State Enterprise “All-Ukrainian State Scientific and Production Center of Standardization, Metrology, Certification and Protection of Consumer” (SE “Ukrmeterteststandard”)

Final Report on
GULFMET Supplementary Comparison of AC Energy (GULFMET.EM-S5)

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1 Introduction

The GULFMET Supplementary Comparison (SC) of AC Energy (comparison identifier – GULFMET.EM-S5) was conducted from February to June 2019.

This project for comparing of national standards of electrical energy was conducted between counties which are member laboratories of regional metrology organizations GULFMET, COOMET and EURAMET. In this comparison three national metrology institutes (NMI) take part: SE “Ukrmetrteststandard” (UMTS, Ukraine); QCC EMI (United Arab Emirates); UME (Turkey).

The State Enterprise “All-Ukrainian State Scientific and Production Center of Standardization, Metrology, Certification and Protection of Consumer” (SE “Ukrmetr-teststandard”), Ukraine was selected as the pilot laboratory. Dr. Oleh Velychko was the comparison coordinator. The pilot laboratory is responsible for providing the travelling standard, coordinating the schedule, collecting and analyzing the comparison data, preparing the draft of report, etc.

2 Participants

List of participating NMIs, countries of origin is show in Table 1.

Table 1 List of participating NMIs, countries of origin and regional organizations

NMI	Country	Regional organization
UMTS – State Enterprise “All-Ukrainian State Scientific and Production Center of Standardization, Metrology, Certification and Protection of Consumer” (SE “Ukrmetrteststandard”) **– pilot**	Ukraine	COOMET
QCC EMI – Abu Dhabi Quality and Conformity Council, Emirates Metrology Institute	United Arab Emirates	GULFMET
UME – TÜBITAK Ulusal Metroloji Enstitüsü	Turkey	EURAMET

List of participant contact information is show in Table 2.

Table 2 List of participant contact information

NMI address	Contact name, e-mail, tel. and fax number
State Enterprise “All-Ukrainian State Scientific and Production Center of Standardization, Metrology, Certification and Protection of Consumer” (SE “Ukrmetrteststandard” – **UMTS),** 4, Metrologichna Str., 03143, Kyiv-143, **Ukraine**	Oleh Velychko Velychko@ukrcsm.kiev.ua Tel./fax: +38 044 526 0335

NMI address	Contact name, e-mail, tel. and fax number
Abu Dhabi Quality and Conformity Council, Emirates Metrology Institute (**QCC EMI**), CERT Sultan Bin Zayed the First Str., Abu Dhabi, **United Arab Emirates**	Jon Bartholomew Jon.Bartholomew@qcc.abudhabi.ae Tel: +971 503862676 Fax: +971 24066677
TÜBITAK Ulusal Metroloji Enstitüsü (**UME**), Gebze Yerleskesi Baris Mah., Dr. Zeki Acar Cad. No. 1 41470, Gebze Kocaeli, **Turkey**	Hüseyin Çayci huseyin.cayci@tubitak.gov.tr Tel.: +90 262 679 5000

3 Travelling standards and measurement instructions

3.1 Description of travelling standard

Selected travelling standard (TS) is Radian Research RD-33-332 serial number 301308 (RD-33-332). The RD-33-332 has a guaranteed accuracy of 0.01% and was successfully used as a travelling standard in Key Comparison of Power (COOMET.EM-K5) [1]. UMTS also was proposed to be the pilot laboratory in COOMET.EM-K5, responsible for providing the travelling standard, coordinating the schedule, collecting and analyzing the comparison data, and preparing the draft report.

More information of the RD-33-332 is available at www.radianresearch.com. Appearance of RD-33-332 is shown on Figure 1.

Figure 1 Appearance of travelling standard RD-33-332

TS RD-33-332 is three-phase electric power meter, works on principles of digital processing of electrical current and voltage signals.

Main characteristics of travelling standard RD-33-332:

input voltage: 30…525 V (RMS);

input current: 0,2…120 A (RMS);

frequency of the input voltage and current signals: 45…65 Hz;

constant of the frequency output: 125 000 pulse/Wh;

supply voltage: 60…525 V (RMS);

working range of the temperature: minus 20 °C…40 °C;

keeping range of the temperature: minus 25 °C...80 °C;

working range of the humidity: 0...95%;

dimensions: 444.5×172×131 mm;

weight: 6.21 kg.

Terminal block of the RD-33-332 is shown on Figure 2.

Figure 2 Terminal block of travelling standard RD-33-332

3.2 Measurements

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 125 000 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.

That is:

$$Frequency = \frac{Power \cdot K_H}{3600}\left[{pulse}/{s}\right].$$

The K_H value of the participant’s laboratory given in terms of pulses per Wh or pulses per kWh. The measurement method is not specified.

The number of pulses on the RD-33-332 set to 1 000 000 (one Million) and the integration time T_{int} for energy measurements approximately equal to:

a) T_{int} = 60 seconds, at 120 V / 5A / PF = 1.0/RPF = 1.0;

b) T_{int} = 120 seconds, at 120 V / 5 A / PF = 0.5 Lag, 0.5 Lead / 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 participant.

Before the measurements of active energy in the RD-33-332 by measuring the output pulses it must be warmed up for 24 hours (connected to the main power supply). Current and voltage signals must be connected for 4 hours before measurement. Following these procedures, short-term shutdown signal current or voltage from travelling standard will not lead to loss of the standard’s characteristics. But if the power supply of travelling standard will be turned off, then the procedure of warming up must be made over again.

Main measurements should be performed with the input signals and environmental conditions such as in Table 3.

Table 3 The measurement points and condition of measurements

Unit	Value of the unit
Voltage	120 V ± 0.2 %
Current	5 A ± 0.2 %
Power factor	1.0, 0.5 Lag, 0.5 Lead deviation from the nominal value not exceeding ± 0.1%
Reactive power factor	1.0, 0.5 Lag, 0.5 Lead deviation from the nominal value not exceeding ± 0.1%
Frequency	50 Hz ± 0.05 Hz and 53 Hz ± 0.05 Hz
Temperature	23 °C ± 1 °C
Humidity	20 % – 70 %
Supply voltage	220 V ± 5 %
Frequency of the supply voltage	50 Hz ± 0.1 Hz

4 Uncertainty of measurement

The uncertainty was calculated following the JCGM 100:2008 Evaluation of measurement data. – Guide to the expression of uncertainty in measurement (GUM) [2]: standard uncertainties, degrees of freedom, correlations, scheme for the uncertainty evaluation.

All contributions to the uncertainty of measurement were listed separately in the report and identified as either Type A or Type B uncertainties. The overall uncertainty, as calculated from the individual uncertainties, was stated. Uncertainties were evaluated at the level of one standard uncertainty and the number of effective degrees of freedom is to be reported.

The main uncertainty components were expected:

experimental standard uncertainty of the mean of N independent measurements;

uncertainty in the primary standard or working standard against which the traveling standard is measured;

uncertainty due to leads correction.

Participants included additional sources of uncertainty also.

5 Traceability to the SI

The traceability to the SI of standards was provided to pilot NMI. All of the participating NMIs made measurements of 50/53 Hz Energy. UMTS measurements of energy are traceable to PTB. QCC EMI measurements of energy are traceable to NMIA. Traceability route for each participating NMI given in Table 4.

Table 4 Traceability route for each participating NMI

NMI	Country	Traceability Route
UMTS	Ukraine	PTB
QCC EMI	United Arab Emirates	NMIA
UME	Turkey	UME

6 Behaviour of the travelling standards

The UMTS as pilot laboratory has performed repeated measurements on the TS RD-33-332 during the course of this comparison. TS RD-33-332 provides extreme linearity coupled with extreme stability. In addition, high resolution and repeatability permits rapid and accurate single revolution testing both in the field and in the lab with the appropriate optical pickup. The RD-33-332 is well-suited for test applications that require multiple measurements with high accuracy and stability.

The first day of starting comparison was 11 February 2019. Comparison finished 24 June 2019. UMTS has performed repeated measurements on TS for 4 months and 12 days. During the course of this comparison the drift effect is calculated.

The average values of energy x_{av} and standard deviation σ are given in Table 5 for frequencies 50 Hz and 53 Hz and PF = 1.0, 0.5 Lag, 0.5 Lead for active and reactive energy. The drifts were small for all measurement points, so they can be neglected.

Table 5 The average values x_{av} and standard deviation σ

Frequency	Power factor	x_{av}, µWh/(VAh)	σ, µWh/(VAh)
Active energy			
50 Hz	1.0	2.70	0.02
	0.5 Lag	3.91	0.02
	0.5 Lead	–6.32	0.02
53 Hz	1.0	2.18	0.02
	0.5 Lag	5.04	0.11
	0.5 Lead	–4.32	0.08
Frequency	**Power factor**	x_{av}, µvarh/(VAh)	σ, µvarh/(VAh)
Reactive energy			
50 Hz	1.0	3.28	0.08
	0.5 Lag	4.23	0.03
	0.5 Lead	–6.32	0.02
53 Hz	1.0	2.02	0.08
	0.5 Lag	5.20	0.07
	0.5 Lead	–4.22	0.15

7 Reported results

7.1 General information and data

A full measurement report containing all relevant data and uncertainty estimates was forwarded to the coordinator within six weeks of completing measurement of the energy. The report included a description of the measurement method (facilities and methodology), the traceability to the SI, and the results, associated uncertainty and number of degrees of freedom.

All measurement results and expended uncertainties, and additional parameters for measurement were identified with the serial number of measures energy and nominal value (Appendix 1).

List of measurement dates of the NMI participants is show in Table 6.

Table 6 List of measurement dates of the NMI participants

NMI	Measurement dates
UMTS1, Ukraine	11–16.02.2019
UMTS2, Ukraine	25.02–04.03.2019
QCC EMI, United Arab Emirates	13–24.03.2019
UMTS3, Ukraine	08–15.04.2019
UME, Turkey	02–17.05.2019
UMTS4, Ukraine	03–14.06.2019
UMTS5, Ukraine	24–28.06.2019

Additional parameters for measurement of the NMI participants are show in Table 7.

Table 7 Additional parameters for measurement of the NMI participants

Parameter	Value	Absolute expanded uncertainty
QCC EMI, United Arab Emirates		
Frequency, Hz	50 and 53	0.005
Voltage, V	120.0	0.1
Current, A	5.0	0.02
Temperature, °C	22.0…24.0	0.3
Relative humidity, %	30…70	2.5
UME, Turkey		
Frequency, Hz	50 and 53	0.005
Voltage, V	120.0	0.06
Current, A	5.0	0.001
Temperature, °C	22.0…24.0	0.3
Relative humidity, %	35…55	3.5

Parameter	Value	Absolute expanded uncertainty
UMTS, Ukraine		
Frequency, Hz	50 and 53	0.005
Voltage, V	120.0	0.06
Current, A	5.0	0.01
Temperature, °C	22.9…23.3	0.3
Relative humidity, %	45…55	2.2

The calibration errors x_i and their standard uncertainties $u(x_i)$ reported by the participants are given in Table 8 for frequencies 50 Hz and 53 Hz and PF = 1.0, 0.5 Lag, 0.5 Lead.

Table 8 Measured results for NMI participants for 50/53 Hz

NMI	50 Hz		53 Hz	
	x_i, µWh/(VAh)	$u(x_i)$, µWh/(VAh)	x_i, µWh/(VAh)	$u(x_i)$, µWh/(VAh)
Active energy				
PF = 1.0				
QCC EMI	–30.0	22.1	–33.6	22.1
UME	–2.7	18.1	–3.6	18.1
UMTS	2.7	19.1	2.2	18.6
PF = 0.5 Lag				
QCC EMI	–12.4	20.9	–8.7	20.9
UME	6.6	22.7	10.7	22.7
UMTS	3.9	27.6	5.0	27.4
PF = 0.5 Lead				
QCC EMI	–17.2	23.4	–25.1	23.4
UME	–7.4	22.7	–13.4	22.7
UMTS	–6.3	27.4	–4.7	27.4
NMI	x_i, µvarh/(VAh)	$u(x_i)$, µvarh/(VAh)	x_i, µvarh/(VAh)	$u(x_i)$, µvarh/(VAh)
Reactive energy				
PF = 1.0				
QCC EMI	–24.9	20.7	–30.3	20.7
UMTS	3.3	18.9	2.0	18.5
PF = 0.5 Lag				
QCC EMI	–9.9	21.1	–4.6	21.1
UMTS	4.2	27.4	5.2	27.7

NMI	x_i, µvarh/(VAh)	$u(x_i)$, µvarh/(VAh)	x_i, µvarh/(VAh)	$u(x_i)$, µvarh/(VAh)
Reactive energy				
PF = 0.5 Lead				
QCC EMI	–16.2	21.7	–22.9	21.7
UMTS	–6.3	28.2	–4.2	27.7

Note: The value for UMTS is measurement result calculated as simple average value.

Detailed uncertainty budgets from all participants are given in Appendix 2.

7.2 Calculation of the reference values and its uncertainties

The key comparison reference values (RV) x_{ref} are calculated as the mean of participant results with GULFMET.EM-S5 data are given by

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

with combine standard uncertainties

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

Reference values and expanded uncertainties for 50 and 53 Hz for active and reactive energy are given in Table 9.

Table 9 Reference values and expanded uncertainties for frequencies 50 and 53 Hz

Frequency	Power factor	x_{ref}, µWh/(VAh)	U_{ref}, µWh/(VAh)
Active energy			
50 Hz	1.0	–7.9	22.6
	0.5 Lag	–1.9	26.8
	0.5 Lead	–10.7	28.2
53 Hz	1.0	–9.2	22.4
	0.5 Lag	1.3	26.8
	0.5 Lead	–15.3	28.0
Frequency	**Power factor**	x_{ref}, **µvarh/(VAh)**	U_{ref}, **µvarh/(VAh)**
Reactive energy			
50 Hz	1.0	–9.5	28.0
	0.5 Lag	–4.7	33.4
	0.5 Lead	–12.5	33.4

Frequency	Power factor	x_{ref}, µvarh/(VAh)	U_{ref}, µvarh/(VAh)
53 Hz	1.0	–12.3	27.6
	0.5 Lag	–1.0	33.4
	0.5 Lead	–15.8	34.2

7.3 Degrees of equivalence

Only one value is reported for NMI participants. Degrees of equivalence of the NMI participants are reported with respect to the measurement at 50 Hz and 53 Hz.

The degrees of equivalence of *i*-th NMI and its combined standard uncertainties with respect to the RV is estimated as

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

$$u_c^2(D_i) = u_c^2(x_i) - u_c^2(x_{ref\ j})\,. \tag{4}$$

Additionally, the performance indicator E_n is calculated as:

$$E_{ni} = \frac{|D_i|}{u(D_i)} \le 1.0 \tag{5}$$

All degrees of equivalence and the E_n number are given in Table 10, and the graphs on Figures 1–12. E_n number for all NMIs for all measurement points satisfy equation (5) and take values from 0.07 to 0.99.

