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CONTRIBUTION TO IMPROVED MEASUREMENT AND CALIBRATION CAPABILITIES IN THE FIELD OF MEASURING INSTRUMENTS FOR HIGH FREQUENCIES

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A b s t r a c t: In the paper, analysis of the measurement infrastructure for examination and calibration of measuring instruments (oscilloscopes and counters) at extremely high-frequencies at the international, regional and national levels is made. The analysis is carried out within the framework of the scientific research project "Development and Upgrade of Laboratory Resources for Research and Introduction of New Analytical Methods in Electrical Metrology", which is implemented under the program for financing scientific and research projects of public interest for 2021 by the Ministry of Education and Science of the Republic of North Macedonia. The main emphasis of the paper is on the development of a procedure and calculation of measurement uncertainty for the calibration of high-frequency meters, according to Euramet Guideline No.7, Calibration of Oscilloscopes. The paper describes the newly installed reference standard measurement system in the Laboratory for Electrical Measurements at UKIM-FEEIT for calibration of instruments for high frequencies, as well as specific measurement results, evaluation of the budget of measurement uncertainties, and established traceability chain in the field of high frequencies.

Key words: measurement uncertainty; calibration; instruments for high-frequencies; measurement traceability

ПРИДОНЕС КОН ПОДОБРЕНИ МЕРНИ И КАЛИБРАЦИОНИ МОЖНОСТИ ВО ОБЛАСТА НА МЕРНИ ИНСТРУМЕНТИ ЗА ВИСОКИ ФРЕКВЕНЦИИ

А п с т р а к т: Во овој труд е направена анализа на мерна инфраструктура за испитување и калибрација на мерни инструменти (осцилоскопи и мерила) при екстремно високи фреквенции, на интернационално, регионално и национално ниво. Анализата е спроведена во рамките на научно-истражувачкиот проект „Развој и надградба на лабораториски ресурси за истражување и воведување нови аналитички методи во електрична метрологија", кој е имплементиран во програмата за финансирање на научноистражувачки проекти од јавен интерес за 2021 година од страна на Министерството за образование и наука на Република Северна Македонија. Главен акцент на трудот е ставен на развојот на постапка и пресметка на мерна неодреденост за калибрација на мерила за високи фреквенции, согласно упатството Еурамет бр. 7, Калибрација на осцилоскопи. Во трудот е даден и опис на новоинсталираниот мерен систем со референтен еталон за калибрација на мерила за високи фреквенции во Лабораторијата за електрични мерења при УКИМ-ФЕИТ, како и мерни резултати, оцена на буџетот на мерна неодреденост и воспоставен е редослед на мерната следливост на високи фревенции.

Клучни зборови: мерна неодреденост; калибрација; мерила за високи фреквенции; мерна следливост

1. INTRODUCTION

The Laboratory of Electrical Measurements (LEM) at the Faculty of Electrical Engineering and Information Technologies (FEEIT) of the "Ss. Cyril and Methodius" University in Skopje (UKIM) [1] is an accredited calibration laboratory according to the standard MKS EN ISO/IEC 17025:2018 [2] with traceability to the international primary reference standards of the International Bureau of Weights and Measures (Bureau International des Poids et

Mesures – BIPM) [3] in certain ranges of several electrical quantities.

The laboratory's mission is to disseminate its international traceability for the needs of electrical measurements in the Republic of North Macedonia, the region of Southeast Europe and beyond. The laboratory's services for the calibration of various types of instruments are continuously used by many national companies and companies from the region of Southeast Europe that perform electrical measurements with various levels of accuracy [1]. LEM has the ability to calibrate a wide range of electrical measuring instruments such as: multimeters, sources of direct and alternating voltages and currents, instruments for specific purposes and reference standards. Furthermore, work is being done on the analysis and development of new analytical methods in the field of measuring electrical quantities, within the framework of the scientific research project "Development and Upgrade of Laboratory Resources for Research and Introduction of New Analytical Methods in Electrical Metrology", implemented under the program for financing scientific research projects of special and public interest for 2021 by the Ministry of Education and Science of Republic of North Macedonia [4].

