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NOTE

Extension to 230 kA with uncertainty reduction for calibration of shortcircuit currents at INRiM

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Abstract

The Istituto Nazionale di Ricerca Metrologica (INRiM) is the only National Metrology Institute (NMI) holding the Calibration Measurement Capability (CMC) for calibrating short-circuit currents up to 170 kA under the framework of the Mutual Recognition Arrangement of the Comité international des poids et mesures (CIPM MRA). This paper presents the extension of this CMC up to 230 kA and the improvement of the measurement uncertainty of the INRiM system for calibrating sensors and measurement systems for high short-circuit currents and for the Joule integral. The extension has been possible by means of a linearity verification of the INRiM system carried out by comparing it with an intrinsically linear measurement system based on a Rogowski coil. This comparison allowed the update and refinement of the uncertainty budget, specifically the component associated with the linearity of the INRiM system, for both the peak current and the Joule integral. An innovative approach has been adopted by applying a median filter to the voltage measurement of the Rogowski coil to remove noise. This filter has been integrated into the calibration software for high short-circuit currents and optimized for the use with Rogowski coils without an integrator.The uncertainties of the INRiM measurement system have been then reviewed and improved for currents up to 170 kA and 230 kA, resulting, in relative parts 4.2×10^{-3} and 5.6×10^{-3}, respectively. Consequently, the extension of the INRiM CMC for calibration of short-circuit currents and for Joule integral up to 230 kA can be considered feasible with the achieved uncertainties.

1. Introduction

Short-circuit and high-current tests are essential to verify the safety and reliability of electrical equipment. The measurement of transient and short-circuit currents is crucial for the design and maintenance of electrical systems. Transient currents, which occur during transient events, such as switching operations or lightning strikes, can damage components and devices. Measurement systems with current sensors, as Rogowski coils [1, 2] or shunts, must be traceable to the national standards held by National Metrology Institutes (NMIs) and comply with the requirements of the standard [3] mainly under dynamic conditions. To calibrate sensors or measurement systems for short-circuit currents, it is necessary to evaluate its current scale factor (SF) for the full range, directly or with a linearity measurement and to calculate the Joule integral. For short-circuit currents, it is sufficient to determine the scale factor of the sensor, whereas for the evaluation of the Joule integral, the overall behavior of the system must be characterized, since the software, responsible for computing this quantity, forms an integral part of the measurement chain. A short circuit current is composed of a high 50 Hz component with an additional transient component which can also be very high. Short-circuit currents, arising in the event of a fault, can cause fires and damage the installation. Therefore, short-circuit tests are fundamental for the correct design and safety of electrical systems. With these measurements, it is possible to determine the maximum current that can flow in the event of a short circuit, a critical factor for the correct sizing of protective devices (such as circuit breakers and fuses) and cables. Measurement systems and

Figure 1. Short-circuit current generator.

comparators were developed both for direct and alternating currents, including for on-site calibrations and without the use of shunts [4–7]. For transient and short-circuit currents, fewer methods are available in literature [8–13], most relying on Rogowski coil-based measurement systems. For short-circuit currents, INRiM, with the LATFC - Laboratorio Alte Tensioni Forti Correnti - (High Voltage and High Power Laboratory), is the only NMI holding the Calibration Measurement Capability (CMC) for calibration of short circuit currents in the framework of the CIPM MRA[1]. In this study, the linearity of the measurement system used at INRiM for calibrations of short-circuit currents has been verified within its operating range and the corresponding uncertainty contribution has been estimated and included in uncertainty budget of the same measurement system.

2. The INRiM measurement system

LATFC calibrates sensors and measurement systems for high short-circuit currents [13]. For the calibrations at the LATFC, these currents are generated by a synchronous generator (figure 1), driven by an asynchronous motor. The motor is disconnected from the power grid immediately before performing the short-circuit at the output. This generator is a Brown Boveri & CIE three-phase alternator. Dating back to the early 1900s, it is the only model of its kind in the country. It features distinctive specifications, including a short-circuit capacity of 60 MVA, a short-circuit current of 8700 A, rotor weight 15 t, a stator weight 20 t, speed of 1000 revolutions per minute (rpm), rated power 5 MVA, six poles, and rotor diameter of 1.5 m.

