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**VOLTAGE COEFFICIENT OF HIGH-OHMIC MOX TYPE RESISTORS**

MOX type high-ohmic precise resistors are used both in highest resistance standards and in structures of pico-ammeters and mega-ohmmeters with highest measuring ranges. The parameters of applied resistors decides about instrument’s accuracy class, available measuring ranges and also have influence on measurement results stabilization time.

High-ohmic resistors, especially those with highest resistance values, show considerable voltage unstablility. Larger when forcing voltages are lower. One of the most important parameters of precise high-ohmic resistors besides quality of work tolerance, temperature coefficient (TCR) and noise tension is VCR – the Voltage Coefficient of Resistance.

This coefficient is given by the producers usually for voltages higher than 10 V [1]. Therefore when there occurs a need of high-ohmic resistor use for different working voltage an resistance vs. voltage measurement $R = f(U)$ has to be made.

The article shows obtained up to now results of MOX high-ohmic resistors voltage coefficients examinations in wide range (1–1000) V. The method of obtaining VCR presented in this article can be applied also for determination of MOX high-ohmic resistors parameters in the lowest working voltages.

1. INTRODUCTION

High-ohmic resistors are playing a very important role in measurements and electrometric apparatus. From these resistors we build among other things constant and decade highest resistance standards and analog i/u converters – necessary in modern electrometric apparatus construction (pico-ammeters, mega-ohmmeters) [1]. Parameters of resistors used in construction of pico-ammeters have an essential influence on its basic features, such as attainable measuring ranges, instrument accuracy class or time of measurement.

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As required by the application the working conditions of the parameters will be different. In high-ohmic resistance standards the operating voltages are usually higher than 10V, while in analog U/I converters these voltages are situated in (0–2) V range [1, 2]. While in the first case, that is in medium and high operating voltages range, the VCR of applied resistor/resistors in known and usually given in the producers catalogue, then in case of low voltages the data is incomplete and insufficient. Also the source literature is missing. However the resistors resistance non-linearity has a significant influence on \( i \rightarrow u \) processing uncertainty and so also on electrometric apparatus precision.

**2. ANALOG I/U CONVERSION**

The measured current \( i_x \) conversion to voltage is possible in one of two types of i/u converters. The simplest i/u converter is a standard high-ohmic resistor \( R_n \) with suitable selected resistance value. Then we are talking about a passive converter. If the above mentioned resistor becomes included in an electrometric operational amplifier negative feedback loop then we talk about a active converter. Because passive converters have a lot of disadvantages (high input and output resistance) the most sensitive produced nowadays pico-ammeters use the active i/u converter. An complete active i/u converter consists of two blocks: the specific i/u converter and reversing normalizing amplifier (Fig. 1).

The main factor limiting the most-sensitive pico-ammeters ranges is the accessibility of small-dimensional precise high-ohmic resistors with highest resistance values \((10^{10} \div 10^{11}) \ \Omega\). These resistors are necessary to obtain the most-sensitive ranges.
of the pico-ammeters on (1–20) pA level. Performing of measurements on these ranges is connected with high systematic and incidental errors having its main source in active i/u converter, mostly in high-ohmic \( R_n \) resistor. The resistors metrological parameters – accuracy and temperature and voltage resistance stability – have a direct influence on i/u converter processing accuracy [3].

3. CONSTRUCTION AND CHARACTERISTICS OF HIGH-OHMIC RESISTORS

Until recently the resistors with highest resistance values, characterized with good parameters (low values of temperature and VCR), were hard to reach and very expensive. However in the last few years the situation considerably improved because there is in sale a new generation of high-ohmic resistors, so called metal-oxide – MOX. In metal-oxide resistors the resistive path is made from semiconducting glaze produced through doped oxide aluminum melting in high temperature. This oxide is obtained through aluminum core oxidation, being then simultaneously the resistor frame or by direct spreading on to the ceramic core. The overall dimensions of the resistor are small, although they are high-voltage resistors (working voltage can be even 10 kV), with few watts of rated power. The accuracy class of resistors with values \( (10^9 \div 10^{10}) \, \Omega \) reaches the level of (1–2) %, and in special realizations even (0,2–0,5)%. Their VCR is very small, usually doesn’t exceed few ppm/V, while the temperature coefficient is also small, about 50–200 ppm/°C. For biggest reachable values \( (10^{11} \div 10^{12}) \, \Omega \) their accuracy is decreasing and the average is about 2–5 %. Also their voltage and temperature coefficients increase. Notice that generally used so far carbon composite resistors were considerably improved, nevertheless they do not equal to the parameters of MOX resistors, especially if we compare their resistance voltage stability.

