An Experimental Setup for Power Loss Measurement up to 1 kHz using an Epstein Frame at CMI

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Abstract: This paper describes an experimental setup used at the Czech Metrology Institute (CMI) to measure the specific power loss of oriented and non-oriented electrical steel sheets up to 1 kHz using an Epstein frame. Special attention is given to a) a description of the hardware that is used, b) a description of the feedback control and measurement software, and c) an analysis of the sources of uncertainty and validation. Calibration expanded uncertainty of (0.5 up to 1.6)% for k = 2 can be achieved with this setup.

Keywords: Epstein, feedback, measurement, power loss, reference sample, uncertainty.

1. INTRODUCTION

Electrical steel is used for transformers or motors and for generators. Therefore, the total power loss is an important parameter for determining the efficiency of the material. Two methods are used for such measurements - the Epstein frame and the Single Sheet Tester (SST). Both methods are defined in the IEC standards [1], [2]. Czech Metrology Institute (CMI), as a national metrology institute, has always provided measurements of total losses in electrical steels with a given metrological traceability using the Epstein frame. However, the setup could only be used for measurements at 50 Hz or 60 Hz. Due to several requests for measurements of total loss also at frequencies higher than 50/60 Hz (up to 1 kHz), a new setup was needed. There are of course commercial automated setups for such measurements, e.g. MPG 200 (Brockhaus Messtechnik), MAG-RJJ-6.0 (R&J Measurement), REMACOMP C–1200 / C-2200 (Magnet-Physik) or the AMH permeameter type (Laboratorio Elettrofisico). However, these systems are not cheap, because they can be used for other measurements (depending on the accessories) and not only for total power loss measurements with an Epstein frame. A new experimental setup for specific total power loss measurements using an Epstein frame was therefore implemented as part of the HEFMAG project at CMI.

2. SUBJECT & METHODS

A. Hardware description

Fig. 1 shows the block diagram of the total power loss measurement using an Epstein frame that was performed at CMI. The analog signal generated by the DAQ (DAC out) is fed back to the analog DAQ input for sampling synchronization (ADC readback) and to the power amplifier feeding the primary winding of the Epstein frame (DUT). The flowing current is measured with a current shunt R and an analog DAQ input (ADC-H). The current shunt value used was 0.09 Ω, 2 Ω or 5 Ω, depending on the Epstein frame and primary current value used. The induced voltage u_B from the secondary winding is applied to the differential input of the PA01 programmable signal attenuator (in-house), since the induced voltage may exceed the maximum range of the A/D inputs of the DAQ, which is ±10 V. The attenuator converts the differential signal into a signal with a common ground (single-ended signal), workable for DAQ. Attenuation is selectable in four levels (1, 5, 20, and 100), using a combination of two optically-isolated digital inputs. Then the signal from the attenuator is applied to the analog DAQ input (ADC-B). The digitized current (as the voltage drop u_H across the current shunt) through the primary winding, the voltage u_B across the secondary winding, and the back-read generated signal entering the power amplifier are read from the DAQ by control software on a computer. The DAQ is a multipurpose USB-6281 (NI) with an 18-bit A/D converter and a total sampling rate of 500 kS/s, a 16-bit DAC, and a set of generic digital I/O ports. The model 7228 (AE Techron) power amplifier supplies the primary winding of the Epstein frame (700 turns realized at CMI or 100 turns from Brockhaus Messtechnik). The power amplifier model 7228 was operated in AC coupled mode. In other words, the DC offset was blocked by a built-in 2 Hz high-pass filter. Epstein frame with 700 turns was used for measuring at 50 Hz and 100 Hz. For frequencies above 100 Hz, an Epstein frame with 100 turns was used.

