ACCURATE CALIBRATION OF RESISTANCE RATIOS BETWEEN 1 MΩ AND 1 GΩ USING SERIES RESISTORS

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Abstract: This paper presents a method for calibrating 10:1 ratios in a high-resistance bridge using series resistors simply and accurately. Using the presented method, the combined relative standard uncertainty for 1 GΩ resistance measurements with a modified Wheatstone bridge was estimated to be on the 1×10^{-6} level. The method was also applied to 1 GΩ resistance measurements using a direct-current comparator resistance bridge. It was found that the 1 GΩ resistances determined by the two bridges agreed within 2.4×10^{-6} Ω/Ω. We expect that the presented method can also be used to calibrate arbitrary resistance ratios.

Keywords: resistance ratio calibration, direct-current comparator resistance bridge, modified Wheatstone bridge, series resistors

1. INTRODUCTION

Since 1996, international key comparisons for 10 MΩ and 1 GΩ resistance have been carried out to confirm international consistency [1–3]. The lowest expanded uncertainty for the 1 GΩ resistance in the key comparisons of the SIM and EURAMET was on the $4 \sim 6 \times 10^{-6}$ Ω/Ω level. While the bridge ratios of the main bridges used in the key comparisons should be calibrated, it is not easy to calibrate them at an accuracy of 1×10^{-6} using known methods. In this paper, we present a series-resistor method to calibrate 10:1 ratios of a high-resistance bridge with relative accuracy of 1×10^{-6}.

2. SERIES-RESISTOR METHOD

The series resistor (hereafter, SR) consists of 10 resistor elements connected in series and one-to-one ratio values can be obtained by comparing a reference resistor, R_S, with each element of the SR. A reference 10:1 ratio value is then obtained by summing the 10 one-to-one ratio values, which are corrected employing the interchange method. Therefore, by definition, a 10:1 ratio error for the $\frac{R_X}{R_S}$ ratio can be expressed by

$$
e_{10} = \frac{r_{mea} - r_{ref}}{r_{ref}} \cong \frac{\left[\frac{\sum_{i=1}^{10} R_i}{R_S}\right]_{mea} - \sum_{i=1}^{10}\left[\left(\frac{R_i}{R_S}\right)_{mea} - e_{1,i}\right]}{10}
$$

$$
= \frac{[\frac{\sum_{i=1}^{10} R_i}{R_S}]_{mea} - [\sum_{i=1}^{10}(\frac{R_i}{R_S})_{mea}]}{10} + \frac{\sum_{i=1}^{10} e_{1,i}}{10},
$$

(1)

where $e_{1,i}$, r_{ref} and r_{mea} denote a one-to-one ratio error, a reference 10:1 ratio value and a measured 10:1 ratio value, respectively.

3. STEP-UP PROCESS

In this paper, the step-up process is carried out to determine the 1 GΩ resistance from 10:1 ratio measurements using an MWB and a direct current comparator resistance bridge (DCCRB)[4,5]. The leakage effect in the MWB measurement is hardly significant[6], and therefore, the measurement accuracy mainly depends on the corrections of 10:1 ratio values. The SR method, which can be easily employed at room temperature to correct the 10:1 ratio values, has three advantages. The first is that the 10:1 ratio can be accurately determined only from one-to-one ratio values which have negligible leakage effects and do not need any active guarding even for high-resistance measurements. The second is that overall uncertainty is mainly limited to the temperature effect, the repeatability of 10:1 ratio measurements and the corrections of the ratios. The third is that using the method does not need calibrated voltage sources; thus, high resistances can be accurately determined.

4. MEASUREMENT SYSTEM

4.1. SRs

SRs of 1 MΩ/step, 10 MΩ/step and 100 MΩ/step as shown in figure 1 were used to determine the 10:1 ratio errors of the MWB and DCCRB.

Figure 1. Picture of series resistors for 10 MΩ/step (middle) and 100 MΩ/step (left).

4.2. Standard resistors for the step-up process
A commercial 1 MΩ resistor (IET-SRL) is used as a reference value. Additionally, 10 MΩ and 1 GΩ resistors made by the DI Mendeleev Institute for Metrology are used. The series value of the SR for 10 MΩ/step in figure 1 is used as a 100 MΩ reference resistance.

4.3. Resistance ratio bridges
A self-made MWB and a commercial DCCRB are used to make 10:1 ratio measurements between the 1 MΩ and 1 GΩ resistance. Here, the DCCRB is also used to confirm the validity of the SR method for the 10:1 ratio calibration. The features of the MWB system are shown in figure 2.
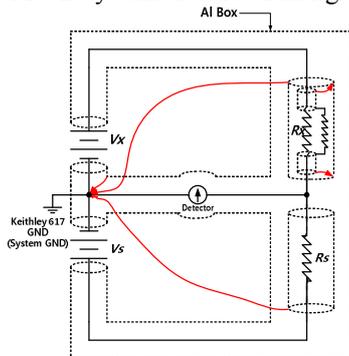

Figure 2. Simplified diagram of the Modified Wheatstone Bridge (MWB) system. The Al case is housed within a temperature and humidity chamber controlled at $23.0\,°C \pm <0.1\,°C$ and $40\,\%\,r.h. \pm 3\,\%\,r.h.$. Additionally, the resistors have a triaxial connection to the calibrators, electrometer and Al case.

