UDC 001.4:389.14:621.317

Features of the application of international quantum measurement standards for electrical units

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Abstract

International measurement standards reproduce the exact values of physical quantities and are used as a reference for calibrating other measuring instruments (MIs). These standards are maintained by international organizations, in particular the International Bureau of Weights and Measures (BIPM). In the modern International System of Units (SI), quantum measurement standards are of utmost importance for the implementation of its units and ensuring metrological traceability to them. Their main feature is that they are based on fundamental quantum effects, which are extremely stable, universal and reproducible anywhere in the world.

The main purpose of international quantum measurement standards is to establish a reference for global metrological traceability of measurements, which is based on comparisons of these standards with national measurement standards and precision calibrations of the latter. This process is facilitated by the implementation of the International Committee of Weights and Measures (CIPM) Agreement on the Mutual Recognition (MRA) of National Measurement Standards, Calibration Certificates and Measurements Issued by National Metrological Institutes.

The international quantum measurement standards of the Volt and Ohm are maintained by the BIPM. They are of paramount importance for the implementation of the SI units of electrical quantities and for ensuring global metrological traceability. The comparison of these standards plays a key role in the implementation of the CIPM MRA. Only a few NMIs maintain national measurement standards based on the quantum Josephson and Hall effects, which partake in special BIPM key comparisons. The smallest measurement uncertainty of 0.2 nV has been achieved during the comparison of Josephson standards. The smallest relative measurement uncertainty from 3.8×10^{-9} to 4.6×10^{-9} has been achieved during the comparison of Hall standards.

Keywords: quantum standard; electrical quantity; calibration; comparison; measurement uncertainty.

Received: 19.06.2025 Edited: 15.07.2025 Approved for publication: 21.07.2025

Introduction

International measurement standards are measuring instruments (MIs) that reproduce the exact values of physical quantities and are used as a reference for calibrating other MIs. An international measurement standard is recognized by signatories to an international agreement and is intended for the use worldwide as defined in the International Vocabulary of Metrology (VIM) [1]. These standards are maintained by international organizations, in particular the International Bureau of Weights and Measures (BIPM). In the modern International System of Units (SI) [2], quantum measurement standards are key to implementing its units and ensuring metrological traceability to them. Their main feature is that they are based on fundamental quantum effects that are extremely stable, universal, and reproducible anywhere in the world.

The main advantages of a quantum measurement standard are: high accuracy, which is determined by fundamental constants; high reproducibility; replacement of old analogue measurement standards; reproduction of a unit without any centralized reference measurement standard. The main purpose of international quantum measurement standards is to establish a reference for global metrological traceability of measurement results, which is based on the comparison of these standards with national measurement standards and precision calibrations of the latter. This process is facilitated by the implementation of the International Committee of Weights and Measures (CIPM) Agreement on the Mutual Recognition (MRA) of National Measurement Standards, Calibration Certificates and Measurements Issued by National Metrological Institutes [3]. As of mid-2025, about 260 national Metrology and Designated Institutes (hereinafter referred to as NMIs and Dis respectively) and four international organizations participate in the CIPM MRA.

1. Main international quantum measurement standards of electrical units

The most precise international measurement standards for electrical units are the quantum standards for the voltage unit based on the Josephson effect (hereinafter referred to as the Josephson standard) and the electrical resistance unit based on the Hall effect (hereinafter referred to as the Hall standard). They allow obtaining electrical units based on two fundamental physical constants: the elementary charge and the Planck constant. With the revision of the SI system in 2018, the numerical values of both constants became fixed.

In the SI system, the ampere (A) is a unit of electric current, which since 2019 has been defined in terms of the elementary electric charge: $e = 1.602176634\times10^{-19}$ C [2].

The main quantum measurement standards for electrical quantities are:

- Josephson standard, which is defined by the expression

$$V = \frac{nhf}{2e},$$

where V is the voltage at the junction, n is an integer (number of “steps”), h is Planck’s constant, f is the frequency of the applied signal (in hertz), e is the elementary charge of the electron;

- Hall standard, which is defined by the expression

$$R_H = \frac{h}{i2e^2},$$

where R_H is the quantum resistance; i is an integer (quantization index, often i = 1, 2, 3, ...).