Table 10 Degrees of equivalence and the E_n values of the NMI participants

NMI	50 Hz			53 Hz		
	D_i, µWh/(VAh)	$U(D_i)$, µWh/(VAh)	E_n	D_i, µWh/(VAh)	$U(D_i)$, µWh/(VAh)	E_n
Active energy						
PF = 1.0						
QCC EMI	–22.1	24.8	0.89	–24.4	24.8	0.99
UME	5.2	21.3	0.25	5.6	21.3	0.26
UMTS	10.6	22.2	0.48	11.4	21.7	0.52
PF = 0.5 Lag						
QCC EMI	–10.5	24.8	0.42	–10.0	24.8	0.40
UME	8.5	26.4	0.32	9.4	26.4	0.35
UMTS	5.8	30.7	0.19	3.7	30.5	0.12
PF = 0.5 Lead						
QCC EMI	–6.5	27.3	0.24	–9.8	27.3	0.36
UME	3.3	26.7	0.12	1.9	26.7	0.07
UMTS	4.4	31.2	0.14	10.6	30.8	0.35

NMI	50 Hz			53 Hz		
	D_i, µvarh/(VAh)	**$U(D_i)$, µvarh/(VAh)**	**E_n**	**D_i, µvarh/(VAh)**	**$U(D_i)$, µvarh/(VAh)**	**E_n**
Reactive energy						
PF = 1.0						
QCC EMI	–15.4	25.0	0.62	–18.0	24.9	0.72
UMTS	12.8	23.5	0.55	14.3	23.1	0.62
PF = 0.5 Lag						
QCC EMI	–5.2	26.9	0.19	–3.6	26.9	0.14
UMTS	8.9	32.1	0.28	6.2	32.1	0.19
NMI	**50 Hz**			**53 Hz**		
	D_i, µvarh/(VAh)	**$U(D_i)$, µvarh/(VAh)**	**E_n**	**D_i, µvarh/(VAh)**	**$U(D_i)$, µvarh/(VAh)**	**E_n**
Reactive energy						
PF = 0.5 Lead						
QCC EMI	–3.7	27.7	0.13	–7.1	27.6	0.26
UMTS	6.2	33.0	0.19	11.6	32.5	0.36

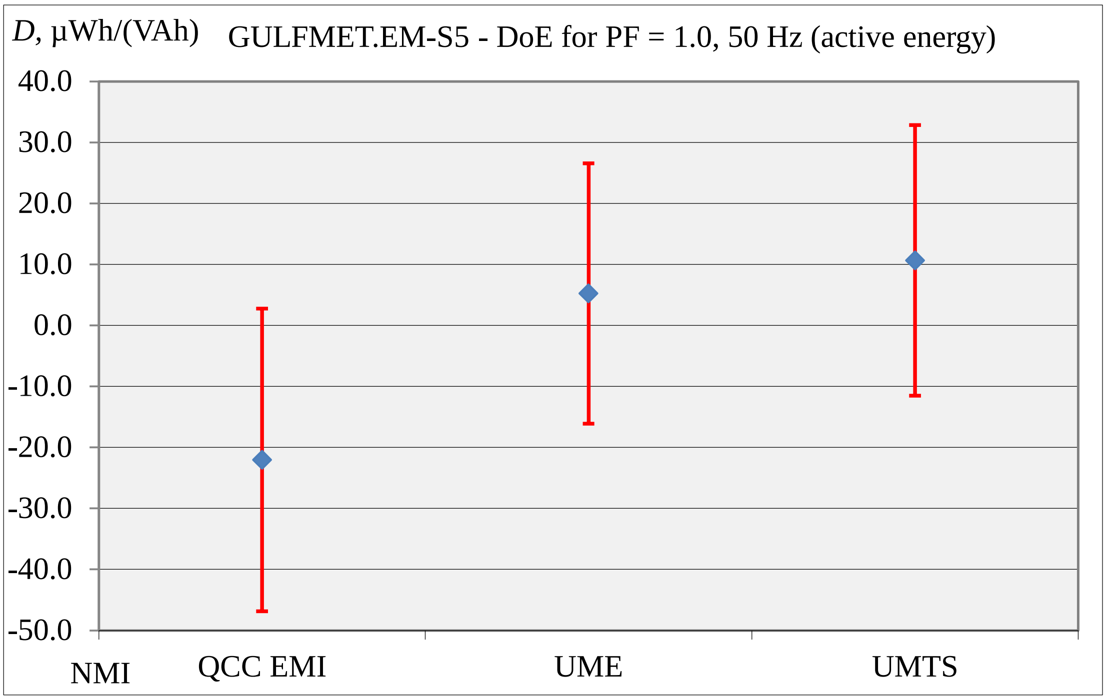

Figure 1 Degree of equivalence of the NMI participants for PF = 1.0, 50 Hz (active energy)

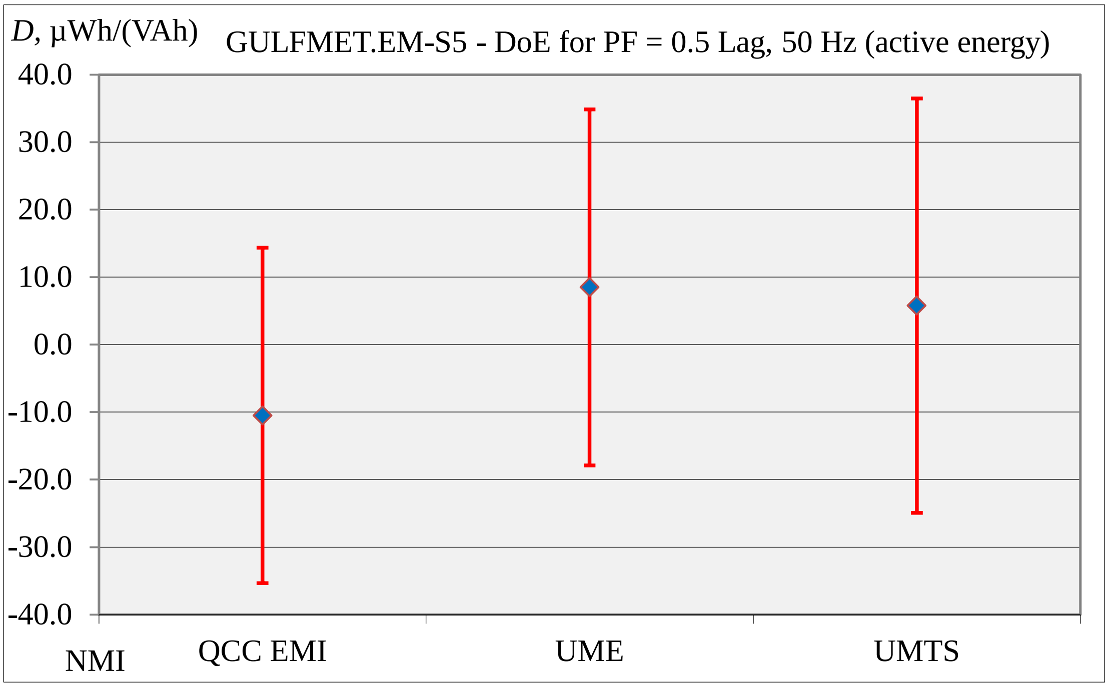

Figure 2 Degree of equivalence of the NMI participants for PF = 0.5 Lag, 50 Hz (active energy)

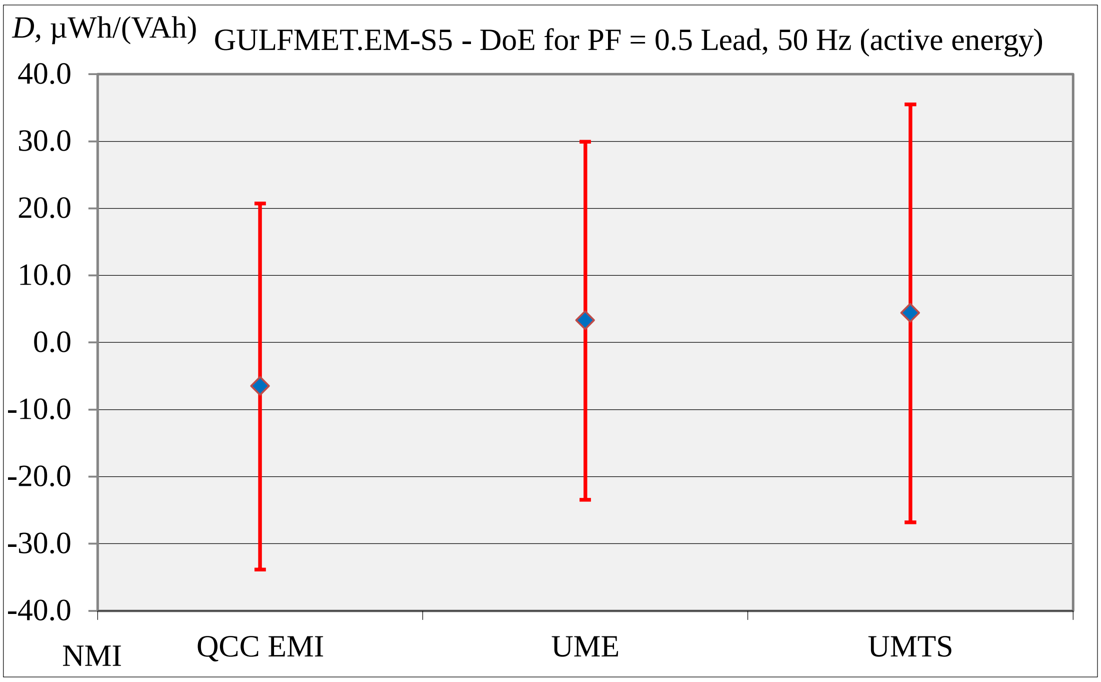

Figure 3 Degree of equivalence of the NMI participants for PF = 0.5 Lead, 50 Hz (active energy)

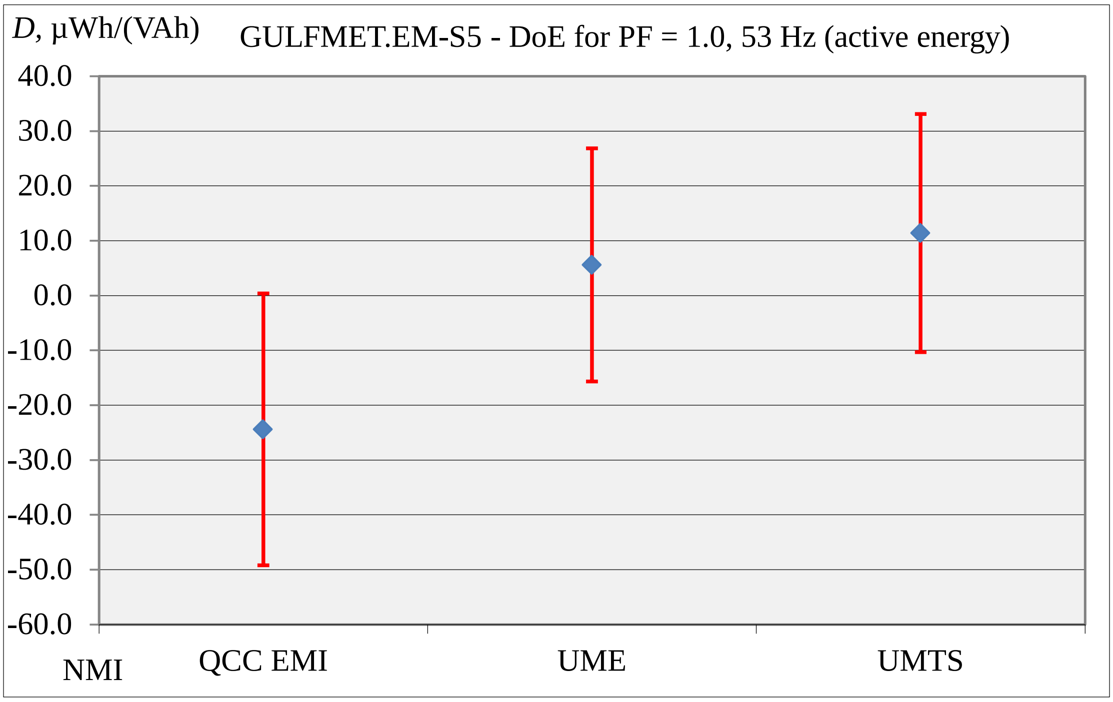

Figure 4 Degree of equivalence of the NMI participants for PF = 1.0, 53 Hz (active energy)

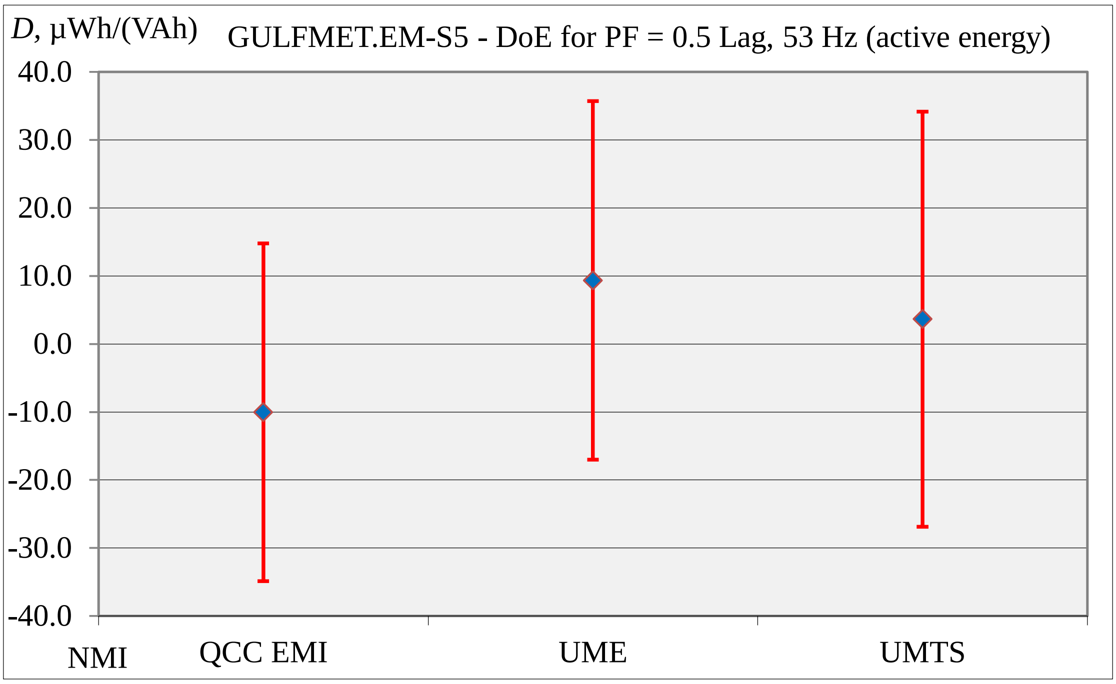

Figure 5 Degree of equivalence of the NMI participants for PF = 0.5 Lag, 53 Hz (active energy)

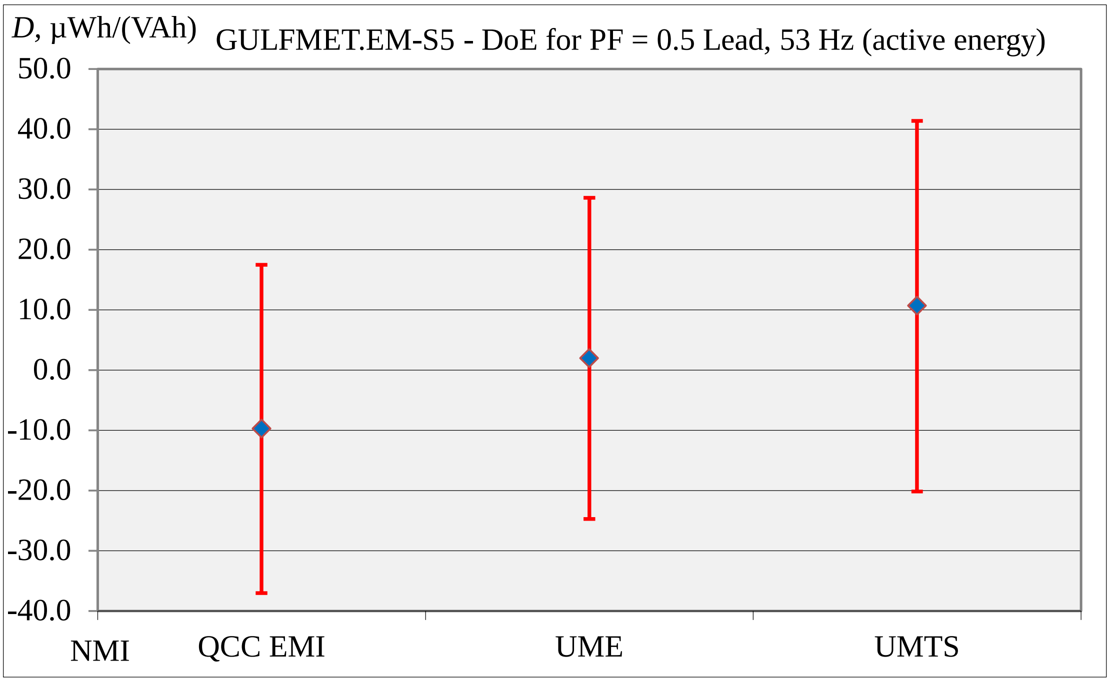

Figure 6 Degree of equivalence of the NMI participants for PF = 0.5 Lead, 53 Hz (active energy)

