METROLOGY, QUALITY, STANDARTIZATION AND CERTIFICATION

FEATURES OF PRECISION MEASUREMENT OF ELECTRICAL ENERGY AT INDUSTRIAL FREQUENCY

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https://doi.org/10.23939/istcmtm2025.01.030

Abstract. Measurement of electrical energy is of great importance in various areas, as it provides control and optimization of energy consumption, technical monitoring and diagnostics of equipment, efficient use of energy resources, accounting and settlements for consumed electricity, etc. When measurement of energy, the amount of energy consumed over a certain period of time is determined. Accurate energy measurement helps to identify energy-consuming processes or equipment and make decisions about modernization or changing the operating mode to reduce costs. Electric energy meters allow you to accurately record the amount of energy consumed. Standards of electric power and energy are used to calibrate and verify electrical energy measuring instruments. They have a different structural structure, which ensures the reproduction of various practically used units of measurement of electric energy. International comparisons of national standards of electric power and energy are carried out, which become the basis for the calibration and measurement capabilities (CMC) of national laboratories. For measurements of active and reactive alternating current electrical energy at power frequency, high-precision standards are used, which are built on the basis of a traditional structural scheme. Only a small number of laboratories of national metrology institutes and designated institutes have published CMC records in the Key Comparison Database (KCDB) of the International Bureau of Weights and Measures (BIPM) for the measurement of active and reactive electrical energy. These laboratories have measurement uncertainties within quite wide limits over a wide range of energy values: for active energy from 16 to 700 ppm; for reactive energy from 16 to 400 ppm.

Keywords: Electric energy, electric power, electric energy measurement, active energy, reactive energy, standard, calibration and measurement capabilities.

1. Introduction

Electricity measurement is of great importance in various fields, as it provides control and optimization of energy consumption, technical monitoring and diagnostics of equipment, efficient use of energy resources, accounting and settlements for consumed electricity, etc. When measuring energy, the amount of energy consumed is determined over a certain period of time. Accurate energy measurement helps to identify energy-consuming processes or equipment and make decisions about modernization or changing the operating mode to reduce costs. Electricity meters allow you to accurately record the amount of energy consumed [1, 2].

Electricity measurement allows you to monitor the operation of electrical devices and detect malfunctions or inefficient operation. Such measurements help the network operator balance the load and prevent system overload, ensuring stable and reliable operation of electrical networks. It is critical for ensuring efficient and safe use of energy, and also helps electricity consumers better manage resources, maintain stable operation of electrical systems, and reduce negative environmental impacts [3–5].

For calibration and verification of electrical energy measuring instruments, standards of electric power and energy are used. Such standards provide high accuracy of measurements of both electric power and energy. They have a different structural structure, which ensures the reproduction of various practically used units of measurement of electric energy. The use of different units of measurement of energy is associated with both certain historical and regional and national features of their use. International comparisons of national standards of electric power and energy are carried out, which become the basis for calibration and measurement capabilities (CMCs) of laboratories of national metrological institutes (NMI) and designated institutes (DI) [6, 7].

2. Drawbacks

A considerable number of scientific works are devoted to the measurement of electric energy. The theoretical and more practical aspects related to the measurement of electric energy are discussed in [1]. The general causes of errors in electric energy meters are described in [2]. In [3] a detailed overview of devices for measuring power and energy is presented, the principle of operation of several devices is given, as well as their applications and advantage / disadvantages. In [4] measures are considered to ensure the accuracy of electric energy measurements. A model of an electric energy metering system based on data from smart sensors is proposed in [5]. Various metrological aspects of accurate electric energy measurements are discussed in [8].

The potential impact of harmonic disturbances on the accuracy of the electricity meter was assessed in [9–12], in particular the impact of harmonic distortions of the measured signal. However, the study of the features of precision measurements of electric energy, the use of units of electric energy, the construction of standards for reproducing these units, and the submission of CMCs to national laboratories remain an urgent issue.

3. Goal

The purpose of the article is to present the results of research into the features of precision measurements of electrical energy, the use of electrical energy units and the construction of standards for reproducing these units, and the calibration and measurement capabilities of national laboratories.

4. Main used units of measurement of electrical energy

When measuring electrical power and energy on alternating current (AC) at industrial frequency (from 40 Hz to 70 Hz), different types of electrical power or energy are determined: active, reactive, apparent, etc. [1].

