The status of and prospects for development of voltage quantum standards

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Abstract. The state and tendencies of the development of voltage standards based on the Josephson effect are considered. The methods of electric voltage reproduction are presented both in the field of dc and ac voltage of arbitrary shape based on the values of fundamental physical constants in the new SI, and directions of improvement and expansion of the field of application are outlined.

The discovery of the Josephson effect in 1962 allowed a revolutionary leap in the field of electrical measurements, which ultimately led to the transition of the international system of standards, in the form of physical artifacts kg, m, second, amperes, to standards based on quantum effects and on the values of fundamental physical constants.

By the development of the voltage standard one can judge about the cycle of transformations expected in this kind of measurement. From the beginning to the 70s of the 20th century the artifact reproducing the unit of electrical voltage had been a standard cell based on electrochemical processes producing a constant and stable electrical voltage. The voltage standard in many countries was represented by a group of standard cells shown in figure 1.

![Figure 1. Group of standard cells.](image)

The value of the unit stored by the group reference of the volt was determined by the Ohm’s law in terms of the resistance unit reproduced by a mercury sample and the ampere reproduced by a silver voltameter (figure 2) based on the Faraday constant. Later on, the unit of resistance was determined by means of a calculable capacitor, and the current strength - by means of an ampere balance.
The Josephson equation [1] obtained in 1962 can be explained in terms of known physical relations, in particular, in terms of a change of the magnetic flux per unit of time.

$$U = \frac{d \Phi}{dt}.$$  

Replacing $d \Phi$ by the number of magnetic flux quanta $n \Phi_0$, and $dt$ by its reciprocal value - frequency $f$ - we obtain the well-known equation

$$U = n \Phi_0 f = n \frac{h}{2e} f = n f / K_J \quad \text{(Figure 3)},$$

where $h$ is the Planck constant, $2e$ is the double electron charge, $K_J$ is the Josephson constant.

The instrumental implementation of the Josephson quantum effect made it possible to use the obtained effect to create standards that reproduce voltage units with values attaining 20 V [2].

$$U = \frac{n(h/2e)f}{I}$$

**Figure 3.** Volt-ampere characteristic of Josephson system.

The implementation of the Josephson effect in the metrological practice entailed issues with direct linkage to the SI due to a significant increase in the accuracy of relative voltage measurements. The
transfer of the unit value from the ampere balance that have an accuracy at the level of several ppm became irrelevant and it was decided to refine the $K_I$ value, which caused the introduction of the $K_{I,90}$ with the uncertainty of 0.4 ppm in the SI (Recommendation 1 CI-1988).

Comparisons of standards based on the Josephson effect conducted by the BIPM showed discrepancies of 0.001 ppm or less. VNIIM developed transportable transfer standards of the voltage unit based on the Josephson effect (Figure 4) and made it available for international comparisons of national voltage standards [3-5]. Significant discrepancies between the uncertainty of relative measurements of voltage standards and the uncertainty of the Josephson constant in the SI was one of the reason for the revision of the existing SI.

![Figure 4. Transportable Josephson voltage transfer standards.](image1)

Further development of Josephson voltage standards is associated with the idea of using exact values of voltage (quantum voltage steps) that depend only on the frequency of irradiation and the number of quantum steps. The transition to approximation of AC voltage with the help of quantum steps made it possible to create instruments [6] to measure alternating signals with an accuracy that allows us to measure the parameters of high-precision generators without using thermo-converters and comparing the AC voltage with the DC voltage (Figure 5). VNIIM participates in this research that by now has enabled us to measure voltages up to 10 V and frequencies up to 10 kHz [7]. Due to this method it is now possible to determine influencing factors when conducting high-precision measurements [8]. We have also investigated the possibility of measuring the parameters of high-precision analog-digital converters [9] (Figure 6). The issues related to transitions between quantum steps [10] that prevent us from reproducing variable signals with a high accuracy have been studied.

![Figure 5. VNIIM JVS and PJVS voltage standards.](image2)
The achievements of the present period of development of the Josephson voltage standards are associated with the use of the pulsed method of irradiation of Josephson junctions [11], in contrast to the irradiation with sinusoidal signals in previous designs. The combination of pulsed-driven method with the delta-sigma modulation method allows us to reproduce the voltage with calculated parameters of the form - rms value, amplitude, amplitude of harmonics, etc., which creates a new level of metrological measurements that cannot be achieved by means of thermo-converters used in AC voltage standards.

The major problems related to this method of AC voltage unit realization that have not been resolved by now are increasing the reproducible voltage up to 10 V and increasing the frequency up to 1 GHz, the issues with hardware application, and the influence of connecting circuits.

