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AN ACCURATE COMPARISON OF HIGH-OHM RESISTANCES USING IMPROVED DVM-BASED SYSTEM

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Abstract – For purpose of accurate resistance standards comparison a digital voltmeter (DVM) based method has been designed and realized. When measuring resistance standards greater than 100 MΩ capabilities of the method are restricted due to influence of DVM's input parameters: input resistance, input offset current and input capacitance. The measurement system for resistance comparison based on two DVMs has been improved using simple electrometer transconductance amplifier that interfaces digital voltmeter with the measuring circuit. Analysis of influence of electrometer's parameters, realization of the electrometer device and calibration of the system has been presented in this paper. Described measurement system has been merged in resistance traceability chain of Primary Electromagnetic Laboratory (PEL) within the Faculty of Electrical Engineering and Computing of the University of Zagreb, thus participating in building of high-ohm resistance standard base up to 1 TΩ.

Keywords: high-ohm resistance comparison, electrometer.

1. DVM-BASED RESISTANCE COMPARISON METHOD

1.1 General

The group of resistance standards in PEL consists of twelve resistors ranging from 1 mΩ to 100 MΩ. An additional experimental groups of high-ohm standards of 10 GΩ and 1 TΩ has been designed for purpose of high-ohm comparison method calibration. Developed comparison method in high-ohm measurement field is based on two digital voltmeters HP 3458A. Operational basics of this method are shown in Fig. 1. R_1 and R_2 are compared resistors connected serially, U is applied voltage, $U_{m1}=U_1(1+p_1)$ and $U_{m2}=U_2(1+p_2)$ are voltages measured with two DVMs designated as DV1 and DV2. R_{V1} and R_{V2} are DVM's input resistances; p_1 and p_2 are relative errors of the voltmeters 1 and 2 respectively. Determination of the resistance ratio R_1/R_2 has two steps, indexed as a) and b) in Fig. 1. At position a) the voltage across R_1 and the total voltage of the series are measured with the voltmeters triggered simultaneously (using GET command) via IEEE-488 bus connected to the PC. Step indexed as b) interchanges position of the resistors and the voltage measurement is repeated. Now the voltmeter DV1 measures voltage drop across the resistance R_2, and voltmeter DV2 is only controlling permanence of voltage supply. Using symbols given in Fig. 1 the ratio r of the resistances R_1 and R_2 is expressed as follows:

$$r = \frac{R_1}{R_2} = \frac{U_{m1a}}{U_{m1b}} \cdot \frac{U_{m2b}}{U_{m2a}}, \qquad (1)$$

$$r = \frac{U_{1a}}{U_{1b}} \cdot \frac{U_{2b}}{U_{2a}} \cdot \left(1 + p_{1a} - p_{1b} + p_{2b} - p_{2a}\right), \qquad (2)$$

$$r = r_0 \cdot (1 + \Delta p), \qquad (3)$$

where r_0 is *true value* of ratio of R_1 and R_2, and Δp associated relative error obtained from brackets in (2). If the resistances R_1 and R_2 are equal, the relative error Δp depends only on the relative error instability of the voltmeters, since they measure the same voltages in both positions. The instability of the HP 3458A relative error is found to be less than $5 \cdot 10^{-8}$ during 1 hour measurement, and thus much affects measurement uncertainty of the 1:1 comparison method. If the resistance ratio is greater then unity, the relative error of the ratio corresponds to the difference of the relative errors of voltages being taken with DV1 from two measuring steps. So produced non-linearity error of the DV1 over the measuring range has to be separately estimated.

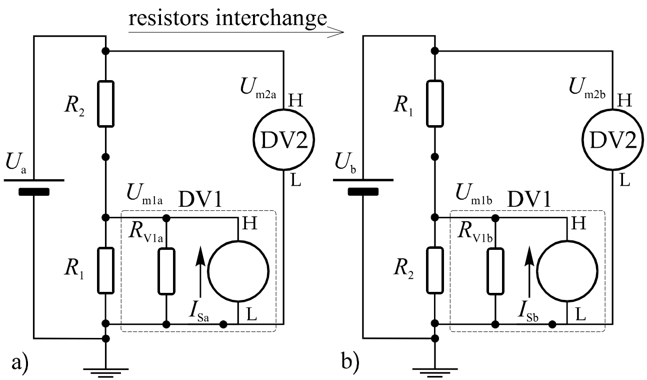

Fig. 1. DVM-based resistance comparison method. Using two voltmeters the effect of current drift during measurement is quite nullified.

