COMPARISON OF HIGH VALUE RESISTANCE STANDARDS USING THE MODIFIED WHEATSTONE BRIDGE AND PICOAMMETER

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Abstract: In this paper is presented the method for comparison of high value resistance standards by using the modified Wheatstone bridge and picoammeter as current detector, instead of low-impedance current-sensing transimpedance amplifier. Basically, the resistance ratio r can be measured on nominal levels 1:1, 10:1 or 100:1, ensuring the traceability chain from the reference standards of 10 MΩ and 1 GΩ for the range of interest 10 MΩ to 100 GΩ.

Keywords: calibration, high resistance standards, zero-current measurement, modified Wheatstone bridge

1. INTRODUCTION

One of main tasks of Primary Electromagnetic Laboratory (PEL), which is a part of the Faculty of Electrical Engineering and Computing of the University of Zagreb (FER), and a part of the Croatian metrology system as a holder of Croatian national standards of dc voltage, resistance and capacitance, is to ensure a traceability chain for group of resistance standard in the range from 1 mΩ to 100 GΩ. The reference standards of PEL are 1 Ω (L&N 4210), 10 kΩ (ESI/Tegam SR104), 10 MΩ (Fluke 742A-10M), and 1 GΩ (SRC-1G) standard[1], which are regularly calibrated at PTB in Germany. Reference standards of 1 Ω and 10 kΩ have been maintaining into the oil-thermostat at a temperature of 23 °C, and their characteristics are presented in [1]. Some other resistance standards of PEL, as well as their maintenance, methods of comparison and achieved uncertainties, were presented in [2-6]. The group of high value resistance standards from 10 MΩ to 100 GΩ is the hindmost incorporated in the resistance traceability chain, and relies on laboratory developed measurement system for high resistance comparison, which is presented in this paper.

2. METHOD FOR COMPARISON OF HIGH VALUE RESISTANCE STANDARDS

The extension of internal laboratory resistance traceability chain to values higher than 100 MΩ requires a measurement method which can accomplish specific requirements regarding suppression of parasitic quantities (parasitic capacitances of measured resistors, insulation leakage currents) and somewhat greater measuring voltages, needed to attain smaller measuring uncertainty [7-10]. The high value resistance comparison method is based on modified Wheatstone bridge ("active-arm" bridge) [11] that is shown in Fig. 1. The active-arm bridge is formed by substituting two of the resistive arms of a standard Wheatstone bridge circuit with two active arms which incorporate two low-impedance voltage sources, namely U_1 and U_2. The source U_2 generates fixed DC voltage, while the voltage of the source U_1 is programmable and serves as a part of bridge balancing feedback loop. The other two arms of the bridge are resistive arms, containing compared resistors R_1 and R_2. The "H" (High) terminals of resistors R_1 and R_2 are connected directly to the respective voltage sources U_1 and U_2, while their "L" (Low) terminals are short-circuited and connected to the input of current detector (picoammeter) **pA**.
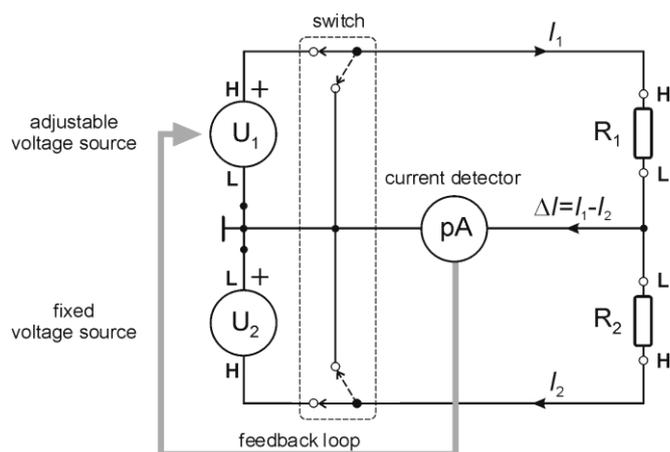

Fig. 1. Schematic principle of high value resistance comparison using Modified Wheatstone bridge ("active-arm" bridge)

The result of this method is the **resistance ratio r_{12}**, which can be measured on nominal levels 1:1, 10:1 or 100:1. The measured ratio corresponds to the function

$$r_{12} = R_1/R_2, \qquad (1)$$

where the measured resistance is calculated from the known reference resistance and the measured ratio r_{12}. The measuring position of reference and measured resistance in this method is irrelevant, but further in this text the measured unknown resistance R_X will be positioned as $\mathbf{R_1}$, and reference resistance as $\mathbf{R_2}$.

