Calculation of Core Loss under Harmonic Excitation for Laminated Steel Structure

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In this paper, a simple method of loss calculation which can effectively consider minor hysteresis loops is proposed. An improved 3-D finite element model for laminated steel structure is established by using the overall modeling based on homogenization method, this facilitates the meshing operations. The calculation results of both flux density and core loss are in good agreement with the measurement results, which verify the accuracy and feasibility of the proposed method.

Index Terms—Laminated transformer core; harmonic excitation; homogenization method; loss calculation

I. INTRODUCTION

Calculation and analysis of core loss are important parts of the optimal design of transformer. A great many of research papers have been published over the years [1]-[4], but the calculation of core loss under harmonic is still on debatable. This paper focuses on the calculation of core loss under harmonic excitation for laminated steel structure. A simple and effective method of loss calculation is proposed together with the overall modeling which is more suitable for engineering.

II. LOSS CALCULATION

According to the loss separation theory, core loss can be expressed as

\[ P = P_h + P_a + P_e \]  \hspace{1cm} (1)

Where \( P_h \) is the hysteresis loss, \( P_e \) is the eddy current loss and \( P_a \) is the anomalous loss. Note that only the eddy current loss can be calculated in theory [5], the hysteresis and anomalous loss under harmonic are mostly approximately obtained by experimental or empirical equations, so in this paper, the hysteresis and anomalous loss are calculated as one term, and assumes that: 1) The hysteresis and anomalous loss are independent of the polarization waveforms in the absence of minor loops. 2) The hysteresis and anomalous loss caused by harmonics are equal to that under sinusoidal excitation at corresponding frequency. In this case, the improved loss model is derived as

\[ P = P_{h/a} + P_e = K_{h/a} f^2 \sum B^2 + K_e f^2 \sum (nB_n)^2 \]  \hspace{1cm} (2)

Where \( P_{h/a} \) is the hysteresis and anomalous loss, \( B \) is the peak value of distorted flux, \( B_n \) is the peak value of \( n \)th flux density, \( f \) is frequency. As shown in Fig.1, the peak value of major loop and minor loops can be obtained. \( P_{h/a} \) can be calculated by adding the contribution of each \( n \)th loops according to the first term in equation (2). The eddy current loss is calculated based on the classical eddy current loss theory according to the second term in equation (2) [6].

Core loss under sinusoidal excitation obtained from Epstein frame experiments at 50Hz to 400Hz and 0.1T to 1.8T based on GB/T 3655-2008, is used to estimate coefficients \( K_{h/a}, \alpha \) and \( \beta \). Experiments are carried out on oriented electrical steels of grade B30P105. \( K_e \) can be determined by

\[ K_e = \sigma d^2 \pi^2 / (6 \rho) \]  \hspace{1cm} (3)

Where \( \sigma \) is the electrical conductivity, \( d \) is the lamination thickness, \( \rho \) is the volume mass density. Table I lists the value of each coefficients.

![Distorted flux density and hysteresis loop](image)

Fig. 1. Distorted flux density and hysteresis loop

TABLE I

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>( K_h )</th>
<th>( K_a )</th>
<th>( \alpha )</th>
<th>( \beta )</th>
</tr>
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<tbody>
<tr>
<td>Value</td>
<td>0.004969</td>
<td>4.39×10^3</td>
<td>1</td>
<td>2.041</td>
</tr>
</tbody>
</table>

III. THE MAGNETIC CHARACTERISTIC TEST SYSTEM

To investigate the effect of harmonic excitation on both core loss and hysteresis loops, a magnetic characteristic test system of iron core is set up, as shown below.

![Magnetic characteristic test system](image)

Fig. 2. The magnetic characteristic test system

In order to get the magnetic flux density in (4), the voltage excitation in (5) is calculated.

\[ B = \sum B_n \cos(n \omega t + \phi_n) \]  \hspace{1cm} (4)

\[ E(t) = N S o B_i \sum n k_2 \sin(n \omega t + \phi_n) \]  \hspace{1cm} (5)

\[ k_2 = B_2 / B_1, \ \theta_2 = \phi_2 - \phi_1 \]  \hspace{1cm} (6)

Where \( n \) is the harmonic order, \( B_n \) is the peak value of \( n \)th flux density, \( \phi_n \) is the phase of \( n \)th harmonic, \( k_2 \) is the content of \( n \)th harmonic, \( \theta_2 \) is the phase difference between first harmonic and \( n \)th harmonic, and \( N \) is the number of turns of coil, \( S \) is the sectional area.

