ACTA IMEKO
ISSN: 2221-870X
September 2023, Volume 12, Number 3, 1 - 7

The evaluation of main results of the RMO Key and Supplementary comparisons for electrical power and energy

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ABSTRACT
To overcome technical barriers in trade between countries, special international agreements on mutual recognition (MRA) of measurement results play an important role. National Metrology Institutes (NMIs) and Designated Institutes (DIs) play a major role in the implementation of these agreements. NMI and DI standards periodically participate in international comparisons to establish their equivalence to other similar standards. A comparative analysis of the results of NMI/DI participants of COOMET.EM-K5 of alternating current active power and GULFMET.EM-S5 of alternating current active and reactive energy comparisons, both in terms of regional and metrological traceability for Regional Metrology Organizations, was carried out. This analysis is related to the need to minimize the cost of NMIs/DIs in order to achieve the required metrological traceability, taking into account the geographical location of the leading NMIs. For checking consistency of these comparisons data ware used E_n number and z scores. The results for all participants of the comparisons are satisfactory both for E_n number and z scores.

Section: RESEARCH PAPER

Keywords: Key comparison; supplementary comparison; electrical quantity; National Metrology Institute; measurement uncertainty

Citation: Oleh Velychko, Tetyana Gordiyenko, The evaluation of main results of the RMO Key and Supplementary comparisons for electrical power and energy, Acta IMEKO, vol. 12, no. 3, article 20, September 2023, identifier: IMEKO-ACTA-12 (2023)-03-20

Section Editors: Jan Saliga, Technical university of Kosice, Slovakia, Jakub Svatos, CVUT Prague, Czech Republic, Platon Sovilj, University of Novi Sad, Serbia

Received January 2, 2023; **In final form** August 22, 2023; **Published** September 2023

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1. INTRODUCTION

To overcome technical barriers in trade between countries, special international Mutual Recognition Agreements (MRA) of measurement results play an important role. This is the basis for global metrological traceability [1]. National Metrology Institutes (NMIs) and Designated Institutes (DIs) play a major role in the implementation of these agreements. NMI and DI standards periodically participate in international comparisons to establish their equivalence to other similar standards.

For mutual recognition of the results of measurements that are carried out in the NMIs of different countries, the Agreement on Mutual Recognition of the International Committee for Weights and Measures – Comité International des Poids et Mesures (CIPM) [2] was concluded. International comparisons of national standards, which are carried out in accordance with the requirements of the CIPM MRA, are the basis for the implementation of this agreement. Publication of the results of conducted key comparisons (KCs) and supplementary comparisons (SCs) are carried out in the Key Comparison Database (KCDB) of the International Bureau of Weights and Measures – Bureau International des Poids et Mesures (BIPM) [3], [4], [5].

BIPM, Consultative Committees (CCs) of CIPM, and Regional Metrology Organizations (RMOs) are organizing and carry out KCs. The RMOs are established on a regional basis (European Association of National Metrology Institute, EURAMET, Asia Pacific Metrology Programme, APMP, Eurasian Cooperation of National Metrology Institutions, COOMET, Inter-American Metrology System, SIM, Intra-Africa Metrology System, AFRIMET and Gulf Association for Metrology, GULFMET) and organize and carry out KCs according to the procedures established within the framework of the CIPM MRA. According to the results of evaluation of national standards obtained in the framework of international comparisons, the reference value (RV) of comparisons with the corresponding uncertainty and the degree of equivalence (DoE) of standards with the corresponding uncertainty are established [6].

Only RMOs organizing and carry out SCs according to established procedures within the CIPM MRA for those measurements that are not covered by the KCs. They complement the KCs and their results are also published in the KCDB BIPM. DoE SCs are not required to be set, but for many SCs they are set. COOMET has recommendations for evaluating the results of both KS and SC [7], [8].

Based on the results of participation of NMI/DI in KCs or SCs or calibration of their standards in other NMI/DI that published CMCs in KCDB of BIPM, Calibration and Measurement Capabilities (CMC) are established [6]. According to the results of the calibration of standards of physical quantities and the assessment of the corresponding measurement uncertainty, metrological traceability is established for a certain hierarchy of standards calibration. The calibration of two standards can be considered as a calibration, when it is used to check and correct the value of the quantity and measurement uncertainty for one of the standards [1].

