The Electrical DC Resistance Scale from 100 kΩ to 1 TΩ at IEN

Flavio Galliana and Giorgio Boella

***Abstract*—At IEN, the scale of resistance in the field 100 kΩ to 1 TΩ has been revised through the characterization of a series of new standard resistors. The preliminary study, realization and characterization of four measurement methods are also described in this paper. The complete description of a new automatic method for the calibration of high-value standard resistors, particularly in the range 10 MΩ–1 TΩ, and their measurement at different voltage levels are also reported. It makes use of a programmable high-stability dc voltage calibrator which supplies a voltage V_{out} to the series of an unknown resistor R_x, and of a standard resistor R_s. A high-precision programmable multimeter (DMM) is used to measure V_{out} and the voltage V_s across the standard resistor, from which the value of the current I is determined. The value of R_x is given by $R_x = (V_{\text{out}} - V_s)/I$.**

The best measurement capabilities of IEN using these four measurement methods span from 0.7 × 10^{-6} for the calibration of the 100 kΩ standard resistor at the measurement voltage of 10 V, to 7.1 × 10^{-4} for the calibration of 1 TΩ standard resistor at the measurement voltage of 500 V.

***Index Terms*—Best measurement capabilities, digital multimeter, DMM-based method, high-value resistor, measurement uncertainty.**

I. INTRODUCTION

THE need of making more and more accurate measurements in the field of high dc resistance, in particular due to the requests of the secondary and industrial laboratories, besides the participation of IEN to a Comité Consultatif d'Electricité (CCE) international comparison on high-resistance measurements, was the reason of a revision of the metrological chain for the resistance scale in the field 100 kΩ to 1 TΩ at IEN. This project has also implied the acquisition of higher quality standard resistors and high-performance digital measurement instruments such as dc voltage calibrators and digital DMMs, the realization of thermostatic enclosures with active regulation of temperature for the standard resistors, the study, characterization, and compatibility verifications of four measurement methods for the entire considered resistance range.

One of these is a new automatic measurement method which allows the measurement of standard resistors, in particular in the range 10 MΩ–1 TΩ (but it also can be used for lower resistance values with lower accuracy). In particular, it allows the determination of the variation of the measurement value of a high-value resistor under calibration when different voltages are applied across its terminals.

II. FEATURES OF THE DECADE STANDARD RESISTORS

The decade resistors forming the resistance scale in the range 100 kΩ to 100 MΩ are wire-wound elements while the ones forming the resistance scale in the range 1 GΩ to 1 TΩ are thick-film standards.

The 100 kΩ to 1 GΩ standard resistors are kept permanently in an air temperature-controlled enclosure with a long-term stability of temperature of (23 ± 0.02)°C while higher value resistors up to 1 TΩ can be placed alternatively in an air temperature-controlled enclosure with a mid-term stability of temperature of (23 ± 0.01)°C.

Temperature coefficients of the standard resistors were determined by placing the resistors in this last air temperature-controlled enclosure, whose temperature can be varied from 16 °C to 35 °C, and they were measured at the temperatures of 19 °C, 21 °C, 23 °C, 25 °C, and to 27 °C with a measurement voltage of 10 V for the 100 kΩ to 10 MΩ standard resistors, of 100 V for the 100 MΩ standard resistor, and of 1000 V for the 1 GΩ to 1 TΩ standard resistors.

Voltage coefficients were evaluated by placing the standard resistors in this enclosure at the temperature of 23 °C and measuring them at four voltage values. The measurements to evaluate both temperature and voltage coefficients have been made by means of the DMM-based method described in the next paragraph.

All these coefficients were evaluated by fitting, with the least squares method, the measurement results at different temperatures (for the determination of the temperature coefficient) and at different voltages (for the determination of the voltage coefficient).

For these fits, we assumed linear behaviors plus quadratic components, except in the case of the determination of the temperature coefficient of the 10 MΩ to 1 TΩ standard resistors and in the case of the determination of the voltage coefficient of the 1 TΩ standard resistor for which we assumed a simple linear behavior. In Table I, the coefficients, only considering their linear behavior and their uncertainties at the 2σ level, due to the fit of the measurement results, are reported.

