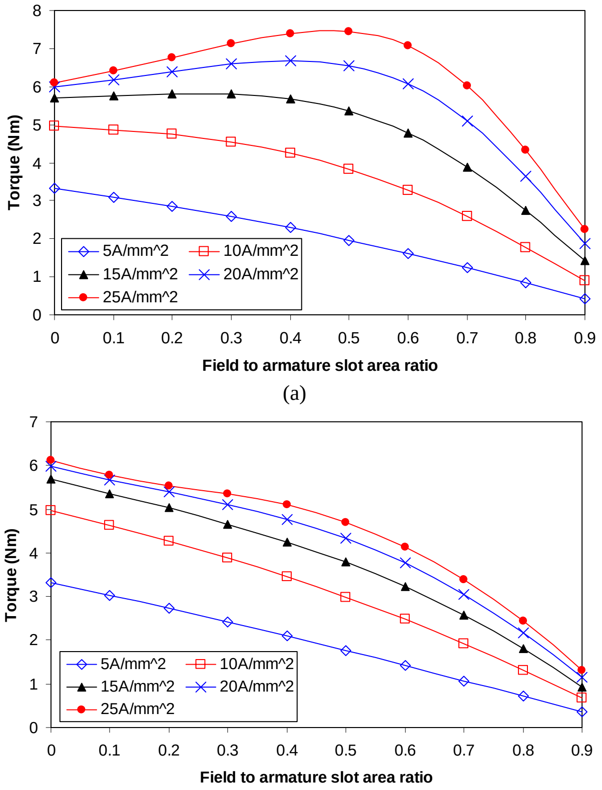


Fig. 10. Flux-linkage waveform of DC excitation winding in 6/13 stator/rotor pole hybrid excited E-core FSPM machine.

In addition, the flux-linkage of DC excitation winding is predicted by 2-D FE analyses, Fig. 10. Although the flux-linkage of single DC excitation coil (coil E1) varies with the rotor position, the total flux-linkage in the DC excitation coils is constant.

B. *Field to Armature Slot Area Ratio*

Further, the ratio of field to armature slot areas is optimized by 2-D FE analyses. For simplicity, the same current density is employed for the DC excitation and armature windings, and, consequently, the copper loss maintains constant when the field to armature slot are ratio varies.



(a)

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Fig. 11. Variation of torque with field to armature slot area ratio in 6/13 stator/rotor pole hybrid excited E-core FSPM machine, I_d=0, equal field and armature current density, and winding packing factor = 1. (a) Flux-enhancing. (b) Flux-weakening.

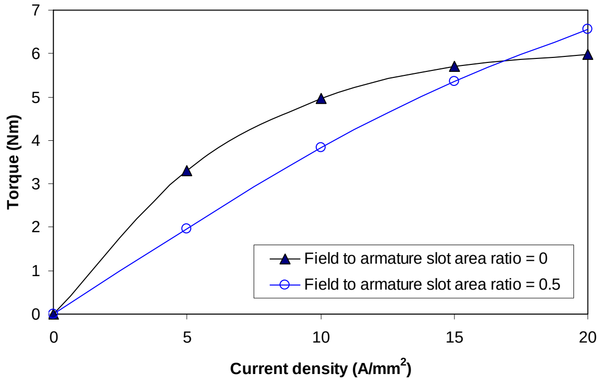

Fig. 12. Comparison of torque-current density characteristics of 6/13 stator/rotor pole E-core FSPM machine with different field to armature slot area ratios, I_d=0, equal field and armature current density, and winding packing factor = 1.

Fig. 11 shows the variation of torque with the field to armature slot area ratio in the hybrid E-core 6/13 stator/rotor pole FSPM machine. When the flux-enhancing current is employed, the torque reduces with the increase of field to armature slot area ratio when the current density < 15 A/mm^2. However, it increases firstly and then reduces when the current density > 15 A/mm^2 since the flux-enhancing current reduces the magnetic saturation as analyzed earlier. The largest torque is obtained when the field to armature slot area ratio = 0.5. On the other hand, when the flux-weakening current is employed, as expected, the flux-weakening capability increases with the field to armature slot area ratio. Overall, the optimized field to armature slot area ratio is 0.5 which is identical to the value employed in the foregoing analysis. In addition, the torque-current density characteristics of the 6/13 stator/rotor pole E-core (field to armature slot area ratio = 0) and hybrid E-core (field to armature slot area ratio = 0.5) FSPM machines are compared in Fig. 12. They have the same copper loss when the current density is identical since their total slot areas are equal. The hybrid excited E-core machine exhibits a higher overload capability than that of the E-core machine although its torque is lower when the current density is small.

