Electromagnetic Performance Analysis of Hybrid-Excited Flux-Switching Machines for Electrical Vehicles by an Improved Magnetic Network Model

Wei Hua, Gan Zhang and Ming Cheng
School of Electrical Engineering, Southeast University, Nanjing 210096, P.R. China
Email: huawei1978@seu.edu.cn

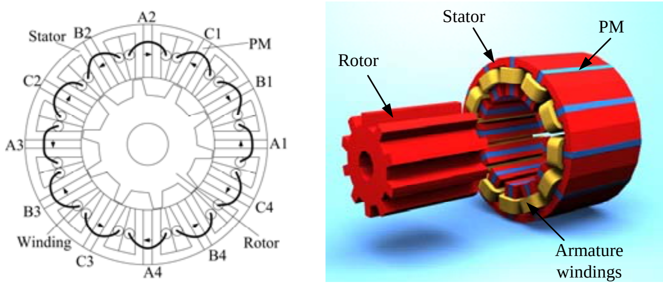
***Abstract*—In this paper, a nonlinear magnetic circuit network model is proposed for a three-phase 12-stator-slot/10-rotor-pole hybrid-excited flux-switching machine for electrical vehicles, which can predict the static electromagnetic characteristics, including the open-circuit air-gap field distributions, phase PM flux-linkage and phase back electro-motive-force (back-EMF) waveforms. To improve the accuracy of the predicted electromagnetic performance, in the improved model, a particular a parallel multi-piece magnet magnetic circuit instead of series single-piece magnet circuit is employed to take the local saturation effect into account. The predicted results are confirmed by finite element analysis.**

Keywords-hybrid-excited; flux-switching; magnetic circuit analysis; finite element analysis; electrical vehicles

I. INTRODUCTION

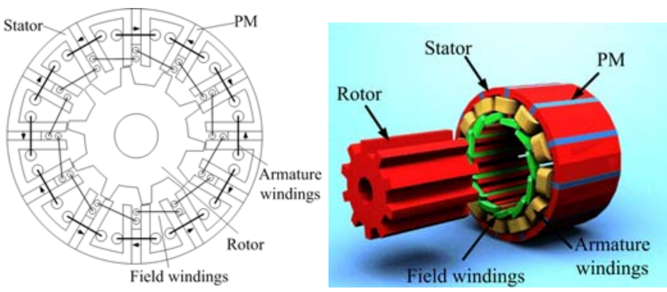
The flux-switching permanent magnet (FSPM) motor is a relatively new topology of stator-PM brushless machines [1], which exhibits attractive merits including the large torque capability, high torque (power) density, essentially sinusoidal back-EMF waveforms, as well as compact and robust structure due to both the locations of magnets and armature windings in stator instead of rotor as those in the conventional rotor-PM machines [2]-[6]. The comparative results between a FSPM motor and a traditional surface-mounted PM (SPM) motor having the same specifications reveal that FSPM motor exhibits larger airgap flux-density, higher torque per copper loss, but also higher torque ripple due to cogging torque [7]. However, for solely permanent magnets excited machines, it is a traditional contradiction between the requests of high torque capability under the base speed (constant torque region) and wide speed operation above the base speed (constant power region) especially for hybrid vehicles applications [8], [9]. Hence, a hybrid-excitation flux-switching (HEFS) machine is proposed in [10]-[11], however, since the introduced field windings are needed to be specially accommodated in an additional frame outside the stator, the original stator laminations of the FSPM motor has to be modified for a HEFS machine. Moreover, the flux regulation capability of the proposed topology is limited.