III. MEASUREMENT METHODS

This section describes the four measurement methods that are in use at IEN for calibration of resistors in the range 100 kΩ–1 TΩ, with particular regard to the new DMM-based method. All these methods start from the same high-precision 10 kΩ resistance standard, which has a low-temperature coefficient ($\alpha_{23} = 0.054 \times 10^{-6}$/°C), a low-power coefficient ($< 1 \times 10^{-6}$/W), and high stability (0.05×10^{-6}/y). This

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TABLE I
MEASURED TEMPERATURE, POWER AND VOLTAGE COEFFICIENTS WITH THEIR UNCERTAINTIES FOR THE STANDARD RESISTORS OF SCALE 100 kΩ TO 1 TΩ OPERATING AT IEN

Standard Resistor	Temperature coefficient at 23 °C	Relative uncertainty %	Power/Voltage Coefficient	Relative uncertainty %
100 kΩ	$1.7 \cdot 10^{-6}$/°C	≅ 25	< $2 \cdot 10^{-6}$/W	*N.A. (Given by the manufacturer)*
1 MΩ	$-1.9 \cdot 10^{-6}$/°C	≅ 27	< $20 \cdot 10^{-6}$/W	
10 MΩ	$-1.8 \cdot 10^{-6}$/°C	≅ 2.5	$-2.6 \cdot 10^{-7}$/V	≅ 58
100 MΩ	$5.0 \cdot 10^{-6}$/°C	≅ 2.9	$-1.1 \cdot 10^{-7}$/V	≅ 60
1 GΩ	$1.8 \cdot 10^{-6}$/°C	≅ 4.1	$-4.2 \cdot 10^{-8}$/V	≅ 0.4
10 GΩ	$3.9 \cdot 10^{-5}$/°C	≅ 7.5	$-1.1 \cdot 10^{-7}$/V	≅ 8.9
100 GΩ	$1.6 \cdot 10^{-5}$/°C	≅ 26	$-1.3 \cdot 10^{-7}$/V	≅ 66
1 TΩ	$-3.7 \cdot 10^{-3}$/°C	≅ 2.6	$-6.2 \cdot 10^{-5}$/V	≅ 2.1

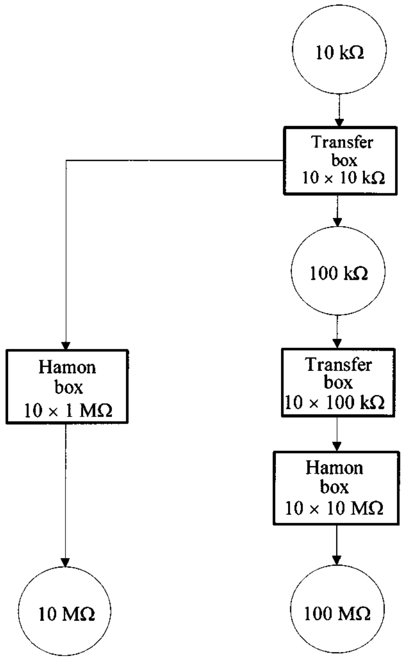

Fig. 1. Traceability chain and scaling diagram of the Hamon transfer boxes method.

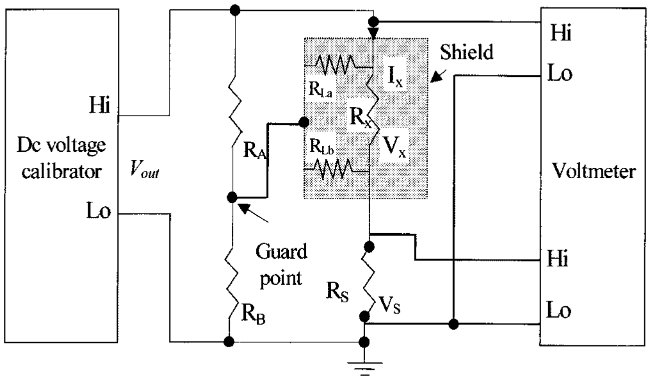

Fig. 2. Scheme of the DMM based measurement method.

resistor is calibrated in terms of the IEN 1 Ω primary group of standard resistors which, in their turn, are referred to the recommended value $R_{K\text{-}'90}$ of the von Klitzing constant by means of the quantum Hall effect [1].