The aim of the paper is to present the achieved contribution to improvement of the measurement and calibration capabilities (CMC) in the field of high frequency measuring instruments, primarily calibration of oscilloscopes, including new laboratory equipment, for strategic expansion of the scope of accreditation of LEM. The developed measurements procedures, and the analysis of the obtained results from the calculation of the measurement uncertainties are in accordance with the Calibration Guide Euramet cg-7, Calibration of oscilloscopes, TC-EM, version 1.0, 06/2011 [5].

The result of each measurement contains a certain uncertainty, which means that it is not possible to obtain an ideally accurate value of the measured quantity [6]. In order to achieve uniformity in the expression of measurement results, in 2008 BIPM published the new version of the Guide to the expression of uncertainty in measurement [7]. To quantify the uncertainty, two parameters are required, the first is the width of the margin or interval of measurement uncertainty, and the second is the reliability or probability, which defines that the "correct value" is within the limits of the given interval [8].

In practice, five elements complete the measurement process: the measurand, the measuring instrument, the reference standard, the measurement method and the operator [9]. The standard is expected to have been checked in the appropriate competent calibration laboratory, either accreditied by European Accreditation Multilateral Agreement (EA/MLA) [9] signatory national accreditation body or a national metrology institute with officially published CMC in the Key Comparison Data Base (KCDB) of BIPM [3], and thus establishing the unbroken chain of traceability in the international metrology system. Traceability in measurements is realized within the framework of the national measurement system, which should be in a traceable relationship with the international SI system of measurement units.

Laboratories accredited by the accreditation bodies that are members of the European cooperation for Accreditation of Laboratories (EAL) [10] must enter the expanded uncertainty U in their calibration certificates. It is calculated according to the expression:

$$U = k \cdot u_c(y), \qquad (1)$$

where k is the coverage factor and u_c is the combined measurement uncertainty. The results of the measurements are conventionally expressed as:

$$Y = y \pm U, \qquad (2)$$

which is interpreted as an interval from $y–U$ to $y+U$ in which the measurement results are found with a given probability.

2. ANALYSIS OF THE CURRENT-STATE-OF-THE-ART OF THE BEST MEASUREMENT AND CALIBRATION CAPABILITIES FOR HIGH-FREQUENCIES AT INTERNATIONAL AND REGIONAL LEVEL

The state-of-the-art analysis of the best measurement and calibration capabilities for high frequencies at the international and regional level started from a survey of published measurement and calibration capabilities of the top national metrology institutes (NMIs) at international level (CMCs in KCDB base of BIPM), but also at the regional level through published CMCs by the national accreditation bodies. The main emphasis is on the comparison of the values for the expanded measurement uncertainties at each NMI. Bellow are the results of the extensive survey which is done for high-frequencies (at 500 kHz and at 1 MHz) for two voltage levels (1 V and 10 V). The expanded uncertainty is presented with a coverage factor of $k = 2$, with a statistical probability of 95%.

In Figures 1 and 2, the comparison of the values of the expanded measurement uncertainties of the national metrology institutes (NMIs) at the international level when measuring alternating voltages of 1 V and 10 V at very high frequencies of 500 kHz and 1 MHz, is given.

Figures 1 and 2 show that the national metrology institute of FR Germany – PTB, has the smallest values of the expanded measurement uncertainty for the considered frequencies at both voltage levels.

