Method for Evaluating the Eddy Current Loss of a Permanent Magnet in Surface PM Motor Using Coupled 2-D and 3-D Finite Element Analyses

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Abstract — To evaluate eddy current losses of permanent magnets (PMs) in interior PM (IPM) motors, we have already proposed the coupled 2-D analysis of the motor and 3-D eddy current analysis of only the PM taking account of the compensation field by itself and replacing the reluctance of the motor with a homogeneous equivalent gap. It was shown that the proposed method can estimate eddy current loss accurately in less computation time. In this paper, to apply the proposed method to surface PM (SPM) motors, the methods of considering the compensation field generated by the neighboring PMs are proposed. Moreover, the equivalent permeabilities of the gap varying in space are introduced. The effectiveness of the proposed method is shown by comparing with the full 3-D analysis of SPM motor.

I. INTRODUCTION

In evaluating eddy current losses of permanent magnets (PM) in PM motors, a 3-dimensional (3-D) eddy current analysis is required because the eddy currents flow 3-dimensionally [1-3]. However, such calculations are computationally very expensive because many time steps are required in 3-D eddy current finite element analysis of a PM motor driven by an inverter power supply when the harmonics corresponding to the carrier frequency are taken into account. Therefore, we have already proposed a coupled 2-D analysis of the motor and 3-D eddy current analysis [4] of only the PM taking account of the compensation field $H_{\mathrm{comp,c}}$ generated by the eddy current in the $\mathrm{PM_c}$ itself and replacing the reluctance of the motor with an equivalent uniform gap [5]. It was shown that the proposed method can estimate eddy current loss accurately in less computation time for IPM motor, in which the $H_{\mathrm{comp,n}}$ generated by the neighboring $\mathrm{PM_n}$ can be neglected because the $\mathrm{PM_c}$ is surrounded by iron core and the flux by $H_{\mathrm{comp,n}}$ generated from the $\mathrm{PM_n}$ passes through the core but not the $\mathrm{PM_c}$.

In this paper, to apply the proposed method to surface PM (SPM) motor, in which the distance between the surface of the $\mathrm{PM_c}$ and the stator core is not constant, moreover, the $H_{\mathrm{comp,n}}$ can not be neglected because the $\mathrm{PM_c}$ is bared from core, the proposed method is improved. First, the spatial variation of the equivalent permeability of the gap added around $\mathrm{PM_c}$ is considered. Next, two methods of considering the H_{comp} generated by the $\mathrm{PM_n}$ are proposed. Finally, the effectiveness of the proposed method is investigated by comparing with the full 3-D analysis of a SPM motor model.

II. SPM MOTOR MODEL

An analyzed model of SPM motor is shown in Fig. 1. Fig. 1(a) is the full 3-D model, in which only one layer of segmented PM is modeled. Figs. 1(b) and (c) are the 2-D model of motor and the 3-D model only of PM, respectively. The rotating speed of rotor is 2,400 min^{-1} and the phase angle of coil current is 40 deg. The current is 1,890AT rms.

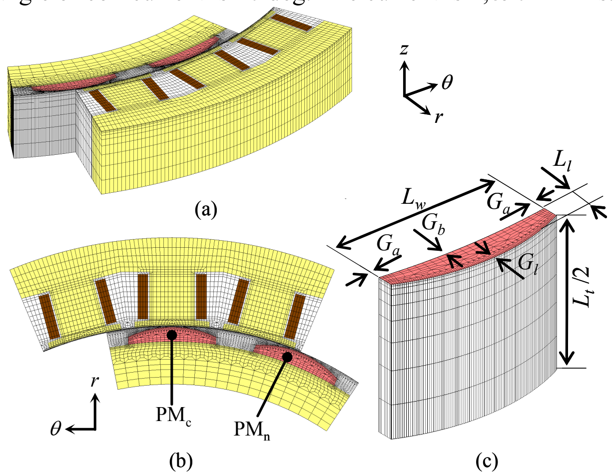

Fig. 1. Analyzed model of SPM motor, (a) 3-D full motor model, (b) 2-D motor model, (c) 3-D model of $\mathrm{PM_c}$.

III. ORDINARY COUPLED 2-D AND 3-D ANALYSES [5]

A. The 2-D Nonlinear Magnetostatic Analysis of the Motor

To obtain the temporally varying flux distributions in the $\mathrm{PM_c}$, in which the eddy current is calculated, we conduct 2-D nonlinear magnetostatic finite element analysis with the ordinary $\boldsymbol{A}$ method ($\boldsymbol{A}$: magnetic vector potential) of the PM motor using the mesh shown in Fig. 1(b) and rotating the rotor.

B. The 3-D Eddy Current Analysis of the PM

The 3-D eddy current analysis of only the $\mathrm{PM_c}$ shown in Fig. 1(b) is carried out using the flux distribution $\boldsymbol{B}_{p,c}$ in the $\mathrm{PM_c}$ obtained from the 2-D analysis. The eddy current in the $\mathrm{PM_c}$ is calculated using the finite element method with the $\boldsymbol{A}$-ϕ method (ϕ: scalar electric potential). In this method, the reluctances of not only $\mathrm{PM_c}$ but also motor cores and gaps should be considered in evaluating the flux generated by compensation field $H_{\mathrm{comp,c}}$. For this purpose, the gaps G_a, G_b, and G_l are added surrounding $\mathrm{PM_c}$ as shown in Fig. 1(c). Moreover, an equivalent permeability μ_l of gap G_l is obtained taking the reluctance R_m of the motor cores and the gaps G_a and G_b into account. R_m is determined from the difference $\Delta\Phi_{m,c}$ of the fluxes interlinking the $\mathrm{PM_c}$ obtained from double 2-D analyses by setting the magnetizations of the PM_c to be $\boldsymbol{M}_c$ and $\boldsymbol{M}_c + \Delta\boldsymbol{M}_c$ as follows;

$$\mu_l = \frac{G_l \mu_r \mu_0 \Delta\Phi_{m,c}}{\mu_0 \left(\Delta M_c \cdot L_l L_w L_t - L_t \Delta\Phi_{m,c}\right) - G_b \mu_r \Delta\Phi_{m,c}} \quad (1)$$

where μ_0 and μ_r are the permeability of vacuum and the recoil permeability of the PM. μ_l is changed with the coil current and rotor position.

