VOL. 20, NO. 2, JANUARY 2025 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences
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THE EVALUATION OF THE LONG-TERM DRIFT OF LOW-RESISTANCE MEASURES USING TIME SERIES

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ABSTRACT

The effect of long-term drift of a precision measure on the calibration of other measuring instruments or measures is necessary for careful monitoring of their real metrological characteristics. If such drift is not taken into account, or taken into account, it can lead to incorrect calibration of other measuring instruments or measures. The results of the evaluation of the long-term drift of five low-resistance precision measures with nominal values of 0.0001 Ω, 0.001 Ω, 0.01 Ω, 0.1 Ω, s 1.0 using polynomial regression of the 3rd order are given. The specified approximations of the drift lines of the resistance measures have a value of the coefficient of determination from 0.44 to 0.84, that is, they confirm their adequacy. The measures have historical calibration data from 2002 to 2023. Sufficient adequacy was achieved in the description of the drift lines for all low-resistance measures. Uncertainties of measurement in the calibration of measures are estimated with values from 0.3 ppm to 6.9 ppm.

Keywords: long-term drift, low-resistance measure, drift, time series, calibration, measurement uncertainty.

Manuscript Received 16 April 2024; Revised 22 January 2025; Published 10 March 2025

1. INTRODUCTION

Measuring low electrical resistances is an important task in the field of electronics and electricity for the development and improvement of technologies: ensuring the quality of materials; determination and reduction of electricity losses; effective electrical circuit design; detection of possible defects or malfunctions, etc. The range of small values of electrical resistance can be extremely wide and depends on specific applications and measurement needs. Accordingly, small resistance values are expressed in fractions of ohms or milliohms [1-4].

The drift of the standard or measure can significantly affect the calibration results of measuring devices. When the standard drifts, measurement inaccuracies may occur in the calibration process, since the standard is used to determine the accuracy of other measuring devices. Such a drift indicates systematic changes in the metrological characteristics of the standard or measure. The influence of standard or measure drift on calibration requires careful monitoring of their metrological characteristics during high-precision measurements or calibration [5-9].

Determining the actual drift of a measure or standard is an important part of the calibration process to ensure reliable and accurate calibration results. Taking into account such a drift requires a systematic approach that allows timely detection and correction of changes in the metrological characteristics of measures. For this purpose, regular calibration of measures is carried out to fix the current measurement characteristics.

The drift of small resistance measures can significantly affect the accuracy and reliability of electrical resistance measurements. The main factors that cause the drift of those measures include: temperature and time drift, internal load effects, etc. Various techniques such as temperature compensation, use of stabilized power supplies, use of compensating resistors, and periodic calibration of measuring instruments are used to reduce the drift effect of such measurements. It is also important to consider the measurement conditions and follow the optimal operating conditions to ensure the stability and accuracy of the measurements.

2. LITERATURE REVIEW

The calibration results of a 10 kΩ standard resistor for about five years from 2015 to 2020 with a well-defined linear drift are shown in [10]. The predicted value at one year was obtained by generalized least squares (GLS) with its respective expanded uncertainty estimated by Monte Carlo method. The expanded uncertainty of the predicted value is 0.0000021 kΩ, which is similar to the uncertainty reported in the last calibration results of the standard resistor.

The methodologies to ensure precision calibration of measuring instruments for the evaluation of historical data of electrical resistance standards of 10 Ω and of 100 Ω are presented in [11]. These methodologies are used for improving the metrological characteristics of measurement uncertainty. The uncertainty of fitting the data to a straight line was estimated by the regression method. Linear regression was applied to the obtained calibration data for a period of five years from 2016 to 2021 for resistance standard of 10 Ω and seven years from 2014 to 2021 for resistance standard of 100 Ω. Estimated uncertainties of the one-year predicted resistance value are 6.4 ppm for 10 Ω and 0.0012 % for 100 Ω.

The stability and uncertainty of resistance measurements using calibrated values of reference resistors of 1 Ω and 10 kΩ are discussed in [12]. The relative uncertainty of the realized values of 1 Ω and 10 kΩ confirmed by international comparisons does not

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exceed $2 \cdot 10^{-7}$. The behaviour of the resistor stabilized fully in 2013, and the calibration history recorded since that time allows predicting the resistance value with the expanded uncertainty 0.12 μΩ/Ω. It was found that the standard resistors under study are characterized by a stable resistance drift, which is well predicted using linear regression.

A pressing issue that is not covered in well-known research articles and papers is the research of the long-term drift of measures of low electrical resistance.

