Hamon-Guarded 10×100 MΩ Network to Increase the Accuracy of the Transfer of the Resistance Unit up to 1 GΩ at INRIM

Pier Paolo Capra and Flavio Galliana

***Abstract*—In the framework of the revision and optimization of the measurement techniques for high-resistance measurements at the National Institute of Metrological Research (INRIM), a 100 MΩ-step Hamon-guarded network was projected and built. With this transfer standard, the 2σ uncertainty of the maintained 1 GΩ standard at INRIM is now on the order of 7.0×10^{-6} at a measurement voltage of 100 V. Details of the Hamon network and stability data in parallel configuration are given and discussed. The result of a verification of the performance of the Hamon network with a measurement method based on a digital multimeter (DMM) and a dc voltage calibrator (DcVC) is reported. A description of the measurement steps from 10 kΩ to 1 GΩ together with an uncertainty budget is also reported.**

***Index Terms*—Guard system, Hamon network, Hamon transfer standard, high-resistance measurements, measurement uncertainties.**

I. Introduction

In THE PAST years, in the field of high dc resistance, the National Institute of Metrological Research (INRIM), which was formerly known as the Istituto Elettrotecnico Nazionale Galileo Ferraris (IEN), developed and characterized a digital multimeter (DMM) dc voltage calibrator (DcVC)-based measurement method for the calibration of standard resistors, mainly in the range of 10 MΩ to 1 TΩ [1]. This method is also suitable for the determination of the voltage coefficients of high-value resistors [2]. With this method, the IEN participated in a Comité Consultatif d'Electricité (CCE) intercomparison on 10 MΩ and 1 GΩ values to obtain the following degrees of equivalence with respect to the reference values: $D_{\mathrm{IENKCRV}} = 0.9 \times 10^{-6}$ with expanded uncertainty $U_{\mathrm{IENKCRV}} = 5.5 \times 10^{-6}$ for the 10 MΩ value, and $D_{\mathrm{IENKCRV}} = 2.5 \times 10^{-6}$ with expanded uncertainty $U_{\mathrm{IENKCRV}} = 19.3 \times 10^{-6}$ for the 1 GΩ value [3].

A revision of the measurement technique based on Hamon transfer boxes [4] has already been performed in [1]. This technique involves four Hamon resistance boxes with ten resistors with nominal values of 10 kΩ, 100 kΩ, 1 MΩ, and 10 MΩ, respectively. These boxes can be configured to individually measure their resistors in parallel or in series to extend the traceability of dc resistance from 10 kΩ to 100 MΩ. In this paper, a description of a recently developed 100 MΩ-step Hamon network with guarding system at INRIM is given. This standard allows to extend the capability of the Hamon scaling technique up to 1 GΩ at INRIM, which also improves the uncertainty of 1 GΩ with respect to the relative expanded uncertainties declared in [1] and of 19.5×10^{-6} declared for the CCE intercomparison [3] for the 1 GΩ value.

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II. 10×100 MΩ Hamon Network

In Fig. 1, a scheme of the projected Hamon network is reported. The ten main 100 MΩ resistors $\mathbf{R_M}$ are thick film-type resistance elements. Before mounting, they were treated with pure isopropylic alcohol to eliminate impurities on their surfaces. They were chosen to obtain the best possible resistor matching at a level of about 1.1×10^{-4}. The network of resistors is kept inside an aluminum cylindrical case. The passage from series to parallel configuration is obtained by means of a mobile element (upper part in Fig. 1). All the connectors and the external cables are coaxial. The Bayonet Neill-Concelman connectors for the series configuration and the binding post connectors for the parallel configuration are placed, respectively, on top and at the bottom of the case [Fig. 2(a) and (b)]. A 10 kΩ thermistor is located inside the case to measure the temperature. The temperature coefficients of the 100 MΩ resistors of the Hamon network were determined by means of the DMM-DcVC-based method by using a temperature-regulated thermostatic enclosure with the capability of setting the temperature in the range from 19 °C to 27 °C. The average temperature coefficients were $\alpha_{23} = 3.3 \times 10^{-6}/°\mathrm{C}$ and $\beta = 5.4 \times 10^{-7}/°\mathrm{C}^2$, which were better than declared by the manufacturer. The voltage coefficient of the series of resistors was negligible (on the order of $1 \times 10^{-8}/\mathrm{V}$).

