A New Epstein Frame for Lamination Core Loss Measurements at High Frequencies and High Flux Densities

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***Abstract*— This paper presents a new Epstein frame optimized for high frequencies and high flux densities. The design philosophy and test results at high power frequencies are presented. The frame achieves high frequency and high flux density performance because of reduced number of turns and reduced number of samples, while using standard 25-cm Epstein samples. For the current application, only the 0.0140-inch (0.36 mm) M45 was used. Measured results obtained show good agreement with the core loss data provided by the steel manufacturers measured using the old frames, at 200 Hz, 300 Hz and 400 Hz. Results at 600 Hz and 1.0 kHz are also presented for the M45 samples along with the test bench used.**

***Index Terms*— Epstein frame, Core losses, High frequency, High flux density.**

I. Introduction

CHOOSING the right lamination material for a particular application is an important motor design step, since lamination properties have a direct link to the efficiency of the motor. Currently, important lamination properties (core loss and permeability) to be used for assessment are presented at 50/60 Hz, 1.0/1.5 T sinusoidal. Electromagnetic designers have to decide on the material based on this single operating point; although under practical working conditions, some motors operate at flux density levels and frequencies beyond this point. In fact, it has been shown that choosing the CRML based on the lamination performance at one operating point is not enough [1].

Under no load conditions and depending on the motor type, magnetic loading can be around 1.5 T, and increases with loading conditions. Some motors inherently operate at near saturation and at high frequencies, such as switched reluctance motors (SRMs). The revolutionary advances in power electronics enabled motor users to control motors. However, like most technological advances, they introduce a new problem: flux waveform distortion in the time that most electromagnetic devices were fully designed for sinusoidal excitations. Even with the traditionally less saturated induction motors, when coupled with variable speed drives (VSDs), their magnetic loading can increase to unexpected levels, due to harmonics from the VSDs. VSDs produce non-sinusoidal voltage waveforms to drive motors designed on data based on sinusoidal supplies at only one operating point. Thus VSDs also warrant some changes in the way motor laminations are selected.

For rotating machines, the IEEE has guidelines for core loss measurements. There are also standardized static fixtures used for direct lamination core loss measurements. In this publication [2], two of the authors have attempted to review these testers: Epstein frame, toroid testers and single sheet testers. Accompanying these fixtures are standards [3][4] that govern their use. Ring testers are more convenient for testing composites samples and laborious for steel laminations. Rings have a geometry closer to that of motors. It is envisaged that in future, the single sheet tester will be preferred, because of its ease of assembly and use. In fact the new frame leans towards the single sheet, in terms of ease of assembly and material quantities. Yet, this new frame has a technical advantage over the SST: the four strips used are a good representation of the material properties in the different directions in a coil. The Epstein frame is by far the most used fixture, with well accepted international standards [3] [4], [5].

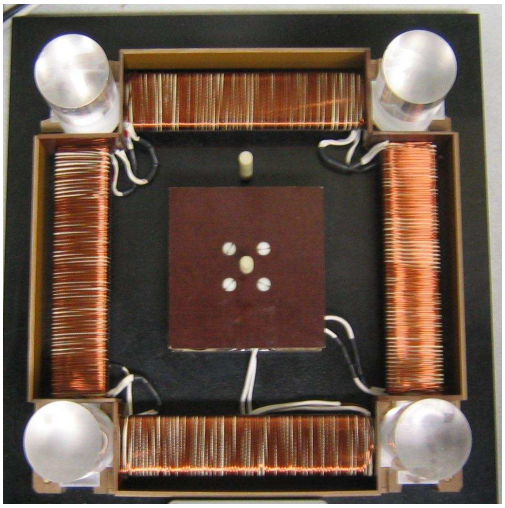

Fig. 1. New Epstein frame

The original Epstein frame was a 50-cm type, with butt joints. These joints tended to increase the magnetic reluctance, thus yielding poor results. The introduction of the 25-cm double lapped joints frame around the 1930's by [6] proved to be major contribution. In fact, most lamination manufacturers use an Epstein frame to grade their laminations. It must be noted that these fixtures have their own errors, which have come to be accepted by their users over the years. The current standardized Epstein frames have limitations. With the current Epstein frames, the maximum induction levels to which the samples can be driven is low. Part of this limitation is in the design of the frame, since the frames have relatively high number of turns, thus requiring a high magnetomotive force (mmf) to drive the samples to higher induction levels with high frequency excitations. In view of this limitation, the ASTM standardized a 352-turn frame intended for high frequency use, not meant to replace the archaic 700-turn one.