3. MATERIALS AND METHODS

The State Enterprise "Ukrmetrteststandard" (Kyiv, Ukraine) keeps precision low-resistance measures Norma Mod. 80 (0.0001 Ω), P310 (0.001 Ω, 0.010 Ω), P321 (0.100 Ω, 1.000 Ω). The high stability of these measures over a fairly long period is confirmed by continuous calibrations. These measures are used in precision measurement setup for calibration of low-resistance measures of less precision, electrical resistance meters, multi meters, and calibrators of electrical quantities. The general view of the precision measurement setup for the calibration of low-resistance measures is shown in Figure-1.

Figure-1. The general view of the precision measurement setup for the calibration of low-resistance measures.

The generalized scheme of the precision measurement setup for the calibration of low-resistance measures is shown in Figure-2. To calibrate precision measures using this measurement setup, a method of comparison measure to be calibrated and a reference measure is used using the P3015 bridge-comparator.

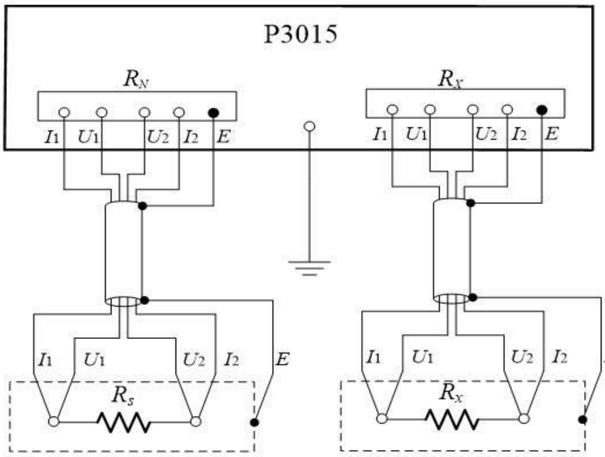

Figure-2. Scheme of the precision measurement setup for the calibration of low-resistance measures.
Rx is a calibrated measure; *Rs* is reference measure.

Controlling and accounting for long-term measure drift is essential to ensure high accuracy and measurement uncertainty during high-precision calibration. Different methods are used to account for the drift of such measures over time. These methods include, in particular, regular calibration, monitoring of operating conditions and the use of ambient temperature stabilization or protection against external influences. They can be used individually or in combination to effectively control measure drift.

Establishing criteria for acceptable deviation of a measure is an important part of the process of managing metrological stability and accuracy. Such criteria may vary depending on the requirements of a particular metrological system or its application. However, there are general approaches to establishing tolerances for the drift of a measure: taking into account historical drift data, if available, to determine typical changes and assess how drift may affect the measurement results; taking into account the possibility of using correction means to compensate for drift and reduce its influence on measurements. Ensuring compliance with established criteria helps ensure the accuracy and reliability of the measurements taken.

4. RESULTS AND DISCUSSIONS

Precision low-resistance measures of State Enterprise "Ukrmetrteststandard" have historical calibration data from 2002 to 2023. The results of calibration of low-resistance measures of 0.0001 Ω, 0.001 Ω, 0.01 Ω, 0.1 Ω, and 1.0 Ω for this period are shown in Table-1 (*U* is expanded measurement uncertainty).

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Table-1. Result of calibration of precision low-resistance measures.

