AUTOMATED RESISTANCE MEASUREMENTS AT NIST

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Abstract

The National Institute of Standards and Technology (NIST) provides a calibration service for dc standard resistors over 17 decades of resistance from 10^{-4} Ω to 10^{12} Ω using seven independent measurement systems. Four measurement systems are completely automated for calibrating resistors from 1 Ω to 1 MΩ. A fifth system for high resistance measurements is semiautomated. Plans are underway to fully automate this system, along with the remaining two measurement systems. The primary consideration to automate a measurement system is to improve the quality of measurements, and not simply to relieve the operator from tedious repetitive measurements. This paper describes the extent and future plans of resistance measurement automation at NIST.

Introduction

At NIST, the U.S. representation of the ohm is based on the quantum Hall effect, and it is maintained at various resistance levels by working reference groups of standards. It is disseminated by a NIST calibration service for standard resistors of nominal decade values in the range from 10^{-4} Ω to 10^{12} Ω.(1) To provide this wide-ranging calibration service for 17 decades of resistance requires the use of seven stand-alone measurement systems for comparing standard resistors.

In 1982 the direct current comparator (DCC) potentiometer system for the calibration of 1 Ω resistors was automated. The success of this project resulted in the development of a second DCC system for the calibration of 10 Ω and 100 Ω resistors in 1985. Since 1989, standard resistors having nominal values of 1 kΩ, 10 kΩ, 100 kΩ, and 1 MΩ have been calibrated using an automated system based on an unbalanced-bridge method. In 1995, an automated resistance-ratio bridge for the

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calibration of high-quality 10 kΩ standards was completed. A fifth system for high resistance measurements (>1 MΩ) is semiautomated. Plans are underway to automate this system fully along with the remaining two measurement systems.

There were many advantages realized in automating these measurement systems. Foremost, the quality of the measurements has improved. 1) Automation has eliminated the bias of the operator and errors that result from transcribing data. 2) Measurements can be taken during non-working hours when electrical and mechanical environmental noise is at a minimum. 3) Measurement precision is improved with the taking of more measurements under a controlled and repetitive balancing algorithm. The precise timing of measurement sequences eliminate short-term drift effects of resistors. 4) Automation relieves the operator from tedious and iterative tasks, allowing more time for research activities. 5) Finally, automation has reduced the part of the calibration fee that is associated with direct labor costs.

This paper briefly describes the automated resistance measurement systems at NIST along with some of the challenges overcome in developing these systems. The status of future automated resistance measurement systems at NIST will also be discussed.

Automated Systems

Each of the four automated resistance measurement systems is controlled by a dedicated personal computer (PC), which communicates with the system's instruments using serial, parallel, and IEEE-488 standard interfaces. In changing from an operator-controlled system to a computer-controlled or automated system, the primary consideration is that the automated system must function at the state-of-the-art level and not increase the uncertainty of the measurement process.

1 Ω Measurements

An automated DCC potentiometer system, shown in Figure 1, is used for the measurement of Thomas-type 1 Ω standards.(2) Fifteen 1 Ω resistors - five of which comprise the working group, along with two check standards and eight test resistors - are connected in series in the primary circuit of the DCC. The value of any resistor in the string can be determined by indirectly comparing its voltage drop to the mean of the voltage drops of the working group via a stable resistor R_D in the secondary circuit of the DCC. Ampere-turn balance is maintained with the adjustment of the slave current source by the output of the demodulator circuit operating in a feedback mode. The voltage balance (D) is made automatic by driving the photocell galvanometer amplifier (PGA) detector to a null condition with a feedback current through an auxiliary 10 turn winding. This feedback current, which is proportional to the difference between the resistors being compared, is monitored by measuring the voltage drop across a 100 Ω resistor using a digital voltmeter (DVM). The feedback circuit (A) is calibrated by inserting an additional unit turn in the primary circuit of the DCC, which changes the voltage balance by 500 parts per million (ppm). A PC controls the operation of the DVM, resistor selection, current reversal, and the feedback calibration signal. The PC also monitors the oil bath temperature, ambient temperature, ambient relative humidity, and barometric pressure.

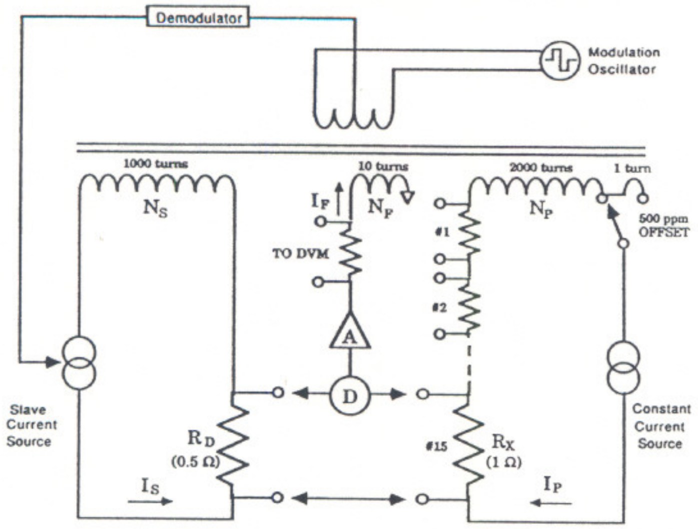

Figure 1. Automated DCC potentiometer for 1 Ω measurements.

