RESISTANCE MEASUREMENTS FROM 10 MΩ TO 1 TΩ AT NIST

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Abstract

Described are the measurement systems and methods used for calibrating standard resistors from 10 MΩ to 1 TΩ at the National Institute of Standards and Technology (NIST). Presently four systems are used for the calibration of standard resistors at and above 10 MΩ. An automated guarded multimegohm bridge has recently been developed to augment a manual guarded Wheatstone bridge and a semiautomated teraohmmeter system. An automated resistance ratio bridge is used during the scaling process. Scaling from one decade to the next is done by using guarded Hamon boxes and the high resistance bridges.

Introduction

The calibration of standard multimegohm resistors from 10 MΩ to 1 TΩ has been done at NIST using a variety of measurement techniques. Since the early 1980's when personal computers (PC's) came into existence, the trend has been to develop automated measurement systems and phase out manually operated systems when appropriate [(1)]. This has only been done if the quality of the calibration is improved by the new system. Presently four systems are on line and used for in-house and customer calibrations at NIST. These systems include a manually operated guarded Wheatstone bridge, a semiautomated teraohmmeter system, an automated resistance ratio bridge, and an automatic guarded multimegohm bridge. A description of each of the measurement systems is given along with limitations in the measurement process and scaling procedures.

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Guarded Wheatstone Bridge

Standard resistors of nominal values from 10 MΩ to 10 GΩ are calibrated using a NIST-built guarded Wheatstone bridge [2]. The manually operated guarded Wheatstone bridge has the capability of making two-terminal measurements on standard resistors from 10 kΩ to 10 GΩ that are within 5000 parts in 10^6 of their nominal values. During the scaling process 10 kΩ standard resistors, measured in terms of the quantized Hall resistance [3], along with Hamon transfer standards are calibrated by the guarded Wheatstone bridge to extend the U.S. representation of the ohm [4] to NIST standard resistors of decade nominal values from 10 MΩ to 10 GΩ. At resistances of 10 GΩ and above, the bridge performance is significantly affected by stray capacitances and leakage currents.

The bridge can be operated in a 1:1 or 10:1 ratio configuration by changing the ratio of the main ratio arms A and B as shown below in Figure 1.

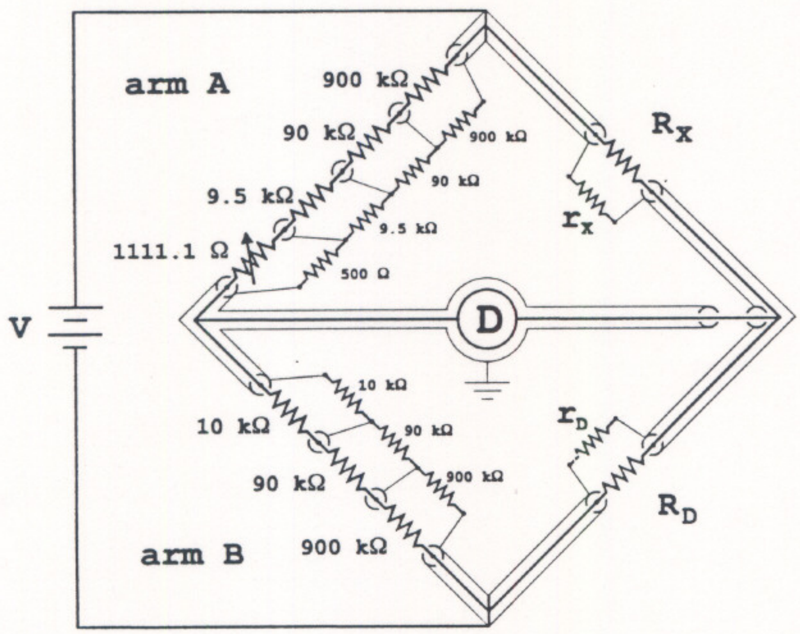

Figure 1. Guarded Wheatstone Bridge.

Arm A contains a 5-decade adjustable resistor having a maximum resistance of 1111.10 Ω giving the bridge an adjustment range of approximately of ±5000 parts in 10^6 when arm A has a nominal resistance of 100 kΩ. Arm B has a nominal resistance of 100 kΩ or 10 kΩ to form a bridge ratio of 1:1 or 10:1, respectively. An additional 900 kΩ can be added to the A and B arms of the bridge allowing voltages above 500 V to be applied to the bridge. This added resistance limits the bridge adjustment to ±500 parts in 10^6 .

