ACTA PHYSICA POLONICA A No. 1 Vol. **146** (2024)

Selected papers presented at the 14th Symposium of Magnetic Measurements and Modelling SMMM'2023

Experimental Verification of the Method for Calculating Losses in DC/DC Converter Cores Based on Sinusoidal Excitations

D. Gzieł[a,*], M. Najgebauer[a] and Ł. Mierczak[b]

[a] *Częstochowa University of Technology, Faculty of Electrical Engineering, Armii Krajowej 17, 42-200 Częstochowa, Poland*
[b] *Brockhaus Polska, Szparagowa 65, 42-280 Częstochowa, Poland*

Doi: 10.12693/APhysPolA.146.59 *e-mail: damian.gziel@pcz.pl

In this paper, the method for calculating losses in magnetic cores operating in a DC/DC power converter is experimentally verified for selected samples. The chosen method of calculating magnetic losses based on loss measurements under sinusoidal excitation is described, and the measurement process is discussed. The results of power loss measurements with a direct current bias for three different magnetic core materials, e.g., ferrite, nickel–iron–molybdenum alloy powder, and nanocrystalline, are presented. A quantitative determination of the deviations for the tested method is proposed, including the frequency dependence of the deviation distribution.

topics: magnetic core losses, power electronics, DC/DC converter, Steinmetz equations

1. Introduction

The key components of power electronic converters are magnetic cores. Their miniaturization is achieved by increasing the switching frequency, which results in higher losses in the magnetic core [1]. The value of these losses depends primarily on the type of core material [2]. The operation of the DC/DC power electronic converter causes the magnetic core of the inductor to operate under non-sinusoidal excitation conditions. In the analyzed case, the magnetic flux density has a triangular waveform, which, in addition to the frequency and amplitude, is characterized by the presence of a direct current (DC) component B_{DC}. The occurrence of the DC part of magnetic flux density B is related to the flow of unidirectional current through the inductor's windings, which causes the core to be magnetized with the DC component of the magnetic field strength H_{DC}. In the case of some magnetic materials, DC pre-magnetization has a significant impact on the loss level and cannot be neglected [3, 4]. The commonly used Steinmetz equation, as well as its modifications, e.g., those described in [5], do not allow one to take into account the influence of the constant component of the magnetic field strength on losses. The method based on the Steinmetz pre-magnetization graph (SPG) proposed in [3] requires many measurements in the converter operating conditions and adjustment of the coefficients for the improved generalized Steinmetz equation (IGSE) to the results obtained for subsequent H_{DC} values. Therefore, there is a need to develop, verify, and improve methods for estimating power losses of magnetic cores operating under such conditions. The article presents the results of experimental verification of the method for calculating losses in magnetic cores operating in a DC/DC converter based on sinusoidal losses for magnetic cores other than those in the original studies [6, 7].

2. Method description

The approach analyzed in this article was presented in [6] and [7]. This method uses sinusoidal losses with equivalent frequency to model losses with non-sinusoidal excitations. The equation for the energy density lost during one complete magnetization cycle with sinusoidal excitation was also analyzed [6]

$$Q_V = \frac{P_V(\tau)}{f} = C_m f^{x(f)-1} B^{y(f)} (c_{t_2}\tau^2 - c_{t_1}\tau + c_t), \tag{1}$$

where C_m, x, y are parameters characterizing the magnetic material; τ — core operating temperature, f — core magnetization frequency; P_V — power losses related to the core volume; c_{t_2}, c_{t_1}, c_t — coefficients of the polynomial taking into account the influence of temperature. This formula is based on the Steinmetz equation, however, it is expressed for energy losses and supplemented with a polynomial taking into account the influence of temperature. The energy losses depend on the derivative of the magnetic flux density $\mathrm{d}B/\mathrm{d}t$. Assuming that $\dot{B} = \mathrm{d}B/\mathrm{d}t$, the arbitrary shape of the magnetic flux density can be represented using a linear-segmental description containing a weighting factor. This approach may also be useful in cases other than a DC/DC converter. The formula for the equivalent frequency of a sinusoidal signal in [7] takes the form

$$f_{\mathrm{eq(sin)}} = \frac{2}{\pi^2} \sum_{k=1}^{K} \left(\frac{B_k - B_{k-1}}{B_{\max} - B_{\min}} \right)^2 \frac{1}{t_k - t_{k-1}}, \qquad (2)$$

