ACTA IMEKO
ISSN: 2221-870X
September 2023, Volume 12, Number 3, 1 - 10

Trans-conductance amplifier calibration protocol establishment – metrology ambiguities, constraints, and measurement uncertainty propagation analysis

Kiril Demerdziev[1], **Marija Cundeva–Blajer**[1]

[1] *Ss. Cyril and Methodius University in Skopje (UKIM), Faculty of Electrical Engineering and Information Technologies (FEEIT), st. Rugjer Boskovik No. 18, 1000 Skopje, Republic of North Macedonia*

ABSTRACT
The primary dilemma, when establishing calibration protocol for testing of any measurement transducer, is whether the concrete unit is going to be regarded as a standalone instrument, or it will be treated as a part of an integrated measurement system. The first approach would provide results that are applicable for broader further usage. The data obtained if the unit is calibrated within the measurement system, may be further used only for performance evaluation of the overall system. The concrete ambiguity is related to the appropriate quantity selection on the basis of which the measurements will be carried out, i.e., whether the measurand is the transducer’s output signal or its transformation coefficient. The determination of the quantity, which is supposed to be recorded, opens a further debate about the appropriate selection of measurement points and the uncertainty evaluation procedure, both in terms of dominant influential factors determination, and in overall uncertainty budget distribution modelling adequacy. In the concrete contribution, an originally developed protocol for high current trans-conductance amplifier examination will be presented, taking into account both perspectives for examination.

Section: RESEARCH PAPER

Keywords: Trans-conductance amplifier; reference standard; calibration protocol; measurement uncertainty

Citation: Kiril Demerdziev, Marija Cundeva–Blajer, Trans-conductance amplifier calibration protocol establishment – metrology ambiguities, constraints, and measurement uncertainty propagation analysis, Acta IMEKO, vol. 12, no. 3, article 14, September 2023, identifier: IMEKO-ACTA-12 (2023)-03-14

Section Editor: Leonardo Iannucci, Politecnico di Torino, Italy

Received January 30, 2023; **In final form** August 1, 2023; **Published** September 2023

Corresponding author: Kiril Demerdziev, e-mail: kdemerdziev@feit.ukim.edu.mk

1. INTRODUCTION

Calibration is a periodic examination of a measurement unit to assess its actual measuring condition [1], [2]. It is carried out by comparing the recordings made by the Unit Under Test (UUT) and the measurements made with a corresponding instrument of higher accuracy class, regarded as a Reference Standard (RS). In electrical metrology, plenty of international standards [3]-[6], recommendations [7], guides [8], [9], as well as regulatory framework exist [10]. They are used as a base for routine examination procedures development, by the personnel of accredited calibration laboratories. In these documents directions are provided, from the perspective that the testing of any measurement unit is supposed to be carried out in specific critical conditions. The critical conditions may be presented in the form of specific test waveforms [5], [7], that simulate the happenings on site, or in the form of measurement points [8], [9] for the whole operating range of the UUT to be covered in the examination.

The framework presented in the internationally adopted documents is the base for developing routine periodic examination schemes regarding instruments such as multimeters, oscilloscopes, and electricity meters [11]-[13]. When more complex measuring units or measurement systems are subjected for calibration, a development of original calibration protocols is required [14], [15]. Electrical transducers are an example of measurement devices that require establishment of unique calibration procedures.

The main metrological ambiguity, in the establishment of calibration protocols for electrical transducers examination, is the fact that they cannot be operated independently, outside of a measurement system. Additionally, for the performance of the transducer to evaluate, both the input and output signals’ variations are supposed to be carefully monitored. The concrete statements open a path for development of two possible examination configurations. In the first one the transducer is supposed to be treated as a standalone unit and in such a manner, both the input and output signals are supposed to be regarded as measured quantities. The results obtained in such configuration are applicable for broader further usage, i.e., for performance evaluation of any possible measurement system in which the concrete transducer may be implemented. In the issued calibration certificate, if the concrete examination scheme is adopted, the results are presented from the perspective of transducer's output or transfer function. They may be further used for documentation of its performance in various measurement systems, in which the concrete unit is going to be implemented. The second scenario regards the concrete UUT as an integrated part of a measurement system. In such testing configuration, the input signal is provided internally, within the system, and it is not recorded during the examination, while the measured quantity is the transducer's output signal only. The generated calibration certificate provides information about the status of the entire measurement system, in which the concrete unit is used for providing output signals in a specific range. Its validity is addressing the system as a whole and the obtained results cannot be used for transducer's performance evaluation if it is used within another measurement system. It is important to emphasize that the choice of the measurement method is supposed to be based on the purpose and applicability of the concrete unit. From the calibration protocol development perspective, the selected measurement configuration later affects the appropriate measurement points selection, and consequently, the uncertainty evaluation procedure, in terms of dominant influential factors determination and in the domain of overall distribution modelling.

In this study we introduced an original calibration protocol for examination of a trans-conductance amplifier, as an example of electrical transducer. The protocol is developed in an accredited laboratory for calibration of instruments for electrical quantities, according to international standard MKC EN ISO/IEC 17025:2018 [16]. The two scenarios for examination scheme establishment discussed above will be covered in the evaluation. For both calibration schemes, an uncertainty propagation analysis will follow. Measurements will be conducted with reference standards of high accuracy class that possess international metrological traceability to BIPM [17] intrinsic standards.

2. MEASUREMENT CONFIGURATION AND EQUIPMENT

The establishment of the calibration protocol, regarding examination of trans-conductance amplifier, is carried out in Laboratory of Electrical Measurements (LEM), at the Faculty of Electrical Engineering and Information Technologies (FEEIT), Ss. Cyril and Methodius University in Skopje (UKIM). In laboratory's disposal, there are several reference standards that are used for both routine calibration procedures realization, as well as for original measurement protocols development [18], [19]. All units are periodically calibrated and maintain international traceability to the BIPM [17] intrinsic primary reference standards.

The UUT, which is used for the development of the examination protocol, is high current trans-conductance amplifier, FLUKE 52120A [20]. The concrete unit is used for both DC and AC, voltage, and current input signals transformation into high current output. Input signals are limited to 2 V and 200 mA, both DC and AC RMS values. The UUT possesses 3 ranges for realization of the high current output, of 2 A, 20 A and 120 A. When voltage to current transformation regime is regarded, the ranges of the UUT correspond to trans-conductance coefficient of 1 A/V, 10 A/V and 100 A/V (for the 120 A range the input voltage value is limited at 1.2 V). In the current amplifier regime, the current gain for every output range equals 10, 100 and 1000, respectively, once again the current input for the 120 A is limited at 120 mA. The transducer's best accuracies, in domain of output current generation, when the input signals are generated from a stable source, are presented in Table 1.

