Electromagnetic Performance Analysis of Hybrid-Excited Flux-Switching Machines by a Nonlinear Magnetic Network Model

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Abstract —In this paper, a nonlinear magnetic network model (NMNM) is proposed to predict the electromagnetic performance of a hybrid excitation flux-switching (HEFS) machine, in which the locations of the magnetic motive forces (MMF) due to field windings are specifically investigated. The proposed NMNM enables the predictions of air-gap field distributions, flux-linkage, back-electro-motive-force (back-EMF), and inductances of both armature and field windings under different excitation conditions, including pure magnets, pure field currents and hybrid excitations. The predicted results from the model are validated by finite-element analysis.

I. INTRODUCTION

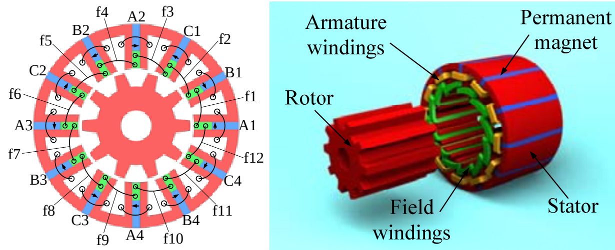
Although nonlinear magnetic circuit models and Fourier analysis for the performance prediction of flux-switching permanent-magnetic (FSPM) machines has been introduced in [1]-[3], the analysis of HEFS machines has not been reported. Hence, in this paper a nonlinear magnetic network model (NMNM) for HEFS machines is proposed to predict the electromagnetic performance of a prototyped HEFS machine having 12 stator slots and 10 rotor poles as shown in Fig. 1 [4]. Moreover, the key design specifications are given in Table I. The detailed topology and operation principle can be found in [4].

II. MODELING OF NMNM

As shown in Fig. 1, since the field windings are introduced to regulate the air-gap flux-density, the modeling of the MMF due to field current is specifically built according to the local magnetic field distributions and flux directions as shown in Fig. 2 with pure magnets excitation (B_r=1.2T), and Fig. 3 with magnets and field current (J_{sf}=5A/mm^2) hybrid excitations. It should be noted that the MMF of field excitations is located in closed circuit branches composed of two series magnetic sources, which is not directly connected with the MMF due to magnets. Furthermore the armature MMF (F_s), field MMF (F_f) and magnet MMF (F_m) can be given by:

$$\begin{cases} F_s = A_s J_{sa} / 2 \\ F_f = A_f J_{sf} / 2 \\ F_m = B_r h_m / (\mu_r \mu_0) \end{cases} \tag{1}$$

where A_s and A_f are cross-section areas of armature slot and field slot respectively, J_{sa} is armature slot current density, h_m is magnet thickness, μ_r is the relative permeability of permanent magnet and μ_0 is the permeability of free space. Hence, the NMNM can be obtained as illustrated in Fig. 4. It should be emphasized that the air-gap branch-connection in NMNM varies with different rotor positions.

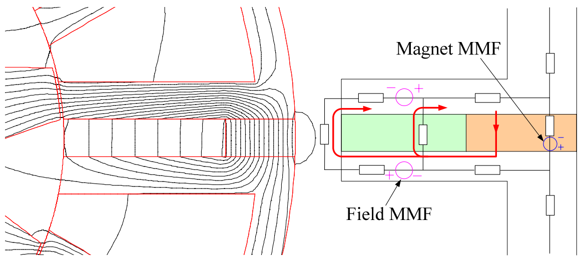


(a) Cross-section. (b) Configuration.

Fig. 1. Topology of a 12-stator-slots/10-rotor-poles HEFS machine.

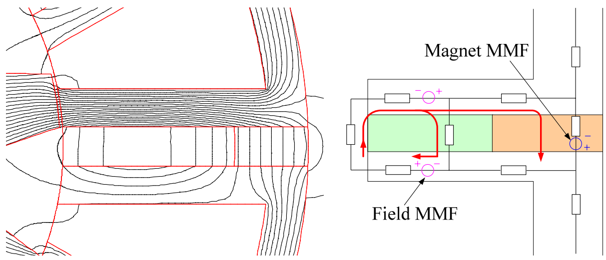
TABLE I KEY DESIGN SPECIFICATIONS OF HEFS MACHINES

Item	HEFS machines
Stator outer diameter, D_{so} (mm)	128
Stator inner diameter, D_{si} (mm)	70.4
Active stack length (mm)	75
Rotor inner diameter (mm)	22
Stator tooth number	12
Rotor pole number	10
Air-gap length (mm)	0.35
Stator tooth width (degree)	7.5
Permanent magnet width (degree)	7.5
Permanent magnet length (mm)	$(D_{so}/2-D_{si}/2)$*0.3
Rotor pole arc (degree)	7.5
Rotor yoke width (degree)	21
Rotor pole height (mm)	8.71



(a) Field distributions. (b) Flux directions.

Fig. 2. Field distributions and corresponding flux directions when B_r=1.2T & J_{sf}=0.



(a) Field distributions. (b) Flux directions.

Fig. 3. Field distributions and corresponding flux directions when B_r=1.2T & J_{sf}=5A/mm^2.