In [12], based on the topology of a purely PM excited FSPM motor as shown in Fig. 1, a novel HEFS motor topology is proposed as shown in Fig. 2, in which the magnets dimensions are reduced to save room for the introduced field windings, whilst both the stator and rotor laminations are unchanged. It should be emphasized that the flux regulation capability of the machine can be simply controlled by adjusting the magnets length in radial direction. On the other hand, although in [2], a lumped parameter magnetic circuit model was proposed for a FSPM motor. However, the above model can not take the saturation into account and the predicted results are relatively coarse. In this paper an improved nonlinear magnetic network model is proposed for a prototyped HEFS machine, which can improve the accuracy of the predicted electromagnetic performance by parallel multi-piece magnet magnetic circuits instead of series single-piece one. The topology and operation principle of the proposed HEFS motor are introduced in section II. The modeling of the nonlinear magnetic network for the machine and the analysis of the electromagnet performance are presented, verified by finite element (FE) analysis in section III. Finally, some conclusions are drawn in section IV.



(a) (b)

Fig. 1. The topology of the 12/10-pole FSPM motor. (a) Cross-section, (b) Configuration.



(a) (b)

Fig. 2. The topology of the 12/10-pole HEFS motor. (a) Cross-section, (b) Configuration.

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II. Topology and Operation Principle

A. Topology

In Fig. 1, a FSPM motor having 12 stator slots and 10 rotor poles [3] is illustrated as the original machine and a novel HEFS motor having the same stator slots/rotor poles combination and dimensions is proposed and investigated in Fig. 2. Obviously, the only difference between the two motors are in the magnets length in the radial direction, i.e., shorter magnets are employed in the HEFS motor to save space for the accommodation of the added field windings. The basic design dimensions of the machine are illustrated in Fig. 3 and listed in Table I. For the detailed descriptions, it can be referred to [3]. It should be noted that a key factor, k_{pm} is defined as the ratio of the magnet length (l_{pm}), to the stator iron length ($k_{sio}R_{so}$) in radial direction. In [12], the k_{pm} is set 0.3 using ferrite magnets, while in this paper the k_{pm} is set 0.6 and the magnet material is NdFeB to investigate the flux-regulation capability.

B. Opertion Principle

The operation principles of the HEFS motor is shown in Fig. 4. Obviously, by controlling the polarity and values of the applied field currents, the airgap flux density of the machine can be easily strengthened (pro-magnetized) or weakened (de-magnetized), which realizes the hybrid excitation function, meanwhile avoids increasing the total volume of the motor.

In addition, the configurations of the field windings can be double-layer or single-layer as shown in Fig. 5 and both have the same function.

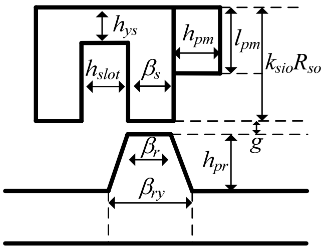
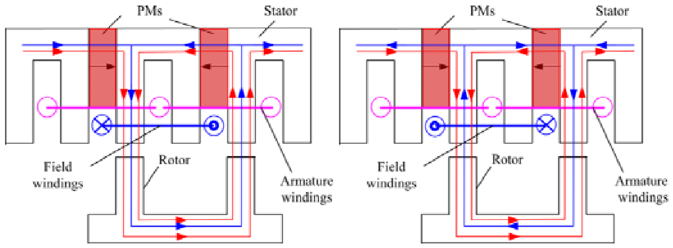


Fig. 3. Design dimensions of the original HEFS motor.

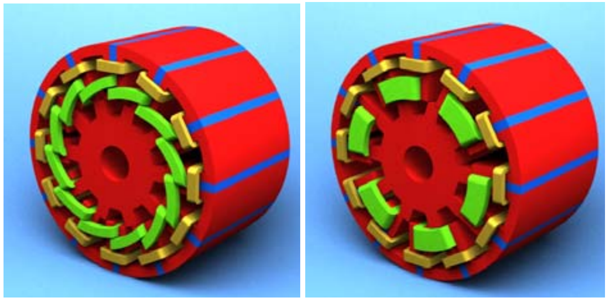
TABLE I
Design Specifications of The Original HSPM Motor

Items	HEFS motor
Base Speed (rpm)	1500
Stator outer radius (mm), R_{so}	64
Stack length (mm), l_a	75
Stator split ratio, k_{sio}	0.55
Rotor inner diameter (mm), R_{ri}	11
Stator slot number, P_s	12
Rotor pole number, P_r	10
Airgap length (mm), g	0.35
Stator pole arc (degree), β_s	7.5
Stator slot arc (degree), h_{slot}	7.5
magnet arc (degree), h_{pm}	7.5
Rotor pole arc (degree), β_r	7.5
Rotor pole-yoke arc (degree), β_{ry}	15
$k_{pm}=l_{pm}/(k_{sio}R_{so})$	0.6
Magnetic material	NdFeB



(a) (b)

Fig. 4. Operation principle of HEFS motor. (a) Pro-magnetized, (b) De-magnetized.



