Estimation of Core Losses in an Induction Motor under PWM Voltage Excitations Using Core Loss Curves Tested by Epstein Specimens

Wen-Chang Tsai
Department of Electrical Engineering
Kao Yuan University
Luju 82141, Kaohsiung County, Taiwan, R.O.C.
Email: dougtsai@cc.kyu.edu.tw

Keyword : Discrete Fourier Transform(DFT), finite element modeling, core loss, induction motor, PWM, Epstein specimens

ABSTRACT

The paper deals with a study on the core losses in induction motor laminations fed by PWM voltages. Discrete Fourier Transform is used to analyze the harmonics of magnetic flux density in induction motor laminations. The distributions and variations in magnetic flux density of the induction motor are evaluated by using a 2D finite element modeling. The measurement of core losses of steel laminations in Epstein Frame is implemented under sinusoidal waveform step by step from 60 Hz to 5000Hz. The core loss curves tested on Epstein laminations are applied to estimate the lamination core losses in a PWM inverter-fed induction motor. The core losses of induction motor laminations under PWM voltage excitations are computed for the DFT harmonic components by using the core loss curves. The total core loss of induction motor laminations can be determined by the summation of the iron losses produced by all the harmonic components. The study for the induction motor is compared and analyzed by two different materials. The 2D profiles of core losses in the induction motor laminations are also shown in the paper.

1. INTRODUCTION

Pulse width modulation (PWM) inverters are largely used to supply industrial rotating motors. The performance of PWM inverter for driving induction motors has been improved and results in significant energy saving. However, the use of PWM voltages supplies leads to a general loss increase both in the motor windings and in the motor steel laminations. It becomes necessary for designers to know details of the steel lamination losses under non-sinusoidal and PWM voltage supplies because the steel lamination losses are very important for the design of motors on improving their performances.

Several methods to predict or measure the core losses in magnetic materials under non-sinusoidal and PWM voltage supplies have been deeply investigated and reported in the previous papers [1-5]. A general formula for prediction of iron losses under non-sinusoidal voltage waveform was studied in [1]. Estimations of core losses in magnetic materials under sinusoidal, square, six-step, non-sinusoidal and PWM voltage supplies were compared and discussed in [2-4]. Two practical lab-measured results of iron losses in electrical steel laminations fed by the variable switching supply frequency of PWM inverter were compared in [5]. The measurement and prediction of core losses in the
induction motors fed by high frequency non-sinusoidal and PWM voltage excitations was investigated and discussed in [6-10].

In this paper, the core losses in induction motor laminations fed by PWM voltages are evaluated using core loss curves tested by Epstein specimens. The study for the core losses of steel laminations in the induction motor is implemented under PWM voltage excitations from 60 Hz to 400Hz. The investigation has been performed on a three-phase 95-hp 460-V squirrel-cage induction motor with 28 stator slots and a cage with 36 rotor bars respectively. The 2D profiles of core losses in the induction motor are shown in the paper.

2. 2D FINITE ELEMENT MODELING

A time-stepping finite element modeling is used for the magnetic field. A 2D FEM of steel laminations in a PWM inverter-fed induction motor consists of about 2640 elements and 1320 nodes.

Fig. 1 The simulated diagram of a PWM inverter-fed induction motor

In three-phase PWM drives, the three phase stator armature windings which are usually labeled A, B, and C, respectively, can be represented by three electrical circuits which are conductively isolated from each other, and magnetically coupled to each other and to the rotor circuits. The schematic layout of a PWM inverter-fed induction motor is shown in Fig. 1.

The governing equation for 2D FEM derived from Maxwell’s equations is given by

$$\nabla \times \left( \nabla \times \vec{A} \right) = \vec{J}_0 + \nabla \times (\nu \mu_0 \vec{M}) - \sigma \frac{\partial \vec{A}}{\partial t} \tag{1}$$

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 stator voltage equation in the $abc$ frame can be expressed as follows:

$$V_{abcs} = r \cdot i_{abcs} + \frac{d}{dt} \psi_{abcs} \tag{2}$$

where

$$v_{abcs} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}, \quad i_{abcs} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}, \quad \psi_{abcs} = \begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix}, \quad r = \begin{bmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{bmatrix}$$

$$\psi_{abcs} = L_s i_{abcs}, \quad L_s = \begin{bmatrix} L_{ls} + L_m & -\frac{1}{2} L_m & -\frac{1}{2} L_m \\ -\frac{1}{2} L_m & L_{ls} + L_m & -\frac{1}{2} L_m \\ -\frac{1}{2} L_m & -\frac{1}{2} L_m & L_{ls} + L_m \end{bmatrix}$$

Inductance profile calculations of $L_{ls}$, $L_m$ and $L_{\Delta m}$ can be obtained from a time-stepping.

For the time-stepping finite element modeling, time step is usually constant. The input
International Forum on Systems and Mechatronics, 2007

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 0.01ms, particularly in high frequency.