The remaining two arms of the bridge consist of the standard or unknown resistor R_X and a dummy resistor R_D. During a measurement run, standard and unknown resistors are substituted alternatively into the R_X arm while the dummy resistor remains constant during the test. The standard, unknown, and dummy resistors are housed in an environmental air chamber that maintains the resistors at constant temperature and humidity.

Teraohmmeter System

At resistances above 10 GΩ, the accuracy, sensitivity, and detector response of the Wheatstone bridge is affected by stray-capacitance effects, increased system noise, and a lack of stable working standards. High resistance measurement methods of charging and discharging resistor-capacitor networks overcome most of these limitations. The teraohmmeter [5] is an instrument that uses an analog integrator technique to measure resistances by forming a resistor-capacitor network with the test resistor and an internal fixed air capacitor. The NIST teraohmmeter system uses a semi-automated commercial teraohmmeter to calibrate standards up to 1 TΩ. Due to the high uncertainties associated with this system, it is only used for 10 MΩ through 10 GΩ standards that cannot be measured on the guarded Wheatstone bridge, i.e., resistors having a correction larger than ±5000 parts in 10^6 of nominal value. Above 10 GΩ, test resistors are compared to a NIST 10 GΩ standard resistor by using the 10:1 and 100:1 internal ratios of the teraohmmeter.

Figure 2 shows a simplified diagram of the teraohmmeter. The unknown resistor R_X and capacitor C are used to form a RC network that is charged by a dc source when switch S is opened. The time Δt required for the output voltage V_0 to change by a known amount, ΔV_0, is measured by a counter circuit. From the test voltage V_i, change in output voltage ΔV_0, capacitance C, and measured time Δt, the resistance R_X can be calculated as

$$R_X = -(1/C)(V_i/\Delta V_0)\Delta t.$$

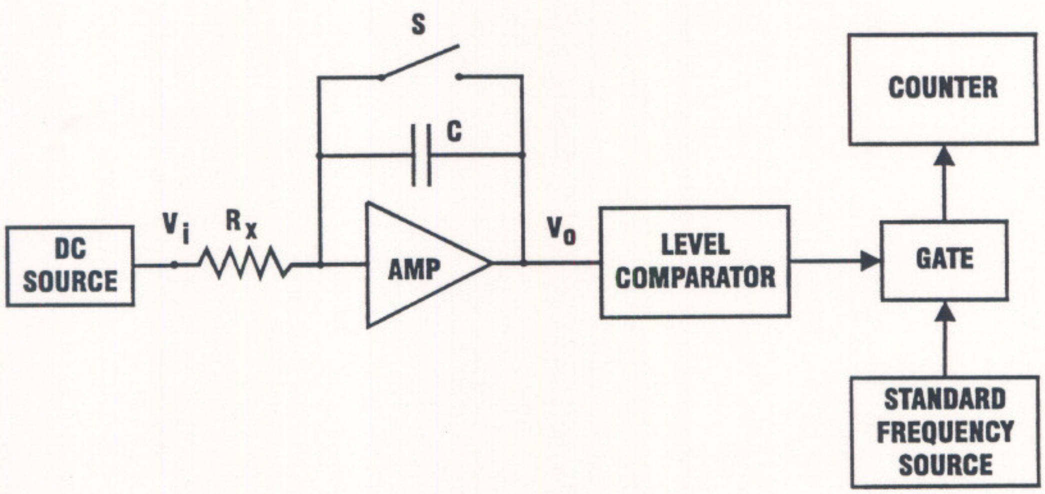

Figure 2. Teraohmmeter system.

The teraohmmeter system is only semi-automated, requiring an operator to set the test parameters and connect each resistor under test to the measurement system.

Automated Resistance Ratio Bridge

Recently a commercial automated resistance ratio bridge [6] has been put into service at NIST to verify the scaling process of the guarded Wheatstone bridge. This bridge is fully automatic and is controlled by a PC via the IEEE-488 bus. The automated resistance ratio bridge can measure standard resistances from 1 kΩ to 100 MΩ with a relative expanded uncertainty (coverage factor = 2) of 1×10^{-6} to 2×10^{-6} with test voltages up to 10 V across each of the two resistors connected to the bridge. Using an internal binary resistance divider [7], the bridge determines the ratio between the two resistors and assigns a value to the unknown resistor based on the value of the standard resistor as shown in Figure 3. Resistance ratios up to 1000:1 can be measured on the bridge. An external DVM having 100 nV resolution is used as a differential detector to provide a system resolution of 8 digits.

