RESEARCH ARTICLE

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Applied signal effect in the potentiometric method on the resistance measurements accuracy

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Abstract. In this paper, the effect of applying dc voltage and dc current sources in using the potentiometric method on the accuracy and the uncertainty of the resistance measurements is studied. This study is done practically for the low and high values of standard resistance ranges from 100 to 10 MΩ. The traceability chain for the used resistors is introduced by using the standard resistors 1 Ω Thomas type, 10 kΩ model SR104, and four Hamon transfer standards. The system operation is remotely controlled by using a LabVIEW program to improve the performance. The measurement results and the uncertainty estimation values are discussed to identify the effect of the applied voltage and current on the different resistance ranges measurement.

Keywords: resistance measurement / potentiometric method / LabVIEW program / traceability chain / measurement uncertainty

1 Introduction

Low- and high-resistance measurements are important fields in electrical metrology. Measurements of low-standard resistors are important for the power industry because of their use in high dc currents calibrations [1]. For high-ohmic standard resistors, it is important to make more accurate measurements because secondary laboratories used them in the calibrations of small dc currents and commercial teraohmmeters [2]. Because of increasing demand for high accuracy for industry and for the scientific metrology, more accurate measurement methods are being developed. There are different methods for measuring low-ohmic resistance standards such as direct current comparator with range extender, direct reading with a digital multimeter (DMM), and substitution method [3]. There are also volt–ampere–metric and ratio technique methods. These methods suffer from some drawbacks such as the current source, and the DMM in the volt–ampere method should be calibrated; the ratio technique depends on the linearity of the DMM [4]. For the high-resistance standards measurements, different methods are used such as current comparator bridge, DMM-based method, substitution method, and modified Wheatstone bridge [5,6].

The most precise methods for resistance measurements are made by bridges where standard resistors are compared with each other [7]. So, resistance measurements can be accurately made by comparing the unknown standard resistor with another standard resistor that has a known and traceable value. When the used instruments are stable, a high accuracy and low uncertainty in the measurement can be obtained. One of these methods is the potentiometric bridge method. This method can be considered a direct application of Ohm's law. A known current could be passed through the standard resistor in series with the unit under test (uut) resistor [8]. Then, the voltage drop ratio across the two resistors is measured. A constant current through the two resistors should be achieved to avoid errors and improve the accuracy [9]. In the potentiometric bridge method, an applied dc voltage source is usually used to pass a constant current through the standard and the uut resistors. So, in this paper, a practical comparison is done with applied voltage source and applied current source. This is done to study their effects on the accuracy and on the precision of the resistance standards measurements in the ranges from 100 mΩ to 10 MΩ to select the best applied source for each range. Traceable and standard resistors are used in this study. The traceability chain at the National Institute of Standards (NIS), Egypt, for the standard resistors from 100 mΩ to 100 Ω is started by using NIS 1 Ω Thomas-type standard resistor. For the standard resistors from 1 kΩ to 10 MΩ, the traceability chain is done by NIS 10 kΩ model SR104 standard resistor and three Hamon transfer standards. NIS standard resistors are periodically calibrated at the BIPM by comparison with their reference standards. Those reference standards are calibrated against the Quantum Hall Resistance (QHR), which is

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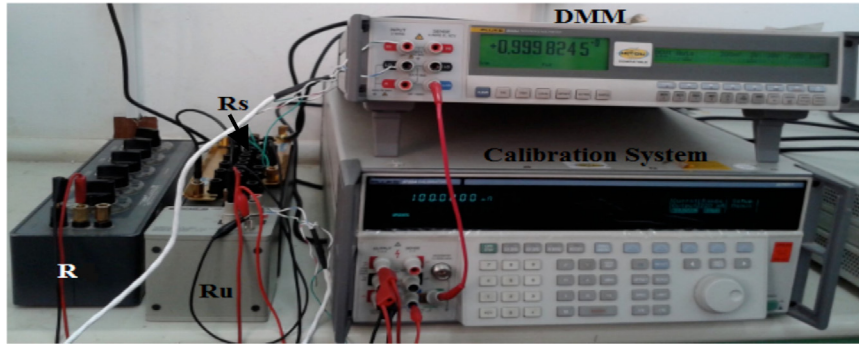* Corresponding author: rasha_sama79@hotmail.com

Fig. 1. Setup of the automated system for standard resistors measurement.

the most accurate resistance standard; therefore, it is used as a primary standard of resistance. The definition of the ohm has been related to the QHE by means of the Von Klitzing constant. It is recommended that all the national metrology institutes use the same value for the Von Klitzing constant, which is $R_{k\text{-}90} = 25.812807\,\text{k}\Omega$ [10].

