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Comparison of power loss measurements in grain-oriented steels

***Abstract**. The paper presents recent achievements in the accurate measurements of power losses in soft magnetic materials. Intercomparison and validation have been developed on the basis of measured power losses in the grain-oriented Fe-Si electrical steel in the Epstein frame. The measurements were performed in the laboratories of PTB, Stalprodukt S.A. and Lodz University of Technology. The uncertainty evaluation of the developed unbalanced bridge method has been presented.*

***Streszczenie.** W artykule przedstawiono wyniki pomiarów strat mocy w materiałach magnetycznych wykorzystując wybrane, współczesne techniki pomiarowe i systemy do pomiaru stratności. Badania stratności blachy elektrotechnicznej, orientowanej zestawiono jako porównanie wyników pomiarów wykonanych w laboratoriach PTB, Stalprodukt S.A. oraz Politechniki Łódzkiej. W pracy przedstawiono również oszacowanie niepewności wyników pomiarów wykonanych w układzie pomiarowym opartym o metodę mostka niezrównoważonego. (**Porównanie pomiarów strat mocy w blachach elektrotechnicznych anizotropowych**)*

Keywords: specific power loss measurement, power losses, unbalanced bridge method, power transducer
Słowa kluczowe: pomiar stratności, magnetyczne straty mocy, mostkowa metoda pomiaru stratności, niezrównoważony mostek pomiarowy, przetwornik mocy

Introduction

Specific power loss and saturation of magnetic polarization are the most commonly controlled magnetic parameters of electrical steels. Both magnetic parameters are relevant in the scientific, production and application evaluation. The best performance is achieved only for raw or semi-finished materials which are available as a sheets or tapes.In this case, the parameters can be specified as material ones. Further processing and assembling of magnetic cores significantly change their magnetic properties. Typically, deterioration of magnetic properties is associated with higher specific power loss value or lower saturation polarization.[1,2]. These parameters can be considered as performance parameters relating to the specific application. A wide-ranging discussion of the influence of magnetic cores manufacturing technology on their final magnetic parameters has been presented in papers [2-5].The discrepancies in the material and performance parameters are not solely dependent on technological processes which are the first and principal source of their changes [6]. The latter source of the aforementioned discrepancies are measurement methods and systems that allow to determine the specific power loss P_s and its dependence on polarization, field strength or frequency[6,7]. The wattmeter method with the Epstein test frame or toroidal sample is recommended in the standards as the basic method of measurement of P_S or $E_{TOT}=P_S/f$ [8,9].Distinct approach to the measurement of the material parameters enables single sheet tester method[10]. Performance parameters and characteristics can be measured using the same wattmeter method which, has multifold technical limitations like frequency range of magnetizing field, maximum field strength and required shape of magnetic flux or magnetizing current in the tested magnetic sample [6,11]. Sinusoidal shape of the magnetic polarization waveform is the one of the widely discussed factors that have a significant impact on the measurement results [6,12-14]. It is recommended to perform tests if the shape of magnetic polarization waveform in the sample or magnetizing current in the excitation coil is sinusoidal and the Form Factor *FF* does not differ by more than 1%.Control and measurement of the shape by analysis of Crest Factor (CF), Form Factor or Total Harmonic Distortion (THD) signal parameters are relatively simple and precise only for the tests within a limited magnetizing frequency range and below the strong magnetic saturation. All other cases lead to significant discrepancies in the material and performance magnetic parameters. Thus, it is not possible to clearly indicate what part of the changes in the values of the considered parameters corresponds to technological sources and metrological ones [15].

Alternative measurement methods and measurement systems allow to increase the accuracy of measurements of magnetic and performance magnetic parameters in certain cases [16,17,18].

Alternative measurement methods of power losses

The recommended wattmeter technique uses an indirect or direct measurement method of active power in the magnetizing winding. Besides, there are methods based on:

- Poynting vector (hysteresisgraph method) [6,19],
- Unbalanced bridge method (UBM) [20],
- Calorimetric method under adiabatic conditions [6,18].