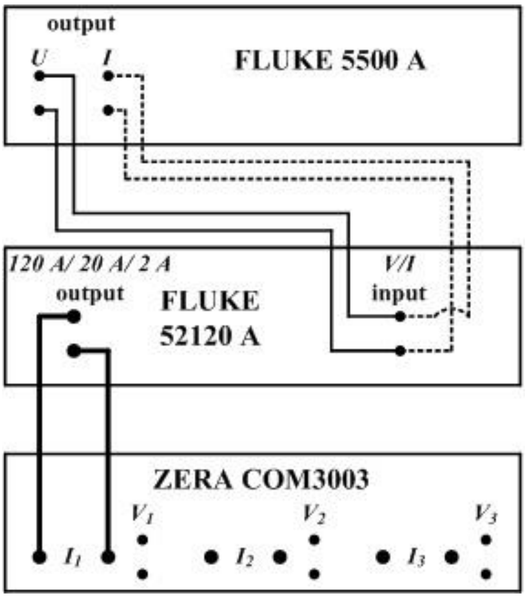

Figure 1. Trans-conductance calibration configuration in LEM

The measurement configuration is illustrated in Figure 1. The two reference standards used for both generation of the input signals, and measurement of the output current, are selected in a way that simple measurement circuitry, with the best possible accuracy, is achieved. A single unit is used for generation of the input signals, and in the further discussion it will be referred to as "reference standard input", RS_I. Another reference standard is used for direct measurement of the high current output, without any further transformation of the signals apart from the transformation performed by the UUT. This unit, in the further text will be referred to as "reference standard output", RS_O.

For generation of the input signals up to 2 V and 200 mA, the secondary (working) reference standard of LEM, FLUKE 5500A [21], in domain of DC and low frequency AC, voltage and current instruments calibration, is used. The RS_I is in fact a multifunction calibrator, intended primary for multimeters, with resolution up to 6½ digits, examination. Its best 1-year specifications, related to direct reproductions of different electrical signals, is presented in Table 2. It may be concluded, by comparing Table 1 and Table 2, that the calibrator is suitable for providing the input signals for calibration of the trans-conductance amplifier [20], except when the AC currents

Table 1. Trans-conductance amplifier FLUKE 52120 A best 1 year specification

Electrical quantity	Best 1 year specification
DC current (DCI)	±0.016 % of setting
AC current (ACI)	±0.035 % of setting

Table 2. FLUKE 5500A best 1 year specification

Electrical quantity	Best 1 year specification
DC voltage (DCV)	±0.005 % of setting
AC voltage (ACV)	±0.03 % of setting
DC current (DCI)	±0.01 % of setting
AC current (ACI)	±0.06 % of setting

amplification working regime of the UUT is regarded. In such a scenario the best accuracy of RS_I is higher than the best accuracy of the UUT, which would lead to deterioration of its basic operating specification.

For measurement of the amplifier's output current, the primary reference standard of LEM, ZERA COM3003 [22], in domain of electrical power and/or energy instruments examination, is used. Even though its primary function is high accuracy power measurements, in the concrete configuration, ZERA COM3003 [22] is regarded as a high current indicator only. As depicted in Figure 1, only the current input terminals of a single phase are used. In Table 3, the best 1-year measurement specifications of RS_O, for both DC and AC currents up to 200 A recording, are illustrated. It can be concluded, by comparing Table 1 and Table 3, that RS_O is well suited for the concrete calibration protocol, when transducer's AC current output is regarded. In the DC signals transformation regime, the standard's accuracy limits are wider than the accuracy limits of UUT, thus the concrete testing scheme would lead into deterioration of its basic specification.

The best accuracies of the three instruments used in the proposed examination protocol may vary from one measuring range to another. For the full specifications, the unit's manuals [20]-[22] should be consulted. As stated in the earlier discussion, the greatest advantage of the proposed measurement configuration is its simplicity and the fact that no further signal transformations are required. The direct generation and measurement of both input and output signals leads to a perspective for simple error and uncertainty model development. The overall calibration error will be comprised only of the instruments' intrinsic error components, i.e., no additional deviations, due to extra transformation of measurement signals and connection of other measurement units will contribute to the overall process. In the concrete configuration, the uncertainty budget would comprise only components directly attributed to both input signals' generation and output currents' measurement. For transfer of the single uncertainty components to the calibration result, presented in any format available, only the transducer's transfer function will be required.

On the other hand, the use of the concrete reference standards introduces several shortcomings as well, which may be observed even before any measurement data is analyzed. The deficiencies related to the accuracy of the instruments related were already introduced in the previous discussion. Additionally, one major deficiency related to the proposed calibration scheme is the fact that the measurement of DC currents higher than 10 A is beyond the accreditation scope of the laboratory. This is the reason for not possessing a better class instrument for monitoring of high current DC output. The RS_O, according to its specification [22], is used primary for AC power and energy measurements, i.e., it possesses lower accuracy in domain of DC signals recording. In term of AC currents measurement, its main deficiency is related to the limited frequency bandwidth at 3.5 kHz, regarding both fundamental and harmonic components. Even though ZERA COM3003 [22], possess current measurement ranges that cover the whole RMS current output span of the UUT, it does not cover the corresponding frequency span of 10 kHz, and with that the full transformation range of FLUKE 52120A [20].

Table 3. ZERA COM3003 best 1 year specification

Electrical quantity	Best 1 year specification
DC current (DCI)	±0.035 % of measured value
AC current (ACI)	±0.005 % of measured value

In the discussion that follows, the proposed calibration scheme will be supplemented, with a discussion about perspectives for appropriate measurement method and measurement points selection, as well as from the perspective of uncertainty budget modelling. The detected advantages and deficiencies will later be verified experimentally, while in the last section of the manuscript, perspectives for eventual improvement of the calibration scheme will be presented.

3. SELECTION OF THE MEASUREMENT METHOD, MEASUREMENT POINTS AND UNCERTAINTY EVALUATION

As stated in the introduction, two concepts for calibration of the trans-conductance amplifier will be regarded and analysed in detail by using real time measurement results. The connection scheme in case of both calibration methods is illustrated in Figure 1, and it consists of two reference standards, labelled as RS_I and RS_O, whose advantages and deficiencies, for the concrete performance, are labelled in section 2 of this manuscript.

The first concept relies on examination of the UUT, by regarding it as a standalone instrument. In the discussion that follows, the concrete calibration method will be referred to as M1. The results obtained if M1 calibration method is adopted, are applicable for presentation of the UUT's performance in any measurement configuration in which it may be included. The calibration report refers to the amplifier, only, and not to the system in which it is inserted. When carrying out a calibration according to M1, the reference quantity, on the basis of which the procedure is conducted, is either the measured output current or the true value of the transformation coefficient. The transformation coefficient is the value of the trans-conductance, in case of voltage-current transformation regime, or the current gain intensity, in case of current amplification regime. Measurements for every combination of input signals transformation are supposed to be carried out besides the calibration method adopted. All measurement ranges of the UUT are supposed to be regarded in the examination as well. The measurement uncertainty, attributed to the measurand, is supposed to encompass all influential factors that affect both the measurement of the output current and the generation of input signals.

