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METROLOGY AMBIGUITIES IN PROTOCOLS FOR TRANS-CONDUCTANCE AMPLIFIER CALIBRATION BY USING HIGH CURRENT ENERGY COMPARATOR

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Abstract:

The main metrological ambiguity in transducers' calibration protocols establishment is whether the unit is going to be regarded as an integrated device in a measurement system, or it will be examined as a standalone instrument. This dilemma is related to the quantity selection on which the procedure development is based and later the measurement uncertainty modelling is performed. Another issue is the appropriate selection of measurement points which are going to embrace the full range of input signals transformation. The discussion is experimentally verified with a real case study considering trans-conductance amplifier calibration by using high current energy comparator.

Keywords: trans-conductance amplifier, measurement uncertainty, reference standard.

1. INTRODUCTION

A calibration procedure is periodic examination of an instrument or a measurement system, conducted by comparison between its actual measurement performance and a known reference value [1]. In the domain of instruments for electrical quantities, plenty international standards [2-5], recommendations [6], and guides [7-8] exist, which are usually adopted as a framework for calibration protocols establishment. The directions presented in these documents impose that examination of any Unit Under Test (UUT) would embrace its most critical operating conditions. Additionally, measurement points are provided [7-8], for the whole measuring range of the UUT to be covered in the calibration.

The framework presented in the internationally recognized standards and guides is usually adopted in the quality systems of calibration laboratories, and is used as a base for routine examination schemes performance [9-11]. On the other hand, when more complex measurement instruments and systems are subjected for calibration, development of original calibration protocols is required. Such unique procedures are developed for examination of specific types of electrical transducers [12-13].

The main metrological ambiguity in the establishment of a calibration protocol for different types of electrical transducers is related to the fact that they cannot be operated independently, outside of a measurement system. If the examination is conducted by measurement of both the input and output signals, then the transducer is calibrated as a standalone unit and the results are applicable for further broader usage. If only its output is compared to a known reference, then the results obtained are valid for the whole measurement system in which the concrete transducer belongs. The measurement method selection would later affect the measurement uncertainty evaluation procedure, in terms of dominant influential factors determination and in overall budget distribution modelling.

In the contribution, an original calibration protocol for examination of a trans-conductance amplifier, as a specific electrical transducer, will be presented. Two scenarios, regarding the UUT both as a standalone instrument and as a part of a measurement system will be realized and the outcomes will be discussed. For the two calibration schemes an analysis of the uncertainty propagation will be conducted. The development of the calibration protocol and its experimental verification are conducted in an accredited calibration laboratory according to international standard MKC EN ISO/IEC 17025:2018 [14].

2. MEASURING EQUIPMENT

The specified calibration protocol is designed and validated in the Laboratory for Electrical Measurements (LEM) at the Faculty of Electrical Engineering and Information Technologies (FEEIT), Ss. Cyril and Methodius University in Skopje (UKIM). The laboratory has on disposal several reference standards (RS), which are periodically calibrated [15-16], and maintains international traceability to the BIPM [17] intrinsic primary international standards.

As already stated, the UUT is a high current trans-conductance amplifier, FLUKE 52120A [18]. The device is intended for both DC and AC input voltage and current signals transformation into DC and AC output currents. The input signals are limited to 2 V and 200 mA. The current output of FLUKE 52120A [18] is realized via 3 ranges of 2 A, 20 A and 120 A and both low current (up to 20 A) and high current (up to 120 A) output terminals.

For the purposes of calibration procedure establishment, two reference standards of LEM are deployed. The secondary standard, FLUKE 5500A multifunctional calibrator [19] is used for providing the low voltage and current input signals. It is DC and low-frequency AC, voltage and current source, primarily intended for calibration of multimeters, with resolution of up to 6 ½ digits. Its best 1 year specification, related to the reproduction of different electrical signals, is illustrated in Table 1.

Table 1: 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

For measurement of the amplifier's output currents, the primary RS of LEM, in domain of electrical power and energy, ZERA COM3003 [20], is used. Even though it is constructed for high accuracy power and energy measurements, in the concrete procedure, ZERA COM3003 is regarded as a high current indicator, i.e. only the current input terminals of a single phase are used. Its best 1 year specification in domain of DC and AC currents measurement is presented in Table 2.

Table 2: ZERA COM3003 best 1 year specifications

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

The main advantage of the two reference standards configuration is the simplicity of the calibration procedure scheme, illustrated in Figure 1. Any additional instrumentation would result in increased complexity of the electrical circuitry, introducing the risk of creating additional errors due to extra connections and further signal transformation.