1.2 Influence of DVM input parameters

According to analysis presented in [5], the relative ratio error of DVM-based high-ohm resistance comparison method is certainly affected with the input parameters of the measuring instrument: input resistance and offset current of the DVM. As shown in Fig.1, input resistance R_{V1} of the DV1 is shunting firstly resistance R_1 at position a), and then resistance R_2 at position b). So produced shunting error depends on instability $p_{RV1}=R_{V1b}/R_{V1a}-1$ during measurement process and also on ratio of R_{V1} and parallel connection of the compared resistors:

$$r=\frac{R_1}{R_2}=\frac{U_{1a}}{U_{1b}}\cdot\frac{U_{2b}}{U_{2a}}\cdot\left[1+\frac{p_{RV1}}{1+\frac{R_{V1}}{R_1\|R_2}\cdot\left(1+p_{RV1}\right)}\right], \qquad (4)$$

$$r=r_0\cdot\left(1+X\right). \qquad (5)$$

Input amplifier stage of HP 3458A shows signs of small current sources on both input terminals (Fig. 1), thus producing resultant input offset current flow into the measuring circuit and causing ratio error as well:

$$r=r_0\cdot\left[1+\frac{I_{Sa}}{I_R}\cdot\frac{r_0}{r_0+1}\cdot\left(\frac{r_0-1}{r_0}+p_{IS}\right)\right], \qquad (6)$$

$$r=r_0\cdot(1+Y_S)\ , \qquad (7)$$

where $p_{IS} = I_{Sb}/I_{Sa}-1$ designates the relative instability of the offset current and I_R is the current through the measured resistor series. It should be emphasized that I_S is pulse-shaped [4] with the period of voltage sampling rate, as a consequence of DVM-integrator's switching when AZERO (auto-zeroing) function is enabled. Influences of both input resistance and the input offset current has also been analysed and measured separately in [5]. The worst-case estimated values of the HP 3458A input parameters are:

$$R_V = 1{,}2\ \mathrm{T\Omega};\quad p_{RV} = 0{,}2;$$
$$I_S = 3\ \mathrm{pA};\quad p_{IS} = 0{,}2,$$

where p_{RV} and p_{Is} designate the relative instabilities of the R_V and I_S respectively. If an interesting period for DVM's input parameters instability estimation is 10 minutes, as much as comparison of high-ohm standard resistors is usually performing, calculated contributions of DVM's input parameter instabilities in the relative error of comparison ratio over a range of high-ohm resistances are given in Table I. Conclusion is that comparison method based on HP 3458A digital voltmeter is not competent for measuring resistance standards greater than 100 MΩ because of considerable measurement uncertainty rise. Since the relative errors in Table I are functions of both parameter value and associated random drift, an adequate correction of resistance ratio error cannot be applied.

TABLE I. Contributions of DVM's input parameter instabilities in the relative error of two nominal ratios $r = R_1/R_2$, 1:1 and 10:1, for three high-ohm resistance values (R_1). The voltage supply of measuring circuit is 10 V.

r	R_1	X	Y_S	$X + Y_S$
1	100 MΩ	4 μΩ/Ω	3 μΩ/Ω	7 μΩ/Ω
	10 GΩ	380 μΩ/Ω	300 μΩ/Ω	680 μΩ/Ω
	1 TΩ	$2{,}8\cdot10^{-2}$	$3\cdot10^{-2}$	$5{,}8\cdot10^{-2}$
10	100 MΩ	0,7 μΩ/Ω	30 μΩ/Ω	30,7 μΩ/Ω
	10 GΩ	69 μΩ/Ω	3000 μΩ/Ω	3069 μΩ/Ω
	1 TΩ	$7\cdot10^{-4}$	$3{,}3\cdot10^{-3}$	$4\cdot10^{-3}$