The development and the use of installations that allow reproducing and measuring voltage with a high accuracy has led to the use of these devices in other areas of measurement. These include measurement of resistance ratios at DC and AC current, measurement of the ratio of inductances, the ratio of capacitances, measurement of power [12], and use of the noise temperature [13] in measurements.

The use of Josephson standards as reference sources allows us to measure AC voltages up to 100 V [14].

The development of Josephson systems technology provides the possibility for creation of practical devices based on high-temperature ceramics with a working temperature at the level of liquid nitrogen, which, unlike systems with a temperature at the level of liquid helium, allows these devices to be used in a wide metrological practice. The first samples of such voltage standards were fabricated in Russia [15].

The introduction of Josephson standards based on fundamental constants and therefore are not strictly connected with other standards, raises the question of conducting such metrological procedures as periodic comparisons and calibration. At present, the BIPM has come to the decision to carry out comparisons of Josephson DC voltage standards once every 20 years, which characterizes the approach to the gradual elimination of this type of metrological procedures that can lead to significant changes in metrological practice with the widespread introduction of lower precision meters methods. The development of quantum measurements and analysis of processes connecting micro- and macrocosm gives rise to ideas that try to identify the presence of quantum processes in living organisms [16], which can lead to revolutionary changes in many aspects of the development of society.

References
[1] Josephson B D 1962 Possible new effects in superconductive tunnelling Phys. Lett. 1(7) pp 251-53
[2] Yamamori H, Yamada T, Sasaki H and Shoji A 2008 A 10 V programmable Josephson voltage standard circuit with a maximum output voltage of 20 V Supercond. Sci. Tech. 21
DOI:10.1088/0953-2048/21/10/105007

[3] Behr R and Katkov 2005 A Comparison of Josephson array voltage standards by using a portable Josephson transfer standard EUROMET.EM.BIPM-K10.a, Final Report

[4] Katkov A, Lovtus V and Behr R 2016 Portable Josephson voltage reference standard Conf. digest CPEM 2016 2 p. DOI: 10.1109/CPEM.2016.7540664

[5] Katkov A and Solve S 2012 Key comparison of the voltage standards of the VNIIM and the BIPM Meas. Tech. 54(11) pp 1313-18

[6] Katkov A S., Lovtus V E, Bykov A I, Shevtsov V I and Novoderezhkin G V 2017 Reproduction of the volt based on SIS- and SNS-type Josephson junctions Meas. Tech. 60 p 589 https://doi.org/10.1007/s11018-017-1240-1

[7] Behr R, Katkov A S, Lee J, Bauer S, Kieler O F and Palafox L 2018 Frequency range extension of the AC quantum voltmeter CPEM 2018 Conf. Digest pp 984-85

[8] Katkov A, Gubler G, Lee J, Behr R and Nissilä J 2014 Influence of harmonics on AC measurements using a quantum voltmeter Conf. Digest CPEM 2014 pp 526-27

[9] Gubler G and Katkov A 2012 Investigation of ADC-Aided AC measurement through the use of PJVS Conf. Digest CPEM 2012 pp 64-65

[10] Katkov A, Behr R and Lee J 2008 Model for transient variation in stepwise synthesized Josephson sinewaves Conf. Digest CPEM 2008 pp 380-381

[11] Benz S P, Hamilton C A, Burroughs C J and Harvey T E 1999 AC and dc bipolar voltage source using quantized pulses IEEE Trans. Instrum. Meas. 48 pp 266–69

[12] Behr R, Palafox L, Williams J M, Djordjevic S, Eklund G, Van Den Brom H E, Jeanneret B, Nissilä J, Katkov A and Benz S. P Binary Josephson array power standard 2010 French College of Metrology ISTE, London, UK. DOI: 10.1002/9780470611371.ch44

[13] Kamper R A and Zimmerman J. E 1971 Noise thermometry with the Josephson effect J. Appl. Phys. 42 p 132 DOI.org/10.1063/1.1659545

[14] Hagen T, Budovsky I, Benz S P and Burrough C J 2018 Calibration system for AC measurement standards using a pulse-driven Josephson voltage standard and an inductive voltage divider CPEM 2018 Conf. Digest DOI: 10.1109/CPEM.2012.6251108

[15] Khorshev S K et al. 2019 Voltage standard based on dry-cooled high-temperature superconductor Josephson junctions. IEEE T. Instrum. Meas. pp 1-8 DOI: 10.1109/TIM.2019.2896011

[16] Petrov M Quantum life https://chrdk.ru/sci/quantum_life