Hybrid Analytical Model of Halbach Array Permanent-Magnet Motors Considering Iron Saturation

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This paper proposes a conformal mapping and magnetic circuit hybrid model for predicting the magnetic field of Halbach array permanent-magnet (PM) motors considering iron saturation. The equivalent PM current replacing Halbach array is introduced to show the analytical air-gap field solution produced by Halbach PM array. In the hybrid analytical model, the slotted air-gap field is calculated using the conformal mapping model while the nonlinear iron field is represented by the magnetic circuit model. The interaction between the air-gap and iron region is based on the air flux source and equivalent saturation current. They are essential to iteratively solve the hybrid analytical model. The finite-element analysis of an 8-pole/9-slot PM motors with Halbach array PM is carried out to verify the effectiveness of the hybrid analytical model.

Index Terms—Analytical models, nonlinear magnetics, permanent magnet motors, magnetic circuits.

I. INTRODUCTION

The Halbach array permanent-magnet synchronous motors (HAPMSM) have outstanding ability to enhance the fundamental amplitude of air-gap field with few harmonic components. Therefore, it can exhibit the feature of high torque density with low torque ripple and has been widely used in flywheel energy storage system [1], electrification transportation system [2], etc. Hence, there are strong demands to design and optimize the HAPMSM with high calculation accuracy and efficiency.

Finite element method (FEM) shows the highest accuracy to predict the performance of HAPMSM but it requires large computational resource [3]. The analytical model based on Poisson/Laplace equation can rapidly predict either slotless or slotted HAPMSM [4][5], but the accuracy is influenced by the saturation level in the iron region. The magnetic circuit model was employed in [6] to account for the iron saturation, but the calculation accuracy cannot be guaranteed if the mesh of magnetic reluctance is coarse and inappropriate.

In this paper, a hybrid analytical model (HAM) which combined conformal mapping model and magnetic circuit model is proposed to account for both slotting effect and saturation effect. The equivalence between the PM current and Halbach PM array is established and therefore the analytical air-gap field solution can be obtained. The air flux is calculated from the conformal mapping model and it flows into iron region to solve the magnetic circuit model of stator. Accordingly, the equivalent saturation current is calculated from the solution of magnetic circuit model and produces the air-gap field representing iron saturation. The calculation of the decreased air-gap field is obtained from conformal mapping model. The solving loop is formed to iteratively predict the magnetic field of HAPMSM. The accuracy of the proposed model is validated by FEM results.

II. HYBRID ANALYTICAL MODEL

The HAM which combines analytical model with magnetic circuit model can accurately predict the electromagnetic performance of HAPMSM. The following assumptions are made for the proposed model: 1) The PM has linear magnetization; 2) The eddy current effect and end effect are neglected. 3) The iron, copper, and PM materials are isotropic and homogenous.

A. Analytical Model

The PMs with radial and tangential magnetization can be regarded as the surface PM current. In HAPMSM, the PM with different magnetization can be represented by radial and tangential magnetized PM and therefore the equivalent PM current can be obtained. Then four conformal mappings are used to considering the slotting effect and obtain the air-gap field [7].

\[
B_{y\nu k} (r_H, \alpha_H) = \frac{\mu_0 i_{eqk} (R_{y\nu}, \alpha_{y\nu})}{2\pi} \left\{ \gamma_{\nu} + \sum_{n=1}^{\infty} \frac{R_{y\nu}^{2n} + R_{y\nu}^{2n+1}}{R_{y\nu}^{2n} - R_{y\nu}^{2n+1}} \sin \left[ n(\alpha_{y\nu} - \alpha_{y\nu}) \right] \right\} 
\]

B. Magnetic Circuit Model

The magnetic field of iron region in the HAPMSM is calculated using magnetic circuit model. When the air-gap field is obtained, the air flux source can be calculated by the integral of radial flux density in the air-gap. According to the Kirchhoff’s voltage law, the magnetic circuit model can be solved based on the BH curve of iron using the Newton-Raphson iteration method. Thus, the iron magnetic potential distribution \( F \) can be used to calculate the equivalent saturation current \( I_{sat} \).

\[
I_{sat} = C_0 F
\]

where \( C_0 \) is the constant incidence matrix.
C. Hybrid Analytical Model

The air flux source and equivalent saturation current are the interface between conformal mapping model and magnetic equivalent model to form the hybrid analytical model. Accordingly, the solving loop is established to calculate the magnetic field distribution of HAPMSM. Based on the air-gap field distribution, the performance of HAPMSM can be determined.

III. Finite Element Validation

An 8-pole/9-slot HAPMSM is designed to show the effectiveness of the HAM. The stator iron is nonlinear in the analysis. The iron of rotor yoke is removed and therefore the Halbach PM array is stuck in the non-magnetic shaft. In Fig. 1, the air-gap field distribution at rated load using HAM agrees well with FEM results. As for electromagnetic torque in Fig. 2, HAM overestimates the electromagnetic torque due to some simplification in surface PM current. However, the torque error is only 3%. The back-EMF waveform calculated using HAM has high accuracy compared with FEM prediction, Fig. 3.

Fig. 1 The air-gap field comparison using HAM and FEM. (a) radial component and (b) tangential component.

Fig. 2 The comparison of torque waveform using HAM and FEM.

Fig. 3 The comparison of back-EMF waveform using HAM and FEM.

The calculation time of HAPMSM using Ansys Maxwell is 280s under rated load condition while it is 25.5s using HAM in MATLAB platform. The HAM can save over 9/10 the computational resource of FEM while the error of torque prediction using HAM is about 3.0%.

IV. Conclusion

In this paper, the hybrid analytical model is proposed for calculating the performance of HAPMSM considering both slotting effect and saturation effect. It combines the advantages of conformal mapping model with magnetic circuit model to significantly improve the calculation. In the conformal mapping model, the equivalent PM current for radial and tangential magnetized PM is introduced to represent the PM with any magnetization direction. The equivalent saturation current is obtained from the magnetic circuit model and represent the saturation level in the iron region. The FEM results validate the high accuracy and efficiency of the proposed model.

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REFERENCES