2. ELECTROMETER INTERFACE

One possible solution for reducing measurement uncertainty of high-ohm resistance comparison is by interfacing DVM with amplifier that exhibits electrometer's input resistance of 10^{15} Ω and input offset current of femtoamperes. What are advantages of this device? If such electrometer amplifier has unity gain, it simply becomes transconductance amplifier (in further text TA) that converts high input impedance (explicitly resistance R_1 or R_2) to low-ohm output impedance (less than 1 Ω), assuring voltage matching to the input impedance of the voltmeter. Input parameters of digital voltmeter are now irrelevant and voltmeter becomes only "passive" programmable device suitable for synchronized voltage measurement. Moreover, analog inputs of electrometer amplifier have constant offset current, so disturbances owing to pulsed parasitic capacitance charging could be significantly reduced. According to Fig. 2, such interface affects resistance ratio with unity gain instability $\Delta p_E = p_{Ea} - p_{Eb}$, and also with instabilities p_{RE} and p_{ISE} of input resistance and input current of the electrometer:

$$r=\frac{U_a\left(1+p_{Ea}\right)}{U_b\left(1+p_{Eb}\right)}\cdot\left(1+\Delta p+X_E+Y_{SE}\right), \qquad (8)$$

$$r=r_0\cdot\left(1+\Delta p+X_E+Y_{SE}+\Delta p_E\right). \qquad (9)$$

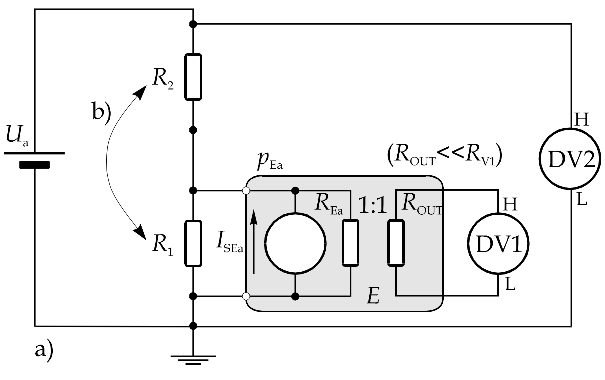

Fig. 2. Electrometer amplifier incorporated into measuring circuit.

Assuming that values of the TA input parameters are like this:

$$R_E = 1\ \mathrm{P\Omega};\quad p_{RE} = 0{,}5,$$
$$I_{SE} = 3\ \mathrm{fA};\quad p_{ISE} = 0{,}5,$$

TABLE II. Calculated contributions of TA input parameter instabilities in relative error of two nominal ratios $r = R_1/R_2$, 1:1 and 10:1 (voltage supply is 10 V), for three high-ohm resistance values (R_1).

r	R_1	X_E	Y_{SE}	$X_E + Y_{SE}$
1	100 MΩ	0,02 μΩ/Ω	0,02 μΩ/Ω	0,04 μΩ/Ω
	10 GΩ	1,7 μΩ/Ω	1,5 μΩ/Ω	3,2 μΩ/Ω
	1 TΩ	166 μΩ/Ω	150 μΩ/Ω	316 μΩ/Ω
10	100 MΩ	0,003 μΩ/Ω	0,04 μΩ/Ω	0,04 μΩ/Ω
	10 GΩ	0,3 μΩ/Ω	4,2 μΩ/Ω	4,7 μΩ/Ω
	1 TΩ	30 μΩ/Ω	420 μΩ/Ω	470 μΩ/Ω

ratio error contributions X_E and Y_{SE} now can be calculated using the same terms in brackets of (4) and (6). The results from Table II evidently illustrate that shunting error and influence of parasitic offset current can greatly be reduced using electrometer amplifier as an interface, especially for measuring resistance ratio on teraohmic level. Uniformity of total errors (X_E+Y_{SE}) for two nominal ratios is now significant, thus error calculation for other nratios between 1 and 10 is simplified. If unity gain instability p_E of TA is expected in range of 10^{-5} to $5{\cdot}10^{-5}$, what is usual value for most instrumentation amplifiers, it should be emphasized that ratios of resistances with values lower than 1 GΩ will be influenced much more with TA gain instability rather than instabilities of TA input parameters. For that reason request on thermal stability of TA is the most important.