In single-phase sinusoidal electric current circuits, active power (P) can be determined through voltage and current, using the expression:

$$P = U \cdot I \cdot \cos\varphi\,, \quad (1)$$

where U is voltage, I is current, φ is phase angle between voltage and current.

In the same circuits, reactive power (Q) can also be determined in terms of voltage and current using the expression:

$$Q = U \cdot I \cdot \sin\varphi\,, \quad (2)$$

Apparent power (S) is a quantity that is related to active and reactive power by the equation:

$$S = \sqrt{P^2 + Q^2}\,, \quad (3)$$

where with inductive load is $Q > 0$, and with capacitive is $Q < 0$.

In the same circuits, active electrical energy (W), which is the real energy consumed by the load to perform a certain work, is defined through these same parameters as:

$$W = U \cdot I \cdot t = P \cdot t\,, \quad (4)$$

where t is time interval.

Reactive energy is the energy used to create magnetic and electric fields in inductive and capacitive elements. This energy characterizes the energy that is not converted into useful work. It arises due to the presence of inductive or capacitive loads that create a phase shift between current and voltage. Unlike active energy, reactive energy does not perform useful work, but only oscillates between the source and the load.

Total energy is the sum of active and reactive energies, which shows the total amount of electrical energy in the system. It is the sum of the active (useful) and reactive (unuseful) components of energy and combines both work and energy returning to the source.

Electrical energy in the International System of Units (SI) is defined in joules (J). However, in practice, especially in household and industrial calculations, another non-system unit is more often used – kilowatt-hours (kWh). One joule is equal to the energy required to move one coulomb of charge through an electric potential of one volt. One kilowatt-hour is equal to 3.6 million joules.

To measure alternating current (AC) electric power and energy at power frequency, several units of measurement are used, each of which corresponds to certain types of power or energy (data from the Key Comparison Database (KCDB) of the International Bureau of Weights and Measures (BIPM)) [13]:

– Joule (1 J = 1 W s) is unit of measurement of electric energy;

– Watt (1 W = 1 J/s) is basic unit of measurement of active power;

– Var (var) – unit of measurement of reactive power;

– Volt-ampere (VA) is unit of measurement of apparent power;

– Watt-second (W·s) and Watt-hour (1·W·h = 1 W 3600 s = 3600 J) is units of measurement of active energy;

– Kilowatt-hour (1 kWh = 1000 Wh = 3.6 MJ) is unit of measurement of active energy;

– kvar-hour 1 (kvar·h = 1000 var·h) is a unit of measurement of reactive energy;

– volt-ampere-hour (VA·h) is a unit of measurement of total energy.

5. Features of standards for reproducing units of electrical energy

The main features of electrical energy measurement are the assessment of different types of electrical energy, the use of three-phase and single-phase systems and types of electricity meters, etc. In three-phase systems, energy measurement is more complicated, since each phase can have its own parameters. Therefore, three-phase meters are used that take into account all three phases separately. In single-phase systems, the measurement process is simpler, since only one phase needs to be measured.

The standard of an electrical energy unit must provide high accuracy of measurements over a long time. For this, stable energy sources, precision electronic components and controlled operating conditions are used. The standard generates reference voltage and current signals at industrial frequency (50 Hz or 60 Hz), which are fed to the electric power or energy meter. The voltage and current sources must be stable and accurate to prevent even minimal deviations from the specified parameters. Distortion of the harmonic shape of the generated signal can affect the accuracy of energy measurement. The phase shift between phase current and voltage directly affects the calculation of active and reactive energies.

Typically, the structural diagram of a high-precision electrical energy standard includes:

– precision AC voltage (*U*) and current (*I*) sources that generate reference voltages and currents that are supplied to the calibration object;

– precision electrical energy meter or measuring system with the lowest possible error;

– voltage and current converters that provide accurate current and voltage measurements;

– precision DC voltage meters;

– phase meter for measuring phase shifts between currents and voltages (for three-phase systems);

– control unit or computer system.

The control unit ensures the operation of the standard, collects and analyzes data from all system components. Almost all modern standards are automated and include: specialized software for controlling the operation of the standard and data collection; automatic adjustment of parameters such as voltage and current; storage and processing of measurement results for further analysis.

Fig. 1 shows the structural diagram of the electrical energy standard most common in national laboratories.

