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EXTREME IMPEDANCE CALIBRATIONS: ENHANCEMENT OF METROLOGY INFRASTRUCTURE

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Abstract:

The metrology infrastructure for electrical quantities in Southeast Europe is underdeveloped as certain areas of electrical instruments' calibrations are not well covered by the existing laboratories, even though there are economic and scientific needs. The paper shows the improvement of the calibration and measurement capabilities for extreme electrical impedance in the accredited Laboratory for Electrical Measurements at the Ss. Cyril and Methodius University in Skopje by deploying new calibration methods of instruments for extreme electrical resistance and inductance. The validation/verification of methods for traceability establishment and the innovative estimation of measurement uncertainty in impedance instruments calibration for improved metrology infrastructure capacity, are presented.

Keywords: extreme impedance, calibration of inductance, calibration of high resistance, CMC

1. INTRODUCTION

Metrology's main goal is to perform the most accurate measurements possible and to interpret the results properly. Metrology infrastructure keeps improving in two ways: 1-it allows measuring very high or very low physical quantities that the current labs cannot provide, or 2-it makes the measurements more accurate by reducing the uncertainty with new, better, or altered methods that already exist, [1]. In Southeast Europe the metrology infrastructure for electrical quantities is underdeveloped i.e., certain essential areas of electrical instruments' calibrations are not sufficiently covered by the existing metrology laboratories, [2]. However, the regional economy and science are expressing evident needs for this kind of calibration and testing facilities. The paper aims to present the boost of the calibration and measurement capabilities (CMCs) for extreme electrical impedance. It presents some challenges faced in developing this infrastructure and how they are being overcome. The accredited Laboratory for Electrical Measurements (LEM) at the Ss. Cyril and Methodius University (UKIM) in Skopje is introducing novel calibration procedures addressing instruments for instruments for very high and very low electrical resistance and inductance, which have not been covered by the existing laboratory scope of accreditation. The validation and verification procedures for establishment of traceability and the innovative techniques for estimation of measurement uncertainty for calibration of impedance instruments are conducted. The final objective of the research is the accreditation of novel calibration methods in the LEM, and contributing to the capacity building of the metrology infrastructure in the field of extreme electrical impedance, in particular in the region of Southeast Europe.

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

The electrical impedance is presented by the combined effect of resistance and reactance in a circuit of alternating current. The reactance can be predominantly inductive or capacitive. So, when talking of metrology of electrical impedance, it is an issue of measurement of electrical resistance, and measurement of reactance. Therefore, the current state of the art in calibration of instruments for electrical impedance is composed of best calibration and measurement capabilities (CMC) of electrical resistance, and best CMC of electrical inductance or capacitance. In this contribution the best CMC for electrical inductance and very high electrical resistance will be presented.

The field of electrical inductance has less developed calibration infrastructure than other electrical quantities, and showing metrological progress in calibrating devices for electrical inductance would be a contribution to the extreme electrical metrology, [3], [7]-[11]. Furthermore, most of the National Metrology Institutes and accredited calibration laboratories in their published CMCs demonstrate restricted scopes in the field of electrical inductance, [4]. The current state-of-the-art in the field of electrical inductance metrology is presented bellow through the comparison of the best CMCs at international level and at regional level of Southeast Europe, where the LEM laboratory is located. In Figure 1, a comparison of the best CMCs at international level and in Figure 2 the best CMCs at regional level of Southeast Europe for electrical inductance of 10 mH are presented, based on the data in the KCDB database of BIPM, [4]. The electrical inductance of 10 mH introduces challenges in the process of calibration and the number of National Metrology Institutes (NMIs) and accredited calibration laboratories which perform these calibrations is rather low, [7]-[11].

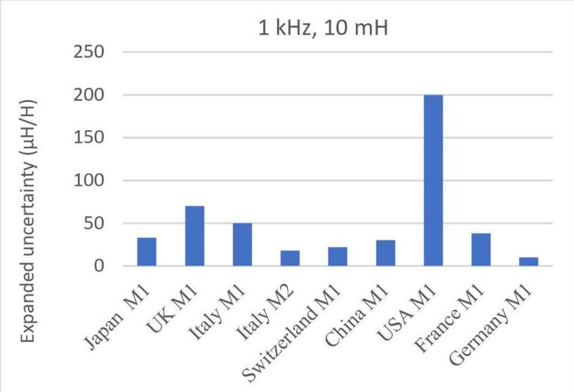

Figure 1. Expanded measurement uncertainties of inductance of 10 mH @1 kHz at the international NMIs