Date	*Rx*, Ω	*U* ppm	*Rx*, Ω	*U* ppm
	0.0001 Ω		0.0010 Ω	
15.04.2002	0.0000999907	23	0.000999991	6.9
23.05.2003	0.0000999911	23	0.000999988	6.9
13.05.2004	0.0000999911	23	0.000999988	6.9
13.09.2005	0.0000999915	23	0.000999991	6.9
12.10.2006	0.0000999920	23	0.000999990	6.9
16.11.2007	0.0000999920	23	0.000999988	6.9
10.11.2008	0.0000999902	23	0.000999988	6.9
13.12.2009	0.0000999922	23	0.000999988	6.9
23.11.2010	0.0000999923	23	0.000999986	6.9
23.11.2011	0.0000999909	23	0.000999987	6.9
11.11.2012	0.0000999919	23	0.000999990	6.9
01.12.2013	0.0000999918	23	0.000999989	6.9
06.12.2013	0.0000999918	23	0.000999989	6.9
07.12.2014	0.0000999914	11	0.000999986	3.0
01.10.2015	0.0000999914	11	0.000999984	3.0
21.04.2016	0.0000999918	11	0.000999989	3.0
14.12.2018	0.0000999915	11	0.000999985	3.0
28.01.2022	0.0000999915	11	0.000999980	3.0
29.06.2023	0.0000999916	2.0	0.000999990	1.0
	0.0100 Ω		0.10000 Ω	
15.04.2002	0.00999984	6.9	0.1000008	6.9
23.05.2003	0.00999987	6.9	0.1000009	6.9
13.05.2004	0.00999988	6.9	0.1000009	6.9
13.09.2005	0.00999985	6.9	0.1000009	6.9
12.10.2006	0.00999984	6.9	0.1000008	6.9
16.11.2007	0.00999989	6.9	0.1000010	6.9
10.11.2008	0.00999985	6.9	0.1000008	6.9
13.12.2009	0.00999984	6.9	0.1000007	6.9
23.11.2010	0.00999982	6.9	0.1000008	6.9
23.11.2011	0.00999983	6.9	0.1000010	6.9
11.11.2012	0.00999985	6.9	0.1000011	6.9
01.12.2013	0.00999983	6.9	0.1000009	6.9
06.12.2013	0.00999983	6.9	0.1000009	6.9
07.12.2014	0.00999985	3.0	0.1000010	3.0
01.10.2015	0.00999982	3.0	0.1000010	3.0
21.04.2016	0.00999983	3.0	0.1000009	3.0
14.12.2018	0.00999979	3.0	0.1000010	3.0
28.01.2022	0.00999982	3.0	0.1000009	3.0
29.06.2023	0.00999983	0.6	0.1000009	0.4
	1.0000 Ω			
15.04.2002	0.999989	6.9		
23.05.2003	0.999989	6.9		
13.05.2004	0.999989	6.9		
13.09.2005	0.999989	6.9		
12.10.2006	0.999989	6.9		
16.11.2007	0.999989	6.9		
10.11.2008	0.999989	6.9		
13.12.2009	0.999989	6.9		
23.11.2010	0.999989	6.9		
23.11.2011	0.999990	6.9		
11.11.2012	0.999990	6.9		
01.12.2013	0.999991	6.9		
06.12.2013	0.999991	6.9		
07.12.2014	0.999990	3.0		
01.10.2015	0.999989	3.0		
21.04.2016	0.999991	3.0		
14.12.2018	0.999989	3.0		
28.01.2022	0.999986	3.0		
29.06.2023	0.999987	0.3		

The results of evaluation of the long-term drift of low-resistance measures of 0.0001 Ω, 0.001 Ω, 0.01 Ω, 0.1 Ω, and 1.0 Ω from 2002 to 2023 using polynomial regression of 3rd orders are shown on Figures 3-7. In the figures, the green solid lines show the average resistance value, and the red dotted lines show the corresponding polynomial approximations of drifts. The indicated approximations of the drift lines of resistance measures have R^2 values equal to 0.21 to 0.75, that is, they confirm their conditional adequacy.

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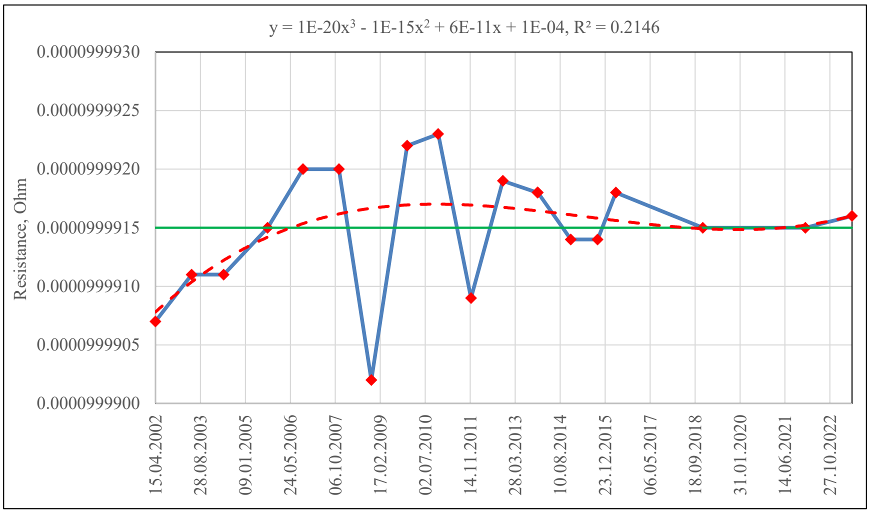

Figure-3. Drift of resistance measure of 0.0001 Ω.