III. Guarding System

An effective guarding system for high-resistance Hamon standards is described in [5]. In our Hamon network, the guarding system consists of ten resistors $\mathbf{R_G}$ with a nominal value of 10 MΩ mounted on the cylindrical body of the main resistors by means of two metal rings, as shown in Fig. 3. By means of the two rings, the leakage resistance of each main resistor is divided into three parts $\mathbf{R_L}$, which are drawn with dashed lines in Fig. 1. Between points $\mathbf{b}$ and $\mathbf{c}$, the guard resistor maintains

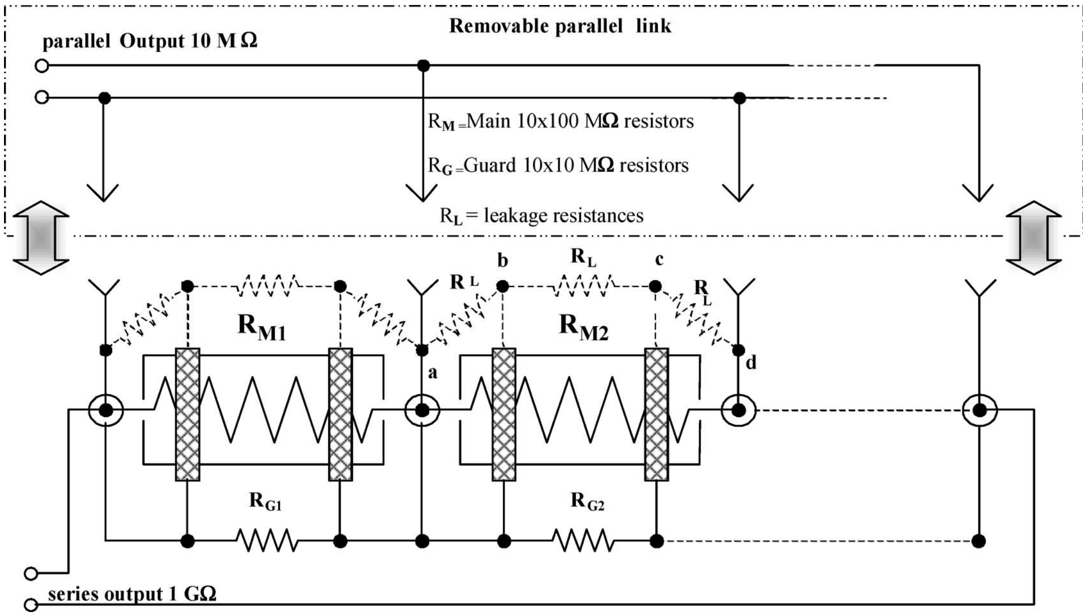
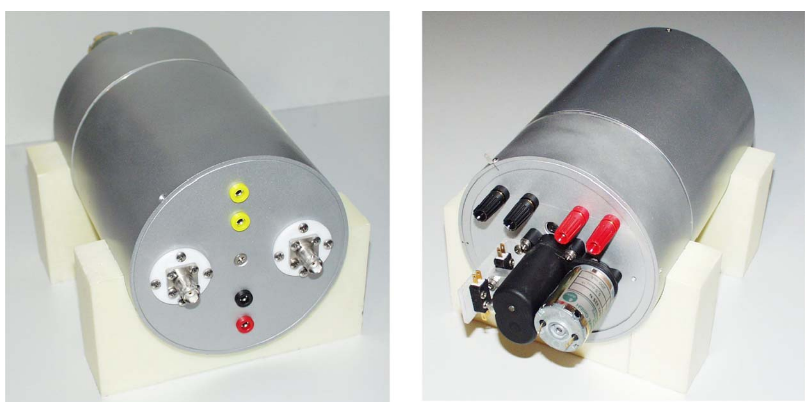


Fig. 1. Scheme of the 100-MΩ-step Hamon network.



(a) (b)

Fig. 2. (a) View of the 1-GΩ output of the Hamon network. (b) View of the 10-MΩ output of the Hamon network.

