Analysis of a Dual-Balance High-Resistance Bridge at 10 TΩ
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Abstract—The NIST guarded active-arm bridge, using a third dc source and a second detector to balance the guard network, is described. Improvements to the NIST active-arm bridge and the design and construction of improved high resistance standards have facilitated the extension of NIST calibration services to the 10 TΩ decade of resistance. The 10 TΩ calibration service has been offered as a special test for NIST customers; the 100 TΩ special test will be available later this year. To ensure the quality of the measurements provided to the customer and to evaluate the bridge, many verifications including the use of check standards, redundant measurement systems, and multiple bridge ratios have been used. Analysis techniques described here for the 10 TΩ decade of resistance can also be applied to the 100 TΩ decade of resistance.

Index Terms—Balance, bridge, detector, guard, measurement, resistance, standard, transfer standard.

I. INTRODUCTION

In recent years, much work has been done at the National Institute of Standards and Technology (NIST) to support the re-establishment of NIST calibration services at 10 TΩ and 100 TΩ. Installation of environmental chambers [1], implementation of the active-arm bridge (AAB) [2], [3], and the development of new standards [4], [5] have been important contributions to the process of improving and extending NIST calibration services in the decade ranges of 10 MΩ to 100 TΩ.

At resistance levels of 1 GΩ and above, resistance standards are of the film-type. These resistors often have larger voltage coefficients (>1 × 10⁻⁶/V) and larger corrections from nominal (>5000 μΩ/Ω) compared to wire-wound standard resistors available at the 100 MΩ level and below [6]. One or a combination of both of these effects can cause a mismatch of the main-to-guard resistor ratios allowing leakage currents to flow through the insulation, \( R_{ins} \), between the main and guard circuits making it difficult to accurately balance the guarded active-arm bridge shown in Fig. 1.

There were two solutions considered to solve this problem of mismatched main and guard resistor ratios. The first was to select the proper guard resistor, \( r_g \), associated with the unknown resistor, \( R_X \). However, this would require some preliminary measurements of the unknown resistor, \( R_X \), to select a well-matched guard resistor, \( r_g \), and would be impractical for an automated calibration system. The second solution, described here, is to monitor the voltage at the junction of guard resistors, \( r_x \) and \( r_s \), and adjust the input voltage of the unknown guard resistor, \( r_s \), until the guard circuit midpoint (\( r_x \) and \( r_s \) junction) is at the same potential as the main circuit midpoint (\( R_X \) and \( R_S \) junction). Once the guard circuit is balanced, then the main circuit can be balanced without unwanted leakage currents flowing through the insulation, \( R_{ins} \), of the midpoint junctions.

II. DUAL-BALANCE ACTIVE-ARM BRIDGE

The NIST guarded active-arm bridge as shown in Fig. 1 consists of programmable sources (\( V_1 \) and \( V_2 \)) that drive the main resistors (\( R_X \) and \( R_S \)) and the guard resistors (\( r_x \) and \( r_s \)). The detector \( D \) measures the difference in current flowing through \( R_X \) and \( R_S \). The active-arm bridge has been evaluated over the range 10 MΩ to 1 TΩ [3]. When measurements were made at 10 TΩ, an accurate balance of the bridge could not be obtained.

Manuscript received March 11, 2000; revised May 14, 2000.

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Publisher Item Identifier S 0018-9456(01)02675-4.
Fig. 3. Measurement of several 10 TΩ standards at 500 V and 1000 V using the dual-balance active-arm bridge. The open symbols (○, △, □) indicate measurements made at 500 V and the filled symbols (●, ■, ▲) indicate measurements made at 1000 V. The dual-balance active-arm bridge was able to measure resistors having large corrections on the order of ±40 000 µΩ/Ω, including one resistor, R3 (○, ●), having a large voltage coefficient on the order of 50 × 10⁻⁶/V.

for all unknown resistors $R_X$. Further investigation revealed that the voltage differences between the main and guard circuits were generating leakage currents due to one of the 10 TΩ unknown resistors $R_X$ having a large correction from nominal on the order of 40 000 µΩ/Ω. This mismatch of the main-to-guard resistor ratios causes errors in the measurement of the difference current in the main circuit by detector $D$.

Fig. 2 shows the dual-balance active-arm bridge configured for measuring resistance standards in the range 1 TΩ to 100 TΩ that may have large corrections from nominal. The programmable third source, $V_C$, which drives the unknown guard resistor, $r_{xg}$, is adjusted until the guard detector, $D_C$, indicates a null between the midpoint of the guard circuit and the interconnection of the sources. After $V_C$ is set, the programmable source $V_1$ can be adjusted to balance the main circuit. The standard resistor $R_s$ and guard resistor $r_s$ are matched to minimize leakages in the standard arm of the bridge. The standard may be a guarded transfer standard [5] with guard resistors matched to the main resistors of the transfer standard.

The data in Fig. 3 shows the measurement results of several 10 TΩ standards at 500 V and 1000 V. The open symbols (○, △, □) indicate measurements made at 500 V and the filled symbols (●, ■, ▲) indicate measurements made at 1000 V. The dual-balance active-arm bridge was able to measure resistors having large corrections on the order of ±40 000 µΩ/Ω, including one resistor (○, ●) having a large voltage coefficient on the order of 50 × 10⁻⁶/V.

Another bridge configuration considered was to place the guard detector $D_C$ between the main and guard circuits. However, when left in place during the main balance, the guard detector created a ground loop between the main and guard circuits, causing an overload of the main detector. Placing the detector between the circuit virtual ground (junction of $V_1$ and $V_2$) and the guard circuit midpoint (junction of $r_{xg}$ and $r_{sg}$) simplifies the automation of the dual balance active-arm bridge.

