Topology Optimization of IPM Motors: Minimization of Iron Losses

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This paper presents topology optimization of IPM motors where their rotor shapes are determined so that the eddy current and hysteresis losses are minimized under the constraint that the average torque is greater than a given threshold. The topology optimization is performed using the on/off method based on the Normalized Gaussian network (NGnet). The rotor which has deep notches is found to be optimal because of its relatively small surface area where the iron losses concentrate.

***Index Terms*—Design Optimization, finite element analysis, permanent magnet motors.**

I. INTRODUCTION

TORQUE characteristics and efficiency of the IPM motors, which are widely used in, e.g., hybrid vehicles [1] and air conditioners *et al.*, strongly depend on the magnitude of remanent field, size and configuration of magnets as well as configuration of flux barriers in the rotors. For this reason, there have been many studies in optimization of the rotor structures of IPM motors. In particular, topology optimization has been attained attentions because it can perform optimization not only with highly flexible shape representation of magnets and flux barriers but also possibility in essential changes of the rotor topology [2]-[4].

There are two major topology optimization methods: level set- and on/off-based methods. The level set method has some advantages; it can find smooth optimal shapes which would be suitable for manufacturing, and it has relatively low computational cost because the optimization is usually performed with deterministic methods. Its applicability is, however, rather restricted because the objective function must be differentiable, in a sense of Fréchet derivative, with respect to the level set function.

On the other hand, because the optimization with on/off method can be carried out with metaheuristic algorithms, it can be applied to wider class of optimization problems with complicated restrictions. The conventional on/off method in which on/off status is attributed to each finite element often results in complicated shapes due to its excessively high degree of freedoms [5]. This problem can be resolved by employing the normalized Gaussian network (NGnet) in which the rotor shape is represented with relatively small number of the Gaussian bases [6, 7]. Although the rotor shape of reluctance motors have successfully been optimized by the NGnet method [6], its validity for optimization of IPM motors considering iron losses and torque characteristics has been unclear.

In this work, the optimization of the rotor core in an IPM motor is performed by the NGnet method considering iron losses as well as torque characteristics. It will be shown that the rotor which has deep notches is optimal because of its relatively small surface area where the iron losses concentrate.

II. OPTIMIZATION METHODS

A. Iron loss analysis

To compute the iron loss in steel iron sheets in IPM motors, we employ the 1-D method [8] in which the flux distribution in one steel sheet is evaluated in the post processing of the 2-D FEA. In this method, the following equations are solved.

$$\frac{\partial}{\partial z}\left(\frac{1}{\mu}\frac{\partial A_x}{\partial z}\right)=\sigma\frac{\partial A_x}{\partial t}, \tag{1}$$

$$\frac{\partial}{\partial z}\left(\frac{1}{\mu}\frac{\partial A_y}{\partial z}\right)=\sigma\frac{\partial A_y}{\partial t}, \tag{2}$$

where z is the thickness direction of the steel sheet, σ and μ denote conductivity and permeability, respectively, and A_x, A_y are x, y components of magnetic vector potential. Equations (1) and (2) are solved under the boundary conditions given by

$$\left(A_x, A_y\right)\Big|_{z=\frac{h}{2}}=\left(\frac{B_y h}{2}, \frac{B_x h}{2}\right), \tag{3}$$

$$\left(A_x, A_y\right)\Big|_{z=0}=\left(0,0\right), \tag{4}$$

where h is thickness of the sheet. After the solutions of (1) and (2), the eddy current loss W_e is computed as follows:

$$W_e=\sum_{i=1}^{N_{\mathrm{E}}}\frac{2\Delta V^i}{Th}\int_0^T\int_0^{\frac{h}{2}}\kappa\sigma\left|\frac{\partial \boldsymbol{A}}{\partial t}\right|^2 dldt, \tag{5}$$

where N_{E}, T, ΔV^i and κ are the number of 2-D finite elements, time period, volume of the i-th 2-D finite element in the rotor core and the correction coefficient for excess eddy current loss, respectively. Moreover, hysteresis loss W_h is computed as follows:

$$W_h=\frac{K_h D}{T}\sum_{i=1}^{N_{\mathrm{E}}}\sum_{k=1}^{ne}\frac{\Delta V^i l_k}{h}\left\{\sum_{j=1}^{N_x^i}\left(B_x^{ij}\right)^2+\sum_{j=1}^{N_y^i}\left(B_y^{ij}\right)^2\right\}, \tag{6}$$

where K_h, D and n_e are the hysteresis coefficient, the density of electrical steel sheet and the number of 1-D finite elements in a steel sheet, and B^{ij}_x, B^{ij}_y are x and y components of the magnetic induction, and N^i_x, N^i_y are the number of peaks in each waveform, respectively.