Comparative analysis of the results of KCs or SCs for NMI/DI participants both in the regional context and in the context of metrological traceability for RMOs is a relevant and important task. This analysis is related to the need to minimize the cost of NMI/DI to achieve the required metrological traceability, taking into account the geographical location of the leading NMIs.

2. THE TRADITIONAL APPROACH FOR EVALUATION OF KC DATA

For CC KC data, KC RV and DoE are necessarily calculated [10], [11]. A RMO KC involving some NMIs that have participated in similar CC KC and using a similar technical protocol allows its results to be linked to those of the CC KC. At the same time, KC RV and DoE are calculated for RMO KC participants, except for links with CC KC NMI. A special procedure for evaluating RMO KC participant data is applied to ensure linkage with CC KC participant data [5], [9], [12], [13].

Distribution of all RMOs by World map is shown on Figure 1.

The COOMET.EM-K5 KC of alternating current (AC) active power of low-frequency 50/60 Hz was carried out in 2016–2018 between 13 NMIs/DIs from five RMOs: COOMET; EURAMET; APMP; GULFMET, and AFRIMET [14], [15].

The KV and DoE of COOMET.EM-K5 KC are published in KCDB [3], [14] for power factor (PF) 1.0, 0.5 Lag, 0.5 Lead, 0.0 Lag, 0.0 Lead at frequencies of 50/53 Hz. Results for PF 1.0 at frequencies of 53 Hz are shown on Figure 2, for example. Results for PF (0.5 Lag, 0.5 Lead, 0.0 Lag, 0.0 Lead) at frequencies of 50/53 Hz are similar to those for PF 1.0, so they are not considered further.

The correlations in traceability between the NMI/DI participants have been neglected for calculating the KC RV.

Figure 1. Distribution of all RMOs by World map.

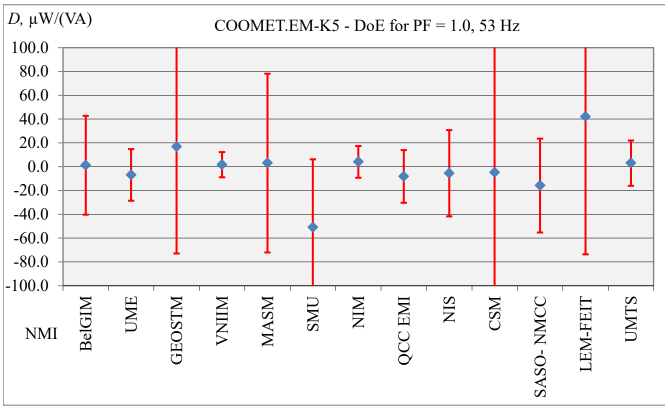

Figure 2. DoE for NMI/DI participants of COOMET.EM-K5 KC for PF = 1.0 0 at frequency of 53 Hz.

Because 3 NMI/DIs have the lowest standard uncertainties then they determine the KC RV. NIM and VNIIM was participants of CCEM-K5 KC [16], and UME was pilot laboratory of EURAMET.EM-K5.1 KC and they have different traceability source.

The KC RV x_{ref} is calculated as the mean of NMI/DI participant results with COOMET.EM-K5 data and is given by formula:

$$x_{\mathrm{ref}} = \frac{\sum_{i=1}^{N} \frac{x_i}{u_{\mathrm{c}}^2(x_i)}}{\sum_{i=1}^{N} \frac{1}{u_{\mathrm{c}}^2(x_i)}} \tag{1}$$

with the combined standard uncertainty

$$u_{\mathrm{c}}^2(x_{\mathrm{ref}}) = \frac{1}{\sum_{i=1}^{N} \frac{1}{u_{\mathrm{c}}^2(x_i)}}, \tag{2}$$

where x_i is the result of i-th NMI/DI participant; $u_{\mathrm{c}}(x_i)$ is the standard uncertainty of i-th NMI/DI participant; N is the total number of NMI/DI participants.

KC RV and expanded uncertainties (k = 2) for PF 1.0, 53 Hz are x_{ref} = -2.1 µW/(VA) and U_{ref} = 5.8 µW/(VA).