The main problem areas encountered in automating this system were the detector/feedback and switching circuits. An initial attempt was made to use a digital nanovoltmeter as the detector to measure the unbalanced voltage between resistors in the DCC circuit directly. The excellent linearity of the digital nanovoltmeter precluded the need to achieve a null balance, and it could be readily interfaced to a PC. However, it proved unsatisfactory due to an excessive ac signal (700-800 Hz) in the DCC windings as a result of core mismatch in the modulator/demodulator network. This ac signal introduced noise greater than 0.5 ppm in the detector circuit that was not entirely filtered out by the nanovoltmeter. The problem was solved by keeping the original PGA as the detector and, because of its poor linearity, constructing a feedback circuit to drive the PGA to a null condition.

The main requirement of the switching system was that it have low thermoelectric voltages, since resistor comparisons are done by a potentiometric method with only 0.1 V across a resistor. A commercial crossbar switch was modified for the selection of resistor potentials to be compared. The critical contacts of the crossbar switch were placed in a thich-walled aluminum box and separated from their actuator coils using plastic rods. This reduced thermal gradients within the box and resulted in low thermoelectric voltages.

10 Ω and 100 Ω Measurements

A second DCC potentiometer was modified for the automated measurements of 10 Ω and 100 Ω resistors. The design, construction, and operation of this system are similar to that for the automated 1 Ω system. The DCC potentiometer was modified to provide automatic current reversal, automatic ratio offset, an external access to a 10 turn winding, and an isolated detector output circuit. The detector-feedback circuit is similar to the one used in the 1 Ω system. However, instead of fifteen resistors, the system is designed to intercompare eight resistors of the same nominal value: two working standards, one check standard, and five unknowns.

1 kΩ to 1 MΩ Measurements

An automated system, based on an unbalanced-bridge technique, was developed to calibrate resistors of nominal decade values of 1 kΩ, 10 kΩ, 100 kΩ, and 1 MΩ.(3) The system is specifically designed to measure differences among six nominally-equal, four-terminal standard resistors (R1,R2, ... R6) as shown in Figure 2. A voltage (V) is applied across points A and A' of the hexagonal ring which divides the ring into two parallel branches each containing three resistors. Then, a DVM is used to measure voltages (V1,V2, ...V6) between opposing equipotential terminals of the resistors. Next, the applied voltage points across the ring are rotated in a clockwise direction to points B and B'. Again voltage measurements are taken between corresponding terminals of the resistors that are at nearly equal potentials. This measurement process is repeated a third time with voltage applied across points C and C'. From the three subsets of measurements for the different connections of the applied voltage, one obtains a set of nine linear equations. Values of the resistors can be calculated if the value of at least one of the resistors in the ring is known.

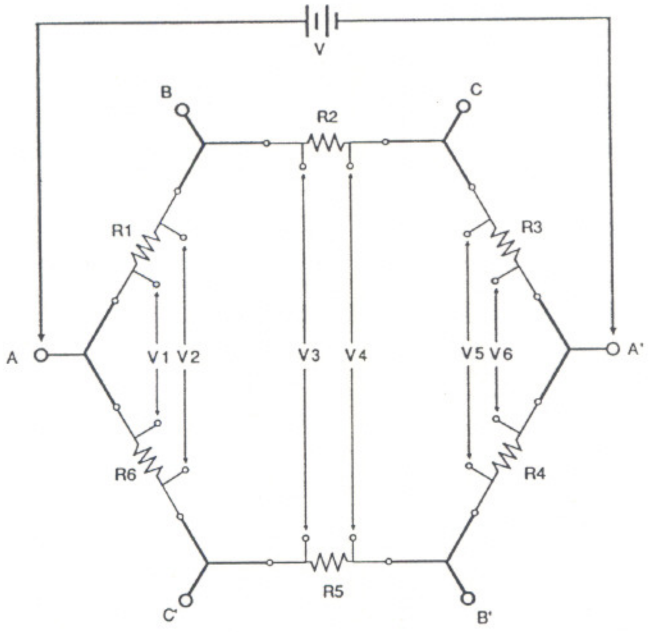

Figure 2. Unbalanced-bridge circuit for six resistors.

A problem encountered in automating this system was that the voltage source and DVM can have leakage resistances to ground on the order of 10^{10} to 10^{11} Ω. These leakage resistances effectively shunt parts of the ring circuit and result in significant measurement errors at the 100 kΩ level and above. To reduce these errors, an active guard network was used to drive the guard terminal of the DVM at nearly the same potential as its input terminals.

