

Reduction of Harmonic Components in Back Electromotive Force of IPMSM Using Topology Optimization

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In this paper, the reduction method of the harmonic components in the back electromotive force (EMF) using the topology optimization is proposed. Because the waveform of the back EMF in the interior permanent magnet synchronous motor (IPMSM) conventionally includes the harmonic components, the torque ripple and other physical quantities tend to deteriorate. By changing the rotor structure of IPMSM using the topology optimization, the harmonic components of the back EMF were successfully reduced. Furthermore, the relationship between the eddy current losses in the permanent magnet and the reduction of harmonic components in the back EMF was also investigated.

Index Terms—Back electromotive force, eddy current loss in permanent magnet, interior permanent magnet synchronous motor, and topology optimization.

I. INTRODUCTION

INTERIOR PERMANENT magnet synchronous motors (IPMSMs) are extensively applied to industrial machines. Because the IPMSMs are particularly implemented on the EVs to realize the carbon neutral society [1], it is essential to improve the performance of IPMSMs.

It is pointed out that the back electromotive force (EMF) affects torque ripple [2]. In the reference, the waveform of the back EMF was changed to the sinusoidal one to realize the sinusoidal change of the flux distribution in the airgap by changing the size of stator core. In reference [3], the relationship between the back EMF and some important physical quantities, such as efficiency and so on, are discussed.

In this paper, using the topology optimization method which changes the magnetic core of the IPMSM rotor, the reduction of the harmonic components of the back EMF was investigated. Then, by adding a term for the average torque to the objective function, the enhancement of torque characteristic was attempted. Furthermore, it was shown that the reduction of harmonic component in the back EMF was related to the reduction of the eddy current losses in the permanent magnet.

II. TOPOLOGY OPTIMIZATION PROCEDURE

A. Mathematical Expression of Design Domain

In this paper, the material density approach is applied to the definition of the iron core area in IPMSM rotor. Therefore, by using the smoothed Heaviside function $H(\phi)$ [4] which changes within the range of $[0,1]$, the reluctivity ν in the design domain is expressed as follows:

$$\nu(\phi, \mathbf{B}) = \{1 - H(\phi)\} \nu_0 + H(\phi) \nu_{\text{iron}}(\mathbf{B}), \quad (1)$$

where ϕ is the design variable, $\mathbf{B}$ is the magnetic flux density, ν_0 and $\nu_{\text{iron}}(\mathbf{B})$ show the reluctivity in vacuum and the iron core, respectively. By changing ϕ in the range of $[-h, h]$, ν changes in the range of ν_0 and $\nu_{\text{iron}}(\mathbf{B})$.

B. Sensitivity Calculation of the Back EMF

To minimize the objective function W comprising the back EMF, the sensitivity (gradient) of W is applied. Therefore, the adjoint variable method [5] in the nonlinear magnetostatic field is used. The back EMF in the winding slots is evaluated by:

$$V(t) = -\frac{d\Phi(t)}{dt} \approx -\frac{\Phi^{(k)} - \Phi^{(k-1)}}{\Delta t}, \quad (2)$$

where $\Phi(t)$ is the linkage flux evaluated in the specified slot, and Δt is the time step size. When the sensitivity of (2) is calculated, two adjoint equations at each rotor position of IPMSM are obtained [4].

C. Optimization Method

The sensitivity $\partial W / \partial \phi$ is applied to the iteration scheme for the steepest descent method (SDM). The update formula of ϕ at n -th iteration is shown as follows:

$$\phi_{n+1} = \phi_n - \frac{h}{\left\| \partial W / \partial \phi \right\|_{\infty}^{(n)}} \frac{\partial W}{\partial \phi} \Big|^{(n)}, \quad (3)$$

where (3) is iterated until the iteration number n reaches k_{DM} .

III. OPTIMIZATION TARGET

A. IPMSM Model

In this paper, IPMSM implemented on the 3rd generation of TOYOTA Prius is set as the optimization target.

Fig. 1 shows the IPMSM model. Fig. 1 (a) shows a quarter cross-section of the reference model. In its IPMSM, the number of poles is 8, and 48 slots. The standard symbol of electrical steel sheet is 30JNE1500. Fig. 1 (b) shows the design domain Ω_D (yellow region) and the region Ω_{EMF} (blue region) for the evaluation of the back EMF. The initial value of ϕ defined in Ω_D is set to zero, thus, its state represents the gray scale region.

The parameters for magnetic field analysis of IPMSM are shown in TABLE I where N is the turn number at each slot, I is the root mean square value, β is the current phase angle, f is the

frequency of the current, σ is the conductivity of permanent magnet (PM), and M is the magnetization intensity of PM. The rotational speed of the IPMSM is 3,000 rpm.