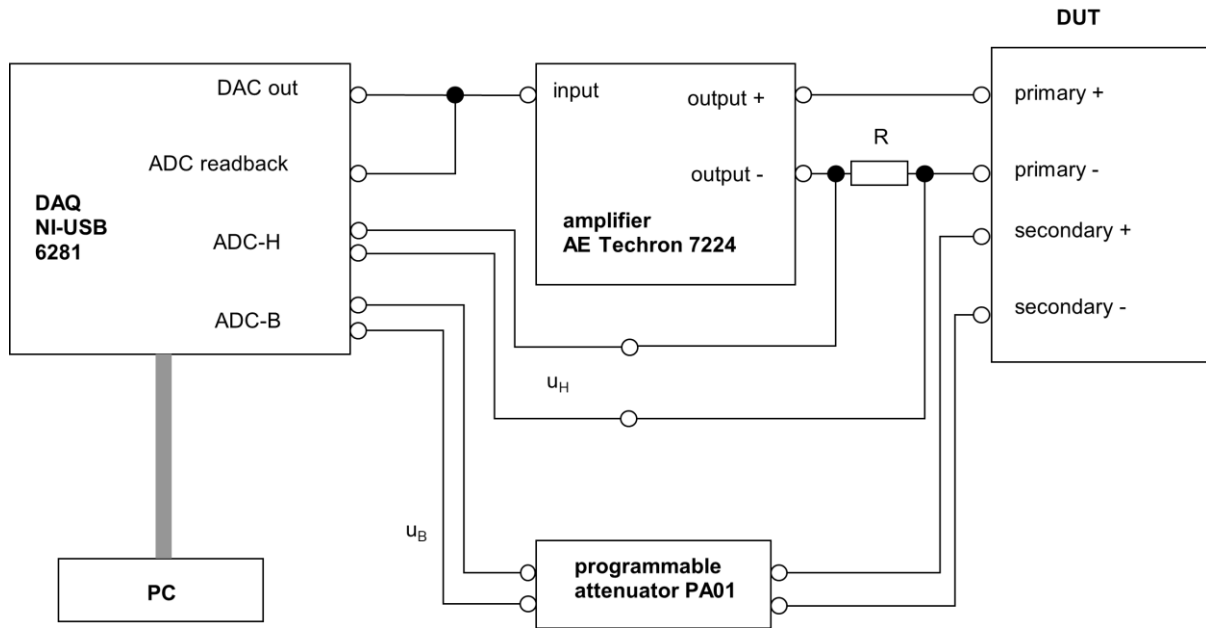*Corresponding author: mulvr@cmi.cz (M. Ulvr)*

Fig. 1. Block diagram for measurements of magnetic losses in electrical steel sheets at CMI using an Epstein frame.

The simplified electronic schematic of the PA01 is shown in Fig. 2. The basis of the signal part of the PA01 is the OPA192 operational amplifier (Texas Instruments), which is connected as a differential amplifier. It converts the input differential signal into an output signal with a common ground. Three relays with a switching contact (S1, S2, and S3) are used to change the resistance in the T-network feedback of the amplifier, which determines its attenuation. It is always assumed that one relay or no relay is closed. This makes it possible to achieve one of four attenuation values, 100 (no relay is closed), 20 (S1 is closed), 5 (S2 is closed), or 1 (S3 is closed). Thin-film resistors with a tolerance of 0.1% were used in the signal path. For alternating signals, the PA01 behaves like a first-order low-pass filter of the Butterworth type. The cut-off frequency varies with the attenuation setting, and the cut-off frequency increases with increasing attenuation. The measured frequency characteristics of the PA01 are embedded as a *.json* file containing a data table for each nominal gain (attenuation) setting, in which a pair of gain/phase values is assigned to each frequency value for a certain range of discrete frequencies. Harmonics are not considered, because the voltage u_B is always sinusoidal due to the feedback control. It is assumed that the DC gain and phase are equal to the gain and phase of the lowest frequency in the table. The frequency response of points that do not directly coincide with any point in the table is calculated by linear interpolation of two directly adjacent points from the table to the desired point.
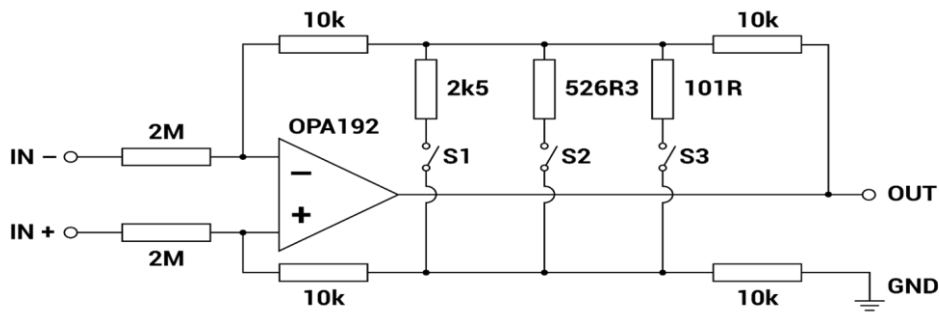

Fig. 2. Simplified electronic schematic of PA01.

