Design and evaluation of a low thermal electromotive force guarded scanner for resistance measurements

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The design and testing of a low thermal electromotive force guarded scanner, developed to provide completely guarded switching when used with actively guarded resistance bridge networks, is described. The design provides a continuous guard circuit trace on the scanner circuit boards that surrounds the relay contacts and protects the measurement circuit from leakages to ground. Modification to the circuit boards and relays of the guarded scanner are explained. Several tests were developed to evaluate the guarding effectiveness, including isolating sections of the guard circuit to create a potential drop between the main and guard circuits. Calibration of standard resistors using the guarded scanner has shown relative differences less than 1×10^{-6}, 30×10^{-6}, and 150×10^{-6} for measurements made with and without the guarded scanner at nominal resistances of 1, 10, and 100 GΩ, respectively. The substitution method was used to significantly reduce the relative differences between channels to less than 0.5×10^{-6}, 3×10^{-6}, and 30×10^{-6} for nominal resistances of 1, 10, and 100 GΩ, respectively. Applications for the guarded scanner in automated direct current measurement systems are presented.   [S0034-6748(99)01306-4]

I. INTRODUCTION

With the automation of measurement systems used to calibrate standard resistors at NIST in the 1980's and 1990's came the need for automating the connection of standard resistors to measurement systems. Automation improves the quality of the measurement process by eliminating operator bias, provides a controlled repetitive algorithm for data collection, and permits data collection during nonworking hours when electrical and mechanical noise is at a minimum.[1]

Type B standard uncertainties attributed to leakage currents flowing to ground have been reduced in many of the resistance measurement systems at NIST by the use of guard networks.[2] Without also guarding the switching of resistors, leakage errors can degrade the accuracy of resistance measurements, especially at resistances ≥ 100 kΩ. One approach to solving the switching problem is a programmable, guarded coaxial panel[3] to which connections are made using a three-axis positioning system to plug coaxial connectors into one another. A second approach, described here, is to design the circuit boards and relays of a low thermal electromotive force (emf) scanner so that the measurement or main circuit path is completely enclosed in a guard circuit. Driving the guard circuit at the same potential as the main circuit increases the effective resistance[4] of the insulation between the main and guard circuits, and very little leakage current is able to flow between the measurement and guard circuits.

Leakage currents that flow to ground potential from the guard circuit have negligible effect on the measurement circuit.

Through a collaborative effort, Data Proof[5] and NIST researchers have developed and evaluated a low thermal-emf guarded scanner that can be used in automated resistance bridges over the range from 100 Ω to 100 GΩ without adding any appreciable uncertainty to that of the measurement process. The techniques used to guard the low thermal-emf scanner, including the redesign of the latching relays and modifications to the printed circuit boards, are presented along with procedures used to evaluate the effectiveness of the guard circuit. Results of the evaluation are reported and several applications for a guarded scanner are discussed.

II. BACKGROUND

Low thermal-emf scanners have been used at NIST successfully in automating measurements over the range 100 Ω to 1 MΩ with expanded uncertainties from 0.5×10^{-6} to 3×10^{-6}, respectively. The largest source of type B standard uncertainty at the 100 kΩ and 1 MΩ levels is leakages to ground. Guarding the scanners and the resistor junctions in the NIST-built unbalanced bridge[2] would reduce the expanded uncertainties at resistance levels of 100 kΩ and above. Automation of guarded NIST measurement systems at 10 MΩ and above[6] would also benefit from the develop-

ment of a guarded scanner. The approach taken was to design a second generation scanner that would provide guarding of the measurement circuit while maintaining the low thermal-emf and low noise characteristics that make the use of these scanners in automated measurement systems successful.

By designing a guard circuit that would drive the coaxial shields at the same potentials as the inner conductors of the main circuit, the effective resistance of the insulation can be significantly increased to provide greater protection of the measurement or main circuit from leakages to ground potential. The effective resistance, R_{eff} is defined as

$$R_{eff} = R_{ins} V_S / (V_S - V_G), \tag{1}$$

where R_{ins} is the resistance of the insulator, V_S is the main circuit potential, and V_G is the guard potential. As an example, matching the guard potential within 1% of the main circuit potential will increase the effective resistance by 100 times the actual resistance of the insulator.

