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

Tsakani Lotten Mthombeni, *Member, IEEE*, Pragasen Pillay, *Fellow, IEEE*, and Reinhold M. W. Strnat

***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. Some of its technical advantages over the current Epstein frames and the single sheet testers are less samples' preparation time and better material representability, respectively. Four lamination types were tested: 0.0250-in (0.64 mm) M36 and cold rolled motor lamination, 0.0184-in (0.47 mm) M19, and 0.0140-in (0.36 mm) M45. The results obtained show good agreement with the core loss data provided by the steel manufacturers measured using the old frames at 200, 300, and 400 Hz. Results at 600 Hz and 1.0 kHz are also presented for the M45 and M19 samples along with the test bench used.**

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

I. Introduction

CHOOSING the right lamination material for a particular electromagnetic 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 addition to flux density waveforms being nonsinusoidal. In fact, it has been shown that choosing the cold rolled motor lamination (CRML) based on the lamination performance (permeability) at one operating point (1.5 T, sinusoidal) is not enough [1].

Under no-load conditions and depending on the motor type, electric motor magnetic loading can be around 1.5 T, which increases with loading conditions. The common perception that core losses are not load dependent is incorrect, e.g., a brushless dc motor (BDCM) under load will have heavily distorted airgap flux density waveform due to armature reaction. Some motors inherently operate at near saturation and at high frequencies, such as switched reluctance motors (SRMs) and BDCMs. 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 caused by switching power devices, while most electromagnetic devices are fully designed for sinusoidal excitations. Even in case of 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 nonsinusoidal 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. Thus, it stands that lamination producers should supply motor designers with more informative core loss data. The least that lamination producers can add to the current test point data are high frequency core loss data with sinusoidal excitations. In the ideal case, laminations could be characterized using similar waveforms as in the actual electric motors.

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 [2], 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. However, rings have a geometry closer to that of motors—making this fixture more appealing to motor designers than do Epstein frames. Interestingly, lamination manufacturers seem to prefer Epstein frames. 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 toward 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 provide a better material representability, as magnetic properties in the different coil directions might be different. The Epstein frame is by far the most used fixture with well-accepted international standards [2]–[4]. This paper intends to show that it is possible to perform high frequency and high flux density tests by varying a few parameters, and still get excellent results.

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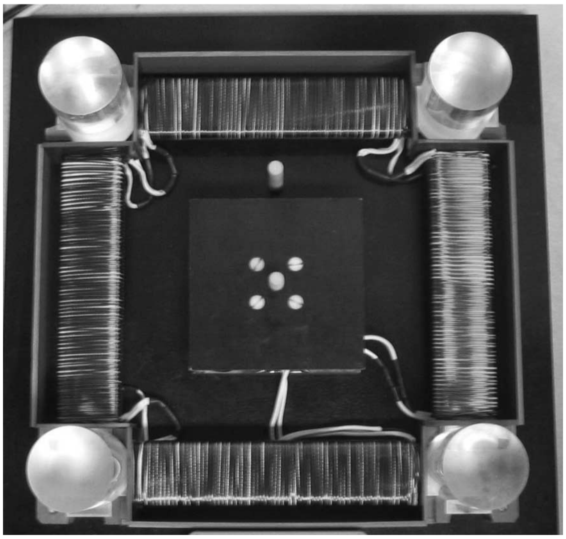

Fig. 1. New 280-turn Epstein frame.

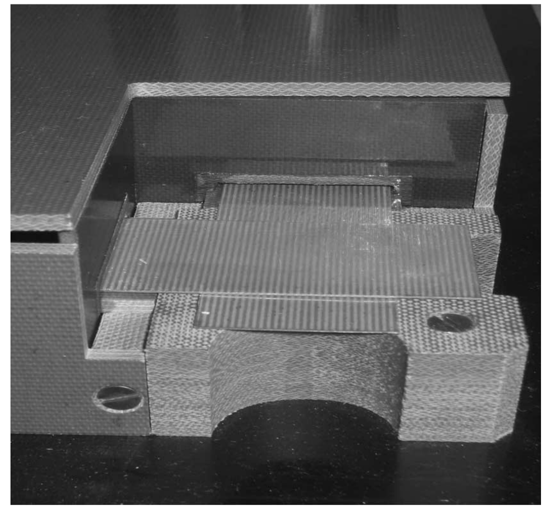

Fig. 2. New Epstein frame, showing space for one sample per limb.