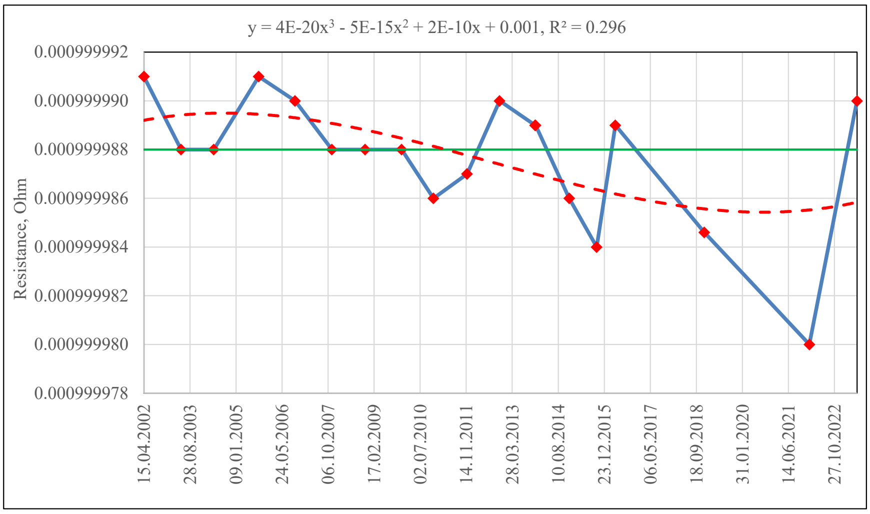

Figure-4. Drift of resistance measure of 0.001 Ω.

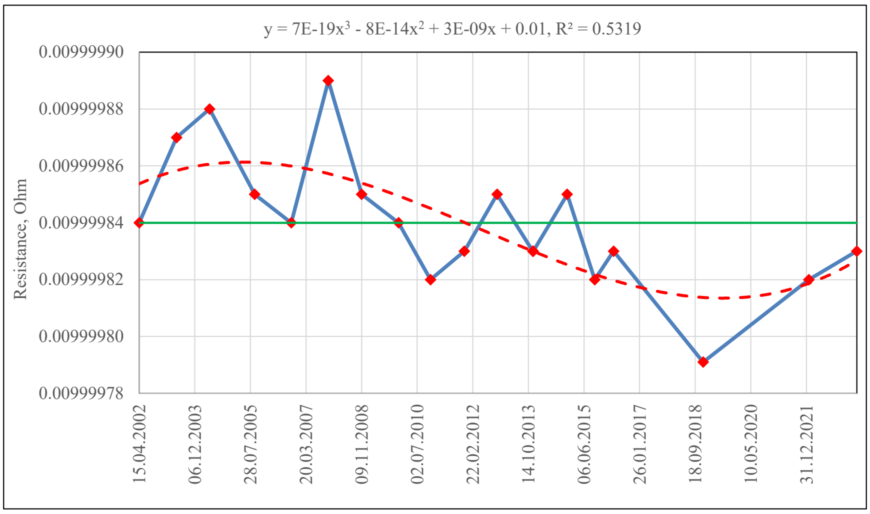

Figure-5. Drift of resistance measure of 0.01 Ω.

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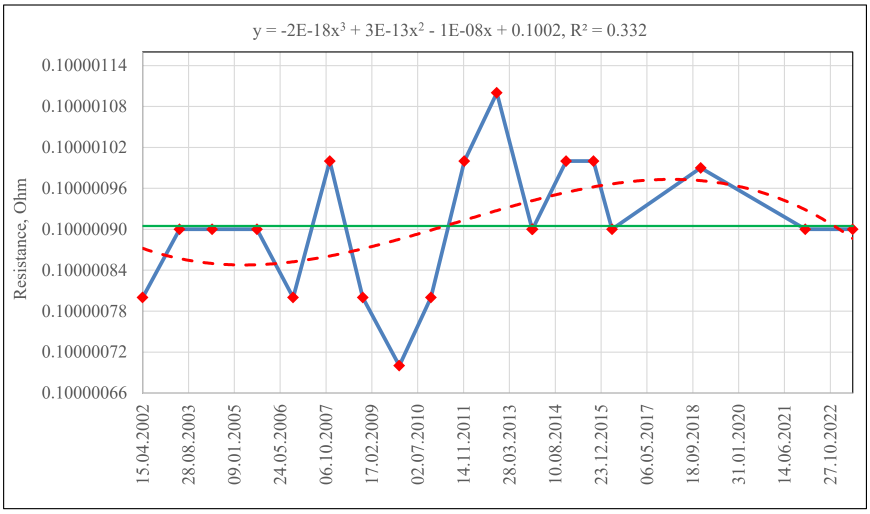

Figure-6. Drift of resistance measure of 0.1 Ω.

