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SI-2019 and prospects for improving the accuracy of electrical measurements

Yu. Pavlenko[1], O. Kolbasin[1,2], O. Vasileva[1]

[1] *National Scientific Centre "Institute of Metrology", Myronosytska Str., 42, 61002, Kharkiv, Ukraine*
iurii.pavlenko@metrology.kharkov.ua
[2] *State Enterprise "Kharkiv Regional Research and Production Center for Standardization, Metrology and Certification", Myronosytska Str., 36, 61002, Kharkiv, Ukraine*

Abstract

Increasing requirements for the accuracy of measurements have led to the need to revise the existing International System of Units (SI). The important element of the SI-2019 reform is "the establishment of the SI base units through seven defining constants, the numerical values of which are fixed".

The approach to the establishment of the measurement units has fundamentally changed. If earlier a definition was given of how the unit is realized, now only the exact numerical values of the fundamental constants are fixed, and their values are expressed in the corresponding SI units. Measurement units are determined on the basis of known physical laws, which include certain fundamental constants.

The article analyzes the changes in SI-2019 related to electrical measurements, and also discusses the prospects for the development of accurate electrical measurements.

Keywords: measurement; measurement units; International System; Josephson effect; quantum Hall effect; single-electron transistor.

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1. Introduction

Increasing requirements for the accuracy of measurements have led to the need to revise the existing International System of Units (SI). The important element of the SI-2019 reform is "the establishment of the SI base units through seven defining constants, the numerical values of which are fixed" [1–3].

The approach to the establishment of the measurement units has fundamentally changed. If earlier a definition was given of how the unit is realized, now only the exact numerical values of the fundamental constants are fixed, and their values are expressed in the corresponding SI units. Measurement units are determined on the basis of known physical laws, which include certain fundamental constants.

At the same time, in the new SI-2019 the division of measurement units into base units and derived ones remained.

The article analyzes the changes in SI-2019 related to electrical measurements, and also discusses the prospects for the development of accurate electrical measurements.

2. Statement of the main material

The SI base unit of electric current – ampere – is set through a fixed value of the elementary charge, equal to e = 1.602176634×10^{-19} C (coulomb).

Since 1990, the reproduction of voltage and resistance units has been based on quantum standards using the Josephson effect and the quantum Hall effect, as well as the conventional value of the Josephson constant $K_{J\text{-}90}$ and the von Klitzing constant $R_{K\text{-}90}$ [3]. This made it possible to increase the accuracy of reproduction of electrical units by approximately two orders of magnitude (at direct current), but contributed to the emergence of an independent, "practical" system of units, which does not coincide with the SI and in which the "practical" kilogram differs from the standard by 10^{-7}, and the "practical" magnetic constant μ_0 is not a fixed number.

The simultaneous redefinition of kilogram and ampere, adopted in SI-2019, made it possible to abandon the agreed values and make sure that the methods used for the practical realization of electrical units fully comply with the definition of SI units.

In the revised SI, the ampere remains the base electrical unit, but it is no longer necessary to set the values of the constants K_J and R_K, since in SI-2019 the Josephson constant K_J and the von Klitzing constant R_K are calculated using fixed numerical values of the exact numerical values e and h using the ratio $K_J = 2e/h$ and $R_K = h/e^2$, which appear in the equations describing the corresponding physical phenomena.

Also note that the electric and magnetic constants, ε_0 and μ_0, will have approximately the same values after redefinition but now with relative uncertainties the same as that of the fine structure constant, $\sim 2.3\times10^{-10}$.

Although SI-2019 does not regulate specific methods for the realization of units, practical recommendations (*Mise en Pratique*) [4] in SI-2019 provide methods that can be used in practice for the realization of SI ampere, volt, ohm and other of SI derived electrical units with the indicated names and symbols, and also indicate the quantum effects of Josephson, Hall, nuclear magnetic resonance and their varieties, as the best primary methods at the moment. They also give the values to the Josephson constant and the von Klitzing constant, which are calculated from the fixed numerical values of the Planck constant h and the elementary charge *e*:

$$K_\mathrm{J} = 483597.848416984\ \mathrm{GHz\ V^{-1}},$$
$$R_\mathrm{K} = 25812.8074593045\ \Omega,$$

and differ from $K_{\mathrm{J}\text{-}90}$ and $R_{\mathrm{K}\text{-}90}$. As a consequence, in the revised SI, the values associated with electrical voltage decreased by 1.067×10^{-7}. The values associated with electrical resistance are increased by 1.779×10^{-8} [5].