For high-precision standards of electric energy, their components of the measuring instruments are calibrated according to the following metrological characteristics:

– electric AC voltage (V);

– electric AC current (A);

– AC frequency (Hz);

– phase angle between currents and voltages (for three-phase systems).

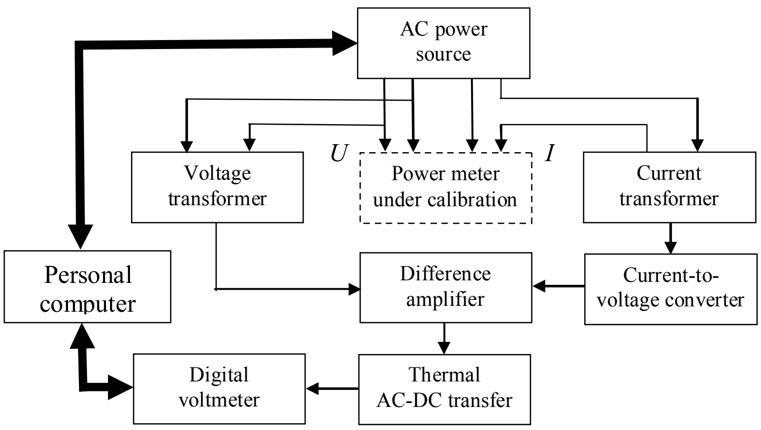

Fig. 1. The structural diagram of the electrical energy standard

National standards of electric energy must undergo periodic comparisons with national standards of other countries to ensure comparability of energy measurement results. Such international comparisons are not very numerous and not very frequent [13]. Among them, one can single out the comparison of the regional metrological organization GULFMET – GULFMET.EM-S5 on energy [14], which was organized and conducted by the State Enterprise "Ukrmetrteststandart" (UMTS), Kyiv, Ukraine, as a pilot laboratory.

6. Calibration and measurement capabilities of national laboratories

Under the on the Mutual Recognition Agreement of National Standards and Calibration and Measurement Capabilities (CIPM MRA) [15], only one national institute is designated as an NMI for each CIPM MRA country, while the others act as DIs.

To be recognized under the CIPM MRA for the publication of CMC records [7], NMIs (DIs) are required to participate in international standard comparisons [6], and the NMI laboratory (DI) must operate a quality management system [16]. The Guide to the Expression of Uncertainty in Measurement (GUM) [17] should be used to calculate measurement uncertainty for both standard comparisons and CMCs.

Analysis of the CMCs records for AC electricity for NMIs (PIs) in the KCDB showed the results shown in Table 1 and Fig. 2. 23 NMIs (DIs) (22 for active energy, 14 for reactive energy) have a total of 78 CMC records. UMTS has such CMC records and is presented in Table 1 and Fig. 2.

Table 1. CMC records on AC electricity for NMI (DI) in KCDB as of the end of 2024

