New International Representations of the Volt and Ohm Effective January 1, 1990

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Abstract—Starting on January 1, 1990, new representations of the volt and ohm based on the Josephson and quantum Hall effects, respectively, are to come into effect worldwide. Their implementation in the U.S. will result in increases in the values of the national representations of the volt and ohm maintained at the National Institute of Standards and Technology (NIST) of 9.264 parts per million (ppm) and 1.69 ppm, respectively. The resulting increases in the values of the U.S. representation of the ampere and U.S. electrical representation of the watt will be 7.57 ppm and 16.84 ppm, respectively.

I. THE VOLT

A. The SI Unit of EMF and Its Representation

The INTERNATIONAL System of Units (SI), the unit system used throughout the world [1], serves as a basis for the promotion of long-term, world-wide uniformity of measurements, which is of considerable economic and technological importance. In the SI, the unit of EMF (E) and electric potential difference (U) is the volt (V). In practice, the volt may be realized in a number of ways including comparing electrical power with mechanical power. However, requirements for the long-term repeatability and world-wide consistency of measurements of EMF and electric potential difference often exceed the accuracy with which the volt can be realized. To meet these severe demands, it has become necessary to establish a representation of the volt (i.e., a "practical unit" of voltage) that has a long-term reproducibility and constancy superior to the direct realizations of the volt itself.

Historically, representations of the volt have been based on electrochemical standard cells. However, at its 13th meeting held in October 1972 [2], the Consultative Committee on Electricity (CCE), one of the principal international bodies concerned with such matters, suggested that the national standards laboratories base their national representation of the volt on the Josephson effect in order to avoid the well-known problems associated with the EMF's of standard cells, for example, their variation with time or drift, severe dependence upon temperature, and occasional unpredictable abrupt changes.

B. Josephson Effect Voltage Standard

The Josephson effect is characteristic of weakly coupled superconductors when cooled below their transition temperatures [3]. An example is two thin films of superconducting lead separated by an approximately 1-nm thick thermally-grown oxide layer. When such a Josephson junction is irradiated with microwave radiation of frequency f, its current versus voltage curve exhibits vertical current steps at highly precise quantized Josephson voltages U_j. The voltage of the nth step U_j(n), where n is an integer, is related to the frequency of the radiation by

\[ U_j(n) = nf/K_J \]  

where K_J, now termed the Josephson constant, is a universal quantity assumed to be equal to the invariant quotient of fundamental constants 2e/h, where e is the elementary charge and h is the Planck constant. Because quantized Josephson voltages depend only upon a readily measured frequency and an invariant quotient of fundamental constants of nature, a representation of the volt based on the Josephson effect will have none of the problems characteristic of standard cells indicated above.

To ensure the consistency of national representations of the volt based on the Josephson effect, the CCE also suggested at its October 1972 meeting that national standards laboratories use an agreed upon or conventional value of K_J, namely [2]:

\[ K_{J,72} = 483 594 \text{ GHz/V} \]  

exactly. While most national laboratories adopted this value, three did not [4]. Indeed, NIST had adopted, starting on July 1, 1972 [5]:

\[ K_{J,NIST,72} = 483 593.420 \text{ GHz/V} \]  

exactly, which is about 1.2 parts per million (ppm) smaller than the CCE value given in (2). At the time, the CCE believed K_J,72 agreed with the SI value to within a relative uncertainty of 0.5 ppm [2]. However, new and significantly more accurate data indicate that the CCE's 1972 conventional value K_J,72 results in a volt representation about 8 ppm smaller than the volt [4].

C. The New 1990 Representation of the Volt

The CCE recommended at its 18th meeting held in September 1988 [6]–[8] that all national standards laboratories that base their representation of the volt on the Josephson effect adopt the same new conventional value of K_J, namely:

\[ K_{J,90} = 483 597.9 \text{ GHz/V} \]
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the volt based on the Josephson effect and $K_{J,90}$ will agree with the volt to within an assigned relative uncertainty of 0.4 ppm (one standard deviation or 1σ). The CCE recommendation was subsequently adopted by its parent body, the International Committee of Weights and Measures (CIPM), at its 77th meeting held in October 1988. Since $K_{J,90}$ exceeds $K_{J,NIST}$ by 9.264 ppm, starting on January 1, 1990 the U.S. representation of the volt will be 9.264 ppm larger than that in effect during the period July 1, 1972 through December 31, 1989.