3. DESIGN AND REALIZATION OF ELECTROMETER INTERFACE

Measurement procedure for high-ohm resistance ratio determination used in PEL is based on several devices designed for special measuring functions consistent with accuracy and automation conditions given in advance. Low-cost design of electrometer TA consists of commercially available instrumentation amplifier INA 116 that satisfies assumed values of input parameters from the analysis above. It is important to know that parameters' values stated from manufacturer do not guarantee that realization of device leads to expected features. Major problem in building an instrumentation amplifier is concerned about insulation conditions of environment in which the device is held (fixtures, sockets, contact leads) that must feature almost ideal characteristics. Electrometer amplifier named E12 has been realized using air-connection technique that eliminates parasitic current flow between differential input terminals. Another limitation is concerned about maximum voltage of 40 V that can be applied to the input terminals of TA. The calculations in Table II are given for 10 V voltage supply, with intention to perform all future high-ohm measurements on low voltages. That will reduce possible influence of resistance voltage coefficients when comparing resistances of nominal ratios different then unity.

Integrated circuit of the TA is based on 3-opamp topology. The amplifier gain can be adjusted with only one external resistor (for unity gain external resistor is excluded). For very sensitive measurements on high-ohmic level a low-noise accumulator battery is necessary. Input connectors of E12 are of GR 874- PL8A type with wide

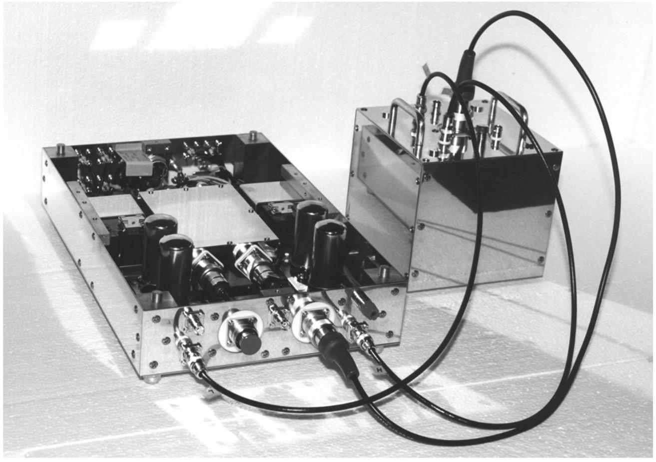

Fig. 3. Commutation device K12 with built-in TA (left) connected to experimental resistance group 10 GΩ (right).

insulator. Used instrumentation amplifier has incorporated active guard outputs for both differential inputs. Comparing voltages in range (0−10) V on both differential inputs and associated guard outputs relative discrepancy less then 0,01 has been estimated. Therefore guarding cable shields using active guard outputs can reduce parasitic currents over the insulation of connecting cables and connectors by factor 10^2. The electrometer E12 is incorporated in metal housing K12 (as seen on Fig. 3) along with mercury wetted relays for resistance interchange and opto-isolated control unit for PC parallel-port operation. Program-controlled measurement procedure uses DC voltage calibrator FLUKE 5440B as voltage supply configured for IEE-488 remote control.

4. ELECTROMETER CALIBRATION

First step in electrometer TA testing was determination of input resistance and input offset current. Input resistance R_E has been established by measuring voltage difference from two cases: first when TA is connected to the calibrator directly and second when TA is connected to the calibrator in series with high-ohm resistor of 100 GΩ. Thermal stability of experimental carbon 100 GΩ resistor is crucial, thus thermostating in range ±50 mK in dry-air enclosed box was applied. Input bias current of TA was measured as voltage drop across 100 GΩ resistor short-connected to the input terminals of TA. The results are combined in Table III.

TABLE III. Measured values of TA input parameters (* extended uncertainty).

	Day	R_E	I_{SE}
1.	10. 7. 2001.	(0,94 ± 0,38) PΩ	(8,8 ± 3,1) fA
2.	11. 7. 2001.	(1,21 ± 0,58) PΩ	(6,4 ± 2,5) fA
3.	12. 7. 2001.	(0,89 ± 0,36) PΩ	(8,1 ± 3,2) fA
$\overline{R}_E \pm \sigma_{RE}{}^*$		(0,96 ± 0,6) PΩ	
$\overline{I}_{ES} \pm \sigma_{IES}{}^*$		(7,5 ± 4,3) fA	