Section II summarizes the development of Epstein frames from their early use. Section III presents a detailed description of the new frame. Section IV describes the test bench used. Section V discusses experimental core loss results measured using this new frame. Section VI concludes the paper, highlighting possible improvements.

II. Current Epstein Frames Summary

The original Epstein frame was a 50-cm type frame 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 1930s [6] proved to be a major contribution. In fact, most lamination manufacturers use an Epstein frame to grade their laminations. Epstein frames have their own errors (some due to the assumptions made), which have come to be accepted by their users over the years. Samples preparation and loading onto the frame can be time consuming. The current standardized Epstein frames have technical 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 a relatively high number of turns, thereby requiring a high magnetomotive force (mmf) to drive the samples to higher induction levels with high frequency excitations. In view of this limitation, the American Society for Testing and Materials (ASTM) standardized the 100-, 200-, and 352-turn frame intended for high frequency use, not meant to replace the archaic 700-turn one.

Fig. 1 shows the new Epstein frame, showing the air flux compensator in the middle of the frame, with support corner weights. Fig. 2 shows a closeup view of the slot openings, which leave just enough space for one sample.

III. New Epstein Frame Description

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 loss measurements at 2.3 T/3.2 kHz in order to cover a wide range of materials in use today. Considering recent demands for high speed and high efficiency motors, these are practical limits. As already, mentioned, VSDs are also a driving factor.

It was decided that this new frame would use the standard Epstein strips (30.48 cm $\times$ 3 cm as required by ASTM 343 [3]). This avoids making too many changes at once and eases transition from the old to the new frame. Moreover, this frame takes only four strips, reducing preparation and loading time. 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, which leave 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.

In measuring core losses with Epstein frames, it is assumed that all the excitation current is responsible for core losses, i.e., losses across R_c, implying that there is no secondary current drawal and that the magnetizing current is small enough to be neglected (large X_m). These are good assumptions, since the secondary side voltage probes do not draw any current due to their high input impedance.

The new frame design philosophy adopted here is derived directly from Faraday's and Ampere's laws. Pretest routines include a table of desired peak (fundamental) flux densities, e.g., from 0.1 to 2.0 T in steps of 0.5 T. Using Faraday's law of induction, the time flux variations in the magnetic samples result in a voltage being induced, whose magnitude is given by

$$\nu(t) - N_2 \frac{d\phi}{dt}. \tag{1}$$

Recalling that flux is defined as, $\phi = BA$, (1) becomes

$$\nu(t) = AN_2 \frac{dB}{dt}. \tag{2}$$

Under pure sinusoidal flux density conditions

$$B(t) = \hat{B}\,\sin(\omega t). \tag{3}$$

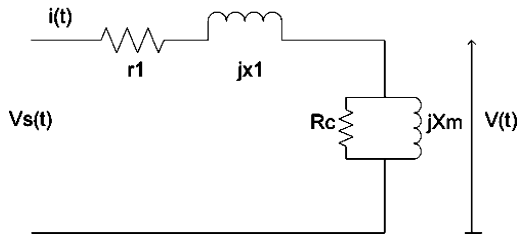

Fig. 3. Schematic circuit diagram of an Epstein frame.

from which the flux density rate of change is given by

$$\frac{B(t)}{dt} = \omega \hat{B}\cos(\omega t). \tag{4}$$

Thus, substituting (4) into (2) and taking the root mean square value (rms) yields

$$V_{\mathrm{rms}} = \sqrt{(2)}\pi f_1 A N_2 B_1 \tag{5}$$

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 $\hat{B}$ is the predetermined peak fundamental flux density.