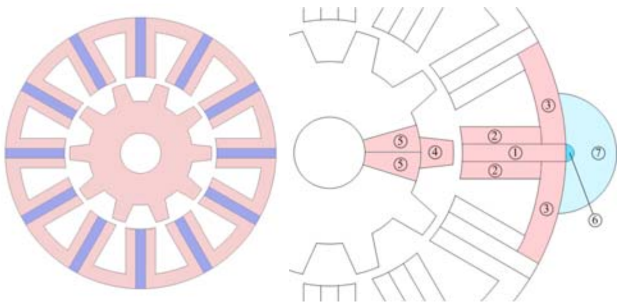
(a) (b)

Fig. 5. Configurations of the field windings of the HEFS motor. (a) Double-layer, (b) Single-layer.

III. Magnetic Network Model

Since the HEFS machine is inherited from the FSPM machine, the magnetic network model is firstly built. Based on the topology of a prototyped FSPM machine having 12 stator slots and 10 rotor poles as shown in Fig.6 (a) [3], the magnet, stator tooth, stator yoke, rotor tooth, rotor yoke, leakage of magnet in local stator outer space and leakage in far stator outer space are labeled by 1-7, respectively as shown in Fig. 6(b). Hence, according to the complexity of the model, a simple series single-piece-magnet, a parallel single-piece-magnet, and a parallel multi-piece-magnet nonlinear magnetic network model are proposed respectively in Fig.7 (a)-(c). The difference between Fig. 7(a) and (b) can be found in Fig. 8(a) and (b) respectively, which compares the magnetic circuit for the FSPM machine at four typical rotor positions. The detailed air-gap permeances calculation are to be presented in the full-paper due to the page limit. Based on the FSPM machine, the model of the HEFS machine can be built as shown in Fig. 9.

A. Simple Model



(a) (b)

Fig. 6. Magnetic circuit modeling of a FSPM machine. (a) Cross-section, (b) Modeling of different parts.