where K — the number of consecutive k-th segments of the linear-segmental magnetic flux density course. For a rectangular voltage waveform magnetizing the inductor core operating in a DC/DC converter, the magnetic flux density waveform in the core is triangular. If this waveform is symmetrical, then the frequency of the equivalent sinusoidal waveform can be expressed as [6]

$$f_{\mathrm{eq(sin)}} = \frac{8}{\pi^2} f_{\mathrm{rect}}, \qquad (3)$$

where f_{rect} is the frequency of the magnetic flux density waveform (excited by a rectangular voltage waveform) in the inductor core operating in a DC/DC converter. In [7], the authors proposed to include the equivalent frequency into the IGSE [8], obtaining a formula expressing the energy loss. Thereby, when the converter operates with a duty cycle of $D = 0.5$, which corresponds to a symmetrical triangular course of magnetic flux density, the equation for the energy lost in the core is simplified to the following form [7]

$$Q_{\mathrm{rect}} = Q_{\mathrm{eq(sin)}} \left(\Delta B_{\mathrm{rect}}, H_{\mathrm{DC}}, f_{\mathrm{eq(sin)}} \right), \qquad (4)$$

where ΔB is peak-to-peak magnetic flux density in the core; Q_{rect} and $Q_{\mathrm{eq(sin)}}$ — energy lost in the magnetic core under rectangular and sinusoidal excitation, respectively. As follows from (4), the energy lost in the core of the inductor operating in a DC/DC converter can be determined on the basis of sinusoidal losses for the equivalent frequency while maintaining the same value of the constant component of the magnetic field strength H_{DC} and the peak-to-peak magnetic flux density in the core, ΔB. Hence, to determine the losses corresponding to the operating conditions of the DC/DC converter, necessary measurements must be carried out.

3. Measurement process

The measurements results presented in [6, 7] confirmed the usefulness of the equivalent frequency method in loss modeling, however, the results obtained only concerned cores made of ferrite material 3C85 (Philips) [7] and iron powder material SK-08KSTB (TOHO ZINC) [6]. For this reason, the aim of this research is to verify the applicability of (4) in the loss calculation for magnetic cores made of other materials. It was assumed that the method verification would be carried out for the duty cycle $D = 0.5$, which corresponds to the symmetrical, triangular shape of the magnetic flux density waveform in a core. Three magnetic cores made of different materials were selected for testing, as presented in Table I (see also [9–11]).

TABLE I

Magnetic cores selected for measurements (A_L — inductance coefficient value for the number of turns $N = 1$) [9–11].

Core material	Core model name	A_L [nH]
N87 (ferrite core)	B64290L0038X087	900
MP (nickel, iron, molybdenum alloy powder material)	MP-065205-2	123
VITROPERM 500F (nanocrystalline core)	T60004-L2063-W627-52	18000

Inductors with powder or ferrite cores are often found in DC/DC converters. If a ferrite core is used, a core with a discrete air gap should be used to enable the inductor to operate at a higher DC. In the case of powder material, the material structure ensures the so-called distributed air gap in the core. In this research, all tested samples were without discrete air gaps to avoid the additional fringing effect associated with these core types [12, 13]. This phenomenon introduces unnecessary complications related to the loss measurements [14, 15], which is not desirable for the verification of the analyzed method. The nanocrystalline material VITROPERM 500F is generally used in the area of electromagnetic compatibility (EMC) applications (e.g., common mode chokes [11]). However, it was included in the research due to its different internal structure compared to the other samples. In order to verify the correctness of the analyzed method, measurements were carried out first in the operating conditions of a DC/DC converter and then with sinusoidal excitation at the equivalent frequency $f_{\mathrm{eq(sin)}}$ in accordance with the assumptions resulting from (4), i.e., with the same H_{DC} and ΔB values. The Brockhaus MPG 200 measurement system was used to measure the magnetic losses of selected cores. The system accuracy is $\leq 0.2\%$ and concerns the measurement of power losses under sinusoidal excitation conditions. In order to obtain core operating conditions corresponding to operation in a DC/DC converter, the “Free Curves” option was used to generate a custom waveform shape of the magnetic flux density by the measuring device. The accuracy of the measurement system for this option is $\leq 1.5\%$. The base clock accuracy of the data acquisition card in the measurement system