Good parameters of oxide MOX resistor caused that they are widely used in electrometer and are excellently suitable for high-ohmic resistance standards construction, especially those with high operating voltage [1, 4].

The primary feature for majority of high-ohmic resistors, distinguishing them from the rest of precise resistors, is the considerable dependence between the resistance and applied voltage [5]. While the temperature and time unstablility of those resistors can be limited (environment temperature stabilization and frequent resistor calibration), then the influence of voltage change can not be practically eliminated, because in principle the high-ohmic resistors work in quite wide voltage range. An very important parameter is then the VCR (Voltage Coefficient of Resistance), described by the dependence (1) determined as a ratio between relative resistance increment value and causing it change of voltage value.
\[ VCR = \frac{\Delta R}{R_{sr}} \cdot \frac{1}{\Delta U} = \frac{R_{U2} - R_{U1}}{R_{sr} \cdot (U_2 - U_1)} \] (1)

Defined so VCR is expressed usually in ppm/V.

4. MEASURING POSITION, METHODS AND RESULTS

The measuring arrangement depend on the chosen measurement method, was set up from: standard, low-voltage bipolar source VCBS-1, internal DC voltage source K6517A, Keithley electrometers/pico-ammeters 6517A and 6514, as well as electronic mega-ohmmeter, prepared in Division of Measurement Instruments and Systems, EMA-M1. Examined high-ohmic resistors were located inside double-shielded, metal screen. The measurement voltage was adjusted continuously/incremental in range (0÷1000) V, where the exact voltage value was determined from precise digital voltmeter Hewlett-Packard 34401A.

The measurement were completed on Ohmite Corp. (USA) MOX high-ohmic resistors from three series 1125-22-1005FE, 1125-23-1009FE and 1125-23-100A-KE with nominal resistance values 10 GΩ, 100 GΩ and 1 TΩ and quality of work tolerance 1.1 and 10%.

4.1. MEASURING METHODS

In high-value resistance measurements it is necessary that the measuring apparatus assures the possibility of measurement execution with two methods: constant voltage (voltage source and ammeter) or with constant current (current source and voltmeter) [5].

4.1.1. HIGH-RESISTANCE MEASUREMENT WITH CONSTANT CURRENT METHODS

The principle of measurement with constant current is illustrated on Fig. 2. The main element of the meter circuit is an electrometric operational amplifier configured as follower. The current source is connected between the output and irreversible input of the amplifier and consists of standard resistor \( R_N \) and reference voltage source \( E_N \). This method, though right for linear objects, in this project was used for comparison reasons in one-point resistance value measurements of examined high-ohmic resistors.
4.1.2. HIGH-RESISTANCE MEASUREMENT WITH CONSTANT VOLTAGE METHODS

The measurement at constant and specified measurement voltage is especially justified in non-linear objects measurement. In this method the measured value is the current flowing through the \( R_X \) resistor at applied test voltage \( E \) and on this basis the resistance \( R_X \) value is determined.

As the pico-ammeter the devices in which the analog i/u converter is used were applied. The main advantage of this method, besides its configuration simplicity, is its possibility of high-ohmic objects examination in wide voltage range practically without the error of method [1, 6]. The simplified meter circuit diagram is shown on Fig. 3.
4.2. NOMINAL RESISTANCE – ACTUAL RESISTANCE.

One of the primary resistor parameters is their rated (nominal) resistance, which in connection with tolerance determines the resistance value interval, in which the actual resistance has to be situated in [4]. By this parameters and high-ohmic resistors voltage coefficients determination the nominal resistance is only a indicator. That is why for the calculations the actual value of resistor resistance has to be taken, which has to be measured with specified uncertainty. Because the resistance value of the high-ohmic resistors depends on applied voltage value, the measurements of actual resistance value in function of measurement voltage \( R = f(U_p) \) were made using methods 4.1.1 and 4.1.2.

4.2.1. MEASUREMENT METHODOLOGY

In resistance measurements using constant value of measurement current method the electrometer Keithley 6514 was used as shown in Fig. 4.

