A Novel Cost-Effective Magnetic Characterization Tool for Soft Magnetic Materials Used in Electrical Machines

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***Abstract*— Energy losses during the magnetization process of soft magnetic laminations depend on the excitation waveform. Manufacturers of magnetic materials may not provide losses for different excitation waveforms. This may affect the accuracy of the predicted losses which are used to estimate the performance of electrical equipment during the predesign stage. Thus, a characterization tool which is capable of measuring hysteresis loops under controlled magnetization is required. Digital characterization systems available in literature use expensive commercial power amplifiers. In this work, a cost-effective power amplifier circuit is developed and interfaced with a LabVIEW program to characterize soft magnetic materials. The measurements for a sinusoidal excitation from the proposed setup are validated with those from a standard commercial measuring setup. The system is also used to measure hysteresis loops for arbitrary magnetization conditions (magnetic flux density (B) with harmonics). The proposed setup can operate over a frequency range 35–500 Hz. A small Epstein frame is also designed for measurements at higher frequencies (>200 and <500 Hz). A provision is also made to predict three components of dynamic hysteresis losses at any frequency in the above range using the loss separation approach. This capability of the setup enables the user to predict the losses at frequencies beyond the capability of the tool. The predicted losses using this algorithm are validated with measured losses. The proposed setup is cost-effective and can be developed easily using basic electronic components.**

***Index Terms*— LabVIEW, loss measurement, loss separation, magnetic characterization, power amplifier, power opamp.**

I. Introduction

SOFT magnetic materials of different grades are used in electrical machines for various applications. Magnetic characteristics of these materials depend on the excitation. Also, some magnetic properties may change due to manufacturing processes [1]. The test conditions to measure different properties of various soft magnetic materials are prescribed in international standards (IEC 60404-1–IEC 60404-14).

Traditional measurement systems use analog electronics, which, in general, facilitates easy control of magnetic flux density waveform [2]. As discussed in [2], a limitation of an analog system is that if the feedback gain is very high, then for any non-standard testing like 2-D measurements, characterization at high flux densities, and so on, there will be an instability in the closed-loop control because of oscillations in the control signal. Due to continuous progress in computers and digital systems, modern measuring devices include microprocessors and versatile computing software programs [2], [3]. In [2], magnetic flux density waveforms are controlled by modifying the magnetizing current. A current mode power amplifier Crown MT2400 [4] is used in [2] to excite samples. The setup has been used to measure hysteresis loops of toroidal samples, laminations, and so on. Magnetic characteristics under rotational magnetization and pulsewidth-modulated (PWM) excitation are also measured. In [5], a digital system has been developed to measure magnetic characteristics and Barkhausen noise. In [6], a LabVIEW-based tool with Kikusui PBX 20-20 power amplifier is developed to measure symmetrical minor loops. A digital tool to characterize toroidal samples under time-varying magnetization is presented in [7]. A digital feedback system that is capable of controlling flux in a magnetic core is proposed in [8]. A measurement setup driven by LabVIEW is developed to characterize Fe–9Cr steel laminations for non-periodic excitation in [9]. A digital characterization setup to measure hysteresis loss components under non-sinusoidal excitation is reported in [10].

All the above-mentioned setups use commercially available power amplifiers. An inverter-based amplifier for a digital characterization setup has been previously designed by Pawar *et al.* [11]. But, the amplifier circuit therein had certain limitations in terms of bandwidth and increased losses due to filtering at relatively high voltage levels. A new excitation circuit for magnetic characterization system using a power opamp device from Texas Instruments is designed in this work to overcome these limitations. Also, instead of using expensive data acquisition systems (DAQs), a Tiva microcontroller [12] is used as the interface which is a cost-effective option. The Tiva microcontroller is capable of sending digital signals and

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receiving analog signals in terms of their corresponding digital values using its 12-bit analog-to-digital converter (ADC). This Tiva microcontroller can be used to establish communication between the software program and the hardware. The functioning of the microcontroller is governed by a C-embedded program written in Code Composer Studio (CCS).

