Electromagnetic Performance Analysis of Axial Field Flux-Switching Permanent Magnet Machine Using Equivalent Magnetic Circuit Method

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***Abstract*—In this paper, the electromagnetic performances of a novel axial field flux-switching permanent magnet (AFFSPM) machine are investigated based on equivalent magnetic circuit (EMC) method. A nonlinear EMC model of the AFFSPM machine is proposed and built, and the static characteristics of the proposed machine, including the air-gap flux density, permanent magnetic flux linkage, back electromotive force (EMF) and inductance characteristics are analyzed. The calculated results are compared with those predicted by finite element method (FEM). Experiments are done with a prototype. The analysis results are consistent with the experimental results well, verifying the feasibility of the equivalent magnetic circuit model.**

***Index Terms*—permanent magnet, axial filed, flux-switching, equivalent magnetic circuit, electromagnetic performance.**

I. INTRODUCTION

The magnetic field distribution and parameters of the machine can be obtained easily and quickly by using the EMC method [1] [2]. An accurate EMC model of AFFSPM machine can contribute to the calculation speed of static characteristics. The EMC model of the machine is developed in Section III. The predicted air-gap flux distribution, back EMF waveform and winding inductances are validated by three-dimensional (3-D) finite element analysis and measurements on a prototype AFFSPM machine.

II. MACHINE TOPOLOGY

A 3-phase AFFSPM machine with 12-stator-tooth and 10-rotor-pole is investigated in this paper, topology of which is shown in Fig. 1. The machine consists of two stators and one rotor both with a doubly-salient structure. The permanent magnet and concentrated armature windings are placed in the stators while there is neither winding nor magnet in the rotor. The magnetization is reverse in bilaterally symmetrical magnets. The main dimensions of the AFFSPM machine are listed in Table I.

III. EMC MODEL

Based on the geometric structure and predicted flux directions, the magnetic field is partitioned into several series and parallel branches. The permeance or magnetic potential sources in the branches connect mutually via magnetic potential nodes. The EMCs of the whole machine make up a magnetic circuit network as shown in Fig. 2.The permeance of

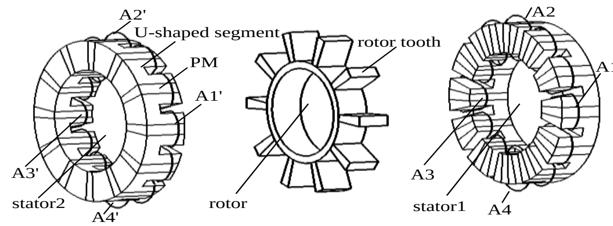
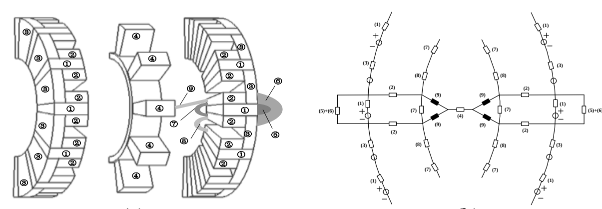


Fig. 1. Topology of AFFSPM machine.

TABLE I
DESIGN SPECIFICATIONS OF THE AFFSPM MACHINE

Items	Dimensions and Parameters
Rated output power/kW	0.6
Rated speed r/min	1500
Stator outer diameter/mm	123
Stator inner diameter/mm	68
Stator length/mm	21
Rotor length/mm	18
Airgap length/mm	1
Magnet arc/degree	7.5
Stator pole arc/degree	7.5
Stator slot ace/degree	7.5
Rotor pole arc/degree	10.5



(a) (b)

Fig. 2. EMC of local structure. (a) Permeance types of AFFSPM machine. (b) Equivalent magnetic network model of the local structure.

the stators, the rotor, the permanent magnet and the flux leakage at any position is deduced, composing the magnetic circuit equations of the whole machine. The air-gap flux branches vary with different rotor position while the magnetic potential nodes in the magnetic circuit remain constant. Nodal magnetic potential method is used to solve the equivalent magnetic circuit of AFFSPM machine. The nodal magnetic potential equations of AFFSPM machine with EMC model are expressed as

$$\begin{bmatrix} G_{11} & G_{12} & \dots & G_{1n} \\ G_{21} & G_{22} & \dots & G_{2n} \\ \dots & \dots & \dots & \dots \\ G_{n1} & G_{n2} & \dots & G_{nn} \end{bmatrix} \begin{bmatrix} F_m(1) \\ F_m(2) \\ \dots \\ F_m(n) \end{bmatrix} = \begin{bmatrix} \Phi_S(1) \\ \Phi_S(2) \\ \dots \\ \Phi_S(n) \end{bmatrix} \tag{1}$$