The second concept relies on a measurement configuration in which LEM's secondary standard, FLUKE 5500A [21] and the trans-conductance amplifier, FLUKE 52120A [20], form an integrated measurement system. The concrete calibration method will be referred to as M2. If M2 calibration method is adopted, the examination is carried out by regarding the measurement system, which comprises of the calibrator and the amplifier, as a UUT. The generated calibration report will refer to the measurement system as a whole and it will not provide information about the amplifier's sole performance. The measured quantity, if M2 is adopted, is the output current and the overall calibration uncertainty is comprised of influence factors that affect its recording, with the laboratory's primary RS [22], only. The performance of the calibrator along with the specification of the trans-conductance amplifier, will define altogether the declared accuracy limits of the measurement system.

The measurement points, in which the calibration will be carried out, are supposed to be selected such that the whole output ranges of UUT are covered in the examination and, in case of AC signals transformation, that the overall frequency scope is regarded as well. The following discussion is valid for any calibration method adopted. The overall measurements are according to the EURAMET cg-15 [8], however due to the excessive length of the measurement protocol only specific selected measurement points are discussed as examples in the paper. When either DC voltages or DC currents are transformed into high DC current output, 4 measurement points are selected for every output range of the transducer. These measurement points correspond to 10 %, 50 %, 90 % and -90 % of the amplifier's output range. When AC input signals are regarded, recordings in 6 measurement points are carried out, which correspond to 50 % and 90 % of the amplifier's output range and are chosen for 3 different frequency values: 50 Hz, 1000 Hz and 3000 Hz. The selected frequency scope is in correlation with the limitations presented in the manual of ZERA COM3003 [22], discussed earlier.

No matter which measurement method is adopted, several recording, n, for the output current are recorded in every measurement point for statistical scattering of measurement data to regard in the further evaluation. In the practical evaluation, $n = 5$ readings are considered sufficient for variations of the measurand to be depicted, since all three instruments possess high accuracy class, high stability over a long period of time and are placed in the top peak of the metrology traceability chain. The measured output current is then presented as mean value from n recordings, $I_{\mathrm{O,M}}$:

$$I_{\mathrm{O,M}} = \frac{1}{n} \sum_{i=1}^{n} I_{\mathrm{O},i}\,, \tag{1}$$

where $I_{\mathrm{O},i}$ are the single readings, recorded with the $\mathrm{RS_O}$. If the measured output current is regarded as the measurand, the calibration result, represented in the form of measurement error, equals:

$$\Delta I_{\mathrm{O}} = K_n\, X_{\mathrm{I}} - I_{\mathrm{O,M}}\,, \tag{2}$$

where K_n is the nominal transformation coefficient, for the selected range and input signals' transformation regime, and X_{I} is the intensity or the RMS value of the input signal. On the other hand, if the transformation coefficient is adopted as a reference quantity based on which the analysis is carried out, the measured value and the subsequent error is:

$$K_{\mathrm{M}} = \frac{I_{\mathrm{O,M}}}{X_{\mathrm{I}}}, \tag{3}$$

$$\Delta K = K_n - K_{\mathrm{M}}, \tag{4}$$

where $I_{\mathrm{O,M}}$, X_{I} and K_n possess the same meaning as described before.

The measurement uncertainty evaluation procedure is carried out by determination and analytical representation of all influence factors that affect the measurement of output current and the generation of input signals. If M1 is adopted for examination, the uncertainties attributed to the measured output current, and the generated input signal are grouped into separate categories. At the end of the evaluation, they are united for obtaining the overall uncertainty related to the calibration result. On the other hand, if the calibration is carried out according to the method M2, only the influence factors related to the output current measurement contribute to the overall calibration uncertainty. The input signals' related components are considered for evaluation of the measurement system's accuracy limits.

The overall uncertainty, attributed to the measured output current, is calculated as standard combined uncertainty [23]-[25], from 4, mutually uncorrelated, components:

$$u_{\mathrm{C,O}} = \sqrt{u_{\mathrm{A,O}}^2 + u_{\mathrm{R,O}}^2 + u_{\mathrm{SP,O}}^2 + u_{\mathrm{CL,O}}^2} \tag{5}$$

where, $u_{\mathrm{A,O}}$ is the uncertainty that exists due to statistical scattering of measurement data, $u_{\mathrm{R,O}}$ is a component that arises from the finite resolution of the $\mathrm{RS_O}$, $u_{\mathrm{SP,O}}$ is the standard's specification related uncertainty, while $u_{\mathrm{CL,O}}$ is a traceability related component, obtained during its level up calibration. The single influence factors are treated as mutually uncorrelated, and this is a usual approach when overall uncertainty in electrical measurements is evaluated [26]. The Type A uncertainty is a result of both fluctuations in the UUT's output and the integration speed of $\mathrm{RS_O}$, the resolution is related to the display setting of the $\mathrm{RS_O}$, the specifications of $\mathrm{RS_O}$ are provided regarding its manufacture quality, and the level up calibration component is a result of the examination protocol conducted with a higher accuracy class RS.

The uncertainty related to the statistical scattering of measurement data is evaluated as Type A uncertainty [23], [24]. It is calculated as standard deviation of the mean value, from the *n* recordings conducted:

$$u_{\mathrm{A,O}} = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} \left(I_{\mathrm{O},i} - I_{\mathrm{O,M}}\right)^2}, \tag{6}$$

and it is obtained by adopting *t*-distribution [23], taking into account the real number of recordings that are conducted and the fact that the single readings of the output current, $I_{\mathrm{O},i}$, may possess random value around the mean, with a specific degree of probability.

The second uncertainty component, related to the finite resolution of the $\mathrm{RS_O}$, is presented as:

$$u_{\mathrm{R,O}} = \frac{R}{2\, k_{\mathrm{R,O}}}, \tag{7}$$

where R is the resolution that corresponds to a specific measurement range of the $\mathrm{RS_O}$, and $k_{\mathrm{R,O}}$ is a factor, which is used for obtaining the standard uncertainty component from the distribution's half width. Usually, when resolution related uncertainty is evaluated, rectangular (uniform) distribution is adopted [24], hence $k_{\mathrm{R,O}} = \sqrt{3}$, taking into account that the actual value of the measurement quantity may be equal to any value within the interval of the reading plus/minus half resolution, with the same degree of probability.