A. Hamon Transfer Boxes and Current Comparator Bridge Methods

The Hamon transfer boxes method makes use of four Hamon resistance boxes which contain at least ten resistors having the same nominal values of 10 kΩ, 100 kΩ, 1 MΩ, and 10 MΩ, respectively, and can be configured to measure the resistors individually, in parallel or in series. Fig. 1 shows the scaling diagram for this method, up to 100 MΩ.

The current comparator method makes use of an automatic commercial current comparator bridge, with a current generator for the 10 kΩ to 100 kΩ comparison and a voltage generator for the further comparisons in 1:10 ratio, up to 1 GΩ.

The experimental procedures adopted by the two methods, their field of application, features of standards and devices utilized, sources and budget of uncertainties for calibration of standard resistors are fully described in [2].

B. Wheatstone Bridge Using Programmable DC Calibrators Method

In this method two programmable dc voltage sources act as two branches of a Wheatstone bridge. This technique first developed at National Physical Laboratory (U.K.) [3] was also implemented in order to check the measurement results of the new DMM based measurement method developed at IEN in the range 1 GΩ–1 TΩ.

C. DMM-Based Method

A scheme of the measurement system is shown in Fig. 2. R_x is the high-value resistor under calibration, and R_s is the reference standard. A programmable voltage source supplies the series $R_x + R_s$ and a digital DMM, on its voltage function, is used to measure the voltage V_s across the standard resistor and the voltage V_{out} applied to the series. The polarity of V_{out} is reversed in order to minimize the effects of thermal voltages and of the input offset current of the DMM [4].

The auxiliary resistive divider, R_A and R_B, provides a suitable guard voltage which minimises the effect of the leakage currents, due to the finite insulation resistances between R_x and its shield, R_{La} and R_{Lb}. To provide this guard voltage a Kelvin-Varley voltage divider can also be involved. The system is controlled by a personal computer.

A suitable measurement process is adopted which reduces the effects, typical of high-voltage measurements, of dielectric absorption and of power dissipation in the attenuation circuit at the input of the DMM. For each measurement voltage the DMM first measures the low-voltage V_s for both polarities, then measures V_{out}, also for both polarities. After completing one measurement cycle and after application of the voltage for a new

TABLE II
FEATURES OF THE USED DMMS

Features	DMM Range	Values
Accuracy : ±[part of reading + scale dependent constant voltage	100 mV	$4.3\cdot10^{-6} + 0.1\ \mu$V
	1 V	$2.7\cdot10^{-6} + 0.4\ \mu$V
	10 V	$2.3\cdot10^{-6} + 2\ \mu$V
	100 V	$4.3\cdot10^{-6} + 40\ \mu$V
	1000 V	$4.3\cdot10^{-6} + 400\ \mu$V
Input bias current	100 mV	< 2 pA
	1 V	< 2 pA
	10 V	< 7 pA
	100 V	< 6 pA
	1000 V	< 6 pA
Input impedance	100 mV	10^{11} Ω to 10^{12} Ω
	1 V	>10^{12} Ω
	10 V	>10^{12} Ω
	100 V	≅ 10^{7} Ω
	1000 V	≅ 10^{7} Ω

TABLE III
BEST MEASUREMENT CAPABILITIES THAT CAN BE REACHED BY THE FOUR METHODS OPERATING AT IEN IN THE FIELD 100 kΩ TO 1 TΩ AT DIFFERENT MEASUREMENT VOLTAGES