10 kΩ Measurements

Recently an automated resistance bridge has been developed for the calibration of high-quality 10 kΩ standards. It is based on the Warshawsky bridge(4) which adds fan resistors at the branch points of the bridge to eliminate first-order effects caused by lead resistances. A schematic diagram of this bridge is shown in Figure 3 without its guard circuit. The main bridge circuit consists of ratio arms A/B, dummy resistor R, the unknown resistor X, and fan resistors a, b, r, and x. The bridge is designed to be self-balancing. The isolated output of the electronic detector is connected to an operational integrator which provides a feedback current to a 0.1 Ω resistor. The voltage drop across this resistor drives the detector to a null condition. The feedback current is monitored by a DVM and is calibrated by introducing offsets in ratio arms A or B via switches S1 and S2. The measurement range of the feedback circuit is ±100 ppm.

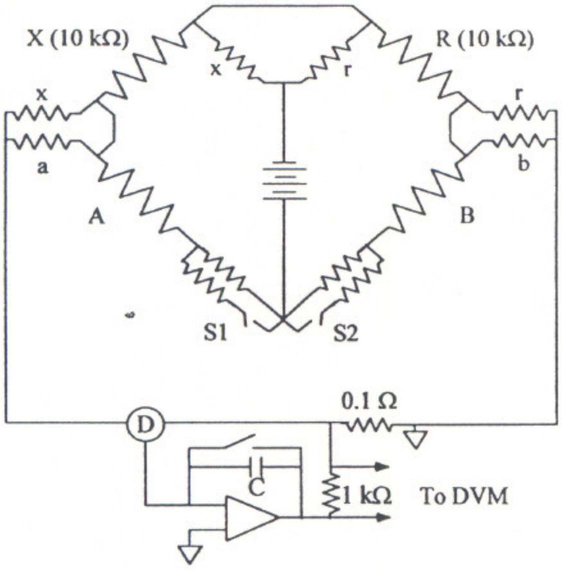

Figure 3. Automated 10 kΩ resistance bridge.

A unique programmable guarded coaxial connector panel$^{(5)}$ was developed for selecting resistors. A computer controlled 3-axis positioning system is used to move a 4-connector vertical arm over a panel of 72 coaxial connectors mounted in a horizontal plane. This provides for 30 four-terminal channels. The shields of the connectors are driven by a guard circuit to suppress errors caused by leakage currents.

Future Plans

NIST has completed the automation of resistance measurements from 1 Ω to 1 MΩ. Future plans are to extend the automation of measurements above and below this resistance range.

Measurements >1 MΩ

Standard resistors of nominal decade values from 10 MΩ to 10 GΩ are measured using a NIST-built guarded Wheatstone bridge. This bridge is manually operated and is limited to the comparison of standard resistors that are within 5000 ppm of nominal. For the measurements of high value resistors outside of this tolerance or with nominal decade values extending from 10 GΩ to 1 TΩ, a semiautomatic technique using a commercial digital teraohmmeter is used. The teraohmmeter is controlled by a PC and the measurement of a single resistor is fully automated. However, the selection of resistors under test has not been automated. Because of the high resistances involved, the automatic selection of resistors has to be done using a guarded scanner. NIST plans to develop a two-terminal version of the programmable guarded switch used for the 10 kΩ measurements.

NIST is also developing an automated Wheatstone bridge arrangement for the measurement of high value resistance standards above 1 MΩ based on reference 6. In it, the resistance ratio arms and the bridge voltage supply of the Wheatstone bridge are replaced by two programmable voltage sources. A PC controls the voltage sources and reads an electrometer detector, via the IEEE-488 interface. Bridge balance is achieved by adjusting one of the voltage sources. Linearity of the voltage source is measured using a calibrated DVM. A guarded scanner will be used for the selection of test resistors. A special environmental chamber(7) has been constructed for housing the resistors under test. The chamber temperature is controlled at 23 ± 0.02 °C and the relative humidity maintained at 35 ± 5%.

Measurements ≤1 Ω

NIST plans to use a modified commercial DCC for the automatic measurement of standard resistors of nominal decade values ≤1 Ω. This measurement system will be primarily used for the calibration of Rosa-type 1 Ω standard resistors or their equivalent, and for all four-terminal standard resistors having nominal values of 0.1 Ω, 0.01 Ω, 0.001 Ω, and 0.0001 Ω. The maximum current capability of the system will be 100 A.

Conclusion

NIST has completed automating its measurement systems for the calibration of standard resistors of nominal decade values from 1 Ω to 1 MΩ. Some of the techniques used to automate these systems may be of interest to other standards laboratories. Automation has improved the quality of the measurements while reducing the amount of operator time spent on these measurements. Plans are underway at NIST to automate the remaining manual systems used to calibrate standard resistors.

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