Design Optimization of the Interior Permanent Magnet Motor for Torque Ripple Minimization using Hybrid Analysis Model

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This paper proposes the new conceptual design method for minimizing the torque ripple of the interior permanent magnet (IPM) motor. To reduce the computational time for predicting the driving performance of the IPM motor and optimizing its structural shape, both the magnetic equivalent circuit (MEC) and the finite element (FE) are employed to perform the magneto-static analysis and the design optimization process. A simple circuit is defined by the reluctance components and the magneto-motive force to represent the total motor system and the FEs are created only in a small design area, such as the stator shoe and the outer rotor, of which shape is important to adjust the airgap flux. In FE domain, the distribution of the level set function represents a detailed shape of the magnetic material. The optimization problem is formulated to minimize the torque ripple, which is calculated by the MEC, and to obtain the optimal distribution of the magnetic material in FE domain, sequentially. To verify the effectiveness of the proposed method, an IPM motor design problem will be provided.

***Index Terms*—Design optimization, hybrid analysis method, interior permanent magnet motor, torque ripple minimization**

I. INTRODUCTION

INTERIOR PERMANENT magnet (IPM) motor has been widely used in the industry due to its high power density. Since the output torque of the IPM motor is the combination of the magnetic torque and the reluctance torque, an important issue of the motor design is the minimization of the torque fluctuation. Thus, many previous researches have proposed various techniques to minimize the torque ripple and it was confirmed that the shape change of the motor is the effective way to satisfy the target torque performance [1]-[2]. Especially, design optimization methods based on finite element (FE) analysis could provide a detailed motor geometry that greatly affects to the torque performance [3]-[4]. However, since the IPM motor has a complex structure, such as the flux barrier and bridge in the rotor, a large number of FE is often required to perform the motor analysis and occurs the huge computational cost.

To overcome inefficiencies in previously developed FE-based design methods, a simple design methodology is presented in this paper by introducing the concept of a hybrid analysis method [5]. The magnetic equivalent circuit with lumped parameters is defined to express the entire motor system first, the FEs are created only in the design domain for minimizing the design variables and saving a lot of computational time. The magnetic potential, which can be calculated in terms of the circuit flux, is used to combine the two different types of analysis domain. The optimization problem is formulated to minimize the difference between the circuit flux, which is obtained from the circuit optimization for minimizing the torque ripple, and the magnetic flux distributed in the FE domain. The outer boundary of the magnetic material is clearly presented by the level set function. A design problem of Interior permanent magnetic motor, which was developed for traction motor of hybrid electric vehicle, is performed to check an advantage of the proposed method.

II. PROBLEM FORMULATION

A. *Magnetic Equivalent Circuit for IPM Motor*

To construct a MEC for predicting the magnetic characteristics of the IPM motor, the reluctance components (R) and the magneto-motive force component from the coil (MMF_{coil}) and the magnet (MMF_{PM}). Since the flux density distribution of the airgap plays an important role in the motor performance, many circuit branches are defined in the airgap, as shown in Fig. 1. Then, the magnetic flux inside the motor (Φ) can be calculated by the following equation.

$$[MMF]=[R][\Phi] \tag{1}$$

B. *Optimization Problem Formulation*

Hybrid analysis optimization process is presented in fig. 2. There are two optimization steps, the first step is MEC reluctance parameter optimization, and second step is shape optimization based on FEM. In the first step, optimal circuit parameters for minimizing the torque ripple, which is calculated in terms of the circuit flux, is obtained by the following problem.