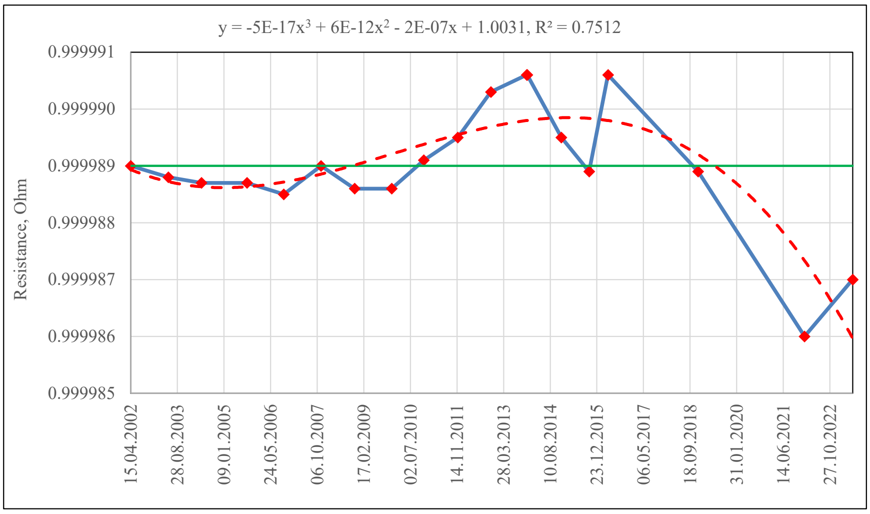

Figure-7. Drift of resistance measure of 1.0 Ω.

The average value of all calibration results of a low-resistance measures from 2002 to 2023 with a nominal value of 0.0001 Ω is 0.0000999915 Ω, with a nominal value of 0.001 Ω – 0.000999988 Ω, with a nominal value of 0.01 Ω – 0.00999984 Ω, with a nominal value of 0.1 Ω – 0.1000009 Ω, with a nominal value of 1.0 Ω – 0.999989 Ω. Measures with nominal values of 0.001 Ω, 0.01 Ω, and 1.0 Ω have a small negative time drift, while a measure with a nominal value of 0.0001 Ω and 0.1 Ω has a small positive time drift.

Calibration of all low-resistance measures at a temperature of 20 °C from 2002 to 2022 was carried out by one of the metrological centers of Ukraine accredited as a calibration laboratory, and calibration of all measures at a temperature of 23 °C in 2023 by PTB (Germany).

The value of low-resistance measure at a temperature of 20 °C is determined by the expression:

$$R_{20} = R_t - R_{nom}\left[\alpha \times 10^{-6}\left(t-20\right) + \beta \times 10^{-6}\left(t-20\right)^2\right], \qquad (1)$$

where R_t and R_{nom} are the value of the resistance of the measure at the calibration temperature and the nominal resistance value at a temperature of 20 °C respectively, Ω; α and β are temperature coefficients which are determined experimentally for each measure, 1/°C and 1/°C^2 respectively.

Values of temperature coefficient and values of the measures at temperatures of 23 °C and 20 °C for low-resistance measures and are given in Table-2.

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Table-2. Values of temperature coefficient and values of the measures at temperatures of 23 °C and 20 °C.

Measure type	R_{nom}, Ω	R_{23}, Ω	R_{20}, Ω	Temperature coefficient of resistance	
				α×10⁻⁶, 1/°C	βα×10⁻⁶, 1/°C
Mod. 80	0.0001	0.0000999971	0.0000999916	19.0	-0.22
P310	0.001	0.000999976	0.000999990	-3.0	-0.56
P310	0.01	0.009999922	0.009999826	4.9	-0.57
P321	0.1	0.10000162	0.10000091	4.1	-0.58
P321	1.0	0.999987	0.999987	1.5	-0.51

The expanded measurement uncertainties of calibration of a low-resistance measure with a nominal value of 0.0001 Ω is 2.0 ppm, with a nominal value of 0.001 Ω - 1.0 ppm, with a nominal value of 0.01 Ω – 0.6 ppm, with a nominal value of 0.1 Ω - 0.4 ppm, with a nominal value of 1.0 Ω - 0.3 ppm.