Both the hysteresis graph and the calorimetric methods do not provide possibility of direct measurement of power losses and eliminate power component associated with the resistance of magnetizing winding. This is crucial for the power losses measurement of small cores, magnetic circuits made of low-loss materials, and testing at low frequencies far below mains frequency. The hysteresis graph method based on Poynting's theorem requires the numerical quadrature of hysteresis loop and accurate measurement of magnetic polarization which can be difficult for the finished magnetic cores. The UBM is very similar to the standard method [8] except that the UBM measures dissipated power without the power component associated with the resistance of the magnetizing winding. In addition, the UBM evaluates the power loss according to the relationship (1), which is different from the measurement function of the other measurement methods. Appropriate measurement is reduced to measuring the voltage signals in the bridge and does not require the use of additional magnetic field sensors. This method can be applied both to the measurement of power losses in magnetic materials as well as magnetic circuits of electrical machines and other magnetic cores. For this reason, the paper presents a metrological verification of the UBM as a comparison of the measurements with results obtained by other methods in PTB and Stalprodukt SA laboratories.

Unbalanced bridge method

The unbalanced bridge method is an indirect method for measuring power losses in magnetic circuits. Formula (1) defines the measurement function of the power loss P_S as relation of the magnetizing current $i_S(t)=v_{CB}(t)/R_3$ and the unbalance voltage $v_{CD}(t)$.

Two-stage measurement procedure requires a balancing of the bridge with DC current supply and appropriate power loss measurement at the set-point peak value of magnetizing current $i_S(t)$.The idea of the unbalanced bridge is illustrated in figures 1a and 1b.

$$(1)\ P_S = \frac{1}{T}\frac{R_{Cu}+R_3}{m_{fe}\cdot R_3^2}\int_0^T v_{CD}(t)\cdot v_{CB}(t)dt$$

where: R_{Cu} – resistance of a magnetizing winding, m_{fe} – core weight, $R_3=R_{SHUNT}$ – shunt resistance.

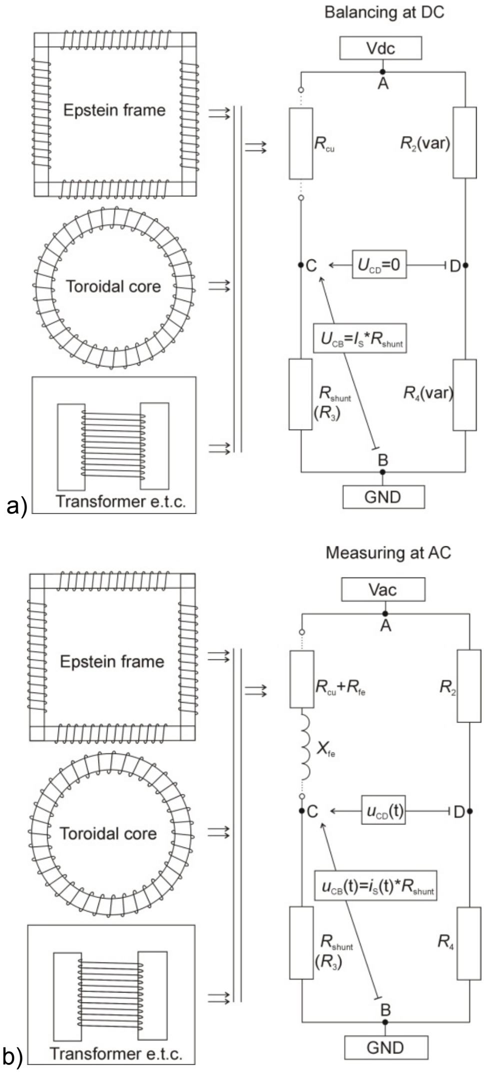

Fig.1. a) Equivalent circuit of the measuring bridge at DC power supply– balancing stage;b)Equivalent circuit of the measuring bridge atAC power supply– stage of P_S measurement;

A more detailed description of the unbalanced bridge method is presented in paper [20].

