2023 IEEE Energy Conversion Congress and Exposition (ECCE) | 979-8-3503-1644-5/23/$31.00 ©2023 IEEE | DOI: 10.1109/ECCE53617.2023.10362857

A Series Resonant Converter based Experimental Measurement of B-H Curve for Core Loss Estimation of a High Frequency Inductor

Mayur Isame
Bajaj Auto Limited
Pune, India
isamemayur93@gmail.com

Shamibrota Kishore Roy
Electrical Engineering Dept.
Indian Institute of Science
Bengaluru, India
shamibrotakishoreroy@gmail.com

Enjeti Prasad
Electrical Engineering Dept.
Texas A&M University
Texas, United States
enjeti@tamu.edu

Kaushik Basu
Electrical Engineering Dept.
Indian Institute of Science
Bengaluru, India
kbasu@iisc.ac.in

***Abstract*—Estimation of core loss is essential for high-frequency converter design. For high-frequency applications, Ferrite is a popular choice. Eddy current loss in ferrite is negligible due to high material resistivity and core loss is dictated by the hysteresis loss. To estimate hysteresis loss, the B-H loop needs to be known for different values of frequencies and B values. However, in the material datasheet, B-H loop data is generally given for a single operating condition. So, from the converter design and optimization point of view, it is essential to obtain the B-H curve for different operating conditions. It may help in predicting the B-H loop for non-sinusoidal excitation experienced in switching converters. In this work, a new B-H loop measurement method is proposed. Compared to the linear amplifier-based conventional measurement technique, the proposed method can be used for high-power and high-frequency applications. Also, it does not require the input DC voltage supply higher than the drop across the device under test (for example, magnetic components like inductor and transformer). The proposed technique is used to measure the B-H loop for a 47 μH, 100kHz inductor designed for the dual active bridge (DAB) converter for a wide range of operating conditions. The experimentally obtained B-H loops are then used to obtain the hysteresis loss. The proposed experimental measurement technique is compared with the analytical method (using the Stientzmez equation) and Ansys Maxwell-based electromagnetic simulation for a wide range of operating conditions.**

***Index Terms*—Core loss, Hysteresis loss, Steinmetz equation (SE), B-H Curve, Series Resonant Converter.**

I. INTRODUCTION

With the advent of Wide Bandgap devices, the switching frequency of power electronic converters has increased substantially. However, an increase in switching frequency may lead to higher core losses and a reduction in the converter efficiency. So, to select a proper magnetic material for a given design and optimize the overall converter efficiency, it is important to estimate core losses for a given magnetic material. Ferrite is a popular magnetic material for high-frequency applications. Eddy current loss is negligible in ferrite due to the high resistivity of the material and core loss is dictated by hysteresis loss [1], [2].

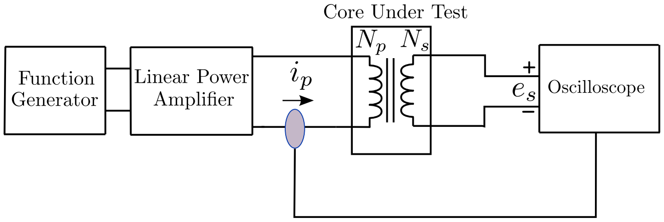


Fig. 1. Existing B-H loop measurement technique

The current through the magnetic components (for example, inductor, transformer, etc.) for most of the power converters are non-sinusoidal and contain significant harmonic components. To estimate the hysteresis loss for the applied non-sinusoidal excitation, the B-H curve is required for different values of B and H values and frequency. However, the B-H loop for any magnetic material is given for a single B and H values and frequency. So, to estimate the hysteresis loss accurately, it is essential to measure the B-H loop for different operating frequencies and B values. It may help in predicting the B-H loop for non-sinusoidal excitation experienced in switching converters.