Transformers after the generator allow the increase of the current up to 230 kA with about 420 V. The reference system used for calibrations (figure 2) consists of the resistive shunt, which allows measurements with currents up to 230 kA. Figure 3 shows the diagram of the measurement setup. During a measurement, if the temperature increase remains within 20 K (compared to 23 °C, therefore up to 43 °C), its effect is included in the uncertainty. Beyond that value,either the cool down is waited or the measurement is discarded. The temperature is measured with two thermocouples inside the shunt.

2.1. The shunt

The INRiM system employs as measurement sensor a compensated coaxial one with nominal current of 100 kA and nominal value of 75 μΩ. Main components of the shunt are shown in figure 4. It has a tubular construction with a coaxial return path. The inner and outer tubes, made respectively of resistive material and copper, are connected at one end. The current to be measured flows through the inner tube and returns via the outer tube in order to minimize inductance. The magnetic flux linkage is also compensated according to the Malewski theory [14] allowing for a response time of less than 500 ns. Therefore, the shunt is suitable for analyzing and representing short-circuit currents. The shunt was characterized by its manufacturer by determining its response time to a current step (figure 5) using a reference transducer described in [15].

Table 1 reports the characteristics of the shunt. Figure 6 shows instead a plot of the T_S and T_R that are respectively the settling and response times of the shunt as a function of the applied currents. T_S represents the

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[2] The Comité international des poids et mesures (CIPM) Mutual Recognition Arrangement (CIPM MRA), established in 1999, is a framework in which the NMIs demonstrate the international equivalence of their measurement standards and of their issued calibration and measurement certificates. The CMCs are reported in the key comparison database (KCDB), which is maintained by the International Bureau of Weights and Measures (BIPM).

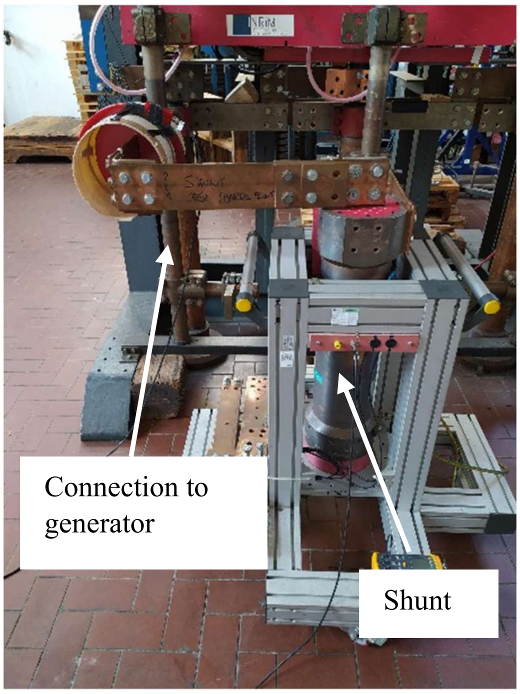

Figure 2. Shunt connected to the short-circuit current generation system.

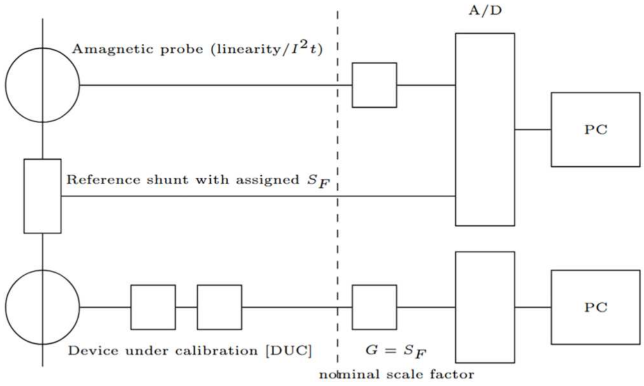

Figure 3. Diagram of the measurement circuit for calibration of high short-circuit currents.