Traditionally, the magnetic properties of silicon steel laminations used in electrical machines are measured at 50/60 Hz, 1.0/1.5 T. In some applications, these materials may be used up to 400 Hz. Thus, characterization at a single operating point is not enough for modern applications. Epstein frames used by electrical equipment manufacturing industries are developed using the procedures described in IEC 60404-2. However, for high-frequency characterization, these frames may require higher voltages which may not be available [13], [14]. In this work, an Epstein bridge is designed for characterization of laminations over a frequency range 200–500 Hz and the required peak value of the voltage for measurements at 500 Hz is 40 V only.

In some applications, measured losses at frequencies >500 Hz may be required. This again calls for building another test bench for frequencies beyond 500 Hz, which is a very tedious job and increases the overall cost of the system. In this setup, a loss separation algorithm [15], [16] is formulated and implemented to predict loss components at frequencies beyond the measuring range of the setup. Hysteresis or iron losses can be separated into three loss components: static hysteresis loss, classical eddy current loss, and excess loss [15]. The parameters of these loss components in the loss separation approach are computed by using measurements at two different frequencies at one induction level. These parameters are used to estimate losses at other frequencies without the need of taking measurements. The algorithm has been validated with the measurements in the frequency range of the proposed setup. This capability of the setup can help electrical steel manufacturers and researchers to determine the three loss components for the material under investigation. The novelties of the proposed tool are design and fabrication of a cost-effective power amplifier circuit, use of a Tiva microcontroller as a DAQ device, and implementation of the loss separation algorithm to separate the three loss components and to predict the losses beyond the frequency range of the setup.

II. Fundamental Concepts Involved in Building the Proposed Setup

Practically, the measurable quantities are circuit quantities: current (i) and voltage (v). However, magnetic properties are represented with field variables: magnetic flux density (B) and magnetic field intensity (H). In this section, electromagnetic concepts that relate circuit and field quantities along with different loss components are presented.

A. Computing Field Quantities From v and i

The Epstein frame is a commonly used test setup to investigate the losses in magnetic materials by manufacturers of steels and electrical machines. As described in IEC 60404-2, this frame is a 1:1 open-circuited transformer. H can be calculated from the primary current (i_p) by applying Ampère's circuital law. The relation between i_p and H is

$$H = \frac{N i_p}{l}. \tag{1}$$

Here, N is the number of primary turns and l is the length of mean magnetic path. B can be calculated from the secondary voltage (v_s) by applying Faraday's law. The relation between v_s and B is

$$B = -\frac{1}{SN}\int_T v_s(t)dt \tag{2}$$

where S is the cross-sectional area of the flux path in the core and T is the time period. It should be noted that B should be computed using the secondary voltage because there is no voltage drop in the winding as the secondary current is zero.

B. Computing the Three Loss Components of Hysteresis Loss

After computing B and H, the hysteresis loss can be calculated by evaluating the area under the BH loop using the following expression [17]:

$$E(\text{W/kg}) = \frac{f}{\rho_v}\int H\,\mathrm{dB}. \tag{3}$$

In the above equation, f is the frequency of excitation and ρ_v is the mass density. The classical eddy current loss component is a function of thickness (d), resistivity (ρ), and rate of variation of B. It can be computed by using the following well-known formula derived from Maxwell's equations [17]:

$$E_{\text{eddy}}(\text{W/kg}) = \frac{(\pi d)^2}{6\rho\rho_v}(B_{\max} f)^2. \tag{4}$$

The proposed formulation is applicable if the magnetic flux density is uniform throughout the thickness of laminations. Therefore, this is valid if the thickness of laminations is less than the skin depth for the operating flux density and frequency. If the skin depth is less than the thickness of laminations, then the eddy current loss formula needs to be modified as given in [17]. The excess loss component is due to microscopic eddy currents that are induced because of domain wall motion [15], [18]. The loss component can be computed by using

$$E_{\text{ex}}(\text{W/kg}) = k_{\text{ex}}(B_{\max} f)^{1.5}. \tag{5}$$

Here, k_{ex} is the excess loss coefficient. It depends on the domain structure of the material. The iron losses can be expressed as

$$E = f E_{\text{static}} + \frac{(\pi d)^2}{6\rho\rho_v}(B_{\max} f)^2 + k_{\text{ex}}(B_{\max} f)^{1.5}. \tag{6}$$

It should be noted that in (6), E_{static} is in J/kg. Among the three loss components, the eddy current loss component can be computed analytically by using (4). In (6), the two unknowns E_{static} and k_{ex} are obtained from measured losses at two different frequencies. The algorithm of the loss separation procedure used in this work is discussed in Section VII.

