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Evaluation of the results of regional metrology organisation comparisons and national inter-laboratory comparisons for electrical quantities

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ABSTRACT
The global metrological traceability fully depends on the implementation of international mutual recognition agreements in field of metrology. The linked results of international comparisons of national standards for alternating current/direct current (AC/DC) voltage transfer difference measurements and electrical power measurements, and national inter-laboratory comparison AC/DC voltage transfer difference and electrical power measurements at industrial frequency was presented. The main goal of this inter-laboratory comparison was the assessment of calibration laboratories capabilities that perform calibration in AC/DC voltage transfer difference and electrical power measurements. The consistency of the data obtained using the E_n numbers and χ^2 test was estimated.

Section: RESEARCH PAPER

Keywords: Comparison of standards; inter-laboratory comparison; calibration laboratory; measurement uncertainty

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1. INTRODUCTION

The global metrological traceability fully depends on the implementation of two Mutual Recognition Agreements (MRAs): the International Committee on Weights and Measures (CIPM) [1] and the International Laboratory Accreditation Cooperation (ILAC) [2]. Metrological traceability at the highest level is ensured by international comparisons of National Metrology Institutes (NMIs) and Designated Institutes (DIs) standards, and metrological traceability at lower levels is ensured by the calibration of working standards in NMIs and DIs or accredited calibration laboratories [3]-[7].

The results of international comparisons of standards of NMIs and DIs of different countries [8]-[12] are used to implement the provisions of the CIPM MRA. Key comparisons are made by the CIPM consultative committees and six Regional Metrology Organizations (RMOs) using agreed technical protocols for the participants. RMOs make supplementary comparisons for those measurements that are not covered by key comparisons, consultative committees, or RMOs. Results of key and supplementary comparisons are published in a special key comparison database – that of the International Bureau of Weights and Measures (BIPM) [13].

The results of the calibration of working standards and measuring instruments, conducted by accredited calibration laboratories for accredited test laboratories [14], are used to implement the provisions of the ILAC MRA. Inter-laboratory comparisons are widely used to confirm the technical competence of accredited calibration laboratories [15]-[21].

Nowadays, AC voltage and electrical power measurements at industrial frequencies have practical importance, as they have become the main basis of the commercial relationships between electricity consumers and electricity suppliers. It should be noted that the main purpose of legal metrology is to control the measuring instruments that are used in commercial transactions and to ensure and guarantee the accuracy of the measurement results throughout the period of use under operating conditions within the limits of the allowed permissible errors.

It is certain that inter-laboratory comparison reports [22] can provide information on where a calibration laboratory that participated in the comparison may need improvement. It should be noted that comparing different results can only be done correctly if the measurement uncertainty of the results is taken into account [4][14].

An important task in the technical confirmation of metrological traceability is to establish both a connection between the results of comparisons of national standards [23]-[25] and a linking of the calibration results of accredited calibration laboratories within the framework of national inter-laboratory comparisons [7][26][27]. The basis for establishing such a connection should be provided by the NMIs or DIs.

The procedure of the linking between key or supplementary comparison results and national inter-laboratory comparison results is described in Section 2. The proposed procedure is applied to AC/DC-voltage transfer difference measurements (Section 3) and AC power measurements (Section 4). The general recommendations for the laboratories that participated in the inter-laboratory comparisons (ILCs) for AC/DC-voltage transfer difference measurements and AC power measurements are presented in Section 5.

2. DESCRIPTION OF THE METHOD

Reference values, their measurement uncertainty, degrees of equivalence, and uncertainties for all participants are determined in the evaluation of the results of the RMO comparisons. In the data evaluation, RMO key comparisons are determined: transformed participant data and their uncertainties; degrees of equivalence, and measurement uncertainty for all participants, with the exception of the linking NMIs and DIs [14].

The following procedure is used in the evaluation of inter-laboratory comparison data with calibration laboratory participation: assigned value and its measurement uncertainty; inter-laboratory differences – degrees of equivalence and their uncertainties; and data consistency characteristics. There are various options to establish an assigned value, particularly the measured value by the reference laboratory, which ensures metrological traceability to the national standard. When conducting an inter-laboratory comparison for calibration laboratories, it is necessary to ensure the stability of the reference sample [18].

