Accurate high-ohmic resistance measurement techniques up to 1 PΩ

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Accurate High-Ohmic Resistance Measurement Techniques up to 1 PΩ

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***Abstract* — An overview is presented on precision high-ohmic resistance measurements for values of 100 MΩ and above. The two main measurement techniques in this resistance range are discussed, the current integration technique and the adapted Wheatstone bridge. The quality of high-ohmic resistance standards, especially their time constants, temperature and voltage dependence, often is limiting the final uncertainty that can be reached. Still, expanded uncertainties (k = 2) of only a few parts in 10^5 are achievable at the 1 TΩ level.**

***Index Terms* — Resistance, resistance measurements, high-ohmic, adapted Wheatstone bridge, teraohmmeter, resistance scaling, precision measurement.**

I. INTRODUCTION

Accurate measurement of high-ohmic resistance is relevant for industry. Reference standards in the TΩ range are especially needed in instruments measuring electric isolation characteristics of materials, in low-conductivity meters or in electrometers. The calibration of such reference standards is, thus, a service increasingly offered by National Metrology Institutes or specialized calibration laboratories.

The aim of this paper is to give an overview of the state of the art in resistance measurements in the range from 100 MΩ up to the PΩ level. The two measurement techniques mainly used in practice, the integration technique and the adapted Wheatstone bridge, are described. Furthermore, information on resistance standards is provided that is very important in realization of low uncertainties in high-ohmic resistance measurements.

II. CURRENT INTEGRATING TERAOHMMETER

One of the frequently used methods for high-ohmic resistors involves charging a capacitor by the current resulting from a voltage applied across the resistor. With careful implementation of this approach, expanded uncertainties (k = 2) of better than 100 parts in 10^6 can be achieved [1, 2].

A schematic of this method is given in Fig. 1. A measurement voltage V_{test} is applied to the unknown resistor R_x. The resulting current is integrated by a high-input impedance operational amplifier with capacitor C as feedback element. The output of the integrator is a linearly ramping voltage. A voltage comparator and timer is subsequently used to measure the time Δt required for the integrator output to change a certain voltage ΔV set by two voltage comparator limits. The value from the unknown resistor R_x then can be calculated via

$$R_x = -V_{\text{test}} \cdot \Delta t \;/\; (C \cdot \Delta V). \qquad (1)$$

Calibration of the setup is performed by measurement of a reference resistor R_s with known value. One of the major advantages of this method is that by using voltages between 10 V and 1000 V and capacitance values between 100 pF and 10 nF, resistors up to 1 PΩ can be conveniently calibrated with quite good accuracy [1, 2].

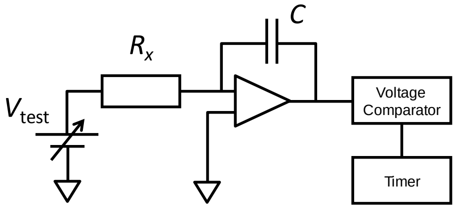

Fig. 1. Schematic overview of the current integration technique for measurement of high-ohmic resistances, as among others applied in commercial teraohmmeters.

Eq. 1 clearly identifies the quantities contributing to the uncertainty in R_x. In practice, major uncertainty contributions are the measured voltage ramp $\Delta V/\Delta t$, leakage in C, noise, and the calibration using R_s.

In practice, this method is most appropriate for transferring resistance values between equal value resistors, since here the majority of the systematic effects cancel out, and for measurement of resistors of very high values, well into the PΩ range.

III. ADAPTED WHEATSTONE BRIDGE

A second successful measurement approach in high-ohmic resistance measurements is an adapted Wheatstone bridge where two of the bridge resistors are replaced by adjustable voltage sources [3]. Refinement of this approach in the past decades has led to excellent expanded uncertainties (k = 2) of only a few parts in 10^6 for 1 GΩ resistance values [4].