For a given testing point (f_1, B_1), the variables in (5) are the number of secondary turns (N_2) and the 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 drive. 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, reducing the samples' preparation time and setting this new frame at a technical advantage over the old frames. With this new frame, material representation is better than the SST, although not as superior as the old frames. In Fig. 1, 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.

IV. Test Bench Description

Fig. 4 shows a schematic diagram of the test bench. 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 (CP) 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. Instantaneous power computations 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.

Due to the nonlinear magnetic behaviour of laminations, the exciting current waveform is normally nonsinusoidal, especially at near-saturation regions. This causes the induced secondary voltage (hence flux) to be nonsinusoidal, resulting in a need for a control effort to keep it sinusoidal. In order to achieve this, a pseudoderivative-feedback (PDF) [7] controller was realized.

The setup and measurement procedures are the same as in the old frame. Standard-sized Epstein strips (30 cm $\times$ 3 cm) are cut from a steel coil, according to the ASTM standard [3]. The arrangement of samples is still the same as in the standard frames, i.e., samples cut along 0° to the rolling direction (L's) are inserted in the opposite limbs, and those cut at 90° to the rolling direction (T's) are inserted in the other two opposite limbs. Four samples are selected. To get a better representation of the coil, samples could be selected from various locations on the coil.

Samples are first demagnetized to remove any previous magnetic signatures and to bring the magnetic domains to some initial position. The excitation signal is applied to the primary windings of the frame, while monitoring the secondary voltage and excitation current. Once the predetermined secondary voltage (rms or peak) has been reached, the product of the secondary voltage and exciting power is taken. This is the instantaneous power representing core losses. The average power obtained is then divided by the effective sample mass, in accordance with ASTM standards [3] and [4].

V. Core Loss Test Results

In order to "calibrate" the system, core loss measurements at 200, 300, 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 [8] was obtained using the standard frames. The following samples were used: 0.0140-in (0.36 mm) semiprocessed M45 steel, 0.0184-in (0.47 mm) fully processed M19 C3 coated, 0.0250-in (0.64 mm) fully processed M36 C3 coated steel, and 0.0250-in CRML (bare) annealed and unannealed steel. This lamination list covers a wide range of commonly used laminations.

In Figs. 5–14, original data refer to the manufacturer supplied core loss data [8], and laboratory 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 results and the data from steel manufacturers. The observed deviations are summarized in Table I. The average percentage deviation here is defined as the average of the ratio of the absolute difference between the new frame results and the original data to the new frame results. Although the frame shows some deviations at these frequencies, the results are still very useful. Hence, the technical advantages of this new frame can be exploited.

While comparing Figs. 8–11, it is interesting to see that M36 outperforms the annealed CRML steel. It is to be noted that this direct comparison is only made for the samples of the same thickness.

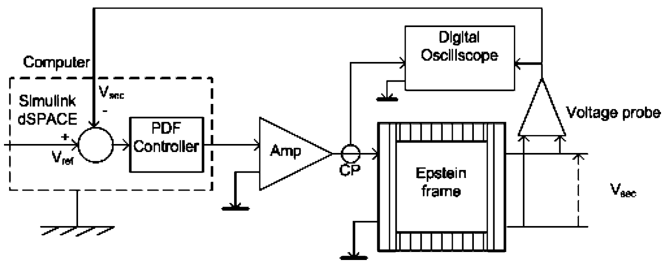

Fig. 4. Test bench used with the new Epstein frame.

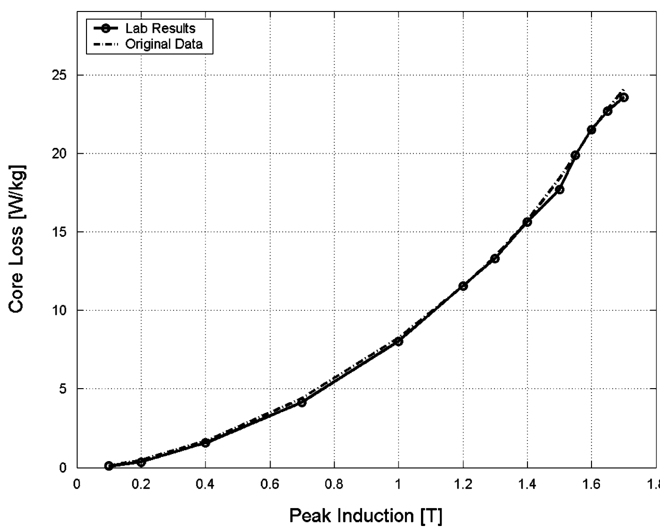

Fig. 5. M45 core losses at 200 Hz.

