Effects of Core Materials and Operating Parameters on Core Losses in a Brushless DC Motor

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Abstract

The development of high-efficiency DC motors is a very important technique subject from the viewpoint of energy saving. In order to increase the motor efficiency, three different grades of electrical steel laminations are used to design a brushless DC (BLDC) motor in the paper since they provide reduced core losses. A measurement of core losses of three different grades of electrical steel laminations in Epstein Frame is implemented to determine the $W_T-B_{\text{max}}$ core loss curves under sinusoidal waveform step by step from 60 Hz to 5000Hz. The core losses in a BLDC motor fed by a PWM control DC Square-Wave voltage supply are estimated using the $W_T-B_{\text{max}}$ core loss curves. The effects of three core materials on the core losses of the BLDC motor have been studied in the paper. The computed core losses are compared to those evaluated by using a 2D finite element analysis. The effects of various operating conditions on the core losses in the BLDC motor laminations are also investigated in this paper. The presented results give guidelines to the selection of core materials and the operating points to improve motor efficiency.

Keywords: Brushless DC (BLDC) Motor, Electrical Steel Laminations, Core Losses

1. Introduction

A growing number of different industrial applications use BLDC motor drives because of their high efficiency, power density, excellent acceleration ability, low operating noise, high reliability and their consistent high speed operation. The studies for the characterization of motor drives using a finite-element model have been reported in [1]. To design the high efficiency motors, the motors’ core losses supplied by PWM inverters were evaluated and presented in previous papers [2-5]. The core losses of permanent magnet synchronous motors have been deeply examined to obtain more accurate results for the designs of high-efficiency motors [6-8].

A BLDC motor designed using three core materials is analyzed for the operating conditions in B-H curves. Core losses are estimated and compared to each operating condition. The core losses in the BLDC motor are computed using the $W_T-B_{\text{max}}$ core loss curves tested by Epstein Frame. Effects of three different core materials on the core losses in the BLDC motor are examined in the paper. The results are compared to those evaluated by using the finite element analysis. The effects of various operating conditions on the core losses in the BLDC motor laminations are also investigated. The investigations are performed on a 120 W 6-pole and 18 slots BLDC motor.

2. Epstein Frame test

The core loss measurement system, which includes Epstein Frame, hall sensors, data acquisition and signal conversion module as well as B-H curve and core loss display on the PC is illustrated in Fig. 1.
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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 as shown in Fig. 2. 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 in [2-3], upon which the ASTM standards are based. The samples must be demagnetized before testing to remove previous magnetic excitations on the samples. A shortcoming of this method is that the flux density is not uniformly distributed due to flux leakage around the joints.

2.1. Measurement procedures and display

The voltage, current and flux of the primary and secondary coils in Epstein Frame are measured with a set of LA55-P and HY 25-P Hall sensors. The voltage and current levels are transduced into dc voltage signals by hall sensor module, transmitting them into the module for signal acquisition, conversion and process. The computer source code is designed in C code program and written into the C8051F30x development system to edit, simulate, debug and burn it into the C8051F30x microchip. The C8051F30x
microchip implements the conversion of the analog signals from voltage, current and flux sensor to the
digital signals as shown in Fig 3(a).
The voltage, current and flux signals detected in the Epstein Frame coils are then extracted and
converted into digital signals for the Labview data acquisition and graphic instrument program. Using
the program, the data is computed, displayed and saved into the computer as Excel files. The
direct-measurement data includes the voltages (V), currents (I) of the primary and secondary coils, and
the computed data of magnetic flux density (B), magnetic field intensity (H), magnetic permeability(µ),
core loss (P_{coreloss}). Furthermore, the acquisition data of B-H curves and core losses are displayed in 2D
and 3D plots on the computer screen as illustrated in Fig. 3(b).