To establish the linking between the results of international comparisons of standards and the results of inter-laboratory comparisons, the optimal is the participation of the NMI or DI as a reference laboratory. The general approach used for the evaluation of RMO comparison data and inter-laboratory comparison data is provided in [7][26][27].

Inter-laboratory differences or degrees of equivalence for the *i*-th calibration laboratory traditionally defined by:

$$D_{lab\ i} = X_{lab\,i} - X_{AV}\,, \tag{1}$$

where $X_{lab\ i}$ is measured value for the *i*-th calibration laboratory, and X_{AV} is the assigned value, which is determined by the reference laboratory.

The expanded uncertainty of U_{AV} measurements is determined by:

$$U_{AV} = k\sqrt{u^2(X_{AV}) + u^2(X_{stab})}, \tag{2}$$

where k is the coverage factor (traditionally k=2); $u(X_{AV})$ is the standard uncertainty obtained during the calibration of the measuring instruments of the reference laboratory; $u(X_{stab})$ is the standard uncertainty about the instability of the measuring instruments during the inter-laboratory comparison.

The expanded uncertainty U_{AV} of the *i*-th calibration laboratory in the inter-laboratory comparison is determined by:

$$U(D_{lad\ i}) = k\sqrt{u^2(X_{AV}) + u^2(X_{lab\ i})}. \tag{3}$$

The results of the inter-laboratory comparison are expressed in relation to the RMO comparison: $D_{NMIj} = X_{NMIj} - X_{RV}$. For this purpose, the degrees of equivalence of the inter-laboratory comparison (indicated $D_{lab\ i}$) are corrected by a correction factor d, which is determined based on the results of the participant laboratory in both comparisons (*NMIj* – *lab1*):

$$d = D_{NMIj} - D_{lab1}, \tag{4}$$

where D_{NMIj} refers to the degrees of equivalence of the NMI or DI i in the RMO comparison; $D_{lab\ i}$ refers to the degrees of equivalence of *lab1* (NMI *i*) in the inter-laboratory comparison, with the uncertainty:

$$U(d) = k\sqrt{\left[u^2(D_{NMIj}) + u^2(D_{lab1})\right]/2} \tag{5}$$

The corrected degrees of equivalence for the *i*-th laboratory participant in the inter-laboratory comparison with respect to linking it to the RMO comparison are estimated as:

$$D'_{lab\,i} = D_{lab\ i} + d \tag{6}$$

with the expanded uncertainty:

$$U(D'_{lab\ i}) = k\sqrt{u^2(D_{lab\ i}) + u^2(d)}. \tag{7}$$

E_n numbers are calculated using this equation:

$$E_n = \frac{D_{lab\ i}}{\sqrt{U^2_{lab\ i} - U^2_{AV}}} \tag{8}$$

where $U_{lab\ i}$ is the expanded uncertainty of a participant's result.

An inter-laboratory comparison result is satisfactory if $|E_{\mathrm{n}}| \le 1$, showing the compatibility of the measurement results. In other words, if $|E_{\mathrm{n}}| > 1$, the result of the inter-laboratory comparison is unsatisfactory.

According to [10], on the basis of measurement results and associated uncertainties presented by the participants of RMO comparisons of national measuring standards, we need to calculate the value of the χ^2 test.

The same formula from [10] can be applied to the evaluation of the consistency of the results of inter-laboratory comparisons for calibration laboratories:

$$\chi^2 = \sum_{i=1}^{n} \frac{{D_{lab\,i}}^2}{u^2(x_{lab\,i})} \tag{9}$$

To check the consistency of inter-laboratory comparisons for calibration laboratories, a criterion value is used, which is calculated based on data provided by the calibration laboratories. The criterion value does not exceed the critical value χ^2 for confidence level 0.95 and the number of degrees of freedom n-1 (n is the number of the calibration laboratory participants in the inter-laboratory comparison):

$$\chi^2 < \chi^2_{0.95(n\,-1)}. \tag{10}$$

3. RESULTS OF THE AC/DC VOLTAGE TRANSFER DIFFERENCE

The results of the Euro-Asian Cooperation of National Metrological Institutions (COOMET) COOMET.EM-S1 supplementary comparison (VNIIM[1], Russia, and UMTS, Ukraine) [28] is expressed in terms of the reference value of the COOMET.EM-K6.a key comparison (VNIIM, UMTS, BelGIM, Belarus, INM, Romania) [29]. VNIIM (Russia) took part both in COOMET.EM-K6.a and COOMET.EM-S1 comparisons therefore it can serve as a linking NMI for these two comparisons.