The automatic operation has a lot of advantages such as reducing the calibration time compared to the manual system; the automated system enables the reporting of results, which prevents the possibility of human errors in recording the data, and also reducing the operator dependence. These advantages lead to ease the performance and increase the precision of the measurement. So, a LabVIEW program is designed for this work to automatically control the system operation through GPIB card and cables.

2 System setup

The automated system consists of a programmable calibration system Fluke model 5720A, dc power supply, digital multimeter (DMM) Fluke model 8508A used in its ratio mode, standard resistor, uut resistor, and a guard resistor as shown in Figure 1.

The calibration system is the source of constant dc voltage V_{dc} for the resistances, which are equal to or above $10\,\Omega$ and also used in its current mode to supply dc current I_{dc}. Dc power supply is used to apply dc voltage V_{dc} for the resistance measurements below $10\,\Omega$. In both cases, a dc current flows through the standard resistor R_s and the uut resistor R_u. It is not necessary to calculate the current passing through the uut resistance. However, it is enough to measure the ratio of the voltage drops across the two resistors V_u/V_s, which is the same as the ratio of the resistances. Then, the uut resistance standard is calculated from the following equation [10]:

$$R_u = (V_u/V_s)R_s\,. \tag{1}$$

A guard resistor R is used to reduce the leakage current effect and consequently improve the measurement accuracy [11], and it is also used to extend the value of the applied current source, especially in the high-resistance measurements. The guard of the resistors R_s, R_u, and R are connected together. All the system is connected to a single ground as shown in Figure 2.

It is important to ensure that the flowing current through R_u and R_s remains constant during the measurement. This is ensured by measuring V_u/V_s five times. Each time is the average of 10 readings measured in the forward and in the reverse directions to minimize the thermoelectric voltage [12]. The average of the five times is then calculated.

3 Traceability of the used standard resistors

The traceability chain is transferred from the NIS standard resistors to other resistors by using Hamon transfer standards. The Hamon transfer standard consists of 10 precise resistors with the same nominal value, which can be connected in series, parallel, or series–parallel [13]. It is connected by using special connectors to provide accurate resistance values of 10, 0.1, and 1 times of the nominal value. The Hamon transfer has the advantage of having the same deviation from the nominal value in the three different connections, low-temperature coefficient, and the transfer accuracy is about 2 ppm [14]. The used standard resistors and Hamon transfer standards are configured to have the same nominal values.

For the standard resistors from $100\,\text{m}\Omega$ to $100\,\Omega$, the traceability chain is made by using the $1\,\Omega$ Thomas-type standard resistor and a $10\,\Omega$ Hamon transfer standard (H10) as shown in Figure 3. The standard resistors $100\,\text{m}\Omega$ and $1\,\Omega$ are directly compared in the ratio 1:1 with the $1\,\Omega$ Thomas-type by using automatic resistance bridge MI model 6010C, 100 A range extender model 6011C, and dc power supply model 6100 A. The $10\,\Omega$ Hamon standard (H10) is connected in parallel and compared with $1\,\Omega$ Thomas-type by using the automatic resistance bridge at a 1:1 ratio. This assigns a value for H10 in its parallel configuration. Then, H10 is used in its series/parallel configuration to be used in its $10\,\Omega$ value, and in series configuration to be used as a $100\,\Omega$ standard resistors.