Table 1. Characteristics of the shunt used.

DC Resistance 500 A at 23.0 °C	75.38 μΩ
AC Resistance 10 kA at 23.0 °C	75.38 μΩ
Temperature coefficient	$<1.1 \times 10^{-3}$/°C
Max heating temperature	20 K

time required for the voltage across the shunt to reach stability and is equal to the circuit's RC time constant. T_R is a parameter that determines how quickly the shunt responds to changes in current.

Figure 7 shows the ratio between the measured and the nominal value of the shunt in DC current. The first value was determined by the manufacturer with its measurement system.

Subsequently, the calibrations of the shunt were performed at INRiM in the laboratory of low-resistance in DC current with a method based on a high-current and high precision comparator bridge. All measurements were carried out with a relative expanded uncertainty [16] of 2×10^{-4}. The low-resistance laboratory performs this calibration at currents up to 500 A due to the limits of its system generation.

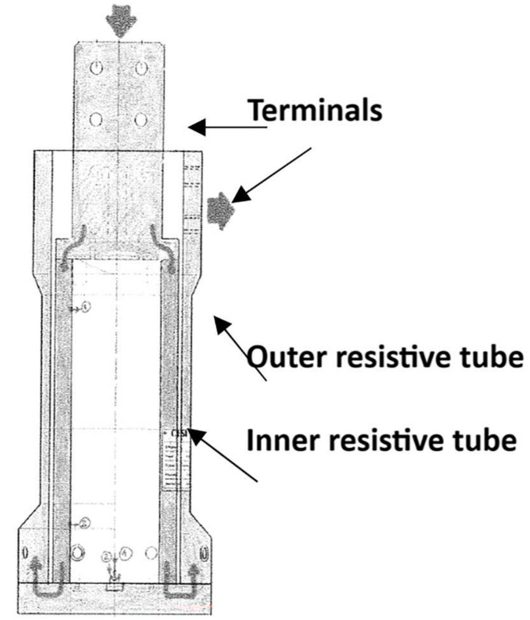

Figure 4. Main components of a compensated coaxial shunt.

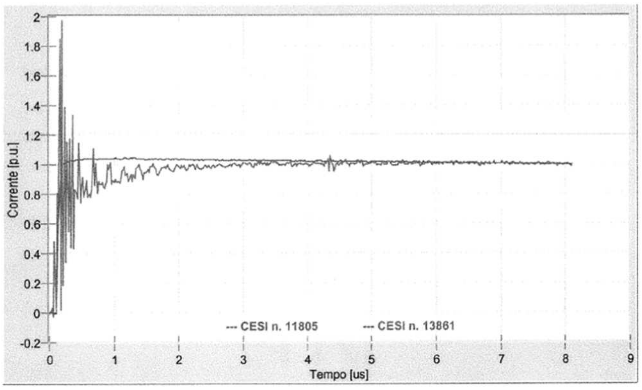

Figure 5. Response time to a current step. The current is in p.u with p.u. base 80 kA.

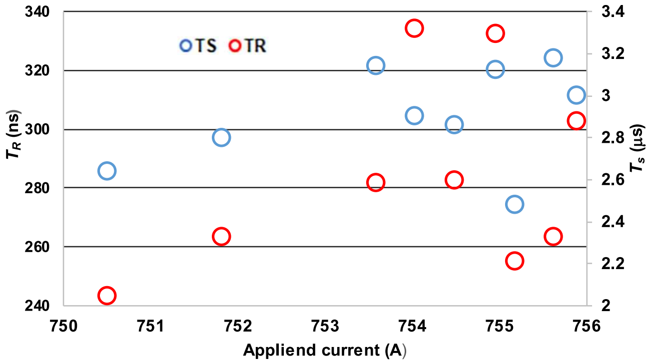

Figure 6. Settling(T_S) and response (T_R) times of the INRiM shunt as a function of the applied current.