Resistor	Measurement Voltage	DMM based method		Hamon transfer Boxes method		Current comparator bridge method	Wheatstone bridge method	
		Type B	Type A	Type B	Type A	(10^{-6})	Type B	Type A
	(V)	($\cdot10^{-6}$)	($\cdot10^{-6}$)	($\cdot10^{-6}$)	($\cdot10^{-6}$)		($\cdot10^{-6}$)	($\cdot10^{-6}$)
100 kΩ	10	6.0	1.0	2.4	0.4	0.7		
1 MΩ	10	6.8	1.6	3.6	0.8	1.5		
	50	7.6	1.1			1.0		
10 MΩ	10	6.4	1.4	4.8	1.0			
	50	7.2	1.5					
	100	7.2	1.5			3.2		
100 MΩ	10	13	3.3	6.0	1.0			
	100	14	2.1					
	250	7.5	1.9			8.4		
	500	7.5	2.5					
1 GΩ	100	13	1.3					
	250	8.3	1.6			64		
	500	8.0	1.5			33		
	700	7.9	1.5			25		
	1000	7.7	1.4				7.5	1.3
10 GΩ	250	16	31					
	500	12	29					
	750	12	28					
	1000	11	26				15	32
100 GΩ	500	130	66					
	750	130	60					
	1000	120	55				101	74
1 TΩ	500	230	670					
	1000	260	700				500	560

cycle, a waiting time is left before starting the measurement of V_s. This waiting time allows for minimizing the above-mentioned effects at the input of the DMM and all transients due to shunt capacitance and to dielectric absorption in the insulator of the high-resistance standard and its connecting cables. For resistors of 10 GΩ or higher, waiting times of more than 1 h may be needed, depending on the insulator materials.

With V_x being the voltage across R_x and I_x being the current flowing through the series, the value of R_x is given by

$$R_x = V_x/I_x = R_s V_x/V_s = (V_{\mathrm{out}} - V_s)R_s/V_s. \qquad (1)$$

Considering R_s, V_{out} and V_s as independent quantities, from (1) applying [5], we obtain for the type B variance $u^2(R_x)$

$$u^2(R_x) = \left(\frac{V_{\mathrm{out}}}{V_s} - 1\right)^2 u^2(R_s) + \frac{R_s^2}{V_s^2}u^2(V_{\mathrm{out}}) + \frac{R_s^2 V_{\mathrm{out}}^2}{V_s^4}u^2(V_s). \qquad (2)$$

For instance, main type B uncertainty components, at the 2σ level, for the calibration of the 10 MΩ resistor relative to a measurement voltage V_{out} of 50 V are given by the following components:

1) calibration uncertainty of the 1 MΩ standard and its stability, $u(R_s)$; 2.5 Ω;
2) accuracy of the DMM in the 10 V range, effect of its input resistance and instability of input bias current and thermal voltages, $u(V_s)$; 26.5 μV;
3) accuracy of the DMM in the 100 V range, $u(V_{\mathrm{out}})$; 220 μV.

From these values, applying (2) we obtain for the 10 MΩ standard $u(R_x) = 72\,\Omega$ which is equivalent to a relative type B standard uncertainty $u_r(R_x)$ of 7.2 × 10^{-6}.

In Fig. 2, as R_{La} is in parallel with R_A, a residual voltage across R_{Lb} is present; this led to consider an additional uncertainty component in the measurement that is usually negligible.

As a matter of fact, let's consider a typical situation in which $R_x = 1\,\mathrm{T}\Omega, R_s = 1\,\mathrm{M}\Omega, R_{La} \cong R_{Lb} \cong 1\,\mathrm{T}\Omega, R_A = 100\,\mathrm{M}\Omega$, R_B =100 Ω, and V_{out} = 1000 V; the parallel between R_A and R_{La} gives a resistance $R_P \cong 9.999 \times 10^7$ Ω; the voltage drop across R_{Lb} is approximately 100 nV. So the current flowing in R_{Lb} is approximately 0.1 aA while the current flowing in R_s is approximately 1 nA. In this case, in the uncertainties budget must be added a relative component of 1×10^{10}, that is obviously negligible.

In Table II, we have reported the 90-day accuracy specifications of the used DMMs given by the manufacturer that we have considered for the determination of type B uncertainties of our measurements. In the same table the measured characteristics of two used Wavetek-Datron DMMs, such as input bias

