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 the multimegohm bridge 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.

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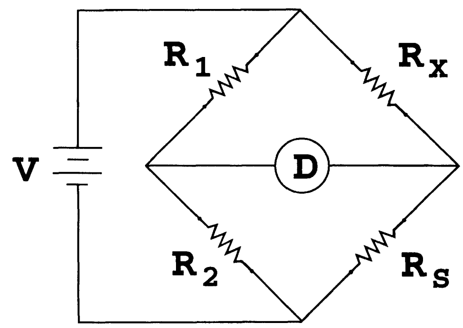

Fig. 1. Conventional Wheatstone bridge.

II. Guarded Multimegohm Bridge

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

$$R_1/R_2 = R_X/R_S \quad (1)$$

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 voltage 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:

$$E_1/E_2 = R_X/R_S \quad (2)$$

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.

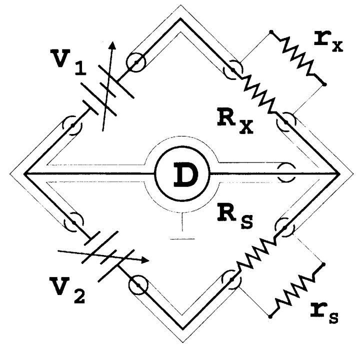

Fig. 2. Guarded multimegohm bridge. Programmable sources (V_1 and V_2) drive bridge resistors (R_X and R_S) and guard resistors (r_X and r_S). Detector D measures difference in currents flowing through R_X and R_S.

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 R_X and R_S. Initially the voltage sources are set to $E_{1\mathrm{Est}}$ and E_2 chosen to have the same nominal ratio of R_X and R_S. The current ΔI is measured by the detector. The estimated output $E'_{1\mathrm{Est}}$ of source V_1, required to drive the bridge to a null, is calculated using the following:

$$E'_{1\mathrm{Est}} = [\Delta I + E_2/R_S]R_X \quad (3)$$

where R_S and R_X are nominal resistances. The source V_1 is then set to the voltage $E'_{1\mathrm{Est}}$ which reduces ΔI to a lower value $\Delta I'$ bringing the bridge closer to a null. A linear fit is then applied to determine the exact setting of V_1 required to reach a null based on the two iterations of $E_{1\mathrm{Est}}$ and ΔI as shown here

$$E_1 = [\Delta I \cdot E'_{1\mathrm{Est}} - \Delta I' \cdot E_{1\mathrm{Est}}]/[\Delta I - \Delta I']. \quad (4)$$

The unknown value R_X can then be solved for by substituting E_1, E_2, and R_S 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 V_1 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 $E_1 = 1.004\,21$ V. Equation (3) and the initial conditions of $E_{2\mathrm{Est}} = 1$ V and $\Delta I = -417$ pA are used to determine an estimated calibrator setting of $E'_{1\mathrm{Est}} = 1.004\,17$ V required to null the bridge. Substituting $E_{2\mathrm{Est}} = 1$ V, $\Delta I = -417$ pA, $E'_{1\mathrm{Est}} = 1.004\,17$, and $\Delta I' = 4.15$ pA into (4) yields a calibrator setting E_1 required to null the bridge that is within 1×10^{-6} of the value determined by a least squares fit of the data shown in Fig. 3.

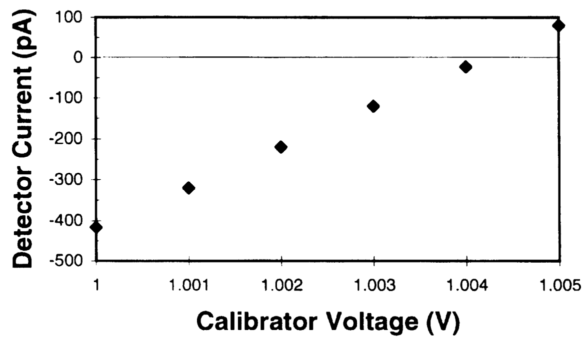

Fig. 3. Detector current versus calibrator voltage shows the linearity of the multimegohm bridge.

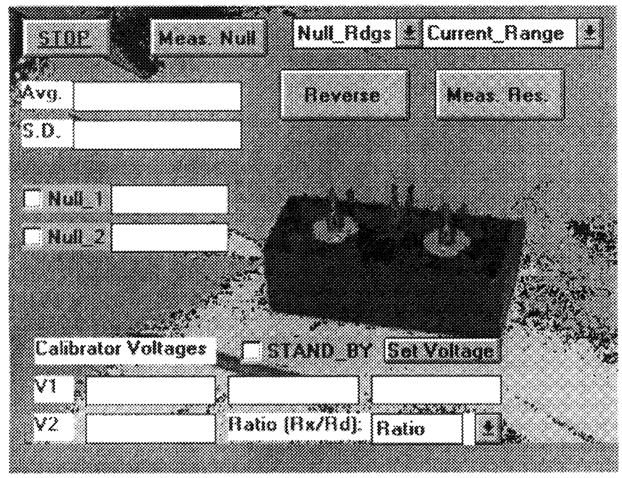

Fig. 4. GUI form used to set test parameters for multimegohm bridge.