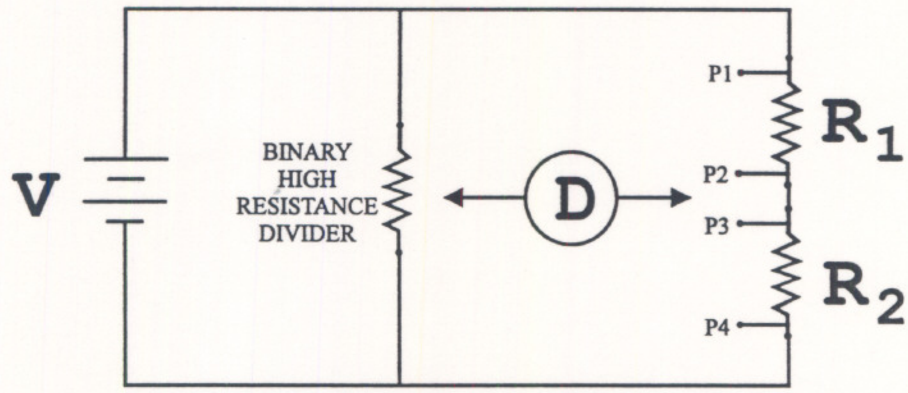

Figure 3. Automated Resistance Ratio Bridge.

This system is primarily used during the scaling process to calibrate NIST standards from 1 MΩ to 100 MΩ. A Hamon box [8], with a series resistance of 10 GΩ and a parallel resistance of 100 MΩ, can be measured in the parallel configuration on the automated resistance ratio bridge. By using the bridge with Hamon boxes, scaling to the 10 GΩ level can be accomplished which is two decades beyond the range of the bridge. Comparisons between the automated resistance ratio bridge and the manual Wheatstone bridge have yielded agreement within 1 part in 10^6 for standards up to 1 GΩ and 3 parts in 10^6 for the 10 GΩ NIST Hamon standard.

A limitation of the automatic resistance ratio bridge is the 10 V maximum test voltage. Many of the standard resistors calibrated by NIST from 10 MΩ to 1 TΩ are thin-film resistance standards. These standards typically exhibit large voltage coefficients requiring them to be calibrated at the specified voltage or voltages at which they will be used; otherwise voltage corrections would have to be applied. NIST has well characterized Hamon boxes with series resistances up to 10 GΩ that have negligable voltage coefficients. These standards can be calibrated on the automated resistance ratio bridge at 10 V and then used at higher voltages with one of the other measurement systems to calibrate customer resistors.

Automated Guarded Multimegohm Bridge

The three systems previously described are all used for different aspects of the process of maintaining and disseminating the U. S. representation of the ohm above 1 MΩ. None of the systems cover the entire range from 10 MΩ to 1 TΩ completely with the lowest possible uncertainty. The guarded Wheatstone bridge and teraohmmeter systems have a degree of manual operation and have constraints that limit their flexibility. The automated resistive ratio bridge test voltage is limited to a maximum of 10 V, thus can only be used to calibrate resistors with very small voltage coefficients or resistors that have well characterized voltage coefficients. To overcome some of these limitations a more versatile system is being implemented at NIST.

An automated guarded multimegohm bridge [9] is formed by replacing two of the resistive arms of a Wheatstone bridge with low impedance programmable voltage calibrators. The bridge is shown below in Figure 4 where V_1 and V_2 are programmable voltage calibrators and detector D is an electrometer with a resolution of ±3 fA in the current mode.

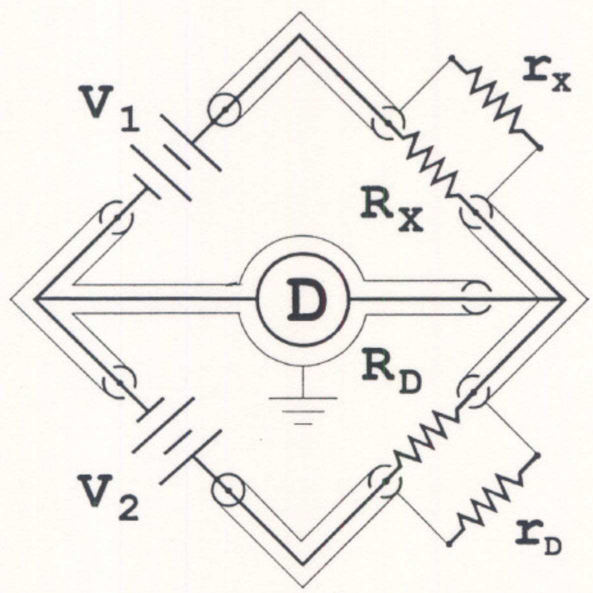

Figure 4. Guarded Multimegohm Resistance Bridge.