II. The Ohm

A. The SI Unit of Resistance and Its Representation

Much of the first paragraph of Section I-A regarding EMF and the volt applies to resistance ($R$) and its SI unit, the ohm (Ω). In practice, the ohm may be realized by means of a Thompson-Lampard calculable capacitor first developed in the early 1960's [9], [10]. Nevertheless, because it is a difficult apparatus to use routinely, most national standards laboratories have continued to base their representation of the ohm on wire-wound standard resistors. However, such artifact standards age, and the various national representations of the ohm now differ significantly from each other, and the ohm with some drifting excessively. Electrical metrologists, therefore, welcomed von Klitzing's 1980 discovery of the quantum Hall effect (QHE) [11] since it promised to provide a method for basing a representation of the ohm on invariant fundamental constants in direct analogy with the Josephson effect.

B. Quantum Hall Effect (QHE) Resistance Standard

The QHE is characteristic of certain high mobility semiconductor devices of standard Hall-bar geometry when placed in a large applied magnetic field and cooled to a temperature of about 1 K [12]. For a fixed current $I$ through a QHE device, there are regions in the curve of Hall voltage versus gate voltage, or of Hall voltage versus magnetic field depending upon the device, where the Hall voltage $U_H$ remains constant as the gate voltage or magnetic field is varied. These regions of constant Hall voltage are termed Hall plateaus. Under the proper experimental conditions, the quantized Hall resistance of the $i$th plateau is defined as the quotient of the Hall voltage of the $i$th plateau to the current $I$, and is given by

$$R_H(i) = \frac{U_H(i)}{I} = R_K/i$$

where $i$ is an integer and $R_K$, now termed the von Klitzing constant, is a universal quantity assumed to be equal to the invariant quotient of fundamental constants $h/e^2$.

C. The New 1990 Representation of the Ohm

At its September 1988 meeting, the CCE also recommended that (i) the national standards laboratories base their national representation of the ohm on the QHE in order to eliminate the problems associated with artifact resistance standards [6]-[8]; and (ii) all national laboratories that choose to use the QHE for this purpose use the same conventional value of the von Klitzing constant, namely:

$$R_K = 25 812.807 \, \Omega$$

exactly, where the subscript 90 again indicates that the new ohm representation is to come into effect starting on January 1, 1990 and not before. The CCE believes that an ideal representation of the ohm based on the QHE and $R_K$ will agree with the ohm to within an assigned relative uncertainty of 0.2 ppm (1σ). These CCE recommendations were also adopted by the CIPM at its October 1988 meeting.

Since August 1983, quantized Hall resistance measurements have been carried out at NIST in terms of the NIST representation of the ohm [13], which is based on the mean resistance of five Thomas-type 1-Ω resistors maintained in an oil bath at 25°C. These data have allowed the drift rate of the NIST ohm representation to be precisely determined, and calculations indicate that on January 1, 1990, it will have to be increased by 1.69 ppm to bring it into conformity with the new internationally adopted ohm representation. Thereafter, the NIST representation of the ohm will remain constant in time and in agreement with the new international ohm representation because both will be based on the QHE and $R_{K,90}$.

Since $A = V/I$ where $A$ is the (SI) ampere and $W = V^2/I$ where $W$ is the (SI) watt, the 9.264 and 1.69 ppm increases in the U.S. representations of the volt and ohm, respectively, imply that on January 1, 1990, the U.S. representation of the ampere will increase by about 7.57 ppm and the U.S. electrical representation of the watt will increase by about 16.84 ppm. Because an ideal ampere representation based on $K_{J,90}$ is expected to agree with the volt to within 0.4 ppm (1σ) and an ideal ohm representation based on $R_{K,90}$ is expected to agree with the ohm to within 0.2 ppm (1σ), ampere and watt representations derived from such ideal volt and ohm representations via the above equations are expected to agree with the (SI) ampere and (SI) watt to within 0.45 and 0.83 ppm, respectively (1σ).

III. OTHER CONSIDERATIONS

The new international volt and ohm representations were adopted to improve the world-wide uniformity of electrical measurements and their consistency with the SI. The CCE and CIPM, therefore, recommended that on January 1, 1990, national standards laboratories that base their representations of the volt and ohm on artifact standards rather than on the Josephson and quantum Hall effects, adjust the values of their volt and ohm representations so that they are also consistent with the new internationally agreed upon values. Further, this consistency is to be maintained through periodic comparisons with a laboratory that bases its representations of the volt and ohm on the Josephson and quantum Hall effects, for example, the International Bureau of Weights and Measures (BIPM) [6]-[8].
The CCE and CIPM recognize that future, more accurate measurements may show that $K_{J,90}$ and $R_{K,90}$ differ somewhat from the SI values of $K_J$ and $R_K$. However, any such differences are expected to be sufficiently small (e.g., a few parts in ten million), that practical electrical measurements will be unaffected. Thus the CCE and CIPM strongly believe that the conventional values $K_{J,90}$ and $R_{K,90}$, and consequently the new volt and ohm representations, will not need to be altered in the foreseeable future [6]–[8].

