Electromagnetic Field Analysis Considering Reaction Field Caused by Eddy Currents and Hysteresis Phenomenon in Laminated Cores

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An analysis method for characteristics calculation of electric machines is proposed in order to take the effects of eddy currents and hysteresis phenomenon in laminated cores into account. In the proposed method, both the effects of eddy currents and hysteresis phenomenon are expressed as a reaction magnetic field against the exciting field. These fields are determined by coupling main electromagnetic field analysis neglecting the detailed structures of laminated cores and sub 1-D nonlinear time-stepping analysis along the thickness of electrical steel sheets. The validity of this coupling is confirmed by comparing the measured and calculated results of the core-material characteristics. The effects of the reaction field on the torque characteristics of rotating machines are also clarified.

***Index Terms*—Finite element methods, magnetic cores, magnetic hysteresis, eddy currents**

I. INTRODUCTION

EDDY CURRENTS and hysteresis phenomenon in laminated cores of electric machines cause several negative effects on the machine characteristics, which are not only the generation of iron loss, but also the iron-loss currents in exciting currents and the hysteresis torques in rotating machines. However, in the usual electromagnetic field analysis applied to electric machines, the laminated cores are often approximated to be solid magnetic materials without conductivity and hysteresis loops. In this case, the iron loss is approximately calculated by post procedure with the result of time variation in flux-density distribution obtained by the main analysis. As a consequence, the effects of the eddy currents and the hysteresis phenomenon in the laminated cores are completely neglected in the main analysis. More accurate analysis is desired in recent years because of the developments of high performance electric machines with low loss, high efficiency, and low torque ripples.

There are several reports, which tried to take these effects into account. Muramatsu el al. proposed the coupling between main electromagnetic field analysis neglecting the detailed structures of laminated cores and sub 1D analysis along the thickness of electrical steel sheet [1]. In this method, the permeability used in the main analysis is modified according to the result of the 1D analysis. Pippuri el al also developed the coupled 2D-1D analysis using complex permeability [2]. In this case, the imaginary part of the permeability is determined according to the eddy-current loss estimated by the sub 1D analysis. However, the effects of the hysteresis phenomenon are neglected in these analyses. One of the authors of this paper reported the method for direct eddy current analysis of the laminated cores in main electromagnetic field analysis [3] and post iron-loss analysis [4]. However, hysteresis phenomenon is also neglected in these analyses because the relationship between magnetic field and flux density is expressed by a single B-H curve. Takeda et al. expanded the post iron-loss analysis to consider both the eddy currents and the hysteresis phenomenon [5] by using play model [6]. However, the effects of the eddy currents in the laminated core are neglected in the main electromagnetic field analysis.

As described above, there are many other papers related to this subject. However, it can be stated that the consideration of both the eddy currents and the hysteresis phenomenon in the main electro-magnetic field analysis is still difficult from the viewpoint of computer resources and stability of nonlinear iterations.

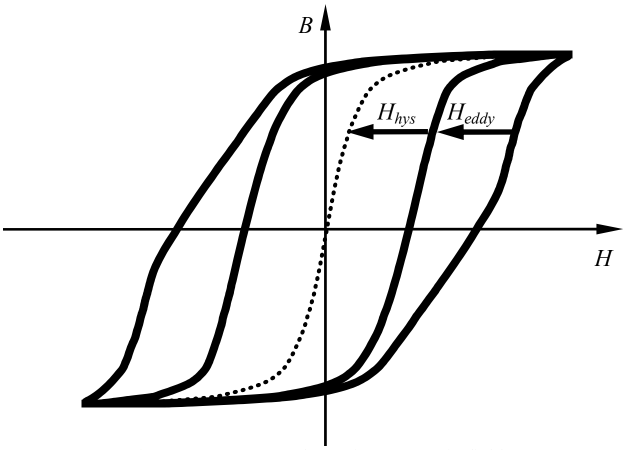

Fig. 1. B-H curve and reaction magnetic fields.

From these view points, in this paper, we have developed a method for characteristics calculation of electric machines to take the effects of eddy currents and hysteresis phenomenon in laminated cores into account. In the proposed method, both the effects of eddy currents and hysteresis phenomenon are expressed as reaction magnetic fields against the exciting field. These fields are determined by iterative calculations of main electromagnetic field analysis and sub 1D analysis. The validity of the proposed method is confirmed by comparing the measured and calculated results of the core-material characteristics. The effects of the reaction field on the torque characteristics of rotating machines are also discussed.

II. OUTLINE OF PROPOSED METHOD

Fig. 1 shows the concept of the generalized reaction field in the proposed method. It is well known that the area of the hysteresis loop is enlarged by the reaction field H_{eddy} caused by eddy currents. It is considered that the hysteresis phenomenon can also be expressed by H_{hys}, which is the shift value of magnetic field from the single B-H curve shown by the dotted lines. Therefore, we defined the generalized reaction field H_{reac} in the laminated core region, as follows:

$$\nabla\times\left(\frac{1}{\mu}\nabla\times\boldsymbol{A}\right)=\nabla\times\boldsymbol{H}_{eddy,ave}+\nabla\times\boldsymbol{H}_{hys,ave}=\nabla\times\boldsymbol{H}_{reac,ave} \quad (1)$$

where μ is the permeability, $\boldsymbol{A}$ is the magnetic vector potential, $H_{eddy,ave}$, $H_{hys,ave}$, $H_{reac,ave}$ are the eddy-currents, hysteresis, and total reaction fields, which are averaged along the thickness of electrical steel sheets in the core. In the proposed method, the main electromagnetic field analysis is carried out by this equation. In this case, the detailed structure of the lamination can be neglected. In addition, μ can be determined by usual Newton-Raphson method according to the single B-H curve.

