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A Comparison of Measurement Procedures for Soft-Magnetic Wound Core Characterisation

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Abstract. The paper describes key features and shows some advantages and disadvantages of two measurement approaches used in determination of magnetic properties of soft-magnetic wound cores. The first approach is based on a measuring principle in which the current through the primary winding determines the sinusoidal magnetic flux density in the core and consequently also the sinusoidal induced voltage in the secondary winding. The second approach is a variation of the impedance method with which complex relative permeability is measured. In it, the controlled variable is the magnetizing current. In the first approach, the custom-made measurement equipment is normally used. The second approach relies on a wide variety of commercially available impedance meters.

Key words: soft-magnetic material, magnetic flux density, magnetic field strength, complex impedance

1 INTRODUCTION

In the production process, the final product quality control is a key indicator of adequacy of several previous operations, this being either appropriate selection of materials or proper material processing technology, etc. At the same time, the final control is also an important common link between manufacturers and buyers who also test the manufactured products. In the so called input quality control, the buyer controls the manufacturer or his compliance with previously agreed criteria. To allow for a correct comparison of measurement results, both sides have to use the same measurement criteria. A comparison of measurement results is acceptable when measurement procedures are carried out in accordance with applicable standards and regulations for a given test area. In this paper, basic requirements imposed on measuring magnetic properties of soft-magnetic wound cores will be given when using two approaches defined in the international standard IEC 404-2 and in the standard ASTM A772/A772M - 00 (2005). The first standard foresees that the measurement procedure is made with sinusoidal magnetic flux density *B* in the tested core. In the second one, the required sinusoid
al quantity is magnetic field strength *H*.

2 THEORETICAL BACKGROUND

Magnetic properties of soft-magnetic wound cores are usually assessed by using the so-called transformer method in which the tested core is equipped with two windings (Fig. 1). With the primary winding with NP turns, an appropriate magnetic field is established in the tested core. The secondary winding with NS turns is used to measure the voltage induced by changes in the magnetic field. Magnetic field strength H induced in the core by the primary current is:

$$H(t) = i_P(t) \cdot N_P / l_{FE} \ , \qquad (1)$$

where lFE is the mean length of the magnetic field path. For a toroidal core with a rectangular cross-sectional area the magnetic field length is:

$$l_{FE} = 2\pi \cdot \frac{\frac{d_z - d_n}{2}}{\ln\left(\frac{d_z}{d_n}\right)} \ . \qquad (2)$$

In equation (2), d_z and d_n denote the outer and inner diameter of the core. On the secondary side, voltage u_S is induced as a result of the changing magnetic flux density *B*:

$$u_S(t) = -N_S \cdot S_{FE} \cdot dB/dt \ , \qquad (3)$$

where S_{FE} is the cross-sectional area of the core.

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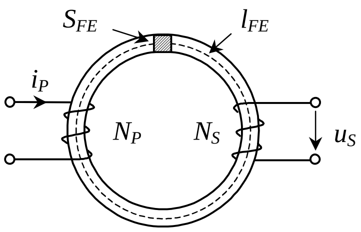

Figure 1. Toroidal core with a primary and secondary coil.

3 Measurement scheme

3.1 Sinusoidal magnetic flux density

When using this measurement approach, the tested core (DUT) is magnetized with a current through the primary winding making the magnetic flux density and consequently the induced voltage on the secondary winding to be sinusoidal. According to the standard IEC404-2, this is achieved when the form factor of the induced voltage deviates from the form factor of the pure sinusoidal waveform (1.11) by less than 1% [1]. The easiest way to meet this condition is to introduce a negative feedback loop in the control circuit [2], as illustrated in the simplified scheme in Fig. 2. At the input of the power amplifier, a reference value of secondary induced voltage u_{S_REF} is present. Taking into account the required sinusoidal voltage and after modifying term (3), one can see that the RMS value of the induced voltage is proportional to the peak value of the magnetic flux density:

$$U_{S\_REF} = 4{,}44 \cdot \hat{B} \cdot f \cdot S_{FE} \cdot N_S \,, \tag{4}$$

where f is the frequency of the induced voltage. The advantage of this control approach is obvious. Namely, to detect the two basic magnetic quantities in a fast and simple way, it is sufficient to measure only the RMS values of the primary current and the secondary voltage. With the first measurement, which takes into account expression (1), the RMS value of the magnetic field strength H is obtained. With the second measurement, the magnetic flux density (peak value!) in the core for given magnetic field strength H caused by the primary current I_P is calculated (4).

