Core Loss Analysis of Permanent Magnet Linear Synchronous Generator Considering the 3-D Flux Path

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This paper presents an analysis of the core loss observed in the stator core that is used in a permanent magnet linear synchronous generator (PMLSG). Core loss is typically calculated using the classical Steinmetz equation; however, the use of these equations leads to erroneous results. Consequently, several researchers have proposed modified versions of this equation taking into account hysteresis loss, eddy current loss, and excess loss. In this study, we calculate all loss coefficients from Epstein test data using a curve fitting method (CFM). Owing to the time harmonics observed with changes in the magnetic flux density, we separate the rotating and alternating field. In addition, we consider the 2-D and 3-D plane flux path that causes magnetic flux leakage. Finally, core loss of the linear machine is calculated using a modified Steinmetz equation that considers flux path.

***Index Terms*—3-D Flux Path, Core loss Analysis, Steinmetz equation, Synchronous Generator Core loss.**

I. Introduction

THIS PAPER presents an analysis of the core loss observed in the stator core that is used in a permanent magnet linear synchronous generator (PMLSG). Core loss is typically calculated using the classical Steinmetz equation, which only considers hysteresis loss and eddy current loss [1]. However, the use of this equation leads to a significant disparity in the theoretically calculated results and the experimentally obtained results. In order to reconcile this observed discrepancy, modifications to the equation have been proposed in Bertotti's model [2-3]. Bertotti's model proposes the inclusion of an excess loss parameter that accounts for the loss associated with a material's thickness, cross-sectional area, and conductivity, and a parameter that describes the material's microstructure. This modified Steinmetz equation accounts for hysteresis loss, eddy current loss, and excess loss. In this paper, the hysteresis loss coefficient, the eddy current loss coefficient, and the excess loss coefficient for the modified Steinmetz equation are derived from the Epstein test data using a curve fitting method (CFM). Owing to the time harmonics observed with changes in the magnetic flux density, we separate the rotating and alternating field. Additionally, we propose a technique that considers the 2-D, and 3-D plane flux path that causes magnetic flux leakage. Finally, core loss of the linear machine is calculated using a modified Steinmetz equation that considers flux path.

II. Core Loss Analysis

A. Analysis Model

Fig.1 (a) shows the distribution of flux density in the 2-D plane, Fig.1 (b) shows analysis model for core loss in the 2-D plane, Fig. 1 (c) shows the distribution of flux density in the 3-D plane, and Fig.1 (d) shows analysis model for core loss in the 3-D plane. The magnetic flux in each point was analyzed using the finite element method (FEM).

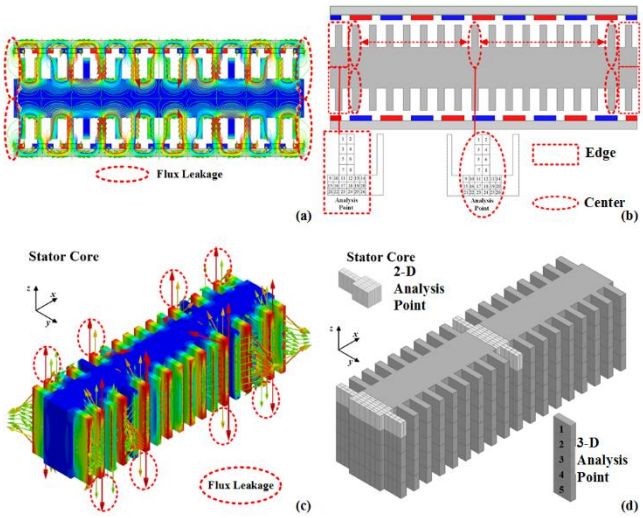

Fig. 1. Magnetic flux distribution and analysis model for PMLSG: (a) 2-D plane flux path on PMLSG, (b) 2-D analysis point for core-loss analysis, (c) 3-D flux path on PMLSG, and (d) 3-D analysis point for core-loss analysis.