In existing literature, linear amplifier based B-H loop measurement technique is used [3], [4]. Fig.1 shows the picture of the experimental set up. Here, DUT is considered to be a high frequency inductor with N_p number of turns. N_s represents the number of secondary turns and it is separately put to measure the flux inside the core accurately. To measure the B-H loop for a given frequency and B value, the DUT is excited through a linear amplifier of required voltage and frequency. Depending on the self inductance of the DUT, magnetising current will be drawn from the input supply and it is measured using a current probe (denoted as i_p). The secondary side (N_s) is connected to a high impedance voltage probe and the voltage induced across N_s is measured (denoted as e_s). Then, the instantaneous values of B and H are given by (1) and (2) respectively, where A_c is the area of the core and l_m is the magnetic path length.

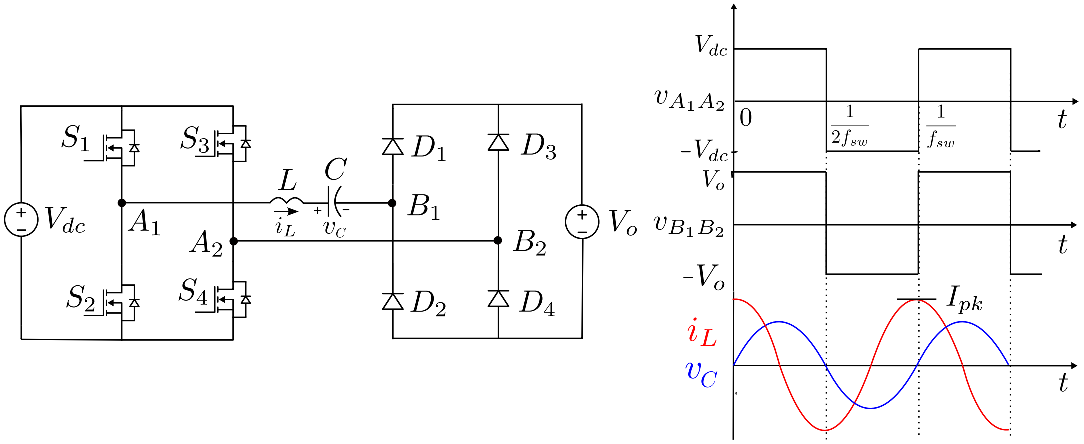


Fig. 2. Proposed B-H loop measurement circuit and the important waveforms at resonance

$$B = \frac{1}{N_s A_c} \int e_s \, dt \tag{1}$$

$$H = \frac{N_P i_p}{l_m} \tag{2}$$

This technique is precise and widely used. However, due to the operation of the active devices in the linear region, this solution generates high power loss and restricts the process at high power levels. Most linear amplifier-based designs use BJT as an active device, limiting the operation frequency. For example, BJT based linear amplifier is suitable for operation up to 5kHz. Also, this method is sensitive to phase discrepancy when subjected to a core with high-quality factor [3]. So, the linear amplifier-based B-H curve measurement approach may not be suitable for the given application where the operating frequency is in the range is 100-200kHz, and the current is in the range of 5-10A. Also, this measurement technique requires input DC bus voltage higher than the voltage across the magnetic material. [5] proposes a measurement technique that provides a direct measurement of the quality factor of an inductor as a function of current at RF frequencies. It also enables indirect calculation of core loss as a function of flux density. The measurement requires a high quality factor capacitor in series with the inductor (DUT) excited by a high frequency RF linear amplifier. However, similar to [3], [4], the proposed technique also uses a high frequency RF linear amplifier and hence, can not be used for high power applications. A machine learning framework for core loss estimation is presented in [6]. However, this method requires a large dataset and computational time.

