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Original
An All-In-One Automatic Multiple Standard for Artifact Calibration of High End Electrical Instruments / Galliana, Flavio; Pollarolo, Alessio. - In: CAL LAB. - ISSN 1095-4791. - 32:2(2025), pp. 20-25.

Availability:
This version is available at: 11696/86639.3 since: 2025-06-30T09:25:45Z

Publisher:
SITA SCHWARTZ

Published
DOI:

An All-In-One Automatic Multiple Standard for Artifact Calibration of High End Electrical Instruments

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An automated temperature-controlled DC Voltage-DC Resistance Multiple Standard (VRMS) for artifact calibration of high end calibrators and multimeters was developed by Measurements International (MI) with the support of the Istituto Nazionale di Ricerca Metrologica (INRiM). The VRMS consists of a 10 V, a 1 Ω, and a 10 kΩ standards selectable via a low thermal scanner. The two resistors are high-stability MI standards while the 10 V standard is based on a low-noise circuit developed by INRIM. A smart feature of the VRMS is its internal algorithm providing updated calibration values of the VRMS standards ensuring their reliably use in the whole period between calibrations. The standards are housed in a thermal box shielding them from temperature changes. The use uncertainties of the VRMS standards are consistent with those for artifact calibration of calibrators and multimeters. The VRMS standards can also act as laboratory references or traveling standards for interlaboratory comparisons (ILCs). MI is currently commercializing the VRMS as 1330A Artifact Transfer Standard.

1. Introduction

Electrical calibration laboratories operate in the five electrical quantities in low frequency (DC and AC Voltage, DC and AC current and DC Resistance), typically in the following ranges to calibrate both generators and meters:

- from 0V to 1000 V for DC and AC Voltage (from 10 Hz to 1 MHz for AC voltage);
- from 0 A to 30 A for DC and AC Current (from 10 Hz to 5 kHz for AC current);
- from 1 Ω to 100 MΩ for DC Resistance.

These laboratories are usually equipped with modern electrical digital programmable instruments as digital multimeters (DMMs) and multifunction calibrators (MFCs) that cover wide ranges and replace standards (often manually operating) that in the past were used to cover the same fields. DMMs and MFCs require annual calibration with traceability to the International System of Units (SI) through the national standards maintained by National Metrology Institutes (NMIs). These instruments can be fully calibrated with a wide set of primary standards, as DC voltage and resistors, DC and AC voltage dividers, AC/DC transfer standards, DC and AC current shunts to cover their measurement ranges. This choice, although granting the best calibration uncertainties, is time consuming and very expensive for the calibration costs of all the reference standards at NMIs. At a slightly lower uncertainty level, DMMs and MFCs can be calibrated using, as traceability transfer standard, a DMM or a multifunction transfer standard [1]. Alternatively, DMMs and MFCs can be calibrated (adjusted) with few primary standards by means of the artifact calibration [2, 3]. To fulfil this need, Measurements International (MI) and the Istituto Nazionale di Ricerca Metrologica (INRiM) jointly developed an automated temperature-controlled DC Voltage and DC Resistance Multiple Standard (VRMS) for artifact calibration. The VRMS standards can also function as laboratory references in National Measurement Institutes (NMIs) or travelling standards for interlaboratory comparisons (ILCs) [4].

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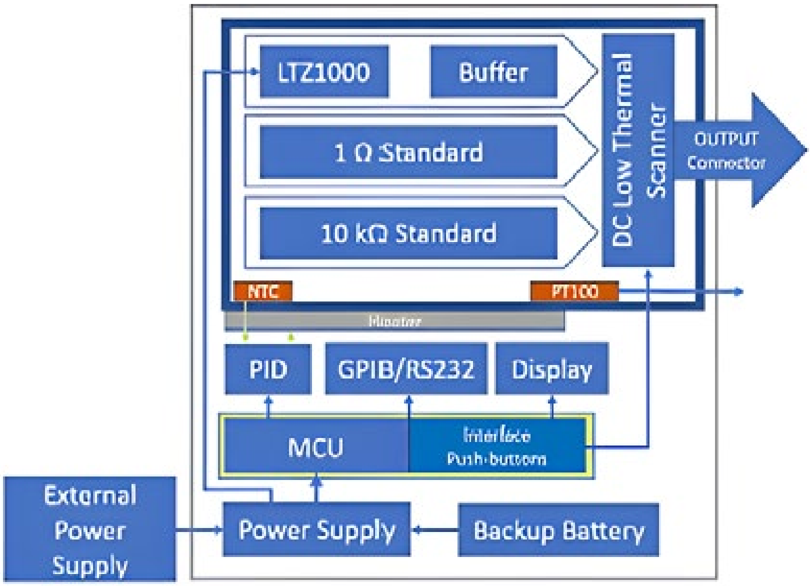

Figure 1. Block diagram of the VRMS. The three standards and the scanner are at constant temperature in an electrostatic shield separated from the electronic control and interfacing system and the power supply. This scheme is reported on the instrument manual [8].

