INTERLABORATORY COMPARISONS OF CALIBRATION RESULTS OF THREE-PHASE ELECTRICAL ENERGY METERS

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Abstract

Reliable measurement of electric energy is of great importance both in industry and for household consumers of both single-phase and three-phase networks. Interlaboratory comparisons (ILCs) are one of the experimental forms of confirming the scope of accreditation of calibration laboratories (CLs). The article is devoted to the analysis of the results of the ILC of a three-phase electric energy meter, which was conducted in 2025. The ILC was conducted with the participation of accredited CLs from Ukraine and Israel. A feature of this ILC was the calibration of the meter both for three phases in general and for each phase separately. Calibration was carried out with a nominal AC voltage of 230 V, frequency 50 Hz, currents from 2.5 A to 100 A at KP 1.0 and 0.5 for positive and negative flow. Processing of the primary ILC data received from the laboratories was carried out using special software "InterLab 1.0", developed in UMTS. The deviation of the results obtained by each laboratory was determined and the consistency of the results obtained was assessed taking into account the measurement uncertainty using the criterion of performance statistics. In general, the laboratories obtained satisfactory results with good consistency. The laboratories fully meet the established requirements for the E_n number and have confirmed their technical competence during the calibration of meters in accordance with the requirements of the international standard ISO/IEC 17025. The results of the ILC allow for the mutual recognition of the results of the calibration of electricity meters by the national accreditation bodies that accredited these CLs.

Keywords

Calibration, energy meter, three-phase voltage, interlaboratory comparison, uncertainty.

1. Introduction

Reliable measurement of electrical energy is important both in industry and for household consumers of both single-phase and three-phase networks. Such measurements affect the accurate calculations of the cost of consumed electrical energy, allow you to manage its consumption and diagnose the electrical network, etc. Monitoring electrical energy consumption helps to detect overloads or malfunctions in the network.

National agencies for laboratory accreditation establish specific requirements for the validation of the scope of accreditation of calibration laboratories (CL) [1] for each type of measurement and range of measured value. Interlaboratory comparisons (ILCs) [2] are one of the experimental forms of such validation of the scope of accreditation of a CL. They are used by accredited calibration laboratories (CLs) to assess and confirm the accuracy, reliability and reproducibility of measurements carried out by these laboratories.

The main purpose of ILCs is to assess the accuracy of measurement standards and measuring instruments used in the laboratory, to confirm the mutual acceptability of results obtained by laboratories to increase confidence in their results, etc. Successful results for a particular laboratory in ILCs are confirmation of its competence in carrying out certain types of measurements by a specific specialist using specific standards and measuring instruments.

2. Drawbacks

A large number of publications are devoted to the issues of organizing ILC and methods of processing the obtained data in specific types of measurements or tests. The assessment of the laboratory results obtained in ILC for specific types of measurements is presented in a number of works, in particular on electrical measurements (electrical energy, reactive power, electrical resistance) [4–8]. The assessment of the measuring capabilities of CL for obtaining high-accuracy and precision data is given in the works [9–11]. At the same time, the actual task of conducting ILC for three-phase electricity meters with the appropriate assessment of its results remains.

3. Goal

The purpose of the study was to evaluate the primary data of laboratories obtained during the ILC for the calibration of three-phase electricity meters. During the study, it was necessary to examine the calibration object in the corresponding ILC, determine the assigned value and its expanded uncertainty, and calculate the degree of equivalence for each of the laboratories participating in the ILC and their expanded uncertainties. The results obtained by the laboratories in the ILC had to be evaluated according to the criteria of performance statistics with the formulation of the corresponding conclusions.