In this paper, a series resonant converter-based new B-H curve measurement technique is proposed. It uses switching devices operated in the cutoff and ohmic regions, reduces the converter loss and helps in measuring B-H curves at high frequencies. Also, it does not require the DC bus voltage higher than the voltage across the magnetic material used for measurement. This method is used to measure the B-H loop for a 47 μH, 100kHz inductor designed for the dual active bridge (DAB) converter for a wide range of operating conditions. The experimentally obtained B-H curves are then used to obtain the hysteresis loss. The proposed experimental measurement technique is validated using analytical method (using Stientzmez equation) and Ansys Maxwell-based electromagnetic simulation for a wide range of operating conditions.

The rest of the paper is arranged in the following order. Details of the proposed core loss measurement technique is described in Section II. Section III describes the simulation and experimental results. Finally, Section IV draws the conclusion.

II. PROPOSED CORE LOSS MEASUREMENT TECHNIQUE

This section presents the proposed B-H loop measurement technique. Series resonant converter (SRC) topology is used for the proposed approach (see Fig.2). The test inductor (L) is used as the series inductor of the resonant tank. C represents the resonant tank capacitor. Active devices S_1 to S_4 are used as primary side active devices. On the other hand, diode D_1 to D_4 are used as devices of the secondary side bridge. An input side of the primary bridge is supplied from a voltage source V_{dc} and the output of the secondary diode bridge is connected to the output capacitor in parallel with the resistive load. The output capacitor is selected such that the ripple in the output voltage is negligible and it can be approximately assumed a DC voltage V_o [7]. The switching frequency of the primary bridge is denoted as f_{sw}. When f_{sw} is equal to the resonance frequency of the LC tank (3), the total instantaneous voltage applied across the LC tank is zero or $v_L = -v_C$ and hence $V_{dc} = V_o$. The current through the inductor L is sinusoidal and the magnitude can be adjusted by varying the load resistance R (4). Also, to obtain the B-H loop for a given frequency, C is adjusted (depending on the value of L) to meet the resonance frequency of the LC tank equal to the desired frequency. The advantages of this approach are as follows:

- The proposed technique uses active devices (SiC MOSFET for this case), which are operated in ohmic, and cut-

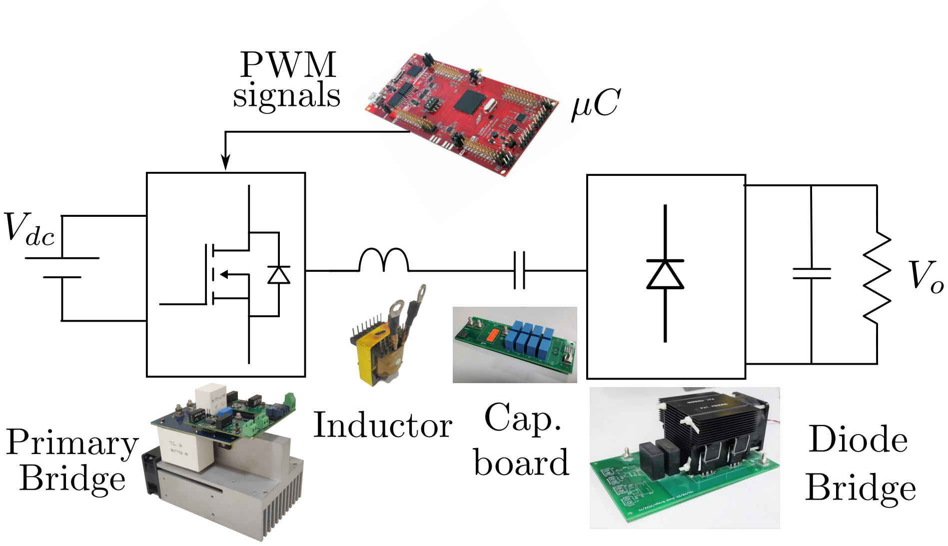


Fig. 3. B-H loop for different operating conditions

off regions, and helps generate high-frequency sinusoidal current waveforms (100kHz range and its multiples).