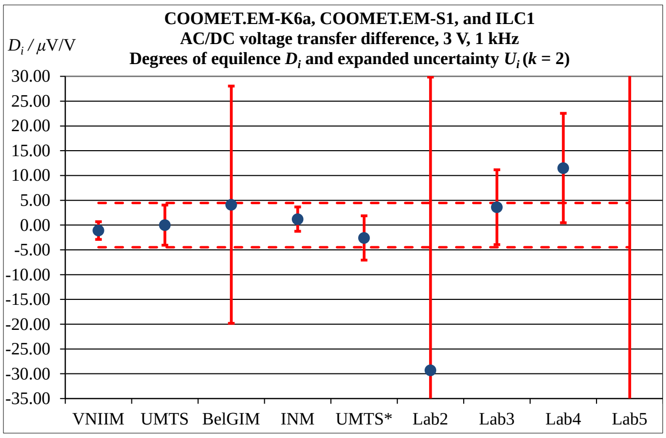

Figure 1. Degrees of equivalence of all laboratories for COOMET.EM-K6.a, COOMET.EM-S1 comparisons and ILC1 in terms of $RV_{K6.a}$ at frequency of 1 kHz.

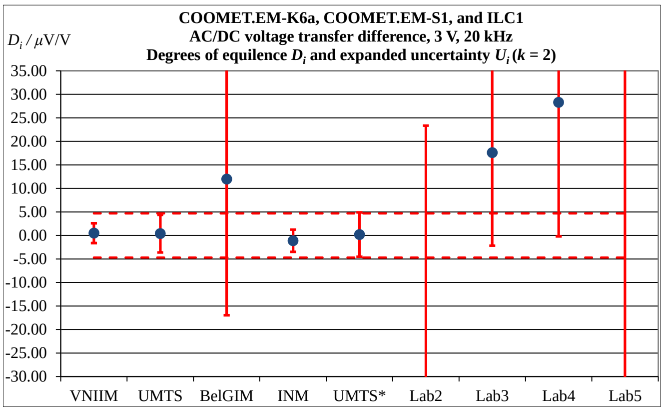

Figure 2. Degrees of equivalence of all laboratories for COOMET.EM-K6.a, COOMET.EM-S1 comparisons and ILC1 in terms of $RV_{K6.a}$ at frequency of 20 kHz

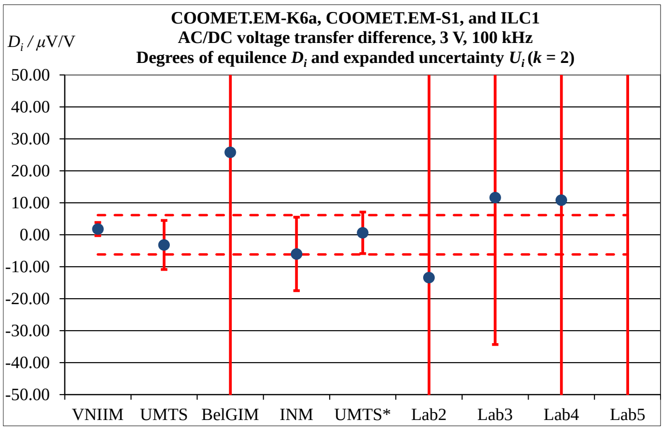

Figure 3. Degrees of equivalence of all laboratories for COOMET.EM-K6.a, COOMET.EM-S1 comparisons and ILC1 in terms of $RV_{K6.a}$ at frequency of 100 kHz.