As shown in Figure 4, the standard resistors from $1\,\text{k}\Omega$ to $10\,\text{M}\Omega$ is done by using $10\,\text{k}\Omega$ model SR104 and three Hamon transfer standard: $10\,\text{k}\Omega$ (H10k), $100\,\text{k}\Omega$ (H100k), and $10\,\text{M}\Omega$ (H10M). The $10\,\text{k}\Omega$ Hamon standard (H10k) is connected in series/parallel and compared with the standard resistor $10\,\text{k}\Omega$ model SR104 by using the automatic resistance bridge at a 1:1 ratio. This gives a value for H10k in its series/parallel configuration to be used as $10\,\text{k}\Omega$ standard resistor. Hamon standard, H10k, is then
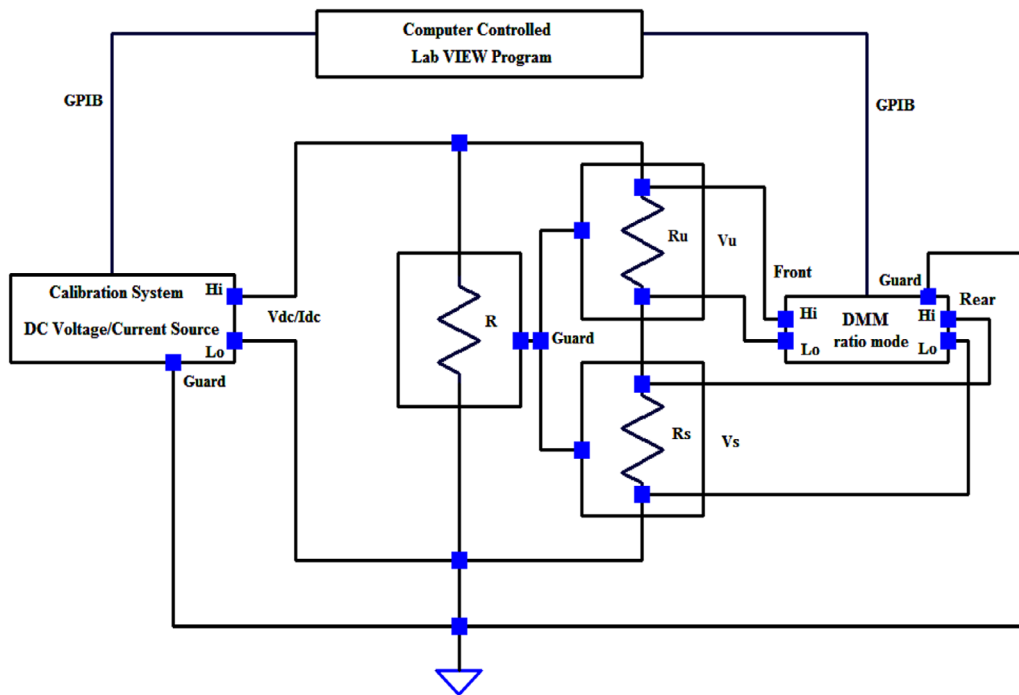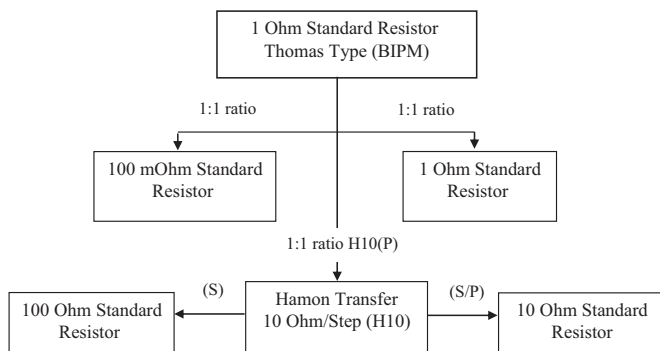
Fig. 2. System setup.

