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doi:10.15199/48.2015.04.13

Core Loss Measurement at High Frequencies

***Abstract**. The author presents the measurement of core loss in ferrite samples at frequencies between 500 kHz and 10 MHz. The measurement uncertainties are determined, and critical parts of the applied methodology are discussed as they significantly affect the achievable repeatability and accuracy. The actual test was based on various types of ferrite material for power applications in switching sources; at frequencies up to 10 MHz, however, NiZn material was used.*

Streszczenie.** Autor przedstawił w pracy pomiary strat w rdzeniach dla próbek ferrytowych dla częstotliwości w zakresie od 500 kHz do 10 MHz. Określono niepewności pomiarowe a także przedyskutowano krytyczne punkty zastosowanej metodologii, ponieważ mogą one znacząco wpływać na osiąganą powtarzalność i dokładność pomiarów. W testach zbadano różne typy materiałów ferrytowych stosowanych w źródłach przełączających w zastosowaniach energetycznych, jednakże dla częstotliwości do 10 MHz zbadano materiał NiZn. **Pomiary strat w rdzeniach dla próbek ferrytowych dla częstotliwości w zakresie od 500 kHz do 10 MHz

Keywords: Ferrite, Core Loss measurement, NiZn, MgZn.
Słowa kluczowe: ferryty, pomiary strat w rdzeniu, NiZn, MgZn.

Introduction

The knowledge of core loss in power ferrites is a necessary precondition for the correct optimization of any switching source design. The measurement of core loss at common frequencies up to 500 kHz is usually performed using a V-A-W power analyzer. However, the high accuracy of such devices is defined for resistance load measurement with cos ϕ=1. A ferrite core constitutes a load whose character is predominantly inductive; thus, while observing the manufacturer-provided data, we need to consider the uncertainty of the phase shift between the voltage and the current as another source of uncertainty B. At frequencies over 500 kHz, the relative total uncertainty of measurement with commonly available V-A-W power analyzers therefore may exceed 40%. For this reason, the author of this paper discusses measurement utilizing a high-frequency coaxial shunt and a common oscilloscope.

Technical description

The elementary prerequisite facilitating the comparability of results obtained from core loss measurement consists in excitation via harmonic waveform of magnetic flux density B [1]. For relatively low excitation levels B, the behavior of the magnetic field strength H in the measured sample can be also regarded as approximately harmonic. Conventional measurements are mostly performed on normalized toroidal cores; however, the condition $d_{MAX}/d_{MIN}<0.8$ is often not satisfied [2]. Whenever the aim is to determine the loss in the specially shaped ferrite core used in a switching source, we can perform the measurement directly on such core, albeit at a lower accuracy. The measurement can be carried out with either one or two windings, and – at higher frequencies - the number of threads is a compromise between homogeneous distribution of the magnetic flux Φ in the core and the core's windings own resonant frequency. A diagram showing two windings is presented in Fig. 1.

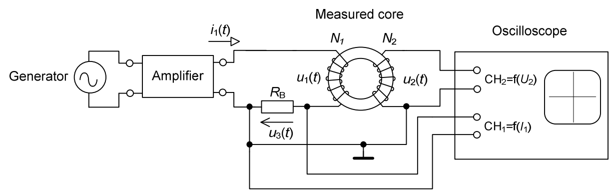

Fig.1. Core loss measurement with two windings

The measuring technique is applicable also for non-harmonic waveforms of the voltages $u_2(t)$ and $i_1(t)$, and the resulting core loss is then given by the formula

$$P=\frac{N_1}{N_2}\cdot\frac{1}{T}\int_0^T u_2(t)\cdot i_1(t)\,\mathrm{d}t=\frac{1}{R_\mathrm{B}}\frac{N_1}{N_2}\cdot\frac{1}{T}\int_0^T u_2(t)\cdot u_3(t)\,\mathrm{d}t \tag{1}$$

where: P – core loss, R_B – shunt resistance, N_1 – number of primary windings, N_2 – number of secondary windings, T – signal period.

The multiplication can be performed with a PC, using the sampled data. The shunt must be non-inductive and coaxial, with its connection to the measuring oscilloscope impedance matched at 50 Ω. The voltage on the winding N_2 is then measured by means of an oscilloscope probe having a low input capacity.