Reference sample and measurement systems

Despite the well-known and widely discussed imperfections [6,7,11,12], the Epstein's frame is still a recognized standard in industrial and laboratory magnetic measurements. The simple reproduction of the tested magnetic circuit in the Epstein frame and the relatively good repeatability of the measurements enable comparison of the power loss measurements. Thus, the 25 cm Epstein frame was used for comparative studies and a package of strips made of grain-oriented electrical steel from Stalprodukt S.A. Table 1 summarizes the most important technical data of the reference sample.

Table 1. Technical parameters of the tested sample

Parameter [units]	Quantity
Electrical steel grade [-]	ET-117 30
Number of strips [-]	28
Strip length [mm]	305.0
Strip width[mm]	30.0
Strip thickness with coating[mm]	0.2828
Volumetric density [$kg\cdot m^{-3}$]	7650
Total weight [g]	554.26

The stripes were annealed to remove mechanical stress and the indication of a folding sequence was applied to maintain the right placement of the strips in the Epstein frame in each case.

Reference measurements were carried out in the PTB (Physikalisch – Technische Bundesanstalt) laboratory according to standard [8]. In the laboratory of the Lodz University of Technology (LUT), comparative measurements were made on the basis of the hysteresisgraph and the unbalanced bridge method. PTB and LUT laboratories used their own measuring systems with defined uncertainty intervals for measurements of power losses, field strength and magnetic polarization. The Stalprodukt laboratory utilized the well-known commercial Brockhaus 200D system which measures according to wattmeter method [8].

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Comparison of power loss measurements

Comparison of measurements with the usage of above-mentioned measuring systems was made at magnetizing frequency of 50.0 Hz and temperature (21 ± 2)°Cof the sample. The reference sample was demagnetized before each test. The measurements of P_S were carried out at the set-points of peak polarization J_P = {1.0 T, 1.3 T, 1.5 T, 1.7 T} with controlled shape of polarization waveform. For each reference measurement of power losses in the PTB laboratory, the peak magnetic field strength was measured for the given value of peak magnetic polarization (Table 2). Each measurement was given with the expanded uncertainty where coverage factor equals k = 2 for a confidence level of 95% [22].

Table 2. Reference measurements of specific power loss at a given magnetic polarization(lab. PTB)

f_{MAG}	Peak magnetic polarization J_P	Specific power loss $P_s \pm u(P_s)$	Field strength$H_P \pm u(H_P)$ at J_P
[Hz]	[T]	[$W\cdot kg^{-1}$]	[$A\cdot m^{-1}$]
50.0	1.0	0.34258 ± 0.00076	19.531 ± 0.038
50.0	1.3	0.5809 ± 0.0013	23.226 ± 0.043
50.0	1.5	0.7912±0.0019	28.32 ± 0.10
50.0	1.7	1.0926 ± 0.0033	65.33 ± 0.98

Figures from 2a to 2d depict a graphical comparison of the results of the power loss measurements carried out in the aforementioned laboratories. Reference measurements carried out in the PTB were labeled as $P_{S\ REF\text{-}PTB}$. The results obtained in the LUT laboratory using the hysteresis method and the UBM method were marked $P_{S\ LUT\text{-}HYST}$ and $P_{S\ LUT\text{-}UBM}$ respectively. Results from the Stalprodukt laboratory were denoted as $P_{S\ SP}$. Reported measurements with uncertainty bars present consistency of the comparison. The bars illustrate expanded uncertainty $U(P_s)$ (k = 2, p = 95%) resulting from the analysis of uncertainty or technical notes of measurement systems [22].