When measuring core losses with sinusoidal excitations on the static fixtures mentioned above, it is necessary to maintain a sinusoidal secondary voltage (or flux). When approaching the saturation flux density level of a material, the secondary voltage becomes distorted and harmonics will influence the results. This distortion is due to current distortion stemming from the magnetic hysteresis inside the samples. A digital controller was designed for this purpose.

Fig. 1 shows the new Epstein frame, showing the air flux compensator in the middle of the frame, with support corner weights. The corner weights (plastic cylinders) are to ensure that the samples are in contact. Fig. 2 shows a close up view of slot openings which are just enough for one sample.

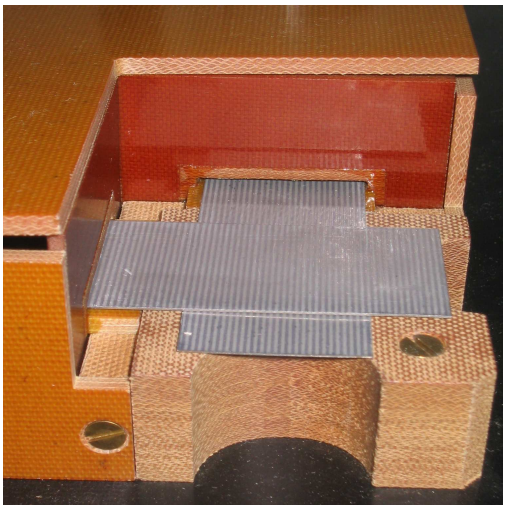

Fig. 2. New Epstein frame, showing space for one sample per limb

Section II presents a detailed description of the new frame, together with the test bench used, followed by a discussion on the measured core loss results using this new frame in Section III. Section IV concludes the paper, highlighting possible improvements.

II. Description of the Frame

The new Epstein frame presented here is suitable for core loss testing with high frequencies and flux densities. In collaborating with motor designers, they expressed the need for a new frame capable of core losses measurements at 2.3 T / 3.2 kHz in order to cover most materials in use today. These are practical limits as magnetic loading of motors can be higher than 50 /60 Hz and harmonics can increase the flux density levels beyond the traditional 1.0/1.5 T.

It was decided that this new frame would use the standard Epstein strips (30.48 cm x 3 cm as required by ASTM 343 [3]).This also avoids making too many changes at once, and for ease of transition from the old to the new frame. Moreover, this frame only takes four strips. The arrangement of samples is still the same as the standard frame, i.e., samples cut along 0^0 degrees to the rolling direction (L's) are inserted in the opposite limbs, and those cut at 90^0 degree to the rolling direction (T's) are inserted in the other two opposite limbs. The new frame is fitted with a compensator coil in the middle to remove the air flux in the housing, and the opening for the samples leaves just enough space for one strip, as shown in Fig. 2. Although the compensator coil is not an absolute necessity at high frequencies, it was still used. The winding pattern (the primary winding on the outside and secondary winding inside) is still the same as with the standard frames.

The design philosophy adopted here is derived directly from Faraday's and Ampere's laws. Equation (1) shows the calculation of the secondary voltage required to establish a predetermined flux density testing point, at a given frequency.

$$V_{rms} = \sqrt{2}\pi N_2 A f_1 B_1, \tag{1}$$

where, V_{rms} is the rms secondary voltage, N_2 is the number of the secondary turns, A is the area of the samples, f_1 is the fundamental frequency of the excitation waveform and B_1 is the predetermined peak fundamental flux density. For a given testing point (f_1, B_1), the variables in (1) are the number of secondary turns and number of samples (determining the area). For a given induction level, in order to be able to reach high frequencies, it was necessary to significantly reduce the turns' count to 280 turns. This results in higher excitation current, therefore this frame is relatively easier to magnetize. The number of strips was also reduced. Typical mass for the new frame is 0.1 kg, whereas the 700 turn standard frame normally takes about 2.0 kg of material. Thus it is relatively easy and faster to load the samples with the new frame. As Fig. 1 shows, there are plastic lightweight supports applied on the corners to ensure that samples have good contact at the corners (minimizing errors due to reluctance). Safety was also a major concern, thus the combination of reduced mass and reduced number of turns ensures that the frame operates at reasonably low voltages.

