A Study on Core Losses of Non-oriented Electrical Steel Laminations under Sinusoidal, Non-sinusoidal and PWM Voltage Supplies

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Abstract

The paper intends to study the iron losses of non-oriented electrical steel laminations under sinusoidal, non-sinusoidal and PWM voltage supplies. The measurement of core losses of electrical steel laminations in Epstein Frame is implemented step by step from 50 Hz to 400Hz. The accuracy of results is verified by simulated modeling of the Ansoft EM software package. The core losses of non-oriented electrical steel laminations under sinusoidal, non-sinusoidal and PWM voltage excitations are compared in the paper. The analyzed results provide motor manufacturers with the important reference to minimize the core losses of the special motors under harmonic voltage supply.

Keyword : Core Loss, Non-oriented, Electrical Steel Laminations, Sinusoidal, Non-sinusoidal, PWM, Epstein Frame

I. INTRODUCTION

Pulse width modulation (PWM) and non-sinusoidal voltages are widely supplied nowadays to industrial motors. Variable-speed operation of motors results in significant energy saving. The use of PWM or non-sinusoidal voltages supplies leads to a general loss increase both in the motor windings and in the tested steel laminations. It becomes necessary for motor designers to know details of the steel lamination losses under non-sinusoidal and PWM voltage supplies by measurements in Epstein tester and computer estimations. To motor designers, the steel lamination losses are very important for the design of motors and the improvement of their performances.

A number of methods to predict core losses under sinusoidal, non-sinusoidal, and PWM voltage supplies have been reported in the literatures [1-12]. In [1], a general formula for prediction of iron losses under non-sinusoidal voltage waveform was discussed. Measured methods and predictions on change of iron losses with the switching supply frequency in soft magnetic materials supply by PWM inverter were found and studied in [2-3]. Estimations of core losses under sinusoidal, square, non-sinusoidal and PWM voltage supplies were compared and discussed in [4-7]. The measurement and prediction of core losses in the induction motors fed by high frequency non-sinusoidal and PWM voltage excitations were investigated in [8-10]. References [11-12] proposed the evaluation methods and presented analysis on core material for motors in automobiles, hybrid or electrical vehicles.

The core losses of non-oriented electrical steel laminations under sinusoidal, non-sinusoidal and PWM voltage excitations at frequency range from 50 Hz to 400Hz are analyzed in the paper.

II. EPSTEIN FRAME

The industrial standard is usually a 28 cm x 28 cm four-sided frame with 700 turns both on the primary and the secondary windings. Steel samples (strips) should be 28 cm long (± 2.05 cm) and 3 cm wide. They must be of multiples of 4, with a recommended minimum number of 12 strips. Strips cut across the rolling direction are loaded on the opposite sides of the frame, while those cut along the rolling direction are loaded on the opposite sides. The equivalent magnetic length is assumed to be 25 cm for each side. The total magnetic length round the frame is 94 cm. A compensator coil, usually at the center of the frame’s interior is required to compensate for the mutual air flux between the primary and secondary windings with no lamination present. The design and detailed technical issues are well addressed by [10], from which the ASTM standards are based. The samples must be demagnetized before testing to remove previous magnetic excitations on the samples. Some of the shortcomings of this method are that flux density is not uniformly distributed due to leakage flux around the joints. The corners have been found to cause errors. The magnetic length (94cm) is estimated, not an accurate value [10].

III. MEASUREMENT PROCEDURES

This measurement determines the magnetic properties of non-oriented electrical steel laminations
using the Epstein test frame as above and 30 cm double-lap-jointed core sheets under voltage frequency range from 50 to 400 Hz. The core loss, rms exciting power, rms and peak exciting current can be obtained in the test. Also, the ac permeability and related properties of non-oriented permeability and related properties of non-oriented electrical steel laminations are calculated under ac magnetization. The test conditions that flux density is increased from 0.03 to 1.5 Tesla and magnetic field intensity is operated between 20 and 12000 A/m. The test procedures are proceeded as follows:

1. Before testing, inspect the test specimens for length if they conform to the expected length within 1/32 inch [0.8mm]. Also, check the test specimens if they were dented, twisted, or distorted and if their width is uniform. Accuracy of the specimen mass is within 0.1%.

2. Source voltage is supplied to coil circuit in primary side to magnetize the test specimens to maximum magnetic induction area. Then slowly and smoothly reduce the voltage to a very low magnetic induction to de-magnetize.

3. After de-magnetization, quickly test the selected test points, increase the input voltage to implement the measurement of B-H curve.

4. Core losses are found by multiplying the primary current with the (induced) secondary winding voltage to give the instantaneous power waveform, whose average value equals the total core losses in the test specimens.

5. Obtain the rms exciting power.

6. Calculate the ac permeability.

7. Read data, draw B-H curve and store them to personal computer.

IV. 2D FINITE ELEMENT MODELING

Ansoft-EM is a 2D/3D finite-element modeling (FEM) analysis software, which is widely used to analyze the engineering problems related on electromagnetic analysis including linear, static, dynamic, thermo and optimization etc.