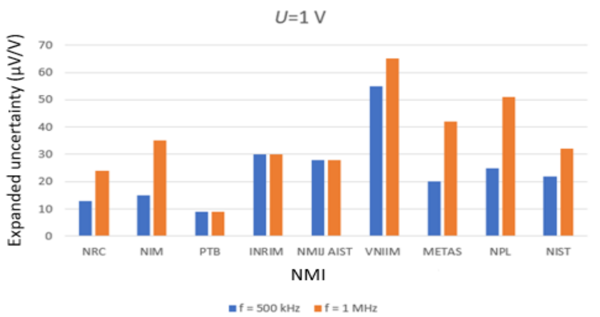

Fig. 1. Expanded measurement uncertainty of 1 V AC voltage at frequency of 500 kHz and 1 MHz at the international NMIs level

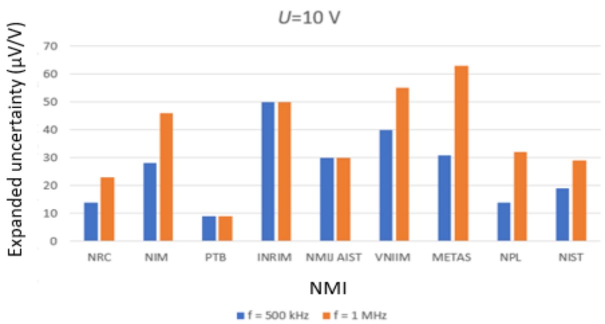

Fig. 2. Expanded measurement uncertainty at 10 V AC voltage at frequency of 500 kHz and 1 MHz at the international NMIs level

Table 1 presents the standards and measurement methods used by the NMIs at the international level that obtained the values of the expanded measurement uncertainties shown above.

In Figures 3 and 4, the comparison of the values of the expanded measurement uncertainties of the national metrology institutes (NMIs) at the regional level in Southeast Europe when measuring alternating voltages of 1 V and 10 V at very high frequencies of 500 kHz and 1 MHz, is given.

According to Figures 3 and 4, it can be concluded that the national metrology institute of R. Slovenia – MIRS/SIQ/Metrology, has the best values of expanded maesurement uncertainty for the considered frequencies at both voltage levels. On the other hand, the national metrology institute of R. Croatia – FER-PEL, has reported the highest values of expanded uncetainty in all analyzed cases.

Table 1

Standards and measurement methods used by NMIs at the international level

Metrology institute	Standard	Measurement method
NRC (Canada)	AC-DC transfer standard / Thermal voltage converter	Direct comparison
NIM (China)	Multifunction calibrator	Comparison
PTB (Germany)	AC voltmeter, multimeter	AC/DC transfer
INRIM (Italy)	AC-DC transfer standard	Resistive dividers
NMIJ AIST (Japan)	AC voltmeter	Comparison
VNIIM (Russian Federation)	AC-DC transfer standard / Thermal voltage converter	Thermal transfer standard
NPL (UK)	AC voltmeter, multimeter	Digital sampling
NIST (USA)	Multimeter	Comparison with reference

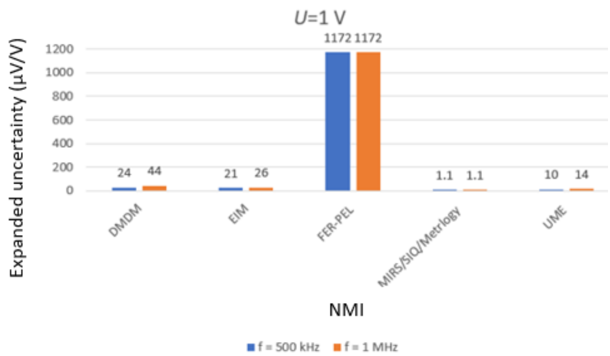

Fig. 3. Expanded measurement uncertainty at 1 V AC voltage at frequency of 500 kHz and 1 MHz at the regional NMIs level (Southeast Europe)

