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Improvement of metrology infrastructure in the area of extreme impedance calibrations

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ABSTRACT
The paper describes how the Laboratory for Electrical Measurements at the Ss. Cyril and Methodius University in Skopje, an accredited calibration laboratory, enhanced its calibration and measurement capabilities for extreme values of electrical impedance. This was conducted through development of new calibration methods for instruments that measure extreme electrical resistance and inductance. The paper also explains how these methods were validated to ensure traceability and how the measurement uncertainty in impedance instruments calibration was innovatively estimated, by deploying the data fusion concept to increase the metrology infrastructure capacity. As the testing facilities for electrical quantities in Southeast Europe are not sufficiently developed, and some calibration areas of electrical instruments are not well provided by the existing laboratories, despite the economic and scientific demands, the relevance of this metrology infrastructure upgrade is evident.

Section: RESEARCH PAPER

Keywords: Extreme impedance; calibration of inductance; calibration of high resistance; CMC

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1. INTRODUCTION

The paper discusses how the metrology infrastructure for electrical quantities in Southeast Europe is being improved. The metrology infrastructure in this region is underdeveloped and some calibration areas of electrical instruments are not well covered by the existing metrology laboratories, even though there are economic and scientific demands for them [1].

The contribution presents how the metrology infrastructure is being enhanced in two ways:

1) by enabling the traceable measurements, i.e., calibrations of very high or low physical quantities that the current labs cannot offer, or
2) by increasing the accuracy of the measurements by lowering the uncertainty with new, better, or modified methods that already exist [2].

The paper reports on how the calibration and measurement capabilities for extreme electrical impedance are upgraded in the accredited Laboratory for Electrical Measurements (LEM) at the Ss. Cyril and Methodius University (UKIM) in Skopje. This is achieved by developing new calibration methods for instruments measuring extreme electrical resistance and inductance, which were not included in the existing laboratory accreditation scope.

The paper also describes how these methods were validated to ensure traceability and how the measurement uncertainty in impedance instruments calibration was innovatively estimated, by deploying the data fusion concept [3].

The research's final goal is the accreditation of the new calibration methods in the LEM, and the enhancement of the metrology infrastructure capacity in the area of extreme electrical impedance, especially in Southeast Europe.

2. ANALYSIS OF CURRENT STATE OF THE ART IN THE METROLOGY OF EXTREME ELECTRICAL IMPEDANCE

The electrical impedance is the combined effect of resistance and reactance in an alternating current circuit. The reactance can be mainly inductive or capacitive. So, metrology of electrical impedance involves measuring electrical resistance and reactance. The current state of the art in calibration of instruments for electrical impedance, consists of: first, best calibration and measurement capabilities (CMC) of electrical resistance, and second, best CMC of electrical inductance or capacitance. This paper will analyse the best publicly available CMCs of National Metrology Institutes (NMIs) or laboratories, for electrical inductance and very high electrical resistance.

The metrological progress in calibrating devices for electrical inductance is a contribution to the extreme electrical metrology, [3], [4]-[8], as the field of electrical inductance has a less developed calibration infrastructure than the other electrical quantities. Moreover, most of the National Metrology Institutes and accredited calibration laboratories have limited scopes in the field of electrical inductance in their published CMCs, [9]. The paper compares the best CMCs at international level and at regional level of Southeast Europe, where the LEM laboratory is situated, to present the current state-of-the-art in the field of electrical inductance metrology. The calibration process of electrical inductance is challenging, and the number of National Metrology Institutes (NMIs) and accredited calibration laboratories that perform these calibrations, is quite low [4]-[8].

The data in the Key Comparison Database (KCDB) of the International Bureau of Weights and Measures (BIPM) [9] are used to compare the best CMCs at international level at 10 mH and 10 H in Figure 1 and Figure 2, respectively.

The data in the KCDB database of BIPM [9] are used to show the comparison of the best CMCs at regional level of Southeast Europe at 10 mH and 10 H in Figure 3 and Figure 4, respectively.

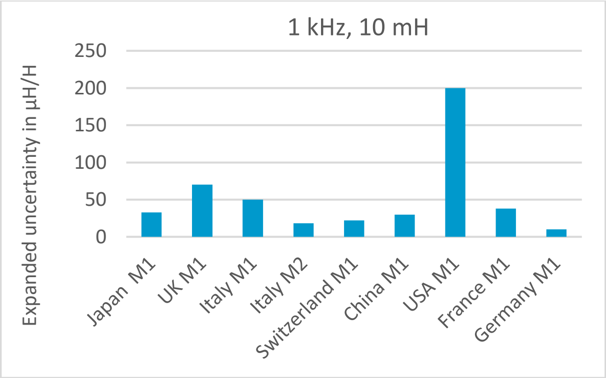

Figure 1. Expanded measurement uncertainties of inductance of 10 mH and @1 kHz, at the international level of NMIs.