NMI	Country	CMCs	Unit	Uncertainty			
				Active energy		Reactive energy	
				Value	Unit	Value	Unit
BEV	Austria	6	Ws, var s, VA s,	80	µWs (VAs)$^{-1}$	80	µvar s (VAs)$^{-1}$
CEM	Spain	6	Wh, VAh, var h	30	µWh (VAh)$^{-1}$	30	µvar h (VAh)$^{-1}$
INACAL	Peru	6	Wh	133	µWh (VAh)$^{-1}$		
Trescal	Denmark	6	Wh, J	25	µJ (VAs)$^{-1}$		
VNIIM	RF	5	Ws, var s	50	µWs (VAs)$^{-1}$	400	µvar s (VAs)$^{-1}$
INMETRO	Brazil	4	Wh, var h	25	µWh (VAh)$^{-1}$	25	µvar h (VAh)$^{-1}$
NIST	United States	4	J, var s	35	µJ (VAs)$^{-1}$	45	µvar s (VAs)$^{-1}$
UMTS	Ukraine	4	Ws, var s	85	µWh (VAh)$^{-1}$	140	µvar h (VAh)$^{-1}$
BIM	Bulgaria	4	W s, var s	16	µWs (VAs)$^{-1}$	16	µvar s (VAs)$^{-1}$
CMS	Chinese Taipei	3	Wh, var h	240	µWh (VAh)$^{-1}$	240	µvar h (VAh)$^{-1}$
EIM	Greece	3	Ws, Wh, var s, var h	70	µWs (VAs)$^{-1}$	70	µvar s (VAs)$^{-1}$
UME	Turkey	2	Ws, var s	200	µWh (VAh)$^{-1}$	200	µvar h (VAh)$^{-1}$
MIKES	Finland	2	Wh, var h	120	µWh (VAh)$^{-1}$	250	µvar h (VAh)$^{-1}$
RISE	Sweden	2	Wh, var h	80	µWh (VAh)$^{-1}$	80	µvar h (VAh)$^{-1}$
SMU	Slovakia	2	Ws, var s	80	µWh (VAh)$^{-1}$		
UDEC	Chile	2	Wh	120	µWh (VAh)$^{-1}$		
CENAM	Mexico	2	var s			20	µvar h (VAh)$^{-1}$
CENAMEP	Panama	2	Wh	95	µWh (VAh)$^{-1}$		
DMDM	Serbia	2	Ws	116	µWh (VAh)$^{-1}$		
SASO-NMCC	Saudi Arabia	2	Ws, var s	60	µWs (VAs)$^{-1}$	60	µvar s (var s)$^{-1}$
EMI	United Arab Emirates	2	Wh, var h	260	µWh (VAh)$^{-1}$	270	µvar h (VAh)$^{-1}$
BFKH	Hungary	2	Ws	200	µWh (VAh)$^{-1}$		
NMIM	Malaysia	1	Wh	700	µWh (Wh)$^{-1}$		
NMISA	South Africa	1	J	50	µWh (VAh)$^{-1}$		
JEMIC	Japan	1	J	32	µJ (VAs)$^{-1}$		
METAS	Switzerland	1	Ws	100	µWs (VAs)$^{-1}$		
VSL	Netherlands	1	Wh	50	µWh (VAh)$^{-1}$		
	Total	78					