B. Objective Function

The objectives of optimization are the minimization of the harmonic component of the back EMF and the maximization of the average torque t_a . Therefore, W is formulated as follows:

$$W = -t_a + \frac{p}{T} \int_0^T \{V(t) - V_o(t)\}^2 dt, \quad (2)$$

where p is the penalty coefficient which adjusts the order of two terms, T is one period, and $V_o(t)$ is the target back EMF which is the sinusoidal waveform.

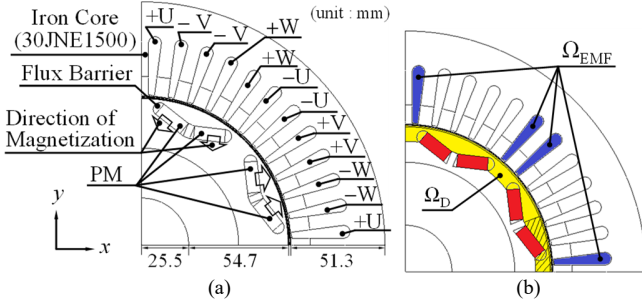


Fig. 1. IPMSM model. (a) Reference model of IPMSM. (b) Design domain and evaluation region for back EMF.

TABLE I

PARAMETERS FOR MAGNETIC FIELD ANALYSIS OF IPMSM MODEL

N [Turn]	I [Arms]	β [°]	f [Hz]	σ [S/m]	M [T]
11	134.0	51	200	7.14×10^5	1.04

IV. OPTIMIZATION RESULTS

In this paper, the case where $p = 1$ in (2) is referred to as case 1, and the case where $p = 5$ is referred to as case 2. The number of iterations k_{DM} in the topology optimization is set to 100.

Fig. 2 shows the rotor structures derived from two cases. In both results, the laminated-structure-shaped iron core was generated inside the flux barriers.

Fig. 3 shows the torque characteristics. In case 1, t_a increased in comparison to that of reference. After both optimizations, the torque ripples in both cases were reduced.

Fig. 4 shows the waveform of the back EMF. Although the higher harmonic components were included in the reference, the resultant waveforms derived from both topology optimization cases were quite similar to the sinusoidal waveform.

Fig. 5 shows the characteristics of the eddy current losses in PMs. By reducing the harmonic components of the back EMF, the eddy current losses were reduced.

V. CONCLUSION

In this paper, the topology optimization method which improves the torque characteristics and reduces the harmonic components of the back EMF was proposed, and its performance was verified in the IPMSM model (TOYOTA Prius).

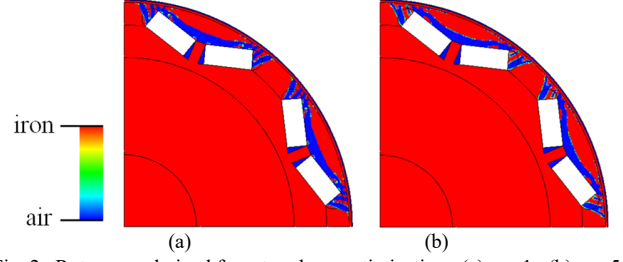


Fig. 2. Rotor core derived from topology optimization. (a) $p = 1$. (b) $p = 5$.

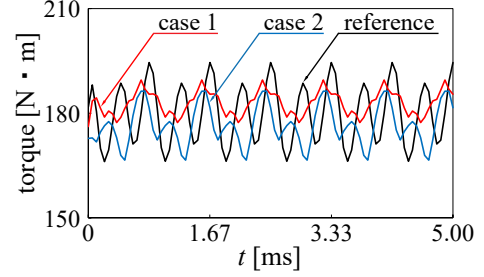


Fig. 3. Torque characteristics (t_a reference: 180.0 Nm, case 1: 184.0 Nm, case 2: 175.6 Nm).

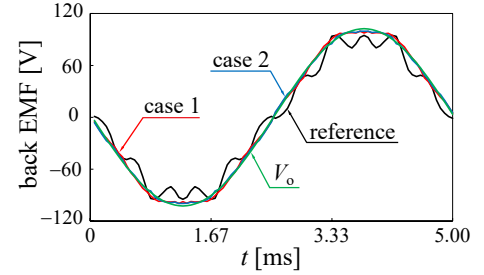


Fig. 4. Characteristics of back EMF.

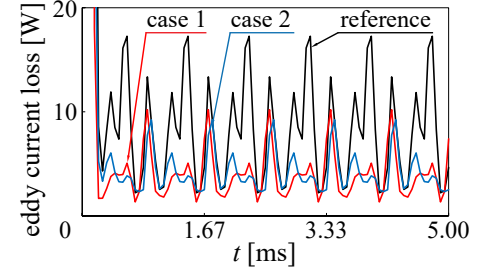


Fig. 5. Characteristics of eddy current losses in PMs.

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