The uncertainty component related to the standard's specification is calculated in a manner which is dictated by the instructions presented in its manual or datasheet. In case of primary RS of LEM, in the Operator manual [22], three different parameters regarding the specification are presented, and it is stated that the overall specification related uncertainty is calculated according to a "root sum of squares" principle. The specification related uncertainty is calculated as standard combined uncertainty of the concrete three components, regarding them as mutually uncorrelated:

$$u_{\mathrm{SP,O}} = \sqrt{u_{\mathrm{AC,O}}^2 + u_{\mathrm{ST,O}}^2 + u_{\mathrm{T,O}}^2}, \tag{8}$$

where $u_{\mathrm{AC,O}}$ is a standard uncertainty related to the declared accuracy limits for DC or AC current measurements, $u_{\mathrm{ST,O}}$ is a component related to the long term stability of the RS$_{\mathrm{O}}$, and $u_{\mathrm{T,O}}$ represents the temperature fluctuations influence on its performance. The concrete uncertainties are evaluated as follows:

$$u_{\mathrm{AC,O}} = \frac{U_{\mathrm{AC,\%}}}{k_{\mathrm{SP,O}}} \cdot \frac{I_{\mathrm{O,M}}}{100}, \tag{9}$$

$$u_{\mathrm{ST,O}} = \frac{U_{\mathrm{ST,\%}}}{k_{\mathrm{SP,O}}} \cdot \frac{I_{\mathrm{O,M}}}{100} \cdot y, \tag{10}$$

$$u_{\mathrm{T,O}} = \frac{U_{\mathrm{T,\%}}}{k_{\mathrm{SP,O}}} \cdot \frac{I_{\mathrm{O,M}}}{100} \cdot \Delta t\,, \tag{11}$$

where $U_{\mathrm{AC,\%}}$, $U_{\mathrm{ST,\%}}$, and $U_{\mathrm{T,\%}}$ are the specification related influence factors, presented in expanded relative form. In equations (9) – (11), $k_{\mathrm{SP,O}}$ is a factor used for determination of the standard uncertainty components from the distributions' boundaries. Given that no additional information is presented in [22], regarding $U_{\mathrm{AC,\%}}$, $U_{\mathrm{ST,\%}}$, and $U_{\mathrm{T,\%}}$ illustration, rectangular distribution is adopted, resulting in $k_{\mathrm{SP,O}} = \sqrt{3}$. In (10), y is a coefficient resembling the elapsed time since the last calibration of the RS$_{\mathrm{O}}$ and it is supposed to be expressed on yearly basis. This is due to the fact that the long term stability of the standard, $U_{\mathrm{ST,\%}}$, is expressed in (%/year) or (ppm/year) format. In (11), Δt represents the temperature fluctuations on the measurement site, due to the fact that the temperature fluctuations related uncertainty, $U_{\mathrm{T,\%}}$, is expressed in (%/K) or (ppm/K) format. As far as the practical part of the analysis is concerned, the measurements were carried out in less than 1 year period since the last calibration of ZERA COM3003 [22], therefore y = 1 year. The examination was conducted in temperature-controlled environment, t = 23 ± 1 °C, hence Δt is taken as 1 °C (or 1 K as stated in the specification), in every measurement point.

The last uncertainty component related to the UUT's output current measurement arises from the measurement traceability, i.e., from the level up calibration of the RS$_{\mathrm{O}}$. In calibration certificates, the uncertainty value is usually presented in relative, expanded form, $U_{\mathrm{CL,\%}}$, while the standard uncertainty equals:

$$u_{\mathrm{CL,O}} = \frac{U_{\mathrm{CL,\%}}}{k_{\mathrm{CL,O}}} \cdot \frac{I_{\mathrm{O,M}}}{100}, \tag{12}$$

where $k_{\mathrm{CL,O}}$ is a coverage factor that corresponds to the distribution adopted for evaluation of the level up calibration uncertainty. For the RS$_{\mathrm{O}}$, $U_{\mathrm{CL,\%}}$, is presented by adopting Gaussian distribution and coverage probability of 95 %, meaning that $k_{\mathrm{CL,O}}$ =1.96.

If the M2 calibration method is adopted, then the overall calibration uncertainty is comprised of output current measurement components only. Its expanded form may be presented as follows:

$$U_{\mathrm{C}} = U_{\mathrm{C,O}} = k_{\mathrm{O}} \cdot u_{\mathrm{C,O}}\,, \tag{13}$$

where k_{O} is a coverage factor that depends on the adopted overall distribution and the stated level of probability. If the conclusions of the Central Limit Theorem [23], [24] are adopted, the overall fluctuations of the measured output current may be approximated with a Gaussian distribution, considering that multiple influence factors are regarded and that they contribute to the overall budget linearly. If the coverage interval of 95.4 % is assumed, then k_{O} equals 2.

If the UUT is regarded as a standalone instrument, i.e., if M1 calibration method is adopted, the overall uncertainty is supposed to be expanded with influence factors that affect the generation of the input signals. The uncertainty attributed to the generated input signals may be presented as:

$$u_{\mathrm{C,I}} = \sqrt{u_{\mathrm{SP,I}}^2 + u_{\mathrm{CL,I}}^2}\,, \tag{14}$$

where $u_{\mathrm{SP,I}}$ is a component related to the specification of the generating unit, RS$_{\mathrm{I}}$, and $u_{\mathrm{CL,I}}$ is an uncertainty referred to its measurement traceability. The specification related component, regarding the proposed measurement configuration, where the input voltages and currents are generated from LEM's working standard, FLUKE 5500A [21], is calculated as:

$$u_{\mathrm{SP,I}} = \frac{1}{k_{\mathrm{SP,I}}} \cdot \left(\frac{U_{\mathrm{AP,\%}}}{100} X_{\mathrm{I}} + U_{\mathrm{AD}} \right), \tag{15}$$

where $U_{\mathrm{AP,\%}}$ is a component of the standard's declared absolute uncertainty given as a percentage of the set up value and U_{AD} is a fixed additional component, i.e., possible measurement drift. The value of 2 is substituted for $k_{\mathrm{SP,I}}$ in (15), due to the fact that the specification of FLUKE 5500A [21] is presented with 95.4 % degree of probability, assuming normal distribution. The level up calibration component is calculated similarly as the corresponding uncertainty of output current measurement:

$$u_{\mathrm{CL,I}} = \frac{U_{\mathrm{CL,I}}}{k_{\mathrm{CL,I}}} \cdot \frac{X_{\mathrm{I}}}{100}, \tag{16}$$

by substituting the value of 2 for $k_{\mathrm{CL,I}}$, taking into account that the expanded uncertainty, presented in calibration certificate of RS$_{\mathrm{I}}$ is presented with a probability of 95.4 %, regarding Gaussian distribution.

