Automated Guarded Bridge for Calibration of Multimegohm Standard Resistors from 10 MΩ to 1 TΩ

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Abstract—The implementation of an automated guarded bridge for calibrating multimegohm standard resistors is described. A guarded multimegohm bridge has been assembled with programmable dc calibrators in two of the arms allowing multiple ratios and test voltages to be remotely selected. A programmable electrometer with a resolution of ±3 fA in the current mode is used to measure the difference in currents flowing through the remaining two arms of the bridge consisting of unknown and standard resistors. The balancing algorithm used to estimate the calibrator setting required to obtain a null is described along with a graphical user interface (GUI) that has been written to provide flexibility to the measurement system and improve control of the instrumentation. Evaluation of the multimegohm bridge from 10 MΩ to 1 TΩ is reported along with a comparison of the multimegohm bridge performance to that of the existing manual and semi-automated systems that it will replace.

I. INTRODUCTION

Calibrations of standard resistors from 10 MΩ to 1 TΩ at NIST are done manually on a guarded Wheatstone bridge or by using a semiautomated procedure with a teraohmmeter [1]. Both measurement systems require a degree of manual operation and have constraints that limit their flexibility. Neither system sufficiently covers the entire range of 10 MΩ to 1 TΩ with the lowest possible uncertainty. A single automated and robust system is being developed at NIST to replace the two aging systems, eliminate operator error, reduce uncertainties, and expand calibration services to resistances above 1 TΩ.

The method of using dc voltage calibrators in two arms of a bridge [2] is the approach selected to accomplish this task. The low output impedance of the calibrators reduces errors caused by leakage currents. Guarding the high side of the detector reduces leakages at that point. A graphical user interface (GUI) [3] has been written to provide flexibility to the measurement system and improved control of the instrumentation. Initial data indicate that the completed bridge should be able to calibrate multimegohm standard resistors at uncertainties of at least a factor of two below those of present NIST calibrations of multimegohm resistors.

II. GUARDED MULTIMEGOHM BRIDGE

For a Wheatstone bridge [4], the equation at time of balance is

\[ \frac{R_1}{R_2} = \frac{R_x}{R_s} \] (1)

where \( R_1 \) and \( R_2 \) are resistances of the ratio arms of the bridge \( R_1 \) and \( R_2 \), respectively, and \( R_x \) and \( R_s \) are values of unknown and standard resistors as shown in Fig. 1. The detector \( D \) and source \( V \) complete the traditional Wheatstone bridge.

In the automated multimegohm bridge, resistors \( R_1 \) and \( R_2 \) are replaced with programmable voltage sources \( V_1 \) and \( V_2 \) set to voltages \( E_1 \) and \( E_2 \) following:

\[ \frac{E_1}{E_2} = \frac{R_x}{R_s} \] (2)

at time of balance. The bridge voltage supplied by source \( V \) shown in Fig. 1 now is generated by \( V_1 \) and \( V_2 \). Substituting programmable voltage sources for the main ratio arm and adding a guard resistor network to the bridge yields the circuit shown in Fig. 2 where \( r_x \) and \( r_s \) are guard resistors.

The outputs of \( V_1 \) and \( V_2 \) drive bridge resistors \( R_x \) and \( R_s \) and guard resistors \( r_x \) and \( r_s \). Leakage currents that affect Wheatstone bridge circuits with high resistance ratio arms are reduced by the low impedance calibrators (<0.1 Ω at dc) and by active guarding of the high side of the detector at the same potential as the \( r_x \) and \( r_s \) interconnection. The low side of the detector where \( V_1 \) and \( V_2 \) are joined is at a virtual ground potential.
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 levels of resistance that have not been supported by NIST calibration services in recent years.

III. BALANCING PROCEDURE

An electrometer with a resolution of ±3 fA in the current mode is used as the detector to measure the difference in the currents, ΔI, flowing through Rx and Rs. Initially the voltage sources are set to E1Est and E2 chosen to have the same nominal ratio of Rx and Rs. The current ΔI is measured by the detector. The estimated output E1′Est of source V1, required to drive the bridge to a null, is calculated using the following:

\[ E_{1\text{'Est}} = \frac{\Delta I + E_2 / R_s}{R_x} \]  

(3)

where Rs and Rx are nominal resistances. The source V1 is then set to the voltage E1′Est which reduces ΔI to a lower value ΔI′ bringing the bridge closer to a null. A linear fit is then applied to determine the exact setting of V1, required to reach a null based on the two iterations of E1′Est and ΔI as shown here

\[ E_1 = \frac{\Delta I \cdot E_{1\text{'Est}} - \Delta I' \cdot E_{1\text{'Est}}}{\Delta I - \Delta I'} \]  

(4)

The unknown value Rx can then be solved for by substituting E1, E2, and Rs into (2).