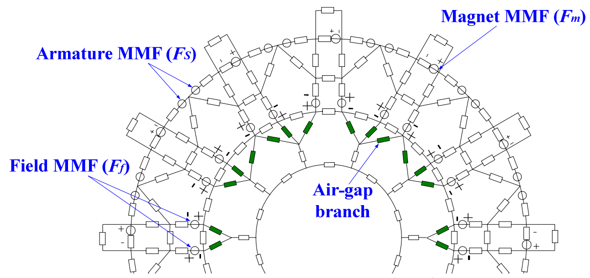


Fig. 4. Nonlinear magnetic network model of half HEFS machines.

III. PREDICTED RESULTS FROM NMNM AND FEA

A. Flux-linkage in armature windings

Fig. 5 and Fig. 6 compares the phase flux-linkage per-turn under different excited conditions, where pro-magnetized and de-magnetized field current densities are 5A/mm^2 and -5A/mm^2 respectively. Obviously, good agreements are achieved by NMNM and FEA. While field excitation shows satisfied flux-regulation capability when B_r=0.4T, it should be noted that the flux of phase A is weakened by both pro-magnetized and de-magnetized field currents as illustrated in Fig. 6 when B_r=1.2T due to significant saturation. Furthermore, Fig. 7 shows the comparison of phase flux waveforms with a direct armature current of the density of 5A/mm^2 under pure magnet excitation.

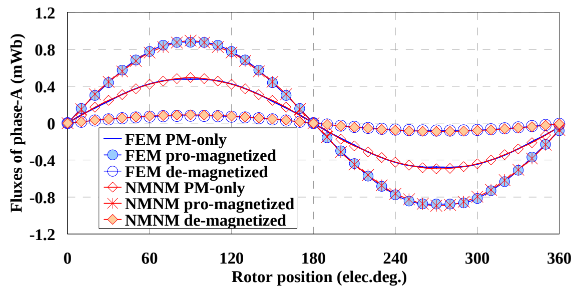


Fig. 5. Comparison of phase flux linkages per-turn when B_r=0.4T.

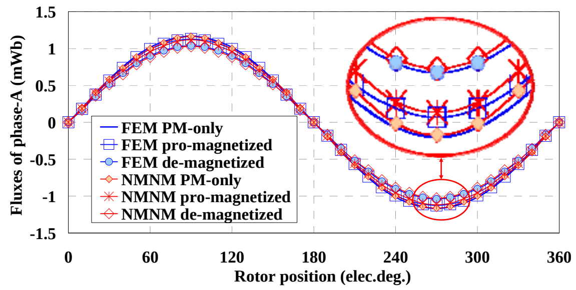


Fig. 6. Comparison of phase flux linkages per-turn when B_r=1.2T.

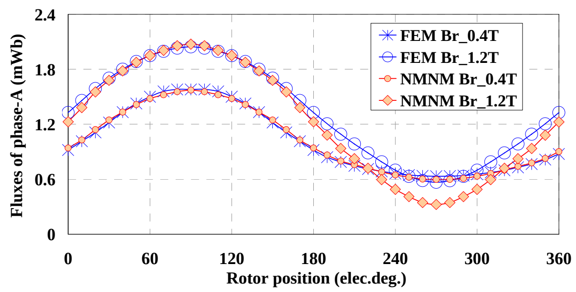


Fig. 7. Comparison of phase flux linkages per-turn when a direct armature current density=5A/mm^2.

B. Flux-linkage in field windings

Moreover, as seen from Fig. 8 and Fig. 9, the flux linkages of field coils can be obtained by NMNM, and also good agreements with FEA can be achieved under different excitation conditions. However, due to saturation effect, the predicted filed fluxes from NMNM differ slightly from those by FEA when B_r=1.2T.

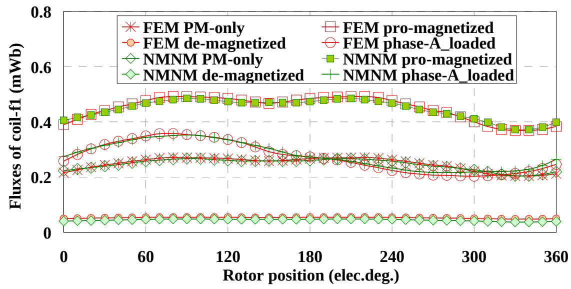


Fig. 8. Comparison of coil-f1 flux linkages per-turn when B_r=0.4T.

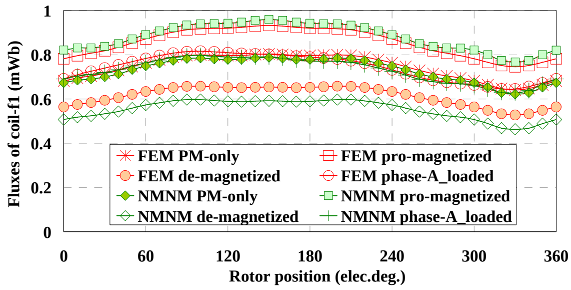


Fig. 9. Comparison of coil-f1 flux linkages per-turn when B_r=1.2T.

IV. CONCLUSION

In this paper, a nonlinear magnetic network model has been proposed to predict the performance of HEFS machines with particular attention on the locations of the magnetic motive forces due to field excitations. The results from the model are validated by FEA. The detailed modeling and results will be presented in full-paper.

ACKNOWLEDGMENTS

This work was supported by National Natural Science Foundation of China (50807007), the Specialized Research Fund for the Doctoral Program of Higher Education of China (200802861038), the Fund Program of Southeast University for Excellent Youth Teachers, Southeast University Science Fund for Distinguished Young Scholars and Southeast University Key Science Research Fund.

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