Finally, the overall uncertainty of the calibration procedure may be calculated, by regarding the input signal generation and the output current measurement components as mutually uncorrelated. If the output current is adopted as the measurand, the expanded measurement uncertainty equals:

$$U_{\mathrm{C}} = k_{\mathrm{C}} \sqrt{\left[\frac{\partial(\Delta I_{\mathrm{O}})}{\partial I_{\mathrm{O,M}}} \cdot u_{\mathrm{C,O}} \right]^2 + \left[\frac{\partial(\Delta I_{\mathrm{O}})}{\partial X_{\mathrm{I}}} \cdot u_{\mathrm{C,I}} \right]^2}\,, \tag{17}$$

where the sensitivity coefficients, $\partial(\Delta I_\mathrm{O})/\partial I_\mathrm{O,M}$ and $\partial(\Delta I_\mathrm{O})/\partial X_\mathrm{I}$, are calculated from (2). On the other hand, if the protocol is oriented toward obtaining the actual value of the transformation coefficient, the expanded calibration uncertainty may be calculated as follows:

$$U_\mathrm{C} = k_\mathrm{C}\sqrt{\left[\frac{\partial(\Delta K)}{\partial I_\mathrm{O,M}}\cdot u_\mathrm{C,O}\right]^2 + \left[\frac{\partial(\Delta K)}{\partial X_\mathrm{I}}\cdot u_\mathrm{C,I}\right]^2}\,, \tag{18}$$

and the corresponding partial derivatives, $\partial(\Delta K)/\partial I_\mathrm{O,M}$ and $\partial(\Delta L)/\partial X_\mathrm{I}$, are obtained from (3) and (4). Even though (3) and (4) represent a nonlinear model, the linear uncertainty propagation law may still be used. The $u_\mathrm{C,O}$ and $u_\mathrm{C,I}$ values are presented in absolute form, i.e. $u_\mathrm{C,O}$ possess the same dimension as the measured output current, while $u_\mathrm{C,I}$ possess the same dimension as the input signal, either it is a voltage or current, both DC or AC. According to (3) and (4), the partial derivatives equal:

$$\frac{\partial(\Delta K)}{\partial I_\mathrm{O,M}} = -\frac{1}{X_\mathrm{I}}\,, \tag{19}$$

$$\frac{\partial(\Delta K)}{\partial X_\mathrm{I}} = \frac{I_\mathrm{O,M}}{X_\mathrm{I}^2}\,, \tag{20}$$

and by their multiplication by the corresponding combined uncertainties, $u_\mathrm{C,O}$ and $u_\mathrm{C,I}$, values are obtained which possess the same dimension as the transformation coefficient, i.e., as the absolute error in its determination.

For depicting the overall fluctuations of the measurand, Gaussian distribution is adopted, considering that multiple influence factors are regarded. If the results are supposed to be presented with statistical certainty of 95.4 %, the coverage factor, k_C, will equal 2.

4. CASE STUDY RESULTS AND ANALYSIS

In the following discussion, specific calibration results, regarding the examination of FLUKE 52120 A [21], transconductance amplifier, will be presented, by considering the two proposed approaches discussed in the previous chapter of the manuscript. For unification of the results, obtained according to both calibration methods, the data in single measurement points will be presented in the form of output current measurement errors, ΔI_O. The discussion will be oriented toward error magnitude comparison, as well as uncertainty propagation analysis, in different signals transformation configurations.

The calibration results, obtained according to the M1 method, for every combination of input signals transformation, in the measurement point that corresponds to 90 % of the 20 A output current range, are illustrated in Figure 2. As can be seen, the measurement errors when AC current output is regarded are lower than the values obtained from the corresponding DC signals transformation configurations. The error is especially small when the amplifier is examined in ACV-ACI transconductance working regime. As stated earlier, the deviations are expected to be lower when AC output currents are measured, since the RS$_\mathrm{O}$ is an instrument intended primarily for AC power and energy recording.

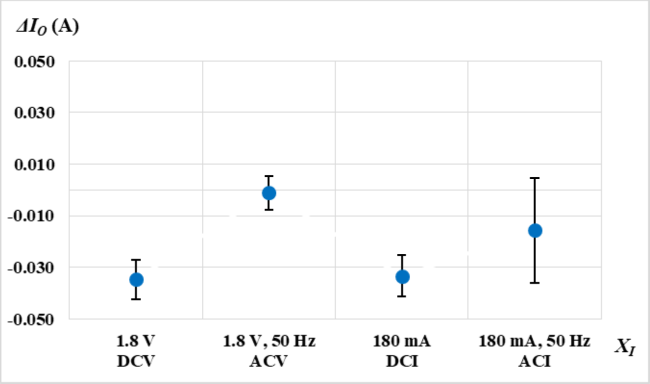

Figure 2. Results for 18 A output current measurement, assuming all combinations of input signals transformation and M1 calibration method

As far as measurement uncertainty is regarded, the lowest value is present in case of ACV input signals transformation. The DC voltage and DC current signals transformation regime results in almost equal overall calibration uncertainty value, while U_C is highest when the UUT is examined in AC current amplification regime. The detailed uncertainty magnitudes are presented in Table 4. It must be noted, before any further discussion, that the uncertainties related to input signals' generation are transformed dimensionally, by multiplication of the originally evaluated components, $u_\mathrm{SP,I}$ and $u_\mathrm{CL,I}$, by the corresponding sensitivity coefficient, $\partial(\Delta I_\mathrm{O})/\partial X_\mathrm{I}$

$$u''_\mathrm{SP,I} = \frac{\partial(\Delta I_\mathrm{O})}{\partial X_\mathrm{I}}\cdot u_\mathrm{SP,I} = K_n u_\mathrm{SP,I}\,, \tag{21}$$

$$u''_\mathrm{CL,I} = \frac{\partial(\Delta I_\mathrm{O})}{\partial X_\mathrm{I}}\cdot u_\mathrm{CL,I} = K_n u_\mathrm{CL,I}\,, \tag{22}$$

for the appropriate uncertainties, attributed to the measured output current to be obtained. The input signals related uncertainties, transformed into output current measurement domain, are referred to as $u''_\mathrm{SP,I}$ and $u''_\mathrm{CL,I}$ and are presented in the last two columns of Table 4.

As can be seen from Table 4, in domain of output current measurement, the dominant uncertainty is related to the traceability of the RS$_\mathrm{O}$, i.e., to its level up calibration, when AC signals transformation is regarded. In case of DC voltages and currents transformation, $u_\mathrm{CL,O}$ is lower than $u_\mathrm{SP,O}$, but both influence factors possess the same order of magnitude value and together dominantly shape the overall budget. As far as the input signals' generation is regarded, it may be concluded that the specification of FLUKE 5500A [21] contributes dominantly into

Table 4. Uncertainty propagation for any combination of signals transformation in measurement point of 18 A, M1 method.