Fig. 3. Traceability chain for standard resistors from $100\,\text{m}\Omega$ to $100\,\Omega$.

used in its parallel configuration to be used as $1\,\text{k}\Omega$ standard resistor. The Hamon standard (H100k) is connected in its parallel configuration to be compared against the $10\,\text{k}\Omega$ model SR104 by the resistance bridge at a 1:1 ratio. It assigns its value in the parallel connection. Then, it is used in its series/parallel configuration as a $100\,\text{k}\Omega$ standard resistor. The H100k is also used in its series configuration to get a value for the H10M in its parallel configuration by using the DMM-based method [15] at 1:1 ratio. This value is used as $1\,\text{M}\Omega$ standard resistor. Then, H10M is connected in series/parallel to be used as $10\,\text{M}\Omega$ standard resistor.

All the measurements are done at 1:1 ratio to allow for the interchange of the standards under measurement. It leads to compensate the linearity error of the potentiometric system [16].

4 Measurement and comparison of results

The practical comparison between the effect of the applied signals, voltage, and current on the accuracy and precision of the resistance standards measurement is done automatically by using a LabVIEW program. The measurements are done at the same environmental conditions. The temperature is $(23 \pm 1)\,°\text{C}$ and the relative humidity is $(50 \pm 10)\%$. The error decreases as the difference between the two resistors decreases, so 1:1 ratio is done. The readings from the DMM in the ratio mode are reported and saved in an excel sheet automatically. The uut resistors from $100\,\text{m}\Omega$ to $10\,\text{M}\Omega$ are calibrated in traceable laboratories. So, their actual values obtained from their calibration certificates are compared with the results obtained from applying dc voltage and dc current in the potentiometric method. Table 1 shows the values of the applied voltage, applied current, actual values of the uut resistors, and deviations from the actual values when applying dc voltage and dc current.

It is seen from Table 1 that the uut resistors $100\,\text{m}\Omega$ and $1\,\Omega$ have a smaller deviation from their actual values by applying dc current than applying dc voltage. The deviation of the uut resistors $10\,\Omega$ and $100\,\Omega$ is nearly equal when dc voltage and dc current are applied. The deviation due to applying dc voltage is slightly smaller than the deviation due to applying dc current for the uut resistors $1\,\text{k}\Omega$, $10\,\text{k}\Omega$, $100\,\text{k}\Omega$, $1\,\text{M}\Omega$, and $10\,\text{M}\Omega$.

5 Uncertainty estimation

The uncertainty budgets for the uut standard resistors measurements by applying a dc voltage signal and a dc
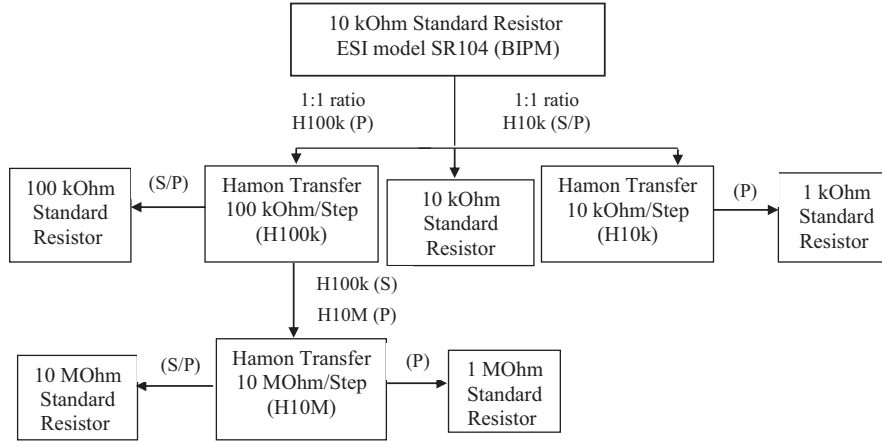
Fig. 4. Traceability chain for standard resistors from $1\,\mathrm{k\Omega}$ to $10\,\mathrm{M\Omega}$.

Table 1. Results of the uut standard resistors.