On the other hand, the concrete measurement configuration results in a single deficiency, even before any measurement data is analyzed. Namely, according to [20], the frequency bandwidth for both current and voltage measurements is limited to 3.5 kHz, regarding both fundamental and harmonic components. The frequency limitation in measurement with the primary RS is not compliant to the frequency range of the UUT [18] and the signal source [19], which results in non-coverage of the full transformation range of FLUKE 52120 A.

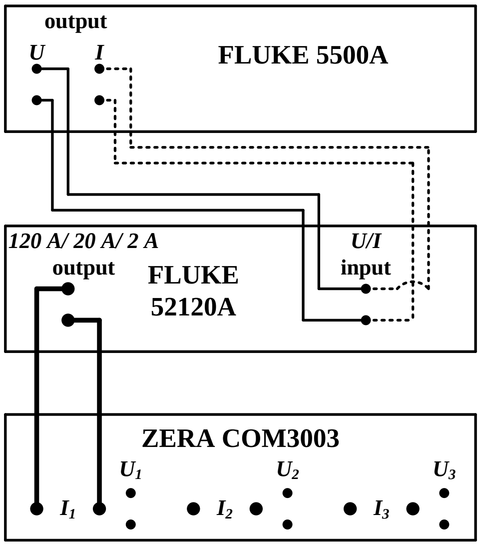

Figure 1: Connection of UUT and the two RS

3. MEASUREMENT POINTS SELECTION AND UNCERTAINTY BUDGET EVALUATION

The first thing which should be determined before the protocol is established, is whether the amplifier is going to be regarded as a standalone unit or it is going to be examined as part of a larger measurement system. The first method (M1) results in performance check of the UUT's output current or transformation coefficient. In such a scenario, the reported measurement uncertainty is supposed to encompass all influential factors that affect both the measurement of the output current and the generation of the input signals. If the second method (M2) is adopted, then the calibration results correspond to the performance of the measurement system, in which the UUT is incorporated. The quantity regarded is the output current and the overall uncertainty will comprise only the components related to its measurement. The signal source performance, as well as the UUT's specifications, are combined together to represent the accuracy limits of the measurement system.

The measurement points, in which the examination is about to take place, are chosen in a way that all measurement ranges and combinations of input signal transformation are covered. For the appropriate selection of the measurement points, remarks presented in EURAMENT cg-15 [7] are implemented. When the input signals are either DC currents (DCI) or DC voltages (DCV), the examination is conducted in 4 measurement points for every DCI output range. The measurement points correspond to 10 %, 50 %, 90 % and -90 % of the UUT's output (or input) range. When AC currents (ACI) or AC voltages (ACV) are regarded as input signals, recordings in 6 measurement points are made. The measurement points correspond to 10 % and 90 % of every output current range, and are chosen for 3 different frequencies of the input signals: 50 Hz, 1000 Hz and 3000 Hz.

In every measurement point, n=5 current output readings are recorded. The most relevant data, obtained as a calibration result, is the arithmetic mean, $I_{O,M}$, of single readings, $I_{O,i}$:

$$I_{O,M} = \frac{1}{n}\sum_{i=1}^{n} I_{O,i} \, . \quad (1)$$

If the analysis is conducted by assuming the output current as a measured quantity, then the measurement error is presented as:

$$\Delta I_O = K_n X_I - I_{O,M} \, , \quad (2)$$

where K_n is the nominal transformation coefficient of the trans-conductance amplifier and X_I is the input signal generated from FLUKE 5500A [19]. The nominal transformation coefficient is the value of the trans-conductance, in case of voltage input/ current output configuration, or the current gain, for low current input/ high current output configuration.

On the other hand, if the transformation coefficient's actual value, K_M, is subject of analysis, the calibration result and the subsequent error equal:

$$K_M = \frac{I_{O,M}}{X_I} \, , \quad (3)$$

$$\Delta K = K_n - K_M \, , \quad (4)$$

where $I_{O,M}$, X_I and K_n possess the same meaning as described above.