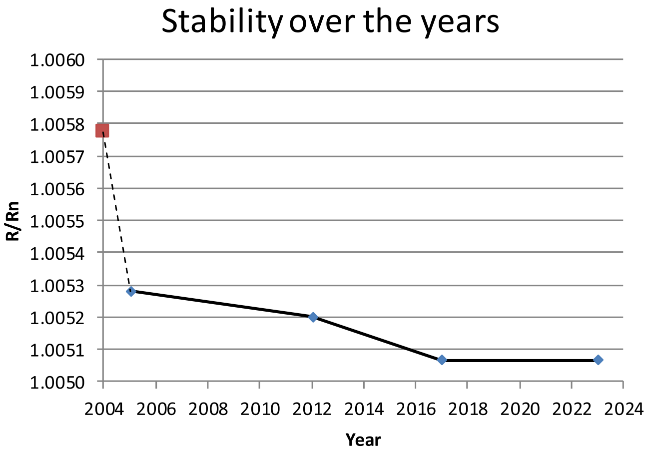

Figure 7. Ratio between the measured (R) and nominal resistance (R_n) values of the INRiM shunt in direct current.

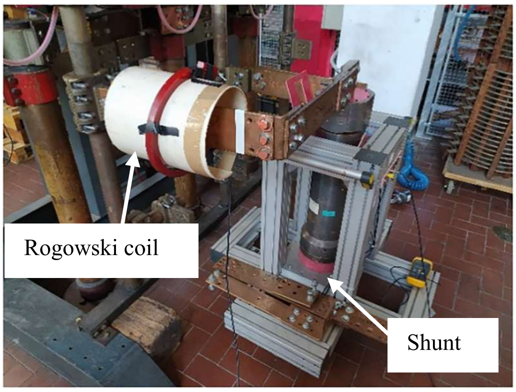

Figure 8. Part of the measurement system for the linearity verification with the Rogowski coil.

3. Measurement system for the linearity verification

The linearity verification of the shunt has been carried out using a system inherently linear by design shown in figure 8, based on a Rogowski coil as required by [3].

Rogowski coils, consisting of windings wrapped in air, do not suffer from magnetic core saturation, therefore, they have intrinsic linearity by design, although this statement is debated [9]. The system architecture remains unchanged in the entire measurement range, from 1 kA to 230 kA. Given that the geometries are kept constant and no non-linear elements are present, the parasitic parameters also exhibit a strictly linear behaviour. The only component that may exhibit non-linearity is the integrator associated with the coil. In the verification described, the output voltage of the coil, used as reference, has been directly acquired with a Keysight 3458A digital multimeter (DMM). These measurements have been then numerically integrated via software to obtain the time profile of the current in the copper busbar, thus avoiding the non-linearities of the electronics of the integrator usually associated with the coil. The steps of the linearity test are:

- Set the measurement circuit of figure 8;
- Activate the generation system described in section 2, consisting of the synchronous generator and the transformers downstream of the generator, which supply both measurement systems equipped with the shunt and the Rogowski coil (figure 2);
- Generate the requested currents in the range 1 kA to 230 kA, then:

  For peak currents and for each supply current:
- Evaluate the current outputs of the shunt by means of the acquired voltages by the DMM connected to the shunt;