Nominal resistance value	Applied voltage	Applied current	Actual value	Deviation by applied voltage, $\mu\Omega/\Omega$	Deviation by applied current, $\mu\Omega/\Omega$
$100\,\mathrm{m\Omega}$	$300\,\mathrm{mV}$	$1.5\,\mathrm{A}$	$100.00240\,\mathrm{m\Omega}$	-302.9	-232.4
$1\,\Omega$	$400\,\mathrm{mV}$	$200\,\mathrm{mA}$	$1.0000007\,\Omega$	-28.0	-14.9
$10\,\Omega$	$2\,\mathrm{V}$	$100\,\mathrm{mA}$	$9.999998\,\Omega$	-219.4	-211.9
$100\,\Omega$	$10\,\mathrm{V}$	$50\,\mathrm{mA}$	$99.999997\,\Omega$	-35.2	-34.3
$1\,\mathrm{k\Omega}$	$30\,\mathrm{V}$	$15\,\mathrm{mA}$	$1.0000007\,\mathrm{k\Omega}$	7.7	10.0
$10\,\mathrm{k\Omega}$	$30\,\mathrm{V}$	$1.5\,\mathrm{mA}$	$10.0000098\,\mathrm{k\Omega}$	0.8	1.1
$100\,\mathrm{k\Omega}$	$30\,\mathrm{V}$	$150\,\mu\mathrm{A}$	$99.999920\,\mathrm{k\Omega}$	8.2	10.5
$1\,\mathrm{M\Omega}$	$30\,\mathrm{V}$	$15\,\mu\mathrm{A}$	$1.0000008\,\mathrm{M\Omega}$	-23.1	-35.0
$10\,\mathrm{M\Omega}$	$30\,\mathrm{V}$	$1.5\,\mu\mathrm{A}$	$10.000020\,\mathrm{M\Omega}$	110.5	116.5

current signal are estimated according to the Guide to the Expression of Uncertainty in Measurement (GUM) [17]. The sources of the uncertainty are the repeatability (Type A), and Type B such as the dc voltage or the dc current calibration, standard resistor calibration, standard resistor drift, temperature coefficient effect, and DMM ratio accuracy. The combined standard uncertainty $U_c(y)$ is given by

$$U_c^2(y) = \sum_{i=1}^{N} (\partial f / \partial x_i)^2 U^2(x_i), \quad (2)$$

where f is the function of R_u as given in equation (1), x_i is the input quantity; R_s, V_s, and V_u, $U(x_i)$ are the standard uncertainties (Type A and Type B evaluations), and the partial derivatives $\partial f/\partial x_i$ is called sensitivity coefficients, C_i.

In equation (1), by considering R_s, V_s and V_u as independent quantities and from equation (2), the combined uncertainty (U_c) is then calculated from:

$$U_c^2(R_u) = C_1^2 \cdot U^2(R_s) + C_2^2 \cdot U^2(V_u) + C_3^2 \cdot U^2(V_s), \quad (3)$$

where U is the standard uncertainty, $C_1{}^2 = \frac{V_u^2}{V_s^2}$, $C_2{}^2 = \frac{R_s^2}{V_s^2}$, and $C_3{}^2 = \frac{V_u^2 R_s^2}{V_s^4}$.

Table 2 shows the uncertainty budget for the uut resistor $10\,\mathrm{M\Omega}$ as an example by applying dc voltage and current, the combined uncertainty, and the expanded uncertainty $(U_{\mathrm{exp.}})$, which is obtained by multiplying the combined uncertainty by the coverage factor (k) that is equal to 2 for confidence level 95% [17].

The uncertainty contribution in ohm is obtained by multiplying the standard uncertainty (U) by the sensitivity coefficients (C_i), which are $C_1 = 1$, $C_2 = 0.67\,\mathrm{M\Omega/V}$, and $C_3 = 0.67\,\mathrm{M\Omega/V}$ for the $10\,\mathrm{M\Omega}$ measurement as an example. The combined uncertainty (U_c) is then obtained as mentioned in equation (3) by calculating the root sum squares of the uncertainty contribution evaluations of Type A and Type B components.

Table 3 shows Type A, Type B, which is the root sum squares of components $(B_1, B_2, B_3, B_4,$ and $B_5)$, and the expanded uncertainties $(U_{\mathrm{exp.}})$ at confidence level 95% associated with the measurement of the uut resistors in the both cases; applying dc voltage source and dc current source.