The Josephson effect occurs in a superconducting tunnel junction (so-called Josephson junction) – these are two superconductors separated by a very thin layer of insulator. When electromagnetic radiation of a certain frequency is applied, a precisely defined voltage arises in this transition, which is directly related to the used frequency.

The sequence of implementing a unit of constant voltage with a Josephson standard is as follows: preparation of a Josephson junction, which becomes a superconductor when cooled; cooling it to a few kelvins (liquid helium or substitutes); application of microwave radiation at a known frequency, for example 70 GHz; measuring the voltage – quantized voltage “steps” (Josephson steps) with an accuracy of 1 part per billion. In large laboratories, arrays of thousands of junctions are used to create a constant voltage of up to 10 V.

When a very thin layer of a semiconductor as a two-dimensional electronic system is placed in a strong magnetic field at low temperature, a special quantum state arises – the quantum Hall effect. In this state, the longitudinal resistance disappears, and the transverse (Hall) resistance acquires discrete (step) values, which are determined exclusively by fundamental constants. The numerical value for i = 1 $R_{\mathrm{H}} \approx 25812.807$ Ohm, which is used as a reference resistance in metrology.

The sequence of implementation of the unit of electrical resistance by the Hall standard is as follows: a semiconductor structure (for example, GaAs/AlGaAs) with a two-dimensional electron gas is used; it is cooled to temperatures below 1.5 K; a strong magnetic field (~10 Tesla) is applied; the Hall resistance is measured, which acquires fixed values according to expression (2).

The issue of development and use of Josephson standards for many years, including classical DC standards, is considered in [7, 8]. Matrices of the same name form the basis of Josephson standards. Programmable Josephson standards at the PTB (Germany) allow calibration of other standards at DC and AC voltage, with measurement uncertainties at the level of 10^{-10} [9]. The PTB Josephson standard allows comparisons with other similar measurement standards in the range up to 10 V with an absolute measurement uncertainty of 1 nV [4].

The progress made by many national laboratories in evaluating and comparing the quality and limitations of Hall standards is reviewed in [10]. Potentiometric and cryogenic bridge current comparator methods for measuring R_H are compared using conventional resistance measurement standards with a relative measurement uncertainty of 2.4×10^{-8}. The traditional Hall standard in the Van der Pauw configuration is reviewed in [11]. The research focuses on the problems arising from the small Hall signal, procedures for limiting the effects of temperature fluctuations, and other potential sources of measurement uncertainty.

2. Use of the BIPM international quantum measurement standards for electrical units

The BIPM uses both types of quantum measurement standards as the reference for its calibration services in the field of electromagnetics (EM). These are the basis for the published BIPM Calibration and Measurement Capabilities (CMCs) [4] in this field. The BIPM electrical laboratories provide services to NMIs for the comparison of their measurement standards with the corresponding BIPM international measurement standards. These BIPM services underpin the CIPM MRA, providing traceability to the SI for many smaller NMIs and allowing larger NMIs to demonstrate the equivalence of their own primary measurement standards and to maintain their CMCs.

To compare primary electrical quantum measurement standards with the lowest possible uncertainty, the BIPM has developed special mobile quantum measurement standards. These are sent to participating NMIs and are accompanied by the BIPM staff for the comparison. These comparisons can also be the basis for knowledge transfer by experienced BIPM scientists. When using the calibration services provided by the standards at the BIPM NMI, it is recommended to limit the calibration frequency of reference resistors and electronic voltage measurement standards (Zener diodes) to one calibration every two years for one type of standard and no more than three standards with the same nominal value.

Since 1991, the BIPM has been conducting regular BIPM.EM-K10 comparisons of Josephson standards for nominal values of 1.018 V and 10 V. Fig. 1 and 2 show the results of the BIPM.EM-K10 comparisons for nominal values of 1.018 V – 25 NMI: PTB, DFM (Denmark), NPL (Great Britain), VSL (Netherlands), SP (Sweden) – 2 results each and 10 V – 29 NMI: NIST (USA) and INMETRO (Brazil) – 2 results each, respectively [4].