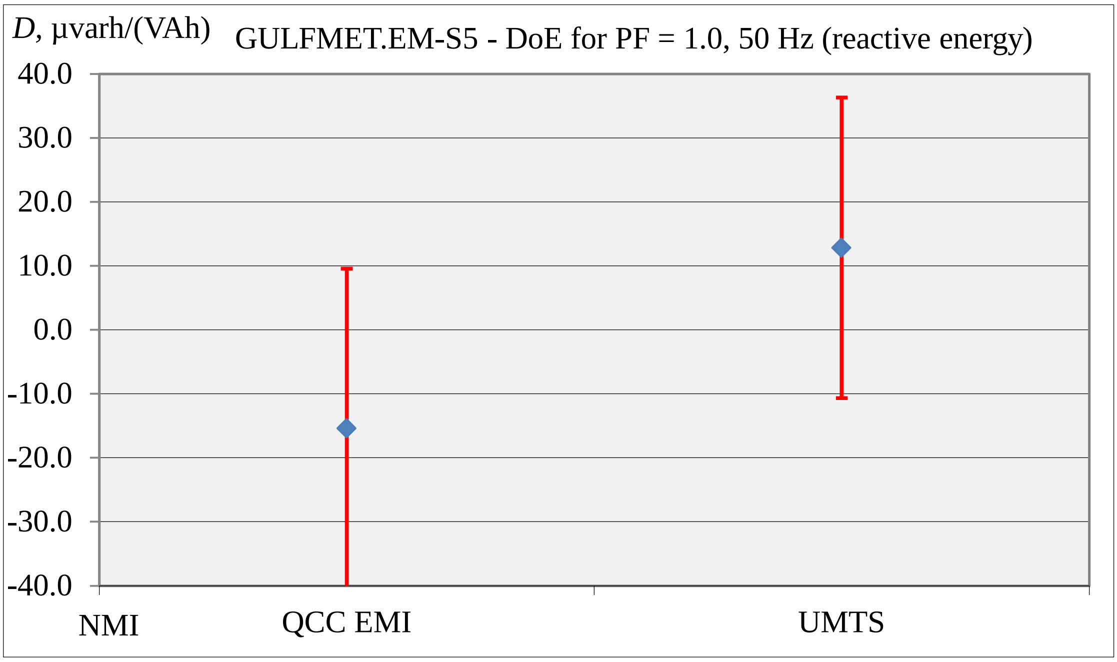

Figure 7 Degree of equivalence of the NMI participants for PF = 1.0, 50 Hz (reactive energy)

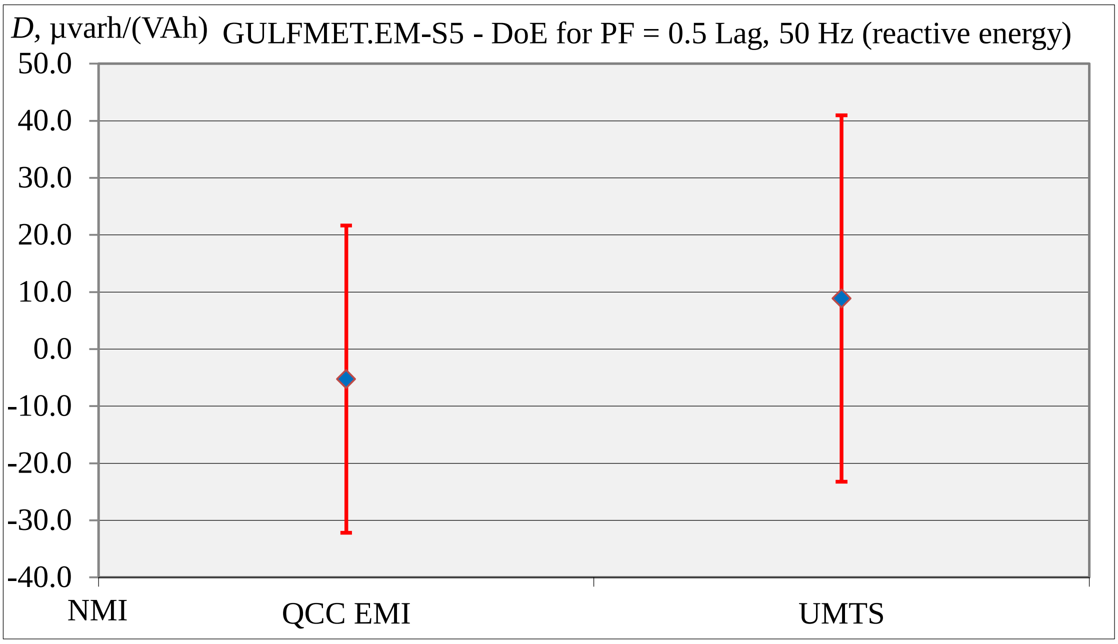

Figure 8 Degree of equivalence of the NMI participants for PF = 0.5 Lag, 50 Hz (reactive energy)

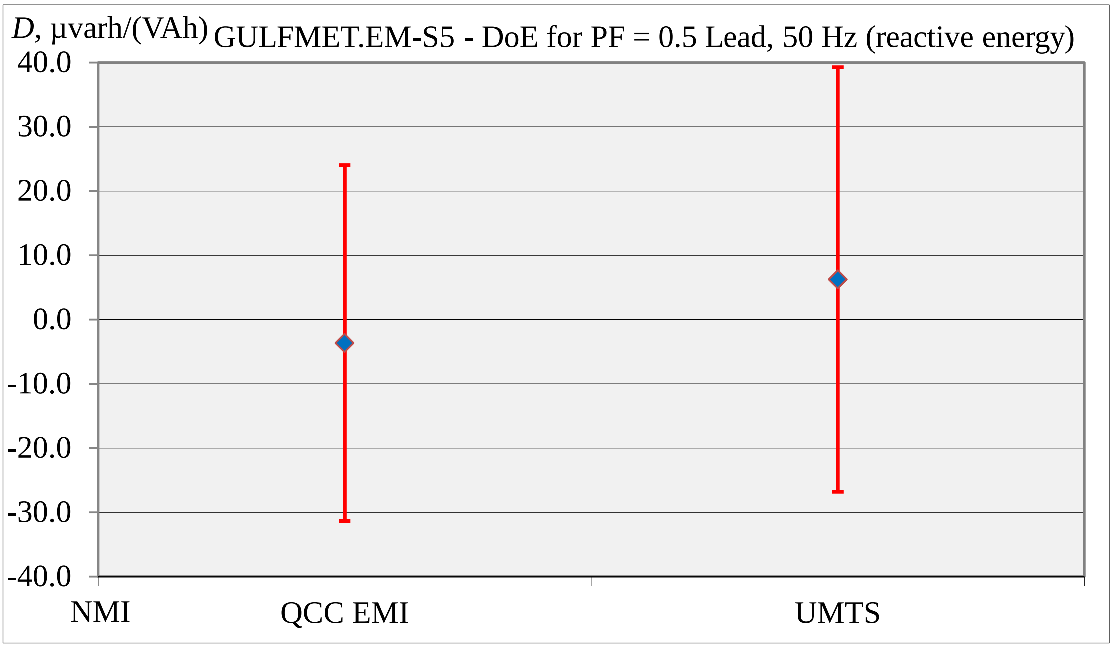

Figure 9 Degree of equivalence of the NMI participants for PF = 0.05 Lead, 50 Hz (reactive energy)

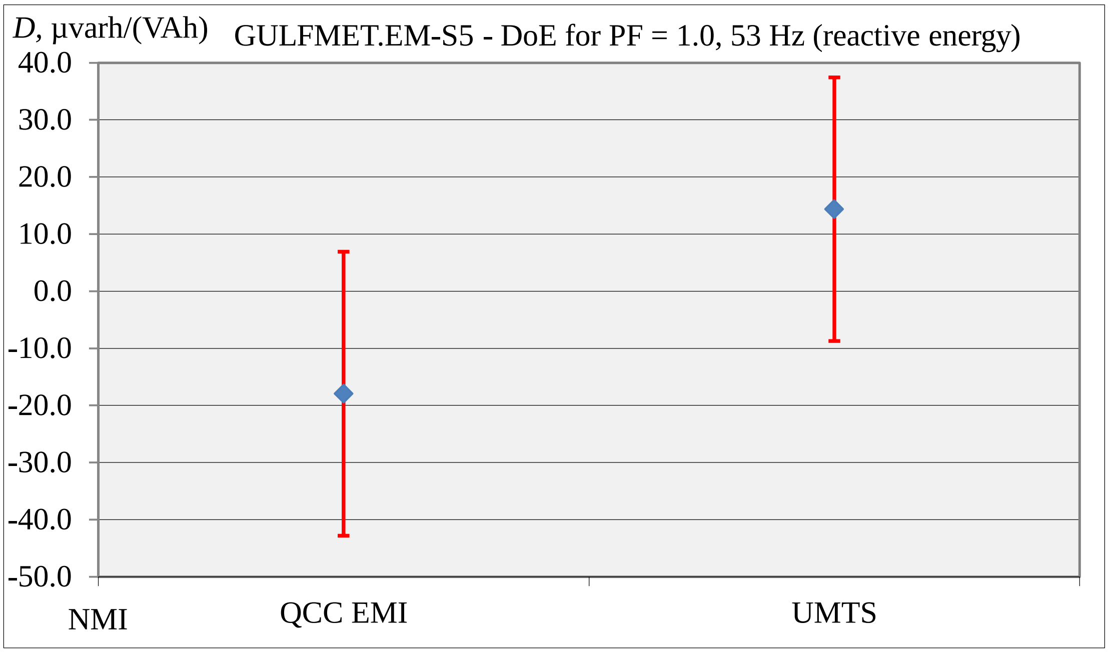

Figure 10 Degree of equivalence of the NMI participants for PF = 1.0, 53 Hz (reactive energy)

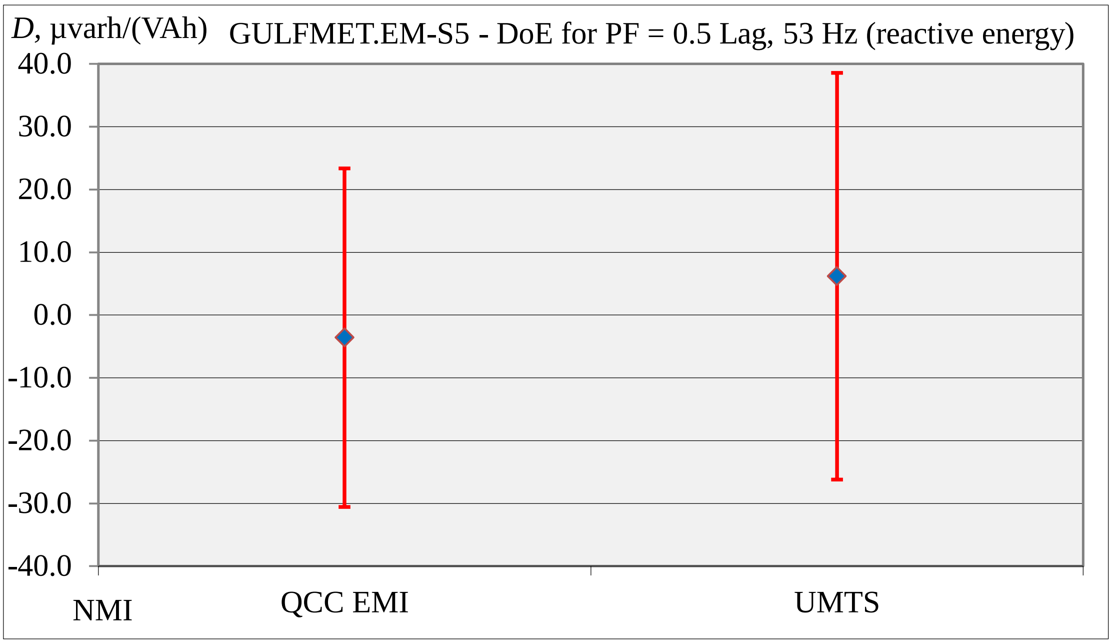

Figure 11 Degree of equivalence of the NMI participants for PF = 0.5 Lag, 53 Hz (reactive energy)

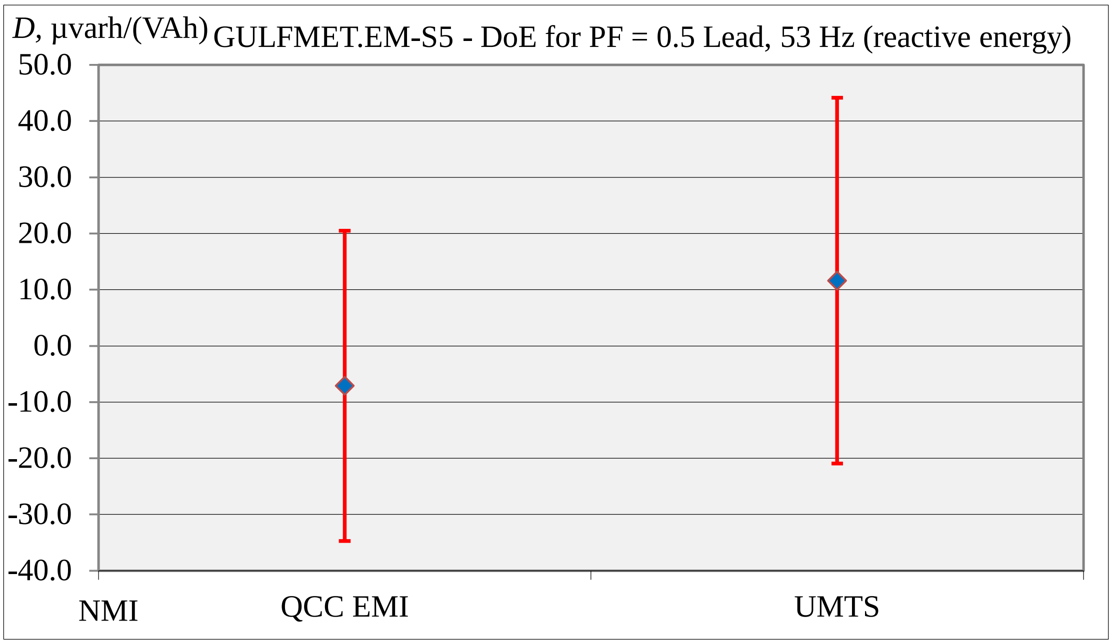

Figure 12 Degree of equivalence of the NMI participants for PF = 0.5 Lead, 53 Hz (reactive energy)

Based on the results of this comparison between UMTS and QCC EMI, it was decided to conduct separate bilateral comparison after additional calibration of the power standard of QCC EMI in the NMIA. In this bilateral comparison, the same travelling standard and technical protocol will be used.

8 Summary

A supplementary comparison of active and reactive energy standards a nominal values of 120 V, 5 A, 50 Hz and 53 Hz for 1.0, 0.5 Lag, 0.5 Lead power factors has been conducted between participating NMIs from three regional metrological organizations (GULFMET, COOMET and EURAMET). In general there is good agreement between NMI participants for this quantity. It is expected that this comparison will be able to provide support for participants' entries in Appendix C of the Mutual Recognition Arrangement. In this comparison, the NMI participants report about three NMIs for realization the traceability of the unit of active and reactive energy.

References

[1] Velychko O., Karpenko S. Final report on COOMET key comparison of power (COOMET. EM-K5). Metrologia, 2019, Vol. 56, Issue 1A, 01010.

[2] JCGM 100:2008 Evaluation of measurement data. – Guide to the expression of uncertainty in measurement.

[3] COOMET R/GM/19:2008 Guidelines on COOMET supplementary comparison evaluation.

Appendix 1

Reported measurement results for each NMI laboratory

QCC EMI (UAE)

Frequency	Power factor	Relative error of energy measurement, µWh/(VAh)	Expanded uncertainty, µWh/(VAh)
Active energy			
50 Hz	1.0	–30.0	22.1
	0.5 Lag	–12.4	20.9
	0.5 Lead	–17.2	23.4
53 Hz	1.0	–33.6	22.1
	0.5 Lag	–8.7	20.9
	0.5 Lead	–25.1	23.4
Frequency	Power factor	Relative error of energy measurement, µvarh/(VAh)	Expanded uncertainty, µvar/(VAh)
Reactive energy			
50 Hz	1.0	–24.9	20.7
	0.5 Lag	–9.9	21.1
	0.5 Lead	–16.2	21.7
53 Hz	1.0	–30.3	20.7
	0.5 Lag	–4.6	21.1
	0.5 Lead	–22.9	21.7

The measurement setup is shown schematically in Figure A1.1.