The need to take into account the magnitude of changes (δ) depends on the relative expanded uncertainty U of specific measurements. In [5] it is proposed not to introduce a correction if $2.5\delta \leqslant U$ or $\delta \leqslant 0.4\ U$.

Another approach is possible, in which the uncertainty component can be neglected if its contribution to the total uncertainty does not exceed 5%. This condition leads to the relation $\delta \leqslant 0.313\ U$.

Thus, the correction can be omitted if:

- voltage-related quantities are measured with a relative expanded uncertainty of more than 2.5×10^{-7} according to [5] or 3.34×10^{-7} according to the second approach;
- the quantities related to resistance and impedance are measured with a relative expanded uncertainty of more than 5×10^{-8} according to [5] or 5.57×10^{-8} according to the second approach.

The values K_J and R_K are given with 15 significant digits. It should be noted that this number of significant digits is the maximum allowable for the widespread Microsoft Excel spreadsheet. However, if you ever need additional precision, you just need to go back to the definitions of K_J and R_K and substitute in them the exact numerical values of *e* and *h*. The obtained values, of course, depend on the assumption about the accuracy of the equations obtained in physics $K_\mathrm{J} = 2e/h$ and $R_\mathrm{K} = h/e^2$.

Josephson voltage standards reproduce voltage according to $U = h\,n\,f/2e$, where n is the number of Josephson junctions used in the measurement and f is the microwave frequency applied to the system.

In quantum Hall resistance standards the resistance R is determined in terms of $R = h/ke^2$, where k is an integer number related to the quantization.

Existing standards provide high accuracy of the realisation of the volt and the ohm, which is proven by comparisons of standards of different countries. For example, the Josephson voltage standard can produce a 10 V voltage within an uncertainty below 1×10^{-9}, and the international comparison of the quantum Hall resistance standards is within a few parts in 10^9.

With quantum voltage and resistance standards, a quantum current and hence the ampere can be obtained by Ohm's law, i.e. $I = U/R = n\,k\,f\,e/2$.

In new SI one ampere can be defined as a number of 1 C/e = 6 241 509 074 460 762 607.776 elementary charges going through a given point in one second.

The counting device, so-called single-electron transistor (SET), allows a single elementary charge *e*, or multiple charges, *Ne*, to go through a potential gate and trigger a counting signal in a fast and controlled speed. By measuring the frequency of the transfer of a fixed number N of elementary charges per event, f, the ampere can be directly realized by counting *e* as $I = N\,e\,f$. Unfortunately, the currents obtained in this case are small, of the order of 100 pA.

According to recommendation *Mise en Pratique* practical realization of the ampere, A: a) The ampere can be realized by using Ohm's law, the unit relation A = V/Ω, or b) by using a single electron transport (SET) or similar device, the unit relation A = C/s; or c) by using the relation $I = CdU/dt$, the unit relation $A = F{\cdot}V/s$, where F is the farad.

The three quantum effects: the Josephson effect, the quantum Hall effect, and the single electron transistor, give a closed triangle of the volt, ohm and ampere realizations (Fig 1).

The practical usefulness of quantum effects and the expansion of their scope after the SI reform has

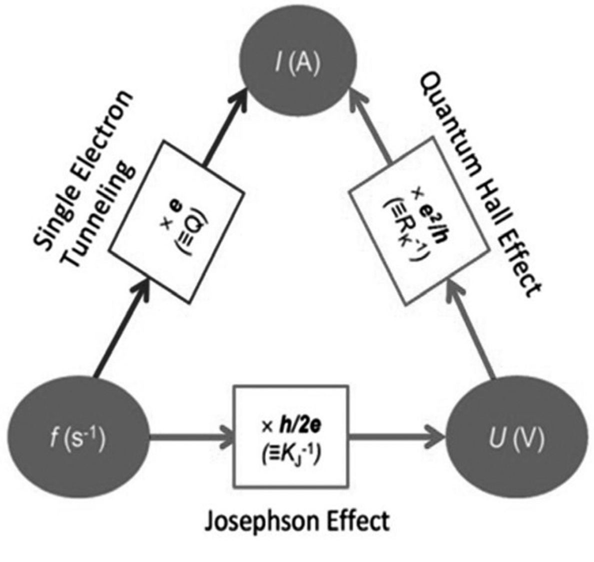

Fig. 1. Illustration of the metrological triangle [6]

become an incentive for the further development and improvement of quantum methods and technologies for their implementation. So, in a relatively short time after the adoption of the CIPM recommendations on the use of quantum effects, tremendous progress was made in this direction: methods for measuring electrical quantities in alternating current using the Josephson effect were developed.

