Loss Calculation Method Considering Hysteretic Property with Play Model in Finite Element Magnetic Field Analysis

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Abstract— This paper proposes a novel estimation method for iron loss by using play model. In the proposed method, iron loss considering hysteretic property is estimated with play model as a post-processing of usual finite element magnetic field analysis based on ordinary magnetization curve. The numerical results are compared with the measured results to demonstrate the effectiveness of the proposed estimation method for iron loss.

***Index Terms*— Magnetic hysteresis, electromagnetic fields, finite element methods.**

I. Introduction

In order to design the energy-efficient electric machinery, it is important to accurately evaluate iron loss and copper loss [1]. A lot of papers reported the estimation method for iron loss in finite element magnetic field analysis [2].

In this paper, we propose a novel estimation method for iron loss by using the play model [3], which can provide the hysteretic property. In the proposed method, the iron loss taking account of hysteretic property is estimated with play model as a post-processing of usual finite element magnetic field analysis based on ordinary magnetization curve. Although the computational cost for the proposed iron loss estimation method is almost the same as that of conventional ones, the accuracy is expected to be improved drastically by considering hysteretic property.

II. Iron Loss Calculation in Finite Element Analysis

A. Conventional iron loss estimation method

The iron loss w can be classified into an eddy-current loss w_e and a hysteresis loss w_h as follows:

$$w = w_e + w_h = k_e(B_m) f^2 + k_h(B_m) f\ , \qquad (1)$$

where k_e, B_m, f, and k_h are eddy-current loss coefficient, maximum flux density of a hysteresis loop, frequency, and hysteresis loss coefficient, respectively. By approximating w/f as a linear function, these loss coefficients are determined [2].

In the conventional iron loss estimation method, a hysteresis loss is evaluated by $k_h(B_m)$. The hysteresis loss coefficient is often treated as constant K_h because the flux density dependence of $k_h(B_m)$ is small [2].

B. Estimation method for iron loss by using the play model

A discretized form of the vector play model [3] represents the hysteretic properties as follows:

$$\boldsymbol{p}_{\zeta n}(\boldsymbol{B}) = \boldsymbol{B} - \frac{\zeta_n(\boldsymbol{B} - \boldsymbol{p}^*_{\zeta n})}{\max(|\boldsymbol{B} - \boldsymbol{p}^*_{\zeta n}|, \zeta_n)}\ , \qquad (1)$$

$$\boldsymbol{H} = \sum_{n=1}^{M} f_{\zeta n}(|\boldsymbol{p}_{\zeta n}(\boldsymbol{B})|)\frac{\boldsymbol{p}_{\zeta n}(\boldsymbol{B})}{|\boldsymbol{p}_{\zeta n}(\boldsymbol{B})|}\ , \qquad (2)$$

where $\boldsymbol{p}_{\zeta n}$ is the play hysteron operator with a width of ζ_n, $\zeta_n = (n-1)B_s/M$, B_s is the maximum measurable magnetic flux density, $\boldsymbol{p}_{\zeta n}^*$ is the value of the play hysteron operator at previous time step, M is the number of hysterons, and $f_{\zeta n}$ is the shape function for the play hysteron operator $\boldsymbol{p}_{\zeta n}$. The identification method for the Preisach model can be applied to the play model [4] because the play model is mathematically equivalent to the Preisach model [5].

In the proposed method, the play model is applied to the time series data of flux densities obtained from the usual finite element analysis and the hysteresis loops in each element are simulated as a post-processing. The hysteresis loss is evaluated from these hysteresis loops directly. The play model can represent not only symmetric hysteresis loops but also dc-biased minor loops [6]. Therefore, it is expected that the proposed method can accurately evaluate the hysteresis loss compared with the conventional estimation method by using iron loss coefficients.

III. Comparison of Estimation Methods for Iron Loss

A. Analysis condition

The effectiveness of the proposed estimation method for an iron loss is investigated. Table I shows the analysis methods. Methods I and II evaluate the iron loss by the hysteresis loss coefficients and the play model, respectively, as a post-processing of the finite element magnetic field analysis based on magnetization curve. Method III evaluates the iron loss directly by taking account of hysteretic property with play model in the finite element magnetic field analysis.

Table II shows the specifications of analyzed model for a ring core and we use the dust core as the iron core. We do not consider an eddy-current loss because the effect of eddy current is negligibly small in the dust core. The play model is identified from 40 measured symmetric loops of the dust core at intervals of 0.05 T from 0.05 T to 2.0 T.

TABLE I
Analysis Method

Method	Magnetic field analysis	Loss calculation
I	Magnetization curve	Iron loss coefficient
II	Magnetization curve	Play model
III	Hysteretic property by play model	Play model