3. ANALYSIS OF CORE LOSSES

3.1 Discrete Fourier Transform

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:

\[
\sum_{k=0}^{N-1} w(k)^2 = \frac{1}{N} \sum_{n=0}^{N-1} |W(n)|^2
\]  

(3)

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

\[
\frac{1}{T} \int_0^T |w(t)|^2 dt \approx \frac{1}{N} \sum_{k=0}^{N-1} |w(k)|^2
\]

(4)

By FFT calculation, Discrete Fourier transform of the flux density in electrical steel laminations can be obtained as

\[
W(n) = \sum_{k=0}^{N-1} w(k) \cdot e^{j2\pi mk/N} \quad n = 0,1,2...N-1
\]  

(5)

3.2 Computation 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

\[
W_T = K_h B_{max}^2 f + K_e (B_{max} f)^2 + K_e (B_{max} f)^{1.5}
\]

(6)

where \(K_h\) is the hysteresis coefficient; \(K_e\) is the classical eddy coefficient; \(K_e\) 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.

4. RESULTS AND DISCUSSIONS

In this paper, a 2D FEM of a PWM inverter-fed induction motor consists of about 2640 elements and 1320 nodes. The study for the core losses of induction motor laminations is implemented under PWM voltage excitations from 60 Hz to 400Hz. The induction motor is operated between 0.03T and maximum flux density 1.5T. The switching frequency of PWM voltage is operated at 2 kHz.
4.1 The $W_T - B_{\text{max}}$ Curves of Two Different Non-Oriented Electrical Steel Laminations

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

(a) The frequency arrange of input supply voltage is varied between 60Hz and 5000Hz.
(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 the core loss vs flux density curve of material A from 60 to 5000Hz under sinusoidal voltage. The core loss vs flux density curve of material B from 60 to 5000Hz under sinusoidal voltage is presented in Fig. 2(b). The results are compared to verify the accuracy of the 2D finite-element modeling.

4.2 Computation of Core Losses in Electrical Steel Laminations

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

The PSDs of peak flux density at 400Hz PWM voltage excitation are shown in the Fig. 3. It is shown in the figure that the peak flux density is 0.545T at 400Hz, 0.06T at 1200Hz and slight components at 800Hz, 1600Hz, and 2000Hz (may be neglected). Fig. 4 presents
a 2D plot of peak flux density (about 0.6T) in the induction motor laminations at 400Hz sinusoidal PWM voltage supply. By substituting the peak flux densities at multiple frequencies of 400Hz as shown in Fig. 3 into Equation (6), the total core losses of two different materials can be compared in Fig. 5. The core losses of the Type A non-oriented steel laminations as in the “▲” mark of Fig. 5 are about 2.88 W/kg at 60Hz, 5.01 W/kg at 100Hz, 9.74 W/kg at 200Hz and 34.13W/kg at 400Hz. The core losses of the Type B ones are approximate to 4.14 W/kg at 60Hz, 6.54 W/kg at 100Hz, 16.37 W/kg at 200Hz and 44.5W/kg at 400Hz as in the “■” mark of Fig. 5.

4.3 Core Losses in Induction Motor and 2D Plots

The computed core losses in electrical steel laminations of the case-study motor for two materials using the tested core loss curves are shown in Fig. 6. First, in Fig. 6, the average core losses of case-study motor using material A under PWM voltage excitations are 401.3 W at 60Hz, 866.3 W at 100Hz, 2607.2 W at 200Hz and 4965.2 W at 400Hz, respectively. On the other hand, those core losses using material B under PWM voltage excitations are 769.1 W at 60Hz, 1276 W at 100Hz, 3372 W at 200Hz and 6422.2 W at 400Hz, respectively.

The 2D profile of core losses of the induction motor with material A is reported in Fig. 7(a). The PWM voltage frequency and maximum flux density are operated at 400Hz and 0.6 T, respectively. The maximum core losses of the induction motor are about 3.8632×10^5 W/m^3 at the red area of Fig. 7(a). The 2D profile of core losses of the induction motor with material B is illustrated in Fig. 7(b). The induction motor is fed by 400Hz PWM voltage and excited to maximum flux density 0.6 T. Then, the maximum core losses of the induction motor are approximate to 4.1949×10^5 W/m^3 at the red area of Fig. 7(b).
5. CONCLUSION

The paper investigates the core losses of two different non-oriented electrical steel laminations under PWM voltage excitations. A 2D finite-element modeling for an induction motor drive was adopted to compare the core losses in the induction motor laminations using two different materials in the paper. Discrete Fourier transform is used to analyze the harmonic components of maximum flux density in the motor laminations.

The results show that the peak value of flux density, the frequency of supply voltage, and the shape of flux density waveform significantly affect the core losses of non-oriented electrical steel laminations. Also, it is evidently shown from results that material B results in more core losses in the induction motor laminations than material A.

The results in the paper have been implemented by using the simulation of a 2D finite-element modeling. They may provide the accurate induction motor model under the PWM inverter excitation. The practical measurement of core losses in the induction motor drive should be made in the future work to verify the accuracy of the simulated model.

6. ACKNOWLEDGEMENTS

The user thanks the National Center for High-Performance Computing for using the Ansoft-EM software package and administrator’s helps during the course of this study.

REFERENCES