1.1 The Artifact Calibration

The artifact calibration is an in-house calibration (adjustment) method requiring only three standards: 10 V, 1 Ω, and 10 kΩ. This procedure updates the internal references of DMMs and MFCs, which then automatically update the other ranges and functions (self-adjustment). Inside the instruments being calibrated, null detectors compare the measurements and dividers scale the measurement ranges. Artifact calibration makes no physical adjustment, but correction constants are stored. At INRiM, portable temperature-controlled setups for artifact calibration of multifunction instruments were already developed [5-7]. Relying on these experiences, MI, with the scientific support of INRiM, developed an automated temperature-controlled DC Voltage and DC Resistance Multiple Standard (VRMS) for artifact calibration. The VRMS includes a 10 V voltage standard and a 1 Ω and a 10 kΩ resistors. It is also equipped with a low-thermal-output scanner to select the standard minimizing electromotive forces (EMFs) and contact resistances during switching operations. The scanner also allows the polarity reversal of the 10 V standard.

2. The VRMS Setup

Figure 1 shows the block diagram of the VRMS. The standards are placed in a temperature-controlled box where the temperature is monitored by a 100 Ω Platinum Resistance Thermometer (PRT). This aluminium box is internal at the VRMS case (thick blue line in Figure 1). The aluminum box containing the standards is anchored to a thermal mass at 35 °C. This stable temperature minimizes thermal changes, enhancing the stability of the standards. The VRMS has an internal battery and supports remote control via RS-232 or GPIB interfaces. A stabilization period of 12 hours is required after powering on the VRMS to ensure that its standards are ready for accurate measurements [8]. The selected standard is connected to the output via a LEMO- connector and a scanner, either for its calibration or as a reference for artifact calibration.

3. The VRMS Standards

The manufacturer's data sheet reports for the three standards a Temperature coefficient (TCR)[2] of 0.1×10^{-6}/°C and stabilities of 1.5×10^{-6}/year and

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[2] For ambient temperatures in the range (23 ± 5) C.

Temperature	Deviation from nominal value $(\times10^{-6})$		
(°C)	10 V	1 Ω	10 kΩ
18	1.91		
19			
20	1.84		
21		9.8	-9.49
22	1.85		
23	2.04	10.1	-9.51
24	1.93		
25		10.2	-9.6
26	1.82		
27			
28	1.84		

Table 1. Temperature dependence of the reference standards. The measurements of the 10 V standard were made placing the VRMS inside the INRIM climatic chamber, but the resistors were measured outside the VRMS case.

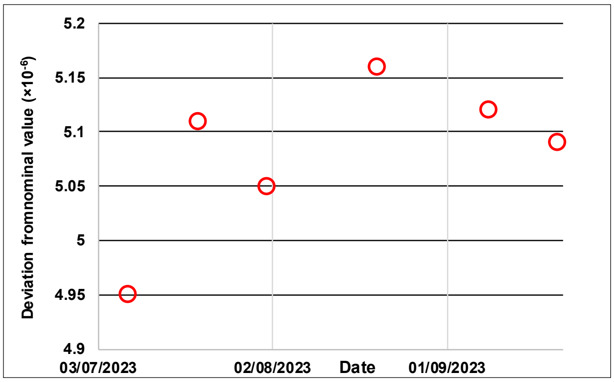

Figure 2. Mean values of the 10 V of a VMRS measured in the INRiM thermal bath.

0.5×10^{-6}/year respectively for the 10 V and for the two resistors respectively. The resistors are manufactured by MI [8]. The 1 Ω is a bifilar non-inductive element with low and negligible temperature and pressure coefficients respectively. Its voltage terminals are welded using Evanohm [9] filler to minimize EMF. An annealing procedure lowers its TCR. The 10 kΩ resistor is instead a metal foil element [10]. The first prototype of the 10 V standard was realized at INRiM with a Zener diode (LTZ1000) maintained at 48 °C. The layout of the 10 V standard minimized thermal effects. The TCR of the standards was evaluated by placing a VRMS in an INRiM thermo-regulated air bath with a stability better than ± 0.01 °C.