The uncertainty components are divided into two categories, i.e. components related to the measured output current, and components related to the generated input signals. The first uncertainty component, related to the measured output current, is a result of the scattering of the single readings around the mean value, (1). This component is referred to as Type A uncertainty [21]. It is calculated as standard deviation of the mean value, $I_{O,M}$, from the n measurements conducted:

$$u_A = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}\left(I_{O,i} - I_{O,M}\right)^2} \, , \quad (5)$$

assuming Gaussian distribution for presentation of the measured data propagation. The second uncertainty component is related to the reference standard's [20] finite resolution, r, and it is calculated by adopting uniform distribution [21-22]:

$$u_R = \frac{r}{2 \cdot \sqrt{3}} \, . \quad (6)$$

The following 3 uncertainty components, emerge from the RS's [20] specification. They are result of the declared accuracy limits of the RS, its long-term stability and temperature influence on its performance. For the data presented in [20], a uniform distribution is adopted, and single uncertainty components are calculated as follows:

$$u_{AC} = \frac{U_{AC,\%}}{k} \cdot \frac{I_{O,M}}{100} \, , \quad (7)$$

$$u_{ST} = \frac{U_{ST,\%}}{k} \cdot \frac{I_{O,M}}{100} \cdot y \, , \quad (8)$$

$$u_T = \frac{U_{T,\%}}{k} \cdot \frac{I_{O,M}}{100} \cdot \Delta t \, , \quad (9)$$

where $U_{AC,\%}$, $U_{ST,\%}$ and $U_{T,\%}$ are the accuracy limits, long term stability and temperature drift of ZERA COM3003 [20], expressed as expanded percentage values. In equations (7)-(9), k is the coverage factor, which for uniform distribution equals √3 [21-22], y is the time that has passed since the last calibration of the RS, and Δt are temperature variations during the measurements. In the moment of measurements less than 1 year has passed since the last calibration of the RS [20], therefore y=1 in the following modelling. As the calibrations in LEM are conducted in a temperature controlled environment, i.e. t=23±1 ˚C, Δt is taken as 1˚C (K) for every measurement point.

The last uncertainty component related to output current measurement arises from the level up calibration of the RS. In calibration certificates, the uncertainty is commonly presented as an expanded value, $U_{CL,\%}$. The standard value then equals:

$$u_{CL} = \frac{U_{CL,\%}}{k} \cdot \frac{I_{O,M}}{100} \, , \quad (10)$$

where $k=1.96$, as the $U_{CL,\%}$ is presented with a coverage probability of 95 %, assuming Gaussian distribution.

The overall uncertainty prescribed to the measured output current is calculated as standard combined uncertainty from 6 mutually uncorrelated components:

$$u_O = \sqrt{u_A^2 + u_R^2 + u_{AC}^2 + u_{ST}^2 + u_T^2 + u_{CL}^2} \, , \quad (11)$$

and if the calibration is conducted by taking the UUT as integrated device in a measurement system (M2), the overall uncertainty equals:

$$U_C = 2 \cdot u_O \, , \quad (12)$$

assuming Gaussian distribution and confidence interval of approximately 95.4 % [21].

If the amplifier is regarded as a standalone instrument, the uncertainty budget is further expanded with components related to the input signal generation. The overall input signal related uncertainty is calculated as:

$$u_I = \sqrt{u_{RS,I}^2 + u_{CL,I}^2}\,, \qquad (13)$$

where $u_{RS,I}$ is the component arising from the signal source's specifications [19] and $u_{CL,I}$ is component corresponding to its level up calibration. The first uncertainty component, $u_{RS,I}$, is calculated as:

$$u_{RS,I} = \frac{1}{k}\left(\frac{U_{GV,\%} \cdot X_I}{100} + U_{AD}\right), \qquad (14)$$

where $U_{GV,\%}$ is part of the specification, expressed as a percentage of the generated value, and U_{AD} is a fixed additional component. In equation (14) X_I is the input signal in FLUKE 52120A, while the coverage factor k equals 2, because in the specifications [19] data is presented by adopting Gaussian distribution and coverage probability of 95.4 %. The second uncertainty component related to the input signals generation is calculated as described in equation (10), but instead of the mean measured output current, $I_{O,M}$, the generated signal intensity, X_I, is supposed to be included.

If the output current is regarded as the measured quantity, then the overall uncertainty is calculated by assuming the input and output related components as mutually uncorrelated:

$$U_C = k\sqrt{\left(\frac{\partial(\Delta I_O)}{\partial I_{O,M}} \cdot u_O\right)^2 + \left(\frac{\partial(\Delta I_O)}{\partial X_I} \cdot u_I\right)^2}\,, \qquad (15)$$

where the sensitivity coefficients $\partial(\Delta I_O)/\partial I_{O,M}$ and $\partial(\Delta I_O)/\partial X_I$ are calculated from equation (2). On the other hand, if the transformation coefficient is regarded as a measurand [21], the overall uncertainty equals:

$$U_C = k\sqrt{\left(\frac{\partial K_M}{\partial I_{O,M}} \cdot u_O\right)^2 + \left(\frac{\partial K_M}{\partial X_I} \cdot u_I\right)^2}\,, \qquad (16)$$

and the sensitivity coefficients, $\partial K_M/\partial I_{O,M}$ and $\partial K_M/\partial X_I$, are calculated from (3) and (4). In both cases the overall uncertainty is presented in expanded form, assuming Gaussian distribution. The coverage factor, k, equals 2, which corresponds to a coverage probability of 95.4 % [21-22].

