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Main results of GULFMET.EM-S5/5.1 supplementary comparisons for electrical energy at frequencies of 50/53 Hz

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Abstract

International agreements are the basis for establishing global metrological traceability. The Arrangement on the Mutual Recognition of National Standards, Calibration and Measurement Capabilities of National Metrology Institutes (NMIs) of the International Committee for Weights and Measures plays a key role in ensuring the international equivalence of national standards in different countries. The main basis of this arrangement is specific guidelines and recommendations, in particular for the comparison of standards.

Regional metrology organisations (RMOs) traditionally carry out both key and supplementary comparisons of national standards of the unit of electric power at frequencies of 50 and 53 Hz, in particular within the framework of COOMET, the pilot laboratory of which was SE "Ukrmetrteststandard". However, supplementary comparison of the national standards at frequencies of 50 and 60 Hz for energy units was conducted only by the RMOs of the American continent – SIM.

The article presents the main results of international supplementary comparisons of national standards of active and reactive electrical energy units at frequencies of 50 and 53 Hz within the framework of the GULFMET.EM-S5 and GULFMET. EM-S5.1 project. Comparisons piloted by the SE "Ukrmetrteststandard" were conducted radially with the participation of the National Metrological Institutes of Ukraine, Turkey and the United Arab Emirates (UAE) during 2019 and 2020.

The drift of the travelling standard was estimated over the entire period of the comparison and was small for all measurement points. The degree of equivalence of national standards active and reactive energy for power factors of 1.0, 0.5 Lag and 0.5 Lead has been established. Results of estimation of consistency of the received data are presented. Values number E_n for all NMIs for all measuring points meet the set requirements. Linked results of GULFMET.EM-S5 and GULFMET.EM-S5.1 supplementary comparisons were presented.

Keywords: supplementary comparison; reference value; electrical energy; measurement uncertainty; National Metrology Institute; linking.

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1. Introduction

International agreements are the basis for establishing global metrological traceability. The Arrangement on Mutual Recognition of National Standards, Calibration and Measurement Capabilities of National Metrology Institutes (NMIs) of the International Committee for Weights and Measures (CIPM MRA) [1] plays an important role in ensuring the international equivalence of national standards of different countries. The main basis of this arrangement is special documents, guidelines, standards and recommendations, in particular on the comparison of standards [2]. NMIs play an important role in the implementation of the CIPM MRA Arrangement.

In addition to key comparisons, Regional Metrology Organisations (RMOs) carry out supplementary comparisons of standards for those measurements that are not covered by key comparisons of the CIPM Consultative Committees or RMOs. The results of all international comparisons of standards are published in a special database of key comparisons (KCDB) of the International Bureau for Weights and Measures (BIPM) [3].

RMO traditionally conducts both key and supplementary comparisons of national standards of electric power unit at frequencies of 50 and 53 Hz, in particular within the framework of COOMET [4, 5], the pilot laboratory of which was SE "Ukrmetrteststandard" (UMTS, Ukraine). However, supplementary comparisons of national standards of the electric energy unit at frequencies of 50 and 60 Hz were organized and carried out only by RMO countries of the American continent – SIM: SIM.EM-S2 [6] in 2003–2004, SIM. EM-S7 [7] in 2010–2011, and SIM.EM-S12 from 2015, which have not yet been completed till now.

The GULFMET supplementary comparisons of national standards of a unit of electric energy at

frequencies of 50 and 53 Hz were conducted from February to June 2019 (GULFMET.EM-S5 [8]) and from December 2019 to June 2020 (GULFMET.EM-S5.1). The pilot laboratory of both comparisons was UMTS (Ukraine). NMI-participants of GULFMET.EM-S5 comparison were UMTS, QCC EMI (United Arab Emirates, UAE), and UME (Turkey). NMI-participants of GULFMET.EM-S5.1 comparison were UMTS and QCC EMI. Those NMIs are members of the RMOs GULFMET, COOMET, and EURAMET. Establishing a link between the results of both comparisons is important.

2. Evaluation of travelling standard and conditions of measurements

Radian Research RD-33-332, which has a guaranteed accuracy of 0.01% and was successfully used in key comparisons of national standards of electric power unit (COOMET.EM-K5), was selected as travelling standard (TS) for comparisons [5, 9]. TS RD-33-332 is three-phase AC power meter, which works on principles of digital processing of electrical current and voltage signals.