Without driving the shields at the appropriate guard potentials, leakage currents can flow to ground from multiple circuit places, including at the connections to resistors under test, unguarded cabling, relays, and circuit boards. The challenge was to develop a configuration that would make it possible to select multiple channels with the relays and still maintain a guard potential around the entire measurement circuit. Figure 1 shows the low thermal-emf scanner with the switched guard shields. The scanner provides guarded shielding from the resistors through the relays to the guarded bridge, permitting the guarded connection of multiple resistors to the bridge.

III. DESIGN

A commercial low thermal-emf scanner[7] was modified to incorporate a switched guard circuit. To connect a shield through the scanner that could be driven at a guard potential along the entire path of the main circuit required guard traces to be placed on the relay circuit boards. The relay contact actuators also needed to be guarded so that leakage currents would not flow through the relays themselves to ground potential.
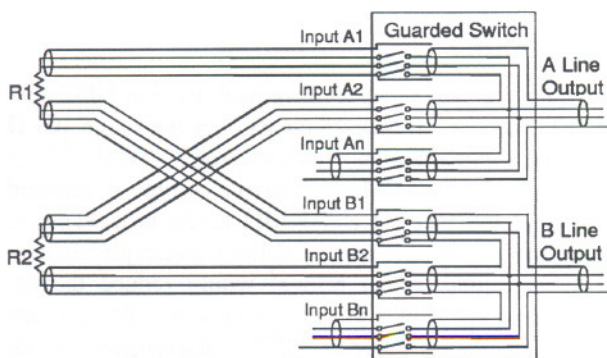

FIG. 1. Low thermal-emf guarded scanner showing switched guard shields. The latching relays connect the guard shields and maintain shielding connections through the relay.

A. Latching relays

In order to minimize thermal-emfs caused by self-heating, the design requires that a short pulse actuates the latching relay. This scanner has typical thermal offsets of less than 20 nV. The actuator consists of a 13 mm by 13 mm steel rocker plate and three gold-plated copper spring multicontact arms. An insulator separates the steel rocker plate from the copper spring contact arms. When the latching relay is pulsed, the copper spring multicontact arms short together the adjacent gold pads on custom plated printed circuit boards.

The relays used for the guarded scanner are modified by drilling and tapping a hole for a small screw to connect the center contact arm to the steel rocker plate. This places the rocker plate at guard potential, thus shielding the main circuit from the relay coils. The circuit design ensures that the rocker plate is at guard potential whether the relay is in the open or closed position. The relay casing base was milled to provide an air gap that eliminates electrical contact with the main and guard traces on the circuit board, removing a leakage path to ground.

B. Relay board

A relay board was designed with guard traces completely surrounding the main circuit paths and gold-plated contact pads as shown in Fig. 2. Where the area between the contact pads was too narrow for guard traces, a notch was cut in the board creating an air gap between the contact pads. The guard traces are plated to the edge of the notches. The relays have three multicontact arms that short out three sets of contact pads on the relay board. One outside contact set switches the current lines, the other switches the potential lines, and the center contact set switches the guard shields.

Due to the high-bulk resistance of the fiberglass circuit board material, most of the leakage current typically flows on the surface of the circuit board. The circuit board has guard traces surrounding the main circuit traces. Where the main circuit crosses from one side of the board to the other so does the guard circuit through vias. Where the shielded cabling connects to the circuit board, the guard circuit vias are notched to the edge of the circuit board to break leakage paths at the circuit board edges. Since the traces on opposite sides of the board are at the same guard potential, leakage currents through the fiberglass insulation are suppressed where the traces cross from one side of the board to the other.