The DoE of i-th NMI/DI D_i and its combined standard uncertainties $u_c(D_i)$ with respect to the KC RV are estimated as

$$D_i = x_i - x_{\mathrm{ref}} \tag{3}$$

$$u_{\mathrm{c}}^2(D_i) = u_{\mathrm{c}}^2(x_i) + u_{\mathrm{c}}^2(x_{\mathrm{ref}}). \tag{4}$$

NMI/DI participant results of RMO EUROMET.EM-K5&K5.1, SIM.EM-K5, and COOMET.EM-K5 KCs of AC active power are linked to those of CCEM-K5 KC and shown on Figure 3 for PF 1.0 at frequency of 53 Hz [3].

DoE of i-th NMI/DI participants of COOMET.EM-K5 KC with respect to linking to CCEM-K5 is estimated as

$$d_i = D_i + \Delta\,, \tag{5}$$

where d_i is best estimate of result from i-th NMI/DI to linking to CCEM-K5; D_i is DoE from COOMET.EM-K5 for NMI/DI participant in COOMET.EM-K5 only; Δ is correction factor with respect to linking to CCEM-K5.

Measurements from the linking NMIs provide estimates

$$\Delta_{iLINK} = d_{iLINK} - D_{iLINK}\,, \tag{6}$$

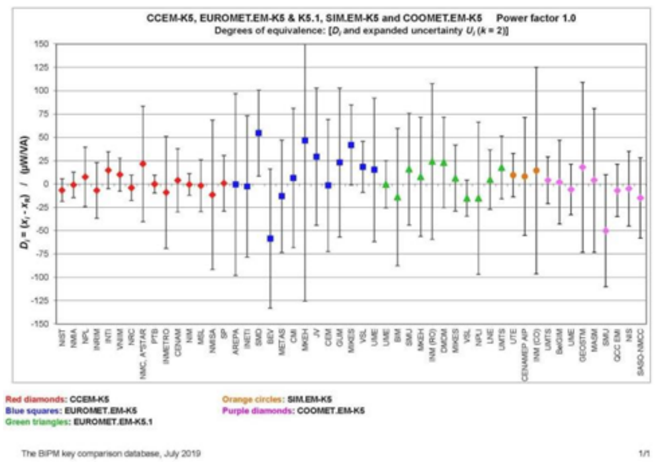

Figure 3. Linked DoE for NMI/DI participants of RMO KCs of power for *PF* = 1.0 at frequency of 53 Hz.

where $\Delta_{i\text{LINK}}$ is correction factor for i-th linking NMI/DI; $d_{i\text{LINK}}$ is DoE for i-th linking NMI/DI from CCEM-K5; $D_{i\text{LINK}}$ is DoE for i-th linking NMI/DI from COOMET.EM-K5.

Two NMIs were linking NMIs (see Figure 3). The correction factor Δ is 0.9 for PF 1.0 at frequency of 53 Hz, for example [3], [16].

3. KC RESULTS IN THE CONTEXT OF RMOS

COOMET.EM-K5 KC was conducted between NMI/DI participants from 5 RMOs (COOMET; EURAMET; APMP; GULFMET, and AFRIMET). NMI/DI participant results (D_i is DoE of i-th NMI/DI participant, $U(D_i)$ is expanded uncertainty of D_i) in the context of RMOs are shown in Table 1 and on Figure 4 for PF 1.0 at frequency of 53 Hz, for example.

E_{ni} number and z_i scores [17], [18], [19] are most often used to check the consistency of KC data. The evaluation of consistency of COOMET.EM-K5 KC data are presented in Table 1 and on Figure 5 for E_{ni} number and Figure 6 for z_i score.

The E_{ni} number is calculated as:

$$E_{\mathrm{n}i} = \frac{|D_i|}{2\,u_{\mathrm{c}}(D_i)} \tag{7}$$

and the z_i scores are calculated by the formula:

$$z_i = \frac{|D_i|}{\sigma}, \tag{8}$$

where σ is the standard deviation for qualification assessment.

The values of the $E_{\mathrm{n}i}$ number for COOMET NMI/DI participants of COOMET.EM-K5 KC varied from 0.03 to 0.19,

Table 1. NMI/DI results of COOMET.EM-K5 in the context of RMOs for PF 1.0 at frequency of 53 Hz.

