Improvement of the INRiM calibration capabilities for lightning impulse voltages from 200 kV to 600 kV

Improvement of the INRiM calibration capabilities for lightning impulse voltages from 200 kV to 600 kV

Stefano Emilio Caria, Flavio Galliana, Paolo Emilio Roccato

***Abstract*— In this paper, an improvement of the calibration measurement capabilities (CMCs) of the Istituto Nazionale di Ricerca Metrologica (INRiM) for measurements of Lightning impulse (LI) voltages from 200 kV to 600 kV, is proposed. This improvement is the result of a more detailed characterization of the INRiM measurement system for LI measurements. The INRiM LI measurements of the most critical waveforms at voltages up to 600 kV for the EURAMET.EM-S42 comparison were submitted to a refinement with a discrete deconvolution method. The comparison results were then recalculated by inserting the INRiM measurements, both with and without deconvolution, (the latter for less critical waveforms) and the updated uncertainties. The INRiM measurements after recalculation were still in agreement with the comparison reference value, even for short impulses (0.84 μs), where the size of the used divider was not optimal. The recalculation did not affect the degrees of equivalence of the other participants and the consistency of the comparison. The new INRiM uncertainties range from 0.5 % of U_t (test voltage) for the long impulse at 600 kV to 2 % of T_1 (front time of the impulse) for the short impulse at 400 kV and 600 kV. A validation of both the new uncertainties and the selected discrete application of deconvolution is also proposed, together with a verification of the compliance of the INRIM measurement system up to 600 kV with the requirements of a reference system.**

***Index Terms*— Lightning impulse, step response, voltage divider, digitizer, convolution, deconvolution, measurement uncertainties, degree of equivalence.**

I. INTRODUCTION

ACCORDING to [1], a lightning impulse (LI) is an impulse voltage with a front time (T_1) shorter than 20 μs. Measurement systems for LI are used to assess the dielectric stress of transient over voltages caused by lightning strikes and disruptive discharges in order to validate electrical components or devices. The LI waveforms can have slightly different trends depending on the duration of the most critical parameter T_1 (rise time of the impulse). If T_1 is 0.84 μs or 1.56 μs, the impulse is short or long respectively. T_2 is instead the time to the half-value of the impulse. The Istituto Nazionale di Ricerca Metrologica (INRiM), through its "Laboratorio Alte Tensioni e Forti Correnti" (LATFC) – High Voltage and High Power Laboratory – is equipped with the necessary instrumentation to calibrate LI impulse waveforms up to 600 kV. In particular, the laboratory employs two measurement systems, each equipped with a different voltage divider, designed for measuring voltages up to 200 kV and 600 kV, respectively. By means of these measurement systems, the LATFC participated successfully at the Supplementary comparison EURAMET.EM-S42 [2]. Despite this achievement, the need for smaller calibration uncertainties from external customers led us to verify whether the INRIM results for the comparison, with smaller uncertainties would still agree with the Comparison Reference Value (CRV). The INRiM capabilities for LI voltages up to 200 kV were already improved by re-evaluating the comparison results introducing smaller INRiM uncertainties in the comparison analysis [3] applying the statistics of the weighted mean as made for the comparison [2]. This re-evaluation followed an additional study of the measurement system. This approach was also used in the present work where the comparison data was reanalyzed by incorporating the claimed uncertainties to validate them. However, from a preliminary recalculation with the new uncertainties, the INRIM results for short time impulses at voltages higher than 200 kV, although still in agreement with the CRV had in some cases a compatibility index not fully satisfactory (see Table 13 for example). For this reason, the measurements of the most critical waveforms were submitted to deconvolution. In fact, mathematical tools such as convolution and deconvolution can minimize errors introduced by voltage dividers, digitizers (which have non-ideal step responses), and software for measurements evaluation. These tools facilitate the correction of non-ideal step responses of each component of measurement systems, thereby enhancing the accuracy and reliability of LI measurements [4-11]. For example, by means of the convolution of step responses, measurement errors were investigated in [4]. The deconvolution allows the reconstruction or correction of an input signal from a distorted output signal and the step response of a measurement system. For example, in [8, 9] the deconvolution was applied to correct the step response of impulse dividers and digitizers. Specifically, in [8], the

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deconvolution was applied to correct for the non-ideal step response of both a digitizer and a large mixed divider. In [9], the results of a system consisting of a12-bit digitizer and a 10 kV divider, after correction by deconvolution, were confirmed by calibrating the system with a calculable impulse voltage calibrator [12]. Although the deconvolution of non-ideal step responses can reduce systematic errors, it may amplify noises particularly in lower ranges of digitizers [13]. However, by reducing systematic errors, the uncertainty of LI measurements can be improved. The noise introduced by deconvolution can be minimized through appropriate filtering. In [13], it is also observed that the effectiveness of deconvolution-based correction is independent of the setup arrangement. Based on these studies, the INRiM measurements of the most critical waveforms for voltages up to 600 kV for the comparison were deconvoluted and the comparison results were successively recalculated with the weighted mean statistics introducing the INRiM measurements with and without deconvolution and the claimed uncertainties. This approach was only relevant for the new calculation of the original data since there was new information about the performance of the measurement system, but the system remains unchanged. In fact, a further characterization of the INRiM measurement system for LI voltages up to 600 kV using a higher-voltage step generator showed that the INRiM system complies with the requirements of a reference measurement system according to [14] (see paragraph IV). From a technical-scientific point of view, the combined approach of:

- Deconvolution of the critical measurements;
- Recalculation of the measurements by means of a metrological-grade software that implements the requirements of the relevant standards;
- Verification of the compliance of the INRiM measurement system up to 600 kV with the requirements for a LI reference system according to [14]:
- Validation of the new uncertainties according to [15] with a restrictive criterion, even for short impulses (0.84 s).

may be a novelty and a possible increase of the knowledge in this field. This approach may also be valuable for future comparisons between National Metrology Institutes (NMIs) in this measurement field, given the high costs associated with performing such comparisons. Nevertheless, this 'a posteriori' claim for lower uncertainties can modify the CRV altering the weighting of the contributions to the CRV itself and could have an impact on the equivalence of the other participants, but fortunately, not in this case. The software for deconvolution may introduce an additional uncertainty that must be estimated by evaluation of a set of test data with established reference values provided by a Test Data Generator (TDG) [1, 14, 16]. With the new uncertainties, the INRiM measurements were still in agreement with the CRV without affecting the results of the other participants.

II. THE LATFC EQUIPMENT

At the LATFC there are two systems for LI voltages measurements differing for the use of two different dividers:

- SAGI 304 (Fig. 1) for LI measurements up to 200 kV;
- Haefely R600 (Fig. 2) for measurements up to 600 kV.

Auxiliary devices of the measurement systems are the:

- Haefely SGSA 800/40 (Fig. 3) impulse generator supplying up to 800 kV as equipped with eight stages each of them supplying up to 100 kV;
- National Instruments' scope PXI-5124 digitizer with max sampling rate: 200 MS/s and resolution of 12 bits;

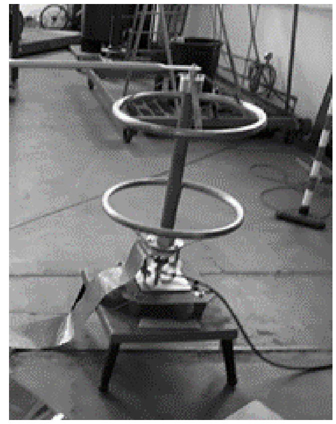

Fig. 1. SAGI 