The TCR of standards were estimated, assuming linear drifts, 22 nV/V/°C, 0.11 μΩ/Ω/°C and 0.16 μΩ/Ω/°C for the 10 V, 1 Ω and 10 kΩ respectively.

Figure 2 shows the drift of the 10 V in the VRMS in the INRIM climatic chamber at 23 °C. It was evaluated on the order of 2.8 nV/V/day, corresponding to about 1.2 μV/V/year, in line with the manufacturer specification. Figure 3 shows the drift of the 10 V outside the VRMS after power on, in a laboratory thermo-regulated at (23 ± 0.5) °C. This test was made during the assembly of the 10 V prototype.

Figure 3 shows that the drift of the 10 V standard without thermal control is significantly higher in the first seven hours after power-up, approximately 2.2×10^{-8} per hour, and decreases to about 1.4×10^{-9} per hour between the 8th and 14th hour. The thermal control of the VRMS, maintained at ± 0.1 °C, combined with a stabilization period of at least 12 hours prior to measurements, improves the stability of this standard. This time period is also consistent with the stabilization of DMMs and MFCs. Figures 4a–c show the long-term stability of the standards of a VRMS, beginning from its assembly. The measurements were performed in a MI laboratory, at (23 ± 0.5) °C. The standards show a significant drift during the first year and a half presumably due to components stabilization. After this stabilization period, the drift decreases and aligns with the manufacturer's specifications.

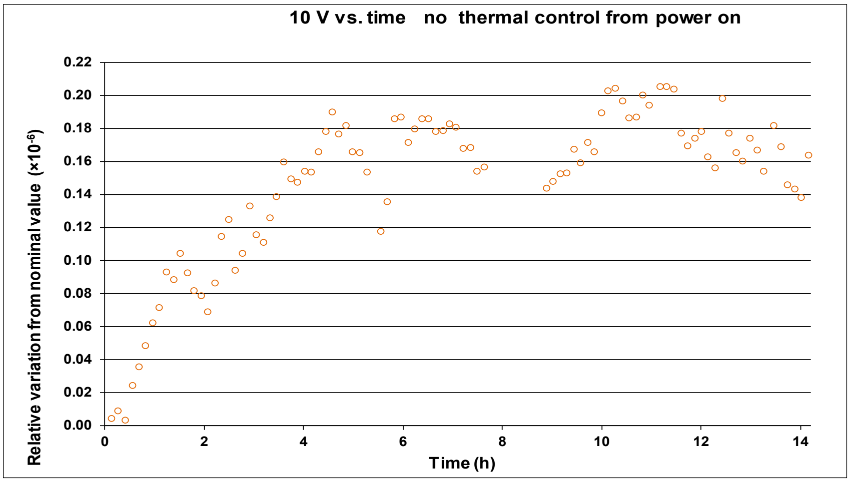

Figure 3. Short-time dependence of the 10 V without thermal control from its power on in laboratory environment.

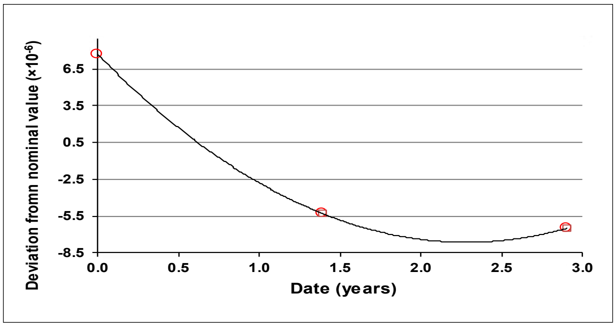

Figure 4a. Long-time stability of the 10 V.

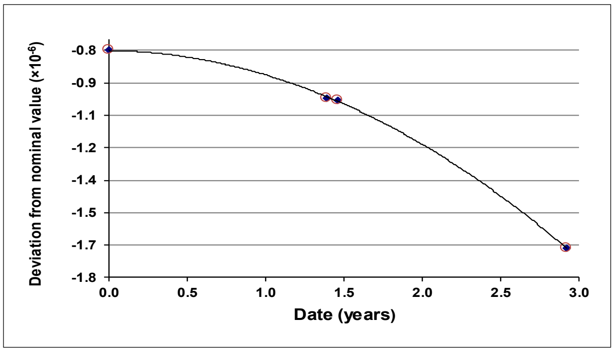

Figure 4c. Long-time stability of the 10 kΩ.

