Core Losses in Motor Laminations Exposed to High Frequency or Non-Sinusoidal Excitation

Lotten T Mthombeni, Student Member, IEEE, P. Pillay, Senior Member, IEEE
Department of the Electrical & Computer Engineering
Clarkson University, Potsdam, NY 13699-5722
E-mail: mthomblt@clarkson.edu

Abstract: **This paper first reviews three internationally standardized core loss measurement methods: Epstein frame, Toroids and Single Sheet testers. A comparison of the Epstein frame and toroid test results is presented for annealed and unannealed steel. Two methods are used to predict core losses under non-sinusoidal supplies. The first method uses the Fourier series and an improved loss separation algorithm to predict core losses under equivalent brushless dc motor flux waveform with known spectrum. For lower harmonics, superposition yielded results close to the measured values. The second method uses the form factor concept and an improved loss separation algorithm to predict core loss. The combination of the improved loss separation algorithm and the form factor concept was found to yield results close to the measured losses under high frequency supplies, such as pulse width modulated waveforms. An Epstein frame with commercial 0.0140-inch electrical steel was used for direct core loss measurements; the methods and test bench used are detailed in the paper, along with test results.**

Keywords: BDCM, Core Loss, Epstein, Harmonics, PWM

I. INTRODUCTION

In electrical machines, core losses amount to 20 – 25 % of the total losses [1], this estimation being valid under sinusoidal supplies, usually 50 Hz or 60 Hz. Magnetic test results (average core loss, at peak induction and frequency, 1.5 T, usually at 60 or 50 Hz, sinusoidal) are considered important parameters when deciding on a suitable steel for a particular application. This is considered by some as the "working point" of the electrical steel for machines operating directly off the mains supply. To motor designers, this working point provides them with the steel characteristics and has a direct impact on the motor design; and consequently, on the overall motor efficiency. Different steel manufacturers use different standardized testing methods to arrive at this working point. Associations such as the American Society for Testing and Materials (ASTM) provide such standards to characterize soft magnetic materials to ensure that standardized methods are used to define this working point. While ASTM and other international standards cover comprehensive methods for characterizing steel under sinusoidal supplies, there are no international standards for variable frequency supplies, such as for square-wave and pulse width modulated (PWM) inverters.

Even with the sinusoidal supplies, core loss results from different steel manufacturers and users, following the ASTM standards [3] do not yield the same results, as will be shown in this paper. The discrepancies were found when comparing loss results from Epstein and toroid testers.

Variable Speed Drives (VSDs) are becoming increasingly popular for motors in industries because of their benefits in improved process control and energy savings. The benefits of employing a VSD are derived at a cost of increased core losses and motor temperature rise. With switched reluctance motors [12] and brushless dc motors (BDCM), the flux density waveforms are naturally non-sinusoidal. While these deviations from sinusoidal waveforms are by design, flux distortions can occur inside the motor, due to bad joints and other factors. With non-sinusoidal supplies becoming pervasive in industry, it becomes necessary for motor designers to know either by measurements or estimations details of the motor core losses.

A number of methods to predict core losses under distorted supplies have been reported in the literature, such as [8] and [9]. In [9] the possibility of estimating core losses using the distorted voltage form factor was discussed. They use an equivalent voltage pulse rise time and hysteresis (measured), classical and excess losses determined from sinusoidal supplies, as inputs to their prediction formula. Reference [8] presented a formula to estimate core losses under distorted supplies, which requires the three loss components and the form factor (calculated or measured) of the distorted voltage as inputs. The two methods in [8] and [9] are similar; in [8] it is generalized to cover PWM waveforms, while in [9] it was mainly for single voltage pulses. Steel manufacturers only provide total loss data as a function of frequency and peak flux density; a loss separation algorithm has to be applied to the data to compute the three loss components. When [8] and [9] reported the formulae for predicting core losses under non-sinusoidal excitations, they used a loss separation method that assumes a hysteresis loss component found from the static *B-H* loop. Recently one of the authors [11] reported an accurate algorithm based on curve fitting and a dynamic hysteresis loss component. The loss separation algorithm and estimation formula are used in this paper to predict core losses under non-sinusoidal supplies. A test bench proposed by [2] is adopted for non-sinusoidal loss measurements.

Section II presents a comparison of core loss testing methods under sinusoidal supplies followed by a comparison of results from two internationally standardized testers: the

Epstein and toroid testers. Section III describes the test bench used to measure core loss under non-sinusoidal supplies followed by a comparison of predicted and measured core loss results under the PWM excitation and equivalent BDCM flux waveform with know spectrum. Section IV presents conclusions drawn from this work.