In calculating the uncertainties of the B-type measurements, we can also employ (for small excitations) the assumption of the harmonic waveform of u_2(t) and i_1(t). Then, for the core losses, there holds

$$P=\frac{N_1}{N_2}\cdot U_\mathrm{2ef}\cdot I_\mathrm{1ef}\cdot\cos(\varphi_\mathrm{u\text{-}i})=\frac{1}{R_\mathrm{B}}\cdot\frac{N_1}{N_2}\cdot U_\mathrm{2ef}\cdot U_\mathrm{3ef}\cdot\cos(\varphi_\mathrm{u\text{-}i}) \tag{2}$$

where: $\phi_{u\text{-}i}$ – phase shift between voltage and current.

Through application of uncertainty theory, the above formula (2) is partially differentiated, and the standard B-type uncertainty of the core loss is given as

$$\begin{aligned} u_{\mathrm{B}P}=&\sqrt{\left(\frac{1}{R_\mathrm{B}}\cdot\frac{N_1}{N_2}\cdot U_\mathrm{3ef}\cdot\cos(\varphi_\mathrm{u\text{-}i})\cdot u_{\mathrm{B}U_\mathrm{2ef}}\right)^2+\left(\frac{1}{R_\mathrm{B}}\cdot\frac{N_1}{N_2}\cdot U_\mathrm{2ef}\cdot\cos(\varphi_\mathrm{u\text{-}i})\cdot u_{\mathrm{B}U_\mathrm{3ef}}\right)^2+}\\ &\sqrt{\left(\frac{1}{{R_\mathrm{B}}^2}\cdot\frac{N_1}{N_2}\cdot U_\mathrm{2ef}\cdot U_\mathrm{3ef}\cdot\cos(\varphi_\mathrm{u\text{-}i})u_{\mathrm{B}R_\mathrm{B}}\right)^2+\left(-\frac{1}{R_\mathrm{B}}\cdot\frac{N_1}{N_2}\cdot U_\mathrm{2ef}\cdot U_\mathrm{3ef}\cdot\sin(\varphi_\mathrm{u\text{-}i})u_{\mathrm{B}\varphi_\mathrm{u\text{-}i}}\right)^2}\end{aligned} \tag{3}$$

where: U_{BP} – uncertainty B Core Loss P, U_{BU2ef} – uncertainty B U_{2ef}, U_{BU3ef} – uncertainty B U_{3ef}, U_{BRB} – uncertainty B U_{RB}, $U_{B\phi\ u\text{-}i}$ – uncertainty B $U_{\phi\ u\text{-}i}$

In formula (3), however, we consider only the uncertainties of determining the amplitude of the measured voltages $u_3(t)$ and $u_2(t)$, their mutual phase shift, and the shunt resistance values R_B. In a measurement under real conditions, we should also include the sensitivity coefficients affecting the uncertainties of the magnetic flux density B_{max} setting and the core temperature setting. While quadratic dependence of the core loss on the magnetic flux density can be considered in small and medium-sized excitations, temperature dependence differs from material to material, and the measurement of multiple auxiliary values is required to determine the sensitivity coefficient of the temperature setting uncertainty. Thus, for quick comparison of the samples, it appears convenient to measure the core loss at the switch point (namely between 90 °C and 140 °C in common cores [2]): here, the self-heating of the core will exhibit the smallest influence on the repeatability of the measurement. The highest effect of the voltage – current phase shift uncertainty will occur if the material is within its optimal application frequency band and the case of small excitations; the phase shift will then approach 90°, and any uncertainty will markedly influence the total core loss result. It is therefore advisable to use an oscilloscope with a bandwidth no less than a 100 times higher than the measured frequency, and an identical electrical length of the current and voltage channels should be ensured.

Measurement

The measured core loss was compared with two windings and one winding. The differences were smaller than 2 %, so in the next measurements was used only one winding. The new measured diagram is in Fig. 2. The Coaxial Shunt added additional phase shift. Its value was measured in vectorvoltmeter BM553 and it is 0,4 ° in frequency 10 MHz. The oscilloscope bandwidth is 500 MHz. The measured ferrite core was in the transformer oil, for the define temperature and restriction self-heating. It was selected two representative materials, 3F3 as MgZn ferrite for switching sources application and 4C65 as NiZn ferrite used in EMI filter. The measured cores have four threads.