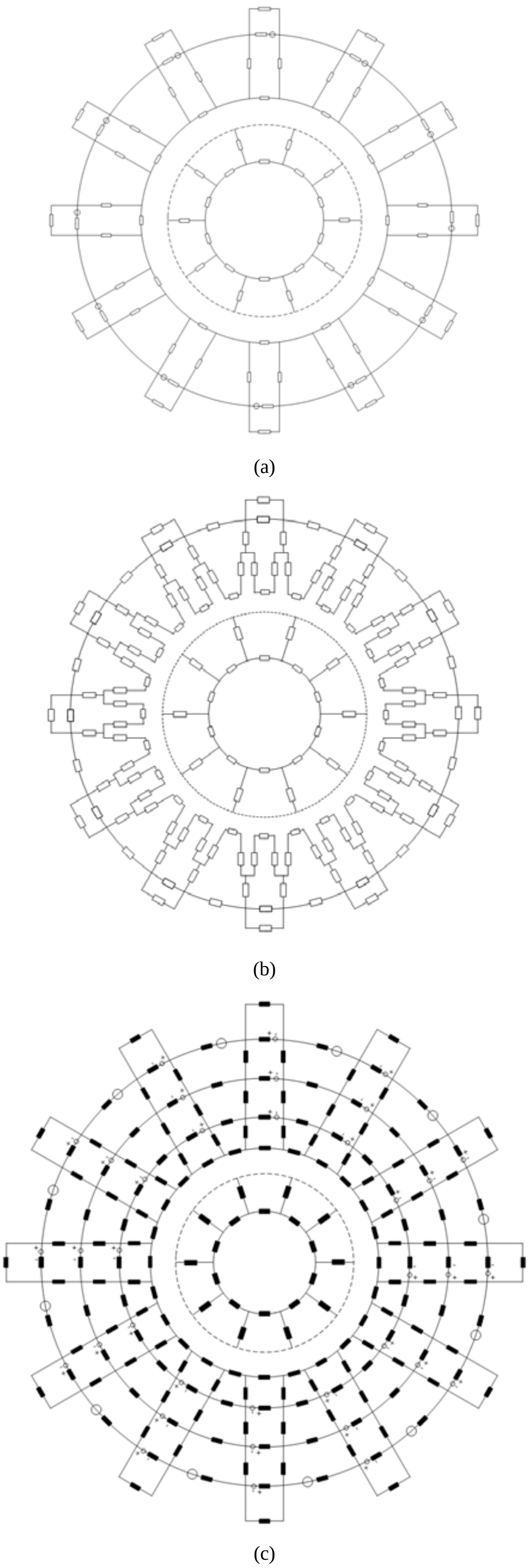


Fig. 7. Three typical magnetic circuit models of a FSPM machine. (a) Series single-piece-magnet, (b) Parallel single-piece-magnet, (c) Parallel multi-piece-magnet.

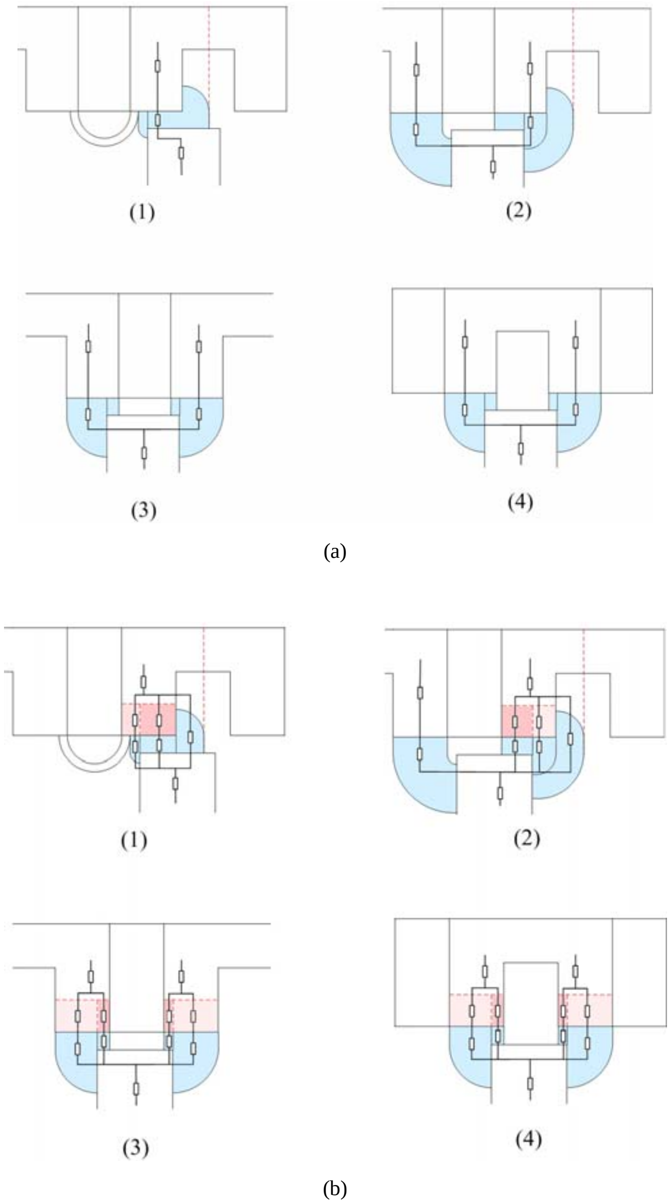


Fig. 8. Typical magnetic circuit models of a FSPM machine at four rotor positions. (a) Series single-piece-magnet, (b) Parallel single-piece-magnet.

