Comparative Study of E-Core Axial Field Flux-Switching Permanent Magnet Machines

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***Abstract*— Some specific design issues of E-core axial field flux-switching permanent magnet(AFFSPM) machines, including the rotor pole width, the split ratio, the stator parameters, are investigated by 3-D finite element method (FEM) for increasing the output torque. The electromagnetic performances of those, 6/10 stator/rotor pole and 6/14 stator/rotor pole E-core AFFSPM machines, are compared and analyzed in the paper. The results show that the 14-rotor pole AFFSPM machine exhibits smaller electromagnetic torque than 10-rotor pole machine, while it can significantly reduce the asymmetry of back-EMF waveform and torque ripples. It is shown that the E-core AFFSPM machines have smaller ratio of mutual- to self-inductance, which is desirable to improve fault tolerant, and higher torque density in contrast with the conventional AFFSPM machine.**

***Index Terms*— Axial field, flux-switching, permanent magnet machine, E-core, torque density.**

I. INTRODUCTION

Incorporating the advantageous features of AFFSPM machines, including short axial size, large torque capability, high efficiency and power density, as well as compact and robust structure [1]-[2], the stator middle teeth are employed in an E-core AFFSPM machine to improve fault tolerant capability and decrease the numbers and volumes of magnets. It is suitable for the direct drive in-wheel applications in the electric and hybrid electric vehicles. Therefore, the 10- and 14-rotor pole is sampled and investigated in the proposed machine respectively.

II. MACHINE MODEL AND COMPUTATIONAL METHOD

A novel E-core AFFSPM machine, as shown in Fig.1, is designed as E-shaped laminated segments in the stator. It is composed of two outer stators and one inner rotor. A concentrated coil A1 is wound around the two adjacent teeth with a piece of magnet in the middle. There are neither magnets nor windings in the rotor. The E-core AFFSPM machine has a half number of stator poles, compared with the 12/10-pole AFFSPM machine. The circumferential magnetized magnets of alternative polarity are employed in the proposed machine. The original design parameters of the E-core AFFSPM machine are obtained with reference to the conventional 12/10-pole one in [3]. Based on 3-D model, the proposed machines are investigated by using FE analysis. The numbers of element and nodes are 104243 and 278483, respectively.

III. OPTIMIZATON OF SPECIFIC DESIGN PARAMETERS

A. Rotor Pole Width

With the variation of rotor pole width and the same total number of stator winding turns, the average electromagnetic torque is increased at first, and then monotonically decreased for the two E-core AFFSPM machines, as shown in Fig. 2.

B. Split Ratio

Assuming the copper loss fixed [4]-[5], the two E-core AFFSPM machines are analyzed with the optimized rotor pole width and the other same original parameters. The variation of torque with split ratio is shown in Fig. 3.

C. Stator Design Parameters

The influences of the stator design parameters on the torque, including the magnet thickness, the stator yoke length, and the side tooth width and middle tooth width of stator E-core, are investigated by 3-D FEM with the optimized rotor pole width, split ratio, and the constant copper loss. In order to simplify the analysis and to highlight the output torque, it is assumed that all other stator parameters remain unchanged while one parameter is varied. For increasing the output torque, the optimal parameters of 6/10- and 6/14-pole E-core AFFSPM machines are presented in TABLE I.