II REVIEW AND COMPARISON OF LOSS TESTERS: SINUSOIDAL SUPPLIES

A. Review of Three Standardized Loss Testers

Three standardized loss testers are reviewed below; followed by a comparison of core loss results obtained using the Epstein and toroid testers for the steel samples cut from the same roll. The cutting and arrangement of the steel was in full compliance with the ASTM standards [3]. Measurement results from unannealed, annealed wet and annealed dry steel are presented for 0.0250-inch electrical lamination steel.

1. 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 and must be of multiples of 4, with a recommended minimum number [3] 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 with the total magnetic length round the frame of 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 [4], from which the ASTM standards are based.

The samples must be demagnetized before testing to remove previous magnetic signatures on the samples. Core losses are found by multiplying the primary current with the (induced) secondary winding voltage to give the instantaneous power waveform, whose average value (less any secondary side burden) equals the total core loss in the samples.

Some of the shortcomings of this method are that flux density is not uniformly distributed due to leakage flux around the joints [5]. The corners have been found to cause errors [5]. The magnetic length (94-cm) is estimated, not an accurate value. The 3 cm strip width is not wide enough for cutting stresses not to propagate to the center of the strips and influence the loss results. Therefore, the material under test must be annealed to relieve stress before testing, especially for grain-oriented steel. The preparation and loading of the strips onto the frame is time consuming.

2. Toroid Tester

The testing setup is very similar to the Epstein frame, except that the sample under test is a wound toroid. The toroid has a primary winding and a secondary winding with excitation applied to the primary and the induced voltage measured on the secondary. For small motors, toroidal fixtures may be relatively accurate, compared to the Epstein frame. This is because of the toroidal geometry, which emulates that of a motor more than the Epstein frame. However, with the smaller toroid testers, cutting stresses may propagate to the center of the samples and affect the results. Stress relieving may thus be necessary to get an accurate result. Core losses are measured in the same manner as the Epstein frame.

Some disadvantages of this tester are that the toroid must be properly wound; which is time consuming. Compared to the Epstein frame, the toroidal tester takes longer to prepare and setup for testing.

3. Single Sheet Tester (SST)

There are three types of yokes: the single-, the double- and the sideway- yoke [6]. International standards [6] recommend double yoke and a 50-cm square sheet with 45 cm equivalent magnetic length. A few excitation turns are wound around the sheet at the center and the induced voltage establishes flux that circulates around the yoke-sheet path, causing current to flow and producing core losses in the sheet. The large sample surface area may prevent cutting stresses from propagating far to the center of the samples, thus the loss results are not heavily affected by these stresses. Multiple single sheet testers are also available, where a number of strips are inserted into different slots and tested at the same time.

However, the double yoke is heavy, costly and large; therefore some pneumatic suspension may be required to place the yoke on the magnetic sheet [6] to avoid damaging the sheet. The yokes' contact surfaces must be ground and etched to reduce eddy losses. A major drawback of this tester is that it requires calibration with either Epstein or toroid testers; whereas the other two methods are independent of each other. In [7], discrepancies in loss results between the SST and the Epstein frame have been reported.

Of the three testers, the SST is relatively easy to prepare and setup. However, the Epstein frame remains widely used to characterize soft magnetic materials. In future, the SST may become a preferable method, because of its simple geometry and ease of assembling compared to the other two methods. When enquiring about the quality of electrical steel, it is important to know which tester was used to characterize the steel, since the three testers may not be in agreement.

B. Epstein vs. Toroid Core Loss Results

Using steel from the same roll, comparative core loss measurements were performed using the Epstein and toroid arrangements. Results are shown in Figs. 1–3, and tabulated in Tables I and II.