C. *Electromagnetic Torque*

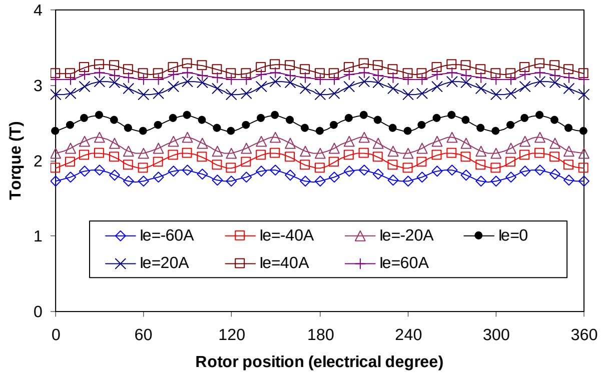

Fig. 13. Electromagnetic torque of 6/13 stator/rotor pole hybrid E-core FSPM machine with different DC excitation currents, I_d=0 and I_q=14.1A.

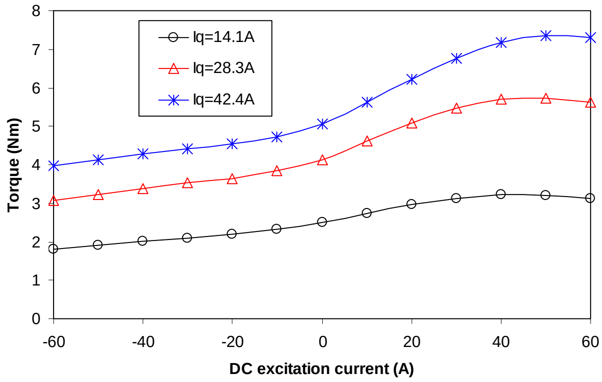

Fig. 14. Variation of torque with DC excitation current in 6/13 stator/rotor pole hybrid E-core FSPM machine with different q-axis currents, I_d=0.

The electromagnetic torque of the 6/13 stator/rotor pole E-core hybrid excited FSPM machine is predicted by 2-D FE analyses. Fig. 13 shows the torque waveforms of the machine with different DC excitation currents. Moreover, the variation of torque with DC excitation current is shown in Fig. 14. Clearly, up to a maximum value of DC current, the flux-enhancing capability is higher than the flux-weakening capability since the flux-weakening current increases the magnetic saturation in the stator teeth which carry the DC excitation windings while the flux-enhancing current reduces the magnetic saturation, Fig. 8. This is opposite from the general hybrid excited PM machines mentioned earlier.

IV. CONCLUSIONS

A novel E-core hybrid excited FSPM machine is proposed and analyzed. Its optimized combination of stator and rotor pole numbers is different from that for the corresponding E-core FSPM machine, being 6/13 and 6/11 stator/rotor poles, respectively. In the proposed machine, the flux-enhancing capability is higher than the flux-weakening capability since the flux-weakening current increases the magnetic saturation in the stator teeth which carry the DC excitation windings while the flux-enhancing current reduces the magnetic saturation. Although the E-core hybrid excited FSPM machine exhibits lower torque per copper loss than that of the corresponding E-core FSPM machine since the slot area reduces due to DC excitation winding, it can easily adjust the torque and voltage.

TABLE I
MAJOR DESIGN PARAMETERS OF FSPM MACHINES

	Conventional	E-core	E-core hybrid
Number of phases	2		
Number of stator poles	12	6	
Number of rotor poles	10	11	11, 13
Outer diameter of stator (mm)	90		
Active axial length (mm)	25		
Airgap length (mm)	0.5		
Outer diameter of rotor (mm)	54	57.5	
PM thickness (mm)	3.6	4.5	
Mass of magnets (g)	143.4	77.4	
Stator tooth width (mm)	3.6	4.5	
Stator back-iron thickness (mm)	3.6	4.5	
E-core middle tooth width (mm)	--	4.5	
Slot area/phase (mm^2)	202	206	
Number of turns of DC excitation windings	--	--	216
Number of turns per phase	72		
Rotor pole width	1/3 of rotor pole-pitch		
Magnet remanence (T)	1.2		
Magnet relative recoil permeability	1.05		
Rated current (A, rms)	10		
Speed (rpm)	400		

APPENDIX – DESIGN PARAMETERS OF FSPM MACHINES

The major design parameters of the optimized conventional, E-core, and E-core hybrid excited FSPM machines are given in Table I.

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