It is seen from Table 3 that Type A and the expanded uncertainties of the uut resistors $100\,\mathrm{m\Omega}$ and $1\,\Omega$ by applying dc current are lower than that when applying dc voltage. So, it is preferred to apply dc currents at these

Table 2. Uncertainty budget for the resistor 10 MΩ.

Uncertainty sources	Probability distribution	Divider	Uncertainty contribution by voltage, Ω	Uncertainty contribution by current, Ω
Repeatability (Type A)	Normal	1	59	144
Applied signal calibration (B_1)	Normal	2	0.6	0.3
Calibration of R_s (B_2)	Normal	2	45	45
Drift of R_s (B_3)	Rectangular	$\sqrt{3}$	0.3	0.3
Temperature coefficient of R_s (B_4)	Rectangular	$\sqrt{3}$	12	12
DMM ratio accuracy (B_5)	Normal	2	1	1
Combined standard uncertainty (U_c)			$\pm\,75\,\Omega$	$\pm\,151\,\Omega$
Effective degrees of freedom			∞	∞
Expanded uncertainty ($U_{\text{exp.}}$) at confidence level 95%, (**k = 2**):			$\pm\,150\,\Omega = 15\,\mu\Omega/\Omega$	$\pm\,302\,\Omega = 30.2\,\mu\Omega/\Omega$

Table 3. Type A, Type B, and Exp. uncertainties of the measured resistors.

Applied signal	Relative uncertainty, $\mu\Omega/\Omega$	Nominal resistance standard value, Ω								
		0.1	1	10	100	1 k	10 k	100 k	1 M	10 M
	Type A	47	6	0.23	0.04	0.06	0.05	0.18	1.7	5.9
DC voltage	Type B	1.16	1	2.12	1.13	1.04	0.23	0.83	3.7	4.5
	Exp. Uncertainty ($U_{\text{exp.}}$)	94	12.2	4.3	2.3	2.1	0.47	1.7	8.1	15
	Type A	15.5	2	0.13	0.03	0.09	0.2	1.3	8	14.4
DC current	Type B	2.94	3.7	2.24	1.44	2.89	2.7	2.85	3.7	4.5
	Exp. Uncertainty ($U_{\text{exp.}}$)	31.6	8.4	4.5	2.9	5.8	5.4	6.3	17.6	30.2

ranges. However, the uut resistors 10 Ω and 100 Ω are very near, thus dc voltages and currents can be applied. For the uut resistors 1 kΩ, 10 kΩ, 100 kΩ, 1 MΩ, and 10 MΩ, the Type A and the expanded uncertainties are lower by applying dc voltage than applying dc current. So, it is recommended to apply dc voltages rather than applying dc currents.

6 Conclusion

In this paper, the effect of applying dc signals, voltage and current, by using the potentiometric method on the accuracy and the uncertainty of the resistance standards measurements in the ranges from 100 mΩ to 10 MΩ is studied. That is to determine the best applying source for accurate measurement of the different standard resistors ranges. The measurements are done automatically to improve the accuracy, increase the precision, and get rid of the recording errors. The traceability chain is also transferred to the different standard resistors from 1 Ω and 10 kΩ NIS standard resistors. It is found from this practical study that applying dc current for the resistors 100 mΩ and 1 Ω is better than applying dc voltage to improve the accuracy and reduce the uncertainty in the measurement. For the 10 and 100 Ω resistances, there is very small difference when applying dc voltage or dc current. So, both of them can be used in the accurate measurements at these ranges. It is preferred to apply dc voltage than dc current in the ranges 1 kΩ, 10 kΩ,

100 kΩ, 1 MΩ, and 10 MΩ because it introduces higher accuracy and lower Type A, more precise, and subsequently lower expanded uncertainty. That is because the low resistance measurements are subjected to additional errors such as lead resistances and nonohmic contact voltage drops, which are significant with respect to the values of the measured resistors, so applying constant current is better. However, most of the high resistance standards have voltage coefficients that their values are functions of the applied voltages, thus applying constant voltage is better than applying current to insure the stability of the applied voltage.

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