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Abstract: The reference measure of electrical resistance as collaborating element can be embedded in appropriate component of Cyber-Physical System. Whereas this measure made on the basis of inverse of conductance quantum is installed in such System, the latter could reach exclusive precision and provide high quality products manufacturing. The article considers the problems with transferring the measure’s value to measuring instruments and validation of gauged resistances. Copyright © 2015 IFSA Publishing, S. L.

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1. Introduction

CPS (further Cyber-Physical System) technologies companies have to utilize the sophisticated metrology equipment for production lines. This involves the estimation of the comparability of CPS component measurement instrument by verification. Development of portable, highly-precise devices is able to provide in-place precision measurements. Chip-scale devices could be directly integrated into equipment to provide continuous quality control and assurance, freeing manufacturers and customers from complex measurement traceability chains and lengthy calibration procedures [1].

A new emerging aim has emerged — metrological assurance embracing the adjustment of necessary measurement precision by means of checked measurement instruments and obtaining the required metrological traceability.

For metrological calibration of measuring instruments usually one applies the direct measurement by the verified measuring instrument of outgoing signal of multivalued measure with determination of the error as a difference of its readout and the mentioned signal. Correction methods of systematic error constituent are realized by operator impact or automatically in offline mode when, for example, self-calibration is carried out [2].

2. Shortcomings

Unique and newly created CPSs often require checking and verification of metrology facilities to ensure their quality work. The existing measures lose
their values (accuracy characteristics) by several orders while transferring them to the end user and that is actually considered a normal metrological practice. However, such practice cannot be deemed adequate for development of CPSs.

3. Goal of the Work

Goal of the work is to provide maintenance at operation stage of Cyber-Physical System by applying the measuring instrument with embedded electrical resistance measure of a new generation, in particular on the basis of the inverse of conductance quantum with its well-known true value of the quantity, since conventional means of metrological serviceability become inefficient.

4. Methodology and Role of Inverse of Conductance Quantum in Checking the Measuring Instruments

4.1. The Basis

Currently the standards of SI units replace standards of old generation in the State Laboratories of Metrology and Standardization practice. They are significantly more precise since are built on the usage of fundamental constants of matter just as it was regarded [3] by participants of Royal Society Discussion Meeting. We discuss below the possibility of implementing the high-precision measure of electrical resistance on the basis of inverse of conductance quantum in checking the measuring instruments for CPS purposes.

The aforementioned measure is proposed to be developed by applying the latest scientific achievements in the area of electrical conductivity. For example, it was established [4] for graphene nanopatterns that the quantum of conductance quantum is equal 12906.34 ± 0.20 Ohms at quantization error (5 ± 15) × 10⁻⁶. The similar works have been conducted during the last 20 years. There were studied some metrological problems of proposed standards of electrical resistance made of different kinds of substance and samples, estimated their values and uncertainties etc. [5-7]. As a result, in [8] there were compared the quantum Hall Effect resistance standards of National Physical Laboratory and the Bureau International de Poids et Mesures. Obtained results have been agreed for the 100 Ω resistance standard as well as for the 10000 Ω/100 Ω and 100 Ω / 1 Ω ratios within a few parts in 10⁷, to a value consistent with the estimated uncertainties. Moreover, it was shown that to limit the impact of the Peltier effect on 100 Ω / 1 Ω ratios measurement, it was recommended to withstand the measures for long time after reversing the DC currents.

4.2. The Model

This work is performed for purposes of CPS Metrological Services whose responsibilities include transferring the researched physical quantity unit (R) to the CPS measuring instrument by its calibration and sequentially checking the CPS electrical circuits or studying the products’ performance. We are trying to engage in research of proposed measure and its implementation in dispersed CPS-components that enables to provide precise operation with high metrological characteristics.

We accept not only the above experimental studies of establishing the inverse of conductance quantum, but its metrological substantiation as a physical quantity directly related to the Boltzmann constant and the charge of electron with particular uncertainties. Then basing on the results for these quantities received by means of different experimental methods and applying the theory of metrology, we study the correlation between researched quantity’s (R_0 = \frac{h}{2e^2} = 12906.4037217 \, \Omega) uncertainty and the other two known uncertainties: the Planck constant h = 6.62606957(29)×10⁻³⁴ J/s and the charge of electron e = 1.602176565×10⁻¹⁹ C. So we try to establish the value of inverse of conductance quantum and its uncertainty. Therefore, we are absolutely not interested in with which uncertainty the studied quantity was measured before in a certain metrological center and in one or another scientific work. For instance, in [9] there was submitted a value of relative standard uncertainty of von Klitzing constant (25812.8074434 Ohms) equal to 3.2×10⁻¹⁰, or it is much more precise than the obtained value. Apparently, it refers to the coverage interval of the results of repeated measurements of resistance standard and ignores the systematic constituent of error because the true value of the quantity is unknown at least in uncertainty model approach.