4. CALIBRATION RESULTS DISCUSSION

In the following discussion, the results from the examination of FLUKE 52120A trans-conductance amplifier, assuming both calibration methods, will be presented. Several aspects of the calibration procedures will be analyzed and the main accent will be stressed on the uncertainty propagation.

Calibration results, in the measurement point that corresponds to 90 % of the 20 A output range, are illustrated in Figure 2. Measurement errors, alongside the calculated expanded uncertainty, are provided, considering the amplifier as a standalone unit, i.e. M1 calibration method is implemented. Each of the measurement points presented, refer to a different input signal transformation. At the bottom of Figure 2, the input signals intensities (and frequency in case of AC signals) are presented.

A first conclusion that can be derived from Figure 2 is that smaller errors are recorded in AC signals transformation measurement points. This phenomenon is related with the performance of ZERA COM3003 [20], taking into account that this reference standard is primary intended for high accuracy AC power and energy measurements.

As long as measurement uncertainty is regarded, it can be seen that the lowest value is recorded in case of ACV-ACI transformation. This is the result of the low output current related uncertainty [20], as well as approximately same order of magnitude accuracy of FLUKE 5500A in domain of the AC voltages generation, [19]. When the transformation of DC signals is regarded, a slight increase in the overall uncertainty is recorded, which is dominantly a result of current output measurement performance. The highest uncertainty is recorded in case of AC current amplification, and it is dominated by the accuracy specifications of FLUKE 5500A [19].

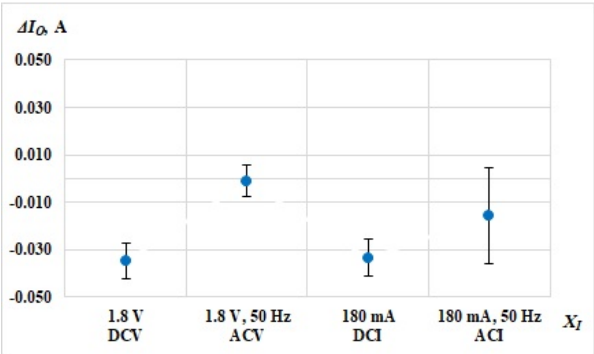

Figure 2: Calibration results for 18 A output current, assuming the UUT as a standalone instrument and regarding every type of input/output signals conversion

The uncertainty propagation in case of different frequencies of the input AC signals, assuming calculation according to M1 calibration protocol and 10 A output current, is illustrated in Figure 3. Errors are little dependent on the input signals frequencies, which is also the case with the uncertainty intensity, if ACV input signals are regarded. In domain of ACI-ACI transformation, the uncertainty increases with the rise of the input signal's frequency. These variations are due to the dominant influence of the signal source specification in the overall budget modelling, which is strongly frequency dependent [19].

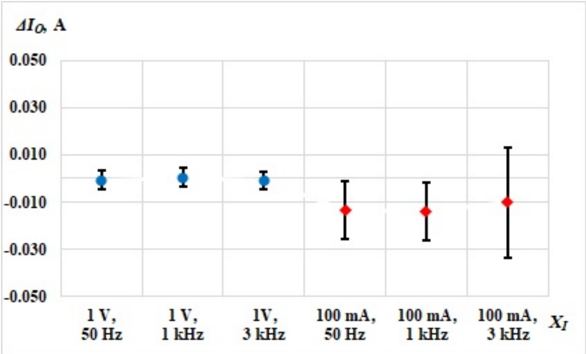

Figure 3: Calibration results for 10 A output current, assuming the UUT as a standalone instrument, and regarding different frequencies of the input signals

In Figure 4 the comparison between the 2 calibration methods, in domain of DC signals transformation, is presented. The measurement point which is chosen for illustration corresponds to 100 A current output of the 120 A range.

