An Automatic Calibration System for
10 MΩ to 1 TΩ DC Standard Resistors

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Abstract

At SCL, a simple automatic system is implemented based on a modified Wheatstone bridge. With this system, measurement uncertainty, u_c , of less than 10×10^{-6} can be achieved for calibrating 10 MΩ to 1 GΩ resistors. u_c for resistance calibration above 1 GΩ become larger, mainly due to the temperature coefficients of the resistors.

1. Introduction

The system comprises a control software written in Visual Basic and a modified Wheatstone bridge, whose two arms are programmable dc calibrators supplying test voltages at selectable magnitudes (1 V to 1000 V) and ratios (1:1 to 1: 100) to the unknown and reference resistors that form the remaining two bridge arms. To minimise the leakage effect, '3-terminal' configuration is used for resistance connection. A programmable electrometer, Keithley 6517, in current mode with a resolution of 0.1 pA is used to measure the current imbalance (i.e. the difference in currents that flow through the unknown and standard resistors). Parameter setting, instrument control, error handling and real-time monitoring of outcomes are performed via a user-friendly graphical user interface.

2. The Resistance Bridge

At the time of balance, the two programmable voltage sources, V_X and V_S, are set to a ratio equal to that of the values of unknown and standard resistors, R_X and R_S.
That is $V_X/V_S = - R_X/R_S$.

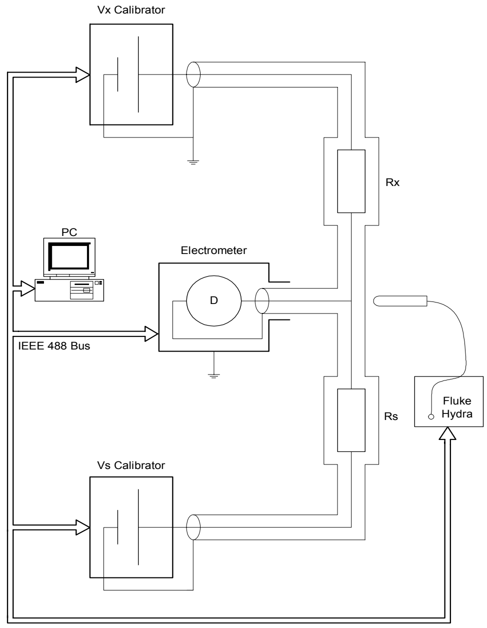

Figure 1: The modified Wheatstone Bridge

To minimise the leakage effect, ‘3-terminal’ configuration is used for connecting resistors to the bridge. As shown in Figure 2, the chassis of the resistors are connected to the Bridge’s earth with this configuration. The leakage paths L_2 and L_3 are placed across the null detector whilst the other two leakage paths L_1 and L_4 are placed across the V_X and V_S calibrators. In this configuration, errors caused by L_1 and L_4 are less than 0.1×10^{-6}, as the output resistances of the calibrators, V_X and V_S, are so low. Obviously, since the impedance of the electrometer is so low, L_2 and L_3 do not cause any significant errors.

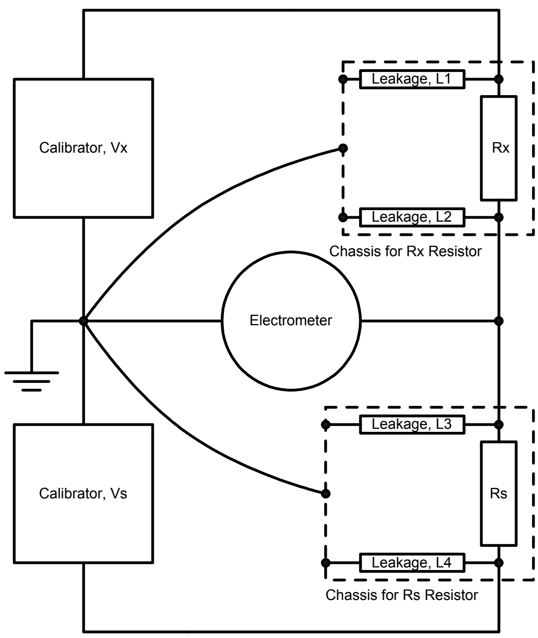

Figure 2: The “3-terminal” configuration

3. The Balance Algorithm

Initially, the voltage sources are set to the nominal ratio of R_X and R_S. An electrometer with resolution of 0.1 pA in the current mode is used as a null detector to monitor the bridge's balance condition, which is indicated by the imbalance current, I_D. In fact, I_D is the difference between the two currents that flow through R_X and R_S.

To balance the bridge, the system works out a new output setting for calibrator *Vs*, based on the magnitude and direction of I_D,, such that $Vs' = Vs - I_D \times R_S$. The system will then check if the bridge has reached the null condition that is acceptable by the operator.

If $(|Vs' - Vs| \div Vs) < B$*, the bridge is considered as its null condition. Otherwise, *Vs* will be set to the new value *Vs'* and the above process will be repeated until the bridge is balanced. (Note *: *B* is a system parameter selected by the operator.)