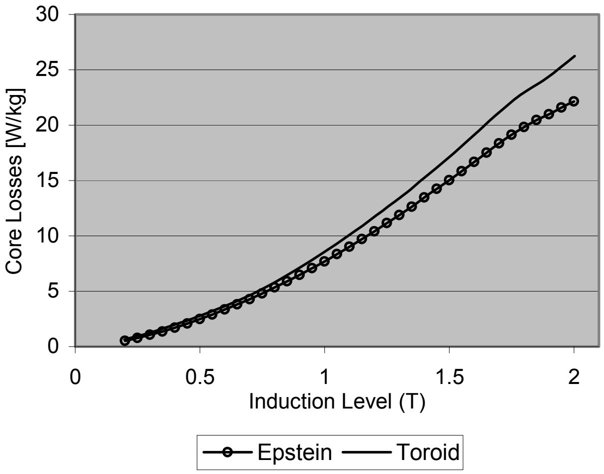

Fig 1: Core loss results for unannealed steel at 60 Hz

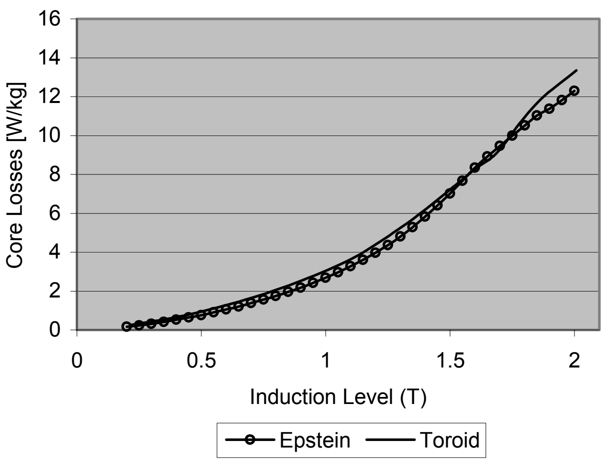

Fig 2: Core loss results for annealed dry steel at 60 Hz

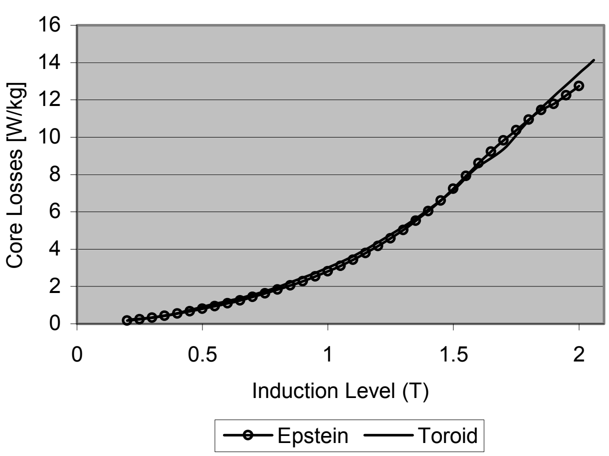

Fig 3: Core loss results for annealed wet steel at 60 Hz

TABLE I: TOROID VS. EPSTEIN RESULTS

60 Hz	Peak Flux [T]	Epstein [W/kg]	Toroid [W/kg]	% Diff.*
Unannealed	1 T	7.70	10.06	30.63
	2 T	22.14	26.24	18.53
Annealed Dry	1 T	2.81	3.05	8.45
	2 T	12.89	13.40	4.03
Annealed Wet	1 T	2.94	3.03	3.04
	2 T	13.34	13.41	0.51

* Based on the Epstein Frame Losses

Table I above compares core loss results obtained using the Epstein frame and toroid tester at a few selected induction levels. From Fig 1, for the unannealed case, the toroid results are relatively higher with a maximum of about 31 % difference at 1.0 T peak induction. For the annealed results, both the Epstein and toroid tester show that annealing reduces total losses significantly, as emphasized by Table II. Table II shows the loss reduction in annealing the test samples.

TABLE II: LOSS REDUCTION BY ANNEALING PER TESTING FACILITY

60 Hz	Peak Flux [T]	Epstein		Toroid	
Loss reduction		[W/kg]	% Red.*	[W/kg]	% Red.*
Unannealed to Annealed Dry	1 T	4.89	63	7.01	70
	2 T	9.25	42	12.84	49
Unannealed to Annealed Wet	1 T	4.76	62	7.03	70
	2 T	8.80	40	12.83	49

* Based on the respective unannealed cases

From Table II, it is noted that the particular annealing process (wet or dry) does not seem have much influence on the total loss reduction. However, as will be shown in the next section, the hysteresis and eddy current losses show dependence on the annealing process. Before annealing, the magnetic path length of the sample is irregular, and since the toroid samples area is usually less than the Epstein frame samples, the Toroid records higher losses. When the samples are annealed, the magnetic structure of the samples is restored and the path length around the toroid becomes uniform. This emphasizes the need for stress relieving (the electrical steel in motors) on the final product – resulting in higher efficiency motors.

Comparisons between the two internationally standardized loss testers (Epstein and toroid) show that there are discrepancies in the loss results. Depending on the steel application, these discrepancies may lead to improper and inefficient designs. To the electromagnetic designer, the loss difference in the two testers may lead to lost design optimization opportunities.

C. Hysteresis and Eddy Current Loss Reductions by Annealing

While it is evident that annealing reduces total core losses, this section investigates the change in the loss components (hysteresis, eddy current loss) after annealing. The total core loss is separated using the loss separation algorithm recently reported by one of the authors [11], results are shown Figs. 4-7 below:

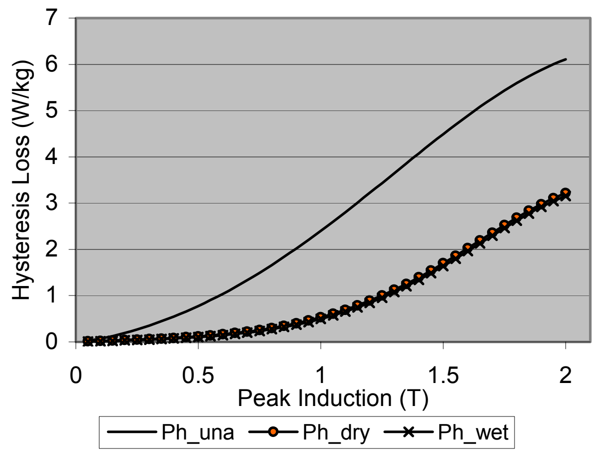

Fig. 4: Hysteresis loss reduction by annealing – Epstein frame

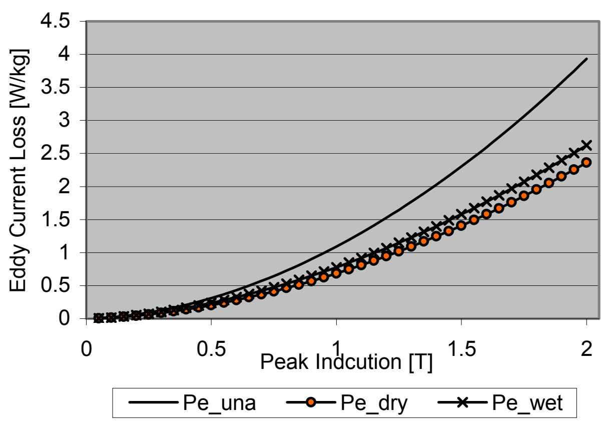

Fig. 5: Eddy current loss reduction by annealing – Epstein frame

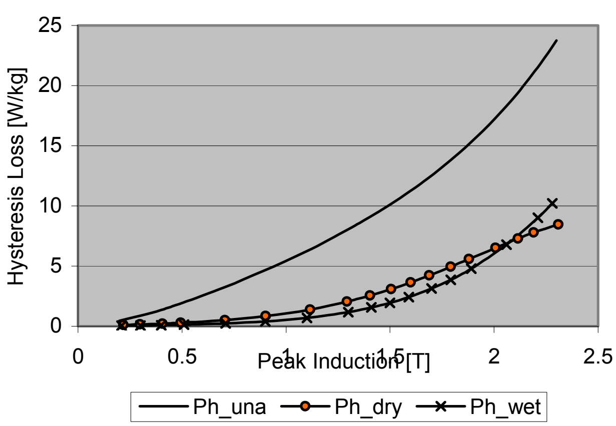

Fig. 6: Hysteresis loss reduction by annealing – Toroid frame

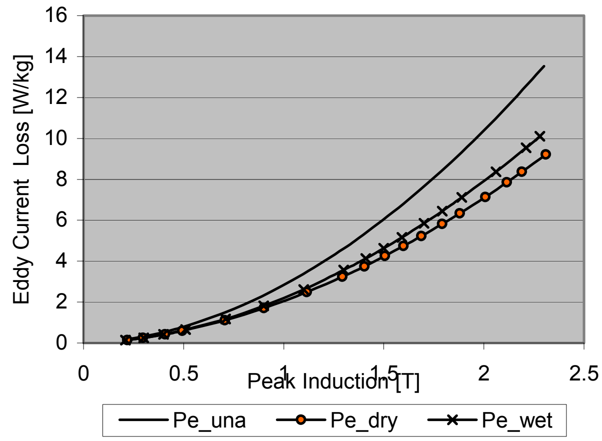

Fig. 7: Eddy current loss reduction by annealing – Toroid frame

Fig. 4 shows the hysteresis loss reduction by annealing as measured on the Epstein frame. It is observed that both dry and wet annealing reduce the hysteresis loss component equally. The same is observed for the eddy current loss component, as in Fig 5. Fig.6 shows the hysteresis loss reduction by annealing as measured by the Toroid tester. These results show some non-uniform reduction in hysteresis losses. Wet annealing shows more hysteresis loss reduction than dry annealed below 2.0 T peak flux. Fig. 7 shows the eddy current loss reduction as recorded using the Toroid tester. Dry annealing reduces the eddy current losses – in agreement with Fig. 5.

The two testers agree that annealing (wet or dry) reduces total core losses (hysteresis and eddy current losses). They also show that dry annealing reduces the eddy current losses. Dry annealing is less expensive to perform. Wet annealing is performed with the steel dew point elevated. Therefore the dry annealing process can be used with some confidence.

III. LOSS PREDICTIONS UNDER NON-SINUSOIDAL WAVEFORMS: BDCM

Accurate prediction of core losses is important for the motor designers – for possible design optimization opportunity. In BDCM machines the ratio of the iron losses to the copper losses is high, thus there exits a significant efficiency improvement and energy savings opportunity by reducing core loss in the machine. Reference [8] presented a formula to estimate core losses under distorted supplies, which requires the three loss components and the form factor (calculable or measured) of the distorted voltage as inputs. The test bench used to measure core loss under non-sinusoidal waveforms is described next, followed by a review of the form factor theory.