This measurement determines the magnetic properties of non-oriented electrical steel specimens in
Epstein test frame as above and 30 cm double-lap- jointed core sheets under voltage frequencies
ranging from 60 to 5000 Hz. The core loss, RMS exciting power, and peak exciting current can be
obtained in the test. Also, the AC permeability and related properties of non-oriented materials are
calculated under AC magnetization. During the test, the flux density B is increased from 0.03 to 1.5
Tesla and the magnetic field intensity H is operated between 20 and 12000 A/m. The test procedures
are implemented as follows:

1. Prior to testing, inspect whether the test specimens conform to the expected length within +/- 
   1/32in. [0.8mm]. Also, check the test specimens to see whether they are dented, twisted, or
distorted and if their width is uniform. Accuracy of the specimen mass is within 0.1%.
2. Exciting voltage is supplied to the coil circuit of the primary side to magnetize the test
   specimens to their maximum magnetic induction area, and then slowly and smoothly, the
   voltage is reduced to a very low magnetic induction in order to de-magnetize.
3. After de-magnetization, quickly test the selected test points, the input voltage is increased to
   measure the B-H curve.
4. Core losses are found by multiplying the primary current by the (induced) secondary winding
   voltage to give the instantaneous power waveform, whose average value equals the total core
   losses in the test specimens.
5. Interpret data, construct B-H curve and W_{1-B_{max}} curve, and save them to personal computer.

3. Time-Stepping Finite-Element Model

A time-stepping finite element modeling is used for the magnetic field. A 2D FEM of non-oriented
electrical steel laminations in the brushless PM dc motor is shown as Fig. 4. The governing equation for
2D FEM derived from Maxwell’s equations is given by

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

where \( \vec{A} \) is the magnetic vector potential, \( \nu \) and \( \sigma \) are the magnetic reluctivity and the conductivity

\[
(1)
\]
of electrical steel laminations, $\bar{J}_0$ is the exciting current density of coils, $\mu_0$ is the magnetic permeability of free space, and $\bar{M}$ is magnetizing vector.

The TSCFE-SS model comprises of two portions, namely, the SS model/algorithm and the TSFE model/algorithm. The two models, the SS model and the TSFE model, are coupled such that the output of these models is used as the input to the other model. Specifically, the output of the SS model is used in the TSFE model to excite the half FE grid of the example machine at every rotor angular position (time sample) in the ac operating cycle, as shown in Fig. 4. In this paper, the half FE model of the BLDC motor consists of about 2430 triangle elements.

Once convergence of the TSCFE-SS iterative process is achieved, the converged non-sinusoidal winding current waveforms, laminated iron core and other performance characteristics are obtained including the comprehensive impacts of space and time harmonics. Accordingly, in this paper, the formulation of the TSCFE-SS model allows simulations of BLDC motors under various forms of operating load conditions and PWM excitation voltage.

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 PWM waveform and accuracy of calculation, each time step should be less than 0.01 ms, particularly in high frequency.
PWM DC Square-Wave Excitations

In the DC Square-Wave voltage circuit, \( RQ1-RQ6 \) are represented as the equivalent resistances of the switching devices, \( Q1-Q6 \), and \( RD1-RD6 \) are the equivalent resistances of the anti-parallel diodes, \( D1-D6 \). Circuit network diagram for a BLDC motor drive is shown in Fig. 6.

4. Core loss computations and measurements

In this section, the formulation and computed results of the core losses for the case-study induction motor are presented.

The core losses of the motor were computed from the radial and tangential components of the periodic, yet non-sinusoidal, time-domain flux density waveforms in each FE of the stator and rotor iron cores. At a given frequency, the core losses of electrical steel laminations in motors is based on

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

where \( K_h \) is the hysteresis coefficient; \( K_c \) is the classical eddy current coefficient; \( K_e \) is the excess or anomalous eddy current coefficient due to magnetic domain; \( B_{\text{max}} \) is the maximum amplitude of the flux density; \( f \) is the frequency.