Input signal, X_I	$u_\mathrm{A,O}$	$u_\mathrm{R,O}$	$u_\mathrm{SP,O}$	$u_\mathrm{CL,O}$	$u_\mathrm{SP,I}$	$u_\mathrm{CL,I}$	$u''_\mathrm{SP,I}$	$u''_\mathrm{CL,I}$
1.8 V, DCV	0.00016 A	0.000029 A	0.0037 A	0.0011 A	0.000048 V	0.000015 V	0.00048 A	0.00015 A
1.8 V, 50 Hz, ACV	0.000032 A	0.000029 A	0.00058 A	0.0011 A	0.0003 V	0.000034 V	0.003 A	0.00034 A
180 mA, DCI	0.00012 A	0.000029 A	0.0037 A	0.0011 A	0.011 mA	0.0066 mA	0.0011 A	0.00066 A
180 mA, 50 Hz, ACI	0.00002 A	0.000029 A	0.00058 A	0.0011 A	0.096 mA	0.031 mA	0.0096 A	0.0031 A

Table 5. Comparison between the overall uncertainties when DC signals are regarded, for 10 % of every measurement range, in both M1 and M2 calibration methods

Transformation regime	UUT output range	X_I	M1 U_C	M2 U_C
DCV-DCI	2 A	0.2 V	0.086 mA	0.085 mA
DCV-DCI	20 A	0.2 V	0.86 mA	0.85 mA
DCV-DCI	120 A	0.2 V	8.6 mA	8.5 mA
DCI-DCI	2 A	20 mA	0.09 mA	0.085 mA
DCI-DCI	20 A	20 mA	0.9 mA	0.85 mA
DCI-DCI	120 A	20 mA	9.1 mA	8.5 mA

the X_I uncertainty magnitude, for every measurement point. If input signals' transferred uncertainties are compared with the output current measurement related components, the previous conclusions, regarding the illustrations in Figure 2, may be verified. In case of AC voltage transformation, where the lowest overall uncertainty was detected, both input signals generation and output current measurement related components contribute equally on the overall budget. The overall uncertainty is dominated by the components that arise from the specification [22] and level up calibration of ZERA COM3003, when DC signals transformation is regarded. The opposite situation is present in case of AC currents amplification, where the highest overall calibration uncertainty was detected. In the concrete measurement point, $u_\mathrm{C,I}$ related influence factors are higher than the components that comprise $u_\mathrm{C,O}$ for an order of magnitude value.

The conclusions derived from the results illustrated in Figure 2 and the data presented in Table 4, may be further used for comparison between the two calibration methods. In Figure 3, errors, recorded for 100 A output current measurement point, when DC input signals are regarded, are illustrated, regarding the two perspectives for calibration. From Figure 3, it can be concluded that the overall uncertainty is approximately constant, nevertheless which calibration method is adopted. The concrete statement may be additionally verified from the data presented in Table 4, even though it corresponds to a different measurement point. In case of DCV-DCI conversion, the overall uncertainty attributed to calibration results, obtained according to the M1 method, is approximately 1 % higher than the corresponding value obtained according to the M2 method. If $u_\mathrm{C,O}$ and $u_\mathrm{C,I}$ are compared, it may be concluded that the input signals' related uncertainty is only 15 % of the value attributed to the output current measurement. Similar conclusion may be derived from the other two measurement points, illustrated in Figure 3, that correspond to DC currents amplification regime of the UUT. The overall uncertainty, obtained if M1 method is adopted, is approximately 6 % higher than the value obtained if a calibration of the whole measurement system, in which FLUKE 52120A is incorporated, is conducted. This implies that for DCI-DCI conversion regime, the input current generation related components possess value which is approximately 35 % of the intensity of the output current measurement uncertainty. For additional verification of the dominant influence factors, the overall uncertainties, in a measurement point that corresponds to a 10 % of every measurement range, are illustrated in Table 5, for both DCV-DCI and DCI-DCI operating regimes of the amplifier. It may be concluded that in the measurement points, which correspond to a same output current, the overall uncertainties are approximately equal if both DCV and DCI inputs are regarded, according to M1. The slight difference is a result of the contribution of $\mathrm{RS_I}$ in the overall budget. In case of M2, the expanded uncertainties are equal in the measurement points that correspond to the same output, considering that only $\mathrm{RS_O}$'s related components contribute to the overall budget. The uncertainties in different ranges, nevertheless which protocol is adopted, for the same input signals, differ for the magnitude of the transformation coefficient.

Alternate uncertainty propagation is recorded when the two calibration methods are compared in AC signals transformation regimes. An example of both ACV-ACI and ACI-ACI conversion results, in a measurement point that corresponds to 90 % of the 2 A output range, is illustrated in Figure 4. The input and output signals have frequency of 1 kHz. From the results presented in Figure 4, the prevalence of the influence factors that affect the generation of the input signals may be recorded. If the UUT is regarded as a standalone instrument, the overall calibration uncertainty is approximately 2.65 times higher than the value obtained if an examination of the overall measurement system is carried out. If AC currents amplification regime is regarded, an even greater difference between the two methods may be spotted. The overall uncertainty, calculated if M1 method is implemented, is between 7.5 times and 17 times higher than the $U_\mathrm{C,O}$ value. The difference is highly dependent on the input signals' frequencies and the concrete propagation will be presented in the discussion that follows. In Table 6, the expanded uncertainty magnitude, for the same input signal, in every output range, is presented, in both calibration methods. From the tabular results, the conclusions may be verified. The output current measurement uncertainty is approximately one third of the overall uncertainty, if M1 is adopted, when AC

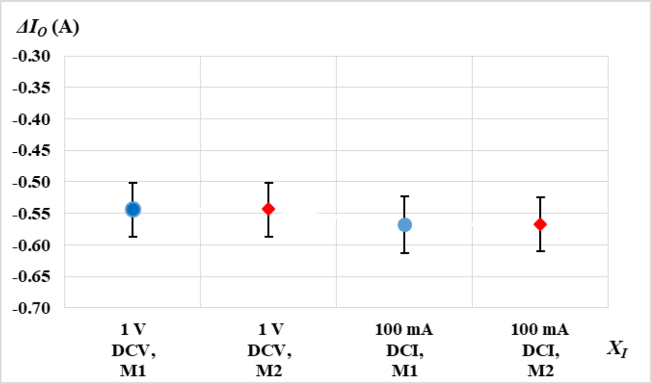

Figure 3. Results for 100 A output current measurement, assuming only DC signals transformation and both, M1 and M2, calibration methods

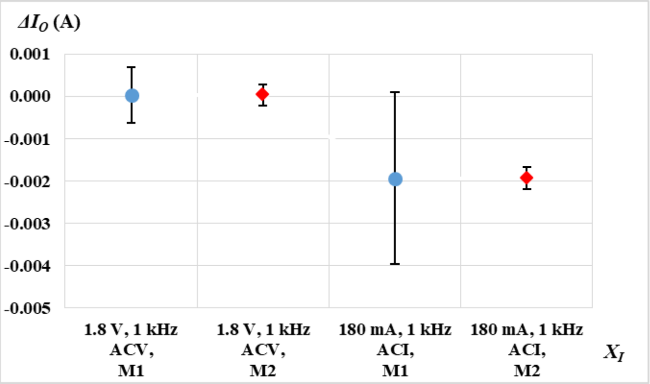

Figure 4. Results for 1.8 A output current measurement, assuming only AC signals transformation and both, M1 and M2, calibration methods

Table 6. Comparison between the overall uncertainties when AC signals are regarded, for 50 % of every measurement range, in both M1 and M2 calibration methods, f=50 Hz

Transformation regime	UUT output range	X_I	M1 U_C	M2 U_C
ACV-ACI	2 A	1 V	0.39 mA	0.14 mA
ACV-ACI	20 A	1 V	3.9 mA	1.4 mA
ACV-ACI	120 A	1 V	39 mA	14 mA
ACI-ACI	2 A	100 mA	1.2 mA	0.14 mA
ACI-ACI	20 A	100 mA	12 mA	1.4 mA
ACI-ACI	120 A	100 mA	120 mA	14 mA

voltage is brought to the amplifier's input. The concrete statement is obtained by comparing the U_C magnitudes, evaluated according to the two calibration methods. In case of AC current amplification regime, for 50 Hz frequency of the input signals, the M1 overall uncertainty is bigger than the $\mathrm{RS_O}$ related components, for approximately one order of magnitude value. As is the case with DC signals, the overall uncertainty in different output current ranges, for the same input signal's intensity, differ for the magnitude of the trans-conductance of FLUKE 52120.