![Fig. 4. Circuit diagram used in high-ohmic resistors resistance measurement using constant current method [7]](image)

Before the measurements the electrometer was warmed up for 24 hours. In purpose of measurement inaccuracy reduction guarding was used. Also digital filters were used: averaging \( R_{AVG}-10 \) and median MED1. In measurements at constant measurement voltage value the mega-ohmmeter EMA-M1 was used. In purpose of obtaining precise results the resistance was determined on the basis of precise digital voltmeter (HP34401A) analog output indication. The final resistance value was determined after disjunctive results rejection and averaging filter \( R_{AVG}-5 \) application. All resistance values readings were taken after indication settling, that is after about 15 to 30 minutes. The measurement were made at constant relative humidity level \( w = 65\% \), while the temperature during the measurements was between (24,5–25,0) °C.
4.3. MEASUREMENT RESULTS

Fig. 5. Resistance values spread for 30 high-ohmic resistors series with nominal resistance 10 GΩ ± 1% at \( I_p \approx 1 \) nA current (Method 4.1.1)

Fig. 6. Resistance values spread for 30 high-ohmic resistors series with nominal resistance 100 GΩ ± 1% at \( I_p \approx 1 \) nA current (Method 4.1.1)
Fig. 7.
Resistance values spread in 10 resistor pieces sample with nominal value
\[ R = 10 \, \text{G}\Omega \pm 1\% \]
measured at \( U_p = 1000 \, \text{V} \)
(Method 4.1.2)

Fig. 8.
Resistance values spread in 10 resistor pieces sample with nominal value
\[ R = 10 \, \text{G}\Omega \pm 1\% \]
measured at \( U_p = 10 \, \text{V} \)
(Method 4.1.2)

Fig. 9.
Resistance values spread in 10 resistor pieces sample with nominal value
\[ R = 10 \, \text{G}\Omega \pm 1\% \]
measured at \( U_p = 1 \, \text{V} \)
(Method 4.1.2)
Fig. 10. Resistance values spread in 10 resistor pieces sample with nominal value $R = 100 \, \text{G}\Omega \pm 1\%$ measured at $U_p = 100 \, \text{V}$ (Method 4.1.2)

Fig. 11. Resistance values spread in 10 resistor pieces sample with nominal value $R = 100 \, \text{G}\Omega \pm 1\%$ measured at $U_p = 10 \, \text{V}$ (Method 4.1.2)

Fig. 12. Resistance values spread in 10 resistor pieces sample with nominal value $R = 100 \, \text{G}\Omega \pm 1\%$ measured at $U_p = 1 \, \text{V}$ (Method 4.1.2)
Fig. 13. Resistance diagrams in function of applied testing voltage $R = f(U_p)$ for MOX high-ohmic resistors with nominal resistance values 10 GΩ (Method 4.1.2)
Fig. 14. Resistance diagrams in function of applied testing voltage $R = f(U_p)$ for MOX high-ohmic resistors with nominal resistance values 100 GΩ (Method 4.1.2)
Fig. 15. Resistance diagrams in function of applied testing voltage $R = f(U_p)$ for MOX high-ohmic resistor with nominal resistance values $R = 1 \ \Omega$ (Method 4.1.2).

Tab. 1. VCR Voltage coefficients for examined MOX high-ohmic resistors with nominal resistance value $R = 10 \ \Omega$ determined according to dependence (1)

<table>
<thead>
<tr>
<th>$\Delta U$ [V]</th>
<th>R10#1</th>
<th>R10#2</th>
<th>R10#3</th>
<th>R10#4</th>
<th>R10#5</th>
<th>R10#6</th>
<th>R10#7</th>
<th>R10#8</th>
<th>R10#9</th>
<th>R10#10</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>0.42</td>
<td>-0.63</td>
<td>-2.80</td>
<td>-0.17</td>
<td>-0.07</td>
<td>0.34</td>
<td>-0.14</td>
<td>-0.19</td>
<td>-0.85</td>
<td>0.33</td>
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<tr>
<td>90</td>
<td>-16.81</td>
<td>-24.55</td>
<td>-0.31</td>
<td>-29.12</td>
<td>-33.33</td>
<td>-27.12</td>
<td>-24.00</td>
<td>-25.91</td>
<td>-18.49</td>
<td>-13.41</td>
</tr>
<tr>
<td>0</td>
<td>3.31</td>
<td>-10.63</td>
<td>-1.86</td>
<td>-4.54</td>
<td>-7.00</td>
<td>-2.80</td>
<td>-3.00</td>
<td>-3.14</td>
<td>5.98</td>
<td>5.98</td>
</tr>
</tbody>
</table>