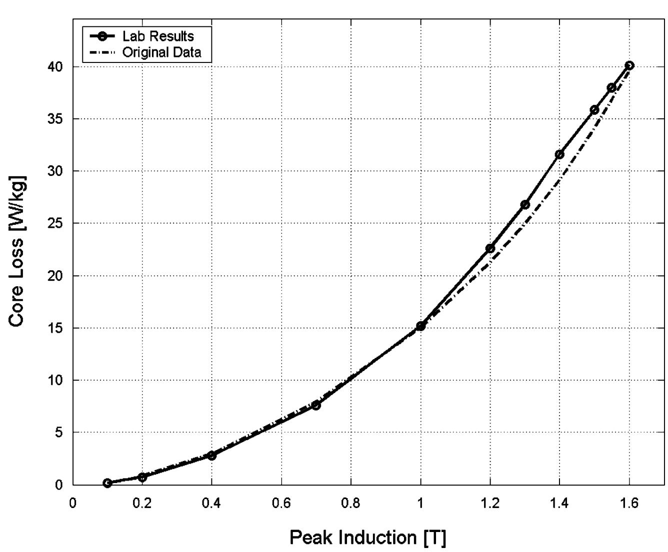

Fig. 6. M45 core losses at 300 Hz.

It must be noted that only thinner gauges could be tested at higher frequencies, since high frequency loss data is not commercially available [8]; hence, comparison of the new and old frame results at high frequencies is not possible. The rationale for steel makers for not characterizing thick laminations at high frequencies could be that if one designs for high frequencies, then one would intuitively choose a thinner gauge. Hence, it is

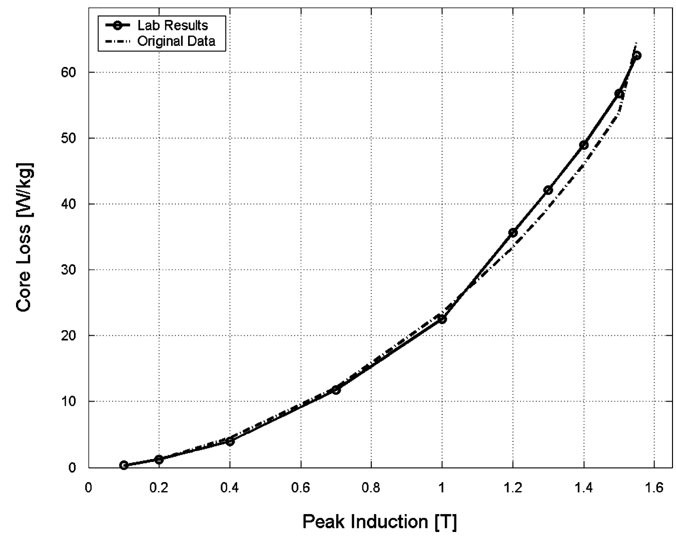

Fig. 7. M45 core losses at 400 Hz.