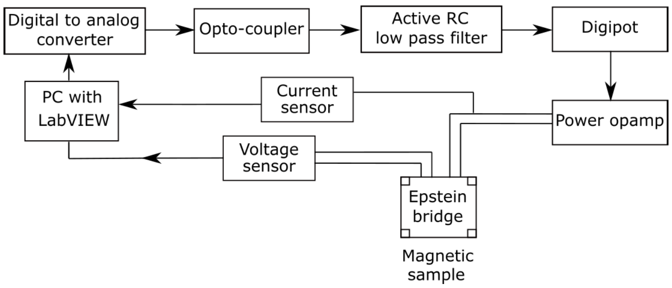

Fig. 1. Block diagram of the proposed setup.

III. Power Amplifier Circuit

The complete schematic and circuit diagram of the proposed setup is shown in Fig. 1. In this setup, the primary voltage required to establish the desired B waveform in laminations of an Epstein bridge is computed using a LabVIEW program. The voltage signal generated in the LabVIEW program is amplified using a power amplifier circuit. The voltage waveform is converted into its corresponding PWM waveform. These pulses are transferred to the hardware part of the setup through a digital-to-analog converter (a Tiva microcontroller) which is isolated from the power circuit of the hardware setup by an opto-coupler as shown in Fig. 1. The proposed power amplifier circuit is shown in Fig. 2.

The pulses from the Tiva board are filtered using a two-stage active low-pass RC circuit designed using opamps. The filtered waveform has a dc bias because of unidirectional pulses. This dc component is removed by using a voltage-level shifter made by using an opamp and a potential divider (trim pot). The output waveform from this stage has a peak of 1 V. This signal is amplified 40 times by a power amplifier designed using a power opamp [19]. The amplitude of the B waveform is adjusted by varying the input to the amplification stage using a digital potentiometer (DigiPot). The position of the wiper in the DigiPot is controlled by pulses sent from the PC via the Tiva board. The proposed amplifier circuit is capable of operating over a frequency range from 35 to 500 Hz and its output voltage can be varied from 5 to 40 V. With this voltage range, laminations can be characterized up to 500 Hz. The design of a small sized Epstein bridge for characterization of laminations over a frequency range 200–500 Hz is discussed in Section IV. The output from the power amplifier is applied to the primary winding of the magnetic tester. The secondary voltage and primary current of the tester are measured by voltage and current sensors designed using opamps. B and H are computed using (1) and (2) which are formulated in the developed LabVIEW program.

IV. Design of an Epstein Bridge for Magnetic Characterization in the Frequency Range 200–500 Hz

As discussed earlier, the Epstein bridge described in IEC 60404-2 requires higher voltages for high-frequency characterization of magnetic materials. In this work, a new Epstein bridge whose dimensions are less than the conventional bridge is designed. The voltage required to magnetize a sample at 500 Hz in this new Epstein bridge is less than 50 V.

TABLE I

Comparison of Dimensions Between Conventional and Modified Epstein Bridges

	Conventional Epstein bridge IEC 60404-2	Modified Epstein bridge
Number of turns	700	360
Length of the sample lamination	30 cm	17 cm
Width of the sample lamination	3 cm	1 cm