The outputs of V_1 and V_2 drive bridge resistances (R_X and R_D) and guard resistances (r_X and r_D). Leakage currents that affect the Wheatstone bridge above 10 GΩ are reduced by the low impedance calibrators and by guarding the high side of the detector with r_X and r_D. The low side of the detector where V_1 and V_2 are joined is a virtual ground.

Multiple bridge ratios up to 1000:1 can be selected by changing the output of the sources. The guarded multimegohm bridge also has the advantage of being able to calibrate standards at 10 TΩ and 100 TΩ, two decades of resistance that have not been supported by NIST calibration services in recent years. Guarded switching [10,11] techniques have also been developed to provide automated substitution of standard and unknown resistors into the bridge.

Scaling

High resistance scaling is achieved by using Hamon boxes to scale from 10 kΩ to 10 GΩ and then back down to 10 kΩ to close the measurement loop. Hamon boxes contain ten component resistors of the same nominal value designed to allow the boxes to be configured in parallel, series-parallel, or series mode; thereby forming standard resistances at three consecutive decade values (e.g. 10 kΩ, 100 kΩ, 1 MΩ). Excluding negligible higher-order terms, the corrections to nominal of the resistances are the same for the series and parallel configurations. The resistance in series-parallel mode is calculated from the correction of the series-parallel resistance of nine of the component resistors, the correction of the tenth component resistor, and the correction associated with the series and parallel resistances. NIST Hamon box resistance standards up to 1 GΩ are made of precision wirewound resistors that have negligible voltage coefficients. The 10 GΩ Hamon box, made of metal-film resistors, also has a negligible voltage coefficient of less than 0.02×10^{-6}/V.

Closed loop scaling from 10 kΩ to10 GΩ and then back to the 10 kΩ starting point, using both the manual Wheatstone bridge and the automated resistance ratio bridge, have shown agreement within 1 part in 10^6 up to 1 GΩ and within 3 parts in 10^6 at 10 GΩ. A closed loop check of the 10 kΩ standards has shown agreement to be within 3 to 5 parts in 10^6 for the return scaling path.

Uncertainties

Sources of error that contribute to the measurement uncertainty of standard resistors are the measurement system, the stability of the standards, and errors accumulated during the scaling process. Presently NIST reports the expanded uncertainties (coverage factor = 2) listed below in Table 1 for standard multimegohm resistors. The wide range of uncertainties for a given value is due to the different calibration systems (Wheatstone bridge and teraohmmeter) and different types of resistors (wirewound and metal-film).

Nominal Resistance	Reported Expanded Uncertainties (10^{-6})
10 MΩ	14 to 140
100 MΩ	40 to 400
1 GΩ	140 to 700
10 GΩ	400 to 700
100 GΩ	700
1 TΩ	1400

Table 1. Multimegohm uncertainties.

Typically a set of measurements made on multimegohm standard resistors will yield a relative standard deviation of the individual readings ranging from 5×10^{-8} to 4×10^{-5} for the guarded Wheatstone bridge and from 1×10^{-5} to 3×10^{-4} for the teraohmmeter system. Nominal resistance, test voltage, temperature and humidity stability, and the quality of the standard are primary factors affecting the reproducibility of measurements on a standard multimegohm resistor.

By using the automated resistance ratio bridge to verify the scaling process and the guarded multimegohm bridge to reduce systematic errors, NIST expects to be able to reduce reported uncertainties by at least a factor of two for the calibration of most standard multimegohm resistors.

Summary

NIST currently offers high resistance calibration services over the range 10 MΩ to 1 TΩ. Presently a manually operated Wheatstone bridge and a semi-automated digital teraohmmeter system are used to provide calibration services in the high resistance range. An automated resistance ratio bridge along with Hamon boxes are used during the scaling process to periodically calibrate NIST standards from 10 MΩ to 10 GΩ in terms of the quantized Hall resistance. An additional system using dc voltage calibrators in two of the bridge arms is being implemented and will eventually replace the guarded Wheatstone bridge and teraohmmeter systems used to calibrate customer resistors. Guarded switching methods are being refined to provide guarded switching for measurements above 1 MΩ.

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