4. Overview of the interlaboratory comparison

The ILC for the calibration of a three-phase electricity meter (UMTS ILC-E5:2025) was conducted by two CLs (SE "Ukrmetrteststandart" – UMTS, Ukraine and SATEC Calibration Laboratory, Israel) from July to September 2025. The UMTS laboratory is accredited by the National Accreditation Agency of Ukraine (NAAU), and the SATEC laboratory is accredited by the Israel Laboratory Accreditation Authority (ISRAC). Both NAAU and ISRAC are signatories to the International Accreditation Cooperation (ILAC) agreement on mutual recognition of calibration results.
The ILC program was developed with requirements of international standards ISO/IEC 17025 [1], ISO/IEC 17043 [2] and ISO 13528 [3].
The calibration item (CI) for ILC is the three-phase energy meter SATEC EM133-XM-HACS(SE) 3×50 A (100 A), serial number of which is 75000208 (Fig. 1). SATEC EM133 meters are a whole family of energy meters, which includes the electricity meter selected for comparison. It has a nominal measured current of 3×50 A (maximum current 100 A) and is intended for applications with transformer power supply and connection to high-voltage power lines.

Fig. 1. Appearance of EM133-XM-HACS(SE) 3×50 A (100 A)

Main characteristics of the CI for ILC:

– measured voltage/supply voltage	from 120/207 V AC to 230/400 V AC (L-N/L-L);
– maximum current	100 A;
– frequency measurement range	50/60 Hz;
– rated currents of the remote current transformer	40 mA
– voltage load for 277 V	< 1.5 VA;
– operating temperature range	from -20°C to 60°C;
– dimensions	125 × 90 × 75 mm.

Main measurements should be performed with the input signals and environmental conditions:

– AC voltage	230 V ± 0.05 %;
– current	from 2.5 to 100 A ± 0.05 %;
– power factor (PF)	1.0, ±0.5 Lag;
– frequency	(50 ± 0.01) Hz;
– ambient temperature	(23 ± 2) °C;
– relative humidity	(40 ± 10) %;
– supply voltage	(230 ± 3) V;
– frequency of the supply voltage	(50 ± 0.05) Hz.

Traceability to the International System of Units (SI) was ensured by calibrating the reference standards used by the participating laboratories in accredited calibration laboratories (Fig. 2). Electrical energy measurements in the UMTS laboratory have metrological traceability to the Physikalisch-Technische Bundesanstalt of Germany (PTB), and SATEC calibration laboratories are traceable to the Czech Metrology Institute (CMI). The UMTS laboratory was a pilot laboratory for the verification of electrical power and energy standards of two regional metrology organizations: the key power verification COOMET. EM-K5 [13] and the additional energy verification GULFMET.EM-S5 [14], which also confirm the traceability of the corresponding measurements.

Fig. 2. Appearance of the National Standard of Ukraine for Units of Electric Power and Power Factor NDETU EM-08-2023

5. The obtained results of the interlaboratory comparison

The full final report of ILC contains all the primary data of the measurements of total electrical energy for all phases, as well as for each phase separately, and the corresponding uncertainty estimates of the ILC participating laboratories. The report includes a description of the measurement method, traceability to SI, as well as the results and associated uncertainties. The calibration errors x_i and their expanded uncertainties $U(x_i)$ of the participating laboratories are given in Table 1 for an AC voltage of 230 V at a frequency of 50 Hz.

Table 1. Results of measurement of total electrical energy across all phases by ILC participating laboratories

Current, A	PF	Flow Positive/ Negative	Calibration error x_i, %		Uncertainty $U(x_i)$, %	
			UMTS	SATEC	UMTS	SATEC
L1						
2.5	1	Positive	0.016	0.012	0.115	0.147
5			0.045	0.023	0.106	0.131
50			0.016	-0.008	0.176	0.175
100			0.031	-0.026	0.097	0.160
5	0.5 Lag		0.150	0.230	0.091	0.334
50			0.017	-0.008	0.161	0.236
100			-0.023	-0.001	0.060	0.245
50	1	Negative	-0.011	-0.013	0.129	0.168
100			-0.037	-0.029	0.048	0.163
50	0.5 Lag		0.079	0.034	0.179	0.257
100			-0.069	-0.073	0.160	0.269
L2						
2.5	1	Positive	0.008	0.019	0.116	0.147
5			0.047	0.044	0.105	0.131
50			0.016	-0.002	0.173	0.175
100			0.033	-0.014	0.100	0.160
5	0.5 Lag		0.089	0.199	0.089	0.334
50			-0.040	0.044	0.164	0.237
100			-0.081	-0.008	0.060	0.245
50	1	Negative	-0.010	-0.003	0.129	0.168
100			-0.034	-0.018	0.047	0.163
50	0.5 Lag		0.027	0.011	0.179	0.257
100			-0.127	-0.022	0.158	0.270
L3						
2.5	1	Positive	-0.015	0.000	0.117	0.147