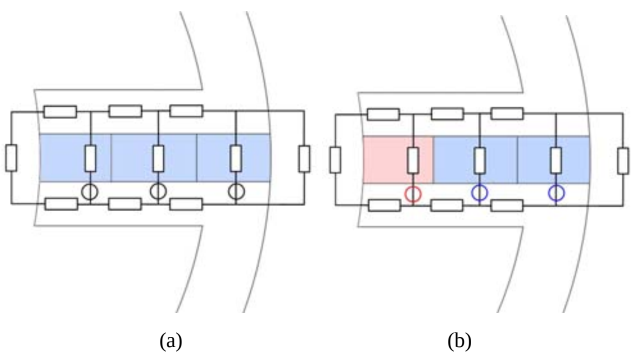
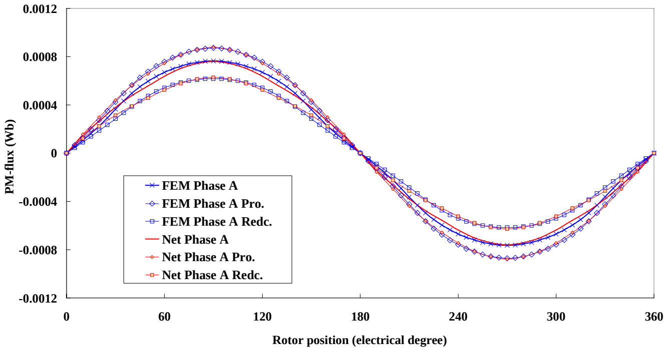


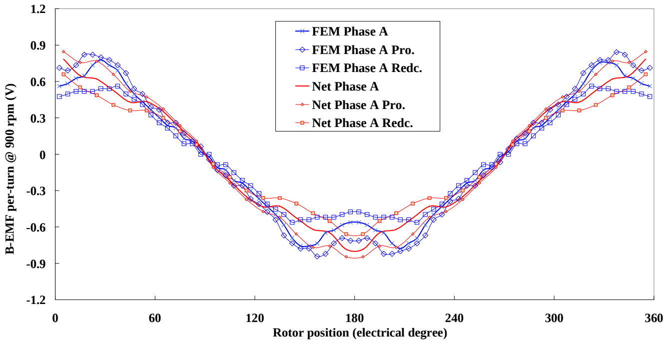
Fig. 9. Multi-piece-magnet magnetic circuit models of a FSPM and HEFS machine. (a) FSPM machine, (b) HEFS machine.

B. Results

To verify the accuracy the proposed model, the predicted flux-linkage and back-EMF per turn from the parallel multi-piece-magnet magnetic network model and FE analysis are compared in Fig. 10, respectively. It can be seen that the flux of magnetic circuit model is agreed with the FE predicted results. Consequently, the back-EMF of the saturated model represents acceptable accuracy.



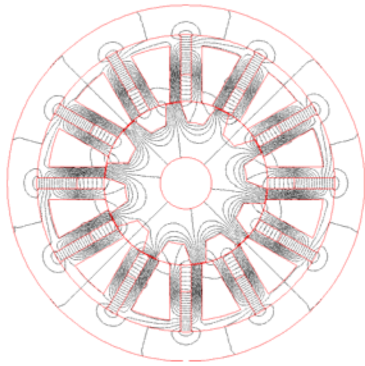
(a)



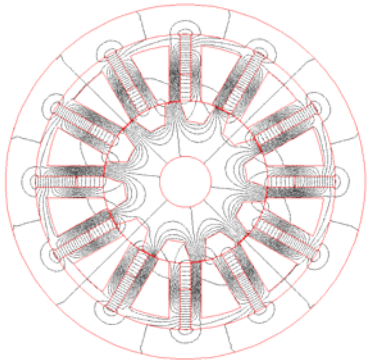
(b)

Fig. 10. Predicted performance based on the parallel multi-piece-magnet model of a HEFS machine under PM, pro-magnetized and de-magnetized conditions. (a) Phase flux-linkage per turn, (b) Phase back-EMF per turn.