- Unlike the linear amplifier-based approach, the input DC supply voltage for the proposed technique is not restricted by the voltage drop across the inductor and can be of a smaller value. This relaxes the requirement of having a high DC voltage source for an inductor with a high voltage drop. Also, another isolated DC-DC converter can be used to feed the power back to source V_{dc} and the experiment will need small power.

$$f_{sw} = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

$$I_{pk} = \frac{\pi V_o}{2R} \tag{4}$$

$$P_{exp} = \int H \, dB \times VOL \tag{5}$$

$$P_{anly} = K_c f_{sw}^{\alpha} B_{max}^{\beta} \times VOL \tag{6}$$

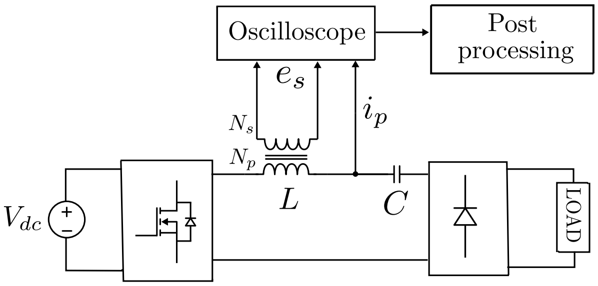


Fig. 4. Proposed B-H loop measurement technique

TABLE I
DETAILS OF DESIGNED INDUCTOR

Parameter	Symbol	Value
Inductance	L	47 μH
Window area	A_w	266.74 mm^2
Core Area	A_c	178 mm^2
Number of turns (Pri)	N_p	14
Number of turns (Sec)	N_s	5
Air gap length	lg	0.96mm

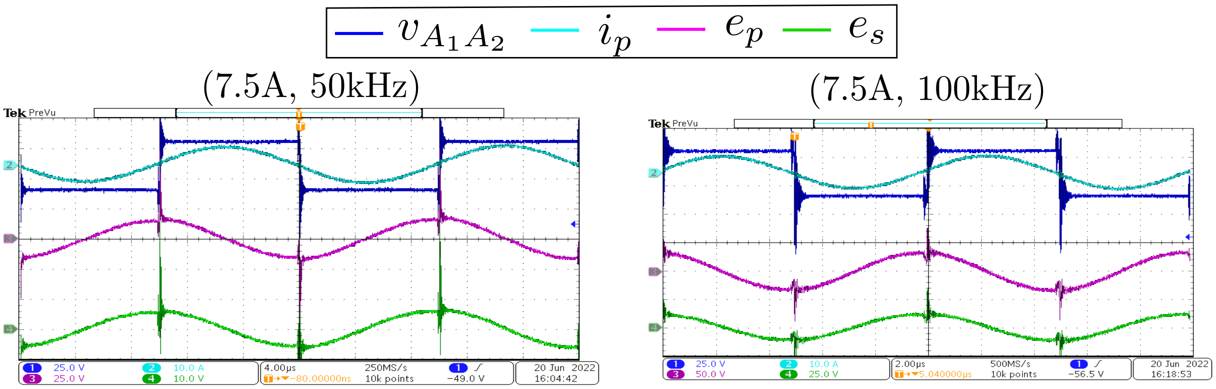
Fig.3 shows the actual measurement procedure of the B-H loop. The inductor L has N_p number of turns. N_s number of secondary turns are put on the inductor to estimate B inside the core. Current i_p and e_s are measured for a given frequency and current magnitude. Then, (1) and (2) are used to calculate the B and H values respectively where A_c is the area of the core and l_m is the magnetic path length. Please note, the eddy current loss is neglected due to high resistivity of ferrite material [1], [2].