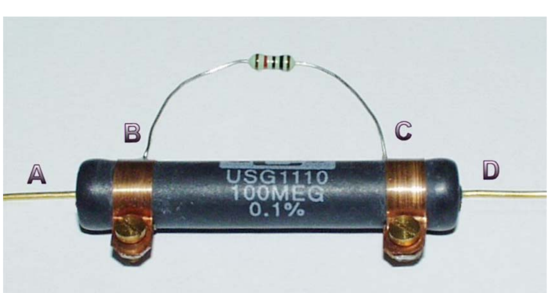


Fig. 3. View of a main 100 MΩ resistor with two metal rings and its 10 MΩ guard resistor.

the same potential as that across the main resistor so that the part of the leakage resistance between **b** and **c** is in parallel with the guard resistor. The potential differences between points **a** and **b** and between points **c** and **d** are almost null, which limit the leakage currents flowing through these parts of the resistor insulation. The shields of the coaxial terminations of the main resistors $\mathbf{R_M}$ are driven to a guard potential that is nearly the same potential as their inner conductors, which limit the leakage current flowing through the insulator material of the connectors. Moreover, a constructed guard driver circuit, whose output sets the voltage of the low side of the guard circuit at the same value of the low side of the Hamon main 100 MΩ resistors, was added (Fig. 4).

Some high-resistance measurements among points A, B, and C (Fig. 3) to evaluate the insulation resistances around the main resistors without the guard resistor were performed. The results are summarized in Table I.

IV. Metrological Verification of the Realized 100-MΩ-Step Hamon Network

To evaluate the performance of the Hamon network as 1:100 transfer standard, the accuracy of the transfer was verified with the DMM-DcVC-based measurement method. The measurement procedure is depicted in Fig. 5. In the first step, the Hamon network, which is in parallel configuration, was calibrated against a high-performance 10 MΩ standard resistor

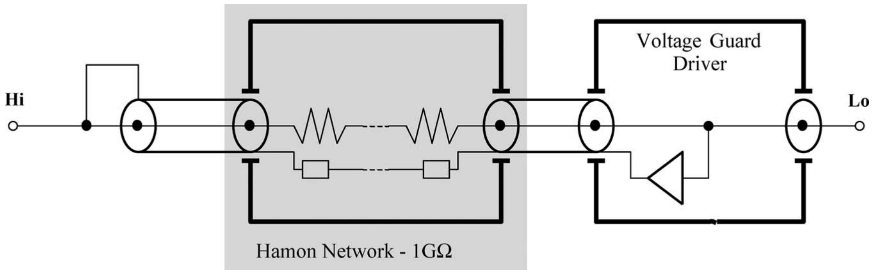


Fig. 4. Scheme of the guard driver circuit associated to the guarding system of the Hamon network.

TABLE I
INSULATION RESISTANCES BETWEEN POINTS A, B, AND C ACCORDING TO FIG. 3

	A vs **B**	**B** vs **C**	**C** vs **D**
Average insulation resistance (x10^{13} Ω)	1.4	1.8	1.5

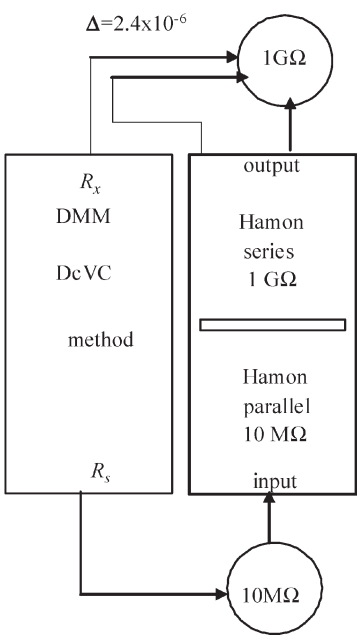


Fig. 5. Scheme of the adopted procedure to verify the Hamon network.

by substitution with a high-precision DMM. In the second step, the series output of the Hamon network was measured with the DMM-DcVC method using the same 10 MΩ as the standard resistor. The measurements were carried out in a shielded laboratory at a temperature of (23 ± 0.5) °C and in an automated way. The measurement voltages for these tests were 10 V and 100 V for the parallel and series configurations, respectively, of the Hamon network. The measurements on the 10 MΩ standard resistor and on the Hamon network in parallel configuration were performed in four terminal configurations. For the guard connection, the instructions of the user manual of the DMM were followed. The 1-GΩ values obtained with the Hamon transfer and with the DMM-DcVC method showed a relative difference of $\Delta = 2.4 \times 10^{-6}$ that is within the uncertainties of the two methods. The result of this test allows the addition of the 100 MΩ step Hamon network to the traceability chain of the Hamon transfer boxes method [1] at INRIM.