The frequency characteristic of measured data will be presented from the M1 calibration method's perspective only. This is a case in which the influence factors that affect the measurement of the output current do not vary with frequency alteration, for the whole frequency bandwidth limited to 3.5 kHz, as stated in the specification of ZERA COM3003 [22]. This implies that the frequency related variations on the overall uncertainty are result of the $\mathrm{RS_I}$ performance only. Output current measurement errors, for measuring point that corresponds to 10 A recordings at different frequencies, for both ACV and ACI input signals, are presented in Figure 5. As can be seen from Figure 5, error magnitudes are slightly dependent on the frequency alteration and are lower when AC voltage input signals are regarded. In case of ACV-ACI transformation, the overall uncertainty is not significantly affected by the input voltage's frequency, because of the calibrator's specification [21] which is flatter in domain of the concrete quantity generation. Additionally, the overall uncertainty is still strongly dependent on the output current measurement influence factors. When the UUT is examined in AC current amplification regime, the overall uncertainty is flat for frequencies up to 1 kHz and it increases more than twice in relation to the previous values, when input currents at 3 kHz are generated into the amplifier.

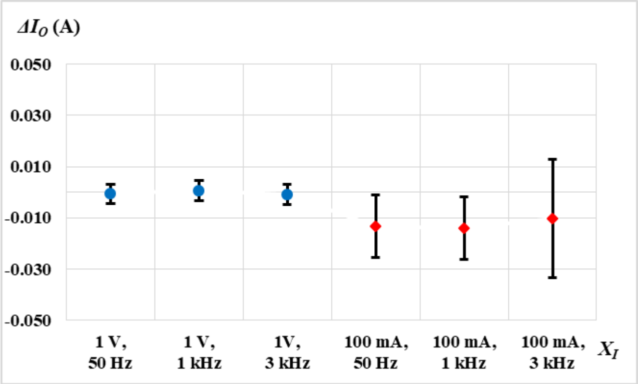

Figure 5. Results for 10 A output current measurement, at different frequencies, assuming AC signals transformation and M1 calibration method

5. PERSPECTIVE FOR IMPROVEMENT OF THE CALIBRATION PROTOCOL

The potential for improvement of the calibration protocol is perceived in addition of other reference standards in the measurement circuitry, which may result in measurement error and overall uncertainty decrease. The introduction of additional measurement units will result in a more complex calibration configuration and in a need of multiple measurement devices synchronization. A limitation regarding the accreditation scope of the laboratory is, once again, present.

The introduction of laboratory's primary RS in domain of DC and low frequency AC voltages and currents instruments calibration into amplifier's input signals' circuitry will affect the measurements, especially when AC current amplification regime is regarded. The concrete RS is an 8½ digit multimeter, Agilent 3458A [27], that possess best 1 year AC current measurement accuracy of ± 0.03 %. Regarding the specification of the used $\mathrm{RS_I}$ [21], presented earlier in Table 2, the addition of the 8½ digit multimeter may decrease the overall calibration uncertainty by 2 times. The concrete conclusion is derived from the earlier practical evaluation presented in Table 4, considering that the dominant influence factor in examined ACI-ACI transformation regime is related to the declared accuracy of FLUKE 5500 A [21]. LEM's primary RS, Agilent 3458A [27], may be connected in the input circuitry, for improvement of the measurement performance, when the transformation of AC voltage signals is examined, as well. However, considering that in the concrete regime, the lowest overall uncertainty is recorded, and that it is distributed equally in terms of input voltage and output current measurement influence factors, the introduction of a higher accuracy class RS will have negligible effect of the overall process.

As the overall uncertainty in case of DC voltage and current transformation is dominated by the influence factors related to high current measurements, eventual improvements are supposed to be carried out in the amplifier's output measurement circuitry. In the disposal of LEM, no other measuring instrument for direct recording of high currents, up to 120 A, is available, beside ZERA COM3003 [22]. Alternative measurement configuration may be accomplished via introduction of additional signal's transformation, by using current shunt, and the 8½ digit multimeter. The best 1-year specification of Agilent 3458A in domain of low DC voltages measurement equals 0.0014 % which is far better than the measurement capabilities of ZERA COM3003, presented in Table 2. A problem for realization of the concrete configuration is related to the shunt's actual resistance determination. The nominal resistance of the shunts that are on LEM's disposal, equals less than 1 mΩ, which is far beyond its current accreditation scope. The measurement capabilities of the 8½ digit multimeter [27] for such low resistance measurements are limited as well, primary due to its resolution, which equals 10 μΩ at the lowest range. Currently, for mitigating this obstacle, the laboratory is in a process of acquisition of more sophisticated standards, with better technical specifications. The evaluation of uncertainty of the perspective measurement system, which is planned to be accredited, is under current research.

6. CONCLUSIONS

In this study, an original calibration protocol for examination of trans-conductance amplifier is presented, developed, and validated in an accredited calibration laboratory. The calibration scheme is realized according to the need for the simplest possible measurement configuration establishment, regarding direct recording of both input and output quantities, with an appropriate level of accuracy. Two perspectives for UUT examination are covered in the concrete work, by regarding the amplifier as a standalone instrument and by assuming that it is an integrated part of a measurement system.

Regarding the calibration method adopted, measurement points are proposed, which are supposed to cover full transformation range of the UUT. Mathematical modelling of measurement uncertainty is presented as well, by analytical evaluation of all influence factors that affect the examination procedure i.e., that may be related to both input signals' generation and output current measurement fluctuations. Given that the input and output signals are generated/ measured directly, single uncertainty components may be attributed to input voltages or currents and high current output at first hand.

From the practical part of the analysis, several important conclusions are derived regarding the adequacy of the proposed configuration. By real-time measurements it may be observed that errors in case of DC signals transformation regime calibration are higher than the corresponding results, if the UUT is regarded as AC signals transducer. The concrete phenomena are dominantly related to the specifications of the RS_O, used for high current output measurement, considering that the concrete unit is primarily an AC power and energy measuring device. From the uncertainty propagation analysis, a comparison between the two proposed calibration methods is presented. It is concluded that when DC signals' transformation is regarded, the dominant influence factors arise from the specification and level up calibration of the RS_O, used for output current monitoring. When AC signals are regarded, the specification of the calibrator, used for input generation, plays the dominant role in the overall budget and the calibration uncertainty significantly differs if the UUT is regarded as a standalone unit in comparison to the scenario where it is regarded as a part of an integrated system. This is especially visible in case of AC current amplification regime, where the overall uncertainty calculated according to the first method is up to 17 times higher than the value obtained if the second approach is adopted.