A. Details of designed inductor

The inductor is designed for a dual active bridge (DAB) based DC-DC converter and used here for the experimental measurement of B-H loop. Input and the output voltages are 400V and 325V, respectively and the power rating is 2.5kW. The switching frequency of the DAB is selected as 100kHz. The value of inductor is 47 μH, peak and RMS current values are 10.7A and 7.71A, respectively. Ferrite (MnZn) N-27 material is used as the magnetic material. Selected core type is EE42/21/15. The details of the inductor is given Table I. Secondary turns are put to estimate the flux in the core. The image of the fabricated inductor is given in Fig.4.

B. Experimental Setup

In this section, the details of the SRC based B-H loop measurement set up is given (see Fig.5). For the primary side bridge of SRC (devices S_1 to S_4), 650V, 39A SiC MOSFET SCT3060ALGC11 from ROHM is used to achieve high



(7.5A, 50kHz) (7.5A, 100kHz)

Fig. 5. Experimental results for different operating conditions

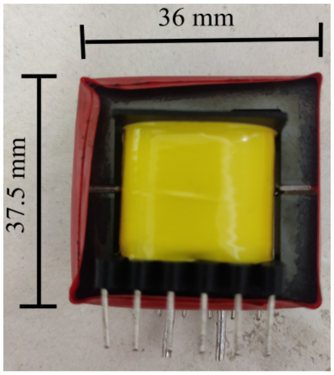


Fig. 6. Picture of the designed inductor

TABLE II
EXPERIMENTAL SET UP

Parameter	Symbol	Value
Input DC voltage	V_{dc}	325 V
Output voltage	V_o	325 V
Series inductor	L	47 μH
Series capacitor	C	3.36-200 nF
Switching frequency	f_{sw}	50-400 kHz
Output filter capacitors	C_f	9.4 μF

switching frequency. Gate driver ADuM4135 from Analog devices is used to drive the SiC MOSFET. Gate driver voltage levels are 18V, -2.5V. SiC Schottky diode of 1200V, 20A from Infenion (IDW20G120C5B) is used for secondary diode bridge (D_1 to D_4). Different values of series resonant capacitors C are used to obtain the B-H curves at different frequencies. Film capacitors are selected because of their good high frequency response and ripple current performance. Please note, there can be some amount of tolerance present in the Film capacitor. This may result in certain amount of deviation of actual resonant frequency from the theoretically estimated value. To account for the resonant frequency variation, f_{sw} needs to be adjusted slightly such that the voltage gain of the SRC converter reaches its maxima. This ensures resonant frequency is equal to switching frequency. The specifications of the experimental set up is given in Table II.

For the accurate measurement of B-H loop, it is essential to measure i_p and e_s signals accurately. For the measurement of i_p, high bandwidth AC-DC current probe TCPA300 (150A, 100MHz) from Tektonix is used. Voltage e_s is measured using high voltage differential probe P5200A (1kV, 50MHz) from Tektronix, 1GHz oscilloscope MDO3104 from Tektronix is used for all the measurement. Matching of propagation delay between voltage and current signals is done using a delay matching instrument available from Tektronix (067-1686-00, Power Measurement De-skew and Calibration Fixture). This minimizes the error due to phase discrepancy.

III. SIMULATION AND EXPERIMENTAL RESULTS

To obtain the B-H loop for the test inductor at a different frequency (f_{sw}) and current (i_p) values, three sets of experiments are performed. The operating conditions (I_{pk}, f_{sw}) are (7.5A, 50kHz), (7.5A, 100kHz) and (3.25A, 200kHz). Fig. 5 shows two sample experimental results for (7.5A, 50kHz) and (7.5A, 100kHz) where the input voltage across the primary input bridge ($v_{A_1A_2}$), inductor current (i_p) and primary and secondary voltages (e_p and e_s, respectively) across the inductor are captured. It can be observed that the i_p, e_p, and e_s are sinusoidal. There is some amount of high-frequency transients observed in the waveforms during the switching of the primary side devices.