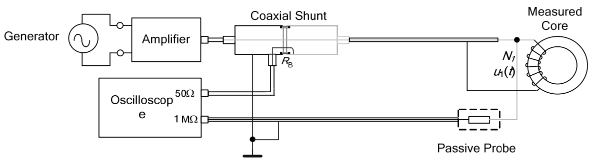

Fig.2. The measured configuration

In the Fig. 3, the dependence of core loss for the 3F3 ferrite material on magnetic flux density B in frequency 500 kHz and temperature 100 °C, where is switch point. In this frequency is phase shift between voltage and current 70° to 89°. The uncertainties of the B-type is 19 % to 4 % in interval B_{max}=1 mT...70 mT.

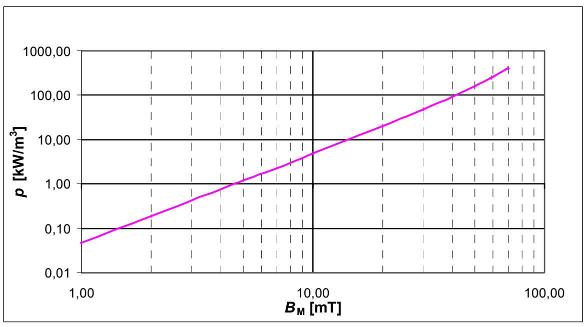

Fig.3. The measured configuration

In the frequency 1 MHz is phase shift between voltage and current 47° to 80° because the material 3F3 is already out of its optimal frequency range. The uncertainties of the B-type is average 3,5 % in interval B_{max}=1 mT...40 mT. So if we measure the ferrite material is in the frequency limit its application, the accuracy measurement is better. The result is in the Fig. 4.

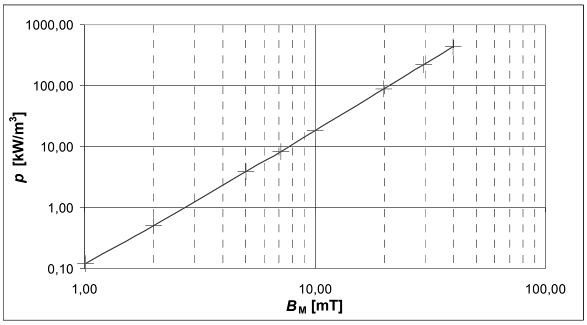

Fig. 4: Core loss material 3F3 in frequency 1 MHz

The material 4C65 was measured in frequency range 6 MHz to 10 MHz. In interval B_{max}=0,01 mT...1 mT is phase shift between voltage and current relative constant 70 °. So the uncertainties of the B-type are smaller than ferrite material 3F3. The result is in the Fig. 5. The uncertainties of the B-type are average 5 %. This is caused higher lossed in NiZn ferrite, but this material is applicable to 30 MHz.

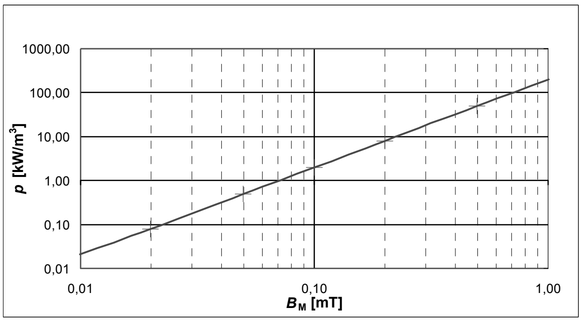

Fig. 5: Core loss material 4C65 in frequency 10 MHz

Conclusion

The paper identifies the most important uncertainties in determining core loss at high frequencies; also, core loss results for the measured materials are specified together with the measurement uncertainties. If we won't decrease uncertainties of the B-type, is it possible using capacitor for setting serial resonance with measured core.

Acknowledgement

The research described in the paper was financially supported by Education for Competitiveness Operative Programme, nos. CZ.1.07.2.3.00.20.0175.

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