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

\[
W_T = C_m f^x (B_{\text{max}}^{y})
\]

where \( C_m \), \( x \), and \( y \) are empirical parameters obtained from experimental measurement under sinusoidal excitation. \( C_m \) is the Steinmetz coefficient; \( x \) and \( y \) are Steinmetz exponent; \( B_{\text{max}} \) is the maximum amplitude of the flux density; \( f \) is the frequency.

The paper deals with the measured core losses vs. flux density under sinusoidal voltage supplies at frequency range 50Hz to 5000Hz. The equivalent magnetic length is assumed to be 25 cm for each side. The total magnetic length around the test frame is 94 cm. The core losses of non-oriented electrical steel laminations (50CS600, 50CS470, 50CS350) measured by Epstein Frame are obtained in Table 1. The measured database would be used to compare with those evaluated by the GSE model in [9].

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Table 1. Core loss database of non-oriented electrical steel laminations measured by Epstein Frame

<table>
<thead>
<tr>
<th>Material</th>
<th>Core Loss (W/kg)</th>
<th>Epstein Frame (%)</th>
<th>Mean Error (%)</th>
<th>Maximum Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50CS600</td>
<td>0.038</td>
<td>0.4</td>
<td>10</td>
<td>3.8</td>
</tr>
<tr>
<td>50CS470</td>
<td>0.034</td>
<td>0.3</td>
<td>10</td>
<td>4.6</td>
</tr>
<tr>
<td>50CS350</td>
<td>0.032</td>
<td>0.3</td>
<td>10</td>
<td>5.2</td>
</tr>
</tbody>
</table>

4.1. Core loss curves of electrical steel laminations

The paper investigates the core losses of non-oriented electrical steel laminations under the frequency range 50 to 5000Hz sinusoidal voltage supplies. The optimal analysis procedure of the GSE method is completed in the paper. The dynamic core loss equations derived from the GSE model was proposed in [9]. The dynamic core loss equation may be used to simulate and obtain the core losses of non-oriented electrical steel laminations, which could not be determined by the existing theory. The flux simulation spans are ranged between 0.3 and 1.5 Tesla and frequencies ranging from 50 to 5000Hz respectively. It is adequate for most application designs such as motors, generators, and low-frequency transformers. The mean estimated accuracy is less than 10% errors, which is far less than the 20% errors of interpolation computation. The dynamic core loss equations are able to provide accurate estimations of the performances of prototype motors during their initial development stage.

The optimal analysis procedure is established for dynamic core loss equations to complete the dynamic core loss models for medium, medium-high, and high grade electrical steel laminations as below:

1. Core loss curves at frequency of 50CS600 electrical steel laminations at frequency range 50Hz to 5000Hz are shown in Fig. 7(a). Circle represents the experimental values measured by Epstein Frame. Mean error is around 6.31%. Maximum error is located at 1.84T/50Hz. The simulated value is 5.25 W/kg, which error is 7.5%.

2. Core loss curves of 50CS470 electrical steel laminations at frequency range 50Hz to 5000Hz are shown in Fig. 7(b). Circle represents the experimental values measured by Epstein Frame. Mean error is about 6.16%. Maximum error is located at 1.84T/50Hz. The simulated value is 4.45 W/kg, which error is 9%.

3. Core loss curves of 50CS350 electrical steel laminations at frequency range 50Hz to 5000Hz are shown in Fig. 7(c). Circles represent the experimental values measured by Epstein Frame. Mean error is close to 6.03%. Maximum error is located at 1.48T/400Hz. The simulated value is 60.8 W/kg, with an error of 17%. 

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5. Results and Discussions

The paper utilizes the Epstein test frame and 64 pieces of test steel specimens (thickness = 0.5mm per piece) to measure core losses in three core materials- 50CS600, 50CS470 and 50CS350 electrical steel laminations. The core losses in the BLDC motor fed by a DC Square-Wave voltage supply with PWM control are evaluated in core loss curves tested by an Epstein Frame and compared with those computed in the finite element model.