A. Test Bench Description

The non-sinusoidal signals are generated in MATLAB SIMULINK and the DSP based dSPACE software offered a real-time interface with SIMULINK and the analog circuit. A high bandwidth linear amplifier (AMP 100 kHz) is used to boost the signals and to excite the Epstein frame. A single-phase transformer (TX) was connected between the amplifier and the Epstein frame. A current probe (CP) and an isolated differential voltage probe were used to measure the exciting current and secondary voltage, respectively. A digital storage oscilloscope (DSO) was used to monitor and store exciting current, secondary voltage and their instantaneous product (power) for offline analysis. The non-oriented magnetic strips tested in our laboratory are from AK Steel, product code DI-MAX, M-45FP 29 gauge. The schematic of the test bench is shown in Fig. 8 below.

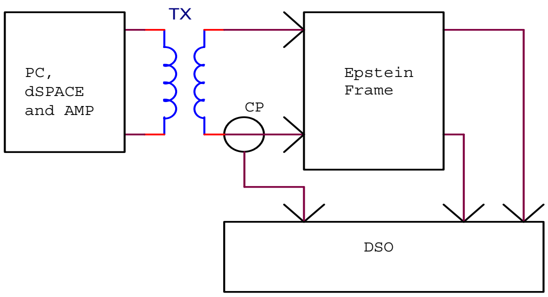

Fig 8: Test bench used to measure core loss under non-sinusoidal excitations

B. Review of the Form Factor Theory

Mathematically, the voltage form factor is defined as the ratio of the (distorted) voltage form factor to the sinusoidal form factor, expressed as the ratio of the rms value to the rectified average voltage. Form factor is related to the equivalent duty ratio of the voltage in the following manner:

$$F_c = \frac{2}{\pi\sqrt{f\alpha}} \quad (1).$$

Where α is the equivalent duty ratio of the voltage waveform. For pure sinusoids, F_c equals to 1.111. The ASTM standards [3] use this value on the secondary voltage of the magnetic sample as a reference. Deviations from this quantity imply that the voltage waveform is not sinusoidal anymore; in this context, the form factor is used to quantify waveform distortion. A full description of the mathematical development of (2) can be found in [8].

$$P_t = P_h^s(f_0) + F_c^2 * P_{cl}^s(f_0) * \frac{f_1}{f_0} + F_c * P_{ex}^s(f_0) * \sqrt{\frac{f_1}{f_0}} \quad (2).$$

Where P_t is the total core loss per cycle under a distorted supply at fundamental frequency f, P_h is the hysteresis loss; P_{cl} is the eddy current losses; P_{ex} is the excess loss component whose existence had been shown by [10] and F_c is the form factor of the secondary voltage of the Epstein frame. The superscript s denotes losses evaluated from a sinusoidal supply at frequency f_o. The three loss components are found by applying a loss separation algorithm reported recently by one of the authors [11].

C. Measurement Results and Analysis: Equivalent BDCM back emf waveforms

The aim is to investigate how close core losses under distorted waveforms can be estimated using the Fourier series. Assuming a BDCM flux density waveform containing the fundamental (60 Hz) with a dominating third harmonic (180 Hz), core loss is estimated using superposition and applying the form factor concept. Core loss data from steel manufacturers is given at discrete frequencies, which may not include the frequency spectrum under consideration, for example, the 180 Hz loss data is not given.

To predict losses at this harmonic frequency, the following procedure was followed: First, the total loss at frequencies around the harmonic frequency of interest was separated using the algorithm in [11]. Secondly, at given flux densities and frequencies (from core loss data), curves of hysteresis losses as a linear function of frequency (f), the eddy current losses as a function of f^2 and the excess loss as a function of $f^{1.5}$ were plotted. Thirdly, using the functions obtained above and substituting the desired harmonic frequency and flux density the corresponding core loss is obtained. Finally, adding the above loss components gives the harmonic core loss. In this way, the core loss components at high frequencies and densities are estimated from steel manufacturer's data.

Fig. 9 shows core losses calculated at a harmonic frequency of 180 Hz, using the 100 Hz, 150 Hz and 200 Hz core loss data from the steel manufacturer.