Tab. 2. VCR voltage coefficients for examined MOX high-ohmic resistors with nominal resistance value $R = 100 \ \Omega$ determined according to dependence (1)

<table>
<thead>
<tr>
<th>$\Delta U$ [V]</th>
<th>R100#1</th>
<th>R100#2</th>
<th>R100#3</th>
<th>R100#4</th>
<th>R100#5</th>
<th>R100#6</th>
<th>R100#7</th>
<th>R100#8</th>
<th>R100#9</th>
<th>R100#10</th>
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</thead>
<tbody>
<tr>
<td>900</td>
<td>-1.53</td>
<td>-0.02</td>
<td>-1.41</td>
<td>-0.19</td>
<td>-2.91</td>
<td>-0.64</td>
<td>0.12</td>
<td>0.09</td>
<td>0.56</td>
<td>0.31</td>
</tr>
<tr>
<td>90</td>
<td>35.10</td>
<td>57.87</td>
<td>60.95</td>
<td>52.50</td>
<td>43.20</td>
<td>33.77</td>
<td>35.01</td>
<td>79.13</td>
<td>51.57</td>
<td>22.53</td>
</tr>
</tbody>
</table>

4.4. Obtained Results Discussion

Measurements using of constant current method were realized in 2-wire circuit. Then the ohmmeter (electrometer in ohmmeter function) makes the resistance measurement using built-in current source and voltmeter. Then in automatic way calculates and displays measured resistance value. The forced current value in the circuit
was equal to $I_F \approx 1$ nA, what responded to voltage about 10 V for resistors with nominal value 10 GΩ and 100 V for resistors with value 100 GΩ (voltage value dependent on examined resistors resistance).

The results obtained with method 4.1.1 confirm intuitive thesis that high-ohmic resistors parameters deteriorate together with their nominal value growth. On the basis of obtained results it can be noticed that for the first case (Fig. 5) high-ohmic resistors with values $R = 10$ GΩ practically all are situated in their tolerance limit. While for values $R = 100$ GΩ (Fig. 6) ten out of thirty examined resistors exceeds the tolerance limit.

In measurement using 4.1.2 method it can be noticed (what was impossible in method 1.1) that measured resistance value depends on applied measuring voltage value. The resistance of examined objects usually grows together with testing voltage decrease (Fig. 7–9). At voltage $U_p = 1000$ V eight resistors were situated in their acceptable resistance deviation range, values of two of them were on the limit of this range (Fig. 7). Further forcing voltage decrease (up to 1 V) caused tolerance limit exceed in case of resistors sample 2, 3, 4, 5, 8. Analogical tendency can be observed on Fig. 10–12.

Resistance – voltage dependence for examined samples was set up on diagrams 13 and 14. In case of resistors $R = 100$ GΩ, samples 1–6, the increase tendency is not so legible like in rest cases. Also an incomprehensible resistance value drop occurred for testing voltage $U_p = 10$ V. In order to verify obtained results the examinations on these resistors series will be repeated and extended on whole available population. On Figure 15 can be seen the diagram $R = f(U_p)$ for single resistor sample with highest met and available resistance value $R=1$ TΩ, made in MOX oxide technology. These resistors were bought for examination relatively recently so they will be an separate publication object.

Received VCR voltage coefficients (Tab. 1–2) confirm strong increase of high-ohmic resistors nonlinearity, bigger when voltage forcing value is smaller.

5. SUMMARY

The investigation results confirm resistance nonlinearity and considerable high-ohmic resistors voltage sensitivity, especially in low operating voltage range. Also preliminarily confirmed that MOX oxide resistors show a feature which is decrease of resistance value together with applied testing voltage increase. The reason of this phenomenon can be the heterogeneity of the resistive semiconducting layer structure and through that non-uniform current density flowing across resistive path (the influence of ultra-thin dielectric layers insulating conducting grain) [4].
In lowest voltage range 5 mV–100 mV the obtained results are ambiguous (large value spread in consecutive measurements and resistance growth at ascending forcing voltage value). The cause of this has to be not taking into account the correction on amplifier polarization input current used in the pico-ammeter with active i/u converter and increased – in comparison with electrometric monolithic amplifier – hybrid amplifier current noises. For the sake of this it is necessary to conduct further investigations in the scope of lowest forcing voltages.

REFERENCES