When there is more data needed to control the core quality (e.g. relative permeability, specific losses, residual magnetic flux density, coercitive magnetic field strength, graphical representation of results, etc.), the measurement approach needs to be to some extend more complex. The solution is in using a microcontroller system which besides calculating the reference value of the secondary induced voltage and performing measurements of the primary current and the secondary voltage also calculates other magnetic parameters of the tested core. To allow for a more user-friendly measurement procedure, the measurement system should be connected to a supervising PC with a custom-built user interface (Fig. 3, more in [2, 4].

Such measurement system is of course a strictly targeted system, designed according to customer needs and requirements and, of course, subject to standards imposed on magnetic measurements. Unfortunately, due to the specific nature of measurements of magnetic properties and the small number of potential users (mostly just core manufacturers and their buyers), there are only a few solutions from established providers of electronic measuring equipment available on the market nowadays. This is consequently reflected also in the purchase price of the (usually unique) measuring system.

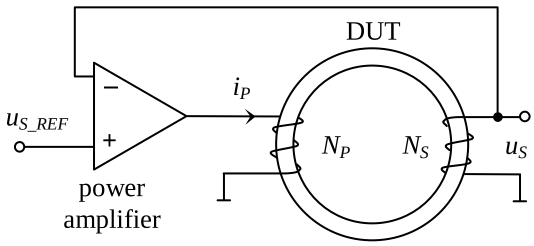

Figure 2. Measurement principle with a negative feedback voltage control loop.

3.2 Impedance method with a sinusoidal current source

The majority of systems measuring magnetic properties are based on the principle, presented in the previous section, i.e. with a current through the primary winding the core is magnetized in a way causing a sinusoidal induced voltage in the secondary winding. This considerably simplifies the calculation of the basic two magnetic parameters (H, B). Besides knowing the parameters of the tested core (mechanical dimensions, filling factor), only the RMS values of the primary current and the secondary voltage should be measured. Much less known is the principle where the core is magnetized with a sinusoidal primary current in which the voltage in the secondary winding is not (always) sinusoidal. The disadvantage of this approach is obvious since the calculation of the two basic magnetic quantities is more demanding, at least when calculating magnetic flux density B. Instead of the simplified expression (4), only the basic relationship between the induced voltage and the magnetic flux density (3) can be used. When using the first approach, the basic magnetic properties (magnetic field strength and magnetic flux density) can be determined with no microcontroller support, which is not the case when

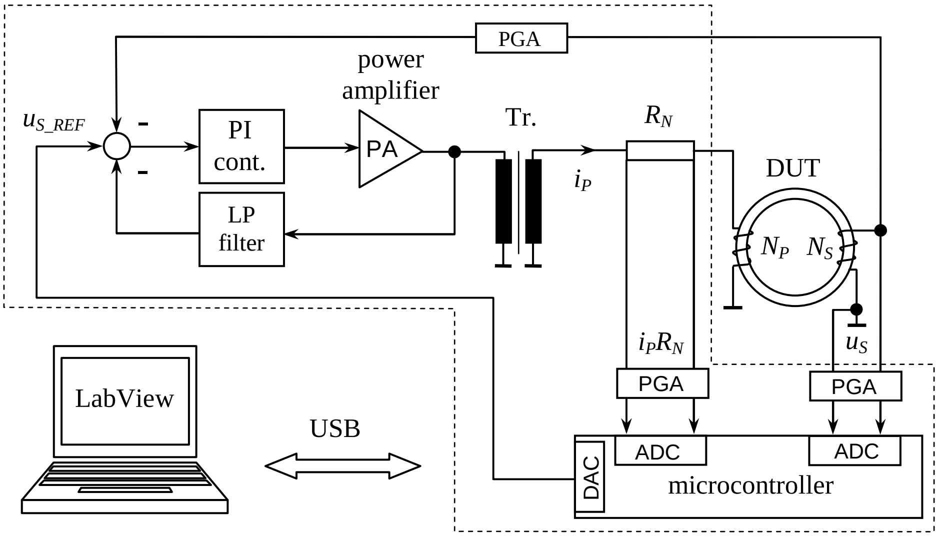

Figure 3. Block diagram of a measurement system.

using the second approach. However, with some restrictions, it is still possible to perform measurements of the magnetic properties sufficiently well even without using a microcontroller or complex calculations and therefore still using a simplified relationship to calculate the magnetic flux density.