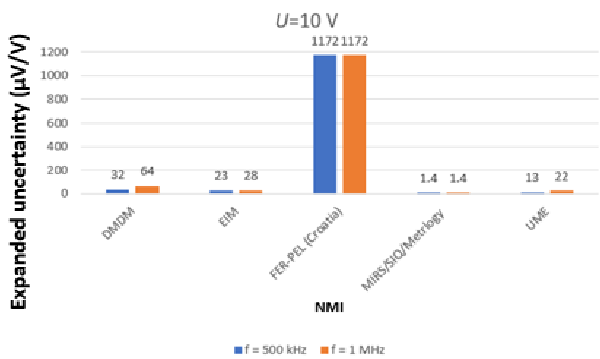

Fig. 4. Expanded measurement uncertainty at 10 V AC voltage at frequency of 500 kHz and 1 MHz at the international NMIs level (Southeast Europe)

The metrology institutes UME from R. Turkiye and MIRS/SIQ/Metrology from R. Slovenia use an AC-DC transfer standard and a thermal voltage converter for direct comparison. The national metrology institutes of R. Serbia (DMDM) and R. Greece (EIM) use standards whose working principle is similar to the standards used by the metrology institutes UME and MIRS/SIQ/ Metrology, with which satisfactory results are obtained in terms of uncertainty. Their standards can be used for calibration of standards of a lower accuracy class as well as for support in the process of calibration of standards from surrounding countires.

3. ANALYSIS OF THE CURRENT-STATE-OF-THE-ART OF THE BEST MEASUREMENT AND CALIBRATION CAPABILITIES FOR HIGH-FREQUENCIES OF THE LABORATORY FOR ELECTRICAL MEASUREMENTS AT UKIM-FEEIT

The Laboratory of Electrical Measurements at UKIM-FEEIT operates with several reference standards in the field of electrical measurements [1]. For the development of new calibration procedures in the field of high-frequencies, in order to expand the scope of accreditation of the laboratory, a new laboratory equipment was acquired – the standard Transmille 4015 Advanced Multiproduct Calibrator [11], shown in Figure 5.

The Transmille calibrator [11] of the 4000 series enables calibration of a wide variety of electrical measuring instruments and is a functional and precise programmable calibration standard. Regarding the need to perform measurements and develop measurement procedures for the calibration of meters in domain of high-frequencies, there are measurement possibilities for the calibration of oscilloscopes with frequency ranges up to 630 MHz. The Transmille 4015 Advanced Multiproduct Calibrator has multiple calibration functions, using built-in software, and has a baseline calibration accuracy of 8 ppm DC voltage measurement ranges [11].

As artefacts of calibration, owned by LEM, two oscilloscopes are used:

• Rigol Digital Oscilloscope 100 MHz DS1102E [12], shown in Figure 6 – an eight-bit, two-channel oscilloscope with a maximum real-time sampling rate of 1 GSa/s and a maximum equivalent sample rate of 25 GSa/s s, with a frequency bandwidth of 100 MHz per channel.

• GW Instek GDS-1072B Digital Storage Oscilloscope 70 MHz 1GS/s [13] – two-channel oscilloscope with a maximum sampling rate of 1 GSa/s in real time with a frequency bandwidth of 70 MHz per channel.

Fig. 5. Transmille 4015 Advanced Multiproduct Calibrator

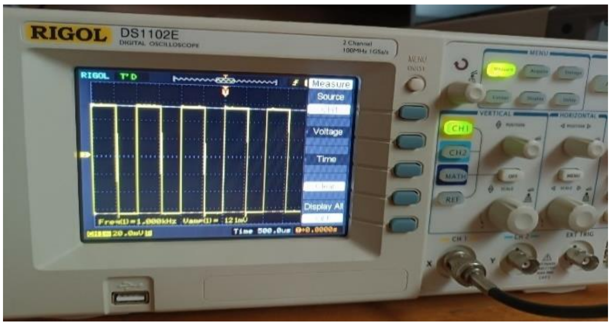

Fig. 6. Rigol Digital Oscilloscope 100 MHz DS1102E

According to the international guideline for calibration of oscilloscopes Euramet cg-7 Ver. 1.0 (06/2011) [5], an in-house original calibration procedure for oscilloscopes was developed with Transmille 4015 as a reference standard.