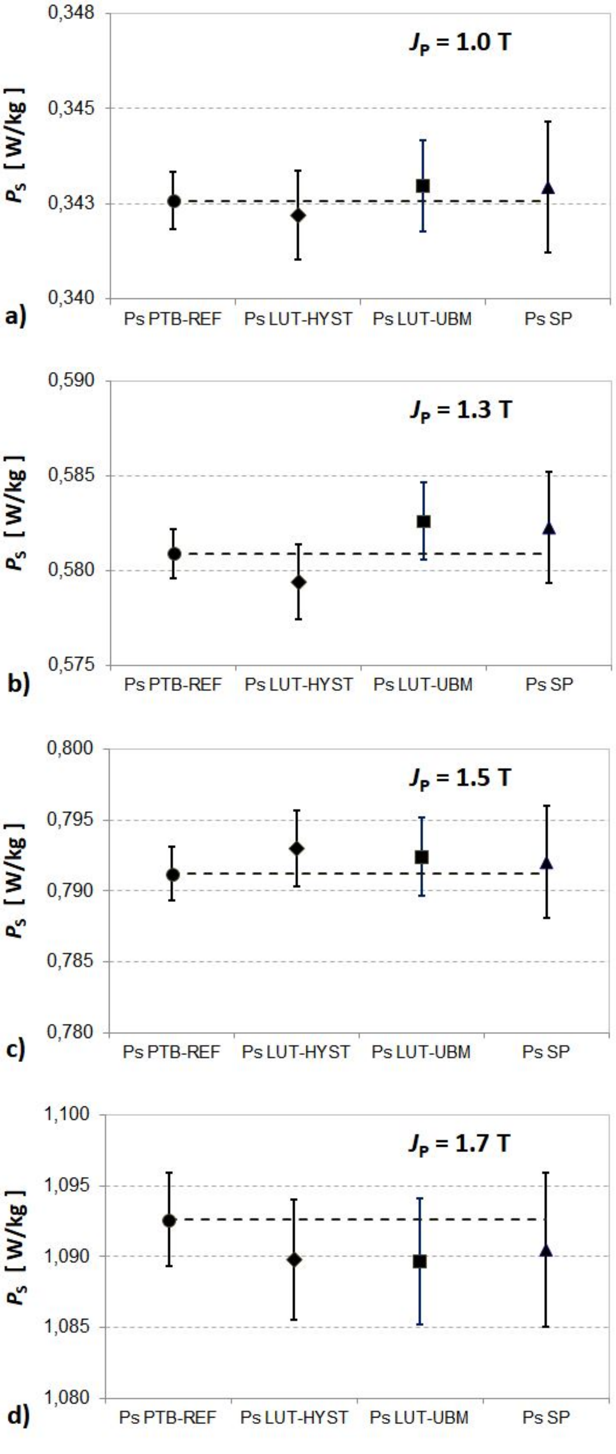

Fig.2. Mutual comparison of specific power loss measurements for a given peak magnetic polarization J_P a) J_P=1.0T, b) J_P=1.3T, c) J_P=1.5T, d) J_P=1.7T

Distinct differences between measurements and reference values shown in figures2a - 2d are summarized in Table 3.

The measurements presented in the comparison have been obtained by means of various methods in a metrological sense and clearly indicate that all systems ensure consistent results. This means that in each case the reference value is within the uncertainty interval of the compared one. Although the declared uncertainty of the measurements in the Stalprodukt laboratory is the greatest, the actual uncertainty of measurements is very small and never exceeds 0.24%.Measurements carried out in the LUT laboratory are characterized by greater scattering which reaches a value of 0.3%. The largest discrepancies are observed when the peak value of magnetic polarization is 1.7 T. This is due to the fact that obtaining a sinusoidal waveform $J(t)$ for high polarization values $J(t)$ is relatively difficult.