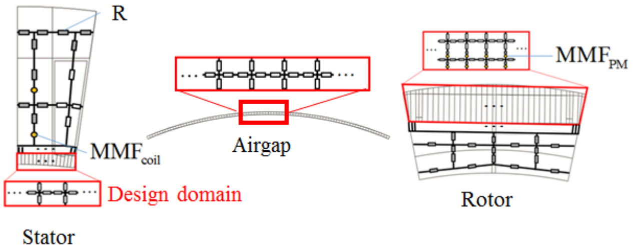

Fig. 1. Configuration of IPM motor MEC model

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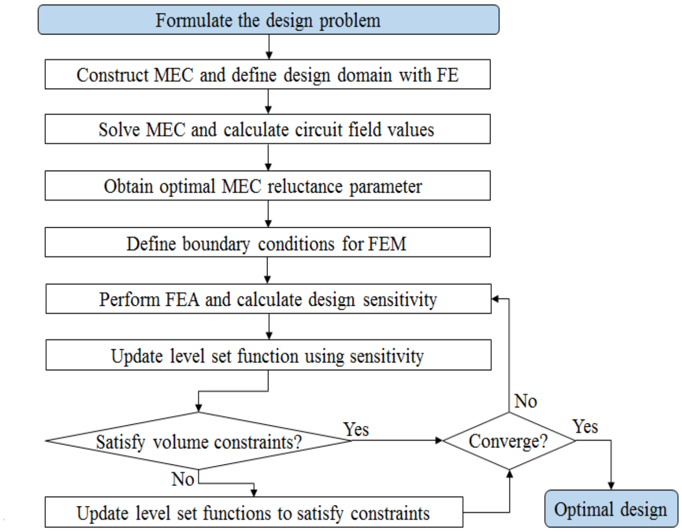


Fig. 2. Process of the hybrid analysis

$$\begin{aligned}&\underset{R}{\text{minimize}}\ T_{\text{ripple,MEC}}(\Phi)\\&\text{subject to }R_{\min}\le R\le R_{\max}\end{aligned}\tag{2}$$

Where $R_{\min}$ and $R_{\max}$ are the minimum and the maximum reluctance value, respectively. The optimal values of the circuit flux (Φ_{opt}) and the reluctance (R_{opt}) are used to define the boundary condition of the FE-based design domain and perform a detailed shape optimization.

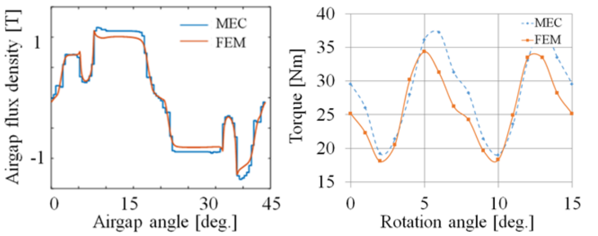
In the second step, the objective function for obtaining the structural design (f_{FE}) is defined as the difference between magnetic flux densities calculated from the MEC ($B_{\text{MEC,opt}}$) and the FE analysis domain (B_{FE}). The optimization problem is formulated to minimize it with the volume fraction constraint (VF) of the magnetic material.

$$\begin{aligned}&\underset{\phi}{\text{minimize}}\ f_{\text{FE}}(\phi)=\left|B_{\text{MEC,opt}}-B_{\text{FE}}(\phi)\right|\\&\text{subject to }g(\phi)=\text{VF}(\phi)-\text{VF}_0\le 0\end{aligned}\tag{3}$$

Where ϕ is the level set function, which is the FE-based design variable.

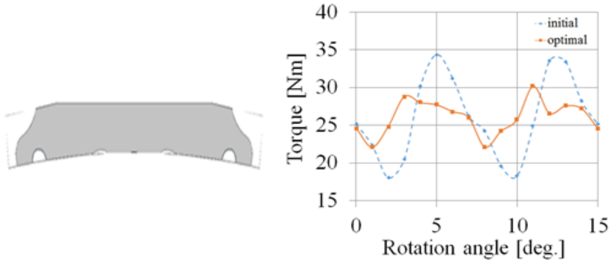
III. DESIGN EXAMPLE

To verify the effectiveness of the proposed method, the torque reduction design of interior permanent magnet motor is performed. The design domain where the FE are created is set to the stator shoe and the outer boundary of the rotor nearby the airgap, as shown in Fig. 1. Before performing the optimization, the airgap flux distribution and the torque profile were calculated for verifying the accuracy of the MEC, as shown in Fig. 3, and it is noted that the circuit variables provide sufficient analysis results to perform the design optimization. The optimal teeth shape and the torque profile are illustrated in Fig. 4 (a). It is noted that the optimal shape of the teeth can reduce the torque ripple about 49.3%, as summarized in TABLE 1.



(a) (b)

Fig. 3. Comparison of analysis results between the FEM and the MEC: (a) Airgap flux distribution (b) torque profile



(a) (b)

Fig. 4. Optimal results: (a) optimal teeth shape (b) torque profile

TABLE I
TORQUE ANALYSIS RESULTS

	Average torque[Nm]	Torque ripple (Peak-peak)
Initial model	25.95	16.35
Optimal model	26.06 (0.3%↑)	8.05 (49.3%↓)

IV. CONCLUSION

This paper presents an efficient optimization method for shape design of an IPM motor. In the proposed design method, the MEC with simple operating equation is employed to estimate the motor performance while reducing the computational time and the detailed shape design also can be achieved by the FE-based design domain.

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