The BIPM.EM-K10 comparisons for the nominal value of 1.018 V are linked only to the results of the corresponding comparisons of the Regional Metrological Organization (RMO) EURAMET. In the BIPM.EM-K10 comparisons for this nominal value, the smallest measurement uncertainty is that of NIM (China) – 0.2 nV, BNM-LCIE (France) and NMIA (Australia) – 0.3 nV each, and 6 more NMIs – 0.4 nV each. In the EURAMET.EM.BIPM-K10a comparisons, MIKES (Finland) has 0.4 nV.

The BIPM.EM-K10 comparisons for the nominal value of 10 V are linked to the results of the corresponding RMO SIM and COOMET comparisons. In the BIPM.EM-K10 comparisons for this nominal value, the smallest measurement uncertainty is that of LNE (France) – 0.2 nV, PTB – 1.0 nV and CENAM (Mexico) – 1.3 nV.

The National Scientific Centre (NSC) “Institute of Metrology” (Kharkiv) maintains a Josephson standard, which did not participate in the specified comparisons, but was calibrated in the BIPM laboratory for nominal values of 1.018 V and 10 V. As of mid-2025, the procedure for the inter-regional review of the CMCs based on the calibration results of the standard has not yet been completed.

Since 1993, the BIPM has been conducting regular BIPM.EM-K12 comparisons of Hall standards for a nominal resistance of 100 Ohm and resistance ratios of 10 kOhm/100 Ohm and 100 Ohm/1 Ohm. Fig. 3–5 shows the results of the BIPM.EM-K12 comparisons for the given nominal values and resistance ratios, respectively [4].

Only 11 NMIs participated in the comparisons of Hall standards for the nominal resistance of 100 Ohm and the resistance ratio of 10 kOhm/100 Ohm, and 9 NMIs for the resistance ratio of 100 Ohm/1 Ohm.

In the BIPM.EM-K12 comparisons: for the nominal resistance of 100 Ohm, the smallest relative measurement uncertainty is that of NIST – 4.0×10^{-9} and PTB – 4.4×10^{-9}; for the resistance ratio of 10 kOhm/100 Ohm – NIM (China) and KRISS (Republic of Korea) – 4.6×10^{-9}; for the resistance ratio of 100 Ohm/1 Ohm – PTB and METAS (Switzerland) – 3.8×10^{-9} and NRC (Canada) – 4.2×10^{-9}.

The NSC “Institute of Metrology” maintains a Hall standard, which did not participate in the specified comparisons, but was calibrated in the BIPM laboratory for nominal values of 1 Ohm, 100 Ohm and 10 kOhm. As of mid-2025, the procedure for inter-regional review of the CMCs based on the results of the calibration of the standard has not yet been completed.