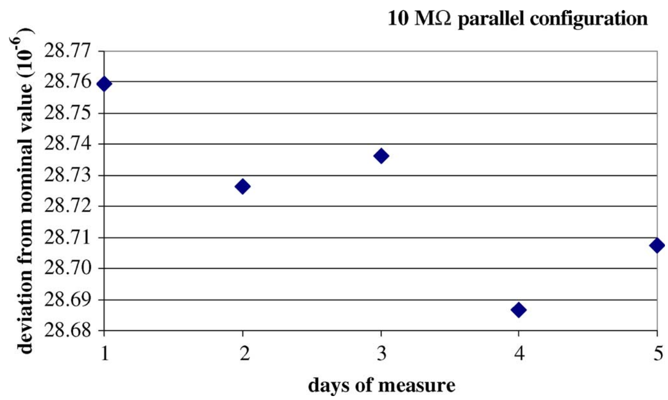


Fig. 6. Stability in parallel configuration of the Hamon network in a five-day measurement period. The resolution reported in the y-axis is deliberately increased to highlight the stability of the Hamon network.

V. CALIBRATION AND USE OF THE 100 MΩ-STEP HAMON NETWORK TO EXTEND THE HIGH DC RESISTANCE TRACEABILITY UP TO 1 GΩ

In Fig. 6, the behavior during a five-day measurement period of the 100 MΩ-step Hamon network in parallel configuration is reported. These measurements aimed to verify the short-term stability of the Hamon network in a typical condition of its use in the Hamon scaling technique. The result of this test demonstrates that the series value of the Hamon network can be used for periods of up to a week without recalibration.

The traceability chain for the calibration of the Hamon network is depicted in Fig. 7. The chain starts from a high-precision 10 kΩ standard with temperature coefficients $\alpha_{23} = -3.4 \times 10^{-8}$/°C and $\beta = -2.9 \times 10^{-8}$/°C^2 and with drift on the order of 7.5×10^{-8}/year [6]. This resistor is calibrated at a 2σ expanded uncertainty of 0.2×10^{-7} in terms of the INRIM 1 Ω primary group of standard resistors referred to the recommended value $R_{\text{K-90}}$ of the Von Klitzing constant [7]. Through a commercial 10×10 kΩ transfer box, the parallel output of a commercial 1 MΩ-step Hamon box[1] is calibrated. Then, the parallel output of the 100 MΩ-step Hamon network is compared with the series output of the 1 MΩ-step Hamon box. All these comparisons are made by substitution in 1 : 1 ratio and in four terminal configuration with a DMM. Finally, the series of 100 MΩ-step Hamon network is compared with a commercial high-performance 1 GΩ resistor

[1]Each resistor of the 10×10 kΩ transfer box is first compared with the 10 kΩ standard. Then, the ten resistors are connected in series and compared with the parallel output of the 1 MΩ-step Hamon box.

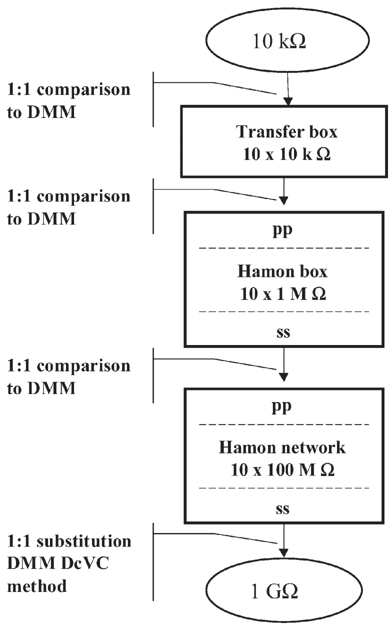


Fig. 7. Traceability chain starting from a high-precision 10-kΩ standard up to 1 GΩ.