The measuring principle based on a standardized procedure for measuring ac or complex permeability using the sinusoidal excitation current [2] will be described below. The principle can be used to measure permeability in the range from the very low to medium magnetic flux densities, where the material starts to exhibit magnetic saturation. The numerical results of relative permeability obtained by using this method are slightly lower compared to results when the core is exposed to a sinusoidal magnetic flux density. However, the second method is far superior in terms of accessibility of the measuring equipment. Namely, for this purpose, a variety of commercially available impedance meters can be used. Another benefit is also a more simple integration of DUT into the measuring circuit, since the measuring principle is based only on one winding (Fig. 4). In this way, the tested core with a single winding is actually treated as a coil with an iron core. While forcing a sinusoidal current (50 Hz) through the winding, the complex impedance of the coil is measured.

To achieve an appropriate density of the magnetic flux in the core, a relatively large magnetizing current is needed. Its value depends on the number of the primary turns and the core size, as seen from (1). Here, a compromise between the number of winding turns and the required current should be made. For a simple integration of DUT into the circuit, a small number of winding turns is desirable. This results in a higher magnetizing current (often in excess of several amps) which the majority of impedance meters are not capable to deliver. As a consequence, the number of winding turns should be chosen according to the impedance meter output current capability.

When measuring the complex impedance of the winding, the winding resistance measured at DC excitation should be subtracted from the result. In the next step, a corrected value of complex impedance Z_{corr} is obtained:

$$Z_{corr} = R_S + jX_S \,, \tag{5}$$

or written in the phase angle (φ) notation:

$$Z_{corr} = \left|Z_{corr}\right| \cdot e^{j\varphi} \,. \tag{6}$$

Having the data of the corrected complex impedance and phase angle, we can now calculate the absolute value of complex permeability μ_r and its components ($\mu_S^{'}$ and $\mu_S^{''}$) – all notations are valid for a serial equivalent circuit [6]:

$$\left|\mu_r\right| = \sqrt{\mu_S^{'2} + \mu_S^{''2}} \,, \tag{7}$$

$$\mu_S^{'} = \frac{L_S}{\mu_0 N_P^2 \dfrac{S_{FE}}{l_{FE}}} \,, \tag{8}$$

$$\mu_S^{''} = \frac{R_S}{\omega \mu_0 N_P^2 \dfrac{S_{FE}}{l_{FE}}} \,. \tag{9}$$

Since the magnetizing current used to magnetize the core was sinusoidal, the magnetic flux density in the core is also sinusoidal or nearly sinusoidal at least in the lower magnetization range where the material is far from being magnetically saturated. This permits us to use expression (4) to calculate magnetic flux density B in a similar way as in the previous section.

If the RMS value of the magnetizing current and the corrected value of the complex impedance are known, then it is possible to calculate voltage U:

$$U = \left| Z_{corr} \right| \cdot I \,, \tag{10}$$

which is then used to calculate the peak value of magnetic flux density B in the core.

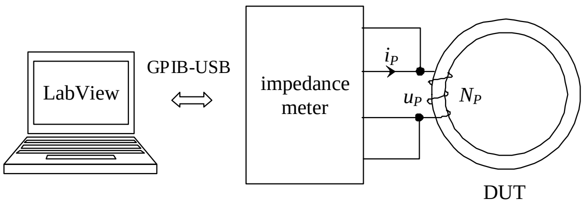

Figure 4. Measurement scheme using an impedance meter.

After rearrangement of (4), one can calculate the peak value of the magnetic flux density in the core:

$$\hat{B} = \frac{U}{4{,}44 \cdot f \cdot S_{FE} \cdot N_P} \,. \tag{11}$$

With the complex impedance, also apparent- and active-power losses can be determined:

$$S = I^2 \cdot \left| Z_{corr} \right| , \tag{12}$$

$$P = I^2 \cdot \left| Z_{corr} \right| \cdot \cos\varphi \,. \tag{13}$$

4 EXPERIMENTAL RESULTS

The presented method for characterization of soft-magnetic wound cores was evaluated by using an impedance meter (Precision Magnetics Analyser, Wayne Kerr 3260B, [7]) equipped with a GPIB-USB interface. With the latter allowed for an automated measurement procedure using the LabView application software on the supervising PC.

Before starting the measurements, the tested core was demagnetized in order to eliminate the impact of any previous magnetization or incorrectly performed measurement. This was made with a special routine that gradually decreased the output current (at a frequency of 50 Hz) of the impedance meter from the preset value (calculated using (1) according to the expected value of the maximum magnetic field strength) down to zero. The demagnetization routine completed, a complex impedance measurement started while gradually increasing the magnetizing current up to the value that corresponds to the magnetic field strength of H = 30 A/m. All calculations and graphical presentation of measurement results were carried out in the user interface (LabView) on a PC.