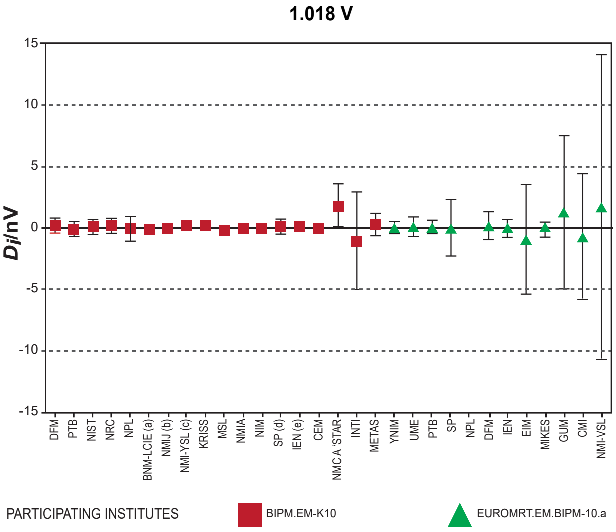

Fig. 1. Results of BIPM.EM-K10 comparisons for the nominal value of 1.018 V

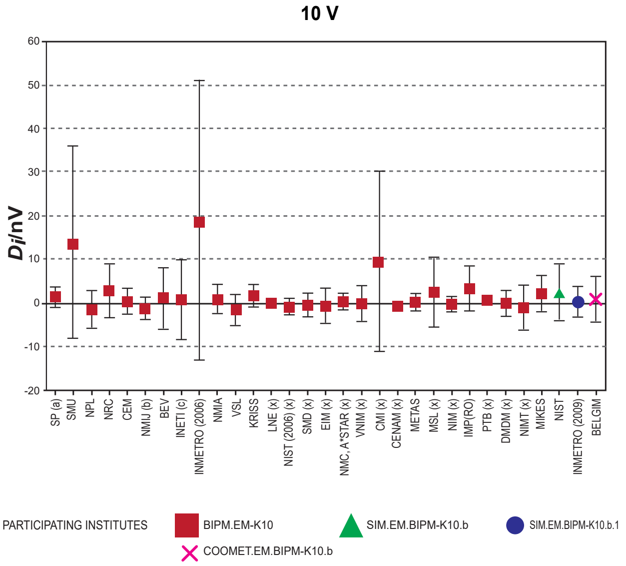

Fig. 2. Results of BIPM.EM-K10 comparisons for the nominal value of 10 V

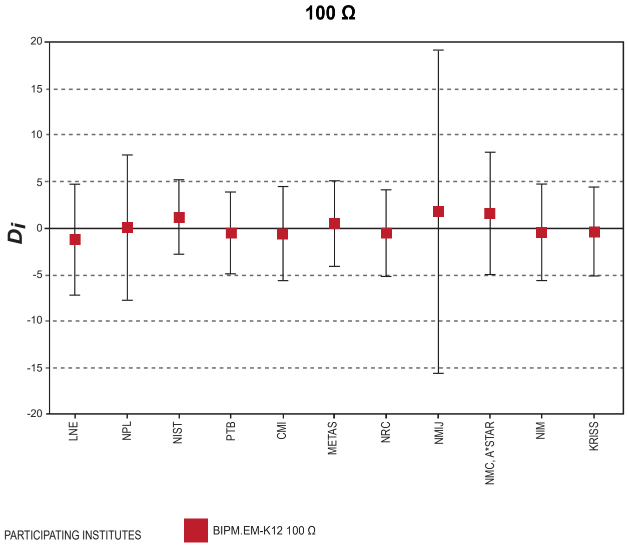

Fig. 3. Results of BIPM.EM-K12 comparisons for a nominal value of 100 Ohm

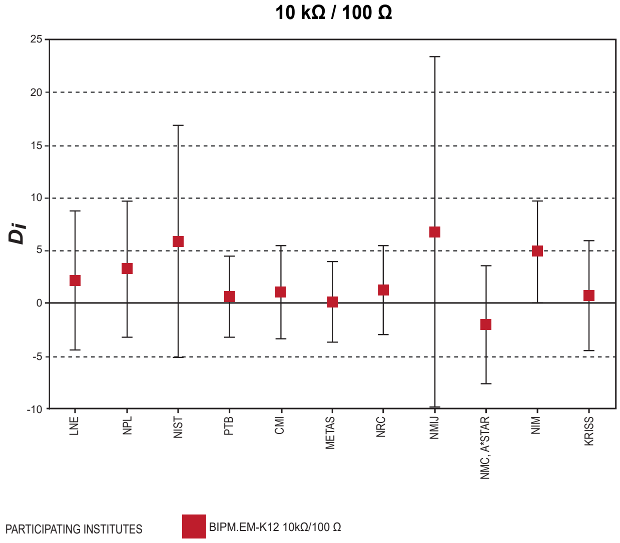

Fig. 4. Results of BIPM.EM-K12 comparisons for the resistance ratio 10 kOhm/100 Ohm