Calibration of oscilloscopes includes two main stages [5]:

• calibration of the vertical deflection (amplitude calibration),

• calibration of the bandwidth (frequency measurement along the horizontal axis).

The two main stages are independent of each other, but both are necessary to perform a complete procedure of oscilloscope calibration. With the reference standard measurement signals are generated as inputs to the oscilloscopes, through which the measurement procedure is experimentally realized. Each set reference value is measured with 12 repetitions according to [5]. The specified measurement values correspond to the analyzed measurement points provided in the Transmille Calibration Certificate [14], issued by the Transmille Calibration Laboratory, accredited by the UKAS (United Kingdom Accreditation Service) [15]. The reported expanded measurement uncertainties are based on the standard (combined) uncertainty multiplied by a coverage factor of $k = 2$ and a statistical probability of approximately 95%.

When estimating the measurement uncertainties and deviation intervals at each measurement point, the standard (combined) measurement uncertainty budget is composed of four influential factors:

• measurement uncertainty Type A – u_A (which corresponds to the standard deviation of all 12 repeated measurements divided by the square root of the number of measurements),

• measurement uncertainty from the resolution of the oscilloscope (the artefact of calibration),

• measurement uncertainty from the specification of the reference standard (for a period of 2 years) [11],

• measurement uncertainty from the calibration certificate of the reference standard (according to the last available Transmille Reference Standard Calibration Certificate) [14].

In this paper, the same measuring points, which were compared in Chapter 2, are analyzed, in order to make a valid and traceable comparison of the obtained results.

Table 2 and Table 3 present the calculated expanded measurement uncertainties U_{MU} and deviations of the voltage ΔU and of the frequency Δf from the given reference value, based on the measured values with the oscilloscopes, at the voltage measurement ranges of 1 V/Div and 10 V/Div as well as at frequencies of 500 kHz (1 µs/Div) and 1 MHz (2 µs/Div), respectively. Figures 7 and 8 show the respective measurement results with the accompanying uncertainties.

Table 2

Expanded measurement uncertainties and deviations from the reference value, based on the measured values by the oscilloscopes at the voltage levels of 1 V/Div and 10 V/Div

Oscilloscope	Standard	Measurement method	U_{MU} at U = 1 V/Div	ΔU at U = 1 V/Div
Rigol Digital Oscilloscope 100 MHz	Transmille 4015	Direct comparison	0.017646 V	0.018 V
Gwinstek GDS-1072B Digital Storage Oscilloscope 70 MHz	Transmille 4015	Direct comparison	0.059349 V	0 V
Oscilloscope	Standard	Measurement method	U_{MU} at U = 10 V/Div	ΔU at U = 10 V/Div
Rigol Digital Oscilloscope 100 MHz	Transmille 4015	Direct comparison	0.08933 V	0.74 V
Gwinstek GDS-1072B Digital Storage Oscilloscope 70 MHz	Transmille 4015	Direct Comparison	0.101961 V	0 V

Table 3

Expanded measurement uncertainties and deviations from the reference value, based on the measured values by the oscilloscopes at the high-frequencies of 500 kHz and 1 MHz

Oscilloscope	Standard	Measurement method	U_{MN} at f = 500 kHz	Δf at f = 500 kHz
Rigol Digital Oscilloscope 100 MHz	Transmille 4015	Direct comparison	2.007403 kHz	1.42 kHz
Gwinstek GDS-1072B Digital Storage Oscilloscope 70 MHz	Transmille 4015	Direct comparison	0.12159 kHz	0.12 kHz
Oscilloscope	Standard	Measurement method	U_{MN} at f = 1MHz	Δf at f = 1 MHz
Rigol Digital Oscilloscope 100 MHz	Transmille 4015	Direct comparison	0.012087 MHz	0.001 MHz
Gwinstek GDS-1072B Digital Storage Oscilloscope 70 MHz	Transmille 4015	Direct comparison	0.00051 MHz	8.3×10^{-6} MHz