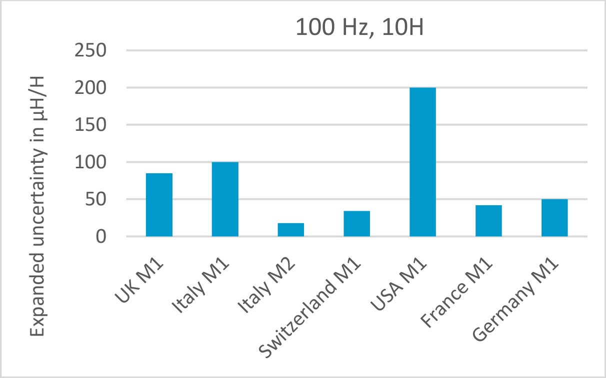

Figure 2. Expanded measurement uncertainties of inductance of 10 H and @100 Hz, at the international level of NMIs.

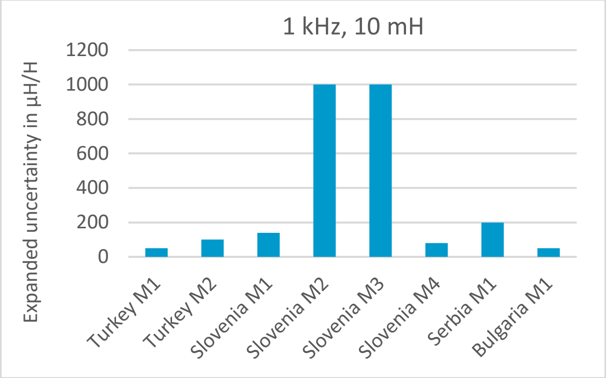

Figure 3. Expanded measurement uncertainties of inductance of 10 mH and @1 kHz, at the regional level of Southeast Europe NMIs.

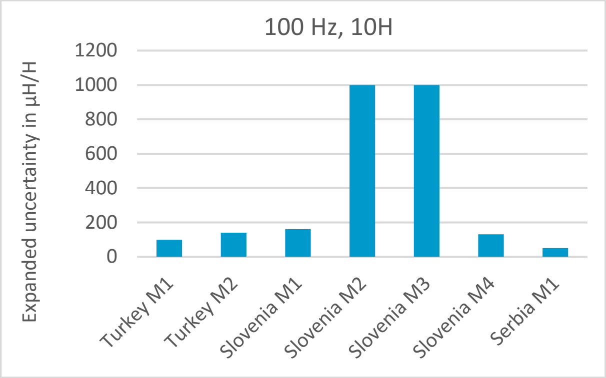

Figure 4. Expanded measurement uncertainties of inductance of 10 H and @100 Hz, at the regional level of Southeast Europe NMIs.

In Figure 5 and Figure 6, the comparison of the expanded measurement uncertainties of the national metrology institutes at the international level for measuring high electrical resistance of 1 GΩ and 1 TΩ are given, respectively [9].

In Figure 7 and Figure 8, the comparison of the expanded measurement uncertainties of the national metrology institutes at the regional level at Southeast Europe for measuring high electrical resistance of 1 GΩ and 1 TΩ are displayed, respectively [9].

3. INTRODUCTION OF CALIBRATION PROCEDURES OF MEASUREMENT DEVICES FOR INDUCTANCE AND EXTREME ELECTRICAL RESISTANCE IN LEM

The LEM, is an accredited laboratory for calibration of measurement devices for electrical quantities, according to ISO 17025:2005 since 2015, and later according to ISO 17025:2017, [1]. However, the LEM laboratory was not accreditated for calibration of electrical inductance instruments.

The reference standard for electrical inductance, Transmille 4015 Multifunction calibrator, with an IND option for inductance generation, was recently obtained by the LEM. Figure 9 displays the reference standard, while Table 2 presents the technical specification [10] at a frequency of 1 kHz. The reference standard is calibrated in the electrical inductance measurement range, at the manufacturer's accredited calibration laboratory, with traceability to the national (National Physical Laboratory of United Kingdom - NPL), and international primary reference standards of electrical inductance (BIPM). The paper presents the results for the calibration case study at 10 mH electrical inductance, with some additional technical

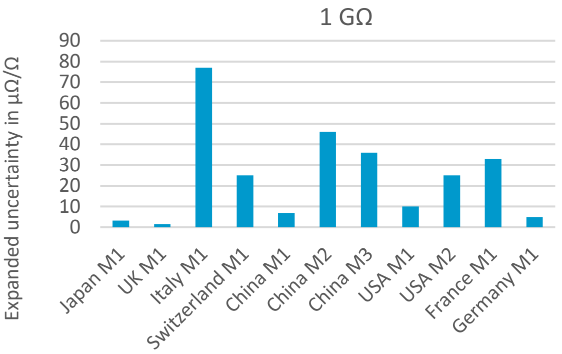

Figure 5. Expanded measurement uncertainties of electrical resistance of 1 GΩ, at the international level of NMIs.