The relation between magnetic flux density and the applied voltage can be written as

$$B \times f \propto \frac{V}{A \times N}.$$

Thus, for a given flux density and frequency, the required level of voltage can be decreased by reducing the cross-sectional area and the number of turns of the primary circuit. In the design procedure, the number of turns is reduced to half the standard value (700 turns) which is equal to 350. But these 350 turns cannot be distributed equally on the four legs of the bridge. Therefore, 360 turns are selected for the primary and secondary windings of the modified Epstein bridge. The diameter of the copper wire selected for the winding is 0.9 mm. With this copper wire, the length of the bobbin for 90 turns is around 15 cm. As the length of the bobbin is decreased, the length of laminations should be decreased. This leads to an increase in the overlap length of laminations in the adjacent bobbins. Therefore, the width of laminations is reduced to one-third of the standard value (3 cm) which is equal to 1 cm. The reduction in the width of the lamination decreases the cross-sectional area of the magnetic circuit and this further reduces the voltage requirement. The length of the lamination is selected as 17 cm to maintain an overlap length of 2 cm per lamination. The main design parameters and their comparison with the parameters of a standard Epstein bridge are given in Table I.

In this small Epstein bridge, an air-core transformer which is present in the standard bridge is not used because the measured leakage inductance of the bridge is 1.7 μH which is very small when compared to its magnetizing inductance of 40 mH. A prototype of the proposed bridge is shown in Fig. 3. Using the proposed power amplifier circuit as shown in Fig. 2, the bridge can characterize magnetic materials from 200 to 500 Hz. It should be noted that a standard Epstein bridge is used to measure losses for frequencies less than 200 Hz. The proposed modified Epstein bridge is used to measure losses for frequencies between 200 and 500 Hz.

V. Digital Feedback LabVIEW Program Developed for Arbitrary Magnetization

A scientific computing platform like LabVIEW, MATLAB, and so on can be used in a digital characterization system to perform mathematical calculations, control the flux density waveform, and save measured data. The proposed hardware setup and small Epstein bridge can be used with any scientific

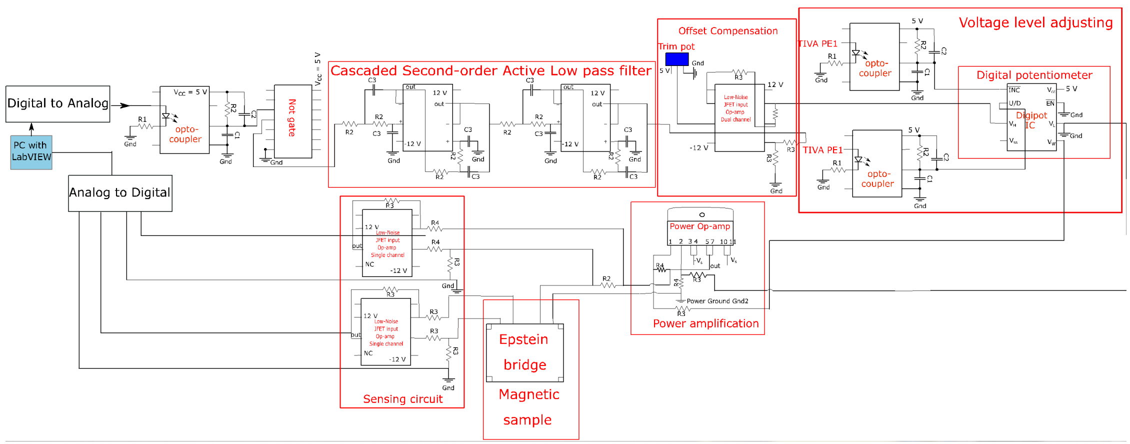

Fig. 2. Circuit diagram of the proposed power amplifier.

TABLE II
PERCENTAGE OF ERRORS BETWEEN THE TWO MEASUREMENTS

B (T)	0.5	0.7	0.9	1.1	1.3	1.5	1.7
Error(%)	3.7	9.3	8.8	9.6	2.3	1.6	3.5

computing platform. In this work, LabVIEW is used as the back-end software platform. The flux density waveform can be controlled by using a digital feedback system whose block diagram is shown in Fig. 4.

First, the voltage signal required for the flux density waveform is calculated by using the differential form of (2). Then, the corresponding PWM signal for the voltage waveform is generated in the LabVIEW program and is sent to the amplifier part of the setup. A PWM carrier of 15-kHz frequency is used to generate the excitation waveform.