The measurement uncertainty of TA input parameters is relatively high due to difficulties when measuring such extreme quantities. However, this simple method has derived parameters very close to manufacturer's data and assumed values. Next step in TA testing was determination of unity gain non-linearity and instability in range (1–10) V. For that purpose two digital voltmeters HP 3458A are used as shown in Fig. 4. In position a) both voltmeters are connected in parallel with the stable voltage source U_{CAL} (calibrator) and simultaneously triggered to obtain next readings:

$$U_{1a} = U_{CAL} \cdot (1 + p_{1a}), \quad (10)$$

$$U_{2a} = U_{CAL} \cdot (1 + p_{2a}), \quad (11)$$

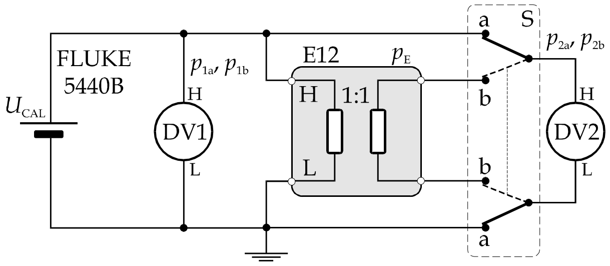

Fig. 4. Measuring circuit for TA gain non-linearity estimation.

where p_{1a} and p_{2a} are the relative errors of the voltmeters DV1 and DV2 respectively. In position b) DV2 toggles to the output terminals of the electrometer and the next relations are satisfied:

$$U_{1b} = U_k \cdot (1 + p_{1b}), \quad (12)$$

$$U_{2b} = U_k \cdot (1 + p_{2b} + p_{EV}), \quad (13)$$

where p_E is unity gain error of TA for applied voltage. From (10) to (13) the following is obtained:

$$\frac{U_{1a}}{U_{1b}} \cdot \frac{U_{2b}}{U_{2a}} - 1 = p_{1a} - p_{1b} + p_{2b} - p_{2a} + p_{EV}, \quad (14)$$

$$\frac{U_{1a}}{U_{1b}} \cdot \frac{U_{2b}}{U_{2a}} - 1 = \Delta p_1 - \Delta p_2 + p_{EV}. \quad (15)$$

Since DV1 and DV2 are reading the same voltage during measurement process, Δp_1 and Δp_2 correspond to the instability of the voltmeters readings. As mentioned earlier, relative instabilities of the voltmeters are less then 10^{-7} during 10 minutes measurement period, therefore this instabilities as well as instability of the calibrator can be neglected. Finally, the relative unity gain error is calculated from (15) as:

$$p_{EV} = \frac{U_{1a}}{U_{1b}} \cdot \frac{U_{2b}}{U_{2a}} - 1. \quad (16)$$

The systematic electrometer error p_{EV} exhibits short-time instability Δp_{EV}, also shown in Fig. 5 as vertical bars. When nominal resistance ratio 1:1 is measured the term Δp_E in (9) corresponds to TA gain instability Δp_{EV}. For other ratios the term Δp_E includes additional error that corresponds to the difference of the TA errors related to the voltages measured in both position of compared resistances.

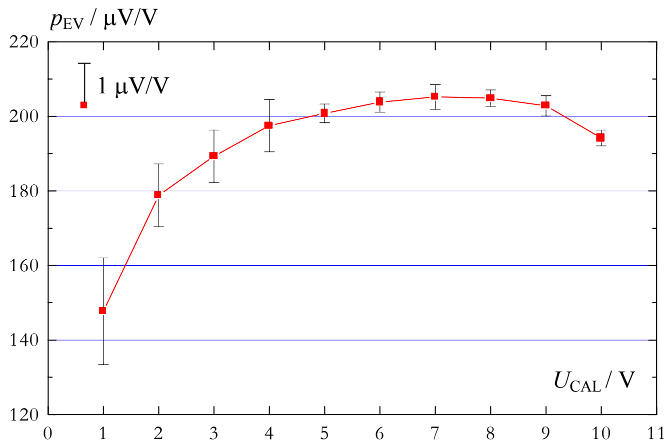

Fig. 5. Estimated non-linearity error of TA over 10 V range.

Determination of TA gain error has been performed several times during few months with reproducibility of p_{EV} better then 1 µV/V. An automated procedure for fast estimation of p_{EV} curve prior to resistance comparison has been added to PC-controlled measurement procedure.