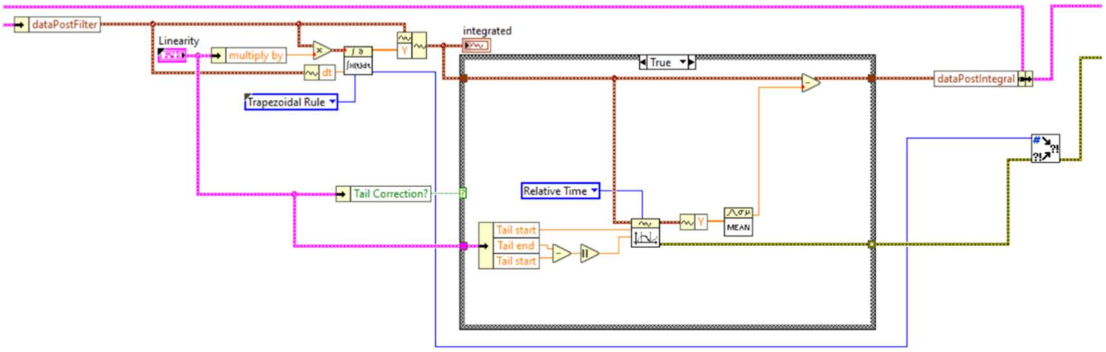

Figure 9. Scheme of the integration method.

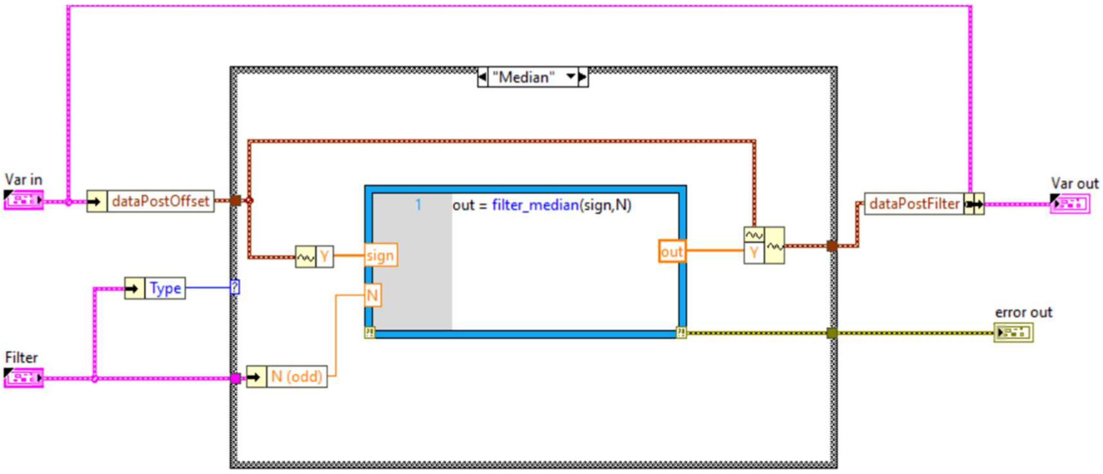

Figure 10. Scheme of the filter used.

- Evaluate the voltage outputs acquired by the DMM connected to the Rogowski coil and processed by the software;
- Calculate the ratio values between the currents from the shunt and the Rogowski coil and their mean ratio;
- Calculate the standard deviation of the mean of the measured ratios.
- For the Joule integral and for each supply current:
- Record the values of the Joule integral provided by the INRiM system and from the s Rogowski system;
- Calculate the ratio between the values of the Joule integral from the two systems and their mean ratio;
- Calculate the standard deviation of the mean of the measured ratios.

The main feature of the DMM used are: 8×10^{-6} DC voltage one-year reference stability, 0.1×10^{-6} DC volts transfer accuracy, high-speed digitizing (up to 100k readings/s), measurement of DC and AC Voltages, DC and AC currents, DC Resistance. For our measurements, the DMM was used in the DC Voltage ranges 0.1 V, 1 V and 10 V where the one year accuracies of the DMM (option 002) span from 4.0×10^{-6} of the reading $+ 5.0 \times 10^{-8}$ of the 10 V range to 5.0×10^{-6} of the reading $+ 3.0 \times 10^{-6}$ of the 0.1 V range. In these ranges the input impedance of the DMM is higher than 10 GΩ.