The results from all participant laboratories in COOMET.EM-K6.a, COOMET.EM-S1, and national ILC1 (five participants) in terms of $RV_{K6.a}$ (1 kHz, 20 kHz, and 100 kHz) are shown in Table 1 [27]. D_{K6a} is degrees of equivalence from COOMET.EM-K6.a, and D_{S1} is degrees of equivalence from COOMET.EM-S1; $U(D_{K6a})$ is the NMI's or DI's expanded uncertainty from COOMET.EM-K6.a, $U(D_{S1})$ is the NMI/DI expanded uncertainty from COOMET.EM-S1, and $U(D_{ILC1})$ is the expanded uncertainty of the i-th calibration laboratory from ILC1.

In accordance with the proposed procedure and using the data in Table 1, the degrees of equivalence for all the participant laboratories in the COOMET.EM-K6.a and COOMET.EM-S1 comparisons as well as national ILC1 in terms of $RV_{K6.a}$ with the expanded uncertainty at frequencies of 1 kHz, 20 kHz, and 100 kHz were calculated, as shown in Figure 1–Figure 3. UMTS took part both in the COOMET.EM-K6.a and COOMET.EM-S1 comparisons and national ILC1; therefore, it can serve as a linking laboratory (reference laboratory).

The results of the estimation of the E_n numbers and χ^2-test of all participant laboratories in COOMET.EM-K6.a and COOMET.EM-S1 comparisons and national ILC1 are shown in Table 2. Results for all NMIs/DIs and Lab participants are satisfied except Lab 4 (E_n = 1.04) at frequency 1 kHz (require correction of the calibration procedure).

4. RESULTS FOR ELECTRICAL POWER STANDARDS

The results of COOMET.EM-S2 supplementary comparison (UMTS, BelGIM and BIM, Bulgaria) [30] expressed in terms of the reference value of EURAMET.EM-K5.1 key comparison (12 participants) [31]. UMTS took part both in EURAMET.EM-K5.1 and COOMET.EM-S2 comparisons therefore it can serve as a linking NMI for these two comparisons. The different travelling standards were used in these comparisons.

UMTS as a pilot laboratory organized and conducted the COOMET.EM-S2 supplementary comparison in power for power factors 1.0, 0.5 Lag, 0.5 Lead, AC voltage 120 V, AC current 5 A at frequencies of 50 Hz and 53 Hz [30]. The radial scheme was used.

Radian Research RM 15-04 was selected as travelling standard for this comparison. RM 15-04 is precision single-phase electrical power meter, works on principles of digital processing of electrical current and voltage signals and well-suited for test applications that require multiple measurements with high accuracy and stability. In addition to its auto ranging capabilities, RM 15-04 features three summing current inputs which can be used to perform closed link testing.

Currently there are about twenty Ukrainian accredited calibration laboratories, but only seven calibration laboratories took part was in ILC2 which organized by UMTS to maintain their accreditation. The main goal of ILC2 was the assessment of calibration laboratory capabilities that perform calibration in power measurement. This inter-laboratory comparison helped to verify first of all technical competence of the staff of participated calibration laboratories, their technical and calibration procedures, environmental conditions [22].

[1] For Abbreviations, see end of the article.

Table 1. Degrees of equivalence of laboratories in COOMET.EM-K6.a, COOMET.EM-S1 comparisons and ILC1 in terms of RV$_{K6.a}$.

Lab	D_{K6a}, µV/V	$U(D_{K6a})$, µV/V	D_{S1}, µV/V	$U(D_{S1})$, µV/V	D_{ILC1}, µV/V	$U(D_{ILC1})$, µV/V	D'_{K6a}, µV/V	$U(D'_{K6a})$, µV/V
1 kHz								
VNIIM	-1.10	1.79	-0.50	1.50			-1.10	1.79
UMTS	0.00	4.04					0.00	4.04
BelGIM	4.10	23.94					4.10	23.94
INM	1.20	2.44					1.20	2.44
UMTS* (Lab 1)			-2.00	4.10	0.00	4.47	-2.60	4.47
Lab 2					-26.70	59.00	-29.30	59.17
Lab 3					6.20	6.10	3.60	7.56
Lab 4					14.10	10.10	11.50	11.04
Lab 5					-48.70	260.00	-51.30	260.04
20 kHz								
VNIIM	0.48	2.11	-1.20	1.50			0.48	2.11
UMTS	0.38	3.99					0.38	3.99
BelGIM	11.98	28.94					11.98	28.94
INM	-1.12	2.37					-1.12	2.37
UMTS* (Lab 1)			-1.50	4.20	0.00	4.50	0.18	4.70
Lab 2					-42.00	65.00	-41.82	65.17
Lab 3					17.40	19.20	17.58	19.77
Lab 4					28.10	28.10	28.28	28.49
Lab 5					68.20	3140.00	68.38	3140.00
100 kHz								
VNIIM	1.81	2.06	-3.80	3.00			1.81	2.06
UMTS	-3.19	7.67					-3.19	7.67
BelGIM	25.80	139.00					25.80	139.00
INM	-5.99	11.50					-5.99	11.50
UMTS* (Lab 1)			-5.00	5.80	0.00	8.50	0.61	6.15
Lab 2					-14.00	95.00	-13.39	95.20
Lab 3					11.00	45.50	11.61	45.91
Lab 4					10.20	78.70	10.81	78.94
Lab 5					1419.00	3140.00	1419.61	3140.01