Two relays are used for each resistor, one for the high side and one for the low side. These further separate and isolate the circuits as shown in Fig. 1. The guard circuit is carried through 22 gauge shielded cables from the scanner input and output lines. These leads were eventually terminated to low thermal-emf coaxial connectors. For high-voltage applications, the guarded scanner leads have been terminated to a triaxial connector, adding an outer shield that is connected to earth ground. The inner shield is then driven at a guard potential.
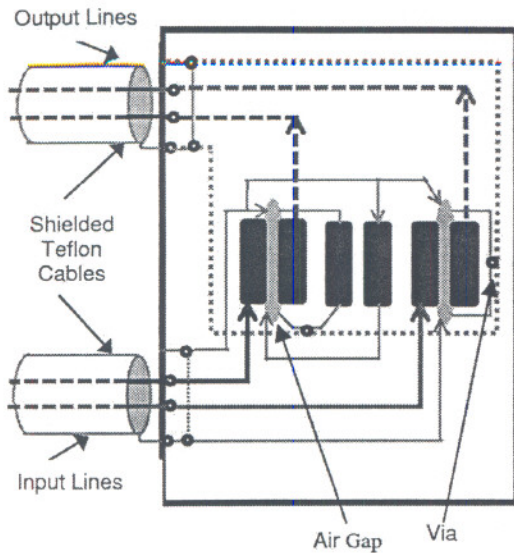
FIG. 2. Relay circuit board of guarded scanner. The center pair of contact pads are connected to the guard traces which surround the main circuit traces and the left and right pairs of contact pads. Air gaps are cut into the board between the main circuit contact pads to prevent current from flowing between the pads when the relay is in the open position. Guard traces extend to the edge of the air gaps forming a boundary around the main circuit contact pads. Closing the relays drives the output lines guard traces at a guard potential. Dashed lines are main and guard traces routed on the opposite side of the relay board. Vias carry the guard circuit to the opposite side of the board.

IV. EVALUATION

Several testing methods were used to evaluate the guarded scanner. These tests were designed to measure the resistance between the main and guard circuits of the scanner and evaluate the effectiveness of the guard circuit. The final tests involved connecting standard resistors to guarded resistance bridges. The substitution method[2] was use to determine the relative differences between the individual guarded channels for resistance measurements made at nominal resistances from 1 MΩ to 100 GΩ. Since standard and test resistors are of the same nominal value, they can be indirectly compared by substitution in the same arm of a bridge circuit. The substitution technique tends to cancel systematic errors such as leakages, bridge nonlinearity, and lead and contact resistances. The guarded scanner was evaluated by using different channels of the guarded scanner to connect the same standard resistors to the same arm of a bridge circuit.

A. Insulation resistance measurement test for leakage

A static test of the insulation resistance between the guard and the main circuit was performed by using a low-current electrometer in series with a battery. The leakage current from the main circuit to the guard was measured with a known voltage applied between the main and guard circuits. Measurements indicated that the insulation resistance between the main and guard circuit paths to be on the order of 10 TΩ. Assuming the guard circuit voltage can be matched within 1% of the voltage of the main circuit, the guarding will increase the effective resistance of the insulation by 100 times to 1 PΩ.
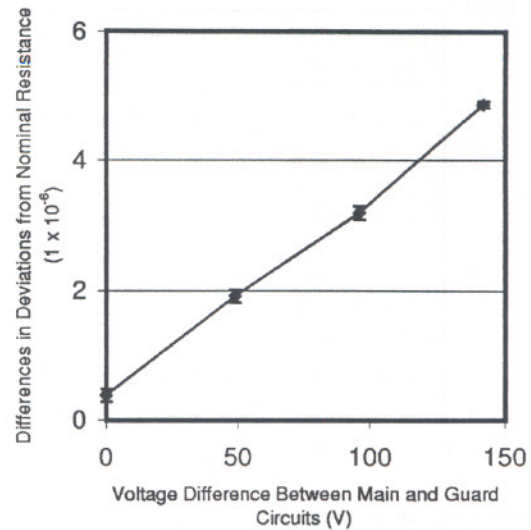

FIG. 3. Leakage between main and guard circuits. A section of guard circuit was isolated and driven at a potential different than the main circuit, forcing leakage current to flow between the main and guard circuits. A difference in detector balance proportional to the voltage difference was observed.

