Third Generation of Adapted Wheatstone Bridge for High Resistance Measurements at NIST

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Abstract — **A third generation of adapted Wheatstone bridge is being developed at the National Institute of Standards and Technology (NIST) to improve high resistance measurements and scaling from 1 TΩ to 10 PΩ. Improvements to extend range and reduce uncertainties include: automated calibration of the voltage sources, modified bridge balancing algorithm, low-noise shielded cables, and software migration to a modern programming environment. Initial measurements agree well within the expanded uncertainties ($k = 2$) of the second generation NIST adapted Wheatstone bridge.**

Index Terms — **standard resistor, high resistance, voltage source, calibration, adapted Wheatstone bridge.**

I. INTRODUCTION

The adapted Wheatstone bridge [1] is an automated measurement technique for the measurement of high resistance standards in the range 10 MΩ to 100 TΩ. An adapted Wheatstone bridge uses low-impedance programmable dc sources (V_1, V_2) in place of two of the resistive ratio arms of a conventional Wheatstone bridge. High resistance standards ($\geq$ 1 MΩ) (R_X, R_S) are used in the other two ratio arms. When the bridge is balanced, the unknown resistor value (R_X) can be determined as

$$R_X = R_S \, (V_1/V_2). \qquad (1)$$

The technique has been used at the National Institute of Standards and Technology (NIST) [2] as well as at other national metrology institutes for measurement of high resistance standards to at least 100 TΩ [3]. The first and second generation adapted Wheatstone bridges at NIST have been in service since 1996 and 2008, respectively. These systems continue to be extensively used for high resistance measurement services and research work at NIST. The age of the software platform, desired modification of the balancing algorithm for measurements above 1 TΩ, and improvements to the voltage source calibration are several factors that made the development of a third generation adapted Wheatstone bridge appropriate at this time.

The earlier NIST adapted Wheatstone bridges use guarded Hamon transfer standards and the substitution technique to build up from lower resistance values in decade steps [4]. Most Hamon transfer standards have ten resistors of the same nominal value which are permanently connected in series. Paralleling fixtures are used to connect the resistors in parallel or series-parallel configurations allowing 1:100 and 1:10 ratios for scaling to higher resistance levels. The guard circuit [2] maintains approximately the same potential as the main circuit at each junction, thus suppressing leakage currents to ground.

The availability of guarded Hamon transfer standards has made the scaling process less dependent on the uncertainty contribution of the voltage ratio as any systematic offsets in voltage at a given range tend to cancel when standard resistors of the same nominal value are measured by the substitution method. For measurements above 1 TΩ, direct calibration of the voltage sources to better than manufacturer specification (6 µV/V) is necessary for evaluating the guarded Hamon transfer standards where parallel to series (1:100) and series-parallel to series (1:10) transfers have been difficult to verify.

The measurement of Wye-Delta resistance networks [5] is difficult with the existing balancing algorithm which drives the bridge to ± 5000 x 10⁻⁶ from null and extrapolates the bridge null from a linear fit. Accurate measurement of a Wye-Delta network requires the low terminal to be at the same potential as the case or ground (i.e. bridge null condition), which is not the situation for the first and second generation NIST adapted Wheatstone bridges.

II. CHANGES TO THE THIRD GENERATION BRIDGE

Over the years, there were improvements to the first and second generation bridges, such as ramping of voltage sources and addition of coaxial automated switching, but no major changes were made to the measurement sequence or balancing algorithm. The dated programming environment along with the eclectic nature of the code made it sensible to make significant changes to the software in a modern programming environment that is widely supported and less likely to be obsolete in the future.

A. Voltage Source Calibration

An interchange of the voltage sources in the third generation bridge yielded a difference in R_X of 6 µΩ/Ω for a 1:1 bridge ratio. Two methods were tested to improve the voltage ratios and reduce this interchange difference to less than 1 µΩ/Ω. The first method was to use a calibrated digital volt meter (DVM) to measure the output of each voltage source and use those voltage measurements in the calculation of the unknown resistance. The second method was to

calibrate the voltage sources against Zener voltage references with an automatic potentiometer and 1200 V range extender at all voltage ranges and store those corrections in tables for recall during the resistance measurement. While both methods reduced the interchange offset error, the second method was selected due to ease of calibration of the voltage sources with the automatic potentiometer, shorter resistor measurement time by not adding voltage measurements to the process, and avoidance of possible issues with switching or ranging of the DVM.