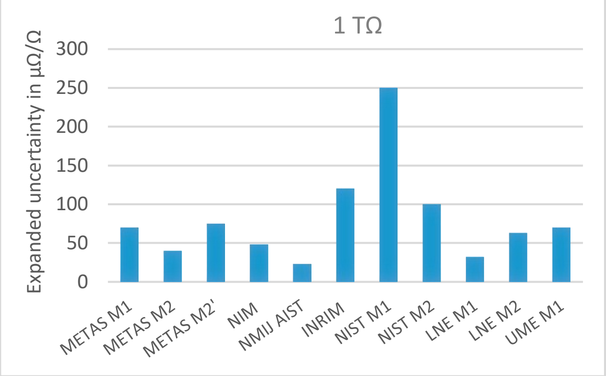

Figure 6. Expanded measurement uncertainties of electrical resistance of 1 TΩ, at the international level of NMIs.

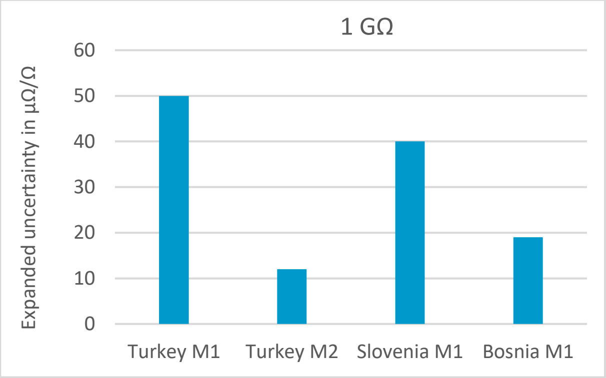

Figure 7. Expanded measurement uncertainties of electrical resistance of 1 GΩ, at the regional level of Southeast Europe NMIs level.

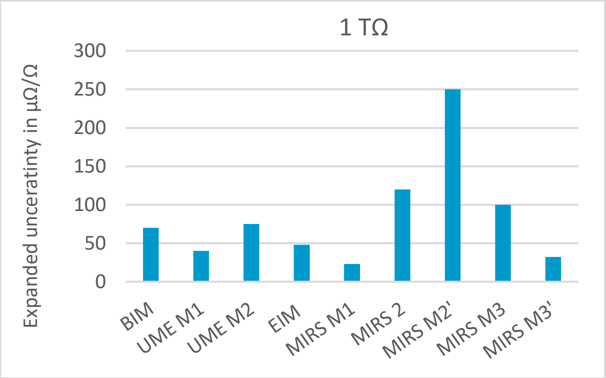

Figure 8. Expanded measurement uncertainties of electrical resistance of 1 TΩ, at the regional level of Southeast Europe NMIs level.

Figure 9. LEM reference standard - multifunctional calibrator Transmille 4015 with inductance calibration option.

specification of the reference standard: Q-factor 8.6, display resolution 10 µH. The suggested measurement method in the range from 1 mH to 100 mH is L_s – serial reference impedance modelling [10]. The IND option is a hidden black box option of the Transmille 4015 Multifunctional Calibrator with technical specifications in Table 1, but there is no publicly available information on the physical system realisation of the inductance reference standard [10].

For the area of high electrical resistance, an analysis was conducted of the international supply of reference standards, because of the gap in calibration and measurement capabilities between top international laboratories, and the regional state of the metrological infrastructure in this metrology area. Based on this analysis, LEM has specified the technical details for the acquisition of high accuracy class artefact, to significantly increase the LEM's CMC.

Table 2 provides the technical details of the new reference standards in LEM, for very high electrical resistance 5 kV IET Labs HRRSQ.

Table 1. Technical specification of the reference standard for electrical inductance of LEM.