After obtaining the i_p and e_s waveforms from the measurement for a given (i_p, f_{sw}) pair, (1) and (2) are used to obtain the B-H loop. Fig. 7 contains the B-H loop for different values of (i_p, f_{sw}). Please note, the high-frequency oscillations present in the waveforms are filtered out while calculating B and H values from e_s and i_p. Please note, the proposed technique may have limited accuracy when $T_{sw} = (1/f_{sw})$ is comparable with the switching transition time. After obtaining the B-H loop, hysteresis loss (P_{exp}) is obtained using (5) where VOL is the volume of the core.

To verify the accuracy of the proposed measurement technique, the Steinmetz parameters for the selected core are obtained from the datasheet @ 20^oC and the values are

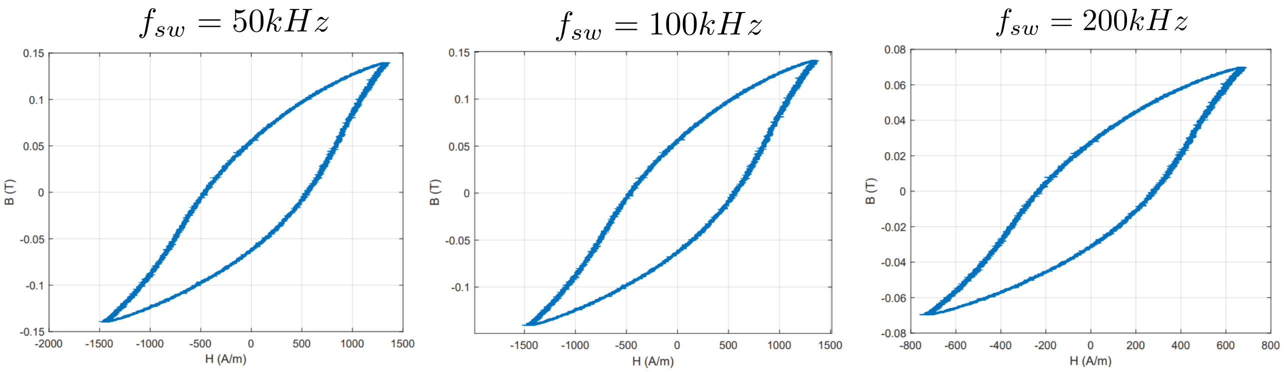
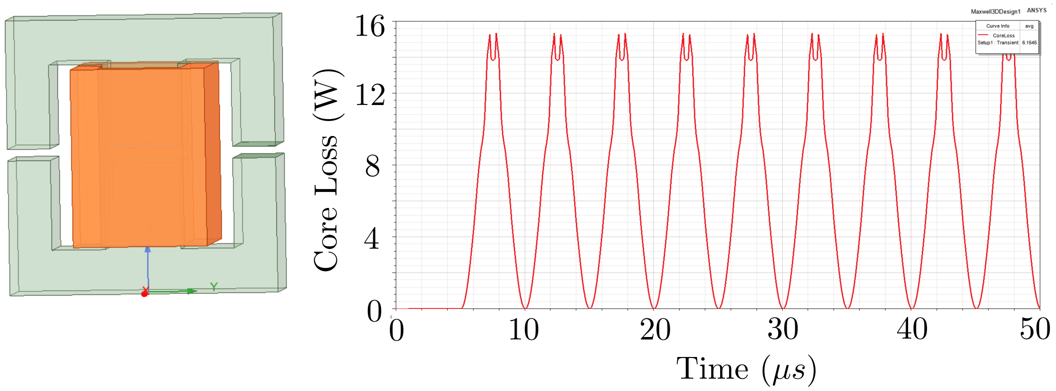


Fig. 7. B-H loop for different operating conditions



(a) (b)