B. Balancing Algorithm and Null Current Measurement

The third generation bridge balances to a true null rather than $\pm$ 5000 x 10^{-6} from null as in the earlier NIST bridges. To minimize the effects of detector and bridge offsets, the measurement sequence starts with measuring the bridge null current (I_{null}) when $V_1 = V_2 = 0$. A pre-balance is done next where V_1 is set to the test voltage of R_X and V_2 is set so V_1/V_2 is the same nominal ratio as R_X/R_S and the detector current (I_D) is measured. The null and detector current measurements are used in equation 2 to determine V_2' for the bridge null balance as

$$V_2' = V_2 + (I_D - I_{null})R_S. \qquad (2)$$

With the voltage sources set to V_1 and V_2', the detector current I_D' is now measured with the bridge balanced. The bridge is balance if the difference of I_D' and I_{null} is less than the detector resolution for the current range. If this condition is not met, an additional adjustment of V_2 is performed and the current measurement repeated. After all iterations, the bridge null current measurement, where $V_1 = V_2 = 0$, is repeated to verify that there is no significant drift in the bridge during the measurement sequence. The process is then repeated for the reverse polarities of V_1 and V_2. Once the measurement sequence is completed, corrections for V_1, V_2, and R_S are applied and R_X is calculated from equation 1. Measurements are typically made 120 s to 300 s (3600 s maximum) after voltage is applied to allow the RC time constants of the system to dissipate. V_1 and V_2 are of opposite polarity.

III. DATA AND RESULTS

The third generation bridge uses the calibrated voltage ratio V_1/V_2 and the standard resistor R_S to determine R_X which is different from the second generation bridge which relies on the substitution technique and guarded Hamon transfer standards. Measurements at 10 TΩ showed the two methods to agree within 50 $\mu\Omega/\Omega$, which is quite acceptable considering possible transfer errors of the guarded Hamon transfer standard at this resistance level. Further testing with an additional Hamon transfer standard at 1 TΩ is planned.

Measurements were also made at 1 PΩ and 10 PΩ using Wye-Delta networks configured from NIST standards and compared to a potentiometric measurement technique [6]. Figure 1 shows measurements made with the third generation

bridge and the potentiometric method on a Wye-Delta network assembled from well characterized high resistance standards at 1 PΩ. Similar results were obtained on two other Wye-Delta networks at 1 PΩ and one at 10 PΩ.
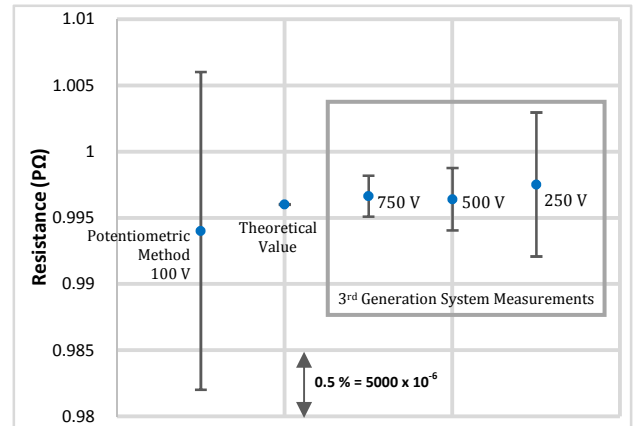

Fig. 1. Measurements made on Wye-Delta networks at 1 PΩ. Error bars are the 1σ standard deviation of multiple measurements over several days. Third generation NIST bridge measurements at several voltages are shown in box to the right. Measurements made on the same Wye-Delta network using the potentiometric method and the theoretical values are shown to the left.

IV. CONCLUSION

The third generation of adapted Wheatstone bridge for high resistance measurements at NIST was built. Improvements include automation of the voltage source calibration and changes to the balancing algorithm which have allowed measurement of Wye-Delta networks. These are shown to result in improved scaling from 1 TΩ to 100 TΩ, which was dependent on guarded Hamon transfer standards. Range has been extended by two orders of magnitude to 1 PΩ and 10 PΩ. These improvements will allow reduction of measurement uncertainties in the 1 TΩ to 100 TΩ range by a factor of three to five.

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