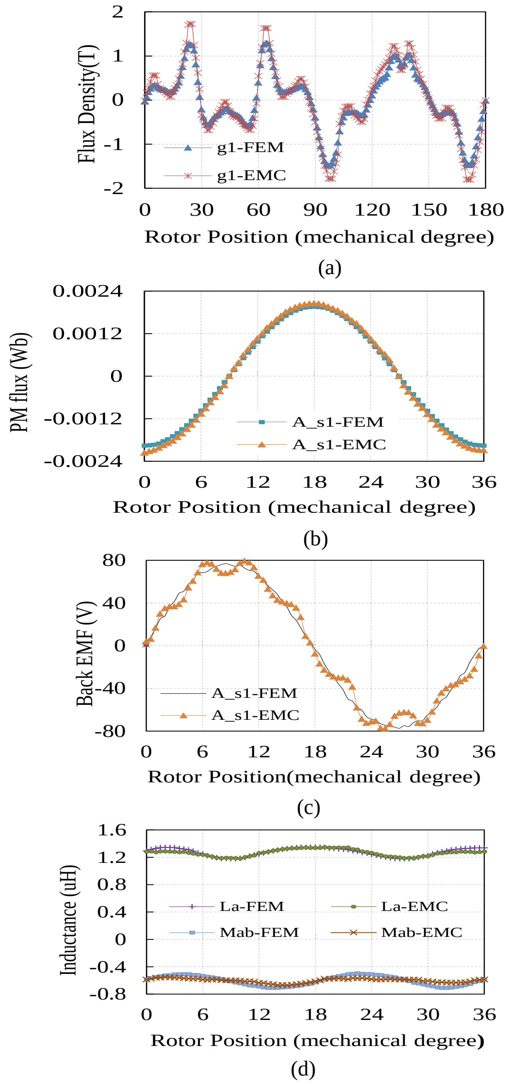


Fig. 3. Static Characteristics of AFFSPM Machine. (a) Air-gap flux density. (b) PM flux per turn of A-phase. (c) Back EMF per turn of A-phase. (d) Inductance per turn of A-phase.

where n is the number of magnetic potential nodes. The magnetic potential matrix is sparse, symmetrical and positive definite, which accelerates the solution of the nodal magnetic potential equations. Generalized multi-variable damping method is adopted to solve the above non-linear equations in this paper.

IV. Static Characteristics Analysis with EMC

The air-gap flux density, permanent magnetic flux linkage, back EMF, and inductance characteristics of the machine are analyzed based on the EMC model. The results are compared with those of FEM, as shown in Fig. 3.

As will be seen, the air-gap PM flux density of AFFSPM machine has a big difference in the peak position with two methods. The value of phase PM flux with EMC method is lower than that with FEM. The phase back EMF waveform with EMC method has more harmonics than that with FEM. The self and mutual inductance values of A-phase calculated with EMC method are lower than those with FEM. It results

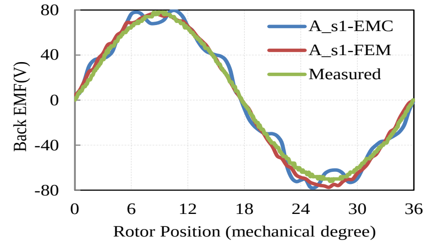


Fig. 4. Back EMF of Prototype.

from the fact that the calculation of inductance relates to the value of flux.

V. Experimental Results

A prototype AFFSPM machine has been constructed and tested to validate the results predicted by the EMC model. The back EMF waveform at rated speed of 1500r/min has been measured, as shown in Fig. 4.

As will be seen, a good agreement is achieved between measured results and EMC prediction. The measured back EMF is smoother than the EMC prediction because of relevant assumptions. Initially, the magnetic field is supposed to be evenly distributed taking no account of magnetic saturation and each single piece of magnet is supposed to be a magnetic circuit branch. These assumptions need to be optimized further to get more accurate results of EMC model prediction.

VI. Conclusions

AFFSPM machine is a novel permanent magnet machine with sinusoidal back EMF and high torque density, which is more suitable for brushless ac operations. In this paper, a nonlinear equivalent magnetic circuit model of AFFSPM machine has been developed to predict the electromagnetic performance, such as the air-gap flux density, phase permanent magnetic flux linkage, phase back EMF and inductances, the predictions being validated by finite-element calculations and experimental measurements. The results show that the EMC method may be applied to the initial design of the machine.

VII. References

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