The measurement of AC Energy is fully automatic thorough counting the number of pulses from the "pulse output" connector which is directly proportional to the measured active energy. The output frequency of RD-33-332 is 20833.3333 Hz.

The TS RD-33-332 is an energy meter of the energy-to-pulse converting type. The energy constant, K_H, of this standard is equal to 125000 pulses/Wh. At 120 V, 5 A and power factor equal to unit, RD-33-332 is able to generate a train of pulses with a frequency equal to 20833.3333 pulses per second.

The pulse frequency is related to electrical energy by the following dependence:

$$f = \left(P \cdot K_H\right)/3600, \quad (1)$$

where K_H value of the NMI participant is given in terms of pulses per W or pulses per kW/h.

The number of pulses on the RD-33-332 is set to 1000000 and the integration time T_{int} for energy measurements is approximately equal to:

$T_{\text{int}} = 60$ s, at 120 V/5 A/Power Factor (PF)/ Reactive PF (RPF) = 1.0;

$T_{\text{int}} = 120$ s, at 120 V/5 A/PF/RPF = 0.5 Lag, 0.5 Lead.

The calibration error x_i should be expressed in μWh/VAh (active energy) and μvarh/VAh (reactive energy) by each NMI participant.

Measurements were performed under the following input signals and environmental conditions:

voltage: 120 V ± 0.2%;
current: 5 A ± 0.2%;
PF/RPF: 1.0; 0.5 Lag; 0.5 Lead ± 0.1%;
input frequency: 50 ± 0.05 Hz and 53 ± 0.05 Hz;
ambient temperature: 23 ± 1°C;
ambient humidity: 20–70%;
supply voltage: 220 V ± 5%;
supply voltage frequency: 50 ± 0.1 Hz.

The first day of starting GULFMET.EM-S5 comparison was 11 February 2019. GULFMET.EM-S5.1 comparison was finished on 29 May 2020. UMTS as a pilot laboratory has performed repeated measurements on TS for 15 months and 18 days. During the course of both comparisons the drift effect was calculated for all PF/RPF points (Table 1 and Fig. 1 for PF = 1.0 at frequency of 53 Hz and active energy only). The average values of energy x_{av} and standard deviation σ are given in Table 1 at frequencies of 50/53 Hz and PF/RPF= = 1.0, 0.5 Lag, 0.5 Lead. The drifts were small for all measurement points, so they can be neglected.

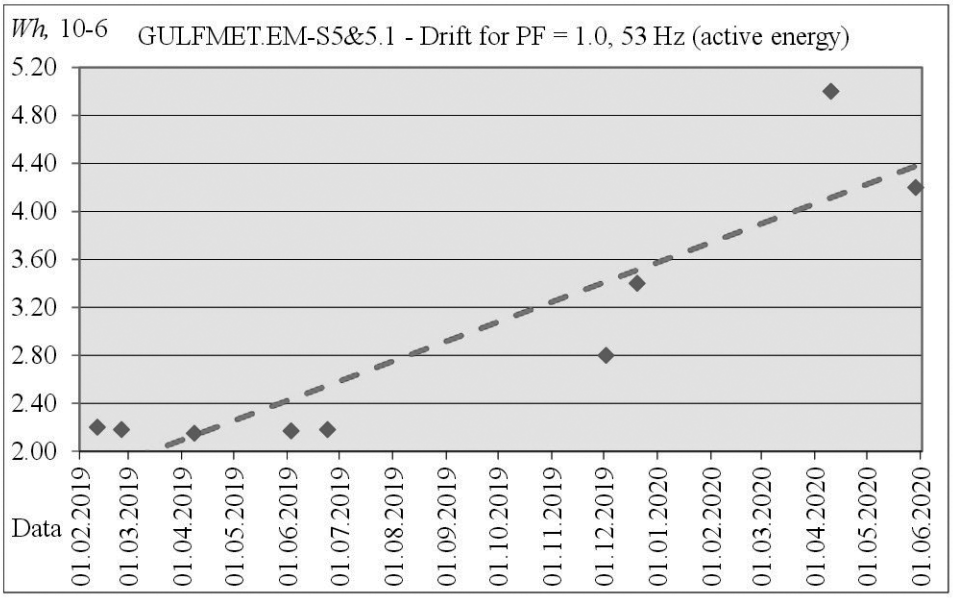

Fig. 1. Drift of TS for PF = 1.0, 53 Hz (active energy)

