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A Dynamic Core Loss Model for Soft Ferromagnetic and Power Ferrite Materials in Transient Finite Element Analysis

D. Lin, P. Zhou, W. N. Fu, Z. Badics, and Z. J. Cendes

Abstract—A dynamic core loss model is proposed to estimate core loss in both soft ferromagnetic and power ferrite materials with arbitrary flux waveforms. The required parameters are the standard core loss coefficients that are either directly provided by manufacturers or extracted from the loss curve associated with nonsinusoidal excitation. The model is applied to calculating core loss in both two-dimensional and three-dimensional transient finite element analysis, and the results are compared with measured data.

Index Terms—Core loss, finite element analysis, hysteresis, minor loop, power ferrite, soft ferromagnetic, transient.

I. INTRODUCTION

I T IS STILL challenging to predict core loss under transient conditions in the design of magnetic power devices such as inductors, transformers, and electric machines. While approaches exist for loss computation in power devices in the frequency domain, an appropriate method for core loss computation in the time domain remains unclear.

In the frequency domain, loss separation is widely used with problems involving magnetic laminations. Loss separation breaks the total core loss into static hysteresis loss \( P_h \), classical eddy current loss \( P_e \), and excess loss \( P_c \) [1]

\[
P_v = P_h + P_e + P_c
\]

\[
= k_h f B_m^\alpha + k_e (f B_m)^2 + k_e (f B_m)^{1.5}.
\]

Given the coefficients \( k_h, k_e, k_e \), and the parameter \( \beta \), the total core loss per unit volume \( P_v \) in the frequency domain can be calculated in terms of peak magnetic flux density \( B_m \) and frequency \( f \). When this approach is applied to the time domain, the computation of the eddy current loss and the excess loss is straightforward. However, the computation of hysteresis loss is still difficult.

With ferrite materials, a well-known empirical approach proposed by Steinmetz a century ago is normally used

\[
P_v = C_m f^\alpha B_m^\beta
\]

where \( C_m, \alpha, \) and \( \beta \) are empirical parameters obtained from experimental measurement under sinusoidal excitation [2]. In order to estimate the power loss with nonsinusoidal excitation, a modified Steinmetz equation (MSE) was developed [3]

\[
P_v = (C_m f_{eq}^{\alpha-1} B_m^\beta) f_r
\]

where \( f_{eq} \) is the equivalent frequency of the nonsinusoidal induction waveform, and \( f_r \) is the repeated frequency. With the introduction of an equivalent frequency, MSE provides a good fit to experimental measurements under triangular magnetization [3]. However, MSE is only suitable in the frequency domain.

Many time-domain hysteresis models have been proposed for instantaneous loss calculation. These are mainly based on the Jiles–Atherton model [4], [5] or the Preisach model [6]. Although these models describe hysteresis phenomena quite well, their practical use is limited by the high number of empirical parameters and/or the prohibitive experimental effort required [3].

In this paper, an alternative time-domain dynamic hysteresis model is developed for soft magnetic and power ferrite materials based on the idea of an equivalent elliptical loop. This model is able to consider the effects of minor loops and predicts instantaneous hysteresis loss with good accuracy. In addition, the required parameters in the model are the same as those required in the frequency domain approaches (1) and (2). These parameters are either directly available from manufacturers or can be easily extracted from standard loss curves under sinusoidal excitation.

II. FORMULATIONS

A typical value of hysteresis loss parameter \( \beta \) in (1) is 2. In this case, the magnetic field \( H \) in a static hysteresis loop can be decomposed into two components: a reversible component \( H_{rev} \) and an irreversible component \( H_{irr} \). As a result, hysteresis loss can be computed by

\[
P_h = \frac{1}{T} \int_0^T (H_{rev} + H_{irr}) \frac{dB}{dt} dt
\]

\[
= \frac{1}{T} \int_0^T H_{irr} \frac{dB}{dt} dt.
\]

The reversible component can be directly obtained from the normal \( B \rightarrow H \) curve without considering a hysteresis loop. In fact, \( H_{rev} \) is related to the reactive power in the material and \( H_{irr} \) is associated with the hysteresis loss. Consequently, the instantaneous hysteresis loss is

\[
p_h(t) = H_{irr} \frac{dB}{dt}.
\]
Equation (5) indicates that the key to computing $p_h(t)$ is the procedure used to obtain $H_{irr}$. Fig. 1 defines an equivalent elliptical loop (EEL) in which $H_{irr}$ is evaluated by tracing an elliptical loop having the same area as that of the original hysteresis loop.