Table 3. Relative differences of the outcomes

J_P	$P_{S\ REF\text{-}PTB}$	$\delta P_{S\ LUT\text{-}HYST}$	$\delta P_{S\ LUT\text{-}UBM}$	$\delta P_{S\ SP}$
[T]	[W·kg^{-1}]	[%]	[%]	[%]
1.0	0.34258	0.11	0.11	0.11
1.3	0.5809	0.26	0.29	0.24
1.5	0.7912	0.23	0.15	0.10
1.7	1.0926	0.26	0.27	0.19

Uncertainty of power loss measurements

The uncertainty of the reference specific power loss and field strength measurements were summarized in table 2. The measurements from the Stalprodukt laboratory were obtained with a 0.5% uncertainty. Declared uncertainty was derived from the Brockhaus specifications and calibration certificates. Uncertainty $u(P_S)/P_S$ of measurements obtained by means of UBM was estimated from relationship (2). Relative combined standard uncertainty $u(P_S)/P_S$ involves all significant sources of uncertainty resulting from the measurement function (1) [22, 23].

$$(2)\ \frac{u(P_S)}{P_S} = \sqrt{\left(\frac{u_B(R_{Cu})+u_B(R_3)}{R_{Cu}+R_3}\right)^2 + \left(\frac{2u_B(R_3)}{R_3}\right)^2 + + \left(\frac{u_B(m_{Fe})}{m_{Fe}}\right)^2 + \left(\frac{u_B(U_{CD})}{U_{CD}}\right)^2 + + \left(\frac{u_B(U_{CB})}{U_{CB}}\right)^2 + (\tan\varphi \cdot u_B(\varphi))^2}$$

Table 4. shows the most relevant type-B uncertainty components $u_B(R_1)$, $u_B(R_3)$, $u_B(U_{CB})$, $u_B(U_{CD})$, $u_B(m_{fe})$ and $u_B(\varphi)$ related to the UBM instruments [6, 23].

Table 4. Type-B uncertainty components of the UBM instrumentation

Source of uncertainty	Instrumentation	Relative uncertainty
$u_B(R_{Cu})$	Keysight 34420A;range 1Ω	0.008%
$u_B(R_3)$	Keysight 34420A;range 1Ω	0.0042%
$u_B(U_{CB})$	NationalInstr. DSA PCI-4461;range ±10V	0.012%
$u_B(U_{CD})$	National Instr. DSA PCI-4461;range ±10V	0.012%
$u_B(m_{fe})$	Scale Radwag WTC3000	0.03%
$u_B(\varphi)$	Analyzer DSA NI-PCI-4461 f_s=200kHz	0.00054%

The sources of uncertainty for the hysteresis method are not presented in the paper because the method uses the same measuring instruments. The estimation of relative combined standard uncertainty is analogous and only differs by the additional uncertainty component resulting from the numerical integration of the area of the hysteresis loop. Expanded interval of uncertainty $U(P_S) = k\cdot u(P_S)$ has been calculated from formula (2) with coverage factor k = 2 and confidence level of 95%.Values of uncertainty presented in the form of bars in figures from 2a to 2 amount to $u(P_{S\ LUT\text{-}HYST})$ = 0.34% and $u(P_{S\ LUT\text{-}UBM})$ respectively.

Summary

Metrological validation of the unbalanced bridge method and measurement system was carried out on the basis of mutual comparison. Presented measurement results of specific power losses with the usage of different measurement methods confirm utility of the applied instrumentation. Outcomes have been referred to values from PTB laboratory and the differences do not exceed the value of expanded uncertainty of the compared measurements.