5			0.047	0.042	0.104	0.131
50			0.010	-0.002	0.175	0.175
100			0.023	-0.021	0.101	0.160
5	0.5 Lag		0.112	0.099	0.089	0.334
50			-0.025	-0.049	0.161	0.236
100			-0.061	-0.056	0.059	0.245
50	1	Negative	-0.017	-0.004	0.127	0.168
100			-0.043	-0.017	0.048	0.163
50	0.5 Lag		0.039	-0.067	0.178	0.257
100			-0.121	-0.087	0.159	0.269
Three phases						
2.5	1	Positive	0.027	0.011	0.034	0.116
5			0.059	0.037	0.034	0.095
50			0.023	-0.003	0.034	0.123
100			-0.007	-0.021	0.038	0.118
5	0.5 Lag		0.206	0.175	0.034	0.259
50			0.012	-0.005	0.033	0.194
100			-0.060	-0.021	0.035	0.196
50	1	Negative	-0.060	-0.021	0.035	0.196
100			0.013	-0.004	0.036	0.119
50	0.5 Lag		-0.016	-0.022	0.045	0.120
100			0.031	0.072	0.033	0.202

Laboratories calculated their measurement uncertainty according to the Guide to the Expression of Uncertainty in Measurement (GUM) [15]. All contributions to the measurement uncertainty were reported in the Final Report of ILC and identified as Type A or Type B uncertainties. The total standard uncertainty was calculated from all individual standard uncertainties. The expanded uncertainty was calculated with a coverage factor of 2 at a confidence level of 95%.

6. Discussion of the results of the interlaboratory comparison

The ILC assigned values (AV) X_{AV} are calculated as the mean of participant data:

$$X_{AV} = \sum_{i=1}^{N} \frac{x_i}{u^2(x_i)} \Bigg/ \sum_{i=1}^{N} \frac{1}{u^2(x_i)}, \tag{1}$$

with expanded uncertainties

$$U(X_{AV}) = 2\sqrt{1 \Bigg/ \left(\frac{1}{u^2(x_{\mathrm{UMTS}})} + \frac{1}{u^2(x_{\mathrm{SATEC}})} \right)}, \tag{2}$$

where x_{UMTS} and x_{SATEC} are measurement error for UMTS and SATEC accordingly, $u(x_{\mathrm{UMTS}})$ and $u(x_{\mathrm{SATEC}})$ are combined standard uncertainty for UMTS and SATEC accordingly.

AV with expanded uncertainties for three phases is given for AC voltage 230 V and at frequency of 50 Hz in Table 2.

Table 2. AV and expanded uncertainties.

Current, A	PF	Flow Positive/ Negative	AV X_{AV}, %	Uncertainty $U(X_{AV})$, %
2.5	1	Positive	0.026	0.0326
5			0.057	0.0320
50			0.021	0.0328
100			-0.008	0.0362
5	0.5 Lag		0.205	0.0337
50			0.012	0.0325
100			-0.059	0.0345
50	1	Negative	0.012	0.0345
100			-0.017	0.0421
50	0.5 Lag		0.032	0.0326
100			-0.069	0.0345

The degrees of equivalence (DoE) of i-th laboratory with expanded uncertainties with respect to the AV is estimated as

$$D_{lab\ i} = x_{lab\ i} - X_{AV}, \tag{3}$$

$$U(D_{lab\ i}) = \sqrt{U^2(x_{lab\ i}) + U^2(X_{AV})}. \tag{4}$$

DoE with expanded uncertainties for laboratories for three phases for AC voltage 230 V at frequencies of 50 Hz are given in Table 3. In the first column of this table, each AC value is assigned a number that can be used to display the

DoE of laboratories in a graphical form (Fig. 3). To analyze the ILC results, special software "InterLab 1.0" [16] developed by UMTS was used, which makes it possible to automate the calculations and analysis of the ILC results evaluation criteria. It allows evaluating the ILC results by the E_n number, as well as other similar criteria. The obtained results of the deviation and uncertainty estimates are displayed using graphs, and the calculated values of the indicators are displayed using histograms.

