Topology Optimization of an IPM Motor Flux Barrier Based on Current Phase Angle Using a Multistep Evolutionary Algorithm

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***Abstract*—This paper derives an effective shape for the flux barrier in an interior permanent magnet (IPM) motor. Generally, IPM motors have many design parameters, such as the current phase angle, the iron core shape of the rotor and stator, and the shape and position of the magnet. The flux barrier plays an important role in controlling the torque characteristics. We apply topology optimization to the rotor core using a multistep evolutionary algorithm to determine an effective flux barrier. Furthermore, we extend the topology optimization to combinatorial optimization in consideration of the effect of the current phase angle. As a result, a reasonable flux barrier with optimal phase angle is described.**

***Index Terms*—design optimization, finite element methods, genetic algorithm, permanent magnet motor, topology**

I. INTRODUCTION

Topology optimization (TO) is an effective method in the design of novel electrical machines, because it has the ability to realize more flexible shapes than either size or shape optimization. Therefore, TO has been applied to electric motors [1], [2]. In various motors, the interior permanent magnet (IPM) has many design parameters, such as the shape of the rotor and stator, the phase angle of the input current, and so on. The flux barrier of the rotor core, which strongly affects the torque characteristics, is one of the most important parts. Therefore, we aim to derive an effective flux barrier by means of TO.

A multistep genetic algorithm (MSGA) [3] is adopted as the TO method. While MSGA has been applied to simple magnetic circuit problems to verify its performance, its effectiveness with rotating machines is still unknown. Because the finite element analysis of rotating machines takes more time than for static apparatus, we implement the MSGA on a PC cluster. Extending MSGA to a finite element mesh composed of quadrilateral elements, TO of the flux barrier is achieved under the condition that the current phase angle is added to the design parameters.

II. BINARY-BASED TOPOLOGY OPTIMIZATION METHOD

A. Chromosome Expression in Consideration of the Topology of a Magnetic Circuit and Current Phase Angle

Not only the flux barrier but also the current phase angle affects the torque characteristics. Therefore, it is significant to add the phase angle to the set of design parameters. Fig. 1 shows a binary expression based on the topology of the magnetic circuit and phase angle. The bit strings are composed of n_d bits for the magnetic circuit and n_θ bits for the phase angle, and the total number of design variables is equal to $(n_d + n_\theta)$. Binary data for the phase angle is transformed to decimal data θ_d. Next, the current phase angle θ_p is determined from the decimal data θ_d as follows:

$$\theta_p = \theta_{\min} + \frac{\theta_{\max} - \theta_{\min}}{2^{n_\theta}}(\theta_d - 1)\,, \tag{1}$$

where $\theta_{\min}$ and $\theta_{\max}$ are the minimum and maximum values of the constraint condition for θ_p. The above expression for a chromosome simultaneously achieves TO of the magnetic circuit combined with the identification of the phase angle.

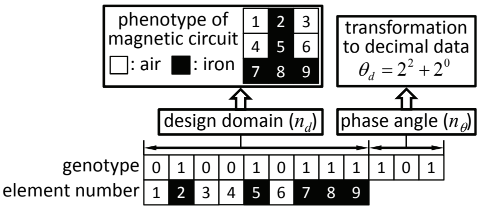

Fig. 1. Relationship between phenotype and genotype information.

B. Construction of Multistep Scheme

To complete the multistep scheme between quadrilateral meshes, as shown in Fig. 2, the coarse solution mesh be allocated to the finer mesh. Determining the inside and outside of the gravitational center (x_c, y_c), based on the element e, is performed by solving the nonlinear equations:

$$f_x(\xi,\eta) = \sum_{k=1}^{4}\{N_k(\xi,\eta)x_k\} - x_c = 0\,, \tag{2}$$

$$f_y(\xi,\eta) = \sum_{k=1}^{4}\{N_k(\xi,\eta)y_k\} - y_c = 0\,, \tag{3}$$

where (x_k, y_k) are the global coordinates of node k on the coarse mesh, (ξ, η) show the local coordinates of the element e, and $N_k(\xi, \eta)$ shows the finite element shape function of the quadrilateral. If ξ and η are in [-1, 1], the element with gravitational center (x_c, y_c) is judged to be inside of e.

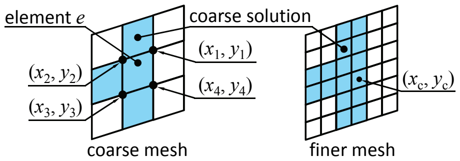

Fig. 2. Allocation of coarse solution to finer mesh in quadrilateral elements.