### III. Standards

A comparison of 10 TΩ standards between NIST and Sandia National Laboratory (SNL) [7] provided a reference point for the measurements to be made with the dual-balance active-arm bridge at 10 TΩ. At the time of this comparison, the two laboratories agreed to within 600 µΩ/Ω for measurements made using digital teraohmmeter systems that have an expanded uncertainty ($k = 2$) of 2000 µΩ/Ω. Periodically after the comparison was completed in 1998 between NIST and SNL, the NIST standards were remeasured at NIST using the teraohmmeter system to establish a history and drift rates for the transfer standards. Long term drift rates on the order of 700 × 10⁻⁶/year were established.
Fig. 4. 10 GΩ/Step guarded Hamon transfer standard C1198 calibrated in series mode (100 GΩ) and parallel mode (1 GΩ) at various voltages. Error bars are the standard deviation of the measurements made at each voltage. Transfer error and voltage dependence are within these error bars.

IV. BRIDGE EVALUATION

Earlier attempts to use the guarded active-arm bridge above 1 TΩ were not successful due to an imbalance of the guard potentials as described earlier. The addition of the second detector and third source to the guard circuit made it possible to complete the main balance of the bridge without overloading the main detector. Fig. 6 shows the sequence of standards and measurement techniques used to measure the 10 TΩ resistance standards in terms of the NIST quantized Hall resistance [8]. Using cryogenic current comparators [9], Hamon transfer standards, and control charts, a value is assigned to a well characterized wire-wound 1 GΩ Hamon transfer standard, J/9, with a combined standard uncertainty on the order of 10 μΩ/Ω. From the 1 GΩ to 10 TΩ decades of resistance, several bridge ratios (1 : 10, 1 : 1, 10 : 1, 100 : 1, 1 000 : 1) using different Hamon transfer standards (C/10, C1098, C1198) and different measurement systems (active-arm bridge, teraohmmeter system) were used to measure the transfer standards and the 10 TΩ standards. The 10 TΩ standards were measured at 500 V and 1000 V.

Fig. 7 shows a typical plot of data for one of the 10 TΩ check standards measured at 1000 V. The 10 TΩ check standards and unknown resistors were measured over a one month period beginning and ending with measurements made using the teraohmmeter system as shown by the filled square (■) markers. The open circle (○) markers show measurements made with the dual-balance active-arm bridge using a 100 GΩ standard configuring the bridge for a 100 : 1 bridge ratio. The triangle open markers (△) show measurements made with the dual-balance active-arm bridge using a 10 GΩ standard configuring the bridge for a 1 000 : 1 bridge ratio. The error bars are for the expanded uncertainty (k = 2) of 2000 μΩ/Ω assigned to the special test (i.e., unique resistance measurements that are not a routine calibration service) of a customer resistor.
Fig. 5. The 1 GΩ/Step guarded Hamon transfer standard C1098 calibrated in series mode (10 GΩ) and parallel mode (100 MΩ) at various voltages. Error bars are the standard deviation of the measurements made at each voltage. Transfer error and voltage dependence are within these error bars.

Fig. 6. Traceability of 10 TΩ calibrations to the NIST quantized Hall resistance. From a well characterized 1 GΩ wirewound Hamon transfer standard, several standards and measurement techniques are used to evaluate the dual-balance active-arm bridge. Hamon transfer standards C1098 and C1198 are used in series and in parallel modes to evaluate the guarded active arm bridge 1:10, 1:1, 10:1, and 100:1 bridge ratios. These Hamon transfer standards are also used in series as standards for the dual-balance active-arm bridge to calibrate 10 TΩ standards.
Fig. 7. Typical calibration of a 10 TΩ standard resistor measured over a one month period. The first and the last measurements were made using the teraohmmeter system and are shown by the filled square (■) markers. The open circle (○) markers show measurements made with the dual-balance active-arm bridge using a 100 GΩ standard and configuring the bridge for a 1000 : 1 bridge ratio. The triangle open markers (Δ) show measurements made with the dual-balance active-arm bridge using a 10 GΩ standard and configuring the bridge for a 1000 : 1 bridge ratio.

Table I shows the uncertainty budget for the 10 TΩ special test. The dominant factor is leakage currents flowing through the insulation of the terminals to ground, shown in the 2nd and 3rd columns. Leakage currents can be further suppressed in resistors designed with guarded terminations [4]. The Type B component of 1000 μΩ/Ω is for a resistor with poor insulation on the order of 10 TΩ. If the insulation were a factor of ten better, i.e., 100 TΩ, then this Type B component could be reduced to 100 μΩ/Ω, therefore reducing the expanded uncertainty to approximately 350 μΩ/Ω as shown in the 4th and 5th columns of Table I. The Type B component for leakage is determined from the effective resistance [5] which is a function of how well the guard circuit is matched to the main circuit. The dual-balance configuration shown in Fig. 2 reduces leakage currents caused by mismatched guard resistors.

V. Summary

An analysis of the dual-balance guarding technique has been reported. Check standards, an existing measurement system, and guarded Hamon transfer standards have been used to evaluate the dual-balance active-arm bridge at 10 TΩ. Measurements at 10 TΩ have been completed and the calibration service at 10 TΩ has been made available as a special test. A special test of 100 TΩ standard resistors is expected to be offered later this year once the assembly and characterization of a new 100 TΩ check standard is completed. The technique
will also be evaluated at nominal values of 1 TΩ and below but is not expected to significantly improve the measurement of standard resistors with corrections close to nominal value.

REFERENCES