B. Curve Fitting Method

The core loss is typically calculated using the classical Steinmetz equation that is given below .

$$P_c = P_h + P_e = k_h f B^n + k_e f^2 B^2 \tag{1}$$

where P_h and P_e represent the hysteresis loss and the eddy current loss. However, when the magnetic flux density is higher than 1.0 Tesla or the frequency becomes high, there is a significant disparity in the theoretically calculated results and the experimentally obtained results. In order to reconcile this observed discrepancy, modifications to the equation have been proposed in Bertotti's model. Bertotti's model proposes the inclusion of an excess loss parameter, which accounts for the loss associated with a material's thickness, cross-sectional area, and conductivity, and a parameter that describes the material's microstructure. Modified Steinmetz's equation expressed as

$$P_c = P_h + P_e + P_a = k_h f B^n + k_e f^2 B^2 + k_a f^{1.5} B^{1.5} \quad (2)$$

where P_e represents the excess loss. In order to calculate the core loss coefficients (k_h, k_e, k_a) that the associated frequency functions are derived from the Epstein test data using a CFM. Table 1 shows the CFM results obtained at each frequency. It can be used to calculate the core loss for a wide operating range.

TABLE I
CORE-LOSS COEFFICIENT AT EACH FREQUENCY

f [Hz]	k_h (10^{-3})	k_e(10^{-6})	k_a (10^{-3})
50	18.06	102.7	0.334
100	19.56	100.9	0.312
200	24.63	98.2	0.256
400	24.63	95.13	0.239
600	26.23	93.64	0.211
800	27.35	65.58	0.133

C. Magnetic Field and Flux Density Harmonics

To improve the precision of analysis result, it is important to separate the alternating field and rotating field. Generally, the core loss occurs in the rotating field is much more than that occurring in the alternating field and they can be distinguished using the axial ratio [4]. Fig. 2 shows the loci of flux density and the axial ratio of the teeth of the center and the teeth of the edge at each point.

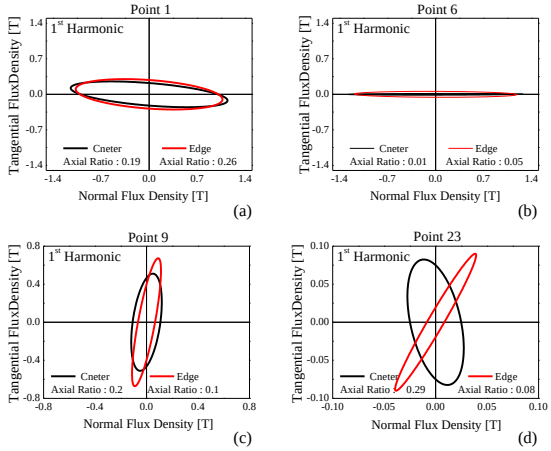

Fig. 2. Loci comparison between teeth of center and teeth of edge: (a) point 1, (b) point 6, (c) point 9, and (d) point 23.

III. ANALYSIS RESULT

A. Modified Steinmetz's Equations

The final modified Steinmetz's equation for distinguishing the alternating field and the rotating field is as

$$P_c = \sum_{l=1,odd}^{\infty} \alpha (k_{hl} f_l B_l^n + k_{el} f_l^2 B_l^2 + k_{al} f_l^{1.5} B_l^{1.5})$$

$$\begin{cases} \alpha = 1, alt.field \\ \alpha = 2, rot.field \end{cases} \quad (3)$$

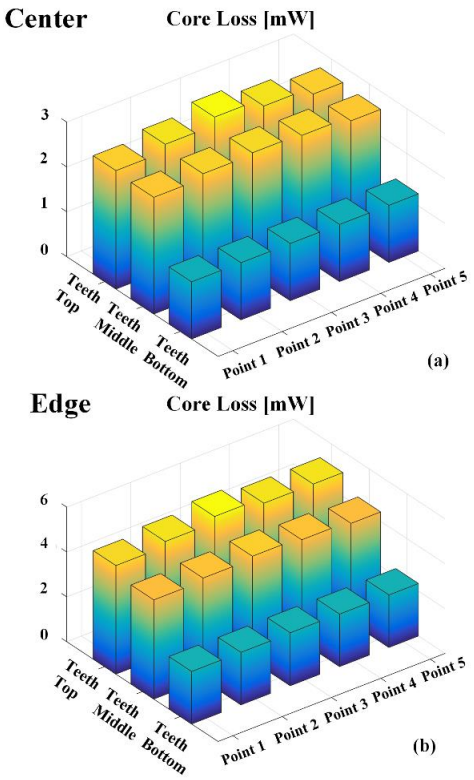

Fig. 3. Results of core-loss analysis considering 3-D flux path at each region: (a) teeth of center, and (b) teeth of edge.

The core loss in each area calculated from (3) is shown in Fig. (3).

IV. CONCLUSION

This paper presents the core loss analysis that complements the error of Steinmetz's equations. Additionally, we consider the 2-D and 3-D flux path that cause magnetic flux leakage. More detailed discussion and analysis will be presented in our final paper.

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