B. Disabled guard circuit to provide path for leakage currents to flow to ground

To determine if the guard circuit of the prototype guarded scanner was working as expected, the guard was bypassed on a portion of the main circuit. This provided an unguarded region where leakage currents could flow to ground. A difference in detector balance proportional to the applied bridge voltage was observed; that is, as the bridge voltage increased, the leakage current increased linearly as is shown in Fig. 3. These test were performed by comparing 10 MΩ standard resistors measured at 100 V using a guarded Wheatstone bridge.[2] The large potential difference between the main and guard circuits decreased the effective resistance of the insulation in the unguarded region of the guard circuit to 3 TΩ.

C. Connection of resistors to a guarded bridge

A series of tests were then performed comparing standard resistors of nominal values from 1 MΩ to 10 GΩ using the guarded Wheatstone bridge and the prototype guarded scanner. Two standard resistors were calibrated on the Wheatstone bridge without the guarded scanner attached. Then the standard resistors were immediately calibrated again with their connection to the bridge being through the guarded scanner. At 1, 10, and 100 MΩ, each of the differences were less than 1×10^{-6}. At 1 and 10 GΩ, the differences were 10×10^{-6} and 100×10^{-6}, respectively. Not all of the features described in the designs of the relays and circuit boards were implemented in the prototype scanner when the initial measurements were made.

After review of these first results, several modifications were made to the designs of the relays and circuit boards of the prototype scanner to eliminate possible leakage paths that were not protected by the guard circuit. Some of the improvements, described earlier, included machining the relay bases, notching the guard vias, adding some additional guard
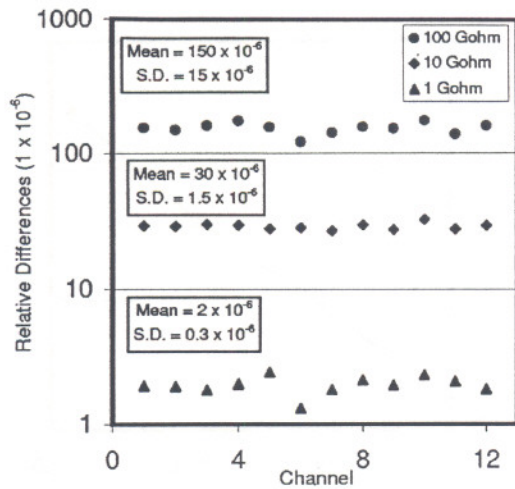
FIG. 4. Relative differences of calibration of standard resistors from 1 to 100 GΩ made using the guarded scanner. Differences between calibrations made with resistors directly connected to measurement system and connection made through each channel of the guarded scanner.
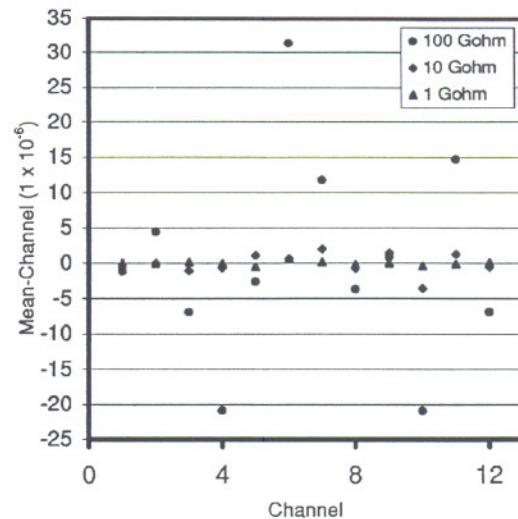

FIG. 5. Relative differences between channels shows deviation between individual channels. The substitution technique may be used for many measurements up to 10 GΩ without significantly increasing the combined uncertainty of the measurement.

traces, and increasing the wire size. Further measurements were made using a new guarded active-arm bridge[6] which was not available when the prototype scanner was first evaluated at NIST. Like the guarded Wheatstone bridge, the active-arm bridge substitutes standard and unknown resistances into one of the guarded bridge arms. Since the active-arm bridge is automated, more data could be collected in a timely manner and measurements could be made at decade resistances above 10 GΩ.