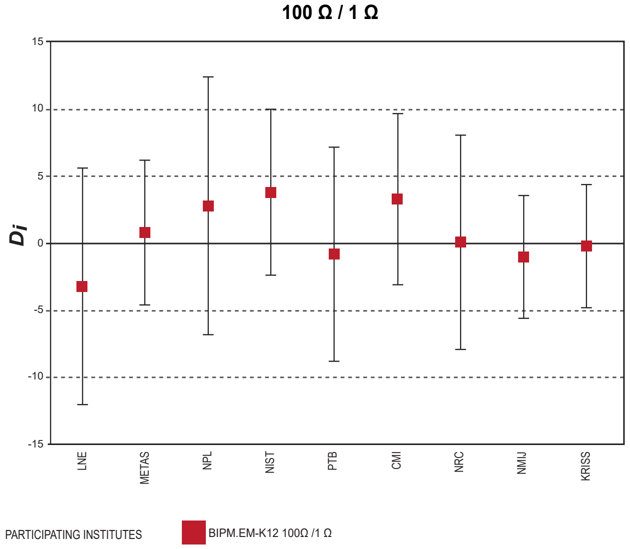

Fig. 5. Results of BIPM.EM-K12 comparisons for the resistance ratio 100 Ohm/1 Ohm

Conclusions

The international quantum measurement standards of the Volt and Ohm are maintained by the BIPM. They are of utmost importance for the implementation of the SI units of electrical quantities and for ensuring global metrological traceability. The comparisons of these standards play a key role in the implementation of the CIPM MRA. Only a few NMIs maintain national measurement standards based on the quantum Josephson and Hall effects, which are accounted in special key BIPM comparisons. The Josephson standards have achieved the lowest measurement uncertainty of 0.2 nV for nominal voltages of 1.018 V and 10 V. The Hall standards have achieved the lowest relative measurement uncertainty of 3.8×10^{-9} to 4.6×10^{-9} for a nominal resistance of 100 Ohm and resistance ratios of 10 kOhm /100 Ohm and 100 Ohm /1 Ohm.

Особливості застосування міжнародних квантових еталонів одиниць електричних величин

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Анотація

Міжнародні еталони відтворюють точні значення фізичних величин і використовуються як основа для калібрування інших засобів вимірювальної техніки. Ці еталони підтримуються міжнародними організаціями, зокрема Міжнародним бюро з мір та ваг (BIPM, International Bureau of Weights and Measures). У сучасній Міжнародній системі одиниць (SI) квантові еталони мають ключове значення для реалізації її одиниць та забезпечення метрологічної простежуваності до них. Основною їхньою особливістю є те, що вони базуються на фундаментальних квантових ефектах, які надзвичайно стабільні, універсальні та відтворювані в будь-якій точці світу.

Основним призначенням міжнародних квантових еталонів є створення основи для глобальної метрологічної простежуваності вимірювань, яка базується на звіреннях цих еталонів з національними еталонами й прецизійному калібруванні останніх. Цьому сприяє реалізація Угоди Міжнародного комітету з мір та ваг (CIPM, International Committee of Weights and Measures) щодо взаємного визнання національних еталонів вимірювань, сертифікатів калібрування та вимірювань, виданих національними метрологічними інститутами (MRA, Mutual Recognition Agreement).

Міжнародні квантові еталони одиниць Вольта та Ома підтримуються BIPM. Вони мають ключове значення для реалізації одиниць електричних величин SI та забезпечення глобальної метрологічної простежуваності. Звірення цих еталонів мають ключову роль у реалізації Угоди CIPM MRA. Лише невелика кількість НМІ зберігають національні еталони на основі квантових ефектів Джозефсона і Холла, які беруть у спеціальних ключових звіреннях BIPM. При звіреннях еталонів Джозефсона досягнуто найменшої невизначеності вимірювань у 0.2 нВ. При звіреннях еталонів Холла досягнуто найменшої відносної невизначеності вимірювань від 3.8×10^{-9} до 4.6×10^{-9}.

Ключові слова: квантовий еталон; електрична величина; калібрування; звірення; невизначеність вимірювань.

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