Fig. 11 shows the FE-based predictions of the magnetic field distributions of the analyzed HEFS machine under only PM, pro-magnetized and de-magnetized conditions. Fig. 12 compares the predicted air-gap distributions from both FE and magnetic network model under only PM, pro-magnetized and de-magnetized conditions. Obviously, generally good agreements of the results from FE analysis and magnetic network models are achieved in the air-gap flux density waveform distributions.



(a)



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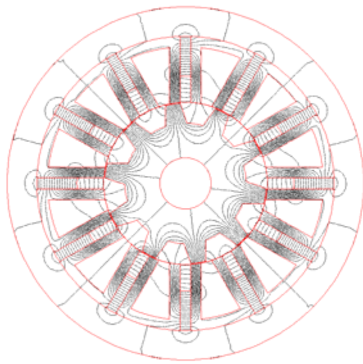
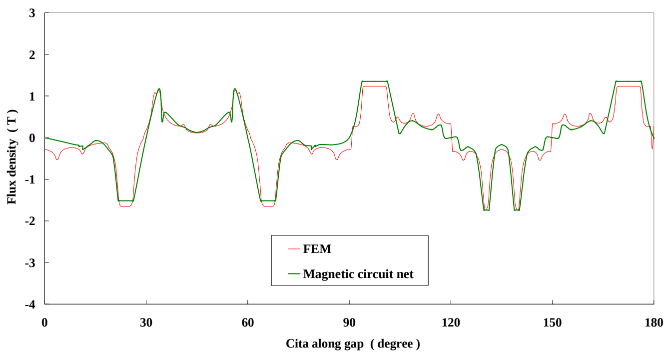
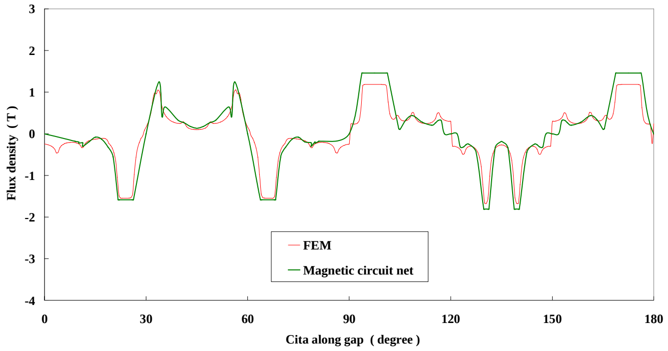


(c)

Fig. 11. Magnetic field distributions of the HEFS machine under PM, pro-magnetized and de-magnetized conditions based on FE analysis. (a) PM, (b) Pro-magnetized, (c) De-magnetized.



(a)



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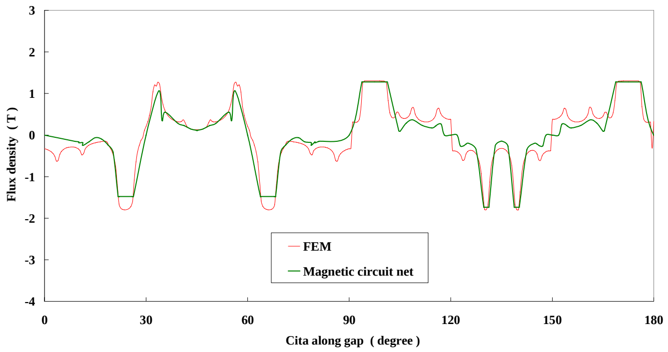

(c)

Fig. 12. Predicted airgap flux-density waveforms based on the parallel multi-piece-magnet model of a HEFS machine under PM, pro-magnetized and de-magnetized conditions. (a) PM, (b) Pro-magnetized, (c) De-magnetized.

IV. CONCLUSION

In this paper, a nonlinear magnetic network model considering saturation for HSPM machines is proposed to improve the accuracy of the predicted electromagnetic performance by employing parallel multi-piece-magnet circuits. The predicted results are confirmed by FE analysis, which indicates the magnetic network model can be used in the preliminary analysis and design stage with acceptable accuracy.

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