The simulated machines must be defined by six procedures in FEM software and then proceed the analysis:

1. Definition of elements, sections, and materials: elements as a node and air gap in 0-Dimension; a beam and a pillar in 1-Dimension; a disc and shell in 2-Dimension; or a tetrahedron and hexahedron in 3-Dimension etc.

2. Draw out the global machine geometry

3. Meshing – divide small mesh to provide the calculations in procedure (5). It may select the direct meshing, manual meshing and adaptive meshing methods.

4. Definition of constraints and loads - constraints is also called as boundary. Loads include concentration, distribution, acceleration, and preserved strain etc.

5. Analysis - the procedure before/after analysis is Pre-processing / Post-processing and provide the information of stress, strain, displacement etc.

(6) Rows, diagrams, or dynamic diagrams show the simulation results.

A time-stepping finite element modeling is used for the magnetic field. A 2D FEM of non-oriented electrical steel laminations and induction coils in Epstein test frame is shown as Fig. 1. The governing equation for 2D FEM derived from Maxwell’s equations is given by

\[ \nabla \times \mu (\nabla \times \vec{A}) = \vec{J}_0 + \nabla \times (\mu_0 \vec{M}) - \sigma \frac{\partial \vec{A}}{\partial t} \]  

where $\vec{A}$ is magnetic vector potential, $\nu$ and $\sigma$ are the magnetic reluctivity and the conductivity of electrical steel laminations, $\vec{J}_0$ is the exciting current density of coils, $\mu_0$ is the magnetic permeability of free space, $\vec{M}$ is magnetizing vector.

The voltage equation for each phase can be written by

\[ V_a = I_a R_a + L_c \frac{dI_a}{dt} + \frac{d\phi_a}{dt} \]

(2)

where $V_a$, $I_a$, $R_a$, and $\phi_a$ are the input voltage, the current, the resistance, and the flux linkage of each phase, respectively. $L_c$ is the end-coil inductance calculated by equivalent method.

For the time-stepping finite element modeling, time step is usually constant. The input voltage needs to be defined for each time step. To improve the sinusoidal waveform and accuracy of calculation, each time step should be less than 0.01 ms, particularly in high frequency.

V. ANALYSIS OF CORE LOSSES

A. Calculation of Core losses

The core losses of magnetic materials in modern studies can be grouped in three categories. First, when a variable magnetic field excites magnetic materials, the steady loss (hysteresis loss) occurs in Weiss area. Secondly, due to excitation of magnetic fields, abnormal eddy current results in the Barkausen jump to get discontinuous shift of block walls. Since Barkausen jump very fast, the dynamic losses due to abnormal eddy current are called as the excess or anomalous eddy loss. This abnormal eddy current is different from the eddy current in the conductor in next term. Last term is the classical eddy losses, which caused by eddy current in the conductor. At a given frequency, the core losses of electrical steel laminations are based on

\[ W_c = K_b B_{\text{max}}^2 f + K_f (B_{\text{max}} f)^2 + K_e (B_{\text{max}} f)^{1.5} \]

(3)

where $K_b$ is the hysteresis coefficient; $K_e$ is the classical eddy coefficient; $K_f$ is the excess or anomalous eddy current coefficient due to magnetic
domain; $B_{max}$ is the maximum amplitude of the flux density; $f$ is the frequency of exciting voltage.

**B. Discrete Spectrum Analysis**

The total power in a signal is the same whether it is calculated in time domain or in frequency domain. This result is known as Parseval theorem. In discrete function, the power can be figured out in time domain and frequency domain as follows:

$$\sum_{k=0}^{N-1} w(k)^2 = \frac{1}{N} \sum_{n=0}^{N-1} |W(n)|^2$$  \hspace{1cm} (4)

Suppose that the sampling points span a range of time T, the mean squared amplitude can be indicated as

$$\frac{1}{T} \int_0^T |w(t)|^2 dt \approx \frac{1}{N} \sum_{k=0}^{N-1} |w(k)|^2$$  \hspace{1cm} (5)

By FFT calculation, Discrete Fourier transform of the core losses for electrical steel laminations can be obtained as

$$W(n) = \sum_{k=0}^{N-1} w(k) e^{-j2\pi nk/N} \hspace{1cm} n = 0,1,2\ldots N-1$$  \hspace{1cm} (6)

**VI. RESULTS AND DISCUSSIONS**

In this paper, a 2D FEM of coils and non-oriented electrical steel laminations in Epstein test frame consists of about 388 elements and 194 nodes as shown in Fig. 1.

**A. The measured $B$-$H$ Curve and core losses**

When the input voltage is increasingly raised to excite the non-oriented electrical steel laminations, the flux density is enhanced quickly at the same time as shown in Figs. 2. After magnetic field intensity is boosted close to 100 A/m, the increment of flux density become slow and saturated. The core losses of non-oriented electrical steel laminations are examined in three test conditions:

(a) Supply voltage frequency is at 50Hz, 60Hz, 100Hz, 200Hz and 400Hz respectively.