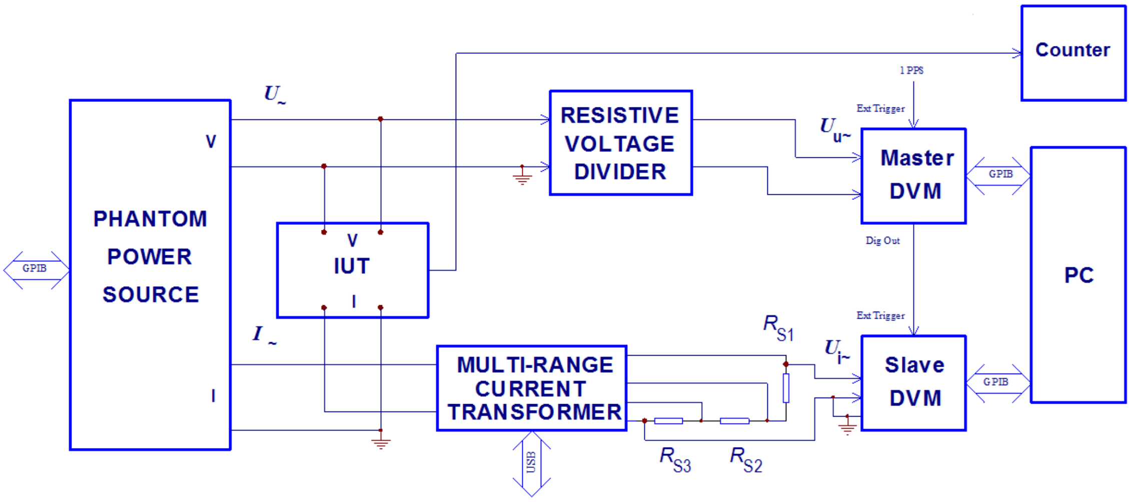

Figure A1.1 Simplified schematic diagram of the measurement setup

Alternating voltage and current from the phantom power source are applied to the Instrument Under Test (IUT) and the inputs of the Resistive Voltage Divider (RVD) and the Multi-range Current Transformer (MCT). The output voltages of the RVD and MCT measured by two digital voltmeters (DVMs), Master DVM and Slave DVM, that are controlled through the PC by “EnergoEtalon” sampling software. The output of the IUT is measured using a Universal Frequency Counter/Timer, as shown in Figure A1.1.

To enable the operation of the Master and Slave DVMs on dc, for calibration purposes, a 1 pulse per second TTL signal is applied to the trigger input of the Master DVM. The LO voltage and the current inputs of the IUT are earthed and so is the output of the MCT. To enable the series connection of the IUT and the MCT current inputs a special current tee is used. The schematic of the current tee is shown in Figure A1.2.

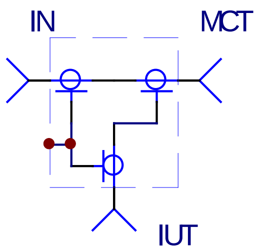

Figure A1.2 Current tee

The voltage drop across the current circuit of the IUT forms a common mode signal on the MCT. However the MCT has been shown not to have any appreciable common mode dependence.

UME (Turkey)

Frequency	Power factor	Relative error of energy measurement, μWh/(VAh)	Expanded uncertainty, μWh/(VAh)
Active energy			
50 Hz	1.0	–2.7	18.1
	0.5 Lag	6.6	22.7
	0.5 Lead	–7.4	22.7
53 Hz	1.0	–3.6	18.1
	0.5 Lag	10.7	22.7
	0.5 Lead	–13.4	22.7

The operating principle of primary AC power measurement standard of TUBITAK UME, known as Digital Sampling Wattmeter (DSWM), shown in the figure below, is based on the use of two sampling voltmeters and on computerized evaluation by means of discrete integration (DI) or discrete Fourier transform (DFT). Similar to others, it consists of two digital sampling voltmeters (DVMs), a precision voltage divider, a set of AC current shunts, a power source, a triggering unit and software.

The voltage and current signals from a phantom power source are applied to the relevant input terminals of the voltage divider and of the AC current shunts. A regulated voltage from secondary terminals of the voltage divider and a voltage obtained from the selected AC current shunt are then applied to the DVMs. With the help of software, DVMs are programmed with the calculated appropriate aperture times for the selected samples per period. Each programmed DVM then samples the applied voltage signals with the help of trigger signal which is synchronized to the power source.

The data from both DVMs are then transferred to the computer via IEEE488. The ratio and phase angle errors of the voltage divider and current shunts were corrected by the software. The amplitudes of both signals, the phase angles between them and the calculated results are displayed during the measurements.

Block diagram of DSWM show on Figure A1.3.

NOTE: AC power standard is used as AC energy standard here by introducing a counter.

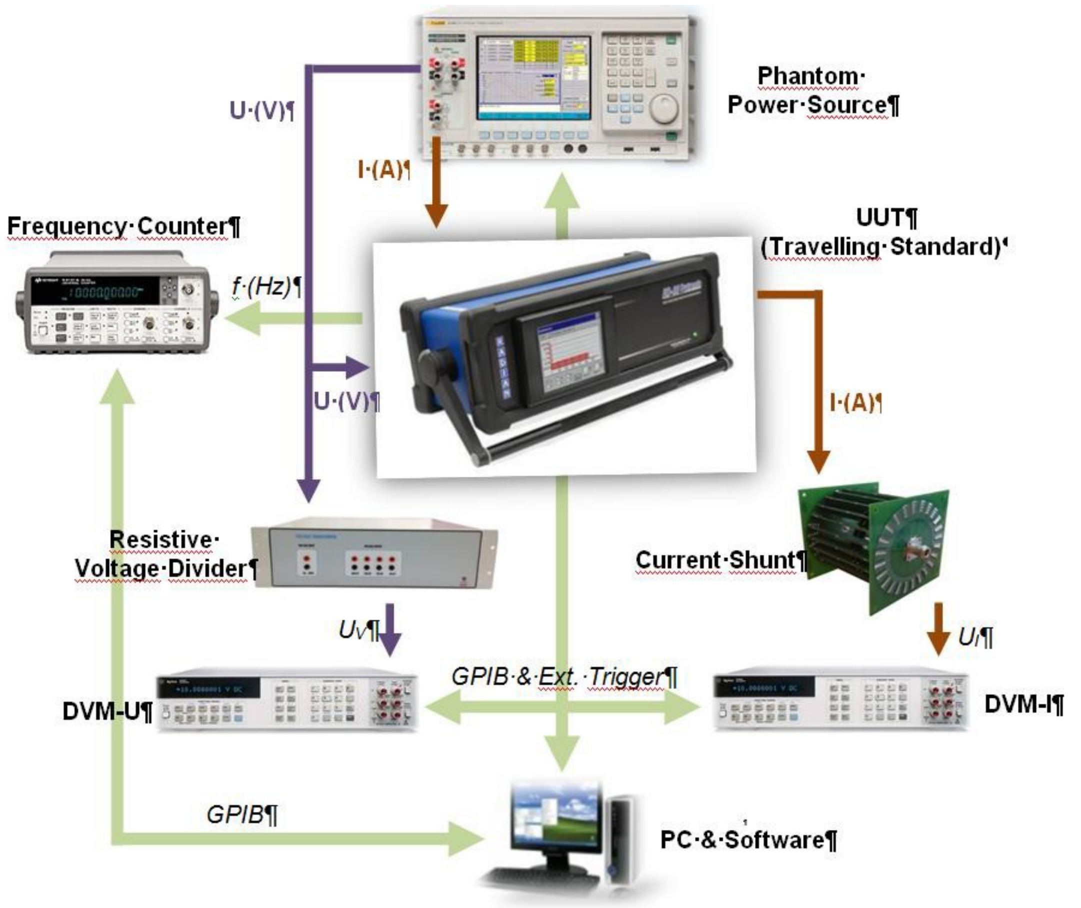

Figure A1.3 Block diagram of DSWM

UMTS (Ukraine)

Frequency	Power factor	Relative error of energy measurement, μWh/VAh	Expanded uncertainty, μWh/VAh
Active energy			
50 Hz	1.0	2.7	19.1
	0.5 Lag	3.9	27.6
	0.5 Lead	–6.3	27.8
53 Hz	1.0	2.2	18.6
	0.5 Lag	5.0	27.4
	0.5 Lead	–4.7	27.4
Frequency	Power factor	Relative error of energy measurement, μvarh/VAh	Expanded uncertainty, μvarh/VAh
Reactive energy			
50 Hz	1.0	3.3	18.9
	0.5 Lag	4.2	27.4
	0.5 Lead	–6.3	28.2
53 Hz	1.0	2.0	18.5
	0.5 Lag	5.2	27.7
	0.5 Lead	–4.2	27.7

As the basis for AC energy standard was used National AC power measurement standard of UMTS by introducing a Standard of Time and Frequency. The block diagram of the measurement setup of AC energy measurement standard of UMTS is shown on Figure A1.4.

The operating principle is based on directly comparing the AC Power to DC Power by using thermoelectric converters. The AC voltage and AC current signals from Highly Stable Power Source are applied to the relevant input terminals of the Precision Resistor Voltage Divider and of the Precision AC/DC current shunt. A regulated AC voltage from secondary terminals of the Precision Resistor Voltage Divider and AC voltage obtained from the selected Precision AC/DC current shunt are then applied to the thermoelectric converters. AC voltage output thermoelectric converters signals are then applied to the DVMs. With the help of software, DVMs are programmed with the calculated appropriate aperture times for the selected samples per period. Each programmed DVM then samples the applied AC voltage signals from thermoelectric converters with the help of trigger signal which is synchronized to the power source. The data from both DVMs are then transferred to the computer via IEEE488.

The DC current and DC voltage signals are generated using a DC Power Source. The DC signals are applied to Precision Resistor Voltage Divider and of the Precision AC/DC current shunt. A regulated DC voltage from secondary terminals of the Precision Resistor Voltage Divider and DC voltage obtained from the selected Precision AC/DC current shunt are then applied to the thermoelectric converters. DC voltage output thermoelectric converters signals are then applied to the DVMs. With the help of software, DVMs are programmed with the calculated appropriate aperture times for the selected samples per period. Each programmed DVM then samples the applied DC voltage signals from thermoelectric converters with the help of trigger signal which is synchronized to the power source. The data from both DVMs are then transferred to the computer via IEEE488.

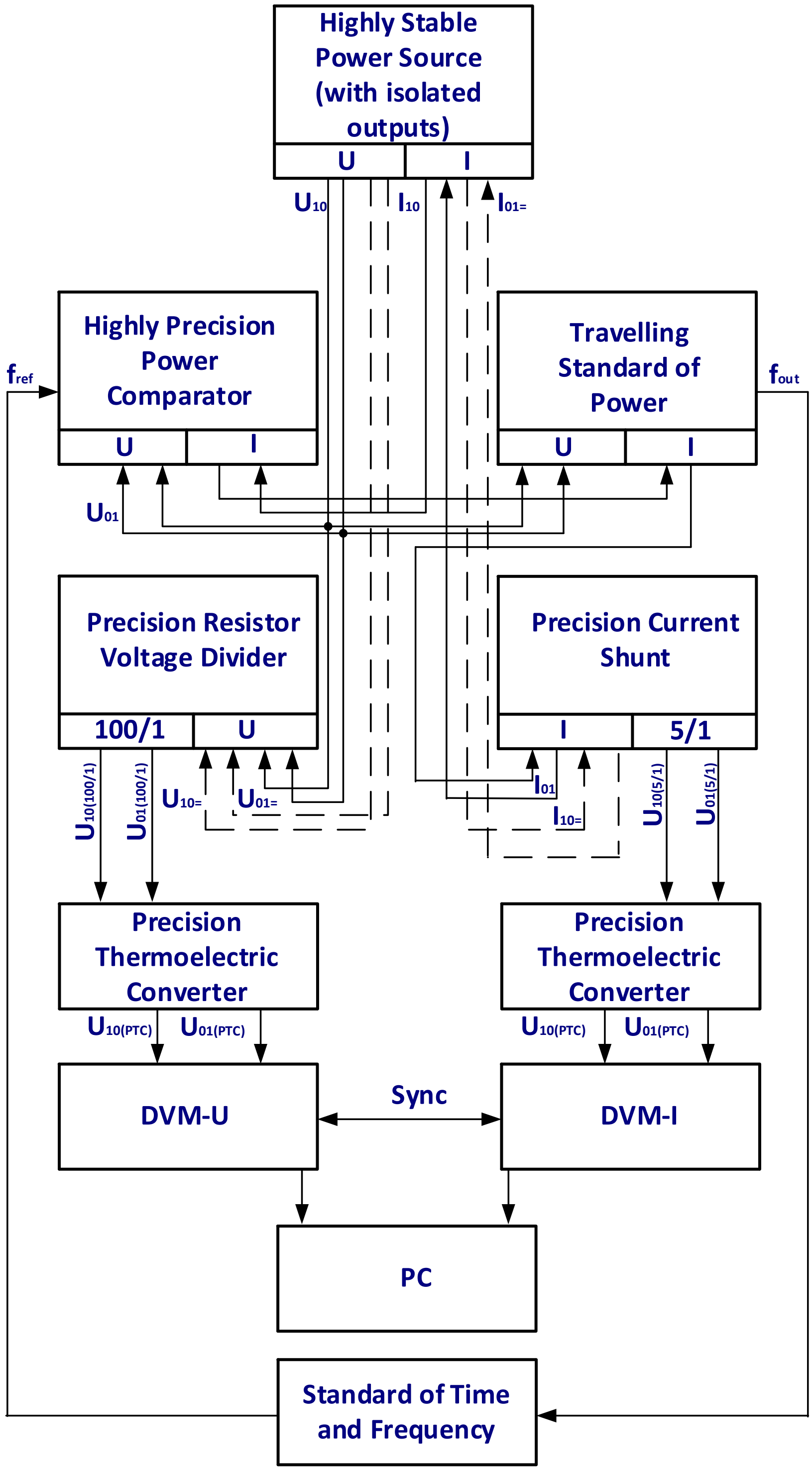

Figure A1.4 Simplified schematic diagram of the measurement setup

When the AC and DC signals are balanced, the AC power is equal to the DC power. All the calculations are made by the software.

As a Standard of Time and Frequency was used Secondary Standard of Time and Frequency of UMTS (Ukraine). National AC power measurement standard of UMTS was synchronized with reference frequency 5 MHz with the main aim of feature forming of reference time scale with standard uncertainty of 24 ns from calibration certificate.