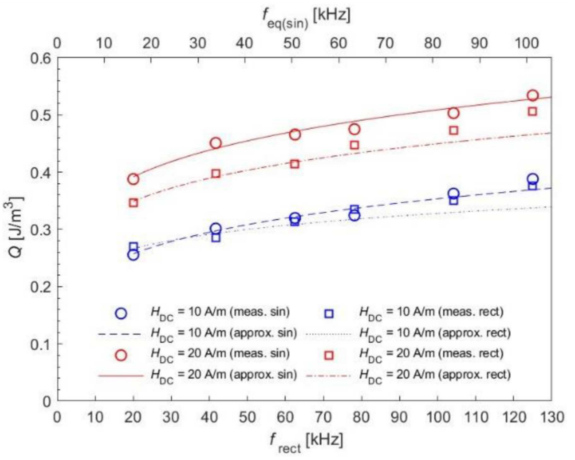

Fig. 1. Energy core losses versus frequency at $\Delta B = 0.1$ T.

is ±0.01%. An additional limitation during measurements is the maximum number of points from which the measurement system can generate a custom waveform. For the maximum frequency of the triangular signal during measurements (rectangular voltage waveform), the f_{rect} frequency is 125 kHz, and this waveform is generated from only 20 points. At the lowest excitation frequency, $f_{\text{rect}} = 10$ kHz, the waveform is generated from 100 points. The results are presented in the form of energy losses Q (per one complete sinewave cycle) related to the core volume, as presented in [6]. Since the accuracy of the measurement system is better with sinusoidal excitations, the energy loss measured for such excitations was taken as a reference point. Due to the fact that formula (3) can be transformed to determine the frequency in the conditions of a DC/DC converter based on the frequency of sinusoidal excitation, the following formula was proposed to assess the accuracy of the analyzed method

$$\delta_{\%} = \frac{\left|Q_{\text{rect}} - Q_{\text{eq(sin)}}\right|}{Q_{\text{eq(sin)}}} \cdot 100\%. \tag{5}$$

4. Results and discussion

Energy losses measured in core operating under conditions corresponding to a DC/DC converter (values indicated by the square marker) and under sinusoidal excitation conditions (at the equivalent frequency and maintaining the same H_{DC} and ΔB values — indicated by the round marker) are presented in the figures below. The curves (solid or dashed) presented in the figures approximate the results based on a power function. Measurements were carried out for two different values of the DC component of the magnetic field strength. In the figures, the lower horizontal axis indicates the frequency of the rectangular voltage excitation, while the upper horizontal axis indicates the corresponding value of the equivalent frequency of the sinusoidal excitation. The vertical axis indicates the energy lost according to the approach presented in [7].

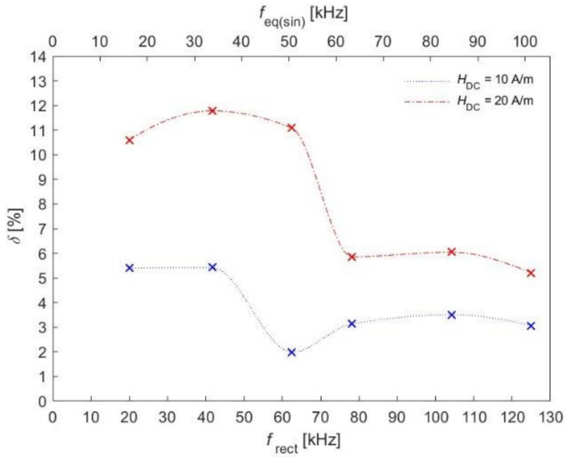

Fig. 2. Method deviation for N87 ferrite core at $\Delta B = 0.1$ T.

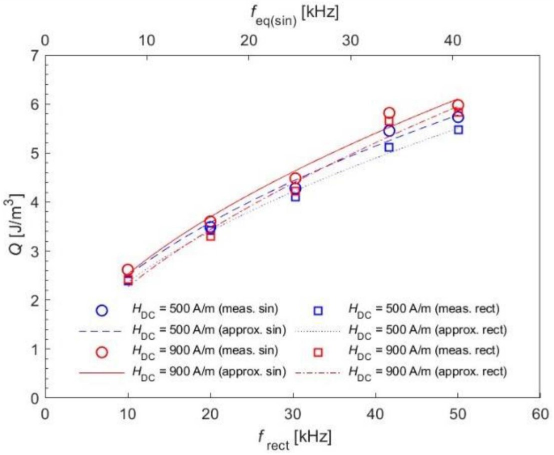

Fig. 3. Energy core losses versus frequency at ΔB = 0.2 T (MP-065205-2 powder core).