5.1. Curves of core loss vs. maximum flux density

Fig. 7 (a) shows the core loss vs. flux density curve of the 50CS600 electrical steel lamination under sinusoidal voltage frequencies ranging from 50 to 5000Hz. The core loss vs. flux density curves of the 50CS470 and 50CS350 electrical steel laminations under sinusoidal voltage frequencies ranging from 50 to 5000Hz is presented in Figs. 7(b) and 7(c) respectively. The experimental and computed results are used to compute the core losses in the BLDC motors.

5.2. 2D Profile of flux density

The PSDs of peak flux density in the BLDC motor under DC 48V Square-Wave voltage and at a

![Diagram of 2D Profile of flux density](image_url)

**Fig 8.** The PSDs of peak flux density in the BLDC motor under PWM DC 48V Square-Wave voltage
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Rated speed of 2200 rpm are shown in Fig. 8. The load-torque, which is a function of speed and its maximum magnitude, is calculated at 2.5 N-m. It is shown in the figure that the peak flux density is 1.4T at 60Hz, 0.14T at 300Hz and 0.06T at 420Hz. Fig. 9 presents a 2D plot of peak flux density (about 1.5T) in the BLDC motor laminations at the speed of 2200 rpm.

5.3. Core Loss Analysis

The paper uses a time-stepping coupled finite-element model to evaluate core losses in the BLDC motor driven by a DC Square-Wave supply with PWM control. The motor is supplied by DC 48V voltage and runs at its rated speed. The operating condition of load-torque is a function of speed and its maximum magnitude of 2.5 N-m. In Fig. 10(a), when the BLDC motor starts and no load torque is applied to the shaft of motor, the maximum core losses of the 50CS600 electrical steel laminations in the BLDC motor gradually increase up to 7.8W. After the motor increases to 600rpm, the motor core loss drops down to 3.78 W and is varied between 7.8 and 3.78 W. The average core losses for 50CS600 electrical steel laminations in the BLDC motor are around 5.79 W. As for depicted in Fig. 10(b), in the same operating condition, the motor rapidly produces peak core losses at about 3.78W on the 50CS470 electrical steel laminations in the BLDC motor. Then, the core losses are reduced to 1.78 W and varied between 1.78 and 3.78 W after the motor runs up to 600rpm. The average core loss for 50CS470 electrical steel lamination in the BLDC motor is about 2.78 W.

Fig. 10 illustrates the 2D core loss profile of the BLDC motor at 2.5 N-m load-torque and 1.5 T flux density. The density of the electrical steel laminations used in the BLDC motor is 7750 kg/m³. Therefore, the maximum core loss of the 50CS470 electrical steel lamination in the BLDC motor is about 2.93×10⁴ W/m³ as represented by the red areas in Fig. 11.
5.4. Core Losses in the BLDC motor at various operating conditions

The core losses in the BLDC motor driven by a DC Square-Wave voltage supply are evaluated from core loss curves tested by an Epstein test frame. The computed core losses are compared to those evaluated by using a 2D time-stepping finite element modeling. The average core losses in the BLDC motor under DC 48V square-wave voltage and load-torque from 0.5 to 2.5 N-m are shown in the Fig. 12(a). The load-torque-2.5N-m, is a function of speed and its maximum magnitude. From the results in the figure, the core losses represented by the solid line and dotted line are determined by the 2D time-stepping finite element modeling and core loss curves tested by an Epstein tester respectively. Also, the core losses of the 50CS600, 50CS470 and 50CS350 electrical steel laminations in the BLDC motor are represented by “◆”, “▲” and “*” marks. The maximum core loss is shown in the 50C600 electrical steel lamination. The maximum motor core losses are located at load-torque 1.0 N-m. The average core losses in the BLDC motor vs. motor speed under DC 48V square-wave voltage are illustrated in the Figs 12(b). From the results in the figures, the core losses indicated by the solid line and dotted line are evaluated by the 2D time-stepping finite element modeling and core loss curves tested by an Epstein tester respectively. Also, the core losses of 50CS600, 50CS470 and 50CS350 electrical steel laminations in the BLDC motor are indicated by “■”, “×” and “●” marks. The core losses are directly proportional to the motor speed. The maximum motor core losses are located at speed = 2200rpm and square-wave voltage = DC 48V, which increases with motor speed. Similarly, the 50C600 electrical steel lamination shows the highest core loss.