NMI	D_i, 10^{-6}	$U(D_i)$, 10^{-6}	E_{ni}	z_i
		COOMET		
VNIIM	1.7	10.6	0.16	0.08
BelGIM	1.2	41.5	0.03	0.06
GEOSTM	16.7	89.6	0.19	0.81
CSM	-4.9	158.1	0.03	0.24
UMTS	3.0	19.0	0.16	0.15
		EURAMET		
UME	-6.9	21.7	0.32	0.34
SMU	-50.9	57.2	0.89	2.48
LEM-FEIT	42.0	115.6	0.36	2.04
		APMP		
NIM	4.0	13.3	0.30	0.19
MASM	3.1	75.1	0.04	0.15
		GULFMET & AFRIMET		
QCC EMI	-8.2	22.2	0.37	0.40
SASO- NMCC	-15.9	39.4	0.40	0.78
NIS	-5.5	36.3	0.15	0.27

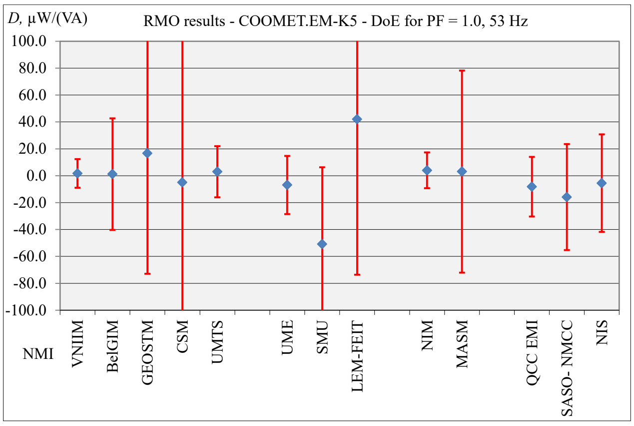

Figure 4. DoE for NMI/DI participants of COOMET.EM-K5 KC in the context of RMOs for *PF* = 1.0 at frequency of 53 Hz.

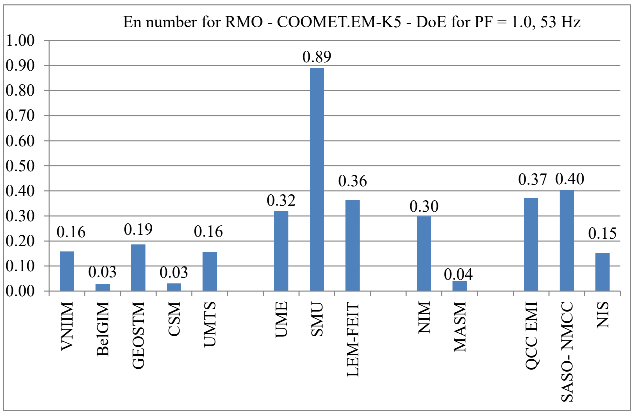

Figure 5. E_{ni} number for NMI/DI participants of COOMET.EM-K5 KC in the context of RMOs for *PF* = 1.0 at frequency of 53 Hz.

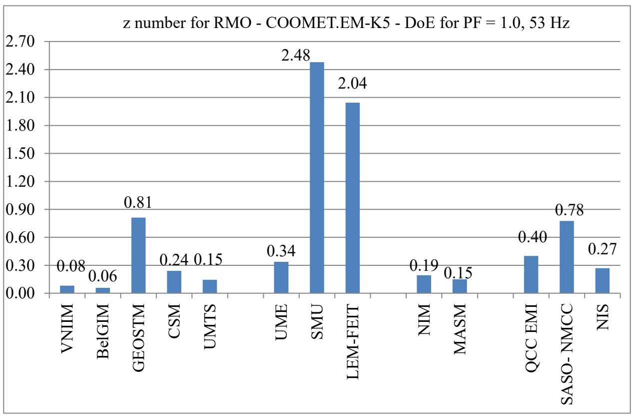

Figure 6. z_i score for NMI/DI participants of COOMET.EM-K5 KC in the context of RMOs for *PF* = 1.0 at frequency of 53 Hz.