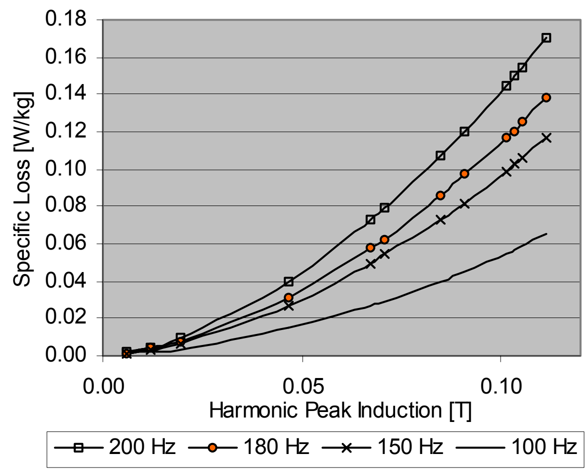

Fig. 9: Interpolation results at harmonic frequencies

As can seen from Fig. 9, the interpolations using the three loss components produce results that have similar flux dependence as the original data from steel manufacturer. Figs. 10-12 compare the total measured and calculated core losses assuming a flux density waveform consisting of 60 Hz and 180 Hz components. This is obtained by separating the total measured and calculated harmonic core losses into the hysteresis, eddy current and excess components. Fig. 13 shows the total loss.

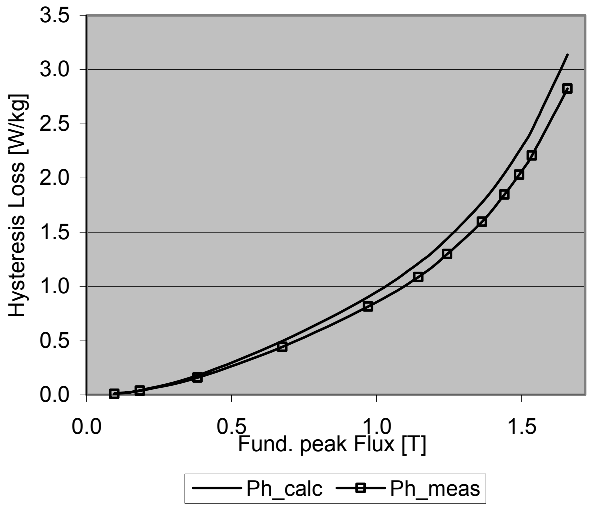

Fig. 10: Comparison of calculated loss from the manufacturer's data and the measured hysteresis losses

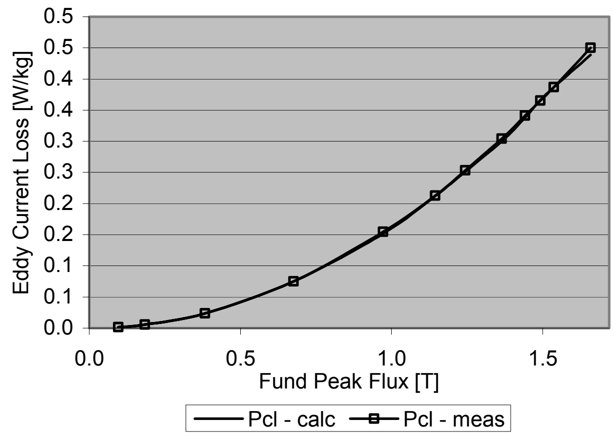

Fig. 11: Comparison of calculated loss from the manufacturer's data and harmonic measured eddy current losses

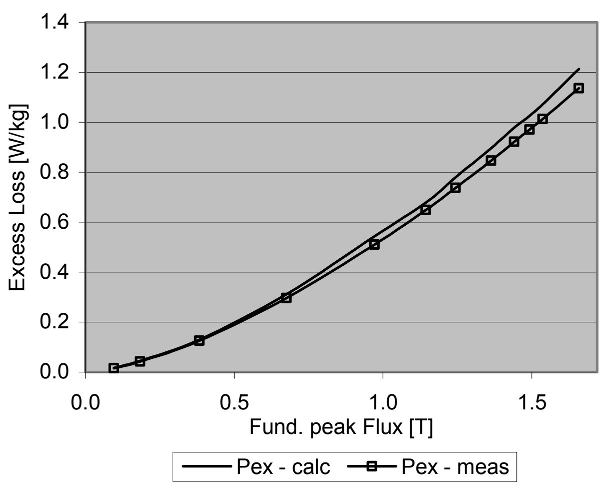

Fig. 12: Comparison of calculated loss from the manufacturer's data and harmonic measured excess core losses

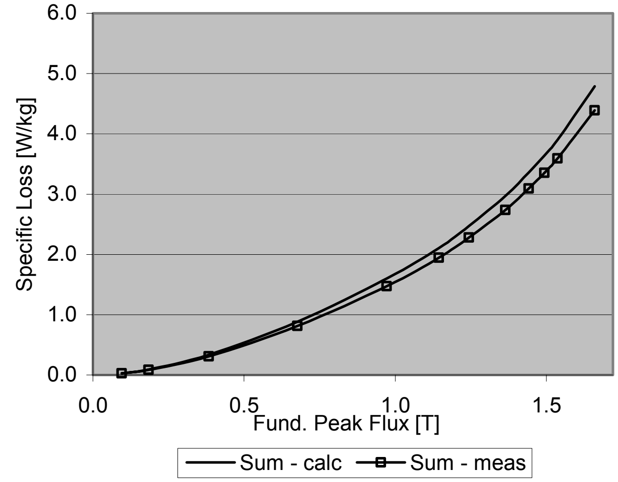

Fig. 13: Comparison of total loss calculated from the manufacturer's data and measured losses