Due to the non-linear magnetic behaviour of laminations, the exciting current waveform is normally non-sinusoidal,

especially at near saturation regions. This causes the induced secondary voltage (hence flux) to be non-sinusoidal, resulting in a need for a control effort to keep it sinusoidal. In order to achieve this, a pseudo-derivative-feedback (PDF) [7] controller was realized. The excitation signals are generated in MATLAB SIMULINK and dSPACE is used for real-time simulation. A high bandwidth linear amplifier (100 kHz) is used to excite the frame. A current probe and an isolated differential voltage probe are used to measure the exciting current and secondary voltage, respectively. A digital storage oscilloscope is used to monitor and store exciting current and the secondary voltage. Mathematical manipulations are done inside this scope to obtain the average core loss. In order to maintain a sinusoidal flux density, a closed loop feedback control was realized in Simulink.

III. Core Loss Test Results

In order to "calibrate" the system, core loss measurements at 200 Hz, 300 Hz and 400 Hz were performed; this is important because most core loss data from laminations manufacturers do not cover high flux levels and high frequencies. It also helps to identify the overlap frequency region between the new frame and the standard frames. It must be noted that the original data from steel manufacturers was obtained using the standard frames (either the 352 or 700 turn frame).

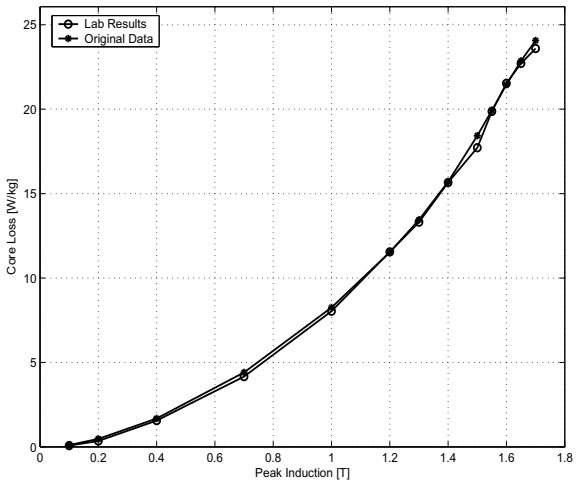

Fig. 3. M45 core losses at 200 Hz

From Figs. 3 and 5, original data refers to the manufacturer supplied core loss data and lab results refer to losses measured with the authors' testing facilities. Repeatability is an important factor in core loss measurements, hence, all tests were done at least two times. These results show good agreement between the new frame and the original data from steel manufacturers. Therefore, the technical advantages this new frame has can be exploited. The frame was also tested at 600 Hz and 1.0 kHz using the M45 samples. Results are shown in Figs. 6 and 7. At higher frequencies, the new frame produces results higher than the old frame. On average, at 600 Hz, the new frame produced a 16.3 % error, and a 24 %