EURAMET – from 0.32 to 0.89, APMP – from 0.04 to 0.30, GULFMET&AFRIMET – from 0.15 to 0.40.

The highest values of E_{ni} number are fixed for EURAMET NMI/DI participants, and the smallest – for COOMET. Results for all NMI/DI participants of COOMET.EM-K5 are satisfactory for E_{ni} numbers (< 1.0), but value of E_{ni} number for SMU from EURAMET several times more than values for all other NMI/DI participants.

Values of z_i scores for COOMET NMI/DI participants are varied from 0.06 to 0.81, EURAMET – from 0.34 to 2.48, APMP – from 0.15 to 0.19, GULFMET&AFRIMET – from 0.27 to 0.78.

The highest values of z_i scores are fixed for EURAMET NMI/DI participants, and the smallest – for COOMET and APMP. Results for all NMI/DI participants of COOMET.EM-K5 are satisfactory for z_i scores (< 3.0), but value of z_i scores for SMU and LEM-FEIT from EURAMET ($2.0 < z_i < 3.0$) indicate a dubious performance characteristic and require precautionary measures.

4. KC RESULTS IN THE CONTEXT OF METROLOGICAL TRACEABILITY

In COOMET.EM-K5 KC took part NMI/DIs, which had metrological traceability to the three main NMIs: PTB (Germany), UME, and NIM. PTB, NIM and VNIIM had own traceability as CCEM-K5 KC participants. PTB was a pilot laboratory for EUROMET.EM-K5 KC. UME was a pilot laboratory for EUROMET.EM-K5.1 KC [20]. QCC EMI has traceability to NMIA (Australia). NMIA was a pilot laboratory for APMP.EM-K5 [3]. Metrological traceability to the CCEM-K5 is provided by NIST (USA), CENAM (Mexico), and NRC (Canada) also, which participated in the KC SIM.EM-K5 [21].

Figure 7 shows the traceability of NMI/DI participants of COOMET.EM-K5 KC. Cells on Figure 7 with a dashed line show NMI that did not participate in COOMET.EM-K5 KC.

NMI/DI results of COOMET.EM-K5 in the context of metrological traceability are shown in Table 2 and on Figure 8. E_{ni} number and z_i score for NMI/DI participants are presented in Table 2 and on Figure 9 only for E_{ni} number and Figure 10 for z_i score.

Values of E_{ni} number for NMI/DI participants with traceability to PTB from EURAMET are varied from 0.03 to 0.89, UME from EURAMET – from 0.03 to 0.40, NIM from APMP – from 0.04 to 0.30, other NMI – from 0.16 to 0.37. The highest values of E_{ni} number are fixed for NMI/DI participants with traceability to PTB, and the smallest – for NIM and UME. Results for all NMI/DI participants are satisfactory for E_{ni} number (< 1.0), but value of E_{ni} number for SMU may indicate the time drift of the power standard since its last calibration in the PTB. In general, NMI/DI participants of comparison may be encouraged to calibrate it standards immediately before of comparison.

Values of z_i scores for NMI/DI participants with traceability to PTB from EURAMET are varied from 0.06 to 2.48, UME from EURAMET – from 0.24 to 0.78, NIM from APMP – from 0.15 to 0.19, other NMI – from 0.08 to 0.40. The highest values of z_i scores are fixed for NMI/DI participants which traceable to PTB, and the smallest – for NIM. Results for all NMI/DI participants are satisfactory for z_i scores (< 3.0). Value of zi scores for SMU and LEM-FEIT ($2.0 < z_i < 3.0$) indicate a dubious performance characteristic and require precautionary measures. In both cases, the specified NMI/DI participants also need to pay attention to improving the level of practical training of staff.

The results of four COOMET.EM-K5 KC participants confirmed their CMC entries in the KCDB BIPM for AC active power: BelGIM, VME, SMU and UMTS. The results of five other KC participants allow drafting their CMC entries in the KCDB BIPM for AC active power, as they did not have such entries in this database: GEOSTM, MASM, QCC EMI, SASO-NMCC, and NIS.

Table 2. NMI/DI KC results in the context of metrological traceability to NMI/DI.