As is well known, in the transition to an alternating current the measurement uncertainty of electrical quantities sharply increases, therefore, an important task is to create an AC voltage standard with using the Josephson effect. Intensive work is underway in this direction [7, 8]. The industry is producing the AC-DC Quantum Voltmeter, which contains the AC-DC Josephson voltage standard. The frequency range of such voltmeter is up to 2 kHz. Typical calibration accuracy $\Delta V/V = 2\times10^{-8}$.

When measuring the AC circuit parameters are characterized by impedance, which can be regarded as a combination of the simplest elements: resistor, capacitor and inductor. The characteristics of the last two elements can only be measured on alternating current.

The capacitance can be calibrated by multiple paths: 1) Conventional calculable capacitor, 2) DC quantum Hall resistance, then AC/DC difference measurement, and finally $R - C$ quadrature bridge, and 3) quantum capacitor. A significant advantage, compared to the original calibration through the calculable capacitor and capacitance bridge, is that the new paths 2) and 3) allow a wider and more flexible calibration range for the capacitor, thereby, shorten the length of the traceability chain. For example, path 2) is typically designed for nF capacitance calibration and μF can be reached if a 100 Ω standard resistor is employed. This may lead to significant applications in power and energy measurement areas.

In the case of path 2), it is possible to increase the accuracy in the case of using the AC quantum Hall standard.

Another factor in increasing the influence of quantum technologies was the stimulation of research towards their greater availability in practical metrology. Helium-free (so-called “dry”) methods of obtaining a cryogenic medium, high-temperature superconductivity technologies (at the temperature of liquid nitrogen), and graphene quantum structures were developed. This made it possible to create a number of new generation of measuring quantum devices.

So, the Hall resistance in graphene is quantized with an uncertainty of up to 1×10^{-9} in relatively weak magnetic fields (with induction up to 3.5 T) at temperatures up to 10 K and at currents up to 0.5 mA, while the samples on GaAs usually operate at currents of tens of microamperes at temperatures up to 2 K and magnetic induction of about (6–8) T. This indicates the enormous potential of graphene for the development of convenient and universal quantum standards, allowing their wider use in industry and science [9, 10].

Finally, quantum methods and effects, their active development have made it possible to solve a number of metrological problems in other types of measurements, for example, the creation of a natural standard of the kilogram based on the Planck constant and quantum electrical measurements (the so-called electric kilogram).

3. Conclusion

The new SI definitions, which came into effect on May 20th 2019, have the electrical base unit ampere and the derived units volt and ohm, now fixed by declared universal constants and therefore inherently stable. The electrical units themselves have now assumed new importance in that they will be used in at least one method to derive the first non artefact kilogram in 130 years.

The BIPM took a deliberate decision to minimize the effects of the redefinitions and for the most part they will succeed. There may be an impact on high end calibration equipment manufacturers.

SI-2019 і перспективи підвищення точності електричних вимірювань

Ю.Ф. Павленко[1], О.І. Колбасін[1,2], О.М. Васильєва[1]

[1] Національний науковий центр “Інститут метрології”, вул. Мироносицька, 42, 61002, Харків, Україна
iurii.pavlenko@metrology.kharkov.ua
[2] Державне підприємство "Харківський регіональний науково-виробничий центр стандартизації, метрології та сертифікації", вул. Мироносицька, 36, 61002, Харків, Україна

Анотація

Зростання вимог до точності та достовірності вимірювань призвело до необхідності переглянути існуючу Міжнародну систему одиниць (SI). Важливим елементом реформи SI-2019 є “встановлення основних одиниць SI через сім визначальних констант, числові значення яких фіксовані”.

Підхід до встановлення одиниць величин докорінно змінився. У SI-2019 одиниці визначаються в неявному вигляді шляхом фіксації точних числових значень основних констант. Одиниці величин реалізуються на основі фізичних законів, які включають до себе ці основні константи.

У галузі електричних вимірювань значного збільшення точності відтворення електричної напруги та електричного опору вдалося досягнути після відкриття у XX сторіччі квантових ефектів Джозефсона та Холла, але при цьому відбувся розрив між методиками реалізації електричних одиниць і теоретичним визначенням основної електричної одиниці SI – ампера через механічні величини.

Наразі в новій системі SI-2019 цей розрив ліквідовано – всі електричні одиниці визначаються через фундаментальні сталі. Показано, що реалізація ампера в принципі можлива із застосуванням квантового ефекту одноелектронного тунелювання, але поки не набула широкого впровадження через малі значення відтворюваного електричного струму.

У статті аналізуються зміни в SI-2019, пов’язані з електричними вимірюваннями, а також обговорюються перспективи розвитку точних електричних вимірювань.