The electrical resistance value of the measure R_X being calibrated is determined by the equation [13–15]:

$$R_X = r \cdot r_{Kres}(R_S - \Delta R_D + \Delta R_{tS} + \Delta R_K) - \Delta R_{tX}, \quad (2)$$

where

R_S is resistance value of the reference measure;

ΔR_D is the drift of the resistance value of the reference measure since its last calibration;

ΔR_{tS} is temperature dependence of the resistance change of the reference measure;

ΔR_{tX} is temperature dependence of the resistance change of the measure being calibrated;

ΔR_K is correction for the resistance introduced by the comparator bridge;

$r = R_{Xi}/R_S$ is the ratio of the values of the measure being calibrated and the reference measures;

R_{Xi} is the obtained value for measurement using of a bridge-comparator (contributions of values and uncertainties are correlated);

r_{Kres} is the correction due to the distribution capability of the bridge-comparator with boundaries $\pm 1 \cdot 10^{-6}$.

Uncertainty budget for 0.001 Ω is given in Table-3.

Table-3. Uncertainty budget for 0.01 Ω.

Quantity, X_i	Estimate, x_i	Standard uncertainty, $u(x_i)$	Probability distribution	Sensitivity coefficient, c_i	Uncertainty contribution, $u_i(y)$
R_S	0.0099999826 Ω	0.0000000031 Ω	Normal (k = 2)	1,0	0.0000000031 Ω
ΔR_D	0.00000006 Ω	0.000000034 Ω	Rectangular ($k = \sqrt{3}$)	1,0	0.000000034 Ω
ΔR_{tS}	0.000000005 Ω	0.0000000028 Ω	Rectangular ($k = \sqrt{3}$)	1,0	0.0000000028 Ω
ΔR_{tX}	0.0000000021 Ω	0.00000000107 Ω	Rectangular ($k = \sqrt{3}$)	1,0	0.00000000107 Ω
ΔR_K	0.000000011 Ω	0.0000000056 Ω	Normal (k = 2)	1,0	0.0000000056 Ω
r	0.999998	0.000000548	Normal (k = 1)	0.01 Ω	0.00000000548 Ω
r_{Kres}	1.000000001	0.00000000096	Triangular ($k = \sqrt{6}$)	1 Ω	0.00000000096 Ω
R_X	0.00999992 Ω				0.0000000345 Ω

Analysis of Figures 3-7 showed that the polynomial approximation of the drift lines of all measures from 2012 to 2023 could be improved, as shown in Figures 9-13. In the figures, the green solid lines show the average resistance value, and the red dotted lines show the corresponding polynomial approximations of drifts. The indicated approximations of the drift lines of resistance measures for this period have R^2 values equal to 0.44 to 0.84, that is, they confirm their adequacy. The average value of all calibration results of a low-resistance measures from 2012 to 2023 with a nominal value of 0.0001 Ω is 0.0000999916 Ω, with a nominal value of 0.001 Ω – 0.000999987 Ω, with a nominal value of 0.01 Ω – 0.00999983 Ω, with a nominal value of 0.1 Ω – 0.1000010 Ω, with a nominal value of 1.0 Ω – 0.999989 Ω.

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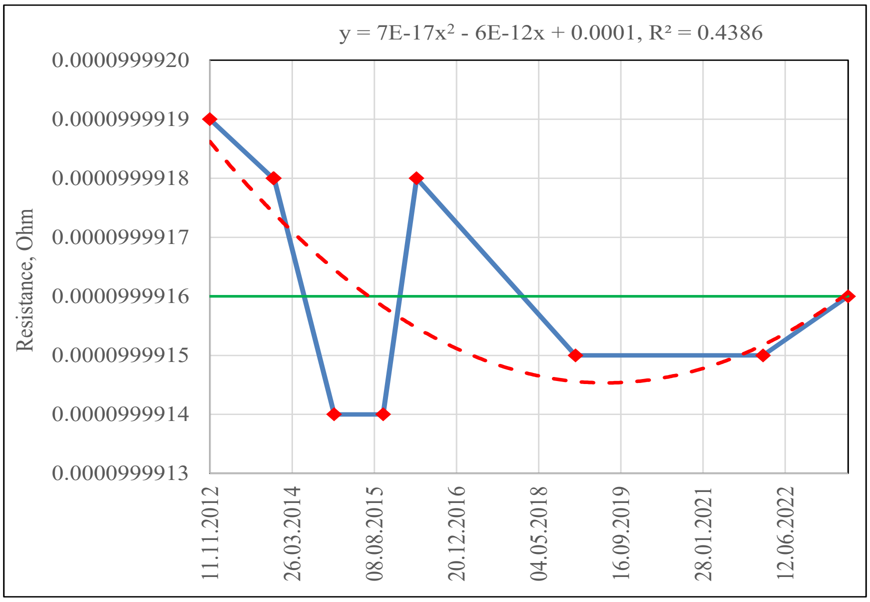

Figure-8. Drift of resistance measure of 0.0001 Ω from 2012 to 2023.