To ensure the aimed uncertainty of measurements, the "4-step measuring procedure" leads to the resistance ratio $r_{12}=R_1/R_2$ as follows:

Step 1: The "H" (High) terminals of resistors $\mathbf{R_1}$ and $\mathbf{R_2}$ are disconnected from voltage sources $\mathbf{U_1}$ and $\mathbf{U_2}$ and short-circuited. The detector $\mathbf{pA}$ measures residual current in the bridge due to internal detector offset voltage, setting the value of zero-point current of the bridge I_{ZERO}.

Step 2: The "H" (High) terminals of resistors $\mathbf{R_1}$ and $\mathbf{R_2}$ are connected to the voltage sources $\mathbf{U_1}$ and $\mathbf{U_2}$, switched on their nominal levels. The detector $\mathbf{pA}$ measures the difference I_{MEAS} of currents I_1 and I_2 which flow through the resistances R_1 and R_2. Using the difference of currents I_{MEAS} and I_{ZERO} the correction of voltage U_1 is calculated, voltage source U_1 is adjusted according to that calculation and the state of the bridge is pushed more toward the balance defined by zero-point current I_{ZERO}.

Step 3: The current detector measures resultant current I_{RES}. After that, the "H" (High) terminals of resistors $\mathbf{R_1}$ and $\mathbf{R_2}$ are disconnected from voltage sources $\mathbf{U_1}$ and $\mathbf{U_2}$ and short-circuited again. The new zero-point current I_{STAT} is measured, which is close but not equal to the previous current I_{ZERO}.

Step 4: The ratio of resistances R_1 and R_2 follows from the ratio r_U of finally adjusted voltage U_1 and fixed voltage U_2, and is calculated as follows:

$$r_U = \frac{U_1}{U_2}. \tag{2}$$

Relative correction k_r of ratio r_U is calculated from difference of resultant current I_{RES} and final zero-point current I_{STAT}, and its value is a few parts per million (or ppm) in the common measurement (parameter KOR in Fig. 3). Finally, the ratio of compared resistances r_{12} is calculated as follows:

$$r_{12} = \frac{R_1}{R_2} = r_U(1+k_r) \tag{3}$$

The voltage ratio r_U is determined by digital voltmeter Agilent 3458A (further in text marked as AG4) using its ability to measure ratio of two DC voltages directly. As shown on the schematic diagram of wiring and connections, presented in details in Fig. 2, the switch device SW is connected directly to the "INPUT" and "SENSE" connectors of AG4, determining programmatically position of the "H" terminals of resistors $\mathbf{R_1}$ and $\mathbf{R_2}$. The voltages U_1 and U_2, generated by voltage calibrators Fluke 5700A and Fluke 5440B, are respectively monitored on "INPUT" and "SENSE" terminals of AG4, which is set-up on RATIO mode measurement. In this mode the voltmeter automatically measures the ratio of voltages U_1 and U_2 with uncertainty comparable to the uncertainty on DCV mode of measurement. The restriction of using Agilent 3458A in RATIO mode comes from voltage limit of 10 V allowed on "Sense" terminal. If measurement procedure requires voltage U_2 greater than 10 V, the Fluke 572 divider is designed to properly reduce this voltage by ratio 10:1 or 100:1, as appropriate.
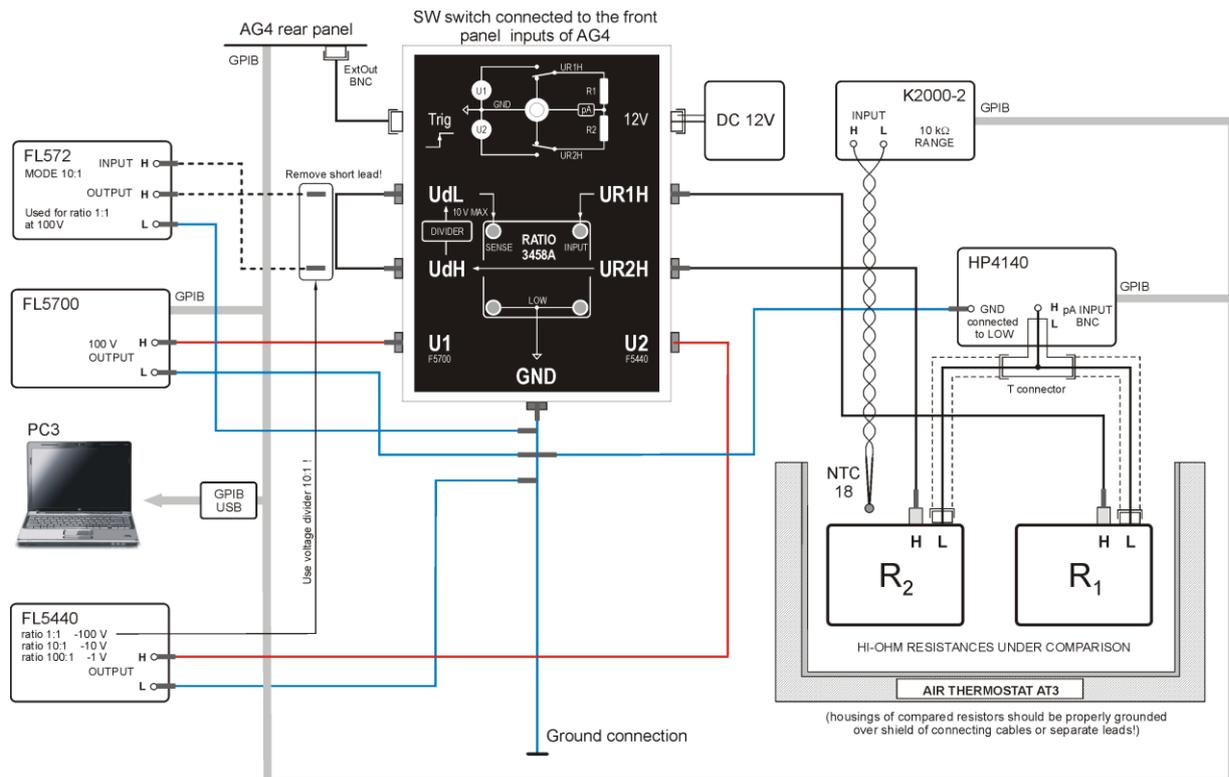