Appendix 2

Reported measurement results for each NMI laboratory

QCC EMI (United Arab Emirates)

PF = 1.0, 50/53 Hz (active energy)

Uncertainty description	Uncer-tainty, µWh/VAh	Distribution	Divisor	Sensitivity coefficient	Standard uncertainty, µWh/VAh	V_{eff}
Error repeatability	3.1	normal	1.0	1.0	3.1	24
Sampling software uncertainty	8.4	normal	2.0	1.0	4.2	∞
DVMu calibration uncertainty	3.0	normal	2.0	1.0	1.5	∞
DVMi calibration uncertainty	3.0	normal	2.0	1.0	1.5	∞
MCT calibration uncertainty (in-phase)	2.0	normal	2.0	1.0	1.0	∞
MCT stability (in-phase)	5.0	rectangular	1.7	1.0	2.9	∞
MCT calibration uncertainty (quadrature)	3.2	normal	2.0	0.0	0.0	∞
MCT stability (quadrature)	5.0	rectangular	1.7	0.0	0.0	∞
Shunt DC calibration uncertainty	1.1	normal	2.0	1.0	0.6	∞
Shunt DC stability	2.0	rectangular	1.7	1.0	1.2	∞
Shunt power coefficient	2.0	rectangular	1.7	1.0	1.2	∞
Shunt AC/DCcorr calibration uncertainty	1.0	normal	2.0	1.0	0.5	∞
Shunt AC/DCcorr stability	2.0	rectangular	1.7	1.0	1.2	∞
Shunt phase def ang corr calibration uncertainty	1.1	normal	2.0	0.0	0.0	∞
Shunt phase def ang corr stability	2.0	rectangular	1.7	0.0	0.0	∞
Uncorrected capacitive loading on the shunt	2.0	rectangular	1.7	0.0	0.0	∞
RVD ratio error uncertainty	1.4	normal	2.0	1.0	0.7	∞
RVD ratio error stability	10.0	rectangular	1.7	1.0	5.8	∞
RVD phase error uncertainty	1.4	normal	2.0	0.0	0.0	∞
RVD phase error stability	10.0	rectangular	1.7	0.0	0.0	∞
RVD change with voltage	1.0	rectangular	1.7	1.0	2.9	∞
Frequency counter uncertainty	1.0	normal	1.7	1.0	5.8	∞
IUT stability	10.0	rectangular	1.7	1.0	5.8	∞
Combined standard uncertainty (V_{eff} = 4500)					11.0 µWh/VAh	
Expanded uncertainty (k = 2.0)					22.1 µWh/VAh	

PF = 0.5 Lag, 50/53 Hz (active energy)

Uncertainty description	Uncer-tainty, µWh/VAh	Distribution	Divisor	Sensitivity coefficient	Standard uncertainty, µWh/VAh	V_{eff}
Error repeatability	2.6	normal	1.0	1.0	2.6	2.6
Sampling software uncertainty	8.4	normal	2.0	1.0	4.2	∞
DVMu calibration uncertainty	3.0	normal	2.0	0.5	0.75	∞
DVMi calibration uncertainty	3.0	normal	2.0	0.5	0.75	∞
MCT calibration uncertainty (in-phase)	2.0	normal	2.0	0.5	0.5	∞
MCT stability (in-phase)	5.0	rectangular	1.7	0.5	1.4	∞
MCT calibration uncertainty (quadrature)	3.2	normal	2.0	0.87	1.4	∞
MCT stability (quadrature)	5.0	rectangular	1.7	0.87	2.5	∞
Shunt DC calibration uncertainty	1.1	normal	2.0	0.5	0.28	∞
Shunt DC stability	2.0	rectangular	1.7	0.5	0.58	∞
Shunt power coefficient	2.0	rectangular	1.7	0.5	0.58	∞
Shunt AC/DCcorr calibration uncertainty	1.0	normal	2.0	0.5	0.25	∞
Shunt AC/DCcorr stability	2.0	rectangular	1.7	0.5	0.58	∞
Shunt phase def ang corr calibration uncertainty	1.1	normal	2.0	0.87	0.48	∞
Shunt phase def ang corr stability	2.0	rectangular	1.7	0.87	1.0	∞
Uncorrected capacitive loading on the shunt	2.0	rectangular	1.7	0.87	1.0	∞
RVD ratio error uncertainty	1.4	normal	2.0	0.5	0.35	∞
RVD ratio error stability	10.0	rectangular	1.7	0.5	2.89	∞
RVD phase error uncertainty	1.4	normal	2.0	0.87	0.61	∞
RVD phase error stability	10.0	rectangular	1.7	0.87	5.0	∞
RVD change with voltage	5.0	rectangular	1.7	0.5	1.4	∞
Frequency counter uncertainty	1.0	normal	1.7	0.5	0.29	∞
IUT stability	10.0	rectangular	1.7	1.0	5.78	∞
Combined standard uncertainty (V_{eff} = 2220)					10.4 µWh/VAh	
Expanded uncertainty (k = 2.0)					20.9 µWh/VAh	

PF = 0.5 Lead, 50/53 Hz (active energy)

Uncertainty description	Uncer-tainty, µWh/VAh	Distribution	Divisor	Sensitivity coefficient	Standard uncertainty, µWh/VAh	V_{eff}
Error repeatability	5.6	normal	1.0	1.0	5.7	9
Sampling software uncertainty	8.4	normal	2.0	1.0	4.2	∞
DVMu calibration uncertainty	3.0	normal	2.0	0.5	0.75	∞
DVMi calibration uncertainty	3.0	normal	2.0	0.5	0.75	∞
MCT calibration uncertainty (in-phase)	2.0	normal	2.0	0.5	0.5	∞
MCT stability (in-phase)	5.0	rectangular	1.7	0.5	1.4	∞
MCT calibration uncertainty (quadrature)	3.2	normal	2.0	0.87	1.4	∞
MCT stability (quadrature)	5.0	rectangular	1.7	0.87	2.5	∞
Shunt DC calibration uncertainty	1.1	normal	2.0	0.5	0.28	∞
Shunt DC stability	2.0	rectangular	1.7	0.5	0.58	∞
Shunt power coefficient	2.0	rectangular	1.7	0.5	0.58	∞
Shunt AC/DCcorr calibration uncertainty	1.0	normal	2.0	0.5	0.25	∞
Shunt AC/DCcorr stability	2.0	rectangular	1.7	0.5	0.58	∞
Shunt phase def ang corr calibration uncertainty	1.1	normal	2.0	0.87	0.48	∞
Shunt phase def ang corr stability	2.0	rectangular	1.7	0.87	1.0	∞
Uncorrected capacitive loading on the shunt	2.0	rectangular	1.7	0.87	1.0	∞
RVD ratio error uncertainty	1.4	normal	2.0	0.5	0.35	∞
RVD ratio error stability	10.0	rectangular	1.7	0.5	2.89	∞
RVD phase error uncertainty	1.4	normal	2.0	0.87	0.61	∞
RVD phase error stability	10.0	rectangular	1.7	0.87	5.0	∞
RVD change with voltage	5.0	rectangular	1.7	0.5	1.4	∞
Frequency counter uncertainty	1.0	normal	1.7	0.5	2.89	∞
IUT stability	10.0	rectangular	1.7	1.0	5.77	∞
Combined standard uncertainty (V_{eff} = 156)					11.6 µWh/VAh	
Expanded uncertainty (k = 2.0)					23.4 µWh/VAh	

PF = 1.0, 50/53 Hz (reactive energy)

Uncertainty description	Uncer-tainty, µvarh/VAh	Distribution	Divisor	Sensitivity coefficient	Standard uncertainty, µvarh/VAh	V_{eff}
Error repeatability	1.97	normal	1.0	1.0	1.97	9
Sampling software uncertainty	8.4	normal	2.0	1.0	4.2	∞
DVMu calibration uncertainty	3.0	normal	2.0	1.0	1.5	∞
DVMi calibration uncertainty	3.0	normal	2.0	1.0	1.5	∞
MCT calibration uncertainty (in-phase)	2.0	normal	2.0	1.0	1.0	∞
MCT stability (in-phase)	5.0	rectangular	1.7	1.0	2.9	∞
MCT calibration uncertainty (quadrature)	3.2	normal	2.0	0.0	0.0	∞
MCT stability (quadrature)	5.0	rectangular	1.7	0.0	0.0	∞
Shunt DC calibration uncertainty	1.1	normal	2.0	1.0	5.5	∞
Shunt DC stability	2.0	rectangular	1.7	1.0	1.2	∞
Shunt power coefficient	2.0	rectangular	1.7	1.0	1.2	∞
Shunt AC/DCcorr calibration uncertainty	1.0	normal	2.0	1.0	0.5	∞
Shunt AC/DCcorr stability	2.0	rectangular	1.7	1.0	1.2	∞
Shunt phase def ang corr calibration uncertainty	1.1	normal	2.0	0.0	0.0	∞
Shunt phase def ang corr stability	2.0	rectangular	1.7	0.0	0.0	∞
Uncorrected capacitive loading on the shunt	2.0	rectangular	1.7	0.0	0.0	∞
RVD ratio error uncertainty	1.4	normal	2.0	1.0	0.7	∞
RVD ratio error stability	10.0	rectangular	1.7	1.0	5.8	∞
RVD phase error uncertainty	1.4	normal	2.0	0.0	0.0	∞
RVD phase error stability	10.0	rectangular	1.7	0.0	0.0	∞
RVD change with voltage	5.0	rectangular	1.7	0.0	0.0	∞
Frequency counter uncertainty	1.0	normal	1.7	0.0	0.0	∞
IUT stability	10.0	rectangular	1.7	1.0	5.8	∞
Combined standard uncertainty (V_{eff} = 6911)					10.3 µvarh/VAh	
Expanded uncertainty (k = 2.0)					20.7 µvarh/VAh	

PF = 0.5 Lag, 50/53 Hz (reactive energy)

Uncertainty description	Uncer-tainty, µvarh/VAh	Distribution	Divisor	Sensitivity coefficient	Standard uncertainty, µvarh/VAh	V_{eff}
Error repeatability	2.1	normal	1.0	1.0	2.1	9
Sampling software uncertainty	8.4	normal	2.0	1.0	4.2	∞
DVMu calibration uncertainty	3.0	normal	2.0	0.5	0.75	∞
DVMi calibration uncertainty	3.0	normal	2.0	0.5	0.75	∞
MCT calibration uncertainty (in-phase)	2.0	normal	2.0	0.5	0.5	∞
MCT stability (in-phase)	5.0	rectangular	1.7	0.5	1.4	∞
MCT calibration uncertainty (quadrature)	3.2	normal	2.0	0.87	1.4	∞
MCT stability (quadrature)	5.0	rectangular	1.7	0.87	2.5	∞
Shunt DC calibration uncertainty	1.1	normal	2.0	0.5	0.28	∞
Shunt DC stability	2.0	rectangular	1.7	0.5	0.58	∞
Shunt power coefficient	2.0	rectangular	1.7	0.5	0.58	∞
Shunt AC/DCcorr calibration uncertainty	1.0	normal	2.0	0.5	0.25	∞
Shunt AC/DCcorr stability	2.0	rectangular	1.7	0.5	0.58	∞
Shunt phase def ang corr calibration uncertainty	1.1	normal	2.0	0.87	0.48	∞
Shunt phase def ang corr stability	2.0	rectangular	1.7	0.87	1.0	∞
Uncorrected capacitive loading on the shunt	2.0	rectangular	1.7	0.87	1.0	∞
RVD ratio error uncertainty	1.4	normal	2.0	0.5	0.35	∞
RVD ratio error stability	10.0	rectangular	1.7	0.5	2.89	∞
RVD phase error uncertainty	1.4	normal	2.0	0.87	0.61	∞
RVD phase error stability	10.0	rectangular	1.7	0.87	5.0	∞
RVD change with voltage	5.0	rectangular	1.7	0.87	2.5	∞
Frequency counter uncertainty	1.0	normal	1.7	0.87	0.5	∞
IUT stability	10.0	rectangular	1.7	1.0	5.78	∞
Combined standard uncertainty (V_{eff} = 6209)					10.5 µvahr/VAh	
Expanded uncertainty (k = 2.0)					21.1 µvarh/VAh	

PF = 0.5 Lead, 50/53 Hz (reactive energy)

Uncertainty description	Uncer-tainty, µvarh/VAh	Distribution	Divisor	Sensitivity coefficient	Standard uncertainty, µvarh/VAh	V_{eff}
Error repeatability	3.3	normal	1.0	1.0	3.2	9
Sampling software uncertainty	8.4	normal	2.0	1.0	4.2	∞
DVMu calibration uncertainty	3.0	normal	2.0	0.5	0.75	∞
DVMi calibration uncertainty	3.0	normal	2.0	0.5	0.75	∞
MCT calibration uncertainty (in-phase)	2.0	normal	2.0	0.5	0.5	∞
MCT stability (in-phase)	5.0	rectangular	1.7	0.5	1.4	∞
MCT calibration uncertainty (quadrature)	3.2	normal	2.0	0.87	1.4	∞
MCT stability (quadrature)	5.0	rectangular	1.7	0.87	2.5	∞
Shunt DC calibration uncertainty	1.1	normal	2.0	0.5	0.28	∞
Shunt DC stability	2.0	rectangular	1.7	0.5	0.58	∞
Shunt power coefficient	2.0	rectangular	1.7	0.5	0.58	∞
Shunt AC/DCcorr calibration uncertainty	1.0	normal	2.0	0.5	0.25	∞
Shunt AC/DCcorr stability	2.0	rectangular	1.7	0.5	0.58	∞
Shunt phase def ang corr calibration uncertainty	1.1	normal	2.0	0.87	0.48	∞
Shunt phase def ang corr stability	2.0	rectangular	1.7	0.87	1.0	∞
Uncorrected capacitive loading on the shunt	2.0	rectangular	1.7	0.87	1.0	∞
RVD ratio error uncertainty	1.4	normal	2.0	0.5	0.35	∞
RVD ratio error stability	10.0	rectangular	1.7	0.5	2.89	∞
RVD phase error uncertainty	1.4	normal	2.0	0.87	0.61	∞
RVD phase error stability	10.0	rectangular	1.7	0.87	5.0	∞
RVD change with voltage	5.0	rectangular	1.7	0.87	2.5	∞
Frequency counter uncertainty	1.0	normal	1.7	0.87	0.5	∞
IUT stability	10.0	rectangular	1.7	1.0	5.77	∞
Combined standard uncertainty (V_{eff} = 1013)					10.8 µvarh/VAh	
Expanded uncertainty (k = 2.0)					21.7 µvarh/VAh	

The power measured by the reference system can be calculated as follows:

$$P_{REF} = \frac{V_{Range\_RVD} \times I_{Range\_MCT}}{V_{Out\_RVD} \times V_{Out\_MCT}} \times P_{DPC}, \tag{1}$$

where:

V_{Range_RVD} = 500 V is the nominal input voltage of the RVD;

I_{Range_MCT} is the nominal range of the MCT set by its controls;

V_{Out_RVD} = 1 V is the nominal output of the RVD;

V_{Out_MCT} = 0.8 V is the nominal output of the MCT across the shunt resistors;

P_{DPC} is the power value at the DVM inputs measured by the Digital Power Comparator (Etalon software) without scaling.

Putting the constant values in (1) gives:

$$P_{REF} = 625 \times I_{Range\_MCT} \times P_{DPC}. \tag{2}$$

The energy measured by the reference system is calculated as follows:

$$E_{REF} = P_{REF} \times T \tag{3}$$

where T is the nominal measurement period.

The measured correction for the IUT, M_{IUT}, is calculated as:

$$M_{IUT} = E_{REF} - E_{IUT}, \tag{4}$$

where E_{IUT} is the energy measured by the IUT.

The correction of the reference system can be expressed as follows:

For active energy:

$$C = -(a+b) \times \cos(\phi) + (\beta - \alpha) \times \sin(\phi) \tag{5}$$

For reactive energy:

$$C = -(a+b) \times \sin(\phi) - (\beta - \alpha) \times \cos(\phi) \tag{6}$$

where:

a (α) represents the voltage amplitude (phase) error in µV/V (µrad);

b (β) represents the current amplitude (phase) error in µA/A (µrad).

Applying (5) and (6) gives a corrected correction for the IUT, C_{IUT}:

Active energy:

$$C_{IUT} = M_{IUT} + \cos(\emptyset) \times [a_{DVM_u} + b_{DVM_i} + a_{Etalon} + b_{Etalon} - a_{RVD} - b_{MCT} - b_{SH-dc} + b_{SH_{ac}-dc}] + \sin(\emptyset) \times [-\beta_{SH} - \alpha_{RVD} + \beta_{MCT}] + C_{IND\_iut} \tag{7}$$

Reactive energy:

$$C_{IUT} = M_{IUT} - \sin(\emptyset) \times [a_{DVM_u} + b_{DVM_i} + a_{Etalon} + b_{Etalon} - a_{RVD} - b_{MCT} - b_{SH-dc} + b_{SH_{ac}-dc}] - \cos(\emptyset) \times [-\beta_{SH} - \alpha_{RVD} + \beta_{MCT}] + C_{IND\_iut} \tag{8}$$

where:

M_{IUT} is the measured correction for the IUT;

ϕ is the phase angle between current and voltage (which determines directly the power factor);

a_{DVM_u} is the correction for master DVM;

b_{DVM_i} is the correction for the slave DVM;

a_{Etalon} is the AC-DC voltage correction for the sampling system;

b_{Etalon} is the AC-DC current correction for the sampling system;

a_{RVD} is the ratio error of the RVD;

b_{MCT} is the ratio error of the MCT;

b_{SH_dc} is the DC error of the MCT shunt (suparesistor);

$b_{SH\_ac\text{-}dc}$ is the shunt AC-DC difference correction;

C_{IND_iut} is the correction for the indicator (counter) used with the IUT;

β_{SH} is the phase or quadrature error of the shunt, also referred to as phase defect angle;

α_{RVD} is the phase error of the RVD;

β_{MCT} is the phase error of the MCT.

