Do Quantum Standards have to be Validated?

Speaker: Bernd Schumacher
Physikalisch Technische Bundesanstalt,
Bundesallee 100, 38116 Braunschweig, Germany
Phone: (+49531) 592-2122; FAX: (+49531) 592-2105
Bernd.Schumacher@PTB.DE

Authors: B. Schumacher, P. Warnecke
Physikalisch Technische Bundesanstalt, Braunschweig, Germany

Abstract

Quantum standard systems are nowadays commercially available. That means that high precision measurements are no longer the sole domain of national metrological institutes (NMI) of the highest level. The NMI's of developing countries and high-level industrial laboratories also have the possibility to use these quantum effects. There is no doubt that the fundamental quantum effects are correct, but the practical application of these quantum standards is a different story. To assure the correct use of such quantum standards validation is essential. This validation includes setting up an uncertainty budget and participation in comparisons.

1. Introduction

Since 1990, the electrical units for voltage and resistance have been realized using quantum standards – the Josephson effect for voltage and the quantized Hall effect (QHE) for resistance. Also in 1990, it was agreed to use conventional values for these effects with the great advantage of having the same realization of these units at any place in the world and at any time without the need for transporting standards, thus removing trade barriers. Although the mentioned effects are error-free, their misuse can possibly lead to locally undetectable sources of error. One way to detect these errors is by the laboratory running a quantum standard participating in comparisons. A prerequisite for participation is that the results are reported with an uncertainty supported by a complete uncertainty budget.

In the following a brief description of the Josephson effect and the quantized Hall effect is given, followed by a summary of practical errors that can occur in the use of these effects. Having pointed out the necessity of comparisons as a tool for error detection, a recipe for the organization and evaluation of comparisons is proposed.

2. Electrical Quantum Standards

2.1 Josephson Effect

If a weak contact is made between two superconductors (e.g. a tip on a plane with a thin oxide layer in-between) at the temperature of liquid Helium (4.2 K), and a current is passed through this weak link, a microwave is generated. This effect can be reversed, that means if a similar contact is irradiated with a microwave (typically up to 70 GHz), a voltage is generated [1]. According to equation (1) the value of this voltage depends only on fundamental constants, Planck's constant h and electron charge e, and the frequency f of the microwave.

$$U = \frac{h}{2e} f \quad (1)$$

Since the fundamental constants do not depend on any other physical quantity, the accuracy of the voltage is determined by the accuracy of the frequency. In principle, this accuracy is the same as for an atomic clock, of the order of a few parts in 10^{13}.

For practical use of the Josephson effect in accordance with the international system of units (SI), a conventional value for the factor $h/2e$ was agreed upon in 1990; it is the Josephson constant K_{J-90} = 483 597,9 GHz/V. More details of the Josephson effect and voltage standards can be found in [2,3].

2.2 Quantum Hall Effect

In special semiconductor structures like MOSFET's or galliumarsenide heterostructures, electrons can be confined to a so-called two-dimensional electron gas. At low temperatures ($T \leq 4.2$ K) and in high magnetic fields (5 T < B < 12 T) measurements of the Hall resistance R_H show flat plateaus and the value of R_H depends only on an integer number i and the fundamental constants h and e [4].

$$R_H(\mathrm{i}) = \frac{h}{\mathrm{i}e^2} \quad (2)$$

Again here we have a quantity that only depends on fundamental constants and an integer number. This may lead to the conclusion that this effect has no error. For practical use of the quantum Hall effect, also, a conventional value was agreed upon in 1990; it is the von-Klitzing constant R_{K-90} = 25812,807 Ω and R_H(i) is then given by

$$R_H(\mathrm{i}) = \frac{1}{\mathrm{i}} \cdot R_{K-90} \quad (2).$$

For the operation of a quantum Hall effect resistance standard there are "Technical Guidelines for Reliable QHR Measurements" [5]. A quantum Hall effect device that fulfills these Guidelines always gives the correct value within the uncertainty of the measurement set-up, which typically is of the order of a few parts in 10^9. More details of the QHE and resistance standards can be found in [6,7].

3. Errors of Quantum Standards

From the above we have learned, that quantum effects are extremely accurate. But there are some practical limits:

- the accuracy only applies at low temperatures, typically 4.2 K;
- thermal EMF's;

- ground loops and electromagnetic interference;
- un-quantized side effects like isolation, parasitic shunt resistances;
- calibration of equipment used to transfer the value of the quantum standard to conventional standards.

3.1 Temperature dependence

Fortunately, the Josephson effect depends on the superconducting properties of the device, so there is a well defined critical temperature, below which the effect is present as described above. For the superconductors used (e.g. niobium), this critical temperature is well above 4.2 K (the boiling point of helium), which means if the sample is immersed in liquid helium, the operating temperature of the device is no problem. For the quantum Hall effect, the situation is different. This effect depends on the quantization of energy states and this can be disturbed by temperature even as low as 4.2 K. So for each QHE device the dependence of $R_H(i)$ on the temperature has to be determined. This determination is one point of the Guidelines mentioned earlier.

3.2 Thermal EMF

A common problem in DC measurements is thermal EMF. Normally this can be solved by polarity reversals, if the thermal EMF is constant during the measurement period. The problem with quantum standards is that you have to transfer a quantity from cryogenic temperatures to room temperature. It is difficult to eliminate temperature variations along the leads to minimize variations in the thermal EMF. Here special lead materials and special precautions for thermal shielding are required.