The amplitude of the required voltage waveform at the primary of the Epstein bridge is controlled by varying the potential at the output of the DigiPot. The wiper of the digipot is shifted according to the number of pulses sent from the LabVIEW in congruence with the required voltage. For example, if the DigiPot has 100 steps and a peak input voltage of 1 V, then to generate a 0.5-V output, 50 pulses are required to be sent to the DigiPot. The measured secondary voltage and primary current of the Epstein bridge are converted to B and H, respectively, using the logic given in Fig. 4. It should be noted that the input to the Epstein bridge in this setup is given from the amplifier circuit discussed in Section II.

In the case of a flux density waveform with harmonics, the fast Fourier transform of the measured B is used to calculate the phase angle of the harmonics with respect to the fundamental component. Simultaneously, the error in the phase is corrected and the updated phase is given to the input voltage waveform. Similarly, the error in the magnitude is corrected by changing the number of pulses given to the DigiPot.

VI. Characterization of a Hi–B Grain-Oriented Material Using the Proposed Tool

The hardware setup for the characterization tool discussed in Sections III–V is shown in Fig. 5. This setup has been used to characterize samples of a Hi–B grain-oriented material used in power transformers at different flux densities and frequencies. The front panel for the LabVIEW program, which contains the details of the measurement (1.5 T, 50 Hz), and a measured hysteresis loop, is shown in Fig. 6.

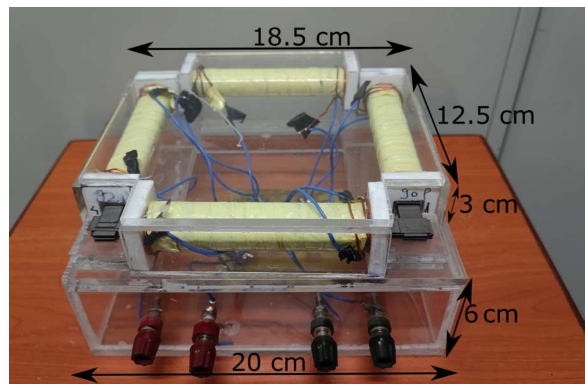

Fig. 3. Proposed small Epstein bridge for high-frequency magnetic characterization.

The accuracy of magnetic measurements is demonstrated by comparing hysteresis losses measured at different flux densities with measurements of the same material taken using a standard characterization tool (Brockhaus MPG 200), and the comparison is shown in Fig. 7. From the figure, one can observe that the losses measured using the proposed setup and the commercial tool are in close agreement. Table II quantifies the percentage of error between the measurements.

The setup can also be used to characterize the material for non-sinusoidal flux density waveforms. The measured hysteresis loop for a B waveform with 1.5 T of the fundamental component and 0.5 T of the third harmonic component is shown in Fig. 8. Similarly, the measured loop for a B waveform with 1.5 T of the fundamental component and 0.3 T of the fifth harmonic component is shown in Fig. 9.

VII. Implementation of Core Loss Separation Approach in the Proposed Characterization Tool

The value of core losses changes with frequency. Some of the soft magnetic laminations may be used in high-frequency

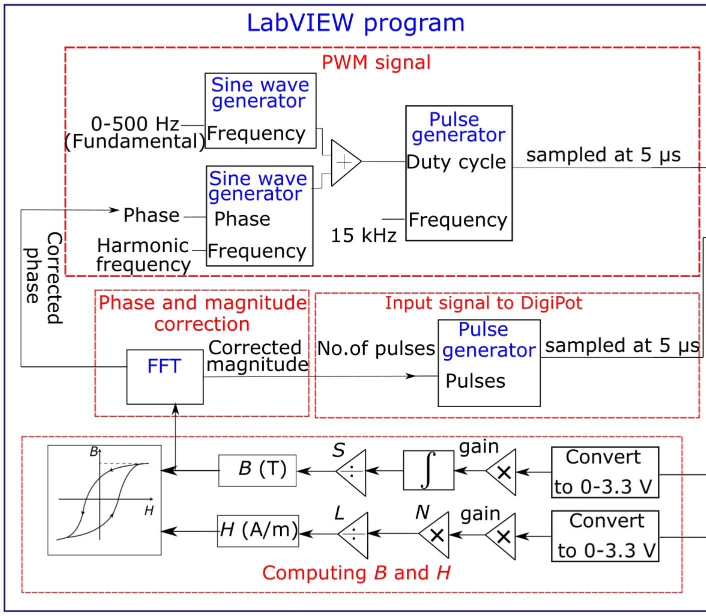

Fig. 4. Block diagram of the digital feedback system.