Table 3. DoE with expanded uncertainties for laboratories.

Current (No), A	PF	Flow Positive/ Negative	DoE $D_{lab\ i}$, %		Uncertainty of DoE $U(D_{lab\ i})$, %	
			UMTS	SATEC	UMTS	SATEC
2.5 (1)	1	Positive	0.001	-0.015	0.0471	0.1205
5 (2)			0.002	-0.020	0.0467	0.1002
50 (3)			0.002	-0.024	0.0472	0.1273
100 (4)			0.001	-0.013	0.0525	0.1234
5 (5)	0.5 Lag		0.001	-0.030	0.0479	0.2612
50 (6)			0.000	-0.017	0.0463	0.1967
100 (7)			-0.001	0.038	0.0491	0.1990
50 (8)	1	Negative	0.001	-0.016	0.0498	0.1239
100 (9)			0.001	-0.005	0.0616	0.1272
50 (10)	0.5 Lag		-0.001	0.040	0.0464	0.2046
100 (11)			0.000	0.009	0.0491	0.2089

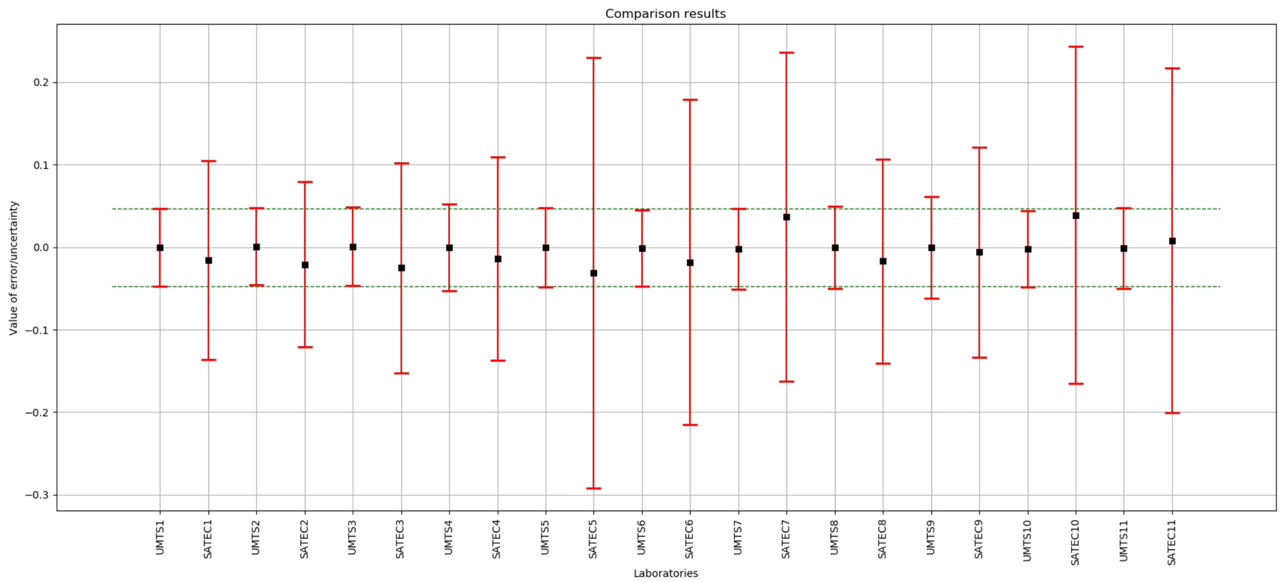

Fig. 3. DoE with expanded uncertainties for laboratories.

The data consistency E_n number is calculated as:

$$E_{n\ lab\ i} = 2\left|D_{lab\ i}\right| / U\left(D_{lab\ i}\right) \leq 1.0. \quad (5)$$

E_n number for laboratories for three phases and AC voltage 230 V at frequencies of 50 Hz are given in Table 4. In the first column of this table, each AC value is assigned a number that can be used to display the E_n number of laboratories in a graphical form (Fig. 4). Laboratories meet the established requirements for E_n number ($|E_n| \leq 1.0$): UMTS – from 0.01 to 0.47; SATEC – 0.00 to 0.50 for all calibration points.