Figures 1 and 2 present the energy loss measurements and the method deviation for ferrite core N87.

As expected, the measured energy losses increased with magnetization frequency. Moreover, the energy loss level was also noticeably dependent on the value of the DC component of magnetic field strength. In the case of the N87 ferrite core, the method provided an acceptable convergence of the measured and calculated values of core losses (Fig. 2). It should also be noted that in the case of the ferrite core, the approximation deviations were about two times higher for the larger DC component of $H_{\text{DC}} = 20$ A/m.

The results obtained for the MP powder core are depicted in Figs. 3 and 4. Generally, the increase in energy losses in the function of frequency

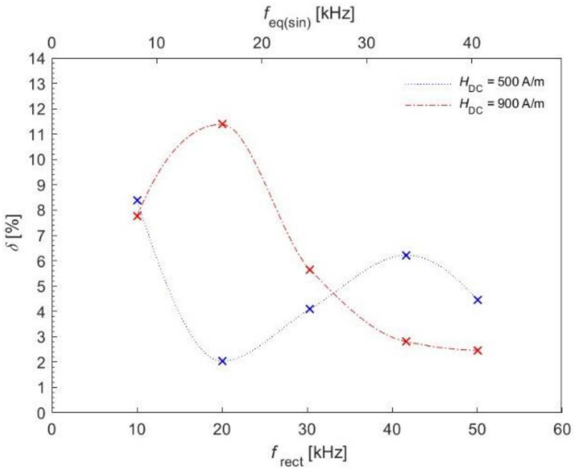

Fig. 4. Method deviation for MP-065205-2 powder core at $\Delta B = 0.2$ T.

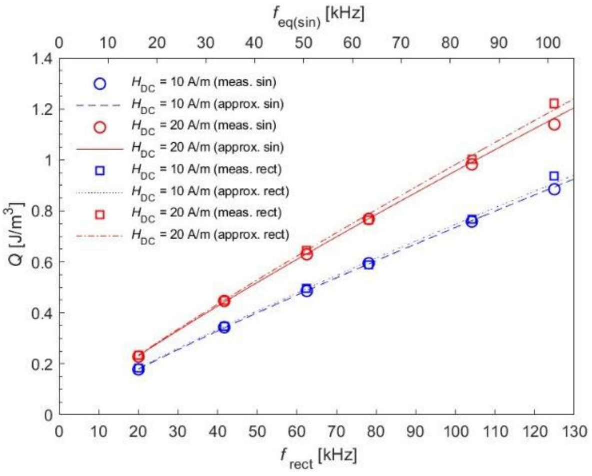

Fig. 5. Energy core losses versus frequency at $\Delta B = 0.2$ T (VITROPERM 500F nanocrystalline core).

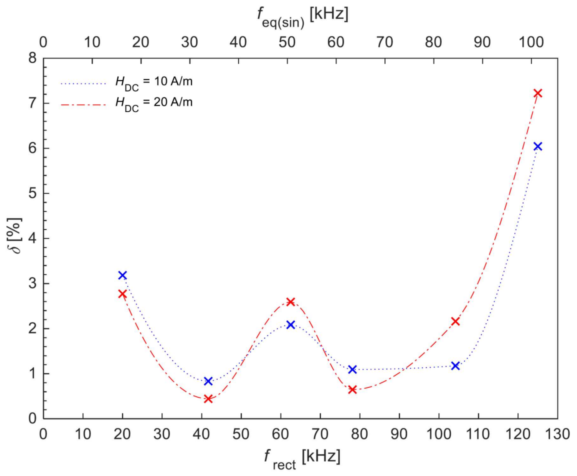

Fig. 6. Method deviation for VITROPERM 500F nanocrystalline core at $\Delta B = 0.2$ T.

is more dynamic than in the case of the N87 ferrite core. On the contrary to the ferrite core, only a very small increase in energy loss depending on the H_{DC} value was observed. This is a favorable feature of the MP powder core, especially for applications in DC/DC converters, because the losses are almost independent of the converter load current for a specific operating frequency. Due to the limitations of our measurement system, this core was measured in a lower frequency range (up to 50 kHz). As shown in Fig. 4, the method deviation does not exceed 12%.

Finally, Figs. 5 and 6 present the results for the last core made of VITROPERM 500F nanocrystalline material. Similarly to the other measured cores, energy losses strongly depended on the core magnetization frequency. For the nanocrystalline core, energy losses determined by the verified method provided small deviations in almost the entire frequency range, and the obtained deviation values indicated a weak dependence on the H_{DC} values.