IV. IMPROVEMENTS OF THE COUPLED 2-D AND 3-D ANALYSES

A. Variable Equivalent Gap

In 3-D eddy current analysis of PM_c of the ordinary coupled 2-D and 3-D analyses for IPM motor, the equivalent permeability μ_l of the gap G_l is uniform in space. However, μ_l should be variable in space for the SPM motor, because the distance between the surface of the PM_c and the stator core is not constant. Therefore, the variable $\mu_l^{(ie)}$ obtained by applying (1) to each element at the surface of the PM_c is specified to each element *ie* of the gap G_l correspondingly.

B. Consideration of Compensation Field Generated by Neighboring PMs

In the ordinary coupled 2-D and 3-D analyses for IPM motor, the compensation field $H_{comp,c}$ generated by itself in PM_c is considered, whereas $H_{comp,n}$ by the neighboring PM_n is neglected because the PM_c is surrounded by iron core and the flux by $H_{comp,n}$ passes through the core but not the PM_c. However, $H_{comp,n}$ cannot be neglected for SPM because the PM_c is bared from core as shown in Fig. 1. Two methods of considering $H_{comp,n}$ are proposed in this paper.

In the first method (Mehod A), the $\boldsymbol{B}_{p,c}$ in the PM_c for the 3-D eddy current analysis of only PM_c is modified by removing the difference $\Delta B_{eddy,c}$ of the flux distributions in the PM_c generated by the $H_{comp,n}$ of the PM_n. First, the 3-D eddy current analysis of only the PM_c at the position of the PM_n is carried out to obtain the $\Delta\Phi_{eddy,n}$ by $H_{comp,n}$ in the PM_n. Second, from the double 2-D analyses of the PM_n described in Section III. B, the relationship between the $\Delta\Phi_{m,n}$ in PM_n and the $\Delta B_{p,c}$ in the PM_c neighboring PM_n are obtained. Then $\Delta B_{eddy,c}$ can be calculated using the obtained $\Delta\Phi_{eddy,n}$, $\Delta\Phi_{m,n}$, and the $\Delta B_{p,c}$. The modified $\boldsymbol{B}_{p,c}^{k+1}$ at iteration k+1 is represented as follows:

$$\boldsymbol{B}_{p,c}^{\ k+1} = \boldsymbol{B}_{p,c}^{\ k} - \Delta B_{p,c} \frac{\Delta\Phi_{eddy,n}^{\ k}}{\Delta\Phi_{m,n}} \quad (2)$$

The 3-D eddy current analysis of only the PM_c is repeated until $\boldsymbol{B}_{p,c}^{k+1}$ converges.

In the second method (Method B), the effect of $H_{comp,n}$ generated from the PM_n is considered by carrying out the 2-D eddy current analysis taking account of the eddy currents in only the PM_n instead of the 2-D magnetostatic analysis mentioned in Section III. A. In the 2-D eddy current analysis, the conductivity σ of the PMs is corrected to modified σ^* using the thickness L_t and the width L_w of the PM as follows:

$$\sigma^* = \sigma L_t / \left(L_t + L_w\right) \quad (3)$$

Then, the 3-D eddy current analysis of only the PM_c is carried out taking account of the compensation field $H_{comp,c}$ generated by only itself.

V. RESULTS AND DISCUSSION

A. Eddy Current Losses

Fig. 2 shows the distributions of the average eddy current loss densities determined using the full 3-D analysis, and the ordinary method and the proposed Methods A and B in the coupled 2-D and 3-D analyses. The distribution obtained from the ordinary method is different from that obtained from the full 3-D analysis by the reasons mentioned above, whereas the result can be improved by Method A, moreover, the result of Method B is in good agreement with that of full 3-D analysis.

Table I compares the discretization data and computation time for the full 3-D analysis and the Method B. It is seen that the Method B can evaluate the eddy current loss in 1/11 of the computation time required for full 3-D analysis.

Methods A and B are compared with each other in more detail in the full paper.

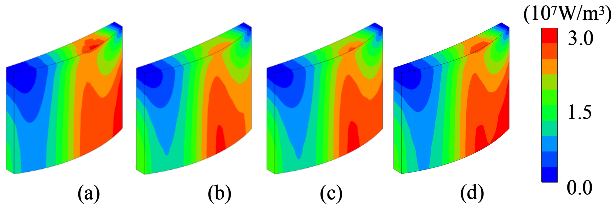

Fig. 2. Distributions of average eddy current loss densities determined using (a) full 3-D analysis, (b) ordinary method, (c) Method A, and (d) Method B.

TABLE I
DISCRETIZATION AND COMPUTATION TIME

Method	full 3-D	Method B	
		motor(2-D)	magnet(3-D)
No. of elements	58,194	6,466	4,680
No. of steps	97	97 × 2	97
CPU time (min)	210	5	15

CPU: Xeon E5420 (2.5GHz)
Convergence criterion ε_{ICCG} of ICCG method: 10^{-7}
Convergence criterion ε_{NR} of NR method: 0.001T

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