Waveforms of magnetic flux density, magnetic field strength and hysteresis loops under different excitations are obtained. It can be found that core loss increases as harmonic order and
IV. CORE MODELING AND SIMULATION

Given the anisotropic lamination structures of transformer core, the homogenization method is proposed, which assumes that flux density is locally uniform in parallel to the lamination [7]. This approach is suitable for low frequency problems, and the laminated core is modeled as a solid core to make modeling easier:

\[
[\mu] = \text{diag} \left[ L_i \mu_0, L_j \mu_0, \mu_0 (1-L_j) \right] \quad (7)
\]

\[
[\sigma] = \text{diag} \left[ \sigma_{y1}, \sigma_{y2}, \sigma_{y3} \right] \quad (8)
\]

Where \(L_i\) is the lamination factor, \(\mu_0\) is the permeability in air, \(\sigma_i\) is the electrical conductivity of silicon steel sheet, \(\epsilon<<1\). The magnetic permeability \(\mu\) and the electrical conductivity \(\sigma\) are modeled as anisotropic. But there are some practical difficulties though the core model is well established: 1) It takes long time to be stable when using voltage source. 2) Due to the limitation of computing resources, a SV (single value) \(B-H\) curve is applied to simulate the magnetic characteristic, rather than a hysteresis loop. 3) The influence of the Rayleigh region is not considered, causing a large error of flux density at 0.1T to 0.8T (as shown below).

![Image](image-url)

Fig. 4. The influence of the Rayleigh region at \(B_{cm}=1.3T, k_3=0.3, \theta=0^\circ\).

According to experiments, Rayleigh describes this region under weak magnetic fields as

\[
M = \chi_0 H + bH^2 \quad (9)
\]

\[
B = \mu_0 (\mu_i H + bH^2) = \mu_0 \mu H \quad (10)
\]

Where \(\mu=\mu_0+bH\), \(b\) is the Rayleigh constant.

To achieve low simulation errors, current source is a better choice, the calculation of equivalent current is shown in Fig. 5. A D.C. magnetization curve of B30P105 tested by Epstein frame is available. Based on that, flux density considering the Rayleigh region is obtained with better accuracy. RMSE from 0.09592 to 0.03162. Results are shown in Fig. 5.

![Image](image-url)

(a) \(B_{cm}=1.21T, k_3=0.3, \theta=90^\circ\)

(b) \(B_{cm}=1.3T, k_3=0.3, \theta=0^\circ\)

Fig. 5. Measurement results and calculation results of average flux density under different conditions.

V. NUMERICAL RESULTS

As shown below, there’s little error between the calculation results and measurement results, the calculation method of core loss proposed in this paper is of universal feasibility.

![Image](image-url)

### TABLE II

<table>
<thead>
<tr>
<th>Excitation conditions</th>
<th>(B_{cm}(T))</th>
<th>(n)</th>
<th>(k)</th>
<th>(\theta)</th>
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<tr>
<td>C1</td>
<td>1.3</td>
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<td>0°</td>
</tr>
<tr>
<td>C2</td>
<td>1.21</td>
<td>3</td>
<td>0.3</td>
<td>90°</td>
</tr>
<tr>
<td>C3</td>
<td>0.94</td>
<td>3</td>
<td>0.3</td>
<td>180°</td>
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<tr>
<td>C4</td>
<td>1.1</td>
<td>7</td>
<td>0.1</td>
<td>0°</td>
</tr>
<tr>
<td>C5</td>
<td>1.08</td>
<td>7</td>
<td>0.1</td>
<td>90°</td>
</tr>
<tr>
<td>C6</td>
<td>1.02</td>
<td>7</td>
<td>0.1</td>
<td>180°</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Excitation conditions</th>
<th>Measurement results/W</th>
<th>Calculation results/W</th>
<th>Error/%</th>
</tr>
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<td>C1</td>
<td>19.71</td>
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<tr>
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<td>15.32</td>
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<tr>
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<td>3.62</td>
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VI. ACKNOWLEDGEMENTS

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REFERENCES