4. Errors in the Resistance Bridge

The calibrator outputs (*Vx* and *Vs*) can be expressed as follows:

$$V_{output} = V_{setting} \times Gain + V_{offset}$$

The offset and gain errors in the voltage sources, V_X and V_S, will cause discrepancy between V_{output} and $V_{setting}$. This discrepancy will eventually give rise to errors in the resistance bridge and measurement results.

4.1 Offset Errors

When both V_X and V_S are set to zero, the current that flows through the electrometer is essentially due to the zero offsets of the calibrators (i.e. V_{X_OFFSET} and V_{S_OFFSET}). This will appear as the bridge's offset current, I_O.

$$I_O = \frac{V_{X\_OFFSET}}{R_X} + \frac{V_{S\_OFFSET}}{R_S}$$

To minimize the offset error, before a measurement is commenced, the system sets V_X and V_S to zero. Then, it activates the electrometer's zero function to eliminate the zero offsets. This is to make sure that the offset current is not included in the imbalance current, I_D. That is: $I_D = I - I_O$

4.2 Gain Errors

Although the calibrator gains, G_X and G_S, are equal to one nominally, it is expected that there will be errors in the calibrator gains.
That is, $G_X = 1 + \delta G_X$ and $G_S = 1 + \delta G_S$. It is expected that $\delta G_x \neq \delta G_s \neq 0$.

Hence, when the bridge is at balance, the apparent ratio R_X and R_S is: $\frac{R_X}{R_S} = -\frac{V_{X\_SETTING}}{V_{S\_SETTING}}$

However, due to gain errors, the actually relationship for R_X and R_S is:

$$\frac{R_X}{R_S} = -\frac{V_{X\_SETTING}(1+\delta G_x)}{V_{S\_SETTING}(1+\delta G_s)}$$

The system will apply a Ratio Correction Factor (*RCF*) to the apparent $R_X : R_S$ ratio in order to correct the gain errors. The reported value for R_X will be as follows:

$$R_X = RCF \times R_S \times -\frac{V_{X\_SETTING}}{V_{S\_SETTING}}$$

where

$$RCF = \frac{1+\delta G_X}{1+\delta G_S}$$

The *RCF* is a operational parameter, which should be determined beforehand and is imported to the system before the measurement commences.

5. System Performance

5.1 1:1 Ratio

To check the bridge's performance at 1:1 ratio, two standard resistors, R_1 and R_2, with nominally equal resistance were used. The bridge's 1:1 ratio error, ε, was determined by:

$$\varepsilon = \sqrt{X \times Y} - 1$$

where X and Y are the resistance ratios measured by the bridge, such that:

$$X = \varepsilon.\frac{R_1}{R_2} \text{ and } Y = \varepsilon.\frac{R_2}{R_1}$$

The bridge's 1:1 ratio error, ε, at test voltages of 10 V, 100 V and 1000 V are:

Test Voltages	Resistance Ratio	Ratio Error, ε
10 V and 100 V	10 MΩ: 10 MΩ	$\leq 0.5\times10^{-6}$
10 V and 100 V	100 MΩ: 100 MΩ	$\leq 0.5\times10^{-6}$
10 V, 100 V and 1 kV	1 GΩ: 1 GΩ	$\leq 1.5\times10^{-6}$
10 V, 100 V and 1 kV	10 GΩ: 10 GΩ	$\leq 5\times10^{-6}$
10 V, 100 V and 1 kV	100 GΩ: 100 GΩ	$\leq 6\times10^{-6}$

5.2 10:1 and 100:1 Ratios

To check the system's performance at these ratios, test resistors were measured by this automatic bridge and the results obtained were compared with those obtained by a manual bridge. The results are agreed within 2×10^{-6} for 1 GΩ and below and within 10×10^{-6} for test resistors higher than 1 GΩ.

6. Estimated Standard Measurement Uncertainty

Uncertainty Contribution	Test Resistor			
	≤1 GΩ	10 GΩ	100 GΩ	1 TΩ
Reference Resistor	2×10^{-6}	5×10^{-6}	30×10^{-6}	160×10^{-6}
Voltage Sources	2×10^{-6}	2×10^{-6}	2×10^{-6}	2×10^{-6}
Null Uncertainty	0.12×10^{-6}	0.58×10^{-6}	1×10^{-6}	3×10^{-6}
Temperature Effect	1×10^{-6}	15×10^{-6}	150×10^{-6}	1500×10^{-6}
Random (Noise) Effect	0.2×10^{-6}	2×10^{-6}	3×10^{-6}	10×10^{-6}
Combined Std. Uncertainty	2×10^{-6}	29×10^{-6}	160×10^{-6}	1500×10^{-6}

7. Conclusion

An automatic modified Wheatstone bridge has been implemented for calibration DC standard resistors from 10 MΩ to 1 TΩ.

8. Reference

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[2] D.G. Jarrett, "Automated Guard Bridge for Calibration of Multimegohm Standard Resistors", IEEE Trans. Inst. Meas., Vol. 46, No. 2, Apr. 1997.