Table 1

The average values and standard deviation for active and reactive energy

Frequency	PF/RPF	Active energy		Reactive energy	
		x_{av}, μWh/(VAh)	σ, μWh/(VAh)	x_{av}, μvarh/(VAh)	σ, μvarh/(VAh)
50 Hz	1.0	3.6	1.1	1.8	2.8
	0.5 Lag	3.9	0.1	3.9	0.5
	0.5 Lead	-6.4	0.4	-6.1	0.4
53 Hz	1.0	2.9	1.1	2.4	0.5
	0.5 Lag	5.1	0.2	4.5	1.3
	0.5 Lead	-4.5	0.4	-4.7	0.6

Table 2

RVs and expanded uncertainties for active energy

Frequency	PF	GULFMET.EM-S5		GULFMET.EM-S5.1	
		x_{ref}, μWh/(VAh)	U_{ref}, μWh/(VAh)	x_{ref}, μWh/(VAh)	U_{ref}, μWh/(VAh)
50 Hz	1.0	-7.9	22.6	-0.1	31.0
	0.5 Lag	-1.9	26.8	1.2	34.3
	0.5 Lead	-10.7	28.2	-5.9	35.5
53 Hz	1.0	-9.2	22.4	-1.7	31.0
	0.5 Lag	1.3	26.8	2.7	34.1
	0.5 Lead	-15.3	28.0	-0.1	31.0

Table 3

RVs and expanded uncertainties for reactive energy

Frequency	RPF	GULFMET.EM-S5		GULFMET.EM-S5.1	
		x_{ref}, μvarh/(VAh)	U_{ref}, μvarh/(VAh)	x_{ref}, μvarh/(VAh)	U_{ref}, μvarh/(VAh)
50 Hz	1.0	-9.5	28.0	-3.0	31.7
	0.5 Lag	-4.7	33.4	-2.7	34.4
	0.5 Lead	-12.5	33.4	-6.4	37.4
53 Hz	1.0	-12.3	27.6	-1.2	30.4
	0.5 Lag	-1.0	33.4	-1.1	34.0
	0.5 Lead	-15.8	34.2	-8.1	36.1

3. Evaluation of results of supplementary comparisons

The comparison reference values x_{ref} are calculated as the mean of participant results with GULFMET.EM-S5 or GULFMET.EM-S5.1 data are given by [10, 11]

$$x_{ref} = \sum_{i=1}^{N} \frac{x_i}{u_c^2(x_i)} \Big/ \sum_{i=1}^{N} \frac{1}{u_c^2(x_i)} \tag{2}$$

with combined standard uncertainties

$$u_c^2(x_{ref}) = 1 \Big/ \sum_{i=1}^{N} \frac{1}{u_c^2(x_i)}. \tag{3}$$

Reference values and expanded uncertainties (U_{ref}) for GULFMET.EM-S5 and GULFMET.EM-S5.1 at frequencies of 50/53 Hz for PF/RPF = 1.0, 0.5 Lag, 0.5 Lead and for active and reactive energy are given in Tables 2 and 3.

Degrees of equivalence (DoE) of the NMI participants are reported with respect to the measurement at frequencies of 50/53 Hz and PF/RPF = 1.0, 0.5 Lag, 0.5 Lead. The DoE of *i*-th NMI participant and its combined standard uncertainties with respect to the RV are estimated as (*j* are for PF/RPF = 1.0, 0.5 Lag, 0.5 Lead):

$$D_i = x_i - x_{ref\,j}, \tag{4}$$

$$u_c^2(D_i) = u_c^2(x_i) - u_c^2(x_{ref\,j}). \tag{5}$$

Additionally, the performance indicator E_n is calculated as:

$$E_{ni} = |D_i| \big/ u(D_i) \le 1.0 \tag{6}$$

Table 4

DoE and the E_n values of the NMI participants (active energy)