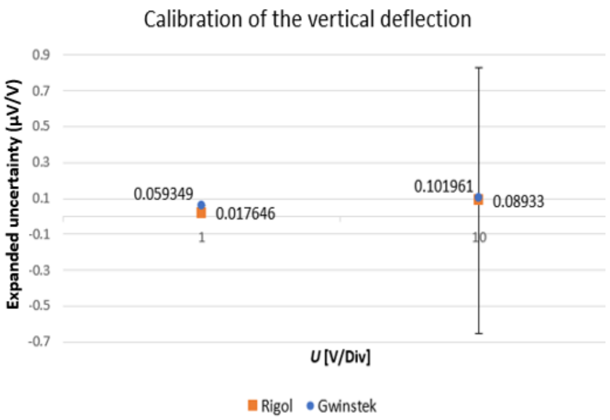

Fig. 7. Expanded measurement uncertainties based on the measured values by the oscilloscopes at the voltage levels of 1 V/Div and 10 V/Div

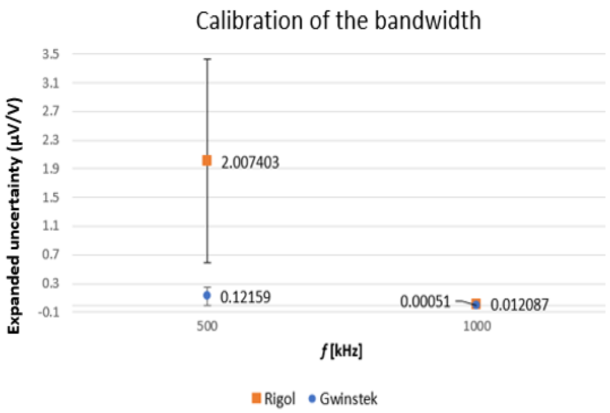

Fig. 8. Expanded measurement uncertainties based on the measured values by the oscilloscopes at the high-frequencies of 500 kHz and 1 MHz

4.CONCLUSIONS

In this paper, a brief overview of the work, objectives and equipment available in the Laboratory of Electrical Measurements at UKIM-FEEIT for the calibration in the field of high-frequency is provided. The identification of the available test equipment (oscilloscopes) which are artifacts for calibration during the development of measurement procedures in the field of high-frequency has been made. The calibration set-up of newly acquired reference standard Transmille 4015 Advanced Multiproduct Calibrator is briefly described, enabling expansion of the scope of accreditation of the LEM and providing the calibration and measurement capability of oscilloscopes and other high frequency instruments with a frequency bandwidth of up to 630 MHz.

The comparison of the best measurement and calibration capabilities in the field of high-frequencies, reported by the NMIs at the international and regional level, expressed through the values of the expanded measurement uncertainty for several measurement points is conducted. The analyzed measurement points were chosen in such a way to enable comparable traceability at the largest number of national metrology institutes.

To achieve long-term sustainability of the recently acquired laboratory equipment and the extended calibration infrastructure, new and modified laboratory procedures are developed and adopted, their accreditation is planned, with the objective of expanding the measurement and calibration capabilities of LEM.

Finally, from the calibration measurements performed in LEM, using both oscilloscopes and Transmille as a reference standard, it can be concluded that the obtained values for the expanded measurement uncertainty are comparable to the reported BIPM values by the national metrology institutes analyzed in this paper. The level of repeatability is acceptable and the all the necessary quality assurance measures for confidence, traceability to SI and unity of the calibration results are performed with appropriate validation methods. The obtained results of the performed calibration enabled the development of a new calibration procedure for high frequency meters, in compliance to the international guideline Euramet cg-7 Ver. 1.0 (06/2011). This makes a significant contribution to the metrological infrastructure for the calibration of high-frequency meters in Republic of North Macedonia and in the region of Southeast Europe.

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