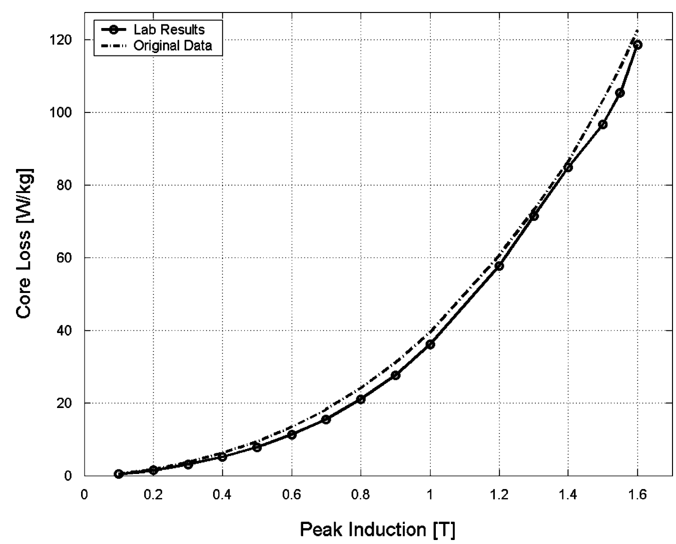

Fig. 8. M36 core losses at 400 Hz.

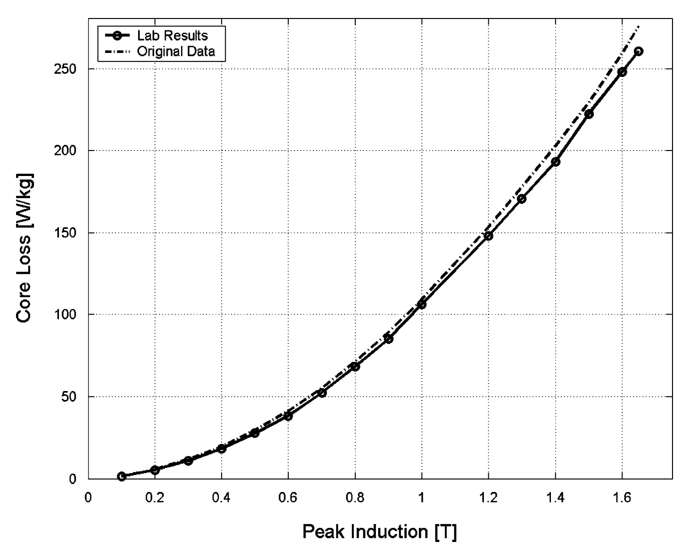

Fig. 9. CRML unannealed core losses at 400 Hz.

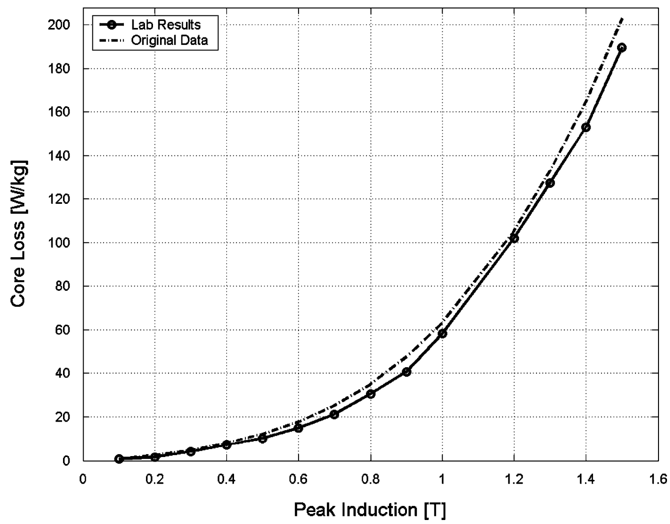

Fig. 10. CRML annealed core losses at 400 Hz.

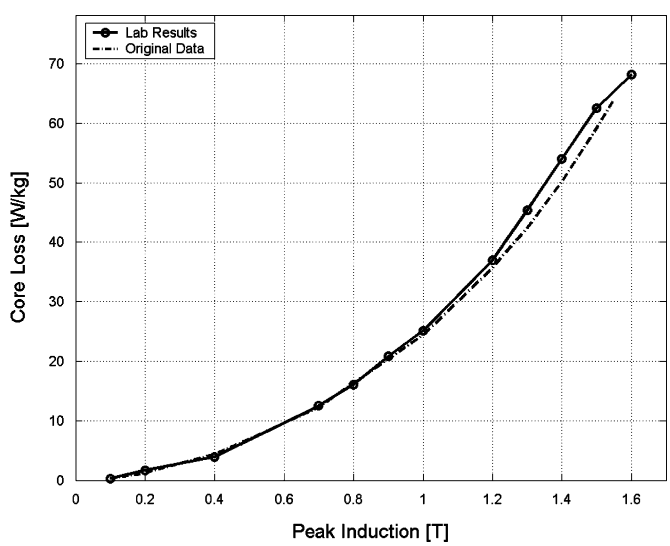

Fig. 11. M19 core losses at 400 Hz.