Frequency	PF	NMI	GULFMET.EM-S5			GULFMET.EM-S5.1		
			D_i, µWh/(VAh)	$U(D_i)$, µWh/(VAh)	E_n	D_i, µWh/(VAh)	$U(D_i)$, µWh/(VAh)	E_n
50 Hz	1.0	QCC EMI	-22.1	24.8	0.89	-10.5	41.6	0.25
		UME	5.2	21.3	0.25	–	–	–
		UMTS	10.6	22.2	0.48	4.8	36.2	0.13
	0.5 Lag	QCC EMI	-10.5	24.8	0.42	-1.8	40.8	0.04
		UME	8.5	26.4	0.32	–	–	–
		UMTS	5.8	30.7	0.19	2.7	43.8	0.06
	0.5 Lead	QCC EMI	-6.5	27.3	0.24	0.3	42.5	0.01
		UME	3.3	26.7	0.12	–	–	–
		UMTS	4.4	31.2	0.14	-0.4	44.8	0.01
53 Hz	1.0	QCC EMI	-24.4	24.8	0.99	-12.3	41.6	0.30
		UME	5.6	21.3	0.26	–	–	–
		UMTS	11.4	21.7	0.52	5.6	36.2	0.15
	0.5 Lag	QCC EMI	-10.0	24.8	0.40	-1.7	40.6	0.04
		UME	9.4	26.4	0.35	–	–	–
		UMTS	3.7	30.5	0.12	2.4	43.4	0.06
	0.5 Lead	QCC EMI	-9.8	27.3	0.36	-4.3	42.0	0.10
		UME	1.9	26.7	0.07	–	–	–
		UMTS	10.6	30.8	0.35	5.5	43.9	0.13

Table 5

DoE and the E_n values of the NMI participants (reactive energy)

Frequency	RPF	NMI	GULFMET.EM-S5			GULFMET.EM-S5.1		
			D_i, µvarh/(VAh)	$U(D_i)$, µvarh/(VAh)	E_n	D_i, µvarh/(VAh)	$U(D_i)$, µvarh/(VAh)	E_n
50 Hz	1.0	QCC EMI	-15.4	25.0	0.62	-4.9	41.1	0.12
		UMTS	12.8	23.5	0.55	2.9	37.4	0.08
	0.5 Lag	QCC EMI	-5.2	26.9	0.19	-3.9	40.8	0.10
		UMTS	8.9	32.1	0.28	6.3	44.2	0.14
	0.5 Lead	QCC EMI	-3.7	27.7	0.13	-0.4	44.8	0.01
		UMTS	6.2	33.0	0.19	0.6	47.2	0.01
53 Hz	1.0	QCC EMI	-18.0	24.9	0.72	-8.1	40.2	0.20
		UMTS	14.3	23.1	0.62	4.2	35.7	0.12
	0.5 Lag	QCC EMI	-3.6	26.9	0.14	-3.2	40.4	0.08
		UMTS	6.2	32.1	0.19	4.8	43.3	0.11
	0.5 Lead	QCC EMI	-7.1	27.6	0.26	-2.4	43.7	0.06
		UMTS	11.6	32.5	0.36	2.8	44.7	0.06

All DoE and the E_n number are given in Table 4 (for active energy at frequencies of 50/53 Hz and for PF = 1.0, 0.5 Lag, 0.5 Lead) and Table 5 (for reactive energy at frequencies of 50/53 Hz and for RPF = 1.0, 0.5 Lag, 0.5 Lead), and the graphs on Fig. 2 (for PF = 1.0, 53 Hz for GULFMET.EM-S5 for active energy) and Fig. 3 (for PF = 1.0, 53 Hz for GULFMET.EM-S5.1 for active energy). E_n number for all NMIs for all measurement points satisfy equation (6) and take values from 0.07 to 0.99 for GULFMET.EM-S5 and from 0.01 to 0.30 for GULFMET.EM-S5.1.