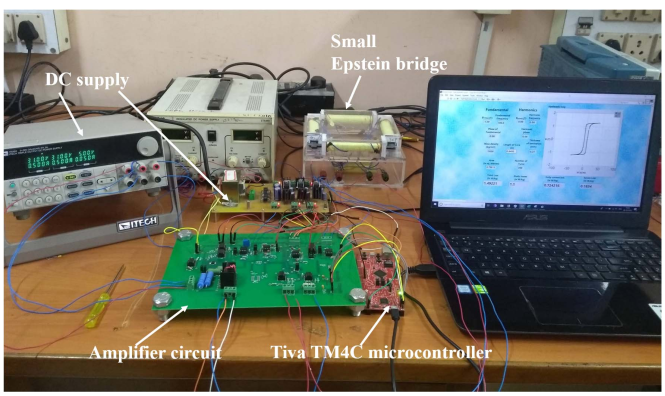

Fig. 5. Hardware implementation of the proposed setup.

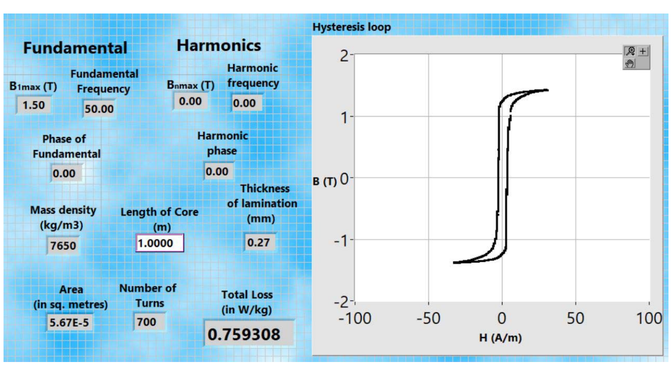

Fig. 6. Front panel for the LabVIEW program for measurements at 1.5 T, 50 Hz.

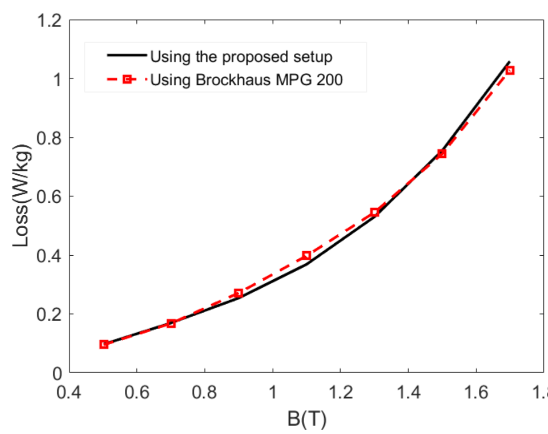

Fig. 7. Variation of total losses at different induction levels at 50 Hz.

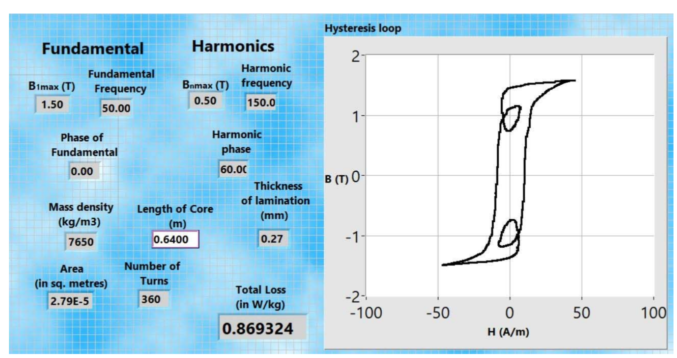

Fig. 8. Front panel of the LabVIEW program for measurements with B having 1.5 T of 50 Hz and 0.5 T of 150-Hz component.

applications. Therefore, loss estimations at high frequencies (>500 Hz) are required.