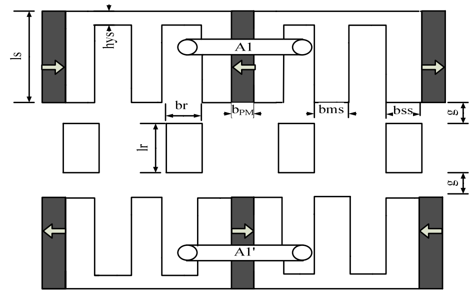

Fig. 1. Two-dimensional topology of E-core AFFSPM machine

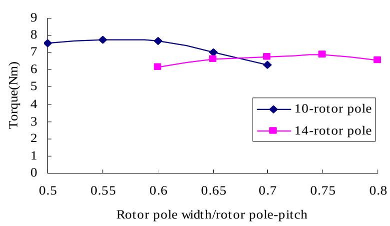

Fig. 2. Variation of torque with ratio of rotor pole width to rotor pole-pitch

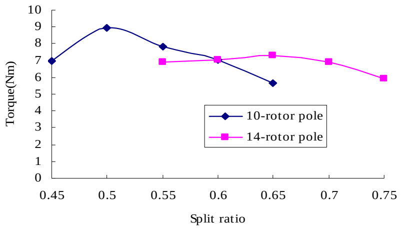

Fig. 3. Variation of torque with split ratio

IV. COMPARISON OF ELECTROMAGNETIC PERFORMANCES

It is demonstrated in Fig. 4 that the asymmetry of back-EMF waveform of the 14-rotor pole machine is significantly reduced in contrast with that of 10-rotor poles machine. It can be seen from TABLE II that the magnet volumes of the 10-rotor pole and 14-rotor pole E-core AFFSPM machine are respectively reduced by 32% and 38% in contrast with that of the conventional AFFSPM machine with the same rated power, and the 6/10-pole E-core AFFSPM machine and the conventional machine exhibit similar torque which is higher than that of the 6/14-pole machine with the same current. The average electromagnetic torque in the 14-rotor pole machine is ～16% lower than that in the 10-rotor pole E-core AFFSPM machine, while the torque ripple is reduced by 45%.There is a significant torque ripple in the AFFSPM machines, which is due to asymmetric back-EMF waveforms and non-ignorable cogging torques. The 3-D FE-predicted and measured variation in average torque with current of 6/14-pole E-core AFFSPM machine are shown in Fig. 5, which indicates they are very close, and therefore the analytical method has a relatively high accuracy. The FE-predicted average self-inductance of phase A and mutual-inductance between phase A and phase B, are also summarized in TABLE II. The self-inductance of the E-core machines is significantly larger than that of the conventional machine, which is desirable to reduce short-circuit current, and the ratio of mutual- to self-inductance of the E-core machines is reduced by about ~30% in contrast with 12/10-pole AFFSPM machine, and therefore the E-core AFFSPM machines can improve fault tolerant capability.

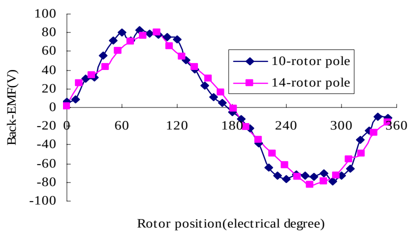

Fig. 4. Back-EMF waveforms of the two E-core machines at 750r/min

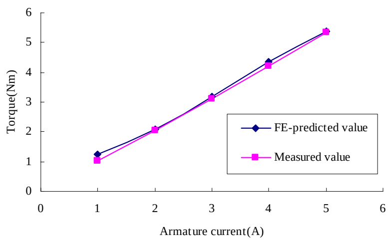

Fig. 5. Torque-current characteristics of the 6/14-pole E-core machine

TABLE I

OPTIMAL PARAMETERS OF E-CORE AFFSPM MACHINE

Items	Values	
	6/10	6/14
Stator outer diameter, D_{so} (mm)	140	
Stator length, l_s (mm)	20	
Stator yoke length, h_{ys} (mm)	7	
Rotor length, l_r (mm)	17.5	
Air-gap length, g (mm)	1	
Magnet thickness, b_{PM} (degree)	10	
Stator E-core side tooth width, b_{ss} (degree)	10	
Stator E-core middle tooth width, b_{ms} (degree)	8	10
Split ratio	0.5	0.65
Rotor pole width b_r (degree)	19.8	18.2

TABLE II

COMPASION OF E-CORE AFFSPM MACHINE WITH CONVENTIONAL AFFSPM MACHINE

Items	E-core		Conventional
	6/10	6/14	12/10
Magnet volumes(mm^3)	51.28	46.67	75.37
Average Torque (Nm)	5	4.2	4.92
Pk-pk Torque Ripple (Nm)	4.7	2.07	2.41
Ripple (% of average torque)	94	49	49
Laa (mH)	0.395	0.252	0.066
Lab (mH)	-0.069	-0.043	-0.031
Lab/Laa (%)	-17.5	-17.1	-47

V. CONLUSION

It is shown that the asymmetric back-EMF waveforms of 10-rotor pole E-core AFFSPM machine can be reduced by 14-rotor pole without rotor skewing. Furthermore, the 14-rotor pole machine exhibits smaller average electromagnetic torque than 10-rotor pole machine, while the torque ripple can be largely reduced. It is also shown that the novel E-core AFFSPM machine can be developed to reduce the cost, improve the fault tolerant performance, and increase torque density with reference to the conventional 12/10-pole AFFSPM machine.

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