A linear relationship, as expected from Ohm's Law (V = RI), exists between the test voltage applied to the unknown resistor by calibrator V1 and the current ΔI measured by the electrometer. The graph shown in Fig. 3 demonstrates that a change in the test voltage will result in a proportional change in the current measured by the null detector. A least squares fit of the data plotted in Fig. 3 shows that the bridge is nulled when E1 = 1.00421 V. Equation (3) and the initial conditions of E2Est = 1 V and ΔI = -417 pA are used to determine an estimated calibrator setting of E1′Est = 1.00417 V required to null the bridge. Substituting E2Est = 1 V, ΔI = -417 pA, \( E_{1\text{'Est}} = 1.00417 \), and ΔI′ = 4.15 pA into (4) yields a calibrator setting E1 required to null the bridge that is within 1 x 10^-6 of the value determined by a least squares fit of the data shown in Fig. 3.

Due to the linearity of the detector, sources, and resistors, the balancing algorithm described here can be used to closely estimate the bridge null from two bridge settings. The true null is then interpolated by a linear fit of the voltage and current at the initial test point and the approximated null point.

Once a bridge null is determined, the procedure is repeated with the voltage sources set to -E1Est and -E2 thus reversing the flow of current, eliminating the effect of constant thermal emfs in the detector circuit.

IV. GRAPHICAL USER INTERFACE

A graphical user interface (GUI) has been written that makes selection of voltage ranges and bridge ratio automatic. Balancing and computations are also controlled by the GUI along with the electrometer and calibrators.

The GUI allows the operator easily to select test parameters such as nominal resistances, test voltages, and bridge ratios. The event driven control structure of the GUI allows the software to respond immediately to changing parameters and handle errors without complex error handling routines.
Changes in bridge parameters can be made without the risk of creating overload conditions such as a test voltage out of the calibrator range or applying voltages that could damage bridge components.

During the development of software for operating the multimegohm bridge, changes to the GUI could easily be made by adding controls for specific functions and test options. Option boxes can quickly be presented allowing the operator to make decisions and choices by pointing to a control and clicking with the mouse button. The GUI written for the multimegohm bridge has individual forms presented to the operator for initiating the measurement system, entering resistor identification, setting test parameters, summarizing the data, branching to additional tests, and shutting down the measurement system. The form used for setting test parameters is shown in Fig. 4.

Other features of the GUI are multiple control options, linking to databases, plotting of data, and a user friendly interface.

V. RESULTS

Table I shows a breakdown of the Type A and Type B standard uncertainties associated with the multimegohm system for ratios of 1:1 and 10:1. Both bridge ratios were evaluated at decade resistances $R_x$ from 10 MΩ to 1 TΩ at 100 V. For the multimegohm bridge, the combined standard uncertainties of a
given set of measurements are lower than those associated with the Wheatstone bridge and teraohmmeter systems as shown in Table II.

Using the substitution method [1], two resistors at each nominal value (10 MΩ to 1 TΩ) were calibrated on the multimegohm bridge and the Wheatstone bridge or teraohmmeter systems. Errors resulting from ratio nonlinearity, leakage currents, and lead and contact resistances tend to cancel by substituting standard and unknown resistors of the same nominal value in the Rx arm of the bridge. Table III shows the relative differences between the standard and unknown resistor for each system at 100 V. Nominal resistances from 10 MΩ to 10 GΩ were calibrated on the Wheatstone bridge and 100 GΩ and 1 TΩ resistances were calibrated on the teraohmmeter system. All resistors were then calibrated on the multimegohm system. The last row shows the differences between the existing measurement systems and the multimegohm bridge. This difference is within the combined standard uncertainties for the Wheatstone bridge and teraohmmeter systems as shown in Table II.

VI. CONCLUSION

An automated bridge for measuring multimegohm standard resistors has been assembled using programmable dc calibrators in two of the arms. A balancing algorithm has been developed that will approximate a null with one iteration. Repeated measurements have shown that the bridge can calibrate standard resistors from 10 MΩ to 1 TΩ with standard deviations of measurements equal to or smaller than those for the measurement systems presently used by NIST to calibrate multimegohm standard resistors. A graphical user interface has been developed that provides flexibility to the measurement system.

Future plans are to evaluate the multimegohm bridge 100:1 and 1000:1 ratio configurations and extend use of the bridge to the 10 TΩ and 100 TΩ decades of resistance.

ACKNOWLEDGMENT

The author would like to thank R. Dziuba for his guidance and insight and R. Elmquist for his encouragement and help with high resistance measurements.

REFERENCES


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