With the exception of a_{DVM_u} and b_{DVM_i} which are measured during the preparatory measurements, all these values can be found in the calibration reports for the system.

UME (Turkey)

PF = 1.0, 50/53 Hz (active energy)

Source of uncertainty	Standard uncertainty, μWh/VAh	Probability distribution	Sensitivity coefficient	Uncertainty contribution, μWh/VAh
Voltage measurement	5.7	normal	1	5.7
Current measurement	6.3	normal	1	6.3
Phase measurement	10.2	normal	0	0.0
Time measurement	0.8	normal	1	1.5
Measurement set up	0.8	rectangular	1	0.8
Standard uncertainty of measurement	2.6	normal	1	2.6
Combined standard uncertainty				9.0
Expanded uncertainty (k = 2)				18.1

PF = 0.5, 50/53 Hz (active energy)

Source of uncertainty	Standard uncertainty, μWh/VAh	Probability distribution	Sensitivity coefficient	Uncertainty contribution, μWh/VAh
Voltage measurement	5.7	normal	0.5	2.9
Current measurement	6.3	normal	0.5	3.2
Phase measurement	10.2	normal	0.87	8.9
Time measurement	3.0	normal	1	3.0
Measurement set up	0.8	rectangular	1	0.8
Standard uncertainty of measurement	4.7	normal	1	4.7
Combined standard uncertainty				11.3
Expanded uncertainty (k = 2)				22.7

UMTS (Ukraine)

PF = 1.0, 50 Hz (active energy)

i	Quantity (unit)	Distribution	x_i	$u(x_i)$	v_i	c_i	$u_i(y)$
1	Mean value of the observation of the differences between the travelling standard and the reference value	normal	2.3	1.9	99	1	1.9
2	Standard deviation of the mean of electric power reproduction	normal	0.1	1.5	99	1	1.5
3	Corrections due to the phase measurement	normal	0.0	0.0	∞	1	0.0
4	Corrections due to the frequency measurement	rectangular	0.0	1.5	∞	1	1.5
5	Corrections due to the drift of temperature measurements	normal	0.0	0.5	∞	1	0.5
6	Corrections due to the AC current measurements	normal	0.1	3.2	∞	1	3.2
7	Corrections due to the AC voltage amplitude measurements	normal	0.1	2.5	∞	1	2.5
8	Corrections due to the thermal converter AC-DC difference (current channel)	normal	0.1	5.0	∞	1	5.0
9	Corrections due to the thermal converter AC-DC difference (voltage channel)	normal	0.0	5.0	∞	1	5.0
10	Corrections due to the influence of temperature coefficient on travelling standard (voltage)	normal	0.0	0.8	∞	1	0.8
11	Corrections due to the influence of temperature coefficient on travelling standard (direct AC current)	normal	0.0	1.5	∞	1	1.5
12	Corrections due to the influence of temperature coefficient on travelling standard (active energy)	normal	0.0	2.5	∞	1	2.5
13	Corrections due to the influence of temperature coefficient on travelling standard (phase angle)	normal	0.0	0.1	∞	1	0.1
14	Corrections due to the influence of temperature coefficient on travelling standard (frequency)	normal	0.0	0.1	∞	1	0.1
15	Short term stability	normal	0.0	0.5	∞	1	0.5
16	Long term stability (for the one operation year)	normal	0.0	1.0	∞	1	1.0
17	Corrections due to the synchronization with standard of time and frequency	normal	0.0	1.4	∞	1	1.4
X_i							2.7
y	Combined standard uncertainty, µWh/Vah						9.5
	Expanded uncertainty (95 %, k = 2), µWh/VAh						19.1

PF = 0.5 Lag, 50 Hz (active energy)

i	Quantity (unit)	Distribution	x_i	$u(x_i)$	v_i	c_i	$u_i(y)$
1	Mean value of the observation of the differences between the travelling standard and the reference value	normal	3.4	3.5	99	1	3.4
2	Standard deviation of the mean of electric power reproduction	normal	0.1	3.0	99	1	3.0
3	Corrections due to the phase measurement	rectangular	0.1	7.0	∞	0.87	6.1
4	Corrections due to the frequency measurement	normal	0.0	1.5	∞	1	1.5
5	Corrections due to the drift of temperature measurements	normal	0.0	0.5	∞	1	0.5
6	Corrections due to the AC current measurements	normal	0.1	6.0	∞	1	6.0
7	Corrections due to the AC voltage amplitude measurements	normal	0.1	5.0	∞	1	5.0
8	Corrections due to the thermal converter AC-DC difference (current channel)	normal	0.1	5.0	∞	1	5.0
9	Corrections due to the thermal converter AC-DC difference (voltage channel)	normal	0.0	5.0	∞	1	5.0
10	Corrections due to the influence of temperature coefficient on travelling standard (voltage)	normal	0.0	0.8	∞	1	0.8
11	Corrections due to the influence of temperature coefficient on travelling standard (direct AC current)	normal	0.0	1.5	∞	1	1.5
12	Corrections due to the influence of temperature coefficient on travelling standard (active energy)	normal	0.0	2.5	∞	1	2.5
13	Corrections due to the influence of temperature coefficient on travelling standard (phase angle)	normal	0.0	0.1	∞	1	0.1
14	Corrections due to the influence of temperature coefficient on travelling standard (frequency)	normal	0.0	0.1	∞	1	0.1
15	Short term stability	normal	0.0	0.5	∞	1	0.5
16	Long term stability (for the one operation year)	normal	0.0	1.0	∞	1	1.0
17	Corrections due to the synchronization with standard of time and frequency	normal	0.0	2.9	∞	1	2.9
X_i							3.9
$\boldsymbol{y}$	Combined standard uncertainty, µWh/VAh						13.8
	Expanded uncertainty (95 %, k = 2), µWh/VAh						27.6

PF = 0.5 Lead, 50 Hz (active energy)

i	Quantity (unit)	Distribution	x_i	$u(x_i)$	v_i	c_i	$u_i(y)$
1	Mean value of the observation of the differences between the travelling standard and the reference value	normal	-6.8	3.9	99	1	3.9
2	Standard deviation of the mean of electric power reproduction	normal	0.1	3.0	99	1	3.0
3	Corrections due to the phase measurement	normal	0.1	7.0	∞	0.87	6.1
4	Corrections due to the frequency measurement	rectangular	0.0	1.5	∞	1	1.5
5	Corrections due to the drift of temperature measurements	normal	0.0	0.5	∞	1	0.5
6	Corrections due to the AC current measurements	normal	0.1	6.0	∞	1	6.0
7	Corrections due to the AC voltage amplitude measurements	normal	0.1	5.0	∞	1	5.0
8	Corrections due to the thermal converter AC-DC difference (current channel)	normal	0.1	5.0	∞	1	5.0
9	Corrections due to the thermal converter AC-DC difference (voltage channel)	normal	0.0	5.0	∞	1	5.0
10	Corrections due to the influence of temperature coefficient on travelling standard (voltage)	normal	0.0	0.8	∞	1	0.8
11	Corrections due to the influence of temperature coefficient on travelling standard (direct AC current)	normal	0.0	1.5	∞	1	1.5
12	Corrections due to the influence of temperature coefficient on travelling standard (active energy)	normal	0.0	2.5	∞	1	2.5
13	Corrections due to the influence of temperature coefficient on travelling standard (phase angle)	normal	0.0	0.1	∞	1	0.1
14	Corrections due to the influence of temperature coefficient on travelling standard (frequency)	normal	0.0	0.1	∞	1	0.1
15	Short term stability	normal	0.0	0.5	∞	1	0.5
16	Long term stability (for the one operation year)	normal	0.0	1.0	∞	1	1.0
17	Corrections due to the synchronization with standard of time and frequency	normal	0.0	2.9	∞	1	2.9
X_i							-6.3
y	Combined standard uncertainty, µWh/VAh						13.9
	Expanded uncertainty (95 %, k = 2), µWh/VAh						27.8

PF = 1.0, 53 Hz (active energy)

i	Quantity (unit)	Distribution	x_i	$u(x_i)$	v_i	c_i	$u_i(y)$
1	Mean value of the observation of the differences between the travelling standard and the reference value	normal	1.8	1.8	99	1	1.8
2	Standard deviation of the mean of electric power reproduction	normal	0.1	1.5	99	1	1.5
3	Corrections due to the phase measurement	normal	0.0	0.0	∞	1	0.0
4	Corrections due to the frequency measurement	rectangular	0.0	1.5	∞	1	1.5
5	Corrections due to the drift of temperature measurements	normal	0.0	0.5	∞	1	0.5
6	Corrections due to the AC current measurements	normal	0.1	3.2	∞	1	3.2
7	Corrections due to the AC voltage amplitude measurements	normal	0.1	2.5	∞	1	2.5
8	Corrections due to the thermal converter AC-DC difference (current channel)	normal	0.1	5.0	∞	1	5.0
9	Corrections due to the thermal converter AC-DC difference (voltage channel)	normal	0.0	5.0	∞	1	5.0
10	Corrections due to the influence of temperature coefficient on travelling standard (voltage)	normal	0.0	0.8	∞	1	0.8
11	Corrections due to the influence of temperature coefficient on travelling standard (direct AC current)	normal	0.0	1.5	∞	1	1.5
12	Corrections due to the influence of temperature coefficient on travelling standard (active energy)	normal	0.0	2.5	∞	1	2.5
13	Corrections due to the influence of temperature coefficient on travelling standard (phase angle)	normal	0.0	0.1	∞	1	0.1
14	Corrections due to the influence of temperature coefficient on travelling standard (frequency)	normal	0.0	0.1	∞	1	0.1
15	Short term stability	normal	0.0	0.5	∞	1	0.5
16	Long term stability (for the one operation year)	normal	0.0	1.0	∞	1	1.0
17	Corrections due to the synchronization with standard of time and frequency	normal	0.0	1.4	∞	1	1.4
X_i							2.2
y	Combined standard uncertainty, µWh/Vah						9.3
	Expanded uncertainty (95 %, k = 2), µWh/VAh						18.6

PF = 0.5 Lag, 53 Hz (active energy)

i	Quantity (unit)	Distribution	x_i	$u(x_i)$	v_i	c_i	$u_i(y)$
1	Mean value of the observation of the differences between the travelling standard and the reference value	normal	4.5	3.5	99	1	3.4
2	Standard deviation of the mean of electric power reproduction	normal	0.1	3.0	99	1	3.0
3	Corrections due to the phase measurement	rectangular	0.1	7.0	∞	0.87	6.1
4	Corrections due to the frequency measurement	normal	0.0	1.5	∞	0.001	0.0
5	Corrections due to the drift of temperature measurements	normal	0.0	0.5	∞	1	0.5
6	Corrections due to the AC current measurements	normal	0.1	6.0	∞	1	6.0
7	Corrections due to the AC voltage amplitude measurements	normal	0.1	5.0	∞	1	5.0
8	Corrections due to the thermal converter AC-DC difference (current channel)	normal	0.1	5.0	∞	1	5.0
9	Corrections due to the thermal converter AC-DC difference (voltage channel)	normal	0.0	5.0	∞	1	5.0
10	Corrections due to the influence of temperature coefficient on travelling standard (voltage)	normal	0.0	0.8	∞	1	0.8
11	Corrections due to the influence of temperature coefficient on travelling standard (direct AC current)	normal	0.0	1.5	∞	1	1.5
12	Corrections due to the influence of temperature coefficient on travelling standard (active energy)	normal	0.0	2.5	∞	1	2.5
13	Corrections due to the influence of temperature coefficient on travelling standard (phase angle)	normal	0.0	0.1	∞	1	0.1
14	Corrections due to the influence of temperature coefficient on travelling standard (frequency)	normal	0.0	0.1	∞	1	0.1
15	Short term stability	normal	0.0	0.5	∞	1	0.5
16	Long term stability (for the one operation year)	normal	0.0	1.0	∞	1	1.0
17	Corrections due to the synchronization with standard of time and frequency	normal	0.0	2.9	∞	1	2.9
X_i							5.0
y	Combined standard uncertainty, µWh/VAh						13.7
	Expanded uncertainty (95 %, k = 2), µWh/VAh						27.4

PF = 0.5 Lead, 53 Hz (active energy)

i	Quantity (unit)	Distribution	x_i	$u(x_i)$	v_i	c_i	$u_i(y)$
1	Mean value of the observation of the differences between the travelling standard and the reference value	normal	-5.2	3.4	99	1	3.4
2	Standard deviation of the mean of electric power reproduction	normal	0.1	3.0	99	1	3.0
3	Corrections due to the phase measurement	normal	0.1	7.0	∞	0.87	6.1
4	Corrections due to the frequency measurement	rectangular	0.0	1.5	∞	0.001	0.0
5	Corrections due to the drift of temperature measurements	normal	0.0	0.5	∞	1	0.5
6	Corrections due to the AC current measurements	normal	0.1	6.0	∞	1	6.0
7	Corrections due to the AC voltage amplitude measurements	normal	0.1	5.0	∞	1	5.0
8	Corrections due to the thermal converter AC-DC difference (current channel)	normal	0.1	5.0	∞	1	5.0
9	Corrections due to the thermal converter AC-DC difference (voltage channel)	normal	0.0	5.0	∞	1	5.0
10	Corrections due to the influence of temperature coefficient on travelling standard (voltage)	normal	0.0	0.8	∞	1	0.8
11	Corrections due to the influence of temperature coefficient on travelling standard (direct AC current)	normal	0.0	1.5	∞	1	1.5
12	Corrections due to the influence of temperature coefficient on travelling standard (active energy)	normal	0.0	2.5	∞	1	2.5
13	Corrections due to the influence of temperature coefficient on travelling standard (phase angle)	normal	0.0	0.1	∞	1	0.1
14	Corrections due to the influence of temperature coefficient on travelling standard (frequency)	normal	0.0	0.1	∞	1	0.1
15	Short term stability	normal	0.0	0.5	∞	1	0.5
16	Long term stability (for the one operation year)	normal	0.0	1.0	∞	1	1.0
17	Corrections due to the synchronization with standard of time and frequency	normal	0.0	2.9	∞	1	2.9
X_i							-4.7
$\boldsymbol{y}$	Combined standard uncertainty, µWh/VAh						13.7
	Expanded uncertainty (95 %, k = 2), µWh/VAh						27.4

PF = 1.0, 50 Hz (reactive energy)

i	Quantity (unit)	Distribution	x_i	$u(x_i)$	v_i	c_i	$u_i(y)$
1	Mean value of the observation of the differences between the travelling standard and the reference value	normal	2.9	1.5	99	1	1.5
2	Standard deviation of the mean of electric power reproduction	normal	0.1	1.5	99	1	1.5
3	Corrections due to the phase measurement	normal	0.0	1.9	∞	1	1.9
4	Corrections due to the frequency measurement	rectangular	0.0	1.5	∞	1	1.5
5	Corrections due to the drift of temperature measurements	normal	0.0	0.5	∞	1	0.5
6	Corrections due to the AC current measurements	normal	0.1	3.2	∞	1	3.2
7	Corrections due to the AC voltage amplitude measurements	normal	0.1	2.5	∞	1	2.5
8	Corrections due to the thermal converter AC-DC difference (current channel)	normal	0.1	5.0	∞	1	5.0
9	Corrections due to the thermal converter AC-DC difference (voltage channel)	normal	0.0	5.0	∞	1	5.0
10	Corrections due to the influence of temperature coefficient on travelling standard (voltage)	normal	0.0	0.8	∞	1	0.8
11	Corrections due to the influence of temperature coefficient on travelling standard (direct AC current)	normal	0.0	1.5	∞	1	1.5
12	Corrections due to the influence of temperature coefficient on travelling standard (reactive energy)	normal	0.0	2.5	∞	1	2.5
13	Corrections due to the influence of temperature coefficient on travelling standard (phase angle)	normal	0.0	0.1	∞	1	0.1
14	Corrections due to the influence of temperature coefficient on travelling standard (frequency)	normal	0.0	0.1	∞	1	0.1
15	Short term stability	normal	0.0	0.5	∞	1	0.5
16	Long term stability (for the one operation year)	normal	0.0	1.0	∞	1	1.0
17	Corrections due to the synchronization with standard of time and frequency	normal	0.0	1.4	∞	1	1.4
X_i							3.3
y	Combined standard uncertainty, µvarh/Vah						9.5
	Expanded uncertainty (95 %, k = 2), µvarh/VAh						18.9