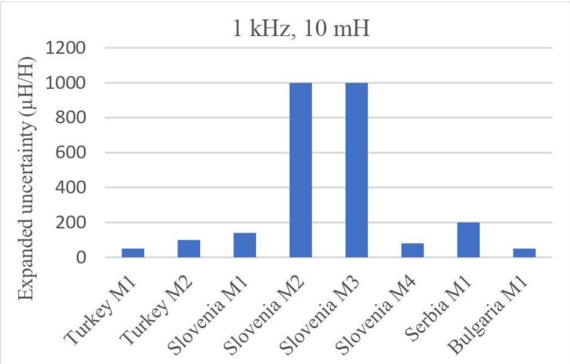

Figure 2. Expanded measurement uncertainties of inductance of 10 mH @1 kHz at the regional NMIs

Figure 3. LEM reference standard multifunctional calibrator Transmille 4015 with inductance calibration option

LEM has been an accredited calibration laboratory for electrical quantities instruments according to ISO 17025:2005 since 2015, and later according to ISO 17025:2017, but it does not have accreditation for electrical inductance instruments. LEM is working on establishment of a new calibration method for inductance instruments examination, [1]. A reference standard for electrical inductance, Transmille 4015 Multifunction calibrator, with an option IND for inductance generation, has recently been acquired. It is illustrated in Fig. 3, while the technical specification [5] is presented in Table 2, at a frequency of 1 kHz. It is calibrated in the electrical inductance measurement range at the producer's accredited calibration laboratory with established measurement traceability to national (NPL) and international primary reference standards (BIPM). As the presented results bellow are for the case study of calibration at 10 mH electrical inductance, some additional technical specification of the reference standard are:, Q-factor 8,6, display resolution 10 µH. The recommended measurement method in the range from 1 mH to 100 mH is L_s – serial reference impedance modelling [5]. The IND option is a built-in black box option of the Transmille 4015 Multifunctional Calibrator and there is no publicly available information on the physical system realisation of the inductance reference standard [5].

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 %

In Fig. 4 and 5, the comparison of the expanded measurement uncertainties of the national metrology institutes at the international and regional level when measuring high electrical resistance of 1 TΩ, are shown, [4]. As a result of the perceived gap in measurement and calibration possibilities between top international laboratories, and considering the regional state of the metrological infrastructure in the area of electrical quantities, an analysis of the international supply of reference standards for electrical quantities that are not covered by the existing LEM reference standards has been carried out. Based on that, LEM has defined a detailed technical specification for the procurement of high accuracy class artefact, for significant expansion of the LEM's CMC. Table 2 shows the detailed technical specifications of the newly acquired reference standards in LEM for very high electrical resistance 5 kV IET Labs HRRSQ.

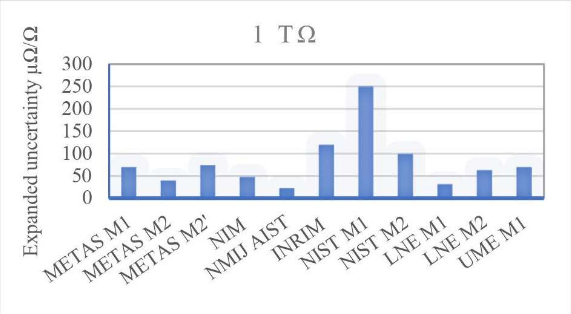

Figure 4. Expanded measurement uncertainties of electrical resistance of 1 TΩ at the international NMIs

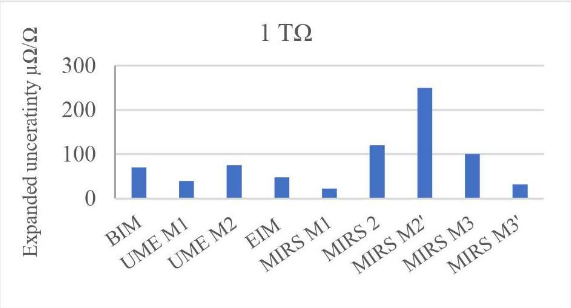

Figure 5. Expanded measurement uncertainties of electrical resistance of 1 TΩ at the regional NMIs level

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

3. CALIBRATION PROCEDURES FOR EXTREME ELECTRICAL IMPEDANCE INSTRUMENTS DEVELOPED IN LEM

The national metrology institutes and the calibration laboratories in the field of electrical quantities develop diverse calibration methods for instruments for impedance i.e. inductance, [7-11] and resistance measurement, [12-14].