5. Conclusions

In this paper, the method of estimating losses of inductor cores operating in the conditions of a DC/DC converter was presented. The analyzed method, based on losses measured at sinusoidal excitations, was verified for three different types of core material. Energy loss values provided by magnetic core manufacturers are usually determined for sinusoidal excitation conditions. Additionally, these losses are not obtained from measurements under DC bias conditions. For this reason, core losses cannot be easily estimated based directly on (3)–(4) without additional measurements. The verified method for loss estimation provided satisfactory results for the core made of nanocrystalline alloy. The maximum deviation of the loss estimation did not exceed 8%, and in a wide frequency range up to 110 kHz, the deviation was lower than 3.2%. For the constant component $H_{\mathrm{DC}} = 10$ A/m, the method gave similar deviation values for both the nanocrystalline and ferrite cores. Slightly larger deviations (for $H_{\mathrm{DC}} = 10$ A/m) occur for the powder core. However, for a higher value of the H_{DC} component, the method deviation in the case of the ferrite core increased noticeably in contrast to the nanocrystalline core. Due to the limitations of the measurement system, the frequency range for the MP powder core was limited (from 10 to 50 kHz). It is worth noting that in the original paper [7], the method for loss calculation was verified for another powder core (SK-08KSTB) for a frequency range limited to approximately 20 to 50 kHz. The results presented in this paper for the MP powder core are within acceptable limits appropriate for practical application.

Concluding, the analyzed method provided satisfactory results for calculating losses in the case of a symmetric triangular waveform of magnetic flux density in nanocrystalline (VITROPERM 500F) and ferrite (N87) inductor cores operating in DC/DC converters and acceptable results for nickel–iron–molybdenum alloy powder material (MP) in limited frequency range. Verification of the correctness of the analyzed method for other magnetic materials in extended frequency ranges, magnetic flux density, and duty cycle will be the subject of further research that would allow us to determine the limits of its applicability.

Acknowledgments

The project was financed under the program of the Polish Minister of Science and Higher Education under the name "Regional Initiative of Excellence" in the years 2019–2023, project number 020/RID/2018/19, the amount of financing PLN 12 000 000.

References

[1] D. Reusch, J. Strydom, J. Glaser, in: *2015 IEEE Energy Conversion Congress and Exposition (ECCE), Montreal*, IEEE, 2015 p. 381.

[2] D. Rodriguez-Sotelo, M. A. Rodriguez-Licea, A. G. Soriano-Sanchez, A. Espinosa-Calderon, F. J. Perez-Pinal, *IEEE Access* **8**, 56238 (2020).

[3] J. Mühlethaler, J. Biela, J.W. Kolar, A. Ecklebe, *IEEE Trans. Power Electron.* **27**, 953 (2012).

[4] A. Brockmeyer, in: *Proc. of Applied Power Electronics Conf. (APEC '96), San Jose*, IEEE, 1996, p. 454.

[5] D. Gzieł, M. Najgebauer, *Przegląd Elektrotechniczny* **96**, 238 (2020).

[6] M. Albach, T. Duerbaum, A. Brockmeyer, in: *PESC Record. 27th Annual IEEE Power Electronics Specialists Conf., Baveno (Italy)*, IEEE, 1996 p. 1463.

[7] H. Matsumori, T. Shimizu, T. Kosaka, N. Matsui, *AIP Adv.* **10**, 045001 (2020).

[8] K. Venkatachalam, C. R. Sullivan, T. Abdallah, H. Tacca, in: *2002 IEEE Workshop on Computers in Power Electronics, 2002. Proc., Mayaguez (PR)*, IEEE, 2002, p. 36.

[9] TDK, Ferrites and Accessories, 2023.

[10] Micrometals, MP-065205-2, 2021.

[11] Vacuumschmelze, Nanocrystalline Vitroperm EMC Products, 2021.

[12] A. Ayachit, M.K. Kazimierczuk, *IET Circuits Devices Syst.* **11**, 209 (2017).

[13] D. Gzieł, A. Jąderko, *Przegląd Elektrotechniczny* **99**, 292 (2023).

[14] A. Ayachit, M.K. Kazimierczuk, *IEEE Magn. Lett.* **7**, 1 (2016).

[15] Y. Miwa, T. Shimizu, K. Takano, H. Ishii, *IEEJ J. Ind. Appl.* **8**, 57 (2019).