NMI	D_i, 10^{-6}	$U(D_i)$, 10^{-6}	E_{ni}	z_i
		PTB		
UMTS	3.0	19.0	0.16	0.15
BelGIM	1.2	41.5	0.03	0.06
GEOSTM	16.7	89.6	0.19	0.81
SMU	-50.9	57.2	0.89	2.48
LEM-FEIT	42.0	115.6	0.36	2.04
		UME		
UME	-6.9	21.7	0.32	0.34
SASO- NMCC	-15.9	39.4	0.40	0.78
NIS	-5.5	36.3	0.15	0.27
CSM	-4.9	158.1	0.03	0.24
		NIM		
NIM	4.0	13.3	0.30	0.19
MASM	3.1	75.1	0.04	0.15
		Other NMI/DI		
VNIIM	1.7	10.6	0.16	0.08
QCC EMI	-8.2	22.2	0.37	0.40

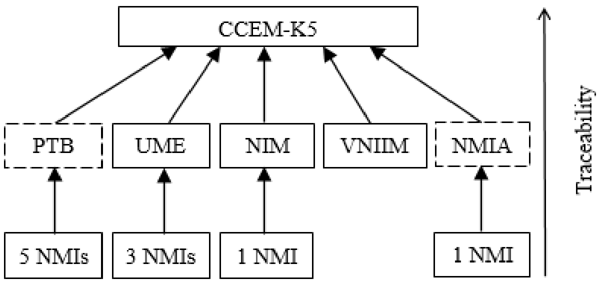

Figure 7. The metrological traceability for NMI/DI participants of COOMET.EM-K5 KC.

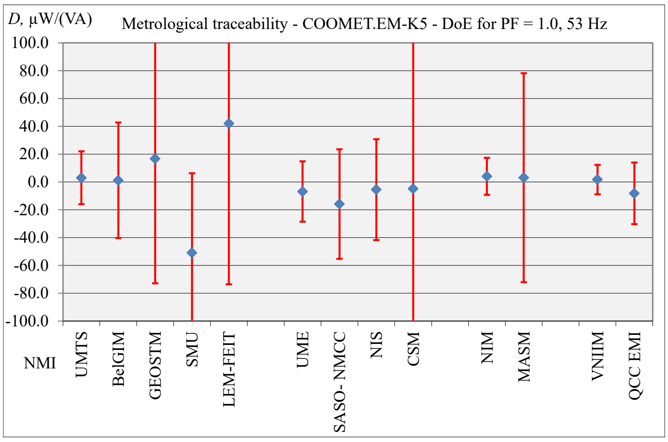

Figure 8. DoE for NMI/DI KC participants of COOMET.EM-K5 KC in the context of metrological traceability for *PF* = 1.0 at frequency of 53 Hz.

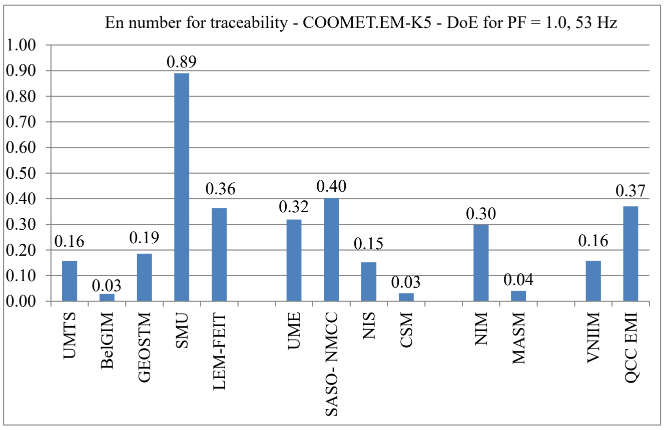

Figure 9. E_{ni} number for NMI/DI KC participants in the context of metrological traceability for *PF* = 1.0 at frequency of 53 Hz.