5. COMPARISON METHOD CALIBRATION

Calculation of relative ratio error according to (9) requires knowledge of exact values of TA parameters R_E, I_{ES} and p_{EV} along with assumed instabilities. Difficulties of uncertainty calculation can be avoided if certain calibration of the method is applied. For that purpose the relative errors in (9) can be divided in two parts, systematic error Δp_{SYS} and random error p_{RAN}, written as follows:

$$r = r_0 \cdot (1 + p_{RAN} + \Delta p_{SYS}). \quad (17)$$

The systematic part Δp_{SYS} includes all non-linearity errors of the voltmeters and electrometer amplifier and it will be called *cumulative error of the method.* Random part p_{RAN} contains instabilities of TA input parameters together with instability of resistances during comparison. The cumulative error of the comparison method has been established using Hamon array of 11 well-balanced and high-stable resistors of 250 kΩ, as shown in Fig. 6. The resistors from R_0 to R_{10} are connected serially and thermostated in oil-bath. Absolute values of this resistors are irrelevant.

Procedure begins with 1:1 comparison of each of the resistors from R_1 to R_{10} with the reference resistor R_0. With assumption that Δp_{SYS} equals zero when 1:1 comparison is

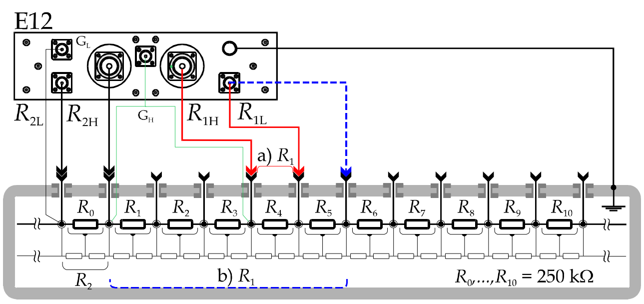

Fig. 6. Calibration of electrometer based comparison method using Hamon array of resistors.

executed (concluded from the analysis above), these ten ratios are given as:

$$r_{1,0} = \frac{R_1}{R_0},\ r_{2,0} = \frac{R_2}{R_0},\ \cdots,\ r_{10,0} = \frac{R_{10}}{R_0}. \qquad (18)$$

True values of nominal ratios r_N from 2:1 to 10:1 are calculated by adding up unity ratios (18) according to following sequence:

$$r_N = \sum_{i=1}^{N} r_{i,0} = \frac{R_1 + R_2 + \ldots + R_N}{R_0},\ N = 2,\ldots,10. \qquad (19)$$

Procedure goes on by comparing series of resistors R_1–R_N with the reference one R_0, hence *measured ratios* r_{Nm} from 2:1 to 10:1 are found:

$$r_{Nm} = \frac{R_1 + R_2 + \ldots + R_N}{R_0} \cdot (1 + \Delta p_{NSYS}),\ N = 2,\ldots,10. \qquad (20)$$

In this step the voltage supply is changed for every ratio with respect of 1 V on the reference resistor. From (19) and (20) the cumulative error Δp_{NSYS} for specific nominal ratio N is calculated as:

$$\Delta p_{NSYS} = \frac{r_{Nm}}{r_N} - 1, \quad N = 2,\ldots,10\ . \qquad (21)$$

The cumulative errors of nominal ratios are shown in Fig. 7. Correction of any resistance ratio is automatically calculated using calibration interpolation curve that fits measured results with deviation better that 1,5 μΩ/Ω. It is important to say that correction of ratio using curve from Fig. 7 is valid only if voltage across R_1 in Fig. 2 is 1 V. For any other voltage combination across the compared resistor the cumulative error is calculated as difference of cumulative errors from Fig. 7 by changing X-axis into volts:

$$\Delta p_{SYS} = \Delta p_{[U(R_1)]SYS} - \Delta p_{[U(R_2)]SYS}, \qquad (22)$$

where $U(R_1)$ and $U(R_2)$ corresponds to the voltages across R_1 and R_2 in position a) on Fig. 2.