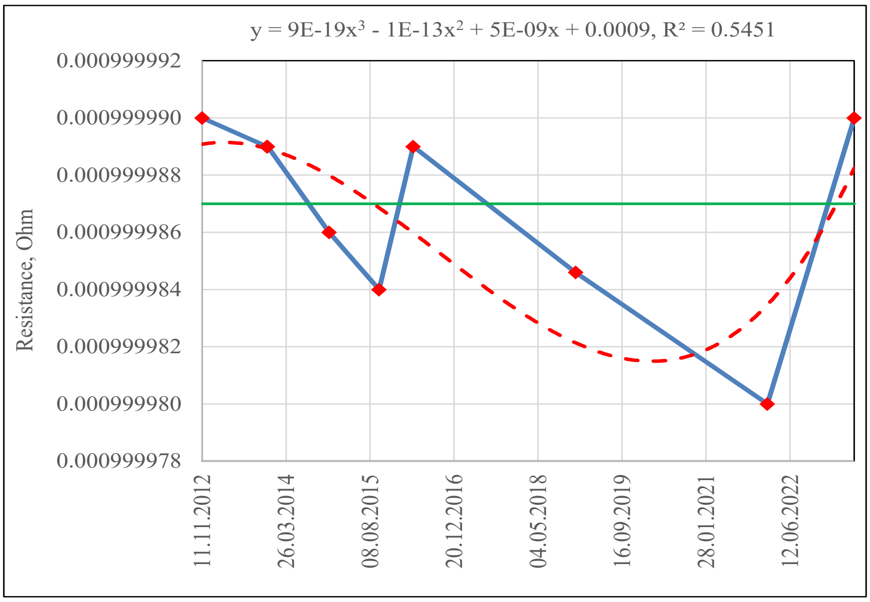

Figure-9. Drift of resistance measure of 0.001 Ω from 2012 to 2023.

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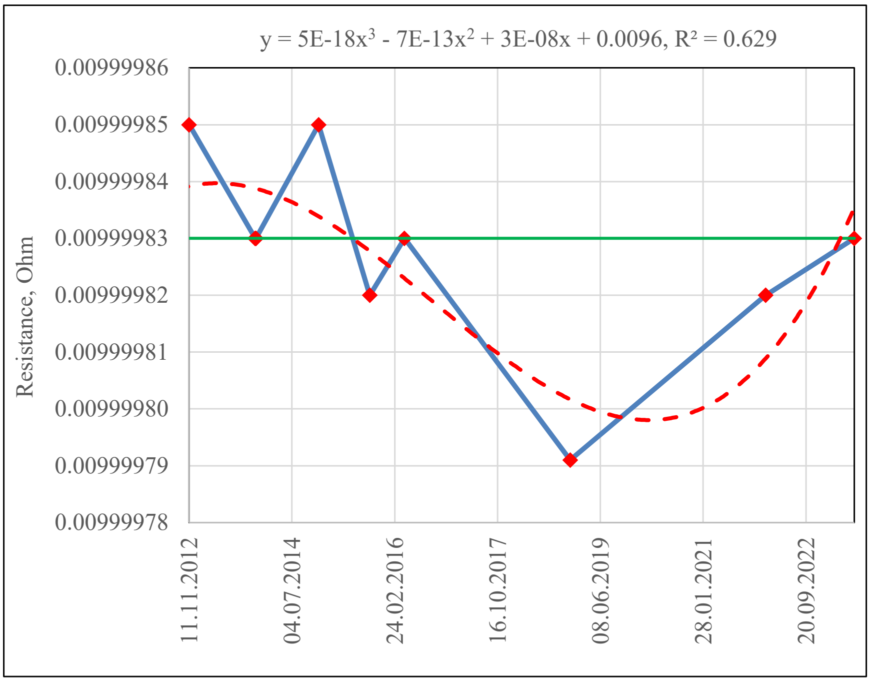

Figure-10. Drift of resistance measure of 0.01 Ω from 2012 to 2023.