IV. REPORTING CALIBRATION RESULTS

The results of voltage and resistance calibrations expressed in terms of the new volt and ohm representations will have a higher precision than the same calibration results expressed in terms of the volt and ohm themselves. Indeed, as implied in Section I-A, this is one of the principal reasons for establishing such representations; but how should the national standards laboratories report calibration results in terms of the new representations?

The CCE and CIPM decided that in the future, it would be best to avoid the use of subscripts or other distinguishing symbols of any sort on either unit symbols (i.e., V, Ω) or quantity symbols (i.e., $E$, $R$), for example, subscripts denoting particular laboratories or dates such as $V_{NIST}$, $E_{NIST}$ or $E_90$ [6], [8]. By not using such distinguishing symbols, the national standards laboratories can avoid giving the impression to the users of their calibration services that there is more than one representation of the volt and of the ohm in general use, that there may be significant differences among national realizations of the new volt and ohm representations, and that the national realizations or the new representations differ significantly from the SI. The CCE believes that (i) the appearance of creating a new unit system outside of the SI is to be avoided; (ii) the new representations of the volt and ohm based on the Josephson and quantum Hall effects are completely satisfactory for the great majority of applications (i.e., it will rarely be necessary to distinguish between the new representations and the SI units); and (iii) any differences among the volt and ohm representations of different laboratories will be negligible from the point of view of the great majority of users (i.e., it will rarely be necessary to distinguish between the representations of different laboratories).

The CCE’s solution to the reporting problem, which was affirmed by the CIPM and which all national standards laboratories that base their national representation of the volt (i.e., their national “practical unit” of voltage) on the Josephson effect. Since all such laboratories are now to use the same conventional value of the Josephson constant, while prior to this date they did not, the significant differences which existed among the values of some national representations of the volt no longer exist. Moreover, the national standards laboratories that do not use the Josephson effect for this purpose are requested to maintain the value of their own national representation of the volt so as to be consistent with the value of the new representation, for example, through periodic comparisons with a laboratory that does use the Josephson effect. An ideal representation of the volt based on the Josephson effect and $K_{J,90}$ is expected to be consistent with the volt as defined in the SI to within an assigned relative one-standard-deviation uncertainty of 0.4 ppm (0.41 μV for an EMF of 1.018 V). Because this uncertainty is the same for all national standards laboratories, it has not been formally included in the uncertainties given in this report. However, its existence must be taken into account when the utmost consistency between electrical and nonelectrical measurements of the same physical quantity is required.
The note for resistor calibration reports would be similar. However, as previously indicated, an ideal representation of the ohm based on the QHE and $R_{\text{K},90}$ is expected to be consistent with the ohm to within an assigned relative one-standard-deviation uncertainty of 0.2 ppm (0.2 μΩ for a resistance of 1 Ω).

V. Conclusion

The apparatus currently in use at the national standards laboratories is such that the total experimental uncertainty associated with a particular national representation of the volt based on the Josephson effect generally lies in the range 0.01–0.2 ppm [4]. As a consequence, with the world-wide adoption starting on January 1, 1990, of the new conventional value of the Josephson constant $K_{\text{J},90}$ and the implementation of the CCE and CIPM recommendation outlined in Section III (first paragraph), all national representations of the volt should be equivalent to within a few tenths of a parts per million. Similarly, the total experimental uncertainty associated with the measurement of quantized Hall resistances also generally lies in the range 0.01–0.2 ppm [14], [15]. Hence, with the world-wide adoption starting on January 1, 1990, of a new representation of the ohm based on the QHE and the conventional value of the von Klitzing constant $R_{\text{K},90}$, all national representations of the ohm should also be equivalent to within a few tenths of a parts per million. Moreover, these new national volt and ohm representations should be consistent with the volt and the ohm to better than 0.5 ppm. Because of this international uniformity and consistency with the SI, it is believed unnecessary for the national standards laboratories to use distinguishing symbols of any sort on either unit symbols or quantity symbols when reporting calibration results in terms of the new representations.