(b) Flux density is varied from 0.03 to 1.5T by increasing supply voltage.

(c) Magnetic field intensity is moved between 20 and 12000 A/m.

Fig. 2 (a) shows $B$-$H$ curves while increasing flux density =1.0 T at different sinusoidal voltage supplies. The $B$-$H$ Curve while increasing flux density =1.5 T at different sinusoidal voltage supplies is presented in Fig. 2(b).

Fig. 3 deals with the measured core loss vs. flux density under sinusoidal voltage supplies at different frequencies. Comparison between the measured and computed core losses at different sinusoidal voltage excitations is obtained in Table 1.

**B. Computation of Core Losses**

The paper used the Epstein test frame and 64 pieces of test steel laminations (thickness =7.75mm per piece) to measure core losses of non-oriented electrical steel laminations as shown in Fig1.

In the Figs. 4(a) and 4(b), the PSDs of core losses under square wave voltage supply at frequency 200Hz and PWM voltage supply at frequency 400Hz are reported respectively. The core losses of the tested steel laminations in Fig. 4(a) are about 13 W/kg at 400Hz and 3.5W/kg at 800Hz. The core losses in Fig. 4(b) are approximate to 80 W/kg at 800Hz; 20W/kg at 1600Hz ...etc. Fig. 5(a) and Fig. 5(b) show the 2D profiles of core losses under sinusoidal and square wave voltage supplies at frequency 400Hz. The 2D profile of core losses under sinusoidal PWM voltage supplies at frequency 400Hz is shown in Fig. 5(c).

Comparison of core losses under sinusoidal, square, and sinusoidal PWM voltage supplies at different frequencies is made in the Fig. 6. It is evidently shown that the sinusoidal PWM voltage results in the most core losses. The sinusoidal wave voltage excites more core losses than the square wave one on the test steel laminations.

**VII. CONCLUSION**

Recently, PWM inverter widely use on the applications of smooth speed control and significantly reducing the starting current for motors. A great mount of motor core losses and conductor copper losses are caused by PWM harmonic current components, resulting in the rise of temperature.

The paper investigates the core losses of non-oriented electrical steel laminations under sinusoidal, non-sinusoidal and PWM voltage supplies. A 2D finite-element modeling was adopted to evaluate the core losses of non-oriented electrical steel laminations in the paper. The estimated results are compared with the experimental measured value to verify the accuracy of the 2D finite-element modeling. Also, Discrete Fourier transform is used to analyze the harmonic components of core losses.

The results clearly show that the varied rate of flux density, the frequency of supply voltage, and the shape of waveform significantly affect the core losses of non-oriented electrical steel laminations. The predicted and experimental results provide motor manufacturers with the important reference to minimize the core losses of the special motors under harmonic voltage supply.

**VIII. ACKNOWLEDGEMENTS**

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REFERENCES


Table 1 Comparison between the measured and computed core losses at different frequencies and sinusoidal voltage excitations

<table>
<thead>
<tr>
<th>Flux Density</th>
<th>0.5T</th>
<th>1.0T</th>
<th>1.5T</th>
</tr>
</thead>
<tbody>
<tr>
<td>50Hz</td>
<td>0.517 (0.52)</td>
<td>795 (1.804)</td>
<td>3,822 (3.934)</td>
</tr>
<tr>
<td>60Hz</td>
<td>0.75 (0.81)</td>
<td>2.15 (2.25)</td>
<td>4.88 (5.05)</td>
</tr>
<tr>
<td>100Hz</td>
<td>0.77 (0.79)</td>
<td>4.31 (4.42)</td>
<td>10.1 (10.33)</td>
</tr>
<tr>
<td>200Hz</td>
<td>1.39 (1.47)</td>
<td>10.8 (11.3)</td>
<td>30.3 (30.9)</td>
</tr>
<tr>
<td>400Hz</td>
<td>6.2 (6.5)</td>
<td>36.3 (37.8)</td>
<td>85.6 (88.3)</td>
</tr>
</tbody>
</table>

( ) is computational value : Coreloss unit:W/kg

Fig. 1 A 2D finite element modeling of non-oriented electrical steel laminations and induction coils in Epstein test frame

Fig. 2 (a) B-H Curve while increasing flux density =1.0 T at different sinusoidal voltage supplies

Fig. 2(b) B-H Curve while increasing flux density =1.5 T at different sinusoidal voltage supplies

Fig. 3 The measured core loss vs. flux density under sinusoidal voltage supplies at different frequencies
Fig. 4(a) The PSD of core losses under square wave voltage supply at frequency 200Hz

Fig. 4(b) The PSD of core losses under PWM voltage supply at frequency 400Hz

Fig. 5(a) The 2D profile of core loss under sinusoidal voltage supplies at frequency 400Hz

Fig. 5(b) The 2D profile of core loss under square wave voltage supplies at frequency 400Hz

Fig. 5(c) The 2D profile of core loss under sinusoidal PWM voltage supplies at frequency 400Hz

Fig. 6 Comparison of core losses under sinusoidal, square, sinusoidal PWM voltage supplies at different voltage frequencies