III. OPTIMIZATION MODEL AND DESIGN GOAL

A. IPM Motor Model

We adopt the IPM motor D-model [4] shown in Fig. 3 as an application target. The D-model is analyzed on the condition that the motor is driven by a three-phase sinusoidal AC current, in which the amplitude of the input current is set to 420 AT with frequency 50 Hz, and the nonlinearity of the iron material 50A350 is imposed on the rotor and stator core. The design domain is set to a half region using axial symmetry.

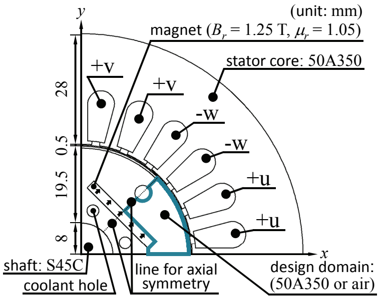

Fig. 3. Optimized model of IPM motor.

B. Objective Function

The TO goal is to maximize the average torque T_{ave} on the condition that the area S_{iron} of the rotor core and torque ripple T_r are kept below the specified values S_0 and T_0. Therefore, the formulation of TO can be defined as follows:

$$\begin{aligned} &\textit{Maximize} && T_{\mathrm{ave}} \\ &\textit{Subject to} && S_{\mathrm{iron}} = \iint_{S_d} dS \le S_0, \\ &&& T_r \le T_0 \\ &&& \theta_{\min} \le \theta_p \le \theta_{\max} \end{aligned} \tag{4}$$

where S_d gives the area of the iron core in the design domain. The constraint condition is unified with a single objective function as the penalty function. The constraint values of $\theta_{\min}$ and $\theta_{\max}$ are set to 0° and 15°, respectively.

IV. OPTIMIZATION RESULTS

The GA parameters are defined as shown in Table I. Uniform crossover and dynamic mutation rates [5] are used to prevent the system from falling into a local minimum, and the step number of the MSGA is set to two. The MSGA is parallelized by MPI (Message Passing Interface) library to the overclocked PC cluster, which is composed of 17 PCs running at 4.2 GHz. The fitness evaluations using finite element method in one generation are allocated to 50 threads on the PC cluster.

Fig. 4 shows the optimized topologies. S_{iron} and T_r of the standard model are adopted as S_0 and T_0, respectively. The protrusions are generated in the flux barrier to improve the torque characteristics. With the addition of the phase angle to the design variables, TO functions effectively, as shown in Fig. 5. $T_{\min}$ is improved by this consideration on the phase angle.

TABLE I
GA PARAMETERS

population number	power of scaling	crossover ratio	dynamic mutation		elite number	fitness
			p_0	γ		
50	1	0.8	0.1	0.01	6	1 / W

As a result, TO including the phase angle improves T_{ave} by $T_{\min}$ increments provided the constraint conditions on T_r and S_{iron} are satisfied, as shown in Table II. Detailed data and the results using various evolutionary algorithms will be given in the full paper.

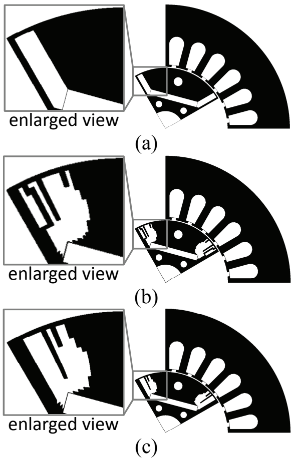

Fig. 4. Optimal topologies: (a) standard model, (b) without phase angle change, (c) with phase angle change.

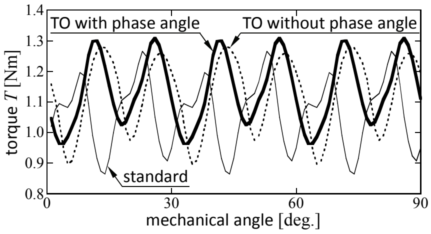

Fig. 5. Torque characteristics.

TABLE II
OPTIMIZATION RESULTS

physical quantity	standard	TO results	
		without phase angle	with phase angle
θ_p [°]	3.90	0	3.57
$T_{\max}$ [Nm]	1.27	1.28	1.31
$T_{\min}$ [Nm]	0.864	0.897	0.964
T_{ave} [Nm]	1.06	1.12	1.14
T_{r}	0.377	0.342	0.303
$S_{\mathrm{iron}}\times10^{-4}$ [m^2]	1.46	1.28	1.29
elapsed time [h]	–	27.0	24.3

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