3.1. The measurement software

The software supporting the measurements has been developed by the LATFC in Labview and integrated into the calibration software for high short-circuit currents, optimizing it for use with Rogowski coils without the integrator. The software validation was performed by comparison with a calculation method developed on a different software platform. To ensure the absence of non-linearity in the integration process, a numerical integration has been employed to eliminate any potential undesired effects introduced by the electronics. The numerical integration method is based on the trapezoidal rule, which offers high accuracy for periodic functions such as the alternating current to be measured. To mitigate numerical errors caused by integration drift, a correction method has been implemented to eliminate any bias in the numerical calculation by compensating for the offset at the end of the integration, after the current pulse in the conductor has ceased (figure 9). Even a small zero offset, when integrated over time, can lead to a significant cumulative error.

To improve the integrated signal, a median filter has been used (figure 10). This is a non-linear digital filtering technique commonly used to remove noise from images and signals. The median filter scans the signal point by point, replacing each value with the median of that value and its neighboring values.

This filter offers the advantage that, compared to a low-pass filter, it maintains good performance even if a DC component is present.

4. Measurement analysis and uncertainty evaluation

For the analysis of the measurements, reference has been made to [3] for which the linearity verification is used to evaluate a measurement system under calibration when the reference system does not have a sufficient measurement range to cover the range of the system under calibration [3] explains how the linearity is assessed comparing the measurements of a system under evaluation and those of an intrinsically linear system. Although the scale factor of the INRiM shunt is updated with direct current calibrations, unfortunately these measurements can be performed up to a maximum current of 500 A. For this reason, the linearity of the shunt has been verified within its intended application range i.e. peak of the short circuit currents up to 230 kA, higher than the maximum value of the INRiM/201 CMC, i.e. 170 kA. To evaluate the uncertainty contribution due to the linearity verification [3], provides the following equation:

$$u_{lin} = \frac{1}{\sqrt{3}} \times \max_{1 \leqslant g \leqslant b} \left| \frac{R_{i,g}}{\overline{R}_g} - 1 \right| \tag{1}$$

Where :

- $\boldsymbol{R_{i,g}}$ is the ratio between the measurement system under linearity verification and the intrinsically linear measurement system;
- $\overline{R}_g$ is the mean of the ratios at different currents.

Table 2 reports the currents at which the linearity verification has been performed (1st column), the ratio between the measurements on the shunt and those on the Rogowski (2nd column), the standard deviation of the mean of the measured ratios (3rd column) and finally the mean ratio value with the final uncertainty contribution calculated with the equation (1). Figure 11 shows the ten measurements of the ratio Shunt/Rogowski at 1 kA. The linearity behaviour of the INRiM system in the whole range is also shown in figure 12. Table 3 reports the same data for the Joule integral.

Reference [13] provided uncertainty budgets according to [16] for calibration of short circuit currents with the INRiM system up to 170 kA. In that budget, a relative uncertainty contribution of 0.23% due to the non-linearity of the shunt was considered. This value was determined by the manufacturer during the shunt characterization up to 80 kA. This uncertainty value is higher than the evaluated ones in this work. Table 5 presents a new and simplified uncertainty budget for peak currents up to 170 kA and up to 230 kA inserting the uncertainty contributions due to linearity reported in table 2. Always in [13], the uncertainty budget for the Joule integral was presented without a contribution for the nonlinearity of the system. In table 6, the same budget has been updated, taking into account the uncertainty component due to the nonlinearity evaluated up to 230 kA. The formula of the expanded uncertainty, valid both for absolute and relative expressions, is given in [16] and is:

$$Y = y \pm U = y \pm kuc(y) \tag{2}$$

where:
Y is the output quantity under measurement (the current);
y is the better estimate of the output quantity;
u_c is the combined standard uncertainty ($k = 1$);
k is the coverage factor;
U the expanded uncertainty ($k = 2$).