TABLE III: COMPARISON OF MEASURED AND CALCULATED TOTAL CORE LOSS FOR THE BDCM WAVEFORM

Fund Peak [T]	Calc. [W/kg]	Meas. [W/kg]	% Diff
0.70	0.882	0.811	8.76
1.00	1.598	1.474	8.43
1.20	2.105	1.942	8.37
1.65	4.788	4.391	9.04

From Table III it is observed that by applying superposition and using the measured harmonic losses produce results within 10 % of the calculated results using the steel lamination manufacturer's data. The calculated and measured classical losses agree very well even when comparing the individual components of loss i.e. hysteresis, eddy current and excess.

The calculated and measured harmonic losses presented are compared with the results from equation (2). The distorted voltage form factor value used in equation (2) was 1.061. Table IV shows the loss differences from Fig. 14:

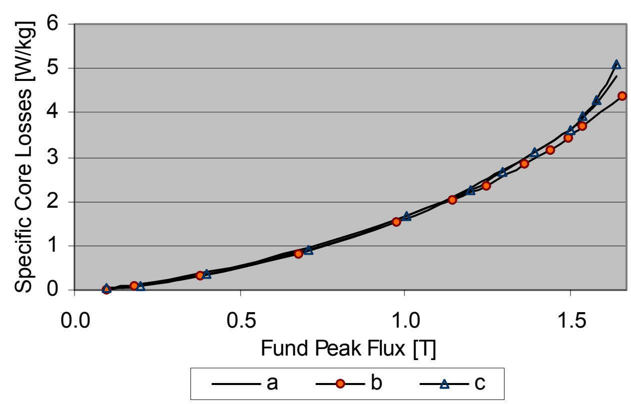

Fig. 14: Predicted and measured results: (a) total calculated harmonic losses using the steel manufacturer's data, (b) the sum of the measured harmonic losses and (c) predicted losses using equation (2)

TABLE IV: COMPARISON OF MEASURED AND CALCULATED RESULTS

Fund Peak Flux [T]	Total Meas. [W/kg]	Total Calc. [W/kg]	% Diff	Pred. (2) [W/kg]	% Diff
0.7	0.811	0.882	8.76	0.92	13.44
1	1.474	1.598	8.43	1.654	12.21
1.2	1.942	2.105	8.37	2.276	17.20
1.65	4.391	4.788	9.04	5.092	15.96

From Fig. 14 and Table IV, the total measured harmonic losses are 9% of the total calculated and produced a maximum error of about 16 % compared with results obtained using equation (2). These results show that the combination of the loss separation algorithm in [11] and superposition can be used to predict core losses under non-sinusoidal excitation with low harmonics, using the steel manufacturer's data.

D. *Measurement Results and Analysis: PWM Waveforms*

To see how well the estimation of loss can be done using equation (2) under high frequency excitations (in particular PWM waveforms): the total loss was measured under a PWM supply and compared with results obtained using equation (2). The PWM loss were measured with the modulation index $m_a = 0.5$ and switching frequency 1.26 kHz and 60 Hz fundamental under synchronous switching. The total measured loss under PWM waveforms was compared with the predicted results using equation 2. The average form factor of the PWM voltages was calculated to be 1.81. Fig. 15 compares the measured and predicted core losses using equation (2), and summarized in Table V.

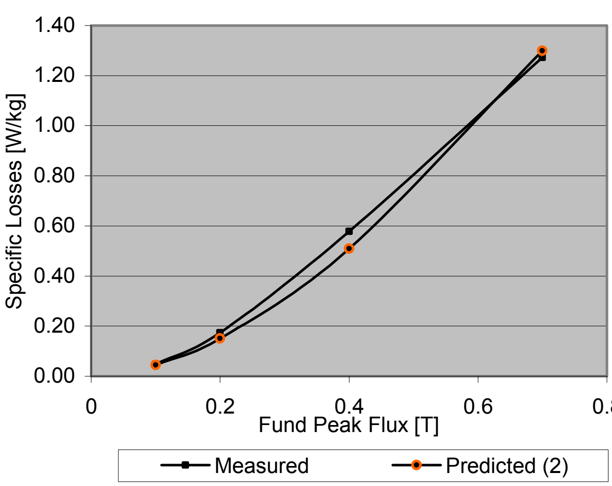

Fig. 15: Measured total losses vs the predicted (using 2) and the calculated losses (using the manufacturer's data)