Fig. 8. Electromagnetic simulation: (a) 3D Model, (b) Hysteresis loss vs time

$\alpha = 1.16$, $\beta = 2.07$, and $K_c = 43.58$ [8]. Please note, in the normal operating range, core loss for ferrite material reduces with the increase in temperature. Also, Steinmetz parameters of any magnetic material is frequency dependent. Hence, parameters corresponding to operating frequency range need to be used for accurate estimation of core loss. Now, using Steinmetz equation (6), the hysteresis loss is obtained for the same operating conditions (f_{sw}, B_{max}). B_{max} represents the maximum flux density for a given operating condition. Also, an electromagnetic simulation is performed for the same inductor. For this purpose, the inductor is modeled in Ansys Mawell 3D with the PEmag tool. Fig.8(a) shows the 3D model of the inductor. The dimensions of the core is taken same as given in Table I. The B-H loops obtained from the experiment are used and the hysteresis loss is obtained (P_{sim}) (see Fig.8(b)). P_{anly}, P_{sim} and P_{exp} are compared in Table III. It can be observed that the P_{sim} and P_{exp} match closely for all operating conditions whereas estimated P_{anly} is less compared to P_{sim} and P_{exp}.

TABLE III

COMPARISON OF P_{anly}, P_{sim} AND P_{exp}

Operating condition	P_{anly} (W)	P_{sim} (W)	P_{exp} (W)
(7.5 A, 50 kHz)	2.45	3.14	3.2
(7.5 A, 100 kHz)	5.47	6.15	6.44
(3.25 A, 200 kHz)	2.91	3.82	3.53

IV. CONCLUSION

A series resonant converter (SRC) based B-H loop measurement technique is proposed in this paper. Compared to the linear amplifier based conventional measurement technique, the proposed method can be used for high power and high frequency applications. The proposed technique is used to measure B-H loop for a high frequency inductor of 47 μH, 10.7A peak, designed for dual active bridge converter. Also, the proposed technique is validated using Steinmetz equation based analytical estimation and Ansys maxwell based electromagnetic simulation. A close agreement between simulation and experimental results are observed. However, Steinmetz equation based analytical estimation underestimates the hysteresis loss and the maximum percentage of error is around 23% when compared with the experimental measurement.

REFERENCES

[1] A. Dhole, S. K. Roy, and K. Basu, “Estimation and measurement of power loss in a high frequency inductor for a dab based dc-dc converter,” in *2021 National Power Electronics Conference (NPEC)*, 2021, pp. 1–6.

[2] C. P. Steinmetz, "On the law of hysteresis," *Transactions of the American Institute of Electrical Engineers*, vol. IX, no. 1, pp. 1–64, 1892.

[3] M. Mu, Q. Li, D. Gilham, F. C. Lee, and K. D. T. Ngo, "New core loss measurement method for high frequency magnetic materials," in *2010 IEEE Energy Conversion Congress and Exposition*, 2010, pp. 4384–4389.

[4] C. Urabinahatti, S. S. Ahmad, and G. Narayanan, "Magnetic characterization of ferromagnetic alloys for high speed electric machines," in *2018 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, 2018, pp. 1–5.

[5] Y. Han, G. Cheung, A. Li, C. R. Sullivan, and D. J. Perreault, "Evaluation of magnetic materials for very high frequency power applications," *IEEE Transactions on Power Electronics*, vol. 27, no. 1, pp. 425–435, 2012.

[6] H. Li, S. R. Lee, M. Luo, C. R. Sullivan, Y. Chen, and M. Chen, "Magnet: A machine learning framework for magnetic core loss modeling," in *2020 IEEE 21st Workshop on Control and Modeling for Power Electronics (COMPEL)*, 2020, pp. 1–8.

[7] Y. Wei, Q. Luo, and H. A. Mantooth, "A resonant frequency tracking technique for llc converter-based dc transformers," *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, vol. 2, no. 4, pp. 579–590, 2021.

[8] Ferrites and accessories, "[online]. available: https://www.tdk-electronics.tdk.com/download/528850/3a7f957d754f899aec42cd946598c5c4/pdf-n27.pdf," (2023), February).