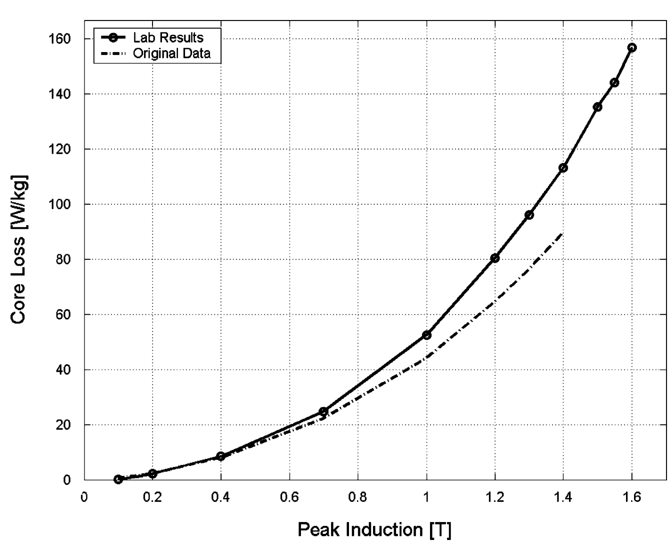

Fig. 12. M45 core losses at 600 Hz.

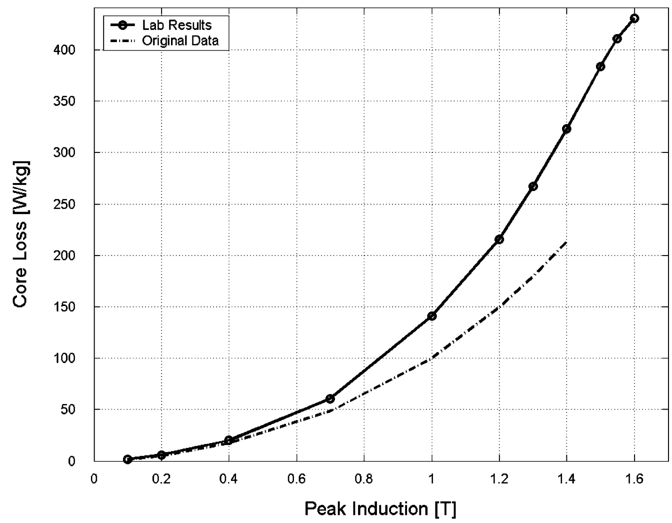

Fig. 13. M45 core losses at 1.0 kHz.

TABLE I
CONVERSION MATRIX

Material Type and Gage	Frequency [Hz]	Average % Deviation
M36 FP 24 gage	400	11.0
M45 FP 29 gage	200	2.30
	300	3.90
	400	5.07
	600	16.0
	1000	24.0
M19 FP 26 gage	400	9.42
	600	8.46
	1000	2.30
CRML 24 gage		
Annealed	400	13.0
Unannealed	400	5.20

not necessary to generate high frequency loss data for thicker samples.

However, electric machines that were designed using these thicker gauges could be operated under variable speed, and the ferromagnetic material would be exposed to high frequencies, resulting in increased core loss and reduced efficiency.

The frame as also tested at 600 Hz and 1.0 kHz using the M45 and M19 samples. Results are shown in Figs. 12 and 15. Again, the new frame shows good performance at these moderately high frequencies.

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 an insight of the core loss increase at higher frequencies and flux densities that the standard frames (352- and 700-turn frames) cannot attain. This is already being done with SSTs. A conversion table such as Table I could be used to correct core loss results at higher frequencies.