Table 2. The results of estimation of E_n numbers and χ^2-test for ILC1.

Lab	E_n	χ^2	$\chi^2_{0.95}(n-1)$
1 kHz			
VNIIM	0.61	2.58	3.33
UMTS	0.00		
BelGIM	0.17		
INM	0.49		
UMTS* (Lab 1)	0.58		
Lab 2	0.50		
Lab 3	0.48		
Lab 4	1.04		
Lab 5	0.20		
20 kHz			
VNIIM	0.23	2.65	3.33
UMTS	0.10		
BelGIM	0.41		
INM	0.47		
UMTS* (Lab 1)	0.04		
Lab 2	0.64		
Lab 3	0.89		
Lab 4	0.99		
Lab 5	0.02		
100 kHz			
VNIIM	0.88	1.57	3.33
UMTS	0.42		
BelGIM	0.19		
INM	0.52		
UMTS* (Lab 1)	0.09		
Lab 2	0.14		
Lab 3	0.25		
Lab 4	0.14		
Lab 5	0.45		

Table 3. Degrees of equivalence of laboratories in COOMET.EM-S2 comparison and ILC2 in terms of RV$_{S2}$.

Lab	D_{S2}, µP/P	$U(D_{S2})$, µP/P	D_{ILC2}, µP/P	$U(D_{ILC2})$, µP/P	D'_{S2}, µP/P	$U(D'_{S2})$, µP/P
power factor = 1.0						
BelGIM	33.9	36.6			33.9	36.6
BIM	-3.0	9.8			-3.0	9.8
UMTS* (Lab 1)	8.5	17.4	0.0	12.3	8.5	17.4
Lab 2			6.0	82.2	-2.5	83.1
Lab 3			566.0	150.5	557.5	151.0
Lab 4			76.0	145.0	67.5	145.5
Lab 5			46.0	104.5	37.5	105.2
Lab 6			46.0	100.0	37.5	100.8
power factor = 0.5 Lag						
BelGIM	60.4	59.2			60.4	59.2
BIM	-2.7	16.4			-2.7	16.4
UMTS* (Lab 1)	29.3	45.7	0.0	13.0	29.3	45.7
Lab 2			22.0	82.0	-7.3	83.0
Lab 3			282.0	150.6	252.7	151.2
Lab 4			112.0	152.0	82.7	152.6
Lab 5			-18.0	101.1	-47.3	101.9
Lab 6			-8.0	70.0	-37.3	71.2
power factor = 0.5 Lead						
BelGIM	-17.0	59.3			-17.0	59.3
BIM	2.7	16.7			2.7	16.7
UMTS* (Lab 1)	-0.2	46.7	0.0	13.0	-0.2	46.7
Lab 2			18.0	82.0	18.2	83.0
Lab 3			308.0	150.6	308.2	151.2
Lab 4			78.0	140.5	78.2	141.1
Lab 5			-22.0	101.1	-21.8	101.9
Lab 6			-12.0	70.0	-11.8	71.2