The ellipse in Fig. 1 can be described as

$$
\begin{cases}
B = B_m \sin(\theta) \\
H_{irr} = H_m \cos(\theta)
\end{cases}
$$

(6)

where $B_m$ is directly obtained from a historical record of the flux density and $H_m$ is determined by requiring that the core loss calculated in the time domain under the same sinusoidal excitation. From (4) and (6), the time-average hysteresis loss with sinusoidal excitation is

$$
P_h = H_m \cdot B_m \cdot 2\pi f \cdot \frac{1}{T} \int_0^T \cos^2(2\pi f t) \, dt
$$

(7)

$$
= H_m \cdot B_m \cdot \pi f.
$$

Let (7) be equal to the frequency domain solution of $P_h = k_h f B_m^2$. Then, one obtains

$$
H_m = \frac{1}{\pi} k_h \cdot B_m.
$$

(8)

Thus

$$
H_{irr} = \frac{1}{\pi} k_h \cdot B_m \cos(\theta).
$$

(9)

With a similar procedure, the eddy current loss and excess loss in the time domain can be expressed as, respectively

$$
p_e(t) = \frac{1}{2\pi^2} k_c \cdot \left( \frac{dB}{dt} \right)^2
$$

(10)

and

$$
p_e(t) = \frac{1}{C_e} k_c \cdot \left( \frac{dB}{dt} \right)^{15}.
$$

(11)

$C_e = 8.763 \times 10^3$ is from the numerical integration of

$$
C_e = (2\pi)^{15} \cdot \frac{2}{\pi} \int_0^{\pi} \cos^{15} \theta \, d\theta.
$$

(12)

Fig. 1. Equivalent elliptical loop (EEL) having the same area as the original hysteresis loop.

For the more general case of $\beta \neq 2$ in (1), (9) is extended to

$$
H_{irr} = \pm \frac{1}{C_{\beta}} k_h \cdot |B_m \cos(\theta)|^{1-\beta}
$$

(13)

where $H_{irr}$ takes the same sign as $dB/dt$ and

$$
C_{\beta} = 4 \int_0^{\pi} \cos^\beta \theta \, d\theta.
$$

(14)

As expected, (13) becomes (9) with $C_{\beta} = \pi$ when $\beta = 2$.

To obtain $B_m$ from the history record of stored elliptical loops, two rules are applied. One is the wiping-out rule: all ellipses inside the current ellipse are wiped out. The other rule is that if a smaller ellipse (minor loop) is created, the current ellipse is pushed into the recorded ellipse list and the new ellipse is taken as the current ellipse.

In the same way, based on the Steinmetz equation (2), the core loss for ferrite material in the time domain is derived as

$$
p_c(t) = |K| \cdot \left[ \frac{dB}{dt} \right]^\alpha
$$

(15)

where

$$
K = \pm \frac{1}{C_{\alpha\beta}} C_m \cdot |B_m \cos(\theta)|^{\beta-\alpha}
$$

(16)

$$
C_{\alpha\beta} = (2\pi)^\alpha \cdot \frac{2}{\pi} \int_0^{\pi} \cos^\alpha \theta \, d\theta.
$$

(17)

When $\alpha = 1, K$ has the measure of the magnetic field $H$, and (15) becomes (5). In this case, only the hysteresis loss component is considered and $K$ becomes $H_{irr}$.

III. VALIDATION

To validate the proposed model, measured data for 3C85 ferrite are used from [5]. The parameters $\alpha = 1.3, \beta = 2.55$, and $C_m = 12$ are quoted from [2]. The computed results are first compared with the measured data under various triangular magnetizations. Thereafter, the proposed model is validated by comparing the computed results to the analytical results when $\alpha = \beta = 1.5$.

A. Triangular Magnetization With Varying Repeat Frequency

The triangular waveform of magnetizing flux density in Fig. 2 is applied for the measurement, where the repeat frequency $f_r$ varies from 2 to 20 kHz while the triangular magnetization cycle $T$ remains constant. Fig. 3 shows the comparison between the computed average core loss based on (13) and the measured data. It can be seen that they match quite well.

Fig. 2. Triangular magnetization with varying repeat frequency ($B_m = 200$ mT and $T = 20$ kHz).
Fig. 3. Comparison between calculation and measurement for triangular magnetization with varying repeat frequency \((\alpha = 1.3, \beta = 2.55, \text{and } C_m = 12)\).

Fig. 4. Triangular magnetization with varying duty cycle \((B_m = 220 \text{ mT and } T^{-1} = 20 \text{ kHz})\).