Once additional core loss data is collected with confidence for different materials and a database is built, the new frame can be used with high confidence at testing points beyond the data provided by the lamination manufacturers. Although with only

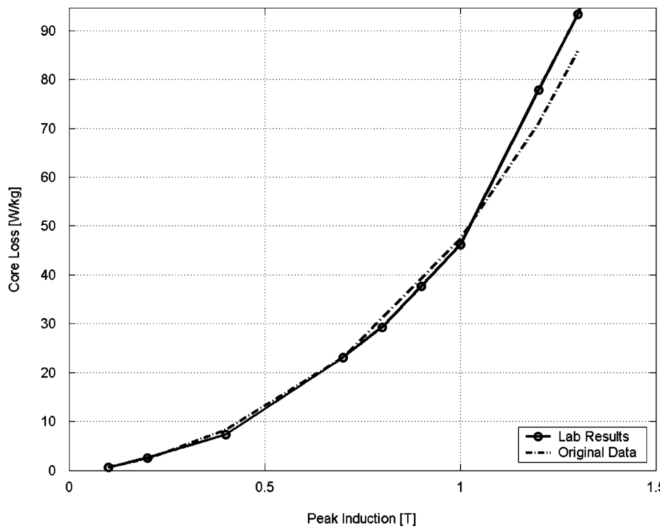

Fig. 14. M19 core losses at 600 Hz.

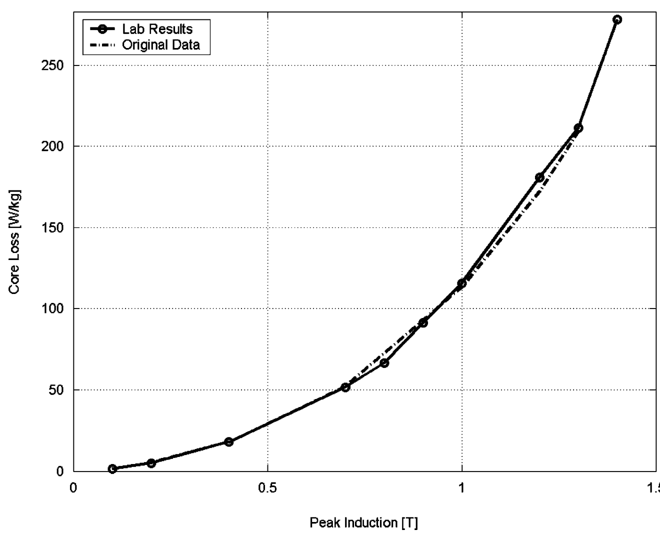

Fig. 15. M19 core losses at 1.0 kHz.

TABLE II
COMPARISON OF THE NEW FRAME WITH STANDARD FRAMES

Frame Type	Number of Samples	Typical Samples Mass [kg]	Comments
280-turn	4	0.1	High frequency capability
352-turn	32	1.0	Low operating voltage Reduced samples preparation time
700-turn	64	2.0	Standard samples size

four strips, this new frame produces results that are quite comparable with other frames, it is up to the standards committees to standardize this kind of a nontraditional frame.

The advantage of the reduced number of samples is reduction in samples' preparation time. This is especially important in steel mills and for lamination vendors, when more tasks can be performed within the same time it would have taken to prepare extra samples. Table II summarizes the important features of the new Epstein frame in comparison with old frames.

VI. CONCLUSION

A new Epstein frame capable of high frequency and high flux density testing has been presented. The idea of using only fours strips calls for a new cost-effective way of measuring core losses. The performance of this frame has been successfully tested on the M19, M36, M45, and CRML samples and found to produce decent results. The deviations observed can be used to construct a conversion matrix, such as shown in Table I, in the same way that the SSTs are commonly used. This new frame has an advantage over the SST that 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. The target test point has not been reached yet; it is hoped that the smaller frame will allow for this to be achieved.

ACKNOWLEDGMENT

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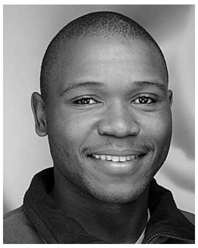

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