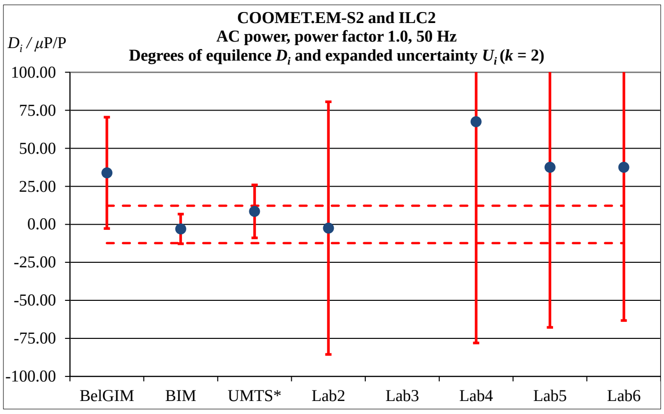

Figure 4. Degrees of equivalence of all laboratories for COOMET.EM-S2 comparisons and ILC2 in terms of RV_{S2} for power factor = 1.0.

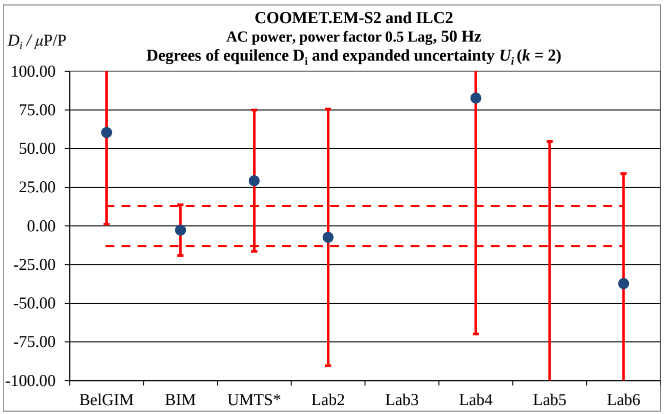

Figure 5. Degrees of equivalence of all laboratories for COOMET.EM-S2 comparisons and in ILC2 in terms of RV_{S2} for power factor = 0.5 Lag.

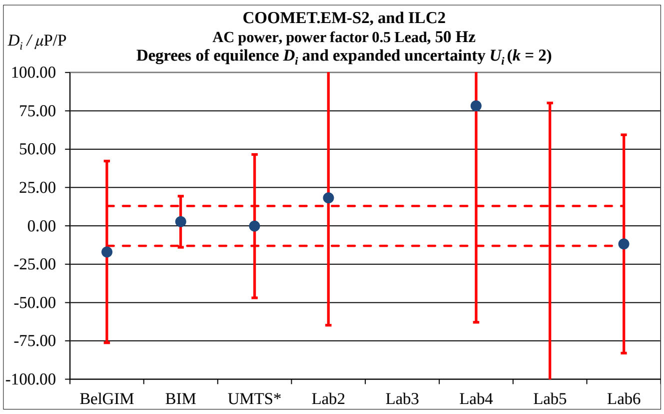

Figure 6. Degrees of equivalence of all laboratories for COOMET.EM-S2 comparisons and ILC2 in terms of RV_{S2} for power factor = 0.5 Lead.

D_{S2} is degrees of equivalence from COOMET.EM-S2; $U(D_{S2})$ is NMI's/DI's expanded uncertainty from COOMET.EM-S2, $U(D_{ILC2})$ is expanded uncertainty of i-th calibration laboratory from ILC2.

In accordance with the proposed procedure and using the data in Table 3, degrees of equivalence for all laboratories for COOMET.EM-S2 comparisons and national ILC2 in terms of RV_{S2} with the expanded uncertainty at frequency of 50 Hz was calculated, which are shown on Figure 4–Figure 6. UMTS took part both in COOMET.EM-S2 comparison and national ILC2 therefore it can serve as a linking Lab (reference laboratory).

The results of estimation of E_n numbers and χ^2-test of all participant laboratories in COOMET.EM- S2 comparison and national ILC2 are shown in Table 4. Results for all NMI/DI and Lab participants are satisfied except Lab 3 (E_n = 3.69 for power factor = 1.0, E_n = 1.67 for power factor = 0.5 Lag, E_n = 2.04 for power factor = 0.5 Lead). Lab 3 result was excluded when calculating of χ^2-test (require correction of the calibration procedure).