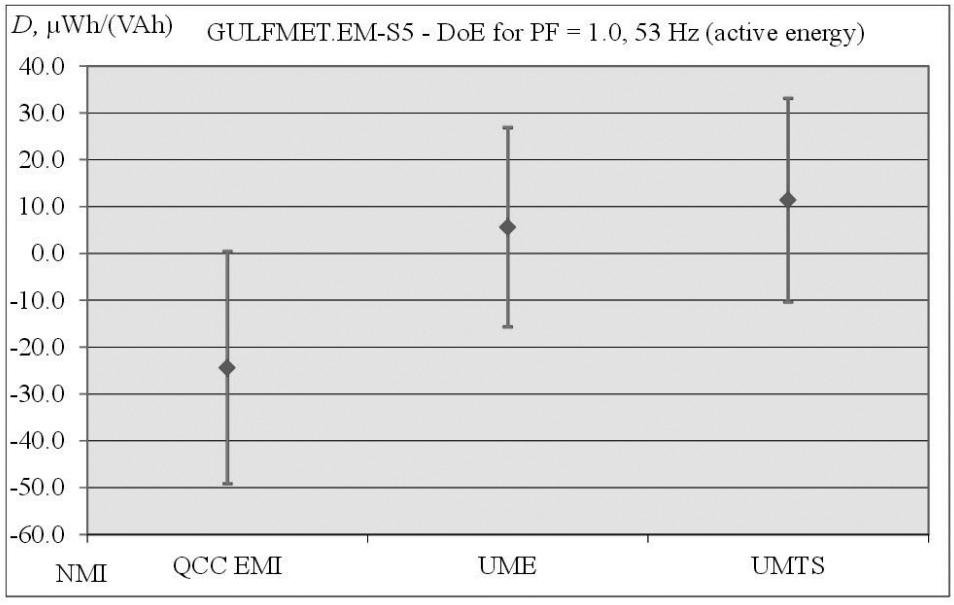

Fig. 2. DoE of the NMI participants for PF = 1.0, 53 Hz for GULFMET.EM-S5 (active energy)

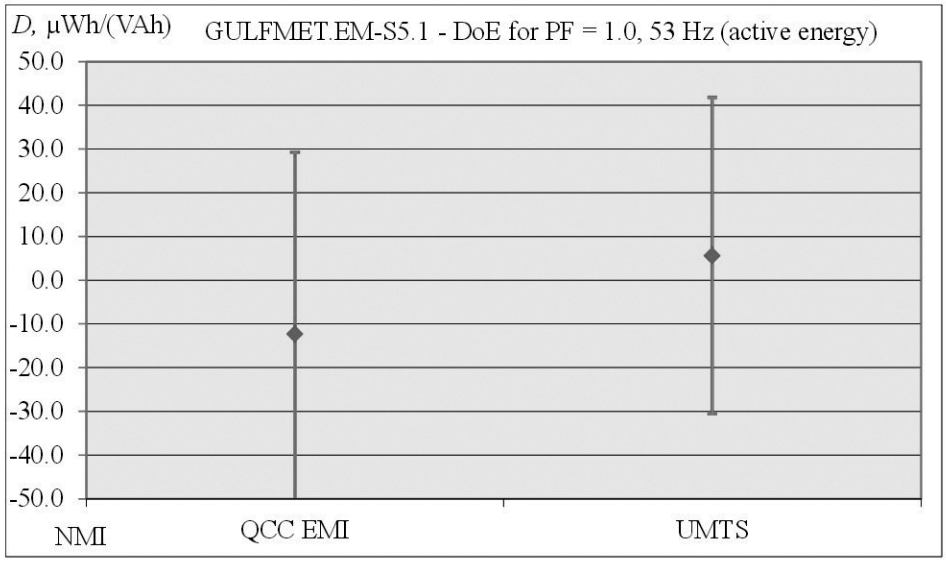

Fig. 3. DoE of the NMI participants for PF = 1.0, 53 Hz for GULFMET.EM-S5.1 (active energy)

4. Linking of results of supplementary comparisons

Through joint NMI participant (UMTS), GULFMET.EM-S5.1 can be linked to GULFMET.EM-S5. Linked DoE of QCC EMI to GULFMET.EM-S5 is estimated as [12–14]:

$$D'_{\text{QCC EMI 5}} = D_{\text{QCC EMI 5.1}} + \Delta, \qquad (7)$$

where $D_{\text{QCC EMI 5.1}}$ is a result of QCC EMI from GULFMET.EM-S5.1 only; $D'_{\text{QCC EMI 5}}$ is a result of QCC EMI which is linked to GULFMET.EM-S5.

The correction factor for linking NMI (UMTS) is estimated as

$$\Delta = d_{\text{UMTC 5}} - D_{\text{UMTS 5.1}}, \qquad (8)$$

where $d_{\text{UMTC 5}}$ is a result for linking NMI (UMTS) from GULFMET.EM-S5; $D_{\text{UMTS 5.1}}$ is a result for linking NMI (UMTS) from GULFMET.EM-S5.1.