![Fig 12. (a) Curves of core losses versus load torque of a BLDC motor at DC 48V Square-Wave voltage Fig. 12(b) Curves of core losses versus rotating speed of a BLDC motor at DC 48V Square-Wave voltage](image)

![Fig 13. Efficiency of a BLDC motor at DC48V Square-Wave voltage](image)

In order to improve motor efficiency with higher grades of core materials, the operating points must be considered. In this paper, load torque and speed are varied with a fixed voltage. Fig. 13 shows the
efficiency of the BLDC motor designed using the 50CS600, 50CS470 and 50CS350 electrical steel laminations as the three core materials. In the low torque region, the core flux density tends to be low and the motor speed high. The back EMFs of the BLDC motor are almost identical to each other. At low load torque, motor speed is high and the 50C600 electrical steel lamination shows the highest core loss, however, since copper loss is dominant, the effect of core loss is not significant to the overall efficiency. Consequently, at low load torque with high speed, the BLDC motor fabricated by the 50C350 electrical steel lamination shows the highest efficiency. However, at high load torque, the motor efficiencies in all three core material designs are almost the same.

6. Conclusions

The specific 0.5mm 50CS600, 50CS470 and 50CS350 electrical steel laminations are extensively applied to industrial motors. In the paper, Epstein Frame test is implemented to establish the database of core losses for medium, medium-high, and high grade 0.5mm electrical steel laminations. The core losses of electrical steel specimens are determined under sinusoidal voltage exciting frequency ranging from 50 Hz to 5000Hz. The database of core losses is able to provide designers the useful designing criteria on estimating the efficiency, and performance of the BLDC motors at various operating conditions. In essence, this paper proposes the core loss curves tested by an Epstein Frame to calculate the core losses in the BLDC motor fed by a DC Square-Wave supply. The computed core losses are compared to those evaluated by using 2D time-stepping finite element modeling. Furthermore, 2D profiles of the core losses and maximum flux densities of the BLDC motor steel laminations under various operating conditions have been presented in the paper. In order to improve motor efficiency with a higher grade of electrical steel laminations, the operating points need to be considered. From the experimentally analyzed results and the presented simulation results, the following conclusions are drawn:

(1) The presented results in the paper may provide an efficient method to evaluate the core losses in the BLDC motor fed by a DC Square-Wave voltage supply with PWM control.

(2) In the BLDC motor driven by a DC Square-Wave voltage supply, the core losses decreases with increasing load-torque. However, the core losses are directly proportional to the motor speed; they increase as the motor speed increases.

(3) The core losses determined by the 2D time-stepping finite element analysis (FEA) are slightly higher than those evaluated from core loss curves tested by an Epstein Frame Tester (E.C.). The error between the two estimation methods is due to certain high frequency harmonic components of flux density being neglected in the E.C. estimation method.

(4) At low load torque, motor speed is high, the 50C600 electrical steel lamination shows the highest core loss. However, since copper loss is dominant, the effect of core loss is considered insignificant towards the overall efficiency. Consequently, at low load torque with high speed, the BLDC motor fabricated using the 50C350 electrical steel lamination shows the highest efficiency. The efficiencies of the BLDC motors designed using the three core materials are almost the same at high load torque with low speed.

The predicted and experimental results provide motor manufacturers an important guideline to minimize the core losses in specific motors under harmonic voltage supply.

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8. References

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