4. Calibration of the VRMS Standards

The 10 V standard can be calibrated either by comparison with a 10 V reference standard or through the Josephson effect [11] via a dedicated connection, using a nanovoltmeter as a null detector. The resistors can be calibrated with current comparator bridges by comparison with reference resistors traceable to the von Klitzing constant [12] or as a direct comparison to the quantum Hall effect with a cryogenic current comparator [13]. Table 2 reports the calibration results of the standards of a VRMS at INRiM.

Nominal values	Calibration values	Measurement current mA	Relative expanded uncertainties (k = 2) (×10⁻⁶)
10V	10.000051 V		0.5
1 Ω	1.0000101 Ω	100	0.5
10 kΩ	9999.905 Ω	0.1	0.5

Table 2. Calibration results at INRIM of a VRMS standards at 23 °C.

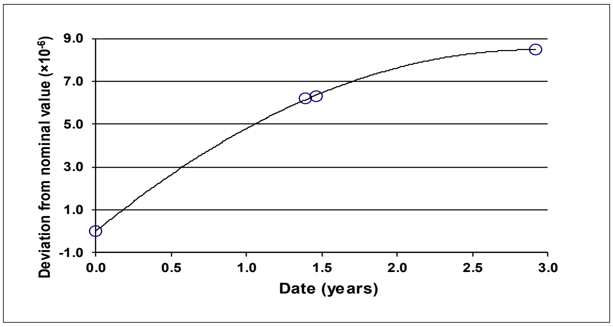

Figure 4b. Long-time stability of the 1 Ω.

5. Performing Artifact Calibration

Figure 5 shows a measurement setup for the artifact calibration of a MFC using the VRMS standards. The connections and calibration steps are usually reported in the user manuals of the instruments undergoing artifact calibration. For example, the Fluke 5720 MFC [14] shows the changes of its internal references as ± part per million (ppm). Table 3 shows a short report of an artifact calibration carried out at INRiM with the VRMS standards.

Figure 5. Photo of the measurement setup for artifact calibration of a J. Fluke 5720 MFC (below) with the VRMS (above).

Standard	**Reference values**	**J. Fluke 5720 reference changes** (ppm)	
10 V VRMS	10.000051 V	6.5 V 13 V	0.3 -0.3
10 kΩ VRMS	9.999905 kΩ	10 kΩ	0.1
1 Ω VRMS	1.0000101 Ω	1 Ω 1.9 Ω	-2.9 -3.7

Table 3. Short report of an artifact calibration at IRiM of a Fluke 5720 MFC with the VRMS standards.

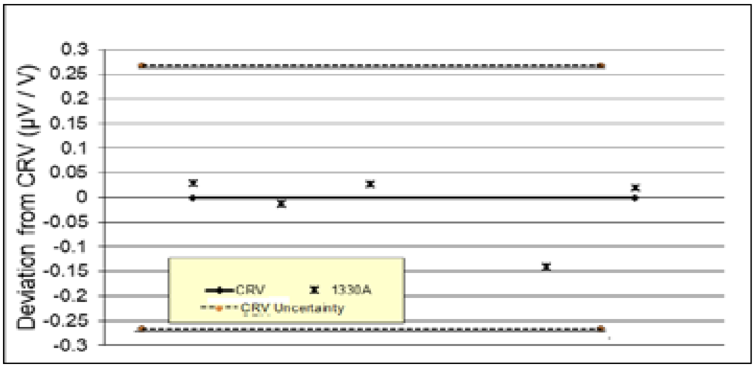

Figure 6. Results of an ILC on DC Voltage at 10 V involving the 10 V standard of a VRMS (1330 A) as one of the traveling standards.

6. Interlaboratory Comparison Involving the 10 V of a VRMS

ILCs [4] are the most important mean for comparing the measurement results of calibration laboratories. They are an effective means to assess the competence of participants and are also important to monitor the quality of calibration results. The 10 V standard of a VRMS was involved as one of the traveling standards in an ILC on DC Voltage. The other traveling standards were two J. Fluke 732B standards. Figure 6 shows the comparison results drift corrected at 10 V regarding only the measurements on the 10 V of the traveling VRMS. The figure shows also the Comparison Reference Value (CRV) and its uncertainty at $k = 2$ [15]. These two parameters are obtained from the measurements and uncertainties of all the participants on all the circulating 10 V standards as weighted mean. The measurements on the VRMS 10 V (MI 1330 A) were satisfactory as falling within the uncertainties of the CRV.