PF = 0.5 Lag, 50 Hz (reactive energy)

i	Quantity (unit)	Distribution	x_i	$u(x_i)$	v_i	c_i	$u_i(y)$
1	Mean value of the observation of the differences between the travelling standard and the reference value	normal	3.7	3.1	99	1	3.1
2	Standard deviation of the mean of electric power reproduction	normal	0.1	3.0	99	1	3.0
3	Corrections due to the phase measurement	rectangular	0.1	7.0	∞	0.87	6.1
4	Corrections due to the frequency measurement	normal	0.0	1.5	∞	1	1.5
5	Corrections due to the drift of temperature measurements	normal	0.0	0.5	∞	1	0.5
6	Corrections due to the AC current measurements	normal	0.1	6.0	∞	1	6.0
7	Corrections due to the AC voltage amplitude measurements	normal	0.1	5.0	∞	1	5.0
8	Corrections due to the thermal converter AC-DC difference (current channel)	normal	0.1	5.0	∞	1	5.0
9	Corrections due to the thermal converter AC-DC difference (voltage channel)	normal	0.0	5.0	∞	1	5.0
10	Corrections due to the influence of temperature coefficient on travelling standard (voltage)	normal	0.0	0.8	∞	1	0.8
11	Corrections due to the influence of temperature coefficient on travelling standard (direct AC current)	normal	0.0	1.5	∞	1	1.5
12	Corrections due to the influence of temperature coefficient on travelling standard (reactive energy)	normal	0.0	2.5	∞	1	2.5
13	Corrections due to the influence of temperature coefficient on travelling standard (phase angle)	normal	0.0	0.1	∞	1	0.1
14	Corrections due to the influence of temperature coefficient on travelling standard (frequency)	normal	0.0	0.1	∞	1	0.1
15	Short term stability	normal	0.0	0.5	∞	1	0.5
16	Long term stability (for the one operation year)	normal	0.0	1.0	∞	1	1.0
17	Corrections due to the synchronization with standard of time and frequency	normal	0.0	2.9	∞	1	2.9
X_i							4.2
$\boldsymbol{y}$	Combined standard uncertainty, µvarh/VAh						13.7
	Expanded uncertainty (95 %, k = 2), µvarh/VAh						27.4

PF = 0.5 Lead, 50 Hz (reactive energy)

i	Quantity (unit)	Distribution	x_i	$u(x_i)$	v_i	c_i	$u_i(y)$
1	Mean value of the observation of the differences between the travelling standard and the reference value	normal	-6.8	4.5	99	1	4.5
2	Standard deviation of the mean of electric power reproduction	normal	0.1	3.0	99	1	3.0
3	Corrections due to the phase measurement	normal	0.1	7.0	∞	0.87	6.1
4	Corrections due to the frequency measurement	rectangular	0.0	1.5	∞	1	1.5
5	Corrections due to the drift of temperature measurements	normal	0.0	0.5	∞	1	0.5
6	Corrections due to the AC current measurements	normal	0.1	6.0	∞	1	6.0
7	Corrections due to the AC voltage amplitude measurements	normal	0.1	5.0	∞	1	5.0
8	Corrections due to the thermal converter AC-DC difference (current channel)	normal	0.1	5.0	∞	1	5.0
9	Corrections due to the thermal converter AC-DC difference (voltage channel)	normal	0.0	5.0	∞	1	5.0
10	Corrections due to the influence of temperature coefficient on travelling standard (voltage)	normal	0.0	0.8	∞	1	0.8
11	Corrections due to the influence of temperature coefficient on travelling standard (direct AC current)	normal	0.0	1.5	∞	1	1.5
12	Corrections due to the influence of temperature coefficient on travelling standard (reactive energy)	normal	0.0	2.5	∞	1	2.5
13	Corrections due to the influence of temperature coefficient on travelling standard (phase angle)	normal	0.0	0.1	∞	1	0.1
14	Corrections due to the influence of temperature coefficient on travelling standard (frequency)	normal	0.0	0.1	∞	1	0.1
15	Short term stability	normal	0.0	0.5	∞	1	0.5
16	Long term stability (for the one operation year)	normal	0.0	1.0	∞	1	1.0
17	Corrections due to the synchronization with standard of time and frequency	normal	0.0	2.9	∞	1	2.9
X_i							-6.3
y	Combined standard uncertainty, µvarh/VAh						14.1
	Expanded uncertainty (95 %, k = 2), µvarh/VAh						28.2

PF = 1.0, 53 Hz (reactive energy)

i	Quantity (unit)	Distribution	x_i	$u(x_i)$	v_i	c_i	$u_i(y)$
1	Mean value of the observation of the differences between the travelling standard and the reference value	normal	1.6	1.5	99	1	1.5
2	Standard deviation of the mean of electric power reproduction	normal	0.1	1.5	99	1	1.5
3	Corrections due to the phase measurement	normal	0.0	0.0	∞	1	0.0
4	Corrections due to the frequency measurement	rectangular	0.0	1.5	∞	1	1.5
5	Corrections due to the drift of temperature measurements	normal	0.0	0.5	∞	1	0.5
6	Corrections due to the AC current measurements	normal	0.1	3.2	∞	1	3.2
7	Corrections due to the AC voltage amplitude measurements	normal	0.1	2.5	∞	1	2.5
8	Corrections due to the thermal converter AC-DC difference (current channel)	normal	0.1	5.0	∞	1	5.0
9	Corrections due to the thermal converter AC-DC difference (voltage channel)	normal	0.0	5.0	∞	1	5.0
10	Corrections due to the influence of temperature coefficient on travelling standard (voltage)	normal	0.0	0.8	∞	1	0.8
11	Corrections due to the influence of temperature coefficient on travelling standard (direct AC current)	normal	0.0	1.5	∞	1	1.5
12	Corrections due to the influence of temperature coefficient on travelling standard (reactive energy)	normal	0.0	2.5	∞	1	2.5
13	Corrections due to the influence of temperature coefficient on travelling standard (phase angle)	normal	0.0	0.1	∞	1	0.1
14	Corrections due to the influence of temperature coefficient on travelling standard (frequency)	normal	0.0	0.1	∞	1	0.1
15	Short term stability	normal	0.0	0.5	∞	1	0.5
16	Long term stability (for the one operation year)	normal	0.0	1.0	∞	1	1.0
17	Corrections due to the synchronization with standard of time and frequency	normal	0.0	1.4	∞	1	1.4
X_i							2.0
y	Combined standard uncertainty, µvarh/Vah						9.3
	Expanded uncertainty (95 %, k = 2), µvarh/VAh						18.5

PF = 0.5 Lag, 53 Hz (reactive energy)

i	Quantity (unit)	Distribution	x_i	$u(x_i)$	v_i	c_i	$u_i(y)$
1	Mean value of the observation of the differences between the travelling standard and the reference value	normal	4.7	4.1	99	1	4.1
2	Standard deviation of the mean of electric power reproduction	normal	0.1	3.0	99	1	3.0
3	Corrections due to the phase measurement	rectangular	0.1	7.0	∞	0.87	6.1
4	Corrections due to the frequency measurement	normal	0.0	1.5	∞	0.001	0.0
5	Corrections due to the drift of temperature measurements	normal	0.0	0.5	∞	1	0.5
6	Corrections due to the AC current measurements	normal	0.1	6.0	∞	1	6.0
7	Corrections due to the AC voltage amplitude measurements	normal	0.1	5.0	∞	1	5.0
8	Corrections due to the thermal converter AC-DC difference (current channel)	normal	0.1	5.0	∞	1	5.0
9	Corrections due to the thermal converter AC-DC difference (voltage channel)	normal	0.0	5.0	∞	1	5.0
10	Corrections due to the influence of temperature coefficient on travelling standard (voltage)	normal	0.0	0.8	∞	1	0.8
11	Corrections due to the influence of temperature coefficient on travelling standard (direct AC current)	normal	0.0	1.5	∞	1	1.5
12	Corrections due to the influence of temperature coefficient on travelling standard (reactive energy)	normal	0.0	2.5	∞	1	2.5
13	Corrections due to the influence of temperature coefficient on travelling standard (phase angle)	normal	0.0	0.1	∞	1	0.1
14	Corrections due to the influence of temperature coefficient on travelling standard (frequency)	normal	0.0	0.1	∞	1	0.1
15	Short term stability	normal	0.0	0.5	∞	1	0.5
16	Long term stability (for the one operation year)	normal	0.0	1.0	∞	1	1.0
17	Corrections due to the synchronization with standard of time and frequency	normal	0.0	2.9	∞	1	2.9
X_i							5.2
y	Combined standard uncertainty, µvarh/VAh						13.8
	Expanded uncertainty (95 %, k = 2), µvarh/VAh						27.7

PF = 0.5 Lead, 50 Hz (reactive energy)

i	Quantity (unit)	Distribution	x_i	$u(x_i)$	v_i	c_i	$u_i(y)$
1	Mean value of the observation of the differences between the travelling standard and the reference value	normal	-4.7	3.9	99	1	3.9
2	Standard deviation of the mean of electric power reproduction	normal	0.1	3.0	99	1	3.0
3	Corrections due to the phase measurement	normal	0.1	7.0	∞	0.87	6.1
4	Corrections due to the frequency measurement	rectangular	0.0	1.5	∞	0.001	0.0
5	Corrections due to the drift of temperature measurements	normal	0.0	0.5	∞	1	0.5
6	Corrections due to the AC current measurements	normal	0.1	6.0	∞	1	6.0
7	Corrections due to the AC voltage amplitude measurements	normal	0.1	5.0	∞	1	5.0
8	Corrections due to the thermal converter AC-DC difference (current channel)	normal	0.1	5.0	∞	1	5.0
9	Corrections due to the thermal converter AC-DC difference (voltage channel)	normal	0.0	5.0	∞	1	5.0
10	Corrections due to the influence of temperature coefficient on travelling standard (voltage)	normal	0.0	0.8	∞	1	0.8
11	Corrections due to the influence of temperature coefficient on travelling standard (direct AC current)	normal	0.0	1.5	∞	1	1.5
12	Corrections due to the influence of temperature coefficient on travelling standard (reactive energy)	normal	0.0	2.5	∞	1	2.5
13	Corrections due to the influence of temperature coefficient on travelling standard (phase angle)	normal	0.0	0.1	∞	1	0.1
14	Corrections due to the influence of temperature coefficient on travelling standard (frequency)	normal	0.0	0.1	∞	1	0.1
15	Short term stability	normal	0.0	0.5	∞	1	0.5
16	Long term stability (for the one operation year)	normal	0.0	1.0	∞	1	1.0
17	Corrections due to the synchronization with standard of time and frequency	normal	0.0	2.9	∞	1	2.9
X_i							-4.2
$\boldsymbol{y}$	Combined standard uncertainty, µvarh/VAh						13.8
	Expanded uncertainty (95 %, k = 2), µvarh/VAh						27.7

Measurement equation is:

$$W_x = W_0 + \delta W_r + \delta W_{CPM} + \delta W_{CFM} + \delta W_{CDTM} + \delta W_{CACCM} + \delta W_{CACVAM} + \delta W_{CACDCI} +$$
$$+ \delta W_{CACDCU} + \delta W_{CTCU} + \delta W_{CTCI} + \delta W_{CTCP} + \delta W_{CTCPA} + \delta W_{CTCF} + \delta W_{STS} + \delta W_{LTS} + \delta W_{VETY}.$$

where:

W_0 – mean value of the observation of the differences between the travelling standard and the reference value;

δW_r – standard deviation of the mean of electric energy reproduction;

δW_{CPM} – corrections due to the phase measurement;

δW_{CFM} – corrections due to the frequency measurement;

δW_{CDTM} – drift of temperature measurements;

δW_{CACCM} – corrections due to the AC current measurements;

δW_{CACVAM} – corrections due to the AC voltage amplitude measurements;

δW_{CACDCI} – corrections due to the thermal converter AC-DC difference (current channel);

δW_{CACDCU} – corrections due to the thermal converter AC-DC difference (voltage channel);

δW_{CTCU} – the influence of temperature coefficient on travelling standard (voltage);

δW_{CTCI} – the influence of temperature coefficient on travelling standard (direct AC current);

δW_{CTCP} – the influence of temperature coefficient on travelling standard (active energy);

δW_{CTCPA} – the influence of temperature coefficient on travelling standard (phase angle);

δW_{CTCF} – the influence of temperature coefficient on travelling standard (frequency);

δW_{STS} – short term stability;

δW_{LTS} – long term stability (for the one operation year);

δW_{VETY} – corrections due to the synchronization with standard of time and frequency (for the one operation year).

Appendix 3

Technical Protocol of Comparison

State Enterprise “All-Ukrainian state research and production center of standardization, metrology, certification consumers’ right protection” (SE “Ukrmeterteststandard”)

TECHNICAL PROTOCOL on GULFMET.EM-S5 Supplementary Comparison of AC Energy

(Edition 1)

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Table of Content

1 Introduction

To support the Calibration and Measurement Capabilities (CMCs) of AC Energy declared by members of COOMET, EURAMET and GULFMET in the framework of the CIPM-MRA, SE «Ukrmetrteststandard» (UMTS) is going to organize in 2019 GULFMET Supplementary Comparison of AC Energy for electric energy standards of low-frequency. Electric energy standard of low-frequency will be compared at 3 National Metrology Institutes (NMIs) from COOMET, EURAMET and GULFMET to establish the relationship between the electrical units of AC Energy at these NMIs.
Reliable measurements of electric energy are the cornerstone of electric restructuring schemes in economies worldwide. Any opportunity of testing the reliability of measuring methods and reference standards at an international level is very valuable to national metrology institutes. Supplementary comparisons in electric energy measurements are strongly fostered by RMOs. The goal of this comparison project is to compare the energy calibration systems of the participating NMIs.
Participating NMIs will be responsible for conducting the tests in their respective laboratories and submitting their test data in the format prepared for this comparison.
UMTS is proposed to be the pilot laboratory, which would be responsible for providing the travelling standard, coordinating the schedule, collecting and analyzing the comparison data, and preparing the draft report. Relevance of the comparison results are expected at the level of better than 0.05%.
The results of this Supplementary Comparison will be described in Draft A and Draft B. The differences between almost all NMI’s values and the reference values will be within the expanded measurement uncertainties at a coverage factor k = 2. This protocol has been prepared following the CIPM MRA-D-05 [1]. For this energy comparison, the test frequencies of 50 Hz and 53 Hz, power factors 1.0, 0.5 Lag, 0.5 Lead and reactive power factors 1.0, 0.5 Lag, 0.5 Lead are proposed. This proposal differs from that early in energy comparisons, where some participants made measurements either at 50 Hz or at 60 Hz.

2 Participants and time schedule of the comparison

Each participant is given 2 weeks to perform the measurements of electrical energy standard of low-frequency (50 Hz and 53 Hz) and 1 week to transfer to the pilot laboratory. The participants and the time schedule of the Supplementary Comparison are given in Table 1 and Table 2. There are 3 participants in this Supplementary Comparison.
Participants should have the travelling standard delivered to the address of the participant scheduled to perform measurements after themselves according to the schedule.

Table 1 List of participants of the supplementary comparison

№	NMI	Abbreviation of NMI	Address	Contact person	e-mail, phone, fax
1	State Enterprise “All-Ukrainian state resear-ch and production center of standardiza-tion, metrology, certi-fication consumers’ right protection” (SE “Ukrmetrteststandard”)	UMTS	4, Metrolo-gichna Str., 03143, Kyiv, Ukraine	O. Velychko	velychko@ukrcsm.kiev.ua Tel./Fax: +38 044 526 0335

№	NMI	Abbreviation of NMI	Address	Contact person	e-mail, phone, fax
2	TÜBITAK Ulusal Metroloji Enstitüsü	UME	TÜBİTAK Gebze Yerleskesi Baris Mah., Dr. Zeki Acar Cad. No. 1 41470, Gebze Kocaeli, Turkey	H. Çayci	huseyin.cayci@tubitak.gov.tr Tel.: +90 262 679 5000
3	Abu Dhabi Quality and Conformity Council Emirates Metrology Institute	QCC EMI	Emirates Metrology Institute Abu Dhabi Quality and Conformity Council (QCC) CERT Sultan Bin Zayed the First Street Abu Dhabi, UAE	J. Bartholo-mew	Jon.Bartholomew@qcc.abudhabi.ae Tel.: +971 503862676 Fax: +971 24066677

Table 2 The list of dates of measurements

Abbreviation of NMI	Dates of measurements	Dates of delivery
UMTS	18.02–03.03.2019	04.03.2019
QCC EMI	11–24.03.2019	25.03.2019
UMTS	01–14.04.2019	15.04.2019
UME	22.04–05.05.2019	06.05.2019
UMTS	13–26.05.2019	Finish

3. Financial aspects and insurance

Each laboratory participating in the comparisons should be at their own expense to perform all the measurements and send travelling standard back to the pilot laboratory (including transportation costs, insurance costs and customs).