B. Topology Optimization based on NGnet

In this method, the on/off states of each finite element are determined through the output of NGnet [7]. The output of NGnet $y(\boldsymbol{x}_e)$ is given by

$$y(\boldsymbol{x}_e)=\sum_{i=1}^{N} w_i b_i(\boldsymbol{x}_e), \tag{7}$$

$$b_i(x_e)=\frac{G_i(\boldsymbol{x}_e)}{\sum_{j=1}^{N} G_j(\boldsymbol{x}_e)}, \tag{8}$$

where $\boldsymbol{x}_e$, N, and w_i are center of the finite element e, number of Gaussian bases and weighting coefficient, respectively. Based on (7), the element state V_e is determined by

$$V_e \leftarrow \begin{cases} on & y(\boldsymbol{x}_e)\geq 0, \\ off & y(\boldsymbol{x}_e)<0. \end{cases} \tag{9}$$

Since the output of NGnet is spatially smooth, the determined rotor shape is expected to have smooth boundaries. In the optimization, the rotor shape is varied by changing $y(\boldsymbol{x}_e)$. Because $y(\boldsymbol{x}_e)$ depends on w_i, the optimization is performed for w_i. In this work, we employ the real-coded genetic algorithm (RGA) to determine the optimal value of w_i.

III. OPTIMIZATION OF IPM MOTOR

A. Optimization problem

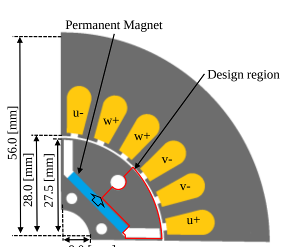
The rotor shape of the IPM motor [7] shown in Fig. 1 (a) is optimized. Design region of the model is 1/8 of the rotor because of symmetry. The Gaussian bases are uniformly distributed in the design region as shown in Fig. 1 (b). The driving condition and specifications are summarized in Table. I. In this optimization, 50A470 is assumed for the core material whose magnetic nonlinearly is considered. The electronic and mechanical parameters of 50A470 are assumed as follows: κ=0.96, K_h=2.56 × 10^6, σ=2.71 × 10^{-2} S/m, D=7.70 × 10^3 kg/m^3.

The optimization is defined as follows:

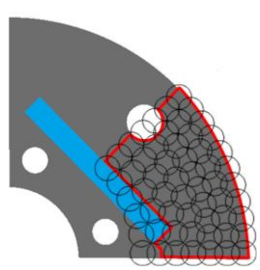
$$F=-\frac{W_{\text{loss}}}{W_{\text{ref}}} \rightarrow \max., \tag{10}$$

$$\text{sub.to} \quad T_{\text{ave}} > T_{\text{ref}}, \quad N_{\text{area}} < 2, \tag{11}$$

where W_{loss} and T_{ave} denote the iron loss in the rotor and average torque, and W_{ref}=1.30 W and T_{ref}=2.08 Nm are iron loss and average torque of the reference model in Fig. 1 (a). Moreover, N_{area} measures the number of disconnected iron cores. Thus, the last condition in (11) states that the iron core in the rotor has to form a connected domain.



(a) IPM motor model [7]



(b) Deployment of Gaussians

Fig. 1 IPM motor for optimization

TABLE I
ANALYSIS CONDITIONS AND SPECIFICATIONS

Rotation speed [rpm]	1500
Current amplitude [A]	$3\sqrt{2}$
Number of turn [turn]	35
Current phase angle [degree]	30
Residual flux density of PM [T]	1.25

B. Optimization Result

The optimized shape is shown in Fig. 2 (a). It is found that there are deep notches which expend from the surface of the rotor to the ends of the magnet. Fig. 2 (b) shows the distribution of the iron loss, which concentrates near the surface of the rotor core. It is suggested from the optimization results that the resultant deep notches effectively reduce the iron losses near the rotor surface and also effectively guide the magnetic fluxes from the magnet to the stator.

In the long version, optimization results in which losses in the stator iron and magnets are taken into account will be reported

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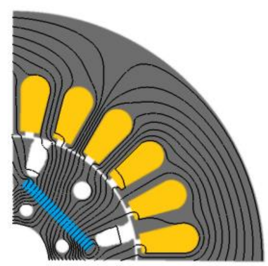
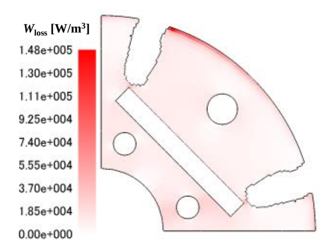


T_{ave} = 2.09 Nm, W_{loss} = 1.04 W

(a) Optimized shape and flux lines



(b) Iron loss density distribution

Fig. 2. Optimization result

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