TABLE V: PWM TOTAL LOSSES VS THE PREDICTED AND SINUSOIDAL LOSS DATA

Fund Peak Flux [T]	Meas. Total [W/kg]	Pred. (2) [W/kg]	% Diff
0.1	0.049	0.0448	8.46
0.2	0.174	0.1505	13.37
0.4	0.577	0.5090	11.86
0.7	1.272	1.2987	2.06

From Table V, it is observed that the improved loss separation method by [11] and equation (2) are used to estimate PWM excitation losses to within 14%. While predicting losses using superposition requires the knowledge of the harmonic spectrum; equation (2) only requires the distorted voltage form factor together with the three loss components (found using the method in [11]) as inputs. Thus the loss separation algorithm in [11] and equation (2) provide a good starting point to estimating core losses under non-sinusoidal supplies and are both practical and easy to apply.

IV. CONCLUSIONS

The need for non-sinusoidal loss characterization standards has been emphasized. The three core loss measuring methods currently used in industry have been reviewed and it is envisaged that the SST will be a preferred method in future. The discrepancies in core loss results between the Epstein and toroid testers have been shown. For unannealed steel, the toroid tester produced relatively higher loss results and both testers showed significant loss reduction after annealing. Therefore, when purchasing electrical steel, it may be necessary to inquire which tester was used to grade the steel. The annealing process (either dry or wet) was found to significantly reduce both hysteresis and eddy current losses. Moreover, dry annealing was found to minimize the eddy current losses.

By applying superposition using the improved loss separation algorithm, it was found that the Fourier series and superposition can be used to predict losses under non-sinusoidal waveforms with harmonics. The loss separation algorithm in [11] and equation (2) produce results that are 15 % less than the total incurred. This is a good starting point to estimating core losses under non-sinusoidal and high frequency supplies such as PWM excitation, since both methods are practical and easy to apply. Future work will involve defining informative core loss data from steel manufacturers that motor designers could use to optimize their designs and to examine how well the techniques work with machines operating in deep saturation lie the switched reluctance machine.

ACKNOWLEDGMENT

The authors acknowledge Black & Decker, Eaton Corporation, KJS Magnetics, Globe Motors, Ispat Inland, Lamination Specialty Corporation, Proto Lamination and Small Motor & Motion Association for assistance with this work.

0-7803-7883-0/03/$17.00 (C) 2003 IEEE

REFERENCES

[1] N. Mohan, T. M. Undeland and W. P. Robbins, "Power Electronics: Converters, Applications and Design," 2nd Ed. 1991, John Wiley & Sons, Inc.

[2] A Boglietti, P. Ferraris, M. Lazzari and M. Pastorelli, "About the possibility of defining a standard method for iron loss measurements in soft magnetic materials with inverter supply," IEEE T. Mag. Vol. 33, No. 5, Dec. Sep/Oct 1997

[3] ASTM Standards, A343, A348, A778

[4] S. L. Burgwin, " Measurement of core loss and ac permeability with the Epstein frame", ASTM, Chicago Ill., June 23 – 27, 1941

[5] M. S. Lancarotte and A. de A. Penteado Jr., "Prediction of magnetic losses under sinusoidal or non-sinusoidal induction by analysis of magnetization rate" São Paulo SP Brazil

[6] Philip Beckley, "Electrical Steels: A handbook for producers and users", European Electrical Steels 2000

[7] J. Sievert, "The measurement of magnetic properties of electrical sheet steel: survey on methods and situation of standards," Journal of Magnetism and Magnetic Materials (JMMM) 215- 216 (2000) 647-651

[8] M. Amar and R. Kaczmarek, "A general formula for prediction of iron losses under non-sinusoidal voltage waveform", IEEE T Mag. Vol. 31, No. 5 Sep. 1995

[9] F. Fiorillo and A Novikov, "An improved approach to power losses in magnetic laminations under non-sinusoidal induction waveform," IEEE T Mag. Vol. 26, No.5 Sep. 1990

[10] G Bertotti, "Physical interpretation of eddy currents losses in ferromagnetic materials," J. Appl. Phys. Vol. 57. Pp. 2110 – 2126, 1985

[11] Y. Cheng and P. Pillay, "An improved Formula for Lamination Core Loss Calculations in Machines Operating with High Frequency and High Flux Density Excitation," IAS Meeting, October 2002

[12] L. T. Mthombeni, P. Pillay and A. S Naidu," Lamination core loss measurements in machines operating with PWM or non-sinusoidal excitation" , IEEE IEMDC 2003, Wisconsin, Madison, June 1 – 4, 2003