So it is sufficiently to know the current values of fundamental physical constants h and e. They were defined with high precision by means of a set of different physical methods. According to the data of the method of Watt balance, installations of studies, such as of X-rays crystal density, Magnetic resonance, Faraday constant, and Josephson constant, CODATA 2010 recommended value of weighted mean Planck constant relative uncertainty to be equal to u_h = 4.4×10⁻⁸ [9]. The same concerns the charge of electron, which uses the results of different research and its evaluation methods (Millikan's oil-drop experiments, E. Rutherford and other investigations). Relative standard uncertainty of electron charge determination is estimated as u_e = 2.2×10⁻⁹ [10].

In the paper below we consider the appropriate prototype of resistance measure (12906. … Ohms) applied for calibration of high-precise measuring instrument. Then we are able to practically obtain a reference point of its scale that is the main in checking the measuring instrument and so raising the accuracy class. This way, the calibration of
measuring instruments and sequentially validation of gauging data can be realized. The advantage of the similar methods of metrological checking is evident. It was demonstrated [11] on examples of checking the temperature, pressure and so on. By continuous controlling the reliability of metrological data and basing on the checked results for previous duration period, forecasting the instrument’s metrological state is developed.

4.3. Measurement Peculiarities

Being at superconductive state, graphene is inherent in the resistance value which corresponds to inverse of conductance quantum that is equal to $(12906.4037 \pm 0.0020)$ Ohms due to transient resistance of contacts. Four-wire circuit is sufficient to carry out the measurement of this resistance [12], and the Winston bridge together with the Hamon network [13] would be sufficient to transfer this value to the current standards (1.0; 100.0 Ohms), and then to adjust precise values of the working resistors to the required denominations.

Due to the development of nanotechnology there is an opportunity to implement the superconductive carbon nanotubes [14-15] as ideal resistive elements in the State standards of electrical resistance. Valid State standards are regulated by current verification schemes. For example, in Ukraine this is the decisive document [16]. It establishes the destination of State standard primary unit of electrical resistance – Ohm, set of basic measuring instruments which are the part of it, the basic metrological specifications of the Standard, and transferring procedure for the magnitude of electrical resistance unit from State primary standard via Secondary standards and Working standards to Working measuring instruments herewith indicating uncertainties and basic methods of verification.

4.4. Standard and Measuring Instruments

For transferring the value of unit to reference standards in the range $3 \times 10^{-3}$ ... $1 \times 10^{9}$ Ohms at DC the State primary standard consists of a set of measuring devices that includes the group of 20 electrical resistance measures of the nominal quantities of 1 and 100 Ohms, comparator, groups of three 1 Ohm measures, set of transitional electrical resistance measures.

The range of values of a physical quantity that is realized by the mentioned standard is equal to 1 Ohm and 100 Ohms. State primary standard provides storage, verification and supervision of the mentioned unit with standard deviation measurement result $S_m$ not exceeding $3 \times 10^{-8}$ Ohm (for 1 Ohm standard the relative deviation is $3 \times 10^{-8}$) at 10 independent observations (Fig. 1).

\[
\delta R_{\text{non-elim. comp}} = 3 \times 10^{-8}
\]

\[
\delta R = \pm 3 \times 10^{-8}
\]

Fig. 1. Instrumental error of state electrical resistance standard.

Non-eliminated component of systematic constituent of relative error is $3 \times 10^{-7}$. Reference standards are used for transferring with standard deviation $1 \times 10^{-7}$ ... $2 \times 10^{-5}$ Ohms by means of verification method (DC comparator) of the unit magnitude to electrical resistance measures of the 1st, 2nd categories and so on. The relative instability (drift) of reference standard’s value for one year operation does not exceed $2 \times 10^{-6}$.

Ohmmeters, DC/AC bridges, unambiguous and ambiguous measures of electrical resistance are usually applied as working measures.

5. Metrological Model Research

5.1. Transferring Scheme

The transferring scheme for the certain physical quantity is rather complex. At each stage of transfer accuracy is lost significantly; almost an order of magnitude. Main attention is paid to the final facility which steers transferring the unit size of electrical resistance. It would be an ambiguous measure of electrical resistance, or the precision measures.

If such measure is a precision resistor, whose operation is based on the reproduction of inverse of conductance quantum, a few metrological problems arise. Namely,

a) How to fit a resistor in the State scheme of verification;

b) Whether there are additional problems related to instability of structure and the drift of determining properties of resistor substance as a result of its transition from the superconductive to a semiconductor state [14];

c) And a number of other special metrological problems [13].