As discussed in Section IV, the size of the Epstein bridge needs to be reduced to characterize materials at high frequencies. Also, the small Epstein bridge presented in Section IV requires around 100 V to characterize the materials at 1 kHz. This needs a ±100 V (bipolar) dc voltage source.

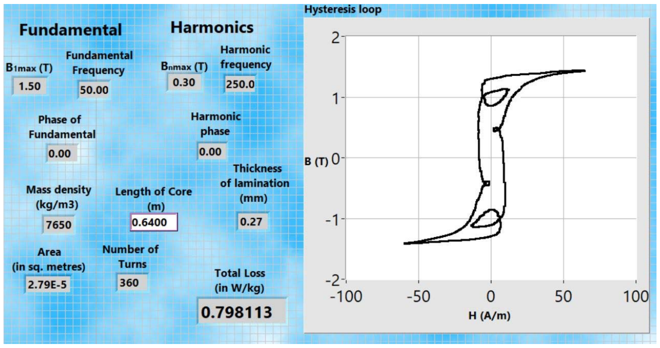

Fig. 9. Front panel of the LabVIEW program for measurements with B having 1.5 T of 50 Hz component and 0.3 T of 250-Hz component.

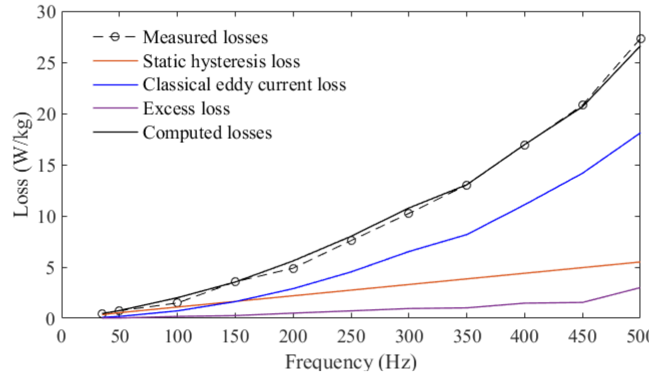

Fig. 10. Comparison of measured and computed losses predicted using the loss separation algorithm.

This may not be a cost-effective option. In the proposed tool, a loss separation approach [15], [16] has been implemented using the following steps to estimate the losses at high frequencies.

1) The losses at two different frequencies at the same induction level (here, 1.5 T at 50 and 150 Hz) are measured.
2) The classical eddy current loss computed using (4) is deducted from the measured losses.
3) The remaining loss components are static hysteresis and excess losses.
4) These two loss components can be determined by solving the following linear equations derived from (6):

$$E_{f_1} - k_{\mathrm{ed}}(B_{\max} f_1)^2 = f_1(E_{\mathrm{static}}) + k_{\mathrm{ex}}(B_{\max} f_1)^{1.5} \quad (7a)$$
$$E_{f_2} - k_{\mathrm{ed}}(B_{\max} f_2)^2 = f_2(E_{\mathrm{static}}) + k_{\mathrm{ex}}(B_{\max} f_2)^{1.5} \quad (7b)$$

where $k_{\mathrm{ed}} = [(\pi d)^2/6\rho\rho_v]$. It should be noted that k_{ed} can be calculated analytically by using material parameters such as conductivity, thickness, and mass density. In the above system of linear equations, E_{static} and k_{ex} are the two unknown parameters that need to be determined.
5) After determining the two parameters, the total loss at any frequency can be calculated in the selected range by substituting the values of $E_{\mathrm{static}}, k_{\mathrm{ed}}, k_{\mathrm{ex}}$ in (6).