5. MEASUREMENT RESULTS AND DISCUSSIONS

Figure 3 graphically illustrates the measurement results for 10:1 ratios in the range between 1 MΩ and 1 GΩ using the MWB and DCCRB. We can summarize the results in figure 3 as follows.
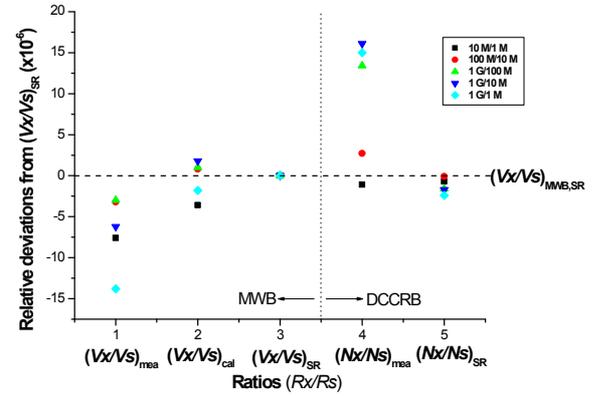.

Figure 3. Graphical presentation of the ratio values measured with the MWB and DCCRB.

Firstly, $[\frac{V_X}{V_S}]_{SR}$ and $[\frac{N_X}{N_S}]_{SR}$ agree within about 2×10^{-6} for all ratio values, which means 1 GΩ resistance can be measured to that accuracy level when the 10:1 ratio measurement values obtained with the MWB and DCCRB are corrected employing the SR method. Secondly, from the MWB results, measured $\frac{10\,M\Omega}{1\,M\Omega}$ and $\frac{1\,G\Omega}{1\,M\Omega}$ ratio values indicate larger deviations from the reference value than other ratio values. We consider that this is due to the effect of the lead resistances connected to the 1 MΩ resistance and errors in voltage ratios that result from having two uncalibrated voltage sources, as clearly shown in table 2. Additionally, $[\frac{V_X}{V_S}]_{cal}$ differs from $[\frac{V_X}{V_S}]_{SR}$ by a few units of 10^{-6}, which we consider results from the lead resistances. Thirdly, in the case of the DCCRB results, the measured ratio values in the three bottom rows of table 2 indicate larger deviations from the reference value, which we consider is due to leakage effects. If the leakage errors are corrected using the SR method, then the corrected ratio values agree with the reference value within 2.4×10^{-6} as shown for $[\frac{N_X}{N_S}]_{SR}$.

6. UNCERTAINTY ESTIMATION

The applied voltage used in the experiments is 100 V DC or less and thus there were no power effects. Leakages are not significant in the MWB measurements and in determining the 10:1 ratio errors. Additionally, even though the leakage effect is significant in DCCRB measurements, it is corrected by the SR method without being directly measured. The uncertainties in 10 MΩ, 100 MΩ and 1 GΩ resistance measurements using the MWB are estimated by applying the series-resistor process and according to the ISO GUM Guide [7], and the results are summarized in table 1.

Table 1. Uncertainty estimation in determining the QHR-based 10 MΩ, 100 MΩ and 1 GΩ resistances from MWB measurements.

Uncertainty Sources		Relative Standard Uncertainty(10^{-6})
QHR-based 1 MΩ resistance		0.28
VNIIM 10 MΩ (n901)	10:1 ratio error correction (by SR method)	0.36
	type A	0.20
	Temperature effect (10 MΩ): $\pm < 0.1\,°C$	<0.50
Combined Standard Uncertainty (RSS)		**0.71**
100 MΩ (SR)	10:1 ratio error correction (by SR method)	0.22
	type A	<0.20
	Temperature effect (100 MΩ): $\pm < 0.1\,°C$	<0.20
Combined Standard Uncertainty (RSS)		**0.80**
VNIIM 1 GΩ (n1092)	10:1 ratio error correction (by SR method)	0.70
	type A	<0.20
	Temperature effect (1 GΩ): $\pm < 0.1\,°C$	<0.50
Combined Standard Uncertainty (RSS)		**1.2**

7. CONCLUSIONS

We presented a method that can simply and accurately calibrate 10:1 ratios of a high-resistance bridge using series resistors. To confirm the validity of the method, 10:1 ratio measurements using an MWB and DCCRB were made between 1 MΩ and 1 GΩ, and they were found to agree within 2.4×10^{-6}. Additionally, the combined standard uncertainty for 1 GΩ resistance measurements was shown to be on the 1×10^{-6} level. We expect that the method can also be applied to calibrate arbitrary resistance ratios.

8. REFERENCE

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