However, the benefits of its implementation are obvious:

a) The performance drift while using fresh specimens of superconducting nanotubes as working
elements of the precision resistor becomes negligible; at the same time the relative instability of measures that make up the reference standard for one year duration, determined at 20°C and at DC, is defined at nominal reference value: from 10 to 1×10³ Ohm – up to 5×10⁻⁶; 1×10⁴ Ohm – up to 6×10⁻⁶; 1×10⁵ … 1×10⁷ Ohm – up to 8×10⁻⁶ [16]

b) The error due to leakage current of the reference measure is quite essential and in contrast the same error of CNT working element becomes negligible owing to its superconductivity.

5.2. Uncertainty Analysis

Proper attention to further CPS development is impossible without assuring the sufficient level of metrological maintenance, the core of which lies in the triangle “embedded metrological hardware – installed metrological software – implemented metrological firmware”. In particular, it facilitates the implementation of industry measurement methods that try to verify the performance of proposed embedded measure of electrical resistance.

Aforesaid enables to realize qualitatively new model of secondary SI unit transfer from the Reference standard to Measuring instruments for CPS purposes by applying the embedded unambiguous measure (of electrical resistance on the basis of inverse of conductance quantum). The model allows to get rid of intermediaries in transferring scheme.

Basing on the mentioned data we have estimated [17] the relative uncertainty of CNT resistor’s value: 

\[ u_k = \pm(u_s + 2u_e) = \pm 8.8 \times 10^{-8}. \]

So, the uncertainty of the studied resistivity is determined by Planck constant and the electron charge uncertainties.

Transition to the mean square error is made by the equation: 

\[ \sigma = u\sqrt{3} = \pm 15.242 \times 10^{-8} \] (Fig. 2). The absolute value of proposed standard tolerance limit is defined as ±0.0019672 Ohm.

5.3. Measurement Scheme for CPS Purpose

Ordinary 4-wire scheme is sufficient to measure the resistance of CNTs. Current is fed by one pair of subminiature electrodes. Another pair of electrodes is used to connect a voltmeter. The scheme of measuring the inverse of conductance quantum may be similar to the described one in [15]. By switching two CNTs in series we can get the value of 25812.8 Ohms, and by switching in parallel – 6453.2 Ohms (Fig. 3).

![Fig. 3. Measurement range of ohmmeter within which calibration is provided.](image)

For 4 CNTs two more denominations of electric resistance – 51625.6 Ohms by sequential switching, and 3226.6 Ohms by parallel switching can be obtained. Otherwise, the easiest way that is simultaneously the most accurate seems to overlap possible values of range from 3226.6 Ohms to 51625.6 Ohms with the increment of 3226.6 Ohms. The transfer of electrical resistance measure value to smaller values of working resistors without losing precision can be carried out as shown below.

5.4. Transfer Size Scheme and Reference Standard for Standardization Purpose

For standardization service purpose the mentioned scheme could be metrologically expedient and a real resistance reference measure could be composed of two rows - (7+6) of superconductive nanotubes that form together a resistance value

\[ R_{\Sigma} = \frac{h}{26e^2} = 992,8002863 \text{ Ohms}. \]

Then the non-eliminated component of systematic constituent of relative error is unchangeable and equal to 15.24×10⁻⁸.

The transfer size scheme of electrical resistance unit on the basis of fundamental constants of substance is realized as follows.

• **First Stage of Transfer**

First of all, the unit is transferred to a higher value - 1000 Ohm resistance that has to be formed by
13-parallel-connected carbon nanotubes (992.8 Ohm) with 7 connected in series resistance of 1.0 Ohm value (Fig. 4).

The mentioned 9 working standards are switched by closing the contacts (Fig. 4b), aiming at forming 100 Ohm resistance value. Then, similarly, the specified on the 1st stage measurement method is carried out to gauge the ratio of the composed 100 Ohm resistance and the 10th working standard of 100 Ohm denomination.

As a result, the non-eliminated component of systematic error of inverse of conductance quantum is successfully transferred to 100 Ohm current working standard while maintaining the sustainable adjusted value of the latter – the current numerical value of the State standard.

6. Conclusions

1. Promising way to improve the efficiency of Cyber-Physical Systems is considered to equip them with embedded metrological subsystems that include the working measures of physical units. The first such measure seems to be the measure of electrical resistance (12906.4037… Ohms), based on carbon nanotube with its particular resistivity that is equal to an inverse of conductance quantum. It enables to improve the precision of electrical subsystems significantly and, as a result, to raise the quality of manufactured products.

2. To achieve sufficient precision in CPS production cycle it is enough to hold in-place ohmmeter calibration at the points that correspond to values, multiple to the inverse of conductance quantum or its certain part, for instance, 1/2 (1/4). This is accomplished by series-parallel connection of several identical measures.

References