D. Results

Measurements were not made at 1, 10, and 100 MΩ, with the active-arm bridge since previous measurements made with the Wheatstone bridge determined that differences between channels were less than 1×10^{-6} for resistances ≤ 100 MΩ. Figure 4 shows the relative difference between measurements made with the resistors directly connected to the active-arm bridge and the resistors connected to the active-arm bridge with the guarded scanner for 1, 10, and 100 GΩ standard resistors. Adding the guarded scanner to the system contributes 2×10^{-6}, 30×10^{-6}, and 150×10^{-6} offsets from the direct measurement of 1, 10, and 100 GΩ standard resistors, respectively, demonstrating a factor of 3 improvement over the prototype scanner results reported in the previous section. The offsets are consistent from channel to channel as shown in Fig. 5 where the difference from the mean of all 12 channels has been graphed. The standard deviation of the measurements reported in Figs. 4 and 5 are 0.3×10^{-6}, 1.5×10^{-6}, and 15×10^{-6} for 1, 10, and 100 GΩ decades of resistance, respectively. The substitution method cancels the large offsets shown in Fig. 4 by allowing the indirect comparison of standards, check standards, and unknown resistors. A type A uncertainty of 0.3×10^{-6}, 1.5 $\times 10^{-6}$, and 15×10^{-6} would need to be added to the uncertainty budget of the measurement system for measurements at 1, 10, and 100 GΩ, respectively. Combined relative standard uncertainties for the NIST active-arm bridge without the guarded scanner are 5.9×10^{-6}, 12.6×10^{-6}, and 51.6

$\times 10^{-6}$ for measurements at 1, 10, and 100 GΩ, respectively. Adding the guarded scanner to the active-arm bridge increases the combined relative standard uncertainty at 100 GΩ to 53.7×10^{-6}, combined relative standard uncertainties at 1 and 10 GΩ remain unchanged.

V. APPLICATIONS IN MEASUREMENT SYSTEMS

Low thermal-emf scanners have been used in dc metrology applications such as standard cell and standard resistor measurements, and guarded scanners may improve the uncertainty of these measurements. Guarded scanners can be used in applications where shielded or guarded multiple standards or components are connected to a measurement system. Automated switching not only relieves an operator of tedious measurements but also permits multiple parameter characterization of multiple units under test. In the case of standard resistors, this facilitates the determination of voltage, temperature, humidity, and pressure coefficients for several resistors and allows selection of the best ones for use as standards.

A. Automated active-arm bridges

Guarded high-resistance bridges that use programmable dc sources[6,8] to obtain a bridge balance can use the guarded scanner to connect standards, check standards, and unknown resistors to the bridge. Such a system was used to evaluate the guarded scanner as described in the previous section. Combined expanded uncertainties for these bridges over the range 10 MΩ to 100 GΩ range from 4×10^{-6} to 56 $\times 10^{-6}$, respectively. Measurements up to 1 GΩ can be made using the guarded scanner without significant increase in the combined expanded uncertainties. The same can be achieved at 10 and 100 GΩ, provided the substitution method is used to cancel relative differences caused by leakage and stray capacitance in the scanner. Figure 6 shows the guarded scanner connecting standard, check standard, and unknown resistors to an automated resistance bridge. Resis-
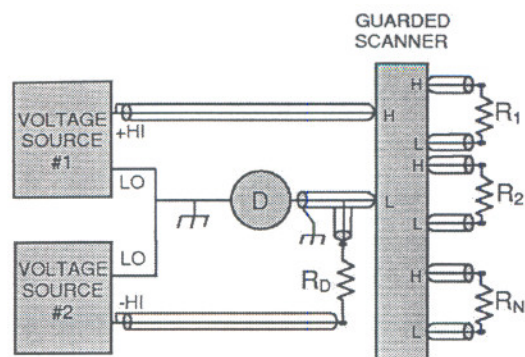
FIG. 6. Guarded scanner used to provide automated connection of many standard resistors (R_1, R_2, through R_N) to automated resistance bridge. Guard circuit is at same potential as main circuit to reduce leakage paths to ground.

tors R_1 through R_N are substituted into the upper arm of the bridge by the guarded scanner while the dummy resistor, R_D, is unchanged in the lower arm during the measurement process, thus reducing systematic errors.