3.3 Ground Loops

To attain high precision, it is necessary to have a perfectly grounded measurement set-up. Here perfect means that there is only a single connection of the measuring circuit to ground. Power line cords may provide unwanted connections to the same ground, thus forming a ground loop. Such a loop is a perfect antenna to pick up any electromagnetic noise present in the laboratory. This noise then may lead to offsets in the measurement signal giving wrong results [8].

3.4 “Un-quantized” side effects

A characteristic feature of quantum effects is that the observed quantities do not change over a certain range of variation of an adjustment parameter. For the Josephson effect, this is the bias current I_B, and for the quantum Hall effect this is the magnetic field strength B. If a Josephson junction has a parallel resistance then I_B will produce an additional voltage drop and hence tilt the voltage plateau. If a QHE device has excessive charge in normally isolating layers then this charge produces an additional Hall voltage and also tilts the plateau. So a criteria for a quantum standard is that the flatness of the respective plateaus must be checked. This is an important part of the QHE Guidelines.

3.5 Calibration of the Measurement Set-up

Using a very accurate quantum standard at cryogenic temperatures requires also having a measurement set-up to transfer the quantity to room temperature standards. This set-up has to consist of calibrated instruments. For the Josephson standard and a direct comparison of a voltage source with this standard this seems to be easy, you only need an accurate measurement of the frequency. The problem is that the calibration of frequency counters above 20 GHz is difficult. The present solution is that a phase-locked-loop counter links the microwave frequency to a 10 MHz reference signal derived from the frequency standard. This method is then validated by a comparison of counters of different Josephson standard set-ups.

For the QHE, the situation is more complex. Unfortunately, nature provides a constant non-decade value, so in any case a resistance ratio bridge is needed. The components of such a ratio bridge, regardless of their nature, have to be calibrated.

4. Organizing a Comparison

These described possible sources of error are part of the input quantities of the uncertainty budget for a quantum standard. To check the calculation of the uncertainty, the operation of a quantum standard measurement system has to be validated by the means of comparisons. There are two possible ways, one is to have a transportable reference quantum standard, the other is to use conventional standards. The first way is more accurate but it is time consuming and not easily available to a large number of laboratories. The second way is less accurate due to the limited stability of the travelling standards, but still helpful as will be explained later.

In the framework of the Mutual Recognition Arrangement (MRA) it is required to assure international comparability of measurements by means of so-called key comparisons (KCs). An example of a key comparison of quantum standards, is the key comparison at the resistance value of 100 Ω that can be directly linked to the QHE (CCEM-K10). This comparison allows a great number of national metrological institutes to compare their realization of the unit of resistance within a reasonable period of time. The Physikalisch Technische Bundesanstalt (PTB) is pilot laboratory for this key comparison. We report on the necessary preparations and possible obstacles occurring in such a comparison.

For the preparation of a comparison, either key or interlaboratory, there is a useful guidance document, provided by the Comité Consultatif d’Electricité et Magnetism (CCEM). Besides other, this document addresses three key issues:

1. the travelling standards have to be well characterized,
2. there has to be a technical protocol to provide all relevant technical and organizational details to all participants,
3. the duration should be limited to 24 month.

There are two main ways to organize comparisons with more than two participants, one is a star-shaped sequence A-B-A-C-A-...-A (A is the pilot laboratory, B, C etc. are the participants), the other is a loop sequence A-B-C-..-A-....-A. The advantage of the first way is that the comparison consists of a number of bilateral comparisons and hence a small uncertainty can be achieved. The disadvantage is that it imposes a very high workload on the pilot laboratory and it can be time consuming. So the loop sequence would be the preferred method and an optimum for the number of participants in each loop is to be determined.

In preparation for the mentioned 100-Ω key comparison, a EUROMET project was carried out that simulated the comparison. The main interest was to see, how commercially available 100-Ω standard resistors behave, when they travel unaccompanied [9]. The project showed that resistors behave rather unpredictably when exposed to shocks or temperature changes, but the mean of the results using three out of the five resistors gave a reference value within an acceptable uncertainty. From the experience with this project, we concluded to select four travelling standards for the key-comparison. Furthermore, it turned out that it was good to have not more than three participants in each loop and allowing the pilot laboratory twice the time for the measurements. This was very helpful in catching up with delays and making it easy to keep the time limit to 24 months. This other main requirement (24 month duration) is important for the interpretation of the results of a KC. For this period, the changes of the travelling standards should be not excessive with regards to the application of statistics. Also, the information for the participants will still be germane because it is unlikely that their measurement set-up has changed.

Experience shows that, even with a well-planned comparison, some problems can occur:

- standards that behaved well during the test period can change their behavior significantly,
- unexpected delays in transportation due to customs procedures can occur,
- participants sometimes have trouble with their measurement set-up.

This requires some effort in organizing and re-organizing of the comparison by the pilot laboratory to make a comparison a success for all that are involved.

5. Conclusion

The high reproducibility obtained with quantum standards for voltage and resistance are not necessarily equivalent to high accuracy of measurement systems upon which they are based. The detection of unforeseen errors and the requirements of the Mutual Recognition Arrangement are good reasons to make interlaboratory comparisons for the validation of quantum standards. Although the results of these comparisons are limited by the properties of the travelling standards, they bring insight into the calibration capabilities of the participating laboratory.

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