TABLE II
RELATIVE STANDARD UNCERTAINTY BUDGET FROM 10 kΩ TO 1 GΩ ACCORDING TO THE METROLOGICAL CHAIN IN FIG. 7

Step	Source of uncertainty	type	1σ ($\times 10^{-6}$)
10 kΩ	Uncertainty and drift of the 10 kΩ standard	B	0.1
	Thermal voltages instability	B	0.2
	DMM non–linearity and instability	B	0.2
	10 kΩ → 10 kΩ RSS of standard deviations	A	0.2
	1:10 transfer error	B	0.5
10x10 kΩ transfer box	Temperature instability and drift	B	0.3
	Thermal voltages instability	B	0.1
	DMM non–linearity and instability	B	0.3
	Standard deviation of the comparison	A	1
10x1 MΩ Hamon box	Temperature instability and drift	B	0.2
	Thermal voltages instability	B	0.1
	1:100 transfer error	B	1
	DMM non-linearity and instability of input impedance and bias current	B	1
	Standard deviation of the comparison	A	1
10x100 MΩ Hamon network	Temperature instability and drift	B	0.3
	Thermal voltages instability	B	0.1
	1:100 transfer error	B	1.2
	Substitution with DMM- DcVC method	B	2
	Standard deviation of the comparison	A	1.2
standard 1 GΩ		**Total RSS**	**3.5**

permanently kept in an air enclosure with temperature of (23 ± 0.02) °C that is used to maintain the resistance unit at 1 GΩ in INRIM. This comparison is made by substitution through the DMM-DcVC method. In a parallel configuration, the 100-MΩ-step Hamon network is calibrated at a voltage of 10 V, whereas in a series configuration, the 100 MΩ-step Hamon network is always used at a voltage of 100 V to maintain the same voltage on the main resistors in the transfer. In Table II, the measurement steps from 10 kΩ to 1 GΩ with their relative standard uncertainty contributions are reported.

VI. CONCLUSION

With the development of this transfer standard, INRIM has appreciably improved its best measurement capabilities in high dc resistance at the 1 GΩ level (7.0×10^{-6} at 2σ level) with respect to the previous declared uncertainties. Moreover, the project of this Hamon network is applicable to higher values of resistance with minor changes. The future aims of our work will be the development of other higher-value Hamon networks to extend the range of the Hamon scaling technique at INRIM. With these new standards eventually controlling their environmental parameters, it will also be possible to set up a calibration system for picoammeters at dc current.

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REFERENCES

[1] F. Galliana and G. Boella, "The electrical DC resistance scale from 100 kΩ to 1 TΩ," *IEEE Trans. Instrum. Meas.*, vol. 49, no. 5, pp. 959–963, Oct. 2000.
[2] G. Boella and F. Galliana, "Analysis of voltage coefficients of high value standard resistors," *Measurement*, vol. 41, no. 1, pp. 1–9, Jan. 2008.
[3] R. F. Dziuba and D. G. Jarrett, "Final report on key comparison CCEM-K2 of resistance standards at 10 MΩ and 1 GΩ," *Metrologia*, vol. 39, p. 01 001, 2002. DOI:10.1088/0026-1394/39/1A/1.
[4] B. V. Hamon, "A 1–100 Ω build-up resistor for the calibration of standard resistors," *J. Sci. Instrum.*, vol. 31, no. 12, pp. 450–453, Dec. 1954.
[5] D. G. Jarrett, "Evaluation of guarded high-resistance Hamon transfer standards," *IEEE Trans. Instrum. Meas.*, vol. 48, no. 2, pp. 324–328, Apr. 1999.
[6] G. Boella, P. P. Capra, C. Cassiago, R. Cerri, G. Marullo Reedtz, and A. Sosso, "Traceability of the 10-kΩ standard at IEN," *IEEE Trans. Instrum. Meas.*, vol. 50, no. 2, pp. 245–248, Apr. 2001.
[7] A. Hartland, "The quantum hall effect and resistance standards," *Metrologia*, vol. 29, no. 2, pp. 175–190, 1992. DOI: 10.1088/0026-1394/29/2/006.

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