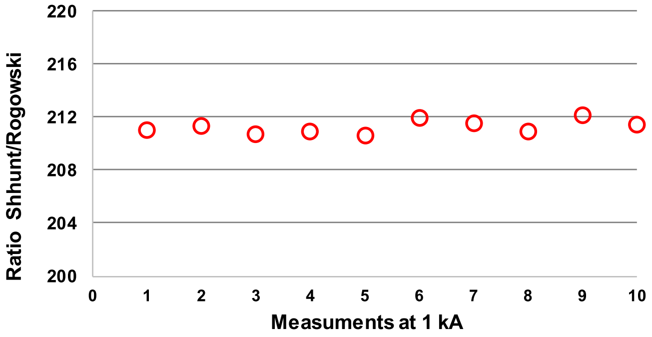

Figure 11. measurements of the ratio Shunt/Rogowski at 1 kA.

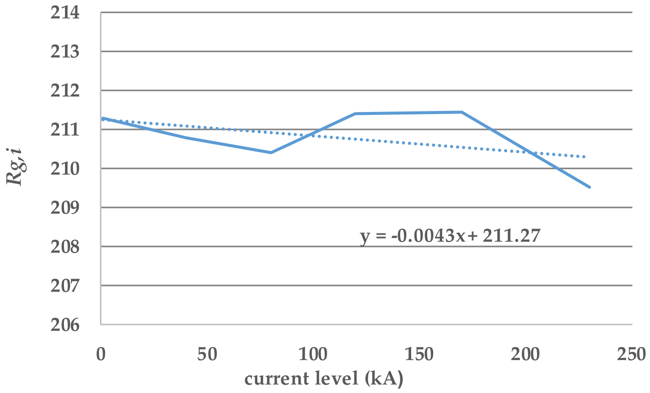

Figure 12. Linearity verification as described in [3].

Table 2. Results of the linearity verification for the peak currents.

Current	Ratio shunt/ Rogowski	standard deviation of the mean (%)
1 kA	211.3	0.08
40 kA	210.8	0.03
80 kA	210.4	0.04
120 kA	211.4	0.3
170 kA	211.5	0.4
230 kA	209.5	0.5
up to 170 kA	$\bar{R}_g = \mathbf{211.1}$;	$u_{lin}(\mathrm{k} = 1) = \mathbf{0.10\%}$
up to 230 kA	$\bar{R}_g = \mathbf{210.8}$	$u_{lin}(\mathrm{k} = 1) = \mathbf{0.17\%}$

Table 3. Results of the linearity check for the Joule integral.

Current	I^2t Ratio shunt/Rogowski	Standard deviation of the mean (%)
80 kA	44.31 k	0.1
120 kA	45.09 k	0.3
170 kA	44.51 k	0.2
230 kA	44.65 k	0.2
up to 230 kA	***Mean ratio*** = **44.64** k;	$u_{lin}(\mathrm{k} = 1) = \mathbf{0.6\%}$

Table 4. Uncertainty budget for short-circuit measurements up to 170 kA and up to 230 kA (peak currents).

Component	*Type*	*Uncertainty contribution* ($k = 1$)
Up to 170 kA		
Peak current of the calibration system calibration system	Rect. B	8.1×10^{-6}
Peak current of the reference system	Normal[a]	1.5×10^{-3}
Self-heating of the reference shunt	Rect. B	1.3×10^{-3}
Reference shunt linearity	Rect. B	1.0×10^{-3}
Reference shunt stability	Rect. B	1.9×10^{-4}
Scale factor	Rect. B	1.3×10^{-4}
$\boldsymbol{u_c = 2.1 \times 10^{-3}}$	**k = 2**	$\boldsymbol{U = 4.2 \times 10^{-3} 1.5 \times 10^{-3}}$
Up to 230 kA		
Peak current of the calibration system	Rect. B	8.1×10^{-6}
Peak current of the reference system	Normal[a]	1.5×10^{-3}
Self-heating of the reference shunt	Rect. B	1.3×10^{-3}
Reference shunt linearity	Rect. B	1.7×10^{-3}
Reference shunt stability	Rect. B	1.9×10^{-4}
Scale factor	Rect. B	1.3×10^{-4}
$\boldsymbol{u_c = 2.8 \times 10^{-3}}$	**k = 2**	$\boldsymbol{U = 5.6 \times 10^{-3} 1.5 \times 10^{-3}}$

[a] The peak current of the reference system was assumed as normal and taking into account the DMM measurements and the uncertainty of the shunt [13].