B. Feedback control and measurement software

According to IEC 60404-2 [1], the shape factor of the sine wave signal on the secondary of the Epstein frame must be maintained at $1.11 \pm 1\%$. This means that feedback control must be applied. Several papers have been published on this subject, solving the feedback control with different variants by the iterative method with controllers [3], [4], [5], by checking the THD parameter [6], or by the harmonic compensation method [7]. The iterative method with the proportional controller was used for its easy implementation. The software (SW) for the feedback control and for the total loss measurements was written in the C# programming language on the .NET Framework 4.8 using the Windows Presentation Foundation (WPF) graphics libraries.
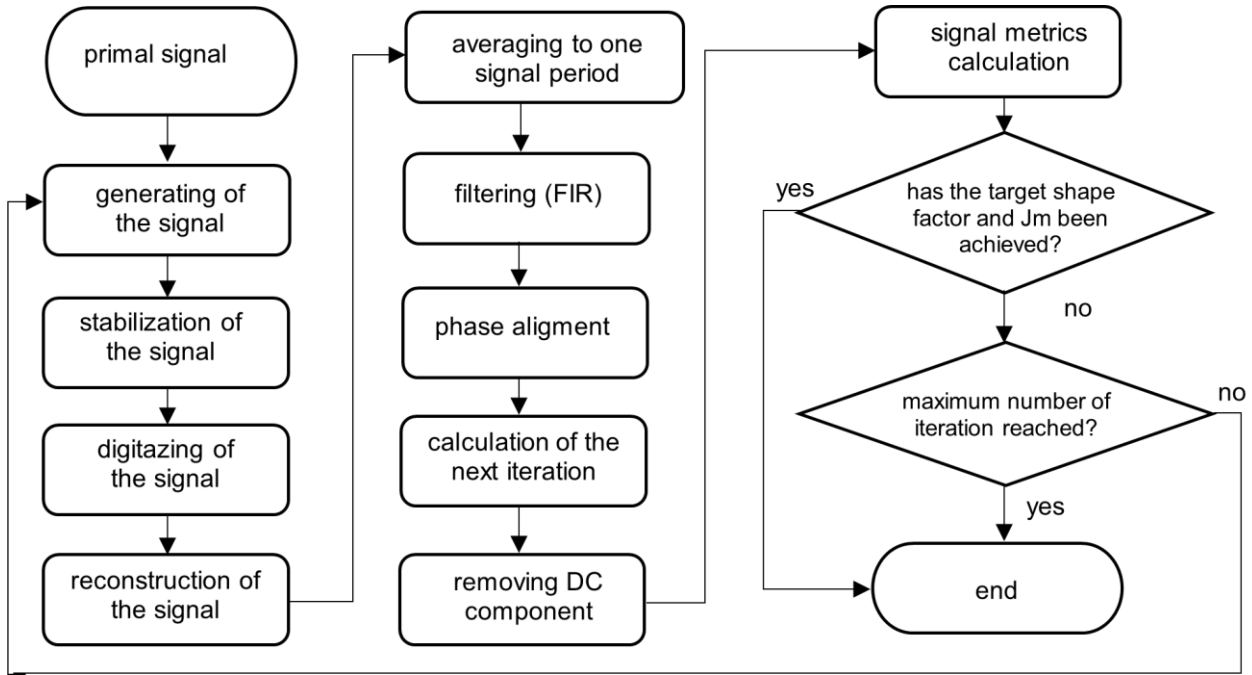
Fig. 3. Block diagram of the iterative loop.

For all manipulations with the signal, it is assumed that the signal is periodic, and if samples preceding (following) one period are needed for the calculation (e.g., FIR filter), samples from the end (beginning) of the same data set are used. The following iteration is calculated according to the principle of the classical proportional controller. However, a phased alignment is performed before the calculation. Due to the physical nature of the magnetic polarization J_m and due to the real elements of the used measurement chain, the phases of the measured signal are shifted relative to the generated signal. To calculate the next iteration, it is first necessary to shift the phase – align the samples – so that the individual data sets are not phase-shifted relative to each other. Using the discrete Fourier transform, the value of the voltage phase on the secondary winding at the fundamental frequency is obtained. The sample set of the target signal is rearranged so that its phase coincides with that of the signal from the secondary winding. The phase of the generated signal from the readback channel is also determined and the output samples from the current iteration are phase-aligned to the phase identical with that of the generated signal. This removes any asynchronicity of the generated signal with respect to the sampled signals. The proportional controller calculates each sample of the output signal of the following iteration ($o_i + 1$) in turn using (3), where t is the phase-aligned target signal, s_s is the phase-aligned, averaged and filtered voltage signal of the secondary winding, K_P is the user-selected amplification factor of the regulator, and o_i is the output signal of the current iteration. The *RMS* index indicates the mean square value of the signal.