TABLE II
ANALYSIS CONDITION

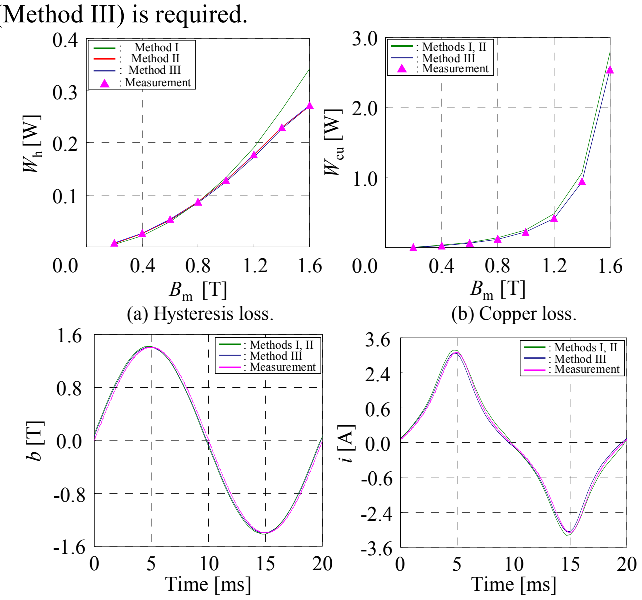
Inner radius : r_{in} [mm]		9.95
Outer radius : r_{out} [mm]		17.01
Thickness : d [mm]		5.03
Magnetizing winding	Number of turns : n	207
	Resistance : R [Ω]	0.324

B. Numerical results for symmetric hysteresis loops

Fig. 1 shows the numerical results for symmetric hysteresis loops. A hysteresis loss coefficient at B_m = 1.0 T is used for Method I as a constant, where B_m is the maximum value of the symmetric loop. The same voltage waveform as the case of the measurement is applied as an input.

As shown in Fig. 1 (c), the flux density waveforms obtained from Methods I, II, and III agree well with the measured results regardless of whether the hysteretic property is considered or not. Therefore, as shown in Fig. 1 (a), the numerical results of iron loss obtained from Methods II and III are very close to the measured results. However, there is a difference between the numerical results obtained from Method I and others. Because the hysteretic magnetic property has a large influence on the numerical results of current waveforms as shown in Fig. 1 (d), the copper loss obtained from Methods I and II shown in Fig. 1(b) also differ from the measured results.

From the above results, Method II can obtain hysteresis loss more accurately than the conventional method (Method I). However, when the influence of copper loss is relatively large, magnetic field analysis considering hysteretic property (Method III) is required.



(a) Hysteresis loss. (b) Copper loss.

c) Flux density waveforms (B_m = 1.4 T). (d) Current waveforms (B_m = 1.4 T).

Fig. 1. Numerical results obtained from Methods I – III (symmetric hysteresis loops).

A. Numerical results for dc-biased minor loops

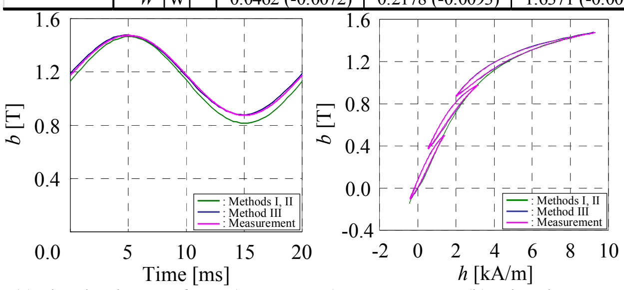
Table III and Fig. 2 show the numerical results obtained from Methods I, II, and III for dc-biased minor loops. The value in parentheses means the ratio of the numerical results obtained from Methods I, II, or III to measured results and B_{max} indicates the maximum flux density value of hysteresis loop including superimposed dc component. The same input voltage waveform as the experiment at B_m= 0.3 T is used and a constant hysteresis loss coefficient at B_m = 0.3 T is used for Method I, where B_m is the amplitude of the ac component of flux density.

As shown in Fig. 2 (a), there is a difference between the numerical results obtained from Methods I or II and measured results. Therefore, as shown in Table III, those obtained from Methods I and II do not agree with the measured results. On the other hand, the numerical results obtained from Method III are very close to the measured results. At B_{max} = 0.5 T, Method I is the most accurate. But flux density and current waveform obtained from Method I is not accurate, therefore it is not necessarily good result.

The detail of the proposed estimation method and further numerical results will be reported in the full paper.

TABLE III
IRON LOSS AND COPPER LOSS

B_{max} [T]		0.5	1.0	1.5
Measurement	W_h [W]	0.0157 (0.00)	0.0199 (0.00)	0.0326 (0.00)
	W_{cu} [W]	0.0309 (0.00)	0.2003 (0.00)	1.6165 (0.00)
	W [W]	0.0466 (0.00)	0.2203 (0.00)	1.649 (0.00)
Method I	W_h [W]	0.0160 (0.0261)	0.0168 (-0.1405)	0.0188 (-0.4011)
	W_{cu} [W]	0.0305 (-0.0142)	0.180 (-0.1015)	1.543 (-0.0453)
	W [W]	0.0465 (-0.0068)	0.1968 (-0.1049)	1.5620 (-0.0521)
Method II	W_h [W]	0.0171 (0.0983)	0.0227 (0.1643)	0.0416 (0.3236)
	W_{cu} [W]	0.0305 (-0.0142)	0.180 (-0.1015)	1.543 (-0.0453)
	W [W]	0.0476 (0.0235)	0.2027 (-0.0779)	1.5848 (-0.0383)
Method III	W_h [W]	0.0167 (0.0678)	0.0228 (0.1672)	0.0375 (0.1948)
	W_{cu} [W]	0.0295 (-0.0451)	0.195 (-0.0265)	1.5997 (-0.0105)
	W [W]	0.0462 (-0.0072)	0.2178 (-0.0093)	1.6371 (-0.0065)



(a) Flux density waveforms (B_{max} = 1.5 T). (b) Minor loops.

Fig. 2. Numerical results obtained from Methods I – III (minor loops).

IV. REFERENCES

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