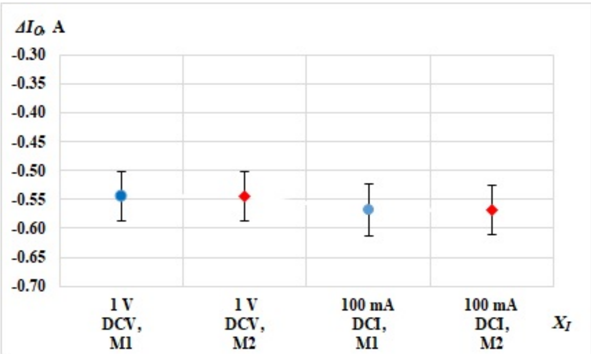

Figure 4: Calibration results for 100 A output current readings, regarding transformation of DC input signals

It can be concluded that the overall uncertainty is approximately equal, nevertheless the calibration method adopted. This implies that, in case of DC signals transformation, the output current measurement uncertainty prevails over the input signal generation related components. In case of DCV-DCI conversion, the overall uncertainty calculated according to M1 is approximately 1 % higher than the value obtained if the amplifier is regarded as a part of a measurement system. The uncertainty accompanied to the input signals generation is approximately 15 % of the uncertainty accompanied to the output current measurement. Similar data is recorded from the measurement points that correspond to DCI-DCI conversion regime. The overall uncertainty calculated according to the first calibration method is approximately 6 % higher than the results obtained if M2 protocol is implemented. When the UUT is examined as a DCI amplifier, the u_I value is approximately 35 % of u_O value.

Considering the AC signals transformation, different disposition of the dominant uncertainty components is recorded. An example of ACV-ACI and ACI-ACI transformation is illustrated in Figure 5, for both M1 and M2 protocols implemented. The input signals with frequency of 1 kHz correspond to 90 % of the 2 A output range.

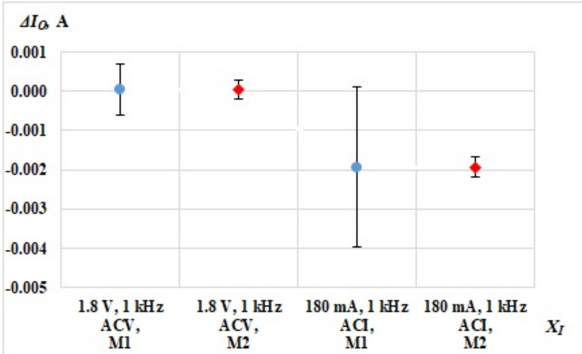

Figure 5: Calibration results for 1.8 A output current readings, regarding transformation of AC input signals

The prevalence of the input signals' related influential factors in the overall uncertainty budget, is presented in Figure 5. If the UUT is regarded as a standalone instrument, in domain of ACV-ACI conversion examination, the overall uncertainty is approximately 2.75 times higher than the value obtained if the M2 protocol is implemented. The input voltage related uncertainty is 2.56 times higher than the value accompanied to the measured output current. If ACI amplification is regarded, then the differences in the uncertainty intensities are even bigger. ACI-ACI conversion regime results in between 8.5 and 17 times bigger uncertainty if M1 method is implemented in relation to the M2 method. The uncertainty intensity propagation depends primary on the input current's frequency.

5. SUMMARY

In the manuscript, an original protocol for trans-conductance amplifier calibration is presented, developed in an accredited calibration laboratory. Two perspectives are analysed, in the first the amplifier is regarded as a standalone unit, while in the second its performance is monitored as part of a measurement system. The results from the first measurement procedure are appropriate for further broader usage, while the second protocol results in measurement data that depict the actual condition of the concrete measurement system only.

The main advantage of the presented calibration scheme is its simplicity, the input signals are generated from a high accuracy signal source, while the output currents are measured directly, without further signal transformation. This approach leads to uncertainty budget modelling, whose components are directly accompanied to both input and output signals. If DC signals are regarded, there is no significant difference in the overall uncertainty intensity between the two considered calibration models. This is due to the fact that the dominant influential factors are related to accuracy of the reference standard intended for output current measurement. On the other hand, when AC current is the measured quantity, there is significant difference between the overall uncertainty propagation in the two regarded scenarios. The signal source's specification is dominant in the shaping of the overall budget in the case when the UUT is regarded as standalone instrument, and it also results in frequency dependence of the uncertainty propagation.

The presented calibration scheme possess certain shortcomings as well. DC current measurement errors are larger than the deviations recorded in case of AC signals transformation regime. This is due to the fact that the energy comparator, intended for output current measurement, is primary intended for AC signals power and energy monitoring. Another deficiency in the output current measurement is related to RS's frequency confinement at 3.5 kHz. Further improvement of the calibration model, may include additional instrumentation for output current monitoring, for example current shunt and high resolution digital voltmeter. This approach may result in error decrease and frequency bandwidth expansion. However it may have adverse effects of additional drift existence due to extra measuring devices' connections influence.

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