On the other hand, $H_{eddy,ave}$ and $H_{hys,ave}$ are determined by iterative calculation of this main analysis and sub 1D analysis, as shown in Fig 2. The sub 1D analysis along the thickness of the steel sheet is carried out at each finite element in the main analysis according to the time variation in flux density calculated by the main analysis. Then, $H_{eddy,ave}$ and $H_{hys,ave}$ are calculated, as follows:

$$\boldsymbol{H}_{eddy,ave} = \frac{2}{h}\int_0^{h/2}\left\{\kappa\int\left(-J_{e\theta}, J_{ez}\right)dz\right\}dz \tag{2}$$

$$\boldsymbol{H}_{hys,ave} = \frac{2}{h}\int_0^{h/2}\left(\frac{\boldsymbol{B}}{\mu} - \boldsymbol{H}\right)dz \tag{3}$$

where κ is the modification factor of excess loss [3], [4], h is the thickness of sheet, $J_{e\theta}$ and J_{ez} are the components of eddy currents that are parallel to the sheet, $\boldsymbol{H}$ is the magnetic field on the DC hysteresis loop, which can be determined from the waveform of $\boldsymbol{B}$ by using existing hysteresis models [6], [7].

III. RESULTS AND DISCUSSION

Fig. 3 shows the measured and calculated iron loss of an electrical steel sheet in Epstein frame test. They agree well.

Fig. 4 shows the calculated exciting currents at 50 Hz. The results by the conventional 2D analysis neglecting H_{reac} is also shown. The result by the 2D analysis underestimates the current because it cannot take the iron-loss current into account. This result implies that the conventional 2D analysis must underestimate the copper loss in the electric machines.

Fig. 5 shows the calculated cogging torque of a 100 kW class permanent magnet motor. The average value by the conventional 2D method is zero, whereas that by proposed method indicates the negative hysteresis torque, which particularly appears in low cogging torque machines.

From these results, the validity and usefulness of the proposed method are clarified.

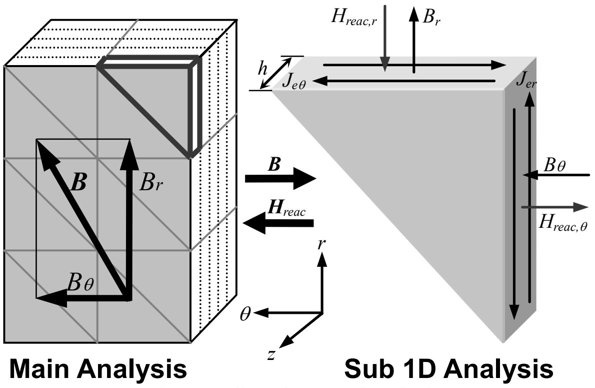

Fig. 2. Outline of proposed method.

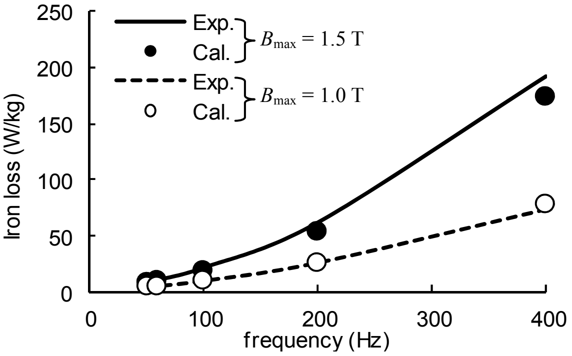

Fig. 3. Experimental and calculated iron losses in Epstein frame.

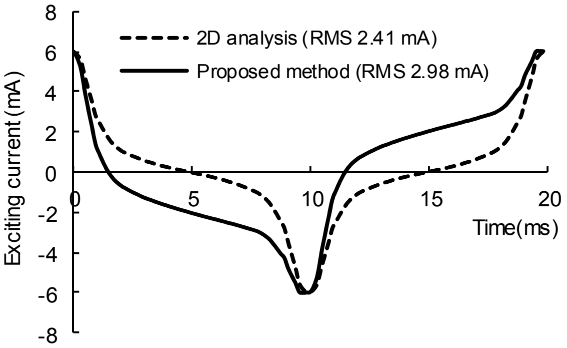

Fig. 4. Calculated exciting current waveforms (1.5 T, 50 Hz).

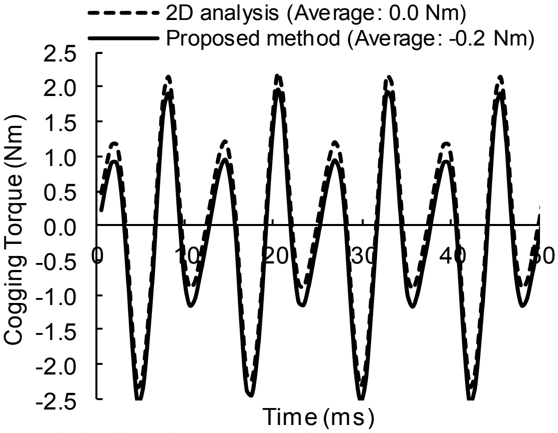

Fig. 5. Calculated cogging torque waveforms of a permanent magnet motor.

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