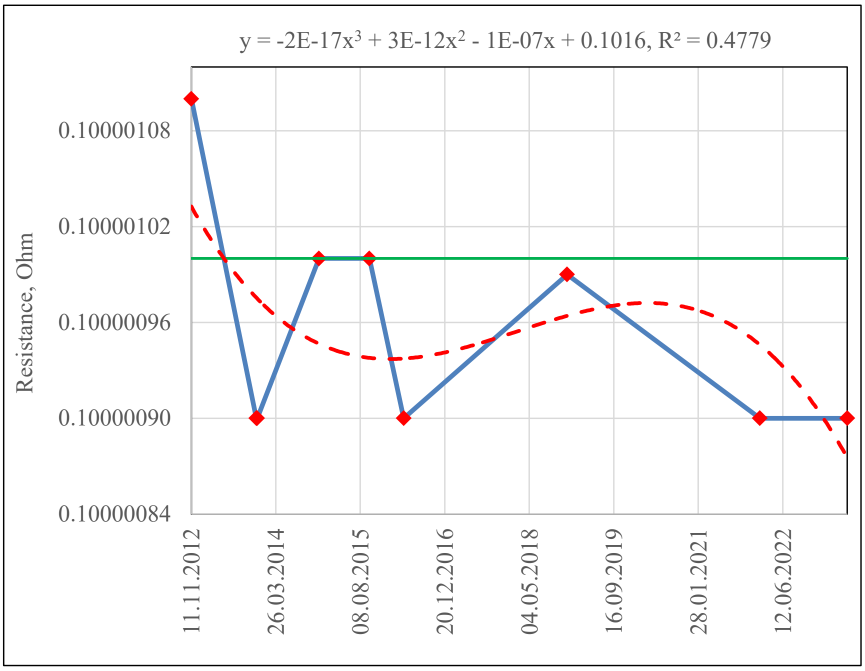

Figure-11. Drift of resistance measure of 0.1 Ω from 2012 to 2023.

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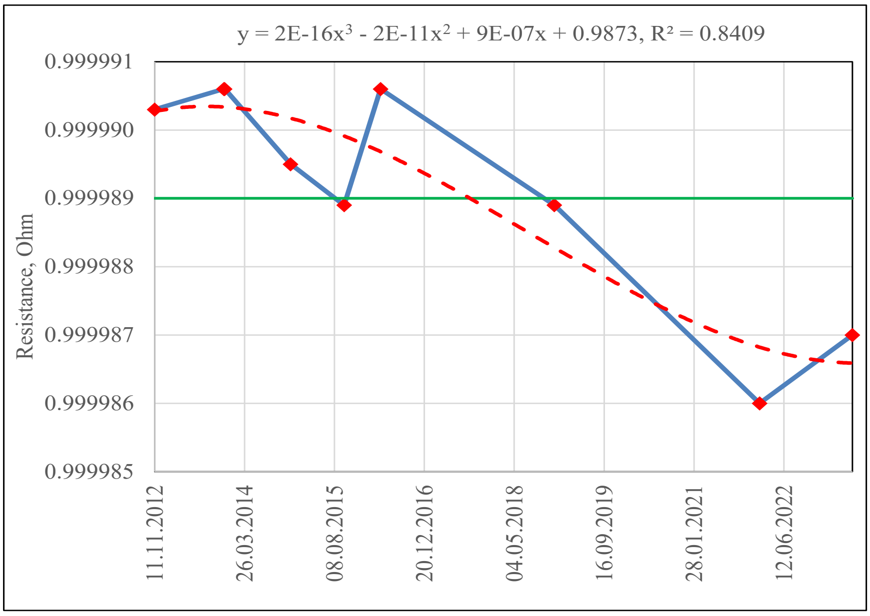

Figure-12. Drift of resistance measure of 1.0 Ω from 2012 to 2023.

5. CONCLUSIONS

The high stability of electrical resistance measures over a fairly long period is confirmed by continuous calibrations with assessment of the corresponding measurement uncertainty. Using an estimate of historical calibration data for electrical low-resistance measures can reduce measurement uncertainty when performing precision calibration of measuring instruments.

Regression analysis methods are most often used to estimate the long-term drift of electrical low-resistance measures. Polynomials of the third degree were sufficient to approximate their drift line. The specified approximations of the drift lines of the resistance measures have a value of the coefficient of determination from 0.44 to 0.84, that is, they confirm their adequacy.

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