Multifunctional Calibrator Transmille 4015 Supplement for calibration of instruments for inductance with specifications for 1 kHz and accuracy of ± 50 µH Transmille IND			
Electrical Inductance	**Q-factor**	**Display resolution**	**Best annual accuracy**
1 mH	1	100 nH	0.5 %
10 mH	2.8	1 µH	0.5 %
19 mH	3.8	1 µH	0.5 %
29 mH	4.7	1 µH	0.5 %
50 mH	6.1	1 µH	0.5 %
100 mH	8.6	10 µH	0.5 %
1 H	29	100 µH	0.5 %
10 H	110	1 mH	0.5 %

Table 2. Technical specification of the reference standard for high electrical resistance of LEM.

Reference standard resistance decade from 100 MΩ to 1 TΩ for voltage of 5 kV IET Labs HRRSQ	
Characteristics	**Value**
Electrical resistance	from 100 MΩ to 1 TΩ
Accuracy class	0.1% to 0.5%
Voltage level	5 kV
Temperature coefficient	25 ppm/°C to 100 ppm/°C
Voltage coefficient	1 ppm/V to 5 ppm/V

4. ESTABLISHMENT OF NOVEL CALIBRATION PROCEDURES FOR EXTREME ELECTRICAL IMPEDANCE INSTRUMENTS IN LEM

Diverse calibration methods for instruments for impedance i.e. inductance [4]-[8] and resistance measurement [11]-[13] are developed by the national metrology institutes and the calibration laboratories in the field of electrical quantities.

The Laboratory for Electrical Measurements (LEM), has developed a calibration procedure of LCR bridges i.e., more precisely a calibration procedure of meters for electrical inductance. The calibration of the electrical inductance measurement range of a LCR-meter is conducted for validation. The UUT is Rohde & Schwartz HM8118 - Programmable LCR-Bridge, with technical specification in [14] and testing set-up as in Figure 10.

The verification of the newly introduced calibration procedure for extreme i.e. very high electrical resistance, is conducted through calibration of a Metrel MI 2077 TeraOhm 5 kV tera-ohmmeter with the technical specifications in [15], with reference standard resistance decade from 100 MΩ to 1 TΩ for voltage of 5 kV IET Labs HRRSQ, as presented in Figure 11.

The uncertainty budget for the two calibration procedures is derived by fusing data as in Figure 12 from a component of type A and components of type B, as in GUM [16]. The uncertainty of type A u_A is obtained from the experimental data subjected to statistical processing, i.e. the mean value X_mean and the standard deviation of the measurement s_A as in:

$$s_\mathrm{A} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_\mathrm{icor} - X_\mathrm{mean})^2}\,, \tag{1}$$

where:

$$X_\mathrm{mean} = \frac{1}{n}\sum_{i}^{n} X_\mathrm{icor}\,, \tag{2}$$

$$X_\mathrm{icor} = X_i - X_\mathrm{ref}\,. \tag{3}$$

X_i is the measured value in the particular point, and X_ref is the reference value from the calibrator or the resistance reference standard.

The following uncertainty components are fused in the type B uncertainty budget u_B:

$u_\mathrm{res\_instr}$ – from the calibrated instrument resolution,
$u_\mathrm{res\_refst}$ – from the reference standard resolution,
$u_\mathrm{d\_refst}$ – from the reference standard drift,
$u_\mathrm{c\_refst}$ – from the reference standard calibration.

The combined uncertainty of type B is:

$$u_\mathrm{B} = \sqrt{u_\mathrm{res\_instr}^2 + u_\mathrm{res\_refst}^2 + u_\mathrm{d\_refst}^2 + u_\mathrm{c\_refst}^2}\,. \tag{4}$$

The total combined uncertainty is:

$$u_\mathrm{c} = \sqrt{u_\mathrm{A}^2 + u_\mathrm{B}^2}\,. \tag{5}$$

With dominant type A uncertainty, and sufficient high number of repeated measurements, the expanded uncertainty deployed in the particular rules for conformity of statement is:

$$u = 2 \cdot u_\mathrm{c}\,. \tag{6}$$

Figure 10. Testing set-up in LEM for calibration of ROHDE & SCHWARZ HM8118 LCR-Bridge with the Transmille 4015 Multifunctional Calibrator.

Figure 11. Testing set-up in LEM for calibration of Metrel MI 2077 TeraOhm 5kV with the 5 kV IET Labs HRRSQ resistance reference standards decade.

The results of the calculation by using the data fusion concept at the measurement point of 10 mH are in Table 3, with values expressed in mH.