$$o_{i+1} = \frac{(t-s_s)K_P o_{i,RMS}}{s_{s,RMS}} + o_i. \tag{3}$$

The DC component is removed from the new output signal $o_i + 1$ by subtracting from each sample the arithmetic mean value of all samples. The shape factor of the voltage on the secondary winding, which is one of the target metrics, is calculated as the quotient of the mean square value and the average absolute value of the signal. The amplitude of magnetic polarization or specific magnetic loss is calculated using equation A.2 or A.3 from Appendix A of the International Standard IEC 60404-2 [1].

With the given SW, it is possible to set all the parameters of the iteration loop (feedback) and the parameters of the measured sample and determine the value of the total losses of the measured sample, including uncertainty. The software also displays the primary and secondary waveforms and the shape factor value of the secondary voltage.

C. Uncertainty analysis

The uncertainty of the total loss measurement using the described setup depends mainly on the uncertainty of the frequency, on the u_H and u_B measurements or on the calibration of the analog DAQ inputs used, on the uncertainty of the calibrated current shunt value used at a given frequency, on the repeatability, and on the uncertainty of the PA01 attenuator. The measured (calibrated) frequency characteristic of PA01 is applied to the *.json* file in the control software, so its uncertainty comes from the calibration and the correction of PA01 can also be made. The other sources of uncertainty determined experimentally are the influence of temperature and the mismatch uncertainty of the Epstein frame and the sample (for example: primary/secondary winding not homogeneously wound, mean path length differs from 0.94 m, given dimensions of the sample could be slightly different from reality and this could affect the cross-sectional area, etc.). The uncertainty budget for the loss measurement with the Epstein frame using the CMI setup is shown in Table 1 and Table 2 (the sensitivity function for all uncertainties is 1).

Table 1. Example of the uncertainty budget using the CMI setup for power loss measurements at 50 Hz.

Source of uncertainty	Type of uncertainty	k-factor	standard uncertainty (%)
current shunt value	B	1	0.005
voltage u_B (DAQ)	B	1	0.05
voltage u_H (DAQ)	B	1	0.05
attenuator PA01	B	1	0.20
frequency	B	1	0.01
temperature influence	B	1	0.05
mismatch uncertainty of the Epstein frame and the sample	B	1	0.06
set value of J_m	B	1	0.05
repeatability	A	1	0.10
total uncertainty	-	1	0.25
total expanded uncertainty	-	2	0.50

Table 2. Example of the uncertainty budget using the CMI setup for power loss measurements at 1000 Hz.

Source of uncertainty	Type of uncertainty	k-factor	standard uncertainty (%)
current shunt value	B	1	0.02
voltage u_B (DAQ)	B	1	0.10
voltage u_H (DAQ)	B	1	0.10
attenuator PA01	B	1	0.70
frequency	B	1	0.01
temperature influence	B	1	0.05
mismatch uncertainty of the Epstein frame and the sample	B	1	0.06
set value of J_m	B	1	0.05
repeatability	A	1	0.35
total uncertainty	-	1	0.80
total expanded uncertainty	-	2	1.60

D. Validation

The setup described above was validated by two methods. First, the measurement of the total loss of the Epstein sample was cross-validated using the measurement software and the TracePQM WattMeter (TWM) using two 3458A-type multimeters. TWM was developed as part of the TracePQM project [8]. The power value P measured by TWM (using the TWM-PWRTDI time domain integration method) was then divided by the effective mass m_a of the Epstein sample to obtain the specific total loss value P_s

$$P_s = \frac{P}{m_a} \text{ (W/kg).} \qquad (4)$$

Second, the setup was compared with the setups of other HEFMAG project participants - PTB Germany, INRIM Italy, NPL United Kingdom, and UNOTT (University of Nottingham) United Kingdom - using several Epstein samples of grain-oriented (GO) and non-oriented (NO) electrical steel sheets. Due to the large amount of measured data, only the results of one GO sample and one NO sample at two frequencies (50 Hz and 1000 Hz for the GO sample and 50 Hz and 400 Hz for the NO sample) at the maximum value of J_m are presented here. The parameters of the Epstein samples are shown in Table 3.