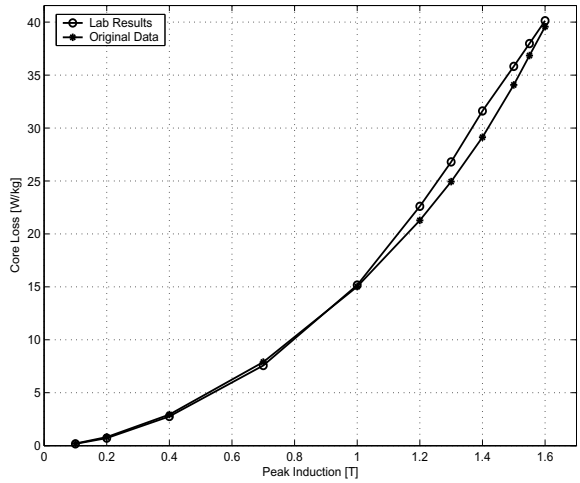

Fig. 4. M45 core losses at 300 Hz

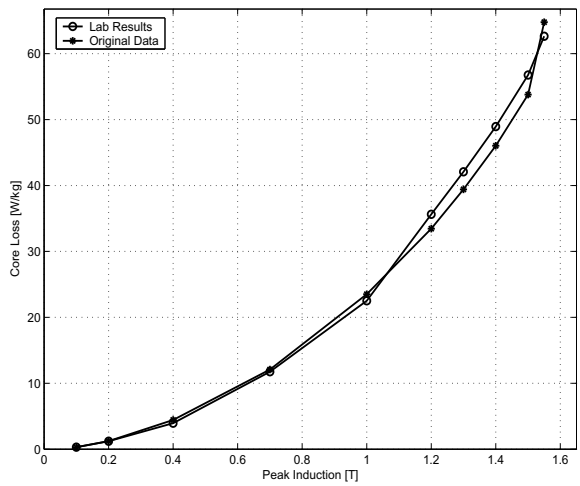

Fig. 5. M45 core losses at 400 Hz

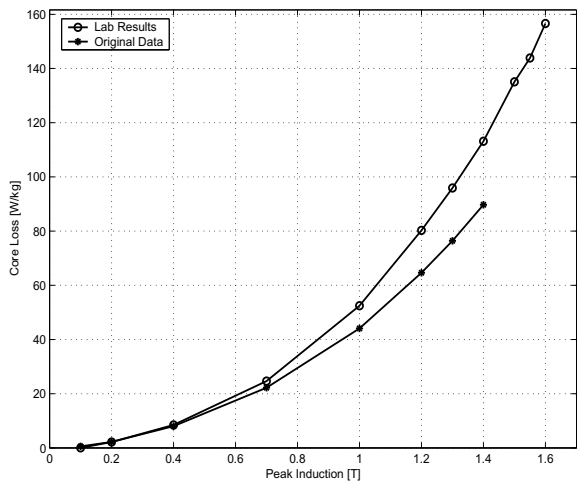

Fig. 6. M45 core losses at 600 Hz

error at 1.0 kHz. The % error here is defined as the ratio of the absolute difference between the new frame results and the original data to the new frame results. Although the frame

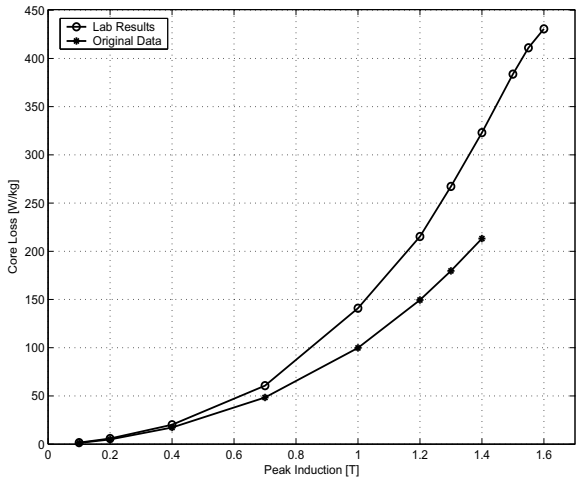

Fig. 7. M45 core losses at 1.0 kHz

shows some deviations at these frequencies, the results are still very useful. The most important feature here is that the frame allows for testing beyond traditional limits. For a given material, one could collect data using this new frame and form a matrix conversion to get insight of core loss increase at higher frequencies and flux densities that the standard frames cannot attain. This is already being done with SSTs, even a lower frequencies.

Although the frame has capabilities for high frequencies, most core loss data from steel manufacturers at high frequencies is limited to the lower induction ranges, i.e., ”below knee-point data”. However, once more core loss data at the comparable points is collected with confidence for different materials, the new frame can then be used with high confidence, beyond the data provided by the lamination manufacturers.

In general, lamination manufacturers would like to expedite production and might see the proposed extra tests (at high frequencies and high flux densities) to be time consuming. In light of this, these tests can be outsourced to steel vendors or shifted to other departments within the mill company, if economics allow. In this way, production is not slowed down: the usual 1.0 T/1.5 T 50/60 Hz tests can be done on the line while the extra tests are done somewhere else.

The next phase of core loss testing using this frame is to evaluate its performance under non-sinusoidal excitations. Core loss results under non-sinusoidal excitations will be compared with the 700-turn frame results. There is a need to understand and quantify core losses under non-sinusoidal excitations [8][9]. This frame can be considered a step toward defining a new way of testing laminations at higher frequencies. The technology must be modified to meet the dynamic demands of the users, as evidenced by the evolvement of the old frames, since their introduction in the 1930’s.

IV. Conclusions

A new Epstein frame capable of high frequency and high flux density testing has been presented. The performance of this frame has been tested on the M45 samples and found to produce results close to that reported by the lamination manufacturers. The deviations observed at 600 Hz and 1.0 kHz can be used to construct a conversion matrix, in the same way that the SSTs are commonly used. This new frame has an advantage over the SST: it has better material representability. More samples are being gathered to evaluate the performance of this frame at even higher frequencies. Also, an even smaller Epstein frame, half the standard size will be prototyped and its performance evaluated.

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