It should be noted that the static hysteresis loss component can be obtained from the hysteresis characteristics measured at a very low frequency (less than 5 Hz). But the voltage required to characterize Epstein laminations at this low frequency is less than the lower voltage limit of the proposed setup. Therefore, the static hysteresis loss component is also determined as a parameter by using the loss separation approach. The capability of the above-implemented algorithm is demonstrated by comparing the measured losses with the estimated losses up to 500 Hz, as shown in Fig. 10. The losses computed using the developed algorithm are in good agreement with the measured losses. The relative errors between measured and computed losses at each frequency is given in Table III. It should be noted that the errors for 50 and 150 Hz are zero because loss data at these frequencies are used for loss separation. The front panel of the LabVIEW program, containing the details of measurements, measured hysteresis loops, and separated losses at 1.5 T and 400 Hz using the algorithm, is shown in Fig. 11. This feature can help electrical steel manufacturers and researchers to determine the three loss components for the material under investigation.

TABLE III
PERCENTAGE OF ERRORS BETWEEN MEASURED AND COMPUTED LOSSES

Frequency (Hz)	Error(%)
35	2.34
50	0
100	13.16
150	0
200	12.53
250	5.21
300	4.47
350	0.31
400	0.18
450	0.12
500	3.05

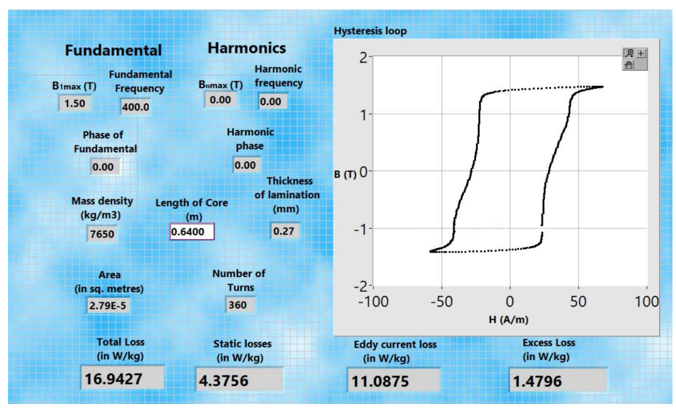

Fig. 11. Front panel for the LabVIEW program for measurements at 1.5 T, 400 Hz.

VIII. CONCLUSION

In this work, the development of a LabVIEW-based characterization tool for soft magnetic laminations is presented. The novelty of the work includes the design and fabrication of a low-cost amplifier circuit and a small Epstein bridge, which can be used to measure losses for a frequency range

200–500 Hz. A loss separation algorithm is implemented in the characterization tool for the first time. This feature can be used to estimate losses at higher frequencies. The proposed tool is capable of characterizing soft magnetic materials for arbitrary flux density waveforms with harmonics. The magnetic losses measured using the proposed setup are compared with measurements taken using a standard commercial setup. The proposed setup can be used to characterize soft magnetic laminations over a frequency range 35–500 Hz.

The loss separation algorithm implemented in this setup enables users to estimate losses beyond the frequency capability of the tool. This algorithm can help researchers and engineers to determine the three loss components for new materials. The proposed amplifier setup and LabVIEW program can be used to characterize magnetic materials in different shapes (e.g., toroids). The setup can also be used to measure rotational losses in a rotational single sheet tester.

The proposed setup is cost-effective compared to the existing tools in the literature and commercial magnetic characterization systems. The existing characterization systems use commercial amplifiers whose cost is around U.S. $1000. The power amplifier proposed in this work is developed using a power opamp and basic electronic components whose cost will be around U.S. $200. Also, in this work, a TIVA microcontroller is used to establish the communication between the software program and the hardware part of the setup. The cost of this microcontroller is much less compared to the DAQ cards used in the existing systems. For a given characterization system, the measuring coil arrangement needs to be changed based on the measurement frequency range. The development of coil systems for different frequency ranges will further increase the cost of the setup. The loss separation algorithm which is implemented in the proposed setup is capable to predict the losses beyond the measuring frequency range of the system. Using this special feature, the need for extra measuring coil systems required to characterize a material for high frequencies can be eliminated and this reduces the cost of the system.

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