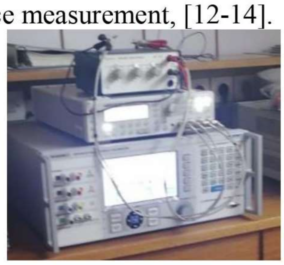

Figure 6. Test set-up in LEM for calibration of ROHDE & SCHWARZ HM8118 LCR-Bridge with the Transmille 4015 Multifunctional Calibrator

In this case study, the Laboratory for Electrical Measurements (LEM), develops a calibration procedure of LCR bridges i.e., more precisely a calibration procedure of meters for electrical inductance and calibration procedure of the electrical inductance measurement range of a LCR-meter is conducted for validation/verification. The UUT is ROHDE & SCHWARZ HM8118 - Programmable LCR-Bridge, with technical specification in [6] and test set-up as in Figure 6.

The developed calibration procedure for extreme i.e. very high electrical resistance is verified by calibration of a Metrel MI 2077 TeraOhm 5kV 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.

Figure 7. Test set-up in LEM for calibration of Metrel MI 2077 TeraOhm 5kV with the 5 kV IET Labs HRRSQ resistance reference standards decade

The uncertainty budget, for the both calibration procedures, is built by fusing data from a component of type A and components of type B, as in GUM, [16]. The uncertainty of type A u_A is calculated 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:

$$s_A = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_{icor} - X_{mean})^2} \quad (1)$$

where

$$X_{mean} = \frac{1}{n}\sum_{i}^{n} X_{icor} \quad (2)$$

$$X_{icor} = X_i - X_{ref} \quad (3)$$

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 uncertainty budget of type B, u_B:

u_{res_instr} – from calibrated instrument resolution,
u_{res_refst} – from reference standard resolution
u_{d_refst} – from reference standard drift
u_{c_refst} – from the reference standard calibration

The combined uncertainty of type B is:

$$u_B = \sqrt{u_{res\_instr}^2 + u_{res\_refst}^2 + u_{d\_refst}^2 + u_{c\_refst}^2} \quad (4)$$

The total combined uncertainty is:

$$u_c = \sqrt{u_A^2 + u_B^2} \quad (5)$$

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:

$$U = 2 \cdot u_c \quad (6)$$

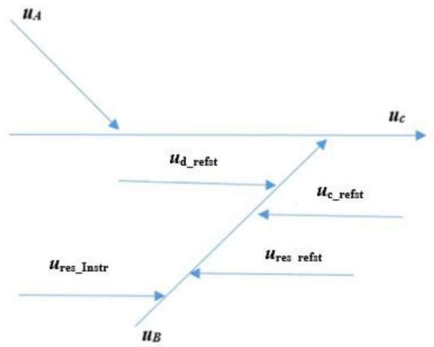

Figure 8. Ishikawa fishbone diagram of the factors in the combined uncertainty budget in calibration of impedance instrument (inductance-meter or tera-ohmmeter)

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:

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

L_{ref} [mH]	L_{mean} [mH]	u_A [mH]	u_{res_instr} [mH]	u_{res_refst} [mH]	u_{d_refst} [mH]	u_{c_refst} [mH]
10.412	10.557	0.001	0.00003	0.00003	0.036	0.037

The derived combined uncertainty is:

$$u_c = 0.037 \text{ mH} \quad (7)$$

and the expanded uncertainty is:

$$U = 0.073 \text{ mH} \quad (8)$$

Similar methodology for calculation of the uncertainty of the calibration of the tera-ohmmeter at the measurement point of 1 TΩ, is applied.

Table 4. Inputs of combined uncertainty budget for calibration of the tera-ohmmeter at 1 TΩ, @1 kV

R_{ref} [TΩ]	T_{mean} [TΩ]	u_{res_instr} [TΩ]	u_{res_refst} [TΩ]	u_{d_refst} [TΩ]	u_{c_refst} [TΩ]
1.0	0.969	0.00003	0.002887	0.000289	0.0019

The derived combined uncertainty is:

$$u_c = 0.00348 \text{ TΩ} \quad (9)$$

and the expanded uncertainty equals:

$$U = 0.007 \text{ TΩ} \quad (10)$$

4. SUMMARY AND CONCLUSIONS

The contribution gives an overview of the current best CMCs for inductance and very high electrical resistance at the global level, and identifies the existing gap of the metrology infrastructure in Southeast Europe.

The Laboratory of Electrical Measurements in Skopje has acquired and installed high accuracy class reference standards for inductance and high electrical resistance and has developed suitable calibration methods. With the expansion of the accreditation scope, the available calibration facilities, contributing to the upgrades of the metrological infrastructure, are improved. The methodology presented is universal and can be used for further development of calibration methods in the field of extreme electrical metrology.

5. ACKNOWLEDGEMENT

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