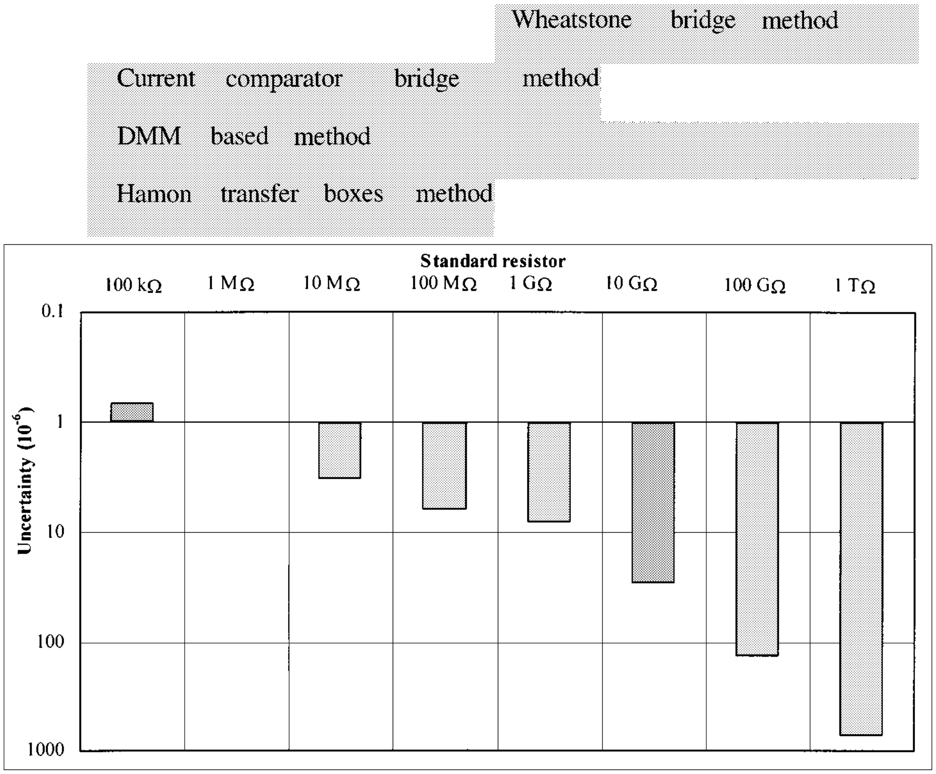

Fig. 3. Best measurement capabilities for the calibration of standard resistors in the field 100 kΩ to 1 TΩ and ranges of the operation of each measurement method.

current and input impedance, are also reported. These characteristics had been determined in a laboratory with a temperature of (23 ± 1)°C and a relative humidity of 30–45%.

Input impedance was determined by measuring with the DMMs, after nulling the effect of the input bias current, the difference between the voltage supplied by a calibrator before and after the insertion of a known high-value resistor in the electrical circuit. For each dc voltage scale of the DMMs, this test was repeated with two different resistors, showing for each case a good degree of compatibility between the obtained measurement results.

The input bias current of the DMMs was determined by making a zero check of the DMMs by inserting a short-circuit across their voltage inputs and successively inserting a known resistor and measuring, for each scale, the voltage drop across this resistor. The bias current was measured also using a pico-ammeter. A good degree of compatibility between the measurement results was obtained with each method.

IV. BEST MEASUREMENT CAPABILITIES

Table III reports the type B and type A evaluated uncertainties of each method at the voltage levels in which they can operate; type B uncertainties were estimated by considering the input bias current and input impedance characteristics of the best DMM between the two tested ones, while type A uncertainties were estimated by evaluating the repeatability of the measurements performed on our standard resistors kept in the air temperature-controlled enclosures whose characteristics were previously described. Finally, Fig. 3 reports the best measurement capabilities at the 2σ level that can be assured by IEN in the calibration of standard resistors in the field 100 kΩ to 1 TΩ together with the range of application of the four methods involved.

V. CONCLUSIONS

In this paper we have presented the metrological organization of the high-resistance scale in the field 100 kΩ to 1 TΩ at IEN. The compatibility tests performed with the four measurement methods described showed a good agreement among them; further information will be given to us by the results of the CCE international comparison.

Moreover, aims of future work in this sector are a better characterization of the DMM based and Wheatstone bridge methods up to 100 TΩ, the acquisition or realisation and characterization of a new 1 TΩ standard resistor, since the measured characteristics of the present one are unsatisfactory.

Future plans include also the characterization of an automatic measurement device based on the DMM-based method with a switching system for the resistors under calibration and for the reference standard resistors placed inside the device itself.

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