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 $-E_{1\mathrm{Est}}$ and $-E_2$ 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.

TABLE I
TYPE A AND TYPE B RELATIVE STANDARD UNCERTAINTIES FOR MULTIMEGOHM SYSTEM (1×10^{-6}). TYPE A RELATIVE STANDARD UNCERTAINTIES ARE REPORTED FOR 1:1 AND 10:1 RATIO CONFIGURATIONS

	Nominal Resistance					
	10 MΩ	100 MΩ	1 GΩ	10 GΩ	100 GΩ	1 TΩ
	Type A Relative Standard Uncertainties (1×10^{-6})					
1:1 Ratio	0.25	0.2	1	10	20	100
10:1 Ratio	0.2	0.1	0.2	4	5	30
	Type B Relative Standard Uncertainties (1×10^{-6})					
Leakages	0.01	0.01	0.01	0.1	1	10
Connections	0	0	0	0	0	0
Linearity	2	2	2	2	2	2
Det. Resolution	0	0	0.01	0.1	1	9
Calibrator	2	2	2	2	2	2
Ambient	1	1	1	5	5	5
Scaling	1	1	1	3	10	20
Standards	2	2	5	10	50	100
	RSS Total of Type B Relative Standard Uncertainties (1×10^{-6})					
	3.7	3.7	5.9	11.9	51.3	103.0

TABLE II
COMBINED RELATIVE STANDARD UNCERTAINTIES FOR MULTIMEGOHM, WHEATSTONE BRIDGE, AND TERAOHMMETER MEASUREMENT SYSTEMS FROM 10 MΩ TO 1 TΩ (1×10^{-6}). COMBINED RELATIVE STANDARD UNCERTAINTIES FOR MULTIMEGOHM SYSTEM ARE REPORTED FOR 1:1 AND 10:1 RATIO CONFIGURATIONS

	Nominal Resistance					
	10 MΩ	100 MΩ	1 GΩ	10 GΩ	100 GΩ	1 TΩ
System	**Combined Relative Standard Uncertainties (1×10^{-6})**					
1:1 Ratio Multimegohm	3.8	3.7	6.0	15.6	55.1	143.6
10:1 Ratio Multimegohm	3.7	3.7	5.9	12.6	51.6	107.3
Wheatstone Bridge	6	13	54	-------	-------	-------
Teraohmmeter	52	111	221	325	325	568

TABLE III
RELATIVE DIFFERENCES OF RESISTANCE MEASUREMENTS FOR MULTIMEGOHM, WHEATSTONE BRIDGE, AND TERAOHMMETER SYSTEMS GIVEN AS DEVIATIONS FROM NOMINAL (1×10^{-6})

	Nominal Resistance					
	10 MΩ	100 MΩ	1 GΩ	10 GΩ	100 GΩ	1 TΩ
System	**Relative Deviation from Nominal (1×10^{-6})**					
Wheatstone Bridge	-27.7	-45.7	115.6	-7797	-------	-------
Teraohmmeter	-------	-------	-------	-------	5801	14918
10:1 Ratio Multimegohm	-23.3	-49.1	115.8	-7844	6000	14613
	Relative Deviation from Nominal (1×10^{-6})					
System Differences	4.4	3.4	0.2	47	199	305

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 R_X 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

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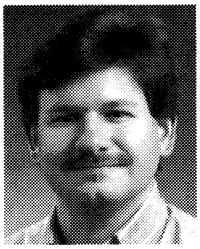
References

[1] R. F. Dziuba., P. A. Boynton, R. E. Elmquist, D. G. Jarrett, T. P. Moore, and J. D. Neal, "NIST measurement services for dc standard resistors," *Nat. Inst. Standards Technol. Tech. Note 1298*, pp. 5, 20–22, 27–28, 47, 1992.

[2] L. C. A. Henderson, "A new technnique for the automated measurement of high valued resistors," *J. Phys., Electron., Sci. Instrum.*, vol. 20, pp. 492–495, Sept. 1987.

[3] R. P. Nelson, *Running Visual Basic for Windows*. Redmond, WA: Microsoft Press, 1993, pp. 13–16.

[4] F. K. Harris, *Electrical Measurements*. New York: Wiley, 1952, p. 258.



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