The combined standard uncertainty for $D'_{\text{QCC EMI 5}}$ is calculated as:

$$u^2\left(D'_{\text{QCC EMI 5}}\right) = u^2\left(D_{\text{QCC EMI 5.1}}\right) + u^2\left(\Delta\right), \qquad (9)$$

where $u(D_{\text{QCC EMI 5.1}})$ is the combined standard uncertainty of QCC EMI result from GULFMET.EM-S5.1 only; $u(\Delta)$ is the combined standard uncertainty of correction factor (combined standard uncertainty of UMTS result from GULFMET.EM-S5).

Linked DoE and the E_n values of the NMI participants to GULFMET.EM-S5 comparison at frequency of 53 Hz (active energy) are shown in Table 6 and on Fig. 4 (for PF = 1.0 only). Linked DoE of QCC EMI to GULFMET.EM-S5 is marked with "*". E_n values for linked DoE of QCC EMI are from 0.03 to 0.58 (not more than 1.0).

Table 6

Linked DoE and the E_n values of the NMI participants (active energy)

Frequency	PF	NMI	Δ, μWh/(VAh)	$U(\Delta)$, μWh/(VAh)	D'_i, μWh/(VAh)	$U(D'_i)$, μWh/(VAh)	E_n
53 Hz	1.0	QCC EMI*	-1.7	18.6	-12.9	36.8	0.58
		QCC EMI			-24.4	31.4	0.78
		UME			5.6	28.8	0.19
		UMTS			11.4	29.1	0.39
	0.5 Lag	QCC EMI*	-0.1	27.4	0.9	34.5	0.03
		QCC EMI			-10.0	34.0	0.30
		UME			9.4	35.1	0.27
		UMTS			3.7	38.3	0.10
	0.5 Lead	QCC EMI*	0.1	27.4	-14.5	36.0	0.52
		QCC EMI			-9.8	36.5	0.27
		UME			1.9	36.1	0.05
		UMTS			10.6	39.2	0.27

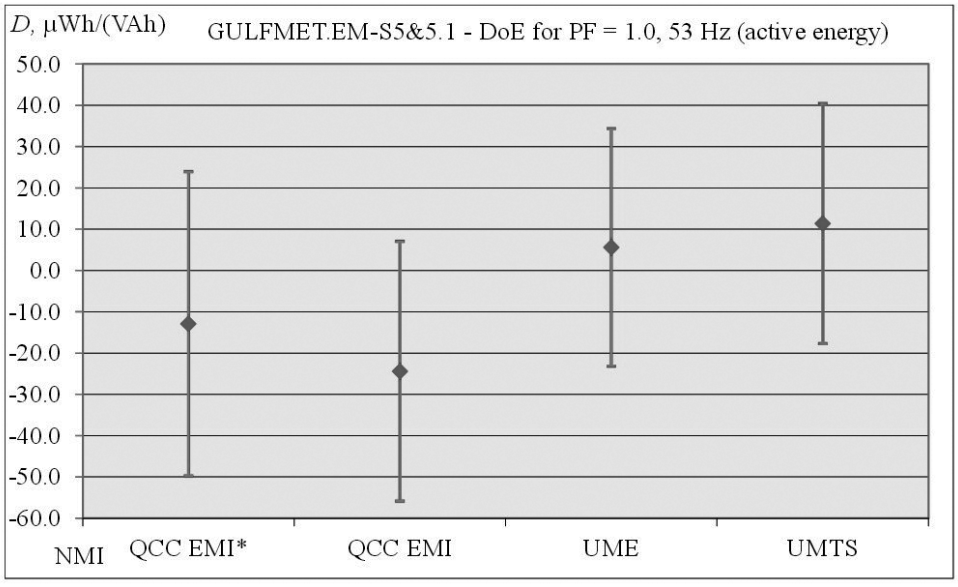

Fig. 4. Linked DoE of the NMI participants of GULFMET.EM-S5 and GULFMET.EM-S5.1 comparisons for PF = 1.0, 53 Hz (active energy)

5. Conclusion

The GULFMET.EM-S5 supplementary comparison of active and reactive energy standards with a nominal values of 120 V, 5 A, 50/53 Hz for 1.0, 0.5 Lag, 0.5 Lead power factors has been conducted between three participating NMIs (Ukraine, Turkey, and UAE) from three regional metrology organisations (GULFMET, EURAMET, and COOMET). In general, there is a good agreement between NMI participants for this quantity.