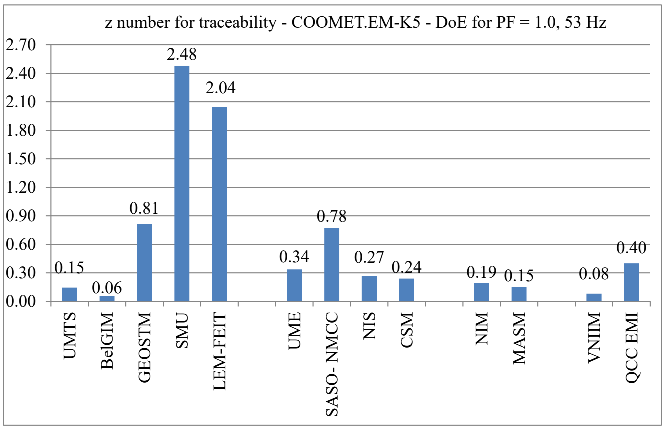

Figure 10. z_i score for NMI/DI KC participants in the context of metrological traceability for *PF* = 1.0 at frequency of 53 Hz.

The results of the three participants of the KC can become the basis for the recognition of their management systems in the field of calibration for electrical and magnetism (EM): MASM, QCC EMI, and SASO-NMCC. The results of two more participants in these comparisons allow preparing draft CMC records for AC active power after they sign the CIPM MRA: CSM, and LEM-FEIT.

5. SC RESULTS IN THE CONTEXT OF METROLOGICAL TRACEABILITY

A comparative analysis of the results of the RMO KCs for NMI/DI participants can only be carried out in the context of metrological traceability. This is due to the fact that such comparisons are carried out only by RMOs and very rarely NMI/DI from other RMOs participates in them.

Electrical energy and electrical power are among the main characteristics of all electrical and electronic systems. Energy represents the overall work done on an electrical system. Power defines the work done per unit time in an electrical system. KCs are carried out by CCEM and five RMOs (EURAMET, COOMET, APMP, SIM, and GULFMET) for AC electric power only within the framework of the CIPM MPA. SCs are carried out by two RMOs (SIM, and GULFMET) for AC electric active energy only within the framework of the CIPM MRA [4].

RMO SCs play their role in establishing metrological traceability and preparing or confirmation CMC of NMI/DIs. KCs are carried out for the standards of the most important and widely used measured quantities. Therefore, there are measurement standards of quantities for which only SCs is used.

SIM conducted SCs of AC active electric energy at low-frequency 53 Hz in 2003–2004 (SIM.EM-S2 [22]), 2010–2011 (SIM.EM-S7 [23]) and 2018 (SIM.EM-S14 [24]). NIS (Egypt) from AFRIMET took part in the SIM.EM-S14 SC. 10 NMI/DIs from SIM participated in all these SCs with satisfactory results.

The GULFMET-S5 SC of AC active and reactive energy at low-frequency 50/60 Hz was conducted in 2019 between three NMIs/DIs (UMTS, UME, and QCC EMI) [25]. In this SC took part NMIs/DIs, which had metrological traceability to the three NMIs: PTB, UME, and NMIA (Figure 7). UMTS was as the pilot laboratory of this KC and traceable to PTB, which had own traceability as CCEM-K5 KC participants. PTB was a pilot laboratory for EUROMET.EM-K5 KC [26]. QCC EMI have traceability to NMIA.

NMI/DI results of GULFMET.EM-S5 SC in the context of metrological traceability are shown on Figure 11. E_{ni} score and z_i score for NMI/DI participants are presented on Figure 12 (for E_{ni} number – left and for z_i score – right).

Values of E_{ni} number for NMI/DI participants are vary from 0.26 to 0.99. Results for all NMI/DI participants are satisfactory for E_{ni} numbers (< 1.0). Values of z_i scores for NMI/DI participants are vary from 0.29 to 1.27. Results for all NMI/DI participants are satisfactory for z_i scores (< 2.0). Value of E_{ni} number and z_i score for QCC EMI may indicate the time drift of the power standard since its last calibration.

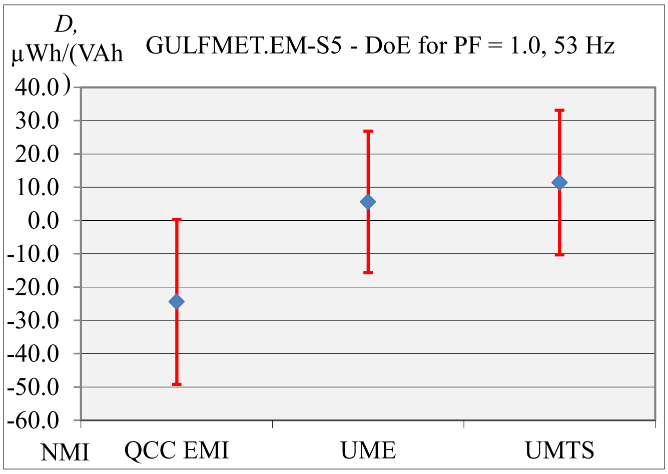

Figure 11. DoE for NMI/DI participants of GULFMET-S5 SC in the context of traceability for *PF* = 1.0 at frequency of 53 Hz.