7. How the VRMS Calculates the Real-Time Value of the Standards

Normally, artifact calibration must be performed as soon as possible after the calibration of the 10 V, 1 Ω, and 10 kΩ standards to minimize their drift. Instead, an algorithm of the VRMS providing real-time values of the standards, allows performing the artifact calibration at any time. The user inserts the calibration values of the standards, calibration dates and the evaluated annual drifts. These data are stored in the control EPROM of the VRMS. By means of a real-time clock and the algorithm, the values of the standards are updated with a linear fit.

$$X_d = X_{cal} \quad + \left(d\frac{D}{365}\right) \tag{1}$$

where:
X_d is the value of a selected standard at the day d;
X_{cal} is the last calibration value of the standard;
D is the estimated annual drift of the standard;
d the number of days after the last calibration.

8. Measurement Uncertainties

When a reference standard is used in the period between two calibrations, its in-use uncertainty should be considered[3] [16]. This uncertain is are obtained summing in quadrature the calibration uncertainty and uncertainty components due to drift, temperature variations, power, and transport effects. The VRMS algorithm reduces drastically the uncertainty component due to the drift. Table 4 reports on the in-use typical uncertainties of the standards of the VRMS. The transport effect, evaluated during an ILC, resulted less than 4.0×10^{-8}.

The uncertainty component due to the drift with the values extrapolation is reduced to:

$$u_{\text{drift}} = \frac{\frac{D}{365}}{\sqrt{3}} \tag{2}$$

Considering a rectangular distribution with amplitude $2D/365$ for the drift where D is the annual drift. The manufacturer values were used for D in the uncertainty budget. The uncertainty component due to the temperature effect is also reduced by the thermo-regulation of the standards in the VRMS. The in-use uncertainties of the VRMS standards also apply when they are used as laboratory references during the interval between their calibrations.

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[3] The use uncertainty has to be considered since the calibration uncertainty of a standard could not be valid after some time after calibration. This is due to the standard drift and to the conditions in which the standard is used that could be different from those in which it was calibrated.

Standard	10 V	1 Ω	10 kΩ	Type
Uncertainty component (*k*=1)	Relative uncertainties (*k* = 1)			
Calibration	$2.5×10^{-7}$	$2.5×10^{-7}$	$2.5×10^{-7}$	Normal B
Drift	$2.4×10^{-9}$	$7.9×10^{-10}$	$7.9×10^{-10}$	Rect. B
Temperature effect	5.810^{-8}	$5.8×10^{-8}$	$5.8×10^{-8}$	Rect. B
Emf	$1.2×10^{-8}$	$1.2×10^{-7}$	negl.	Rect. B
Power effect	-	$1.4×10^{-7}$	$1.0×10^{-7}$	Rect. B
Pressure effect	negl.[4]	negl.	negl.	Rect. B
Transport effect	$2.3×10^{-8}$	$2.3×10^{-8}$	$2.3×10^{-8}$	Rect. B
$u_{\text{in-use}}(xi)$ (*k* =1)	**$2.5×10^{-7}$**	**$3.1×10^{-7}$**	**$2.5×10^{-7}$**	**Combined uncertainty** (*k*=1)
$U_{\text{in-use}}$ (*xi*) (k =2)	**$0.5×10^{-6}$**	**$0.6×10^{-6}$**	**$0.5×10^{-6}$**	**Expanded uncertainty** (*k*=2)

Table 4. In-use uncertainty budget according to [15].

Conclusions

The VRMS is a cost-effective and practical choice for artifact calibration of high-end f MFCs and DMMs allowing artifact calibration at any time. Performing this process allows for much better control of the drift and performance of the internal references of DMMs and MFCs compared to traditional instruments, which are only checked during calibration (typically once a year) and can drift out of calibration without the user's knowledge. This lack of awareness may have costly and potentially dangerous consequences. The VRMS specifications meet the uncertainty requirements of MFCs and DMMs for artifact calibration. The VRMS is also suitable for ILCs for DC resistance and DC voltage. Future works aim to improve the data extrapolation algorithm as the number of calibrations increases.

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[4] The pressure coefficient is 0.025 μΩ/Ω in the 700–1200 hPa range, so, since the resistors are in a box and in a pressure-monitored laboratory, the contribution due to pressure can be considered negligible.