Due to the rather high technical and personnel equipment of the QCC EMI laboratory, the pilot laboratory organised special bilateral GULFMET.EM-S5.1 supplementary comparison with the same travelling standard in order to provide an opportunity to improve the results of comparisons by this NMI participant.

QCC EMI improved its results in GULFMET. EM-S5.1 comparison compared to GULFMET.EM-S5 comparison. It is expected that this comparison will be able to provide support for participants' entries in Appendix C of the Mutual Recognition Arrangement. In both comparisons, the NMI participants report about three NMIs for realisation the traceability of the unit of active and reactive energy at frequencies of 50/53 Hz for 1.0, 0.5 Lag, 0.5 Lead power factors.

Основні результати додаткових звірень для електричної енергії GULFMET.EM-S5/5.1 на частотах 50/53 Гц

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Анотація

Міжнародні угоди є основою для встановлення глобальної метрологічної простежуваності. Угода про взаємне визнання національних еталонів, калібрувальних і вимірювальних можливостей національних метрологічних інститутів (НМІ) Міжнародного комітету з мір та ваг (CIPM MRA) відіграє ключову роль у забезпеченні міжнародної еквівалентності національних еталонів різних країн. Основою цієї Угоди є конкретні вказівки та рекомендації, зокрема щодо звірення еталонів.

Регіональні метрологічні організації (РМО) традиційно проводять як ключові, так і додаткові звірення національних еталонів одиниці електричної потужності на частотах 50 і 53 Гц, зокрема, в рамках КООМЕТ, пілотною лабораторією яких було ДП "Укрметртестстандарт". Однак додаткові звірення національних еталонів на частотах 50 і 60 Гц для електричної енергії проводилися лише РМО американського континенту – SIM.

Надано основні результати міжнародних додаткових звірень національних еталонів активної та реактивної електричної енергії на частотах 50 і 53 Гц у рамках проєктів GULFMET.EM-S5 і GULFMET.EM-S5.1. Звірення, проведені ДП "Укрметртестстандарт", здійснювалися за радіальною схемою за участю національних метрологічних інститутів України, Туреччини та Об'єднаних Арабських Еміратів (ОАЕ) протягом 2019–2020 рр.

Дрейф еталона передавання оцінювався протягом усього періоду порівнянь і був невеликим для всіх точок вимірювання. Встановлено ступінь еквівалентності національних еталонів активної та реактивної енергії для коефіцієнтів потужності 1.0, 0.5 Lag і 0.5 Lead. Надані результати оцінки узгодженості отриманих даних. Значення E_n показника для всіх точок вимірювання відповідають встановленим вимогам для всіх НМІ. Надано прив'язку результатів додаткових звірень GULFMET.EM-S5 і GULFMET.EM-S5.1.

Ключові слова: додаткове звірення; опорне значення; електрична енергія; невизначеність вимірювань; національний метрологічний інститут; прив'язка.

Основные результаты дополнительных сличений GULFMET.EM-S5/5.1 для электрической энергии на частотах 50/53 Гц

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Аннотация

Представлены основные результаты международных дополнительных сличений национальных эталонов единиц активной и реактивной электрической энергии на частотах 50 и 53 Гц в рамках проектов GULFMET.EM-S5 и GULFMET.EM-S5.1. Сличения, проводимые ГП "Укрметртестстандарт", осуществлялись по радиальной схеме при участии национальных метрологических институтов Украины, Турции и Объединенных Арабских Эмиратов (ОАЭ) в 2019–2020 гг.

Дрейф эталона передачи оценивался в течение всего периода сличений и был незначительным для всех точек измерения. Была установлена степень эквивалентности национальных эталонов активной и реактивной

электрической энергии для коэффициентов мощности 1.0, 0.5 Lag и 0.5 Lead. Представлены результаты оценки согласованности полученных данных. Значения E_n показателя для всех точек измерения соответствуют установленным требованиям для всех НМИ. Представлена привязка результатов дополнительных сличений GULFMET.EM-S5 и GULFMET.EM-S5.1.

Ключевые слова: дополнительное сличение; опорное значение; электрическая энергия; неопределенность измерений; национальный метрологический институт; привязка.

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