Fig. 2. Schematic diagram of wiring and connections

Compared resistance standards R_1 and R_2 are placed into the air-type ultrathermostat AT3, in which the temperature of 23 °C is maintained, and measured by the precise negative temperature coefficient resistor (NTCR), which has resistance $R_N = 10000\,\Omega$ at a temperature of 25 °C, measured by the digital multimeter Keithley 2000. The picoammeter HP 4140 serves as the current detector **pA**. The measurement method is automated using the ordinary PC with installed GPIB interface, on which all instruments are connected. For the measurement procedure the self-developed application is used, written in the NI LabVIEW software package. The main window of the programme, which is shown in Fig. 3, contains all selectable parameters and enables the monitoring of the calibration process and measured results. For the further analysis all data are stored on the disc.

3. RESULTS OF MEASUREMENTS

The presented measuring procedure has been tested on the group of high value resistance standards ranging from 10 MΩ to 100 GΩ. Those standards have known temperature coefficients and their time drift is established by the periodic calibration during the past several years [12].

The results of ratio measurements of high resistance standards by presented method are given in Table 1.

Table 1. Measurement results of comparison of high resistance standards using the described method

Compared resistances	Measured ratio r_{12}	Nominal measuring voltages	s
$R_1 = 100$ MΩ $R_2 = 10$ MΩ	9,998675	$U_1 = 100$ V $U_2 = 10$ V	0,15 ppm
$R_1 = 1$ GΩ $R_2 = 100$ MΩ	9,993283	$U_1 = 100$ V $U_2 = 10$ V	0,42 ppm
$R_1 = 10$ GΩ $R_2 = 1$ GΩ	10,00932	$U_1 = 100$ V $U_2 = 10$ V	1,2 ppm
$R_1 = 100$ GΩ $R_2 = 10$ GΩ	9,975415	$U_1 = 100$ V $U_2 = 10$ V	2,1 ppm

Here, r_{12} is ratio calculated by (3), and s is experimental standard deviation of 17 repeated measurements in sequence. Very low deviation of results confirms immunity of method on parasitic quantities, even if the current which flows through detector **pA** is on femtoampere level.
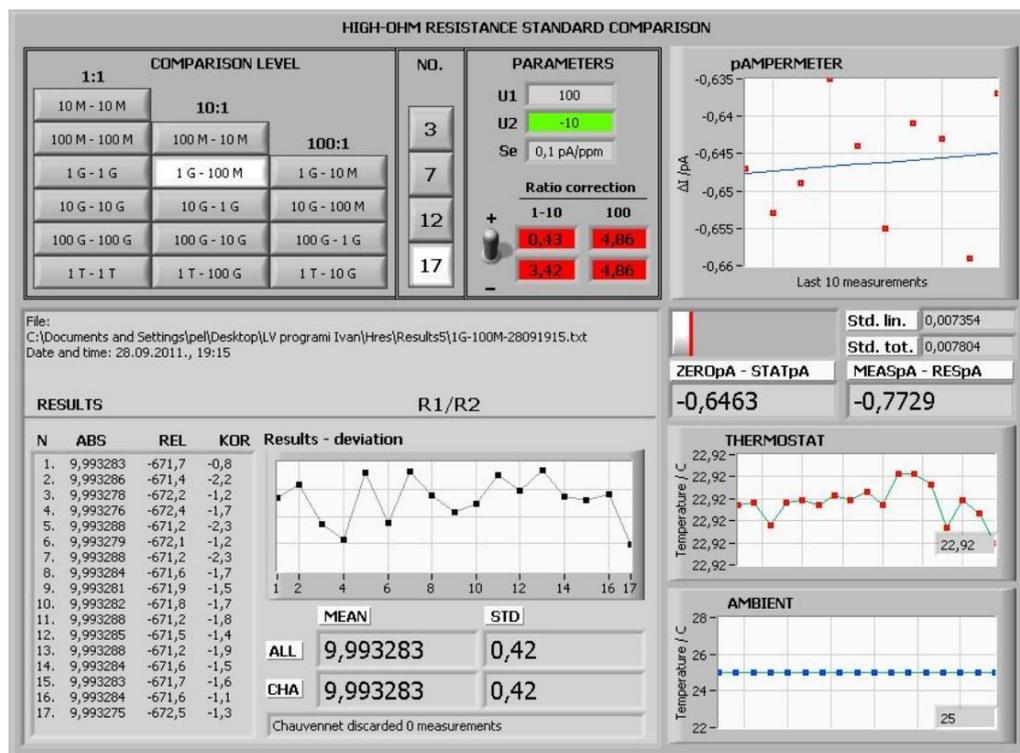