B. Ring method

The ring method or unbalanced bridge[2] is used at NIST to calibrate standard resistors from 1 kΩ to 1 MΩ. The ring method uses two low thermal-emf scanners to apply current to a resistor network and measure potential drops in the resistor network. The circuit in Fig. 7 shows the large combination of connections and the large number of measurements required that make this method impractical without automated low thermal-emf switching. A programmable dc source and low thermal-emf scanner apply current to the bridge at terminal pairs AA', BB', and CC' sequentially. Thirty-six potential measurements across many pairs of terminals 1 through 12 are measured using a digital voltmeter and a second low thermal-emf scanner. A guarded ring stand has been designed for use with guarded low thermal-emf scanners to reduce the type B relative standard uncertainty caused by leakages to ground. Implementation of the guarded scanner and guarded ring stand is expected to reduce the present expanded combined uncertainties of 2×10^{-6} and 3×10^{-6} at 100 kΩ and 1 MΩ resistances, respectively, by approximately 50%.

C. Volt box calibration

Other dc measurement applications such as the calibration of voltage ratio standards or volt boxes[9] having combined standard uncertainties on the order of 10×10^{-6} can be automated with the guarded scanner. Volt boxes use guard networks to reduce leakages to ground by driving the guard resistors and shields at the same potential as the main resistors. The measurement of voltages at many tap points during calibration requires connection to the main and guard networks. A guarded scanner can be used to automate the calibration of volt box ratios the same way low thermal-emf scanners have been used to automate the ring method measurement system.
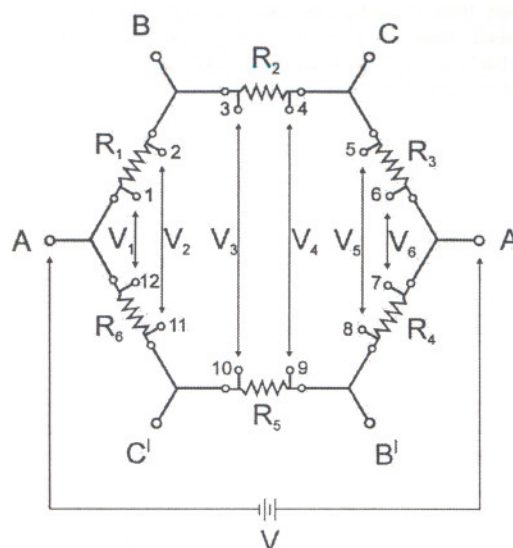

FIG. 7. Ring method system for calibration of standard resistors of the same nominal value in the range 100 Ω to 1 MΩ. Low thermal-emf scanners are used to apply the current to terminal pairs AA', BB', and CC' and provide connection for digital volt meter to measure potentials at terminals 1 through 12. Guarding the bridge is expected to reduce uncertainties for 100 kΩ and 1 MΩ measurements.

D. Cryogenic current comparator bridges

Guarded switching for cryogenic current comparator (CCC) bridges[10] provides a means of shielding the sensitive low current measurements from electrostatic noise. CCCs are used for scaling in the range 1 Ω to 10 kΩ with ratio accuracies on the order of 5×10^{-9}. CCCs have also been used for resistance measurements in the range 100 kΩ to 1 MΩ with increased uncertainty. An optically isolated interface has been developed for the guarded scanner, permitting automated connection of standard resistors to CCCs for calibration against other resistors or a quantized Hall resistance[11] without compromising the ratio accuracy of the CCC.

E. Other applications

Other metrology applications with uncertainties on the order of 1×10^{-6} can benefit from guarded switching. Often guard networks and shields are used to provide protection from leakages and noise. Discontinuous and incomplete shielding leaves circuits unguarded and permit noise to enter a measurement system compromising the uncertainty of the measurement system and making automation difficult if not impossible. The guarded low thermal-emf scanner provides a way to automate high-precision measurements without significantly increasing the uncertainty budget of the measurement.

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[5] Certain commercial equipment is identified in this article in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment identified is necessarily the best for the purpose.

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