Table 3. Parameters of the Epstein samples.

Sample	Density (kg/m^3)	Cross section ($\times 10^{-5}$ m^2)	Weight (kg)	Number of strips
NO 0.3	7600	2.64974	0.24140	12
GO 0.18	7650	2.61590	0.25640	20
		2.09280	0.20504	16

3. RESULTS

Samples with parameters according to Table 3 were used to validate the described setup. The results of cross-validation using the TWM tool are shown in Table 4, where f is the frequency, P_{s1} is the value measured with the CMI setup and U(P_{s1}) is its relative expanded uncertainty (k = 2), P_{s2} is the value measured with the TWM tool and U(P_{s2}) is its relative expanded uncertainty, and δ_r is the relative difference between P_{s1} and P_{s2}. Measurements were performed at J_m = 1.5 T at 50 Hz and at 1.4 T at 400 Hz (NO 0.3 sample) and at J_m = 1.8 T at 50 Hz and 400 Hz and at 1 T at 1000 Hz (GO 0.18 sample). The results are in good agreement - the relative differences are within the stated expanded uncertainties of the values measured with the CMI setup.

Table 4. Results of cross-validation using the TWM tool.

Sample	f (Hz)	P_{s1} (W/kg)	U(P_{s1}) (%)	P_{s2} (W/kg)	U(P_{s2}) (%)	δ_r (%)
NO 0.3	50	2.158	0.80	2.146	0.46	-0.54
	400	28.460	1.30	28.801	0.30	1.19
GO 0.18	50	0.9290	0.50	0.9262	0.42	-0.31
	400	19.460	0.60	19.520	0.22	0.29
	1000	27.110	1.00	27.303	0.15	0.73

For all measurements, the evaluation of the HEFMAG comparison was performed following procedure B in [9]. Based on the power loss data and their uncertainties of all participants, the reference value and its uncertainty (including other necessary characteristics) were calculated using the M-P (Mandel-Paul) mean [10]. The maximum J_m value had to be chosen to measure the power loss at each frequency due to the limitations of each participant's setup. For this reason, the GO 0.18 sample was measured at 1.8 T at 50 Hz, but only at 1 T at 1000 Hz. The same reason applies to the NO 0.3 sample. The graphical results of the HEFMAG round robin comparison of the two described samples can be found in

Fig. 4, Fig. 5, Fig. 6, and Fig. 7, where the red line is the reference value, the red dashed lines are the border of the expanded uncertainty of the reference value, the colored dots are the points measured by the participant, and the black lines are the expanded uncertainties of the measured values. The results are in good agreement, as can be seen from the graphs. Examples of the waveforms of the u_H and u_B voltages can be found in Fig. 8 and Fig. 9.
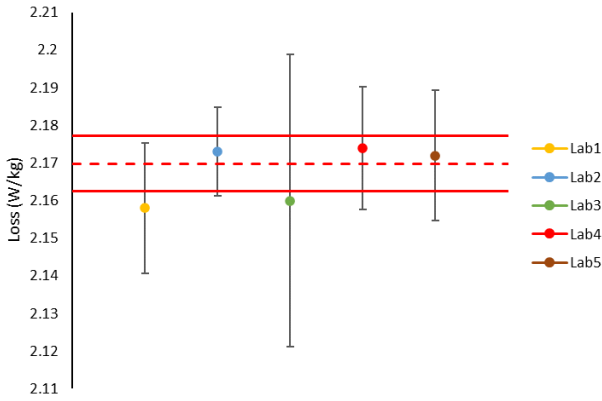