A critical evaluation of the impedance method was then performed by comparising the measurement results with the results obtained with the measurement procedure explained in Section 3.1, which is based on a sinusoidal secondary induced voltage (laboratory instrument MDK [2, 4]). Though the tested core is exposed to completely different states when using the impedance method, the controlled quantity is the (magnetizing) current and not the induced (secondary) voltage; the measuring results at least in the lower part of the magnetizing curve practically coincide with those obtained using the MDK instrument.

In the part below, we present results of comparative measurements of a toroidal wound core type 60/50/30 (external and internal diameter and height of the core in mm) with a filling factor of 0.95. The measurements were performed with N_P = 35 turns and the winding resistance of R_{DC} = 74 mΩ. The number of primary turns was chosen based on the maximum output current of the impedance meter (200 mA) and the estimated magnetic field strength at a density of 1.6 T, which for the used core material is some 30 A/m.

In Fig. 5, calculated magnetic flux density B using the impedance method (index WK) versus the magnetic field strength (for the magnetizing current from 0 to 140 mA) is given. The same figure also shows the curve with measurement results obtained with the MDK instrument. As seen, the measurement results are practically identical in the lower part of the magnetizing curve, i.e. up to the value of the magnetic field strength of some H = 15 A/m. From that point on, the measurement results start to differ, since the material is approaching magnetic saturation. Although the core is magnetized with a sinusoidal current, the measured voltage is no longer sinusoidal (the meter actually measures the RMS voltage at a given current and then calculates and displays the value of the complex impedance!). Of course, from here on the basic assumption that justifies such measurement of magnetic properties is no longer fulfilled and all the calculations are wrong.

In Fig. 6 and 7, the calculated results for specific power dissipation (W/kg or VA/kg) for different levels of core magnetization are given. Like in Fig. 5, results for the two measurement methods are displayed (indices WK and MDK). From these two figures, too, one can see that the calculated results for specific power dissipation in the lower part of the magnetizing curve are completely identical for both measuring procedures.

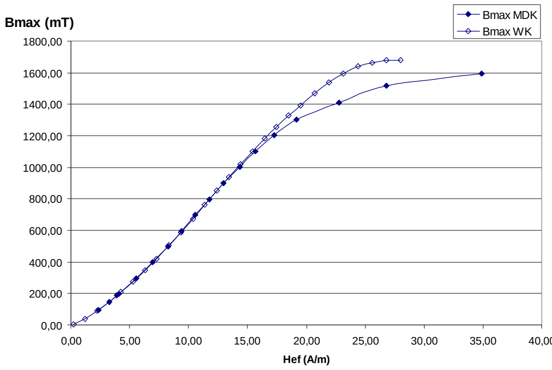

Figure 5. Magnetic flux density vs. magnetic field strength.

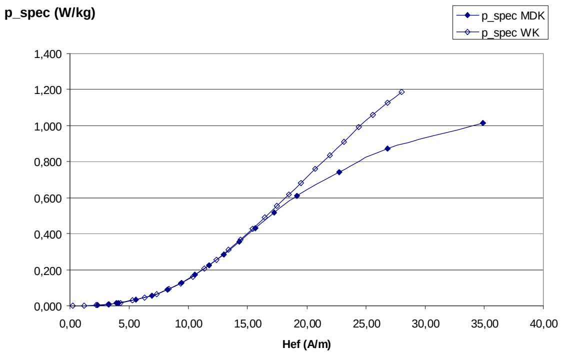

Figure 6. Specific losses (active power) vs. magnetic field strength.

The impedance measurement can thus be implemented even when more demanding measurements of the magnetic properties of cores are required, but in a limited area, only in the lower part of the material magnetizing curve. Of course, the key question here is up to which value of the magnetic field strength can the thus obtained measurement results be trusted. This particularly applies to cases with no measurement system enabling a comparative measurement or the instrument available, indicating that the material is already in the magnetically saturated. Based on the analysis of several types of wound cores, a good indicator of the useful measuring range of the method is the complex impedance itself. Its graphical representation as a function of the magnetization current or magnetic field strength (Fig. 8) always has a relatively distinct maximum. With the maximum of the complex impedance we therefore get the upper limit of the magnetic field strength to which we can trust the measurement results – the same applies also to the basic principle of a complex permeability measurement [2]. The calculated results of complex permeability and of its two components as a function of the magnetic field strength are given in Fig. 9. Again, a relatively distinct maximum of complex permeability appears at the magnetic field strengths that are the same as in the case of the complex impedance depicted in Fig. 8.