Table 4. E_n number for laboratories for three phases.

Current (No), A	PF	Flow Positive/ Negative	E_n for UMTS	E_n for SATEC
2.5 (1)	1	Positive	0.03	0.12
5 (2)			0.05	0.19
50 (3)			0.04	0.19
100 (4)			0.03	0.10
5 (5)	0.5 Lag		0.01	0.12
50 (6)			0.01	0.08
100 (7)			0.02	0.19

50 (8)	1	Negative	0.03	0.13
100 (9)			0.01	0.04
50 (10)	0.5 Lag		0.02	0.20
100 (11)			0.01	0.04

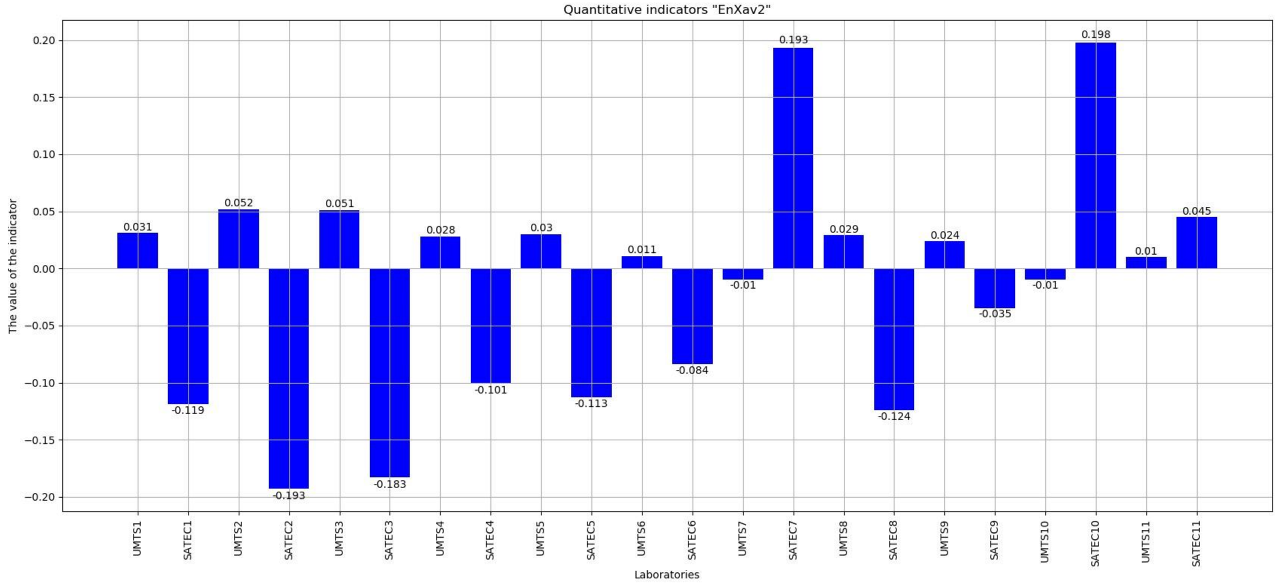

Fig. 4. E_n number for laboratories for three phases.

7. Conclusions

The ILC on the calibration of three-phase electricity meters was carried out with the participation of accredited CLs from Ukraine and Israel. A feature of this ILC was the calibration of the meter both for three phases in general and for each phase separately. Calibration was carried out with a nominal value of alternating voltage of 230 V with a frequency of 50 Hz at currents from 2.5 A to 100 A at PF 1.0 and 0.5 for positive and negative flow. Processing of the primary ILC data received from the laboratories was carried out using special software “InterLab 1.0”, developed at UMTS. In general, the laboratories received satisfactory results with good consistency. The laboratories fully comply with the established requirements for the E_n number ($|E_n| \leq 1.0$) and have confirmed their technical competence in calibrating meters in accordance with the requirements of the ISO/IEC 17025 standard. The results of the ILC allow for mutual recognition of the calibration results of electricity meters by the national accreditation bodies that accredited these CLs.

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Conflict of Interest

The authors state that there are no financial or other potential conflicts regarding this work.

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