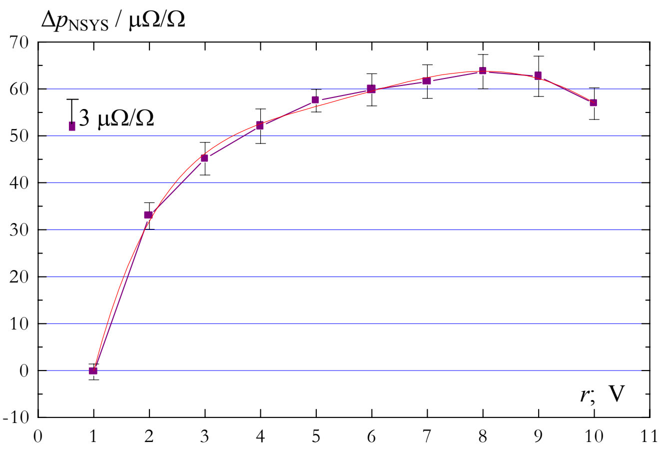

Fig. 7. Cumulative error of comparison method for nominal ratios in range from 1:1 to 10:1.

6. RING RESISTANCE COMPARISON

Uncertainty of the TA-based method due to errors of its voltage measuring devices can also be reached by ring comparison of several high-stable resistances of the same value. For that purpose three well-balanced Tetrinox 1 MΩ resistors have been chosen and placed in sealed air-thermostat with temperature deviation less then 50 mK. The resistances are designated in order as R_1, R_2, and R_3. Procedure is based on consecutive 1:1 comparison of two resistances in sequence and stops with comparison of the last resistance with the first one:

$$r_{12} = \frac{R_1}{R_2} \cdot (1 + p_{12}), \qquad r_{23} = \frac{R_2}{R_3} \cdot (1 + p_{23}),$$
$$r_{31} = \frac{R_3}{R_1} \cdot (1 + p_{31}). \qquad (23)$$

The most part of device systematic errors is nullified, and only uncompensated errors will cause relative error of the ratios above. The ring comparison error p_{RC} can be found by multiplication of the terms from (23):

$$q = r_{12} \cdot r_{23} \cdot r_{31} = 1 + (p_{12} + p_{23} + p_{31}),$$
$$q = 1 + p_{RC}. \qquad (24)$$

All ratio measurements are performed in the same conditions. If the relative ratio errors in (23) are of systematic type, they will not much differ one from another and will cause good repeatability of p_{RC}. In that case residual error of the 1:1 comparison is $p_{1:1} = p_{RC}/3$ and should be added to measurement uncertainty budget. However, if repeatability of ring comparison error is not a case, limits of error for 1:1 comparison is expressed by means of standard deviation of p_{RC} from a number of performed ring comparisons. The results of five ring comparisons using TA method are shown in Table 4.

Table IV: Results of ring comparison of three 1 MΩ resistors for the purpose of method uncertainty estimation.

n	r_{12}	r_{23}	r_{31}	q	p_{RC} / μΩ/Ω
1.	1,0000003	0,9999976	1,0000022	1,0000001	0,1
2.	1,0000003	0,9999981	1,0000017	1,0000001	0,1
3.	1,0000004	0,9999978	1,0000020	1,0000002	0,2
4.	1,0000004	0,9999978	1,0000021	1,0000003	0,3
5.	1,0000003	0,9999976	1,0000020	0,9999999	–0,1

From results given in Table IV the mean value of p_{RC} = 0,12 μΩ/Ω and related standard deviation of 0,15 μΩ/Ω is calculated. Conclusion is that uncertainty of 1:1 comparison method owing to voltage measurement is less then 0,5 μΩ/Ω and can be practically neglected when resistances of GΩ and greater are compared. On the other hand when measured ratio is not unity, non-linearity of the electrometer causes additional uncertainty of 5 μΩ/Ω, that includes interpolation curve error from Fig. 7 and deviation of Δp_{SYS} calculation according to (22).

7. CONCLUSION

Improvement of the DVM-based measurement system for high-ohm resistance comparison using electrometer transconductance amplifier as an interface has been fully analysed and realized in low-cost manner. The results of measuring input parameters of TA lead to conclusion that uncertainty of the method using TA interface can be effectively reduced by factor 10^2 comparing to simple DVM-based method. Furthermore, calibration of the measuring system showed that TA interface has negligible influence in total uncertainty budget of the method. Preliminary comparisons of 10 GΩ and 1 TΩ resistance standards in PEL yielded very satisfactory results that certainly will improve measurement capability of high-ohm resistance comparison method, particularly on low voltages.

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