Fig. 4. Comparison results of sample NO 0.3 at $J_m = 1.5$ T and 50 Hz.
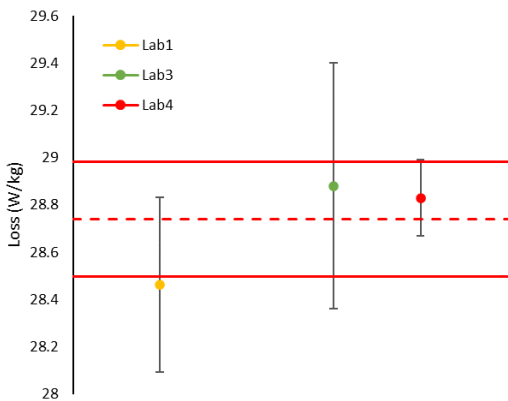
Fig. 5. Comparison results of sample NO 0.3 at $J_m = 1.4$ T and 400 Hz.
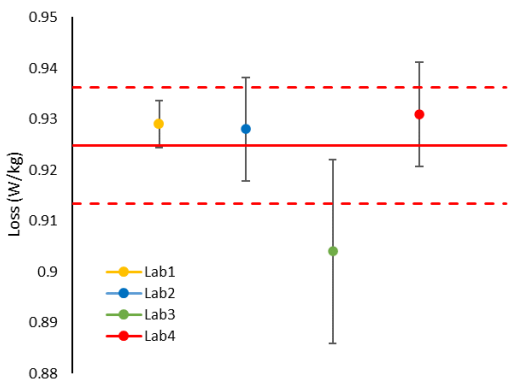
Fig. 6. Comparison results of sample GO 0.18 at $J_m = 1.8$ T and 50 Hz.
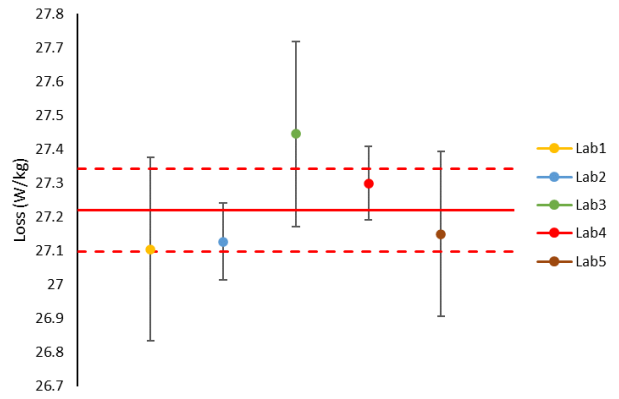
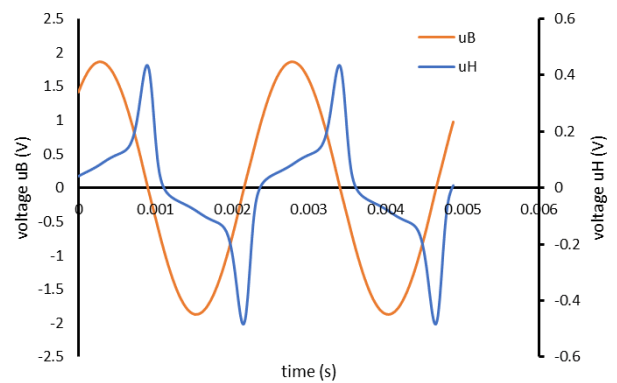Fig. 7. Comparison results of sample GO 0.18 at $J_m = 1.0$ T and 1000 Hz.

Fig. 8. Example of waveforms of u_H and u_B for NO 0.3 sample at $J_m = 1.4$ T and 400 Hz. Form factor value of u_B voltage is 1.11106, $R = 0.09$ Ω.
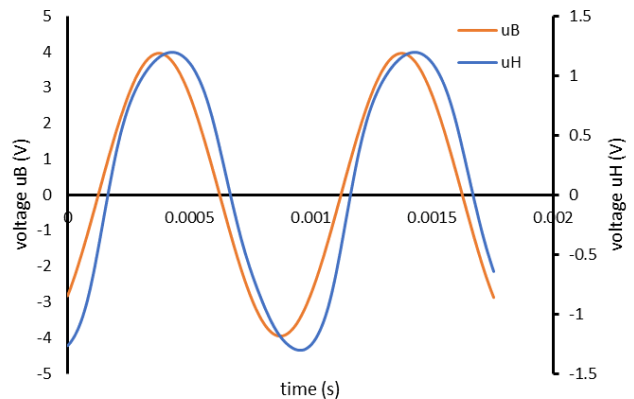

Fig. 9. Example of waveforms of u_H and u_B for GO 0.18 sample at $J_m = 1.8$ T and 1000 Hz. Form factor value of u_B voltage is 1.11075, $R = 2$ Ω.

4. CONCLUSION

A new experimental setup for the total loss of electrical steel sheets using an Epstein frame at the CMI was described. The hardware, feedback control and measurement software, and uncertainty analysis were described in detail. The total loss measurement with the new software was validated by comparison with the TWM software using two 3458A type multimeters and by comparison of reference samples

measured at INRIM, NPL, PTB, and UNOTT as part of the HEFMAG round robin comparison. The results confirm that the described setup can be used for specific total loss measurements of Epstein samples up to 1 kHz with an expanded uncertainty of (0.5 up to 1.6)% for k = 2.

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