In the end of the contribution, an improved measurement solution is presented, regarding introduction of the highest accuracy class reference standard available. The concrete RS may provide accuracy improvement in some parts of the proposed protocol, however in the others, constraints regarding the eventual further signal transformation, from the perspectives of the laboratory's accreditation scope, are detected.

REFERENCES

[1] Fluke Corporation, Calibration: Philosophy in Practice – Second edition, USA, 1994, ISBN 0-9638650-0-5

[2] K. Demerdžiev, V. Dimčev, Uncertainty budget evaluation principle in high and low resolution digital multimeters calibrations, Journal of Electrical Engineering and Information Technologies 4 (2019) 2, pp. 5-13. DOI: 10.51466/JEEIT1941-205d

[3] European Committee for Electrotechnical Standardization (CENELEC), Electricity metering equipment (a.c.) Part 1: General requirements, tests and test conditions – Metering equipment (class indexes A, B and C), EN 50470-1:2006+A1:2018, Brussels, Belgium, 2018.

[4] European Committee for Electrotechnical Standardization (CENELEC), Electricity metering equipment (a.c.) Part 2: Particular requirements - Electromechanical meters for active energy (class indexes A and B), EN 50470-2:2006+A1:2018, Brussels, Belgium, 2018.

[5] European Committee for Electrotechnical Standardization (CENELEC), Electricity metering equipment (a.c.) Part 3: Particular requirements - Static meters for active energy (class indexes A, B and C), EN 50470-3:2006+A1:2018, Brussels, Belgium, 2018.

[6] International Electrotechnical Committee (IEC), Electricity metering equipment - Particular requirements - Part 23: Static meters for reactive energy (classes 2 and 3), IEC 62053-2:2020. Geneva, Switzerland, 2020.

[7] International Organization of Legal Metrology (OIML), Active electrical energy meters. Part 1: Metrological and technical requirements and Part 2: Metrological controls and performance tests, OIML R 46-2 & 1:2012, Paris, France, 2012.

[8] European Association of National Metrology Institutes (EURAMET), Guidelines on the Calibration of Digital Multimeters – EURAMET cg-15, Version 3.0, Braunschweig, Germany, 2015. Online [Accessed 17 Augusr 2023] https://www.euramet.org/Media/docs/Publications/calguides/EURAMET_cg-15__v_2.0_Guidelines_Calibration_Digital_Multimeters.pdf

[9] European Association of National Metrology Institutes (EURAMET), Calibration of Measuring Devices for Electrical Quantities, Calibration of Oscilloscopes – EURAMET cg-7, Version 1.0, Braunschweig, Germany, 2011. Online [Accessed 17 Augusr 2023] https://www.euramet.org/Media/docs/Publications/calguides/EURAMET_cg-7__v_1.0_Calibration_of_Oscilloscopes.pdf

[10] European Parliament and Council, EU Directive on Measuring Instruments (MID), 2014/32/EU, Brussels, Belgium, 2014.

[11] Laboratory of Electrical Measurements – Faculty of Electrical Engineering and Information Technologies, Working Instruction on Calibration of Multimeters, RU 7.2.01, Skopje, North Macedonia, 2019.

[12] Laboratory of Electrical Measurements – Faculty of Electrical Engineering and Information Technologies, Working Instruction on Calibration of Calibrators, RU 7.2.03, Skopje, North Macedonia, 2019.

[13] Laboratory of Electrical Measurements – Faculty of Electrical Engineering and Information Technologies, Working Instruction on Expression of Uncertainty – General Procedure, RU 7.2.04, Skopje, North Macedonia, 2019.

[14] A. Delle Femine, D. Gallo, C. Landi, M. Luiso, Advanced instrument for field calibration of electrical energy meters, IEEE Transactions on Instrumentation and Measurement 58.3 (2008) pp. 618-625. DOI: 10.1109/TIM.2008.2005079

[15] D. Naumovic-Vukovic, S. Skundric, D. Kovacevic, S. Milosavljevic, Calibration of high accuracy class standard current transformers, In Proceedings of XIX IMEKO World Congress Fundamental and Applied Metrology, Lisbon, Portugal, 6-11 September 2009, pp. 621-625. . Online [Accessed 17 Augusr 2023] https://www.imeko.org/publications/wc-2009/IMEKO-WC-2009-TC4-318.pdf

[16] International Organization for Standardization (ISO), General requirements for the competence of testing and calibration laboratories, ISO/IEC 17025, Geneva, Switzerland 2017.

[17] BIPM website. Online [Accessed 23 January 2023] https://www.bipm.org/en/

[18] K. Demerdziev, M. Cundeva-Blajer, V. Dimchev, M. Srbinovska, Z. Kokolanski, Improvement of the FEIT laboratory of electrical measurements best CMC through internationally traceable calibrations and inter-laboratory comparisons, Proc. of the XIV Int. Conf. ETAI, Struga, R. North Macedonia, September 2018.

[19] K. Demerdziev, M. Cundeva-Blajer, V. Dimchev, M. Srbinovska, Z. Kokolanski, Defining an uncertainty budget in electrical power and energy reference standards calibration, In Proceedings of IEEE EUROCON 2019-18th Int. Conf. on Smart Technologies, Novi Sad, Serbia, 1-4 July 2019, pp. 1-6.

DOI: 10.1109/EUROCON.2019.8861600
[20] FLUKE Corporation, 52120A Transconductance Amplifier Users Manual, USA, 2012.
[21] FLUKE Corporation, 5500A Multi – Product Calibrator Operator Manual, USA, 1994.
[22] ZERA GmbH, Three Phase Comparator COM3003 Operation Manual, Königswinter, Germany, 2012.
[23] JCGM 100 with member organizations (BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML), Evaluation of measurement data – Guide to the expression of uncertainty in measurement (GUM), 2008.
[24] P. Osmanovik, K. Stankovik, M. Vujisik, Мерна несигурност – Measurement Uncertainty, Akademska Misao, Belgrade, Serbia, 2009, ISBN 978-86-7466-376-9 [in Serbian].
[25] J. V. Nicholas, D. R. White, Traceable Temperatures: an Introduction to Temperature Measurement and Calibration, John Wiley and Sons, New York, USA, 2001, ISBN 0-470-84615-1.
[26] European Accreditation (EA), Evaluation of the Uncertainty of Measurement in Calibration, EA-4/02, Netherlands, 2022.
[27] Agilent Technologies, 3458A Multimeter User’s Guide, USA, 2000.