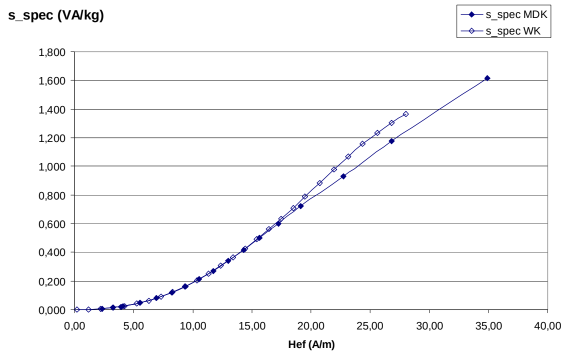

Figure 7. Specific apparent-power losses vs. magnetic field strength.

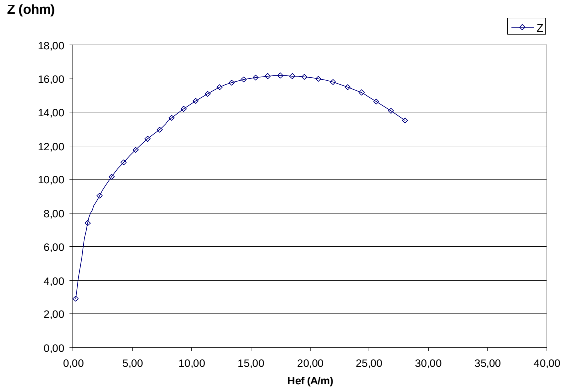

Figure 8. Complex impedance vs. magnetic field strength.

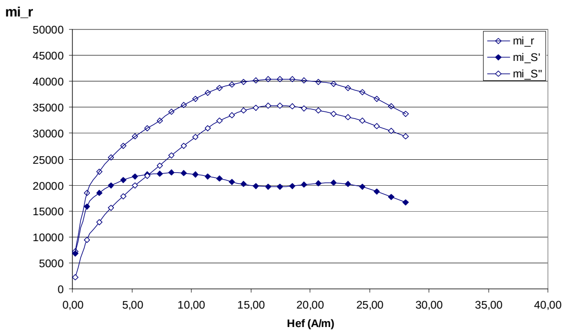

Figure 9. Complex permeability and their components vs. magnetic field strength.

5 Conclusion

The paper presents and compares two approaches to measuring magnetic properties of soft-magnetic wound cores. The purpose of having them compared is mostly to find out whether it is possible to conduct a more sophisticated measurement of the magnetic properties with commercially available measurement equipment and whether such results are comparable with results of standardized measurement procedures.

The basic advantage of the first approach is by all means the sinusoidal secondary induced voltage enabling a considerable simplification of the calculation of the magnetic flux density in the core for a given degree of magnetization. In principle, the data about magnetic field strength H and magnetic flux density B can be obtained indirectly by measuring the RMS values of the primary current and the secondary voltage (i.e. already with two RMS instruments). We find the major disadvantage to be a relatively complex power stage delivering an adequate magnetizing current, since the control scheme must contain a negative feedback loop of the induced voltage. When measuring magnetic properties of toroidal cores, a particular attention should be paid to integration of the core in the test circuit. Taking into account the shape of the core, which is very unpractical for being mounted in the measuring windings, it is clear desirable that the number of primary and secondary turns should be kept as low as possible. This in turn implies that the power stage must provide a relatively large (primary) current. And of course, with a small number of secondary turns, the induced voltage in the secondary winding is relatively small, too. These characteristics of the measurement approach therefore require the use of a custom-built microcontroller measuring system, which usually includes a supervisory computer with an appropriate user interface for setting up the required measurement conditions, graphical representation of measurement results and their printing and archiving.

With the second approach (sinusoidal magnetizing current), the power stage is in principle more simple, for being sufficient to use an appropriate (current capacity!) sinusoidal current source. The approach is in principle intended to be used to measure complex permeability. However, in this paper we wanted to show how such procedure can be used for a more comprehensive analysis of magnetic properties. The measurement procedure in this case is based on measuring the complex impedance of the coil when placed on the core to be tested. Based on the measured complex impedance, we can then calculate the magnetic flux density for a given magnetic field strength. But such calculation is of course justified and correct only at sinusoidal (induced) voltage being the result of a sinusoidal magnetic flux density in the core! As discussed above, the magnetic flux density in this procedure is not controlled, since we control the magnetizing current. Nevertheless, our comparative analysis of the obtained measurement results of both measurement approaches shows that using the impedance method in the lower part of the material magnetizing curve is fully reasonable. The upper limit of the usable area of the method is determined by the magnetic field strength at which the complex impedance reaches its maximum. Despite some notable advantages of the presented impedance method, we can not ignore the fact that the measurement approach does not fully comply with the standard, and because of some simplification, it can therefore not be used in the final quality control of products, but only as a tool for rapid monitoring during the production process.

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