Fig. 3. Example of measurement set-up components visible on the front panel
of the high resistance comparison program; some explanations are as follows:

N	number of comparison in sequence (total number of comparisons is NO.= n);
ABS	absolute values of measured ratios r_{12}, eq. (3);
REL	relative deviations of ratios r_{12} from nominal ratio (expressed in μΩ/Ω i.e. ppm);
KOR	correction k_r of the ratio due to instability of zero-point current (in ppm);
MEAN	arithmetic mean of ratios r_{12};
STD	(experimental) standard deviation of ratios r_{12} (in ppm);
ALL	the values of AR.MEAN and STD are related to all (n) comparisons;
CHA	the values of AR.MEAN and STD are related to n_{ch} measured ratios after Chauvennet criterion has been applied [13].

Estimation of uncertainty budget for measured resistance R_1 comes from basic relation by which the resistance R_1 can be determined is:

$$R_1 = R_2 \cdot r_{12} \cdot \left(1 + k_d \pm m_d\right). \qquad (4)$$

The quantities which determine the final measurement result are:

R_2 – resistance standard as the reference one (with the known value of its resistance) used for this comparison;

r_{12} – measured resistance ratio;

k_d – correction of voltage ratio, measured by voltmeter AG4 in RATIO mode;

m_d – detector offset instability, thermoelectric voltages and other influences estimated from the analysis of the measurement set-up.

Therefore, the contributions to the combined uncertainty budget are:

$u(R_2)$ – uncertainty of the estimated value of reference resistance R_2 for the mean date of comparison;

$u(r_{12})$ – uncertainty of the measured resistance ratio r_{12} (standard deviation of the mean value for the mean date of comparison);

$u(k_d)$ – uncertainty of the correction of voltage ratio which is determined from the calibration of voltmeter in RATIO mode prior and after the comparison procedure, estimated from the analysis of the measurement set-up: the value of $u(k_d) = 0,5$ ppm should be used without using voltage divider on "SENSE" input, while the value of $u(k_d) = 1$ ppm should be used if voltage divider on "SENSE" input is used;

$u(m_d)$ – uncertainty contribution due to detector offset instability, thermoelectric voltages and other influences estimated from the analysis of the measurement set-up and performed measurements in the past; estimated value of $u(m_d) = 0,5$ ppm should be taken.

4. CONCLUSIONS

The use of picoammeter as a current detector in modified Wheatstone bridge shows that influence of leakage currents in measuring circuit can be greatly reduced because the only sensitive measuring point (i.e., connection of "Low" terminals of compared resistors to detector input) is kept on potential very close to ground. The "4-step measuring procedure", given in section 2, utilizes short-circuiting of measuring objects finding in that way the "true zero" – residual offset current in the bridge which have to be established by bridge balancing loop when voltages are enabled. Consequently, the ratio of compared high resistance standards can be measured by the presented method with the experimental standard deviation at the $\mu\Omega/\Omega$ level (i.e., part per million or ppm), which is very satisfactory for those levels of resistance values. Systematic errors in this method can be caused by short-term detector offset instability which impairs relative correction k_r of measured ratio in (3). Furthermore, in order to reduce error of voltage ratio measurement by the single voltmeter Agilent 3458A, it should be calibrated in RATIO mode regarding ratio level of actual measurement. Since the comparison of resistances in chain requires measurement of ratios of 10:1, change of measuring voltage by factor 10 during two subsequent comparison in necessary, and further investigation will be aimed to determinate the voltage coefficients of used high resistance standards. However, the mentioned influences are at the levels which ensure the uncertainty of measurement to be as low as a few $\mu\Omega/\Omega$.

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