Table 4. The results of estimation of E_n numbers and χ^2-test for ILC2.

Lab	E_n	χ^2	$\chi^2_{0.95(n-1)}$
	power factor = 1.0		
BelGIM	0.93	1.67	2.73
BIM	0.31		
UMTS* (Lab 1)	0.49		
Lab 2	0.03		
Lab 3	3.69		
Lab 4	0.46		
Lab 5	0.36		
Lab 6	0.37		
	power factor = 0.5 Lag		
BelGIM	1.02	2.27	2.73
BIM	0.16		
UMTS* (Lab 1)	0.64		
Lab 2	0.09		
Lab 3	1.67		
Lab 4	0.54		
Lab 5	0.46		
Lab 6	0.52		
	power factor = 0.5 Lead		
BelGIM	0.29	0.54	2.73
BIM	0.16		
UMTS* (Lab 1)	0.00		
Lab 2	0.22		
Lab 3	2.04		
Lab 4	0.55		
Lab 5	0.21		
Lab 6	0.17		

5. GENERAL RECOMMENDATIONS FOR CALIBRATION LABORATORIES

The comparative analysis of the results of provided by the relevant calibration laboratories allow the following general recommendations to be drawn:

Lab1, Lab2, Lab3, and Lab5 for ILC1 meet the established requirements ($|E_n| \leq 1$) when calibrating the travelling standard at frequency of 1 kHz confirming the qualification of the participated calibration laboratory, therefore do not require any corrections in their work;

Lab 4 for ILC1 only has an unsatisfactory result at a frequency of 1 kHz (E_n = 1.04); therefore, it requires correction in the calibration procedure.

Lab1, Lab2, Lab3, Lab4, and Lab5 in ILC1 meet the established requirements ($|E_n| \leq 1$) when calibrating the travelling standard at frequencies of 20 kHz and 100 kHz, confirming the qualification of the participated calibration laboratory; therefore, they do not require any corrections.

Lab1, Lab2, Lab4, Lab5, and Lab6 for ILC1 meet the established requirements of the criterion ($|E_n| \leq 1$) when calibrating the travelling standard for 120 V, 5 A, power factor = 1.0, 0.5 Lag, and 0.5 Lead at a frequency of 50 Hz, confirming the qualification of the participant calibration laboratory; therefore, they do not require any corrections.

Concerning Lab3 in ILC2, failures were only detected in the measurements for 120 V, 5 A, power factor = 1.0, 0.5 Lag, and 0.5 Lead at a frequency of 50 Hz; therefore, it requires a serious correction in the calibration procedure.

General recommendations for Lab 4 in ILC1 and Lab3 in ILC2 follow:

to review the existing calibration procedures or develop new ones in accordance with the requirements of international standards for accredited laboratories;

to reconsider the approaches to the evaluation of the measurement uncertainty in the applied calibration procedures, in accordance with which the evaluation of the expanded uncertainty was performed; and

to systematically carry out technical training for laboratory staff to perform the calibration of measuring equipment and pay special attention to the provisions of international and national documents for the evaluation of measurement uncertainty.

6. CONCLUSIONS

The proposed procedure for linking the results of international comparisons of national standards and inter-laboratory comparison results has been applied to AC/DC voltage transfer difference measurements and AC power measurements. The presented linked results showed good agreement between all participant laboratories. To check the consistency of the linked results, the E_n number and χ^2 test were used.

Participation in inter-laboratory comparisons provides independent verification of a calibration laboratory's competence and demonstrates to the public, customers, accreditation bodies, regulators, and laboratory management that procedures are under control and gives stakeholders technical confidence in the service which calibration laboratory provide.

The positive results of calibration laboratories that participated in the inter-laboratory comparisons mean the metrological traceability to the NMI or DI of accredited calibration laboratories through the periodical calibration of their standards.

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ABBREVIATIONS

BelGIM - Belarusian State Institute of Metrology, Belarus
BIM - Bulgarian Institute of Metrology, Bulgaria
INM - National Institute of Metrology, Romania
UMTS - State Enterprise "Ukrmetrteststandard", Ukraine
VNIIM - D. I. Mendeleev Institute for Metrology, Russia