In addition, each laboratory participating in the comparisons should be at their own expense to cover all costs from the moment of arrival travelling standard in the country, up to the moment of sending back to the pilot laboratory.

Expenses may include (but are not limited to): charges at check travelling standard (customs fees, brokerage services, transportation within the country) and the costs of returning the standard pilot laboratory. The appraised cost of selected travelling standard is Radian Research RD-33-332 (serial number 301308) is 20,000 Euro.

IMPORTANT: In order to have the final time schedule of the comparison, all the participants should inform the pilot laboratory whether they agree to send the travelling standard by a customs agency, or may want to be responsible of a different way to transport the traveling standard.

4. Travelling standard and measurement instruction

4.1. Description of the travelling standard

Selected travelling standard is Radian Research RD-33-332 serial number 301308 (RD-33-332). The RD-33-332 has a guaranteed accuracy of 0.01% and was successfully used as a travelling standard in Key Comparison of Power (COOMET.EM-K5) [2]. UMTS was proposed to be the pilot laboratory in COOMET.EM-K5, which would be responsible for providing the travelling standard, coordinating the schedule, collecting and analyzing the comparison data, and preparing the draft report.

The measure process of measuring AC Energy is fully automatically with the help of connector output count number of pulses which is directly proportional to the measured active power. The output frequency of RD-33-332 is 20833.3333 Hz. More information of the RD-33-332 is available at www.radianresearch.com. Appearance of RD-33-332 is shown on Figure 1.

Figure 1 Appearance of travelling standard RD-33-332

Travelling standard RD-33-332 is three-phase electric power meter, works on principles of digital processing of electrical current and voltage signals.

Main characteristics of travelling standard RD-33-332:

– input voltage: 30…525 V (RMS);
– input current: 0,2…120 A (RMS);
– frequency of the input voltage and current signals: 45…65 Hz;
– constant of the frequency output: 125 000 pulse/Wh;
– supply voltage: 60…525 V (RMS);
– working range of the temperature: minus 20 °C…40 °C;
– keeping range of the temperature: minus 25 °C...80 °C;
– working range of the humidity: 0...95%;
– dimensions: 444.5×172×131 mm;
– weight: 6.21 kg.

Terminal block of the RD-33-332 is shown on Figure 2.

User manual for RD-33-332 is attached. All participants of the comparison should have learned the documentation before comparison conducting. Specification of equipment that will be sent to participants on Supplementary Comparison of AC Energy GULFMET.EM-S5 is shown in Table 3.

Figure 2 Terminal block of travelling standard RD-33-332

Table 3 The specification of equipment that will be sent to participants on Supplementary Comparison of AC Energy

No.	Name of equipment	Quantity
1	Selected travelling standard RD-33-332 (serial number 301308) (Figure 1)	1 piece
2	Power cable (Figure 3)	1 piece
3	Current cable (Figure 4)	2 pieces
4	Voltage cable (Figure 5)	2 pieces
5	Pulse cable (Figure 6)	1 piece
6	Clamping nuts for connection current cables of travelling standard RD-33-332 (Figure 7)	6 pieces
7	Container of travelling standard RD-33-332 (Figure 8)	1 piece

Figure 3 Power cable of travelling standard RD-33-332

Figure 4 Current cables for connection travelling standard RD-33-332

Figure 5 Voltage cables for connection travelling standard RD-33-332

Figure 6 Pulse cable for connection travelling standard RD-33-332

Figure 7 Clamping nuts for connection current cables of travelling standard RD-33-332

Also to each of partisipant will be send “Operations Manual RD-33 Portatable Three-phase Electricity Standard” and CONTRACT for participation.

4.2 Unpacking and packing

Travelling standard will be transported in a container, which is designed for safe transportation of the standard Figure 8. Upon arrival, participants should check the container and make sure that all parts are present according to the list. After the measurement model should be carefully packed back into the container, in which it has arrived. Linear dimensions of container: 600 mm x 450 mm x 290 mm. The weight of container (with the content) is about 15 kg.

Figure 8 Container of travelling standard RD-33-332

If the damage of the container is detected, travelling standard should be packed in new containers, which will provide the necessary protection during transportation.

Upon receipt of travelling standard it is necessary to check the container for external damage and verify the completeness of travelling standard in accordance with the attached list.

The copy of the technical description of RD-33-332 is attached. It is necessary to familiarize with the features of travelling standard before starting the measurement. It must be carefully removed from the container.

Opening the corpus of RD-33-332 is strictly prohibited. If some defects of travelling standard are found, the participating laboratory should have immediately informed the pilot laboratory by fax or e-mail. If the repair of travelling standard is needed, the participant of comparisons should send travelling standard in a pilot laboratory.

Participants must inform the pilot laboratory by fax or e-mail about the arrival of travelling standard by using the form shown on Figure 9.

Confirmation note for receipt		
Date of arrival		
NMI		
Name of responsible person		
The travelling standard	□ Damaged	□ Not Damaged
Additional notes:		

Figure 9 Sample form for the information of arrival of travelling standard RD-33-332

The participating laboratory should inform the pilot laboratory about departure of RD-33-332 by using the form shown on Figure 10.

Confirmation note for dispatch	
Date of shipment	
NMI	
Name of responsible person	
Shipment information (company name etc.)	
Additional notes:	

Figure 10 Sample form for the information of departure of travelling standard RD-33-332

After the measurements, each participant of comparison must send the travelling standard to the pilot laboratory. The laboratories participating in the comparison are responsible for arranging shipment of travelling standard to the pilot laboratory.

5. Description of the method of measurement

5.1 Operations before measurements

Before the measurements of active power in the RD-33-332 by measuring the output pulses it must be warmed up for 24 hours (connected to the main power supply). Current and voltage signals must be connected for 4 hours before measurement. Following these procedures, short-term shutdown signal current or voltage from travelling standard will not lead to loss of the standard’s characteristics. But if the power supply of travelling standard will be turned off, then the procedure of warming up must be made over again.

The result to be reported is the calibration error of the travelling standard, defined as the difference between the measured quantity indicated by the traveling standard and the quantity applied to it, and divided by the applied VAh. The calibration error should be expressed in ± μWh/VAh. The error is positive if the travelling standard's indication is more positive than the applied quantity.

The RD-33-332 measurement principle is based upon the fundamentals of a high-speed charge-balance integrating analog to digital signal converter. RD-33-332 Dytronic utilizes two separate A/D converters. One accepts a current signal and is linked with two current references. The other accepts a voltage signal and is linked with two voltage references. These of course are for the analog voltage and current inputs of the RD-33-332. Both operate independently to provide the digital signal processor with signals accurate enough to meet the requirements of a true portable electricity standard. Gain error, charge timer resolution, signal to noise ratio and signal distortion were major areas dealt with and improved in development

Also before the measurements, it is necessary to familiarize design features and work principles of travelling standard by using technical description (user manual) of RD-33-332. Connection travelling standard in accordance with the scheme is shown on Figure 11.

To carry out measurements on Supplementary Comparison of AC Energy (GULFMET.EM-S5) all the participants need to use a single-phase switching circuit. And as the reference of output signal is used frequency output. This is programmed to issue pulses used for phase A.

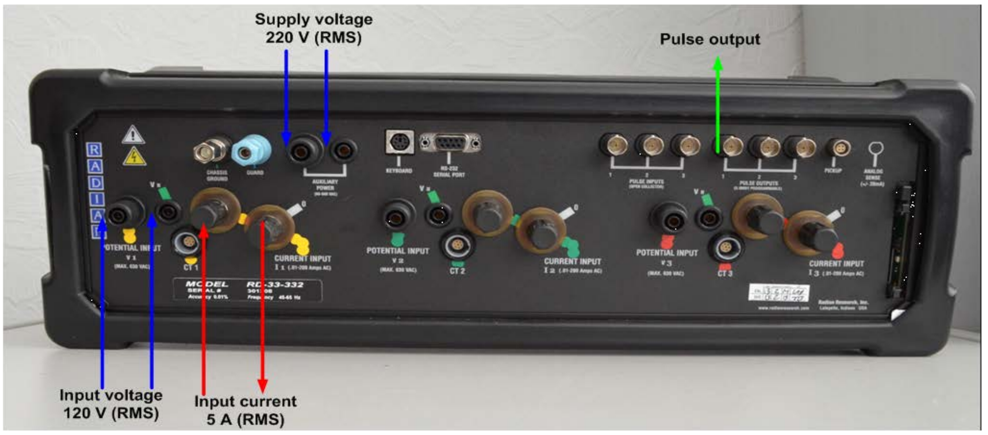

Figure 12 Connection scheme for travelling standard RD-33-332

5.2 Measurements

The travelling standard 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 125 000 pulses/Wh. At 120 V, 5 A and power factor equal to unit, RD-33-332 are able to generate a train of pulses with a frequency equal to 20833.3333 pulses per second.

Recommended method: The comparison of electric pulses

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. That is:

$$Frequency = \frac{Power \cdot K_H}{3600} \left[{pulse}/{s} \right]$$

RD-33-332 is provided with a built-in comparator. As shown in Figure 3, BNC port allows access to the built-in comparator. If the participation NMI wants to use the in-built pulse comparator on the RD-33-332, it should input the K_H of its energy reference standard at RD-33-332. Use the scroll down menu to input the constant. The K_H value of the participant's laboratory should be given in terms of pulses per Wh or pulses per kWh. The measurement method is not specified. Make sure that voltage and current are within at least 0.2 % of the values shown in Table 4:

1. for the voltage and current sources, make sure that their frequency is set at 50 Hz and 53 Hz, according to the testing points shown in Table 4;
2. at every testing point shown in Table 4, make as many independent measurements of the calibration error of the travelling standard as stated on the calibration procedures of the laboratory;
3. Complete the calibration of the travelling standard by obtaining the mean value of its calibration error obtained at the testing points shown in Table 4. The calibration error is defined as the difference between the measured quantity indicated by the travelling standard and the quantity applied to it, and divided by the applied quantity. The calibration error of the travelling standard should be expressed in µWh/VAh.
4. the number of pulses on the RD-33-332 should be set to 1 000 000 (one Million);
5. for 1 million pulses, the integration time T_{int} for energy measurements will be approximately equal to:

a) T_{int} = 60 seconds, at 120 V / 5A / PF = 1.0/RPF = 1.0;
b) T_{int} = 120 seconds, at 120 V / 5 A / PF = 0.5 Lag, 0.5 Lead / RPF = 0.5 Lag, 0.5 Lead.

6. the average of at least 10 sets of measurements should be reported;

7. the travelling standard should be de-energized between each set of measurements for at least one hour, followed by at least one hour warm-up period.
Main measurements should be performed with the input signals and environmental conditions such as in Table 4.

Table 4 The measurement points and condition of measurements

Unit	Value of the unit
Voltage	120 V ± 0.2 %
Current	5 A ± 0.2 %
Power factor	1.0, 0.5 Lag, 0.5 Lead deviation from the nominal value not exceeding ± 0.1%
Reactive power factor	1.0, 0.5 Lag, 0.5 Lead deviation from the nominal value not exceeding ± 0.1%
Frequency	50 Hz ± 0.05 Hz and 53 Hz ± 0.05 Hz
Temperature	23 °C ± 1 °C
Humidity	20 % – 70 %
Supply voltage	220 V ± 5 %
Frequency of the supply voltage	50 Hz ± 0.1 Hz

5.3 Uncertainty of the measurements

Uncertainty of the measurements should be calculated according to the GUM – Guide to the expression of uncertainty in measurement JCGM 100:2008 [3] (GUM 1995 with minor corrections). With the results of measurements should be given a model that describes how the measurement result was obtained considering all influencing quantities (voltages, currents, etc.). For each of the influencing quantities should be given the description of the source of uncertainty and an assessment of this uncertainty. All influencing quantities, their uncertainties, influencing coefficients, degrees of freedom and levels of confidence should be given in the budget of the uncertainty.
The budget of the uncertainty (Table 5) should include such number of influencing quantities and their uncertainties, which ensures the highest level measurements of electric energy for each of the laboratories.

Table 5 A suggestion format of the uncertainty budget

i	Quantity (unit)	Distribution	x_i	$u(x_i)$	v_i	c_i	$u_i(y)$ (µWh/VAh)
1							
2							
y	Std uncertainty of measurement						
		Coef. level = 95 %				$k = 2$	
		Expanded uncertainty (µWh/VAh) =					

6. The measurement report

Each participating NMI of the comparisons shall provide a report within 6 weeks from the date of departure travelling standard to the next participant.
The report shall be sent to the coordinator of comparisons by e-mail: velychko@ukrcsm.kiev.ua
The report shall include:
- description of measurement methods;
- description of the measurement circuit and used the standard possibilities of electricity;

- confirmation of the traceability of the measurements (if participating laboratories has its own electric power units playback system, or must provide proof of traceability from another lab).
- temperature and humidity in the laboratory during the measurement;
- measurement results: certain amendments travelling standard values (6 values) for frequencies 50 Hz and 53 Hz, Power factor: 1.0, 0.5 Lead, 0.5 Lag and Reactive power factor: 1.0, 0.5 Lead, 0.5 Lag.
- values of the respective standard uncertainties, the effective values of the degrees of freedom and expanded uncertainty;
- detailed budget of uncertainty, which will be included in a report on the comparisons.

If between the measurements of any member, provided the pilot laboratory and preliminary comparisons reference value is detected a significant difference, it will be reported to the appropriate party. No other information on the measurement results will not be reported.

7. Report on comparisons

7.1 The reference value and the degrees of equivalence

This protocol has been prepared following the guidelines of the CCEM as given in [1]. The principles of the method of computation of the reference value are as follows [4]:

1. For the calculation of the reference value (RV), the weighted mean over the participating laboratories will be used. If the uncertainty contribution of a participant due to the traceability to another NMI participating in this comparison amounts to a substantial part of the overall uncertainty value, the result will not be taken into account in the calculation of the RV.
2. The degree of equivalence among the participating laboratories shall be expressed quantitatively by two terms:
- the difference of the participating laboratory from the RV;
- the uncertainty of this difference at a 95.45 % level of confidence.

4. In order to compare the results of the different participants, including the pilot laboratory, each of the participants should report a single measurement result for each of the testing points shown in Table 4.
5. The bilateral degrees of equivalence. As requested per the CCEM, the bilateral degrees of equivalence among the participating laboratories in a supplementary comparison will not be explicitly shown, but the formula for obtaining them will be included, thus allowing the participating laboratories to calculate their bilateral degree of equivalence from the data resulting from the difference between the participating laboratories and the RV.

7.2 Reports

Preliminary and final reports on the results of comparisons will be prepared by the pilot laboratory. The report will be prepared by the pilot laboratory within 4 months after the end of the measurement, and sent to the participants. The report is only for the participants of comparisons and is confidential. The report should be directed to the pilot laboratory for 2 months from the date of distribution of the Draft A. Comments will be considered in the Draft B. Draft B will be completed within 6 months after the end of the measurement. The final report will be prepared within 1 month from the receipt of the comments on the Draft B.

References

[1] CIPM MRA-D-05. Measurement comparisons in the CIPM MRA. p.28 https://www.bipm.org/utils/common/documents/CIPM-MRA/CIPM-MRA-D-05.pdf

[2] Velychko, O. and Karpenko, S., Final report on COOMET Key Comparison of Power (COOMET.EM-K5), SE “Ukrmetertеststandard”, December 2018, p.136.

[3] JCGM 100:2008 Evaluation of measurement data – Guide to the expression of uncertainty in measurement.

[4] Recommendation COOMET R/GM/19:2008 Guidelines for evaluating data supplement comparisons COOMET.