Значні зусилля в науковій сфері докладаються для доказів сумісності одиниць вольта, ома та ампера, які реалізуються квантовими еталонами, шляхом перевірки замикання так званого метрологічного трикутника.

Науковий та технологічний прогрес у реалізації квантових ефектів дозволяє розповсюдити переваги квантових еталонів на сферу вимірювань на змінному струмі. Також спостерігається значний прогрес у підвищенні робочих температур вище 10–70 K при реалізації квантових ефектів завдяки застосуванню нових матеріалів, таких як графен тощо.

Ключові слова: вимірювання; одиниці величин; Міжнародна система; ефект Джозефсона; квантовий ефект Холла; одноелектронний транзистор.

SI-2019 и перспективы повышения точности электрических измерений

Ю.Ф. Павленко[1], А.И. Колбасин[1,2], Е.М. Васильева[1]

[1] *Национальный научный центр “Институт метрологии”, ул. Мироносицкая, 42, 61002, Харьков, Украина*
iurii.pavlenko@metrology.kharkov.ua
[2] *Государственное предприятие “Харьковский региональный научно-производственный центр стандартизации, метрологии и сертификации”, ул. Мироносицкая, 36, 61002, Харьков, Украина*

Аннотация

Возрастающие требования к точности измерений привели к необходимости пересмотра существующей Международной системы единиц (SI). Важным элементом реформы SI-2019 является “установление основных единиц SI посредством семи определяющих констант, числовые значения которых являются фиксированными”.

Коренным образом изменился подход к установлению единиц величин. Если раньше было дано определение того, как реализована единица измерения, то теперь фиксируются только точные числовые значения фундаментальных констант, а их значения выражаются в соответствующих единицах SI. Единицы величин определяются на основе известных физических законов, которые включают в себя определенные фундаментальные константы.

В статье анализируются изменения в SI-2019, связанные с электрическими измерениями, а также обсуждаются перспективы развития точных электрических измерений.

Ключевые слова: измерение; единицы величин; Международная система; эффект Джозефсона; квантовый эффект Холла; одноэлектронный транзистор.

References

1. On the Revision of the International System of Units (SI). Resolution 1 (CGPM 26th Meeting, Versailles, November 13–16, 2018). *Measurement Techniques*, 2019, vol. 62, pp. 472–473. doi: https://doi.org/10.1007/s11018-019-01648-4
2. SI Brochure: The International System of Units (SI). 9th edition, 2019. Available at: https://www.bipm.org/en/publications/si-brochure/
3. Comité Consultatif d'Électricité: Rapport de la 18e session. Édité par le BIPM, Pavillon de Breteuil, F-92312 Sèvres Cedex, France, 1988, pp. E65–E66.
4. Consultative Committee for Electricity and Magnetism, Mise en pratique for the definition of the ampere and other electric units in the SI. SI Brochure, 2019. Appendix 2. Available at: https://www.bipm.org/utils/en/pdf/si-mep/SI-App2-ampere.pdf
5. CCEM Guidelines for Implementation of the ‘Revised SI’. Consultative Committee for Electricity and Magnetism, 2017. Available at: https://www.bipm.org/documents/20126/2070959/CCEM+Guidelines+for+Implementation+of+the+Revised+SI.pdf/1d4ad52d-5fca-6c15-dc4d-7b0a74e3816e
6. Likharev K.K., Zorin A.B. Theory of the Bloch-wave oscillations in small Josephson junctions. *Journal of Low Temperature Physics*, 1985, vol. 59, pp. 347–382.
7. Ernst O. Goebel, Uwe Siegner. The New International System of Units (SI). Quantum Metrology and Quantum Standards. WILEY-VCH, 2019. doi:10.1002/9783527814480
8. Stock M., Davis R., de Mirandés E., Milton M.J.T. The revision of the SI – the result of three decades of progress in metrology. *Metrologia*, 2019, vol. 56, no. 2, pp. 1–14. doi: https://doi.org/10.1088/1681-7575/ab0013
9. Semenchinskiy S.G. Kvantovyy effekt Kholla i postoyannaya Klittsinga [Quantum Hall effect and von Klitzing constant]. *Izmeritelnaya tekhnika*, 2021, no. 1, pp. 9–13 (in Russian). doi: https://doi.org/10.32446/0368-1025it.2021-1-9-13
10. Semenchinskiy S.G. Ob elektricheskikh edinitsakh SI [About the electrical units of the SI]. *Zakonodatelnaya i prikladnaya metrologiya*, 2019, no. 2(159), pp. 7–9 (in Russian).