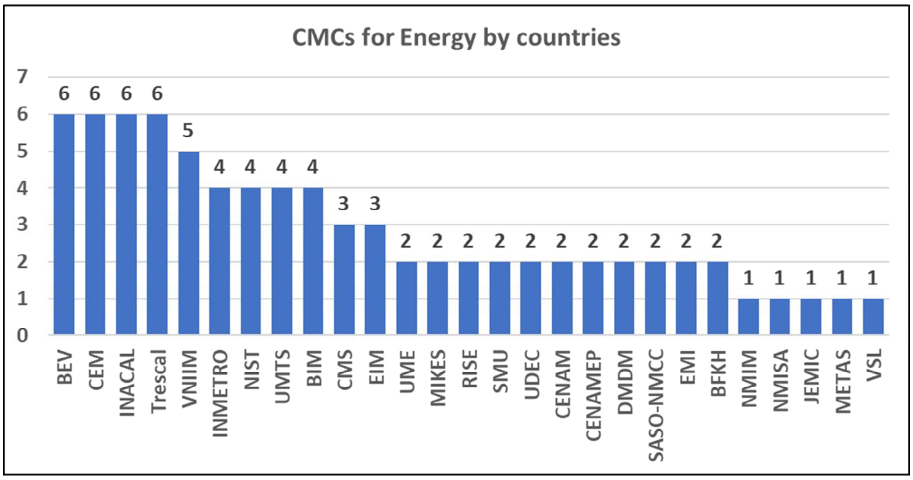

Fig. 2. CMC records for energy by country

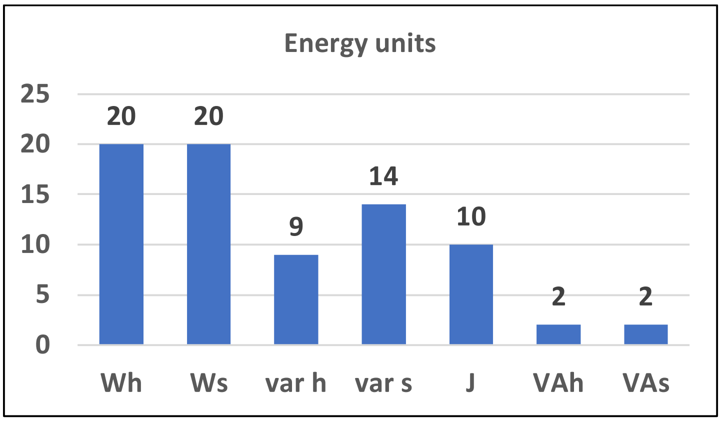

Fig. 3. CMC records for energy by units

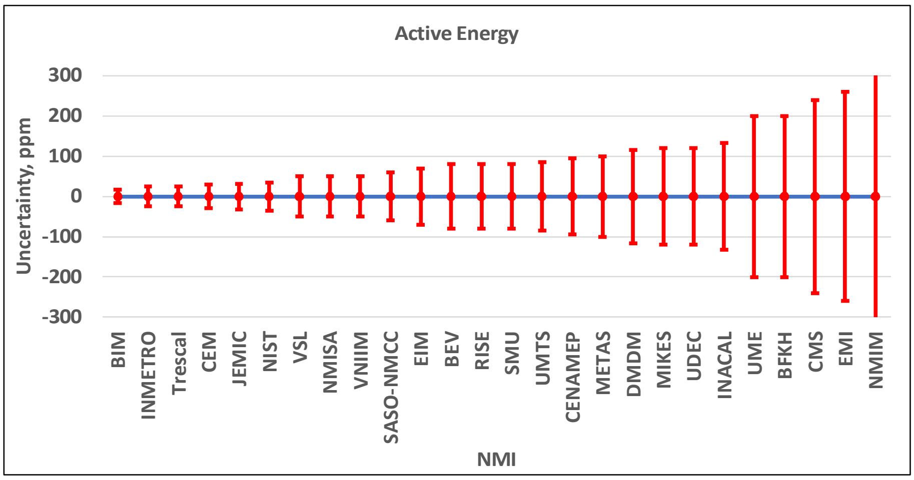

Fig. 4. Measurement uncertainty for active energy according to NMIs (DIs)

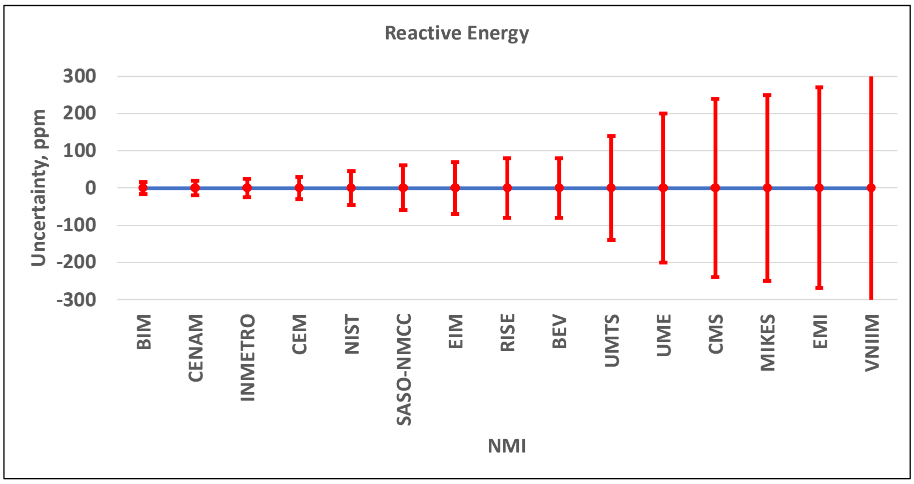

Fig. 5. Measurements uncertainty for reactive energy according to NMIs (DIs)

In CMC records for AC electric energy, the units of measurement shown in Fig. 3 are used. For active energy, the units of Watth and Watts are most often used (20 times each), and for reactive energy, varh (9) and vars (14) [13].

In CMC records of NMI (DI), the uncertainties of measurement of active and reactive AC electric energy are given, which are shown in Fig. 4 and 5, respectively. The measurement uncertainty in a wide range of energy values: for active energy it varies from 16 to 700 ppm, and for reactive energy – from 16 to 400 ppm [13]. It should be noted that UMTS has CMC records for both active and reactive energies.

7. Conclusions

When measuring active and reactive AC electrical energy at industrial frequency, different units of measurement are used. To perform such measurements, high-precision standards are used, which are built on the basis of a traditional structural scheme. Only a small number of NMI (DI) laboratories have published CMC records in the KCDB regarding the measurement of active and reactive electrical energy, including the Ukrainian DI – SE "Ukrmetrteststandard". These laboratories have measurement uncertainties within quite wide limits in a wide range of energy values: for active energy from 16 to 700 ppm; for reactive energy from 16 to 400 ppm.

Conflict of Interest

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

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