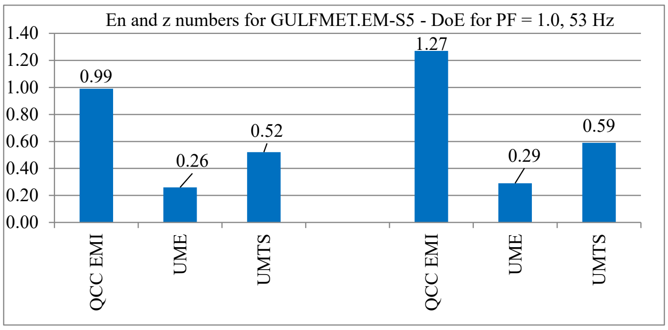

Figure 12. E_{ni} number and z_i score for NMI/DI participants of GULFMET-S5 SC in the context of metrological traceability for *PF* = 1.0 at frequency of 53 Hz.

6. CONCLUSIONS

A large number of both KCs and SCs for electrical energy and electrical power standards are carried out within the framework of the CIPM MPA. This is due to the fact that these physical quantities are one of the main characteristics of all electrical and electronic systems. KCs for such standards have been carried out by CCEM and three RMOs (EURAMET, COOMET, and CIM). SCs were carried out only by two RMOs (SIM and GULFMET) and only for electrical active energy of alternating current [4].

A good agreement between the results of NMI/DI participants of the COOMET.EM-K5 KC of active AC power from five RMOs and the GULFMET.EM-S5 SC of active AC energy from RMO GULFMET is observed. The comparative analysis of the results of the indicated KC and SC shows both the geographical context and the context of the metrological traceability of the NMI/DI participants in those comparisons.

All NMI/DI participants of the specified KC and SC have metrological traceability of the active power AC or active energy AC unit to the world's leading NMIs. The traceability of participants in NMI/DI comparisons was carried out by linking NMIs participating in CCEM-K5 KC (PTB, NIM and VNIIM) and NMIs as pilot laboratories of RMO KC (UME and NMIA). This comparative analysis can be useful for NMI/DI from different RMOs to minimize their costs in order to achieve the required metrological traceability of national standards for the specified physical quantities.

For RMOs such as COOMET, EURAMET, APMP and GULFMET, the results of COOMET-K5 KC and GULFMET-S5 SC are the basis for peer review of the quality management systems of some NMIs/DIs for their calibration services (MASM, QCC EMI, SASO-NMCC) under the CIPM MRA. These comparisons also provide support for CMC records for all other NMI/DI participants within the CIPM MRA. Both NMI/DI participants of COOMET-K5 KC (GEOSTM, MASM, QCC EMI, SASO-NMCC, and NIS), and one NMI/DI participant of GULFMET-S5 SC (QCC EMI) that does not yet have CMC records in the KCDB of BIPM have this capability.

ABBREVIATIONS

AC	- alternating current
AFRIMET	- Intra-Africa Metrology System
APMP	- Asia Pacific Metrology Programme
BIPM	- Bureau International des Poids et Mesures
CC	- Consultative Committee
CIPM	- Comité International des Poids et Mesures
CMC	- Calibration and Measurement Capabilities
COOMET	- Eurasian Cooperation of National Metrology Institutions
DI	- Designated Institute
DoE	- degree of equivalence
EM	- electrical and magnetism
EURAMET	- European Association of National Metrology Institute
KC	- key comparison
KCDB	- Key Comparison Database
MRA	- Mutual Recognition Agreement
NMI	- National Metrology Institutes
PF	- power factor
RMO	- Regional Metrology Organization
RV	- reference value
SC	- supplementary comparison
SIM	- Inter-American Metrology System

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