A schematic of the bridge is given in Fig. 2. One voltage source applies a voltage V_1 across the unknown resistor R_x. The second voltage source applies a voltage V_2, with opposite polarity, across the reference resistor R_s and is adjusted until the null-detector reads a null signal. In this situation, the

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applied voltage ratio $-V_1/V_2$ equals the resistance ratio R_x/R_s, and R_x can be determined via the following simple formula:

$$R_x = R_s \cdot (-V_1/V_2). \quad (2)$$

A significant advantage of this approach is that very low uncertainties can be achieved since the applied voltages can be readily calibrated with good accuracy. In addition, leakage effects are small since the sensitive bridge point voltage is balanced to zero voltage. For measurements up to 100 GΩ, the null-detector can be either a nanovoltmeter or electrometer, and similar results are achieved for both null-detection methods [4]. For higher resistance values, where the value of R_s becomes comparable to the input impedance of the nano-voltmeter, only current null-detection should be used.

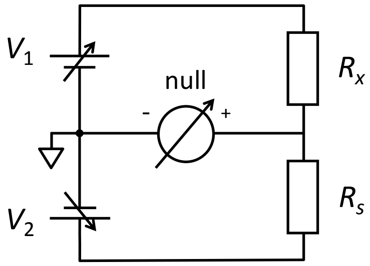

Fig. 2. Schematic overview of dual-arm voltage bridge, with voltage sources V_1 and V_2, null-detector, and standard resistors R_x and R_s.

It is important to correctly balance the bridge at an applied measurement voltage, that is to the null-detector signal seen when both voltage sources were earlier set to zero volt. Major uncertainty sources in this approach are the calibration of the voltage sources, noise, offset voltages, and the reference resistor R_s.

IV. RESISTANCE STANDARDS

The performance of high-ohmic resistance standards is critical in achieving high accuracy in measurements made by the systems described above. Influence factors such as voltage coefficient of resistance (VCR), temperature coefficient of resistance (TCR), relative humidity effects, long-term drift, short-term settling time, construction material properties, and resistor configuration are the primary factors that impact the performance of a high-ohmic resistance standard. As independence of all of these influence factors is not achievable in practice, especially in the TΩ and PΩ ranges, choices are made to minimize or correct the influence factors during the construction or measurement of the high-ohmic standard.

The voltage and temperature dependence of standards can be measured and approximated by appropriate fitting models, thus allowing a correction to the test conditions. VCR can be reduced by using multiple resistive elements but if this is not done with care, other problems may arise, such as reduced ruggedness of the standard or increased short-term settling time. Hermetically sealing the resistance element will protect it from changes in relative humidity which can cause leakage across the resistance element and swelling of the substrate, both which are reversible effects. The long-term drift often decreases in the months or years following construction of the resistance standard as the mechanical strains induced during the construction approach an equilibrium. Heat treatment of the resistance element prior to hermetic sealing accelerates the aging process, thus reducing the long-term drift [5].

The short-term settling time or RC time constant is the most challenging influence factor as it can contribute to very long times for a single measurement and lead to systematic errors. Conformal coatings and epoxy encapsulation, often applied to protect the precious metal oxides of the resistance element from physical damage and contamination, can increase the RC time constant. Selection of resistance elements with short settling time or the removal of the protective layers are two strategies for minimizing settling times. The dielectric and charge-retaining properties of materials used to hermetically seal and mount the resistance element may also add capacitance to the standard and need to be carefully selected.

The configuration and mounting of the resistance elements is the remaining influence factor. The use of guarding in the hermetically sealed container and the connectors can suppress leakage currents to ground. Delta-wye networks of three resistance elements have also been used to form divider-networks to simulate resistance standards much higher in resistance than the components.

V. CONCLUSION

Two high-precision measurement techniques for resistance measurements in the range from 100 MΩ up to 1 PΩ have been discussed, as well as the factors affecting their accuracy. Both techniques can be readily automated which is extremely useful since high-ohmic measurements typically require long settling times. A good indicator for correct measurements in both approaches is agreement between measurement values for positive and negative applied measurement voltage.

High-ohmic resistors are difficult to make of high quality. Best resistors are hermetically sealed to limit humidity effects. However, adverse effects of temperature and voltage are inevitable and measurements at the highest level therefore require accurate temperature measurement and control, as well as careful evaluation of the dependence on voltage.

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