Table 5. Uncertainty budget for the Joule integral up to 230 kA.

Component	Type	Uncertainty contribution (k = 1)
Joule integral of the calibration system	Rect. B	9.8×10^{-7}
Joule integral of the reference system	Rect. B	1.2×10^{-8}
Self-heating of the reference shunt	Rect. B	1.3×10^{-3}
Sampling	Normal A	1.2×10^{-2}
Linearity of the reference shunt	Rect. B	6.0×10^{-3}
Numerical integration	Rect. B	1.0×10^{-2}
$\boldsymbol{u_c = 1.7 \times 10^{-2}}$	**k = 2**	$\boldsymbol{U = 3.4 \times 10^{-2}}$

The uncertainty values reported in Tables 4–5 are the uncertainty contributions ($k = 1$) defined in [16] as the product of the combined standard uncertainties and their sensitivity coefficients. In these tables, an uncertainty component due to the DMM and algorithm (software) was not not added since in [13], a detailed analysis of the effects of possible disturbances due to the DMM and to the algorithm was made. Some DC voltages were applied to simulate the behavior in presence of a continuous component, similar to the unidirectional component of short-circuit currents. The results show that the resulting error resulted almost negligible for the scope of our measurements.

4.1. Discussion and perspectives for future work

Currently, among NMIs, INRiM is the only one holding the CMC for calibration of short-circuit currents. This represents an important specificity. Other specificities of the present work can be:

- The extension of the calibration range up to 230 kA by means of a linearity verification;
- An innovative filtering strategy consisting in applying a median filter to the voltage measurements of the Rogowski coil in order to remove noises from the signal to be successively integrated to be converted in current;
- The reviewing of the calibration uncertainties.

Being INRiM the only NMI with this CMC, no international comparisons are possible. Therefore, the applied linearity verification can represent an alternative method to validate a CMC extension. This method can be of interest for other NMIs or test laboratories. The study of the linearity of the INRiM measurement system for short-circuit currents calibration, allowed also to better evaluate the behavior of the system itself as a function of the peak current and of the Joule integral. The uncertainty contributions due to the non-linearity

Table 6. Comparison between existing CMCs and featured ones.

Ranges	(0.1 ÷ 170) kA	(0.1 ÷ 170) kA	170 ÷ 230) kA
	Today CMC	**Featured CMCs**	
Current	6.0×10^{-3}	4.2×10^{-3}	5.6×10^{-3}
Joule integral	3.2×10^{-2}	3.2×10^{-2}	3.4×10^{-2}

have been evaluated and the uncertainty budgets related to the INRiM CMC for calibration of short-circuit currents and for the Joule integral up to 170 kA have been updated. Uncertainties up to 230 kA were also evaluated for the same quantities.Therefore, the current CMC can be extended up to 230 kA by dividing it into two ranges: up to 170 kA and up to 230 kA. Table 6 lists the CMCs changes.

In view of the traceability requests for currents higher than 230 kA, the possibility of extending the linearity verification up to 250 kA, the maximum value for the INRiM shunt,will be considered. The feasibility of on-site calibration will also be evaluated, taking the opportunity to verify the linearity of the customers' systems while simultaneously assessing the linearity of the INRiM system between 230 kA and 250 kA.

Ethics statement

The authors declare they have no conflicts of interest with the instrumentation manufacturers.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://zenodo.org/records/18246196.

Author contributions

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Data curation (equal), Methodology (equal), Software (equal), Writing – review & editing (equal)

Paolo Emilio Roccato 0000-0002-0939-3360
Conceptualization (equal), Methodology (equal), Supervision (equal)

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