The derived combined uncertainty is:

$$u_\mathrm{c} = 0.037\ \mathrm{mH} \tag{7}$$

and the expanded uncertainty is:

$$U = 0.073\ \mathrm{mH}\,. \tag{8}$$

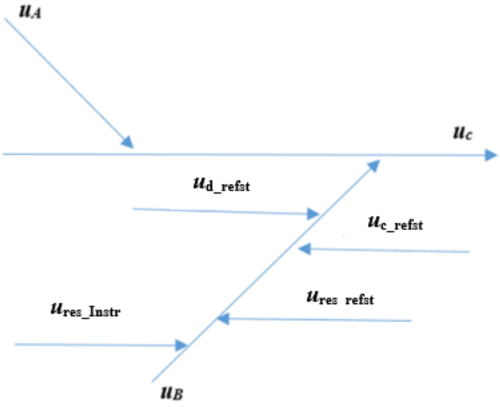

Figure 12. Ishikawa fishbone diagram of the factors fused in the combined uncertainty budget in calibration of impedance instrument (inductance-meter or tera-ohmmeter).

Table 3. Inputs of combined uncertainty budget for calibration of the RLC-meter at 10 mH, @1 kHz.

L_ref in mH	L_mean in mH	u_A in mH	$u_\mathrm{res\_instr}$ in mH	$u_\mathrm{res\_refst}$ in mH	$u_\mathrm{d\_refst}$ in mH	$u_\mathrm{c\_refst}$ in mH
10.412	10.557	0.001	0.00003	0.00003	0.036	0.037

The results of the calculation by using the data fusion concept at the measurement point of 10 H are in Table 4, with values expressed in H.

The derived combined uncertainty is:

$$u_{\mathrm{c}} = 0.037\ \mathrm{H} \tag{9}$$

and the expanded uncertainty is:

$$U = 0.073\ \mathrm{H}\,. \tag{10}$$

Similar data fusion methodology for calculation of the uncertainty of the calibration of the tera-ohmmeter at the measurement points of 1 GΩ and 1 TΩ is applied, and presented in Table 5 and Table 6, respectively.

The derived combined uncertainty at 1 GΩ is:

$$u_{\mathrm{c}} = 0.00065\ \mathrm{G\Omega} \tag{11}$$

and the expanded uncertainty equals:

$$U = 0.013\ \mathrm{G\Omega}\,. \tag{12}$$

The derived combined uncertainty at 1 TΩ is:

$$u_{\mathrm{c}} = 0.00348\ \mathrm{T\Omega} \tag{13}$$

and the expanded uncertainty equals:

$$U = 0.007\ \mathrm{T\Omega}\,. \tag{14}$$

5. DISCUSSION AND CONCLUSIONS

An overview of the current best CMCs for inductance and very high electrical resistance at the global and regional level is provided, enabling identification of the existing gap of the metrology infrastructure in Southeast Europe in comparison to the top international metrology offer.

The Laboratory of Electrical Measurements in Skopje has enhanced its accredited CMC in the area of calibration of instruments for extreme electrical impedance, through the acquisition and installment of high accuracy class reference standards for inductance and high electrical resistance and development calibration methods, which are experimentally validated.

The gained significant expansion of the accreditation scope, through the advanced and upgraded calibration facilities, is contributing to the improvement of the metrological infrastructure, in particular in the region of Southeast Europe.

Table 4. Inputs of combined uncertainty budget for calibration of the RLC-meter at 10 H, @1 kHz.

L_{ref} in H	L_{mean} in H	u_{A} in H	$u_{\mathrm{res\_instr}}$ in H	$u_{\mathrm{res\_refst}}$ in H	$u_{\mathrm{d\_refst}}$ in H	$u_{\mathrm{c\_refst}}$ in H
10.336	10.4996	0.0002	0.0001	0.00001	0.0362	0.0367

Table 5. Inputs of combined uncertainty budget for calibration of the tera-ohmmeter at 1 GΩ, @1 kV.

R_{ref} in GΩ	R_{mean} in GΩ	$u_{\mathrm{res\_instr}}$ in GΩ	$u_{\mathrm{res\_refst}}$ in GΩ	$u_{\mathrm{d\_refst}}$ in GΩ	$u_{\mathrm{c\_refst}}$ in GΩ
1.0	0.984	0.001	0.000577	0.000005	0.00005

Table 6. Inputs of combined uncertainty budget for calibration of the tera-ohmmeter at 1 TΩ, @1 kV.

R_{ref} in TΩ	R_{mean} in TΩ	$u_{\mathrm{res\_instr}}$ in TΩ	$u_{\mathrm{res\_refst}}$ in TΩ	$u_{\mathrm{d\_refst}}$ in TΩ	$u_{\mathrm{c\_refst}}$ in TΩ
1.0	0.969	0.00003	0.002887	0.000289	0.0019

The methodology presented is universal and can be used for further development of calibration methods in the field of extreme electrical metrology.

6. ACKNOWLEDGEMENT

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