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REFERENCES

[1] Wilczynski W., “Influence of magnetic circuit production,” *J. Mater. Science*, 38 (2003), 4905–4910
[2] Bali M., Muetze A., Member S., Influences of CO 2 Laser, FKL Laser , and Mechanical Cutting on the Magnetic Properties of Electrical Steel Sheets, *IEEE Trans. Industry Applications*, 51 (2015), no. 6, 4446–4454
[3] Klimczyk P.K., Anderson P., Moses A., Davies M., Influence of Cutting Techniques on Magnetostriction Under Stress of Grain Oriented Electrical Steel, *IEEE Trans. Magn.* 48 (2012), no. 4, 1417–1420
[4] Kedous-Lebouc A., Messal O., Youmssi A., Joint punching and frequency effects on practical magnetic characteristics of electrical steels for high-speed machines,*J. Magn. Magn. Mater.*, 426 (2016), 658–665
[5] Chwastek K., Najgebauer M., Szczygłowski J., Wilczyński W., Modelling the influence of anisotropy on magnetic properties in grain-oriented steels, *Przegląd Elektrotechniczny*, 1 (2011), no. 83, 125-128
[6] Fiorillo, F.: Characterization and measurement of magnetic materials, Elsevier, Netherlands 2004
[7] Kolasa J., Bajorek J. Influencing factors on uncertainty of electrical sheet magnetic property calculations using a Epstein frame, *Przeglad Elektrotechniczny,* 83 (2007), no 1, 69-73
[8] Magnetic Materials—Part 2: Methods of Measurement of the Magnetic Properties of Electrical Steel Strip and Sheet by Means of an Epstein Frame, IEC 60404-2, 2008.
[9] Magnetic Materials—Part 4: Part 4: Methods of measurement of D.C. magnetic properties of magnetically soft materials, IEC 60404-4, 2008.
[10] Magnetic Materials—Part 3: Methods of Measurement of the Magnetic Properties of Electrical Strip and Sheet by Means of a Single Sheet Tester, IEC 60404-3, 2010.
[11] Sievert J., The measurement of magnetic properties of electrical sheet steel – survey on methods and situation of standards, *J. Magn. Magn. Mater.*, 215–216 (2000), 647–651
[12] Marketos P., Zurek S., Moses A.J., Calculation of the mean path length of the Epstein frame under non-sinusoidal excitations using the double Epstein method, *J. Magn. Magn. Mater.*, 320 (2008), 2542–2545
[13] Barbisio E., Fiorillo F., Ragusa C., Predicting loss in magnetic steels under arbitrary induction waveform and with minor hysteresis loops,*IEEE Trans. Magn.*, 40 (2004), no. 4, 1810–1819,
[14] Bajorek J., Gaworska D., Measurement of the losses of electrical steel sheet samples at high magnetic flux density, *Przegląd Elektrotechniczny*, 6 (2012), no 88, 125–127
[15] Antonelli E., Cardelli E., Faba A., Epstein frame: How and when it can be really representative about the magnetic behavior of laminated magnetic steels, *IEEE Trans. Magn.*, 41 (2005), no. 5, 1516–1519
[16] Wulf M., Makaveev D., Houbaert Y., Melkebeek J., Design and calibration aspects of small size single sheet testers,*J. Magn. Magn. Mater.*, 254–255 (2003), 70–72
[17] Manyage M. J., Pillay P., New Epstein frame for core loss measurements at high frequencies and high flux densities,*Conf. Rec. - IAS Annu. Meet.* (*IEEE Ind. Appl. Soc.)*, 22 (2008), no. 3, 614–620
[18] Zámborszky F., Tóth D., Palánki Z., Csizmadia E., Electrical and Calorimetric Power Loss Measurements ofPractically Ideal Soft Magnetic Cores, *IEEE Trans. Magn.,* 50 (2014), no. 4, 6300604
[19] Bajorek J., GaworskaD., Determination of active power density by method of hysteresis loop area planimetr, *Przegląd Elektrotechniczny*, 4 (2010), no 86, 55–58
[20] Majocha A., Gozdur R., Bridge method of measurements of the power loss, *Przegląd Elektrotechniczny*, 4 (2010), no 86, 79–82
[21] Penin J., Landgraf F. J. G., Guimara G. C., Should Epstein strip arrangement be changed?, *J. Magn. Magn. Mater.* 304 (2006), 571–573
[22] Evaluation of measurement data – Guide to the expression of uncertainty in measurement,*JCGM 100:2008*,France: BIPM Joint Committee for Guides in Metrology
[23] Ahlers H., Ludke J., The uncertainties of magnetic properties measurements of electrical sheet steel,*J. Magn. Magn. Mater.*, 215–216 (2000), 711–713