Fig. 5. Comparison between calculation and measurement for triangular magnetization with varying duty cycle \((\alpha = 1.3, \beta = 2.55, \text{and } C_m = 12)\).

Fig. 6. Comparison of analytical results with the predictions of EEL and MSE for triangular magnetization with varying duty cycle.

Fig. 7. Computed instantaneous core loss of a 250-kVA three-phase amorphous metal power transformer with \(C_m = 19.16, \alpha = 1, \text{and } \beta = 2.45\). The MSE (3) are also included in Fig. 6. It can be seen that EEL provides exactly the same values as the analytical results, whereas the MSE does not. When the duty cycle approaches 1, the error by the MSE can reach to 40%.

**IV. APPLICATIONS**

The proposed model has been used to compute the core loss for both soft ferromagnetic and power ferrite materials in two-dimensional (2-D) and three-dimensional (3-D) transient FE analysis. In the 3-D case, the scalar model (5), (10), and (11) for soft materials is modified as

\[
p_h(t) = \left\{ \left[ H_x \frac{dB_x}{dt} \right]^3 + \left[ H_y \frac{dB_y}{dt} \right]^3 + \left[ H_z \frac{dB_z}{dt} \right]^3 \right\}^{\frac{2}{3}} \quad \text{(18)}
\]

\[
p_e(t) = \frac{1}{2\pi^2 k_e} \cdot \left\{ \left( \frac{dB_x}{dt} \right)^2 + \left( \frac{dB_y}{dt} \right)^2 + \left( \frac{dB_z}{dt} \right)^2 \right\}^{\frac{1}{2}} \quad \text{(19)}
\]

\[
p_c(t) = \frac{1}{C_e} \cdot \left\{ \left( \frac{dB_x}{dt} \right)^2 + \left( \frac{dB_y}{dt} \right)^2 + \left( \frac{dB_z}{dt} \right)^2 \right\}^\frac{2}{3} \quad \text{(20)}
\]

For ferrite materials, the 3-D model based on components \(p_{x\alpha}, p_{y\beta}, \text{and } p_{z\beta}\) from (15) are expressed as

\[
p_h(t) = \left\{ \left( p_{x\alpha} \right)^{2/\beta} + \left( p_{y\beta} \right)^{2/\beta} + \left( p_{z\beta} \right)^{2/\beta} \right\}^{\beta/2} \quad \text{(21)}
\]

Equations (18) to (21) can also be used for 2-D core loss computation when the z component is set to zero.

Two applications are presented. One is the core loss computation for a 250 kVA three-phase amorphous metal power transformer with five legs. Using 3-D transient FE analysis, the computed instantaneous core loss is shown in Fig. 7. Fig. 8 gives...
In Fig. 10, the coefficient $k_c$ for classical eddy current loss component is derived from

$$k_c = \pi^2 \cdot \sigma \cdot d^2 / 6$$

(22)

where $d$ is the lamination thickness and $\sigma$ is the conductivity. Coefficients for hysteresis and excess loss components are derived through a curve regression algorithm. When $\beta = 2$, (1) can be written as

$$P_v = k_1 B_m^2 + k_2 B_m^{1.5}.$$  

(23)

Based on the manufacturer-provided loss curve $(B_m, P_v)$, $k_1$ and $k_2$ are determined from

$$f(k_1, k_2) = \sum_{i=1}^n [P_{vi} - (k_1 B_{mi}^2 + k_2 B_{mi}^{1.5})]^2 = \text{min}.$$  

(24)

Thus, $k_h$ and $k_c$ are given by

$$k_h = (k_1 - k_c f_0^2) / f_0$$

(25)

$$k_c = k_2 / f_0^{1.5}$$

(26)

where $f_0$ is the frequency at which loss curve is measured.

From Fig. 10, it can be observed that there are 12 loss spikes in one period, say from 0.02 to 0.04 s. This is caused by the 12 slots in one pole pair. The periodic variation of the envelope of the loss spikes is due mainly to the uneven yoke of the square stator laminations.

V. CONCLUSION

A dynamic core loss model is proposed to predict instantaneous core loss in unison with both 2-D and 3-D transient FE analysis. This model is practical for industrial applications because it provides reasonable accuracy and all necessary parameters are either directly available or extracted from manufacturer-provided loss curves.

This model is able to consider both pulsating and rotating field effects. The effect of dc bias magnetization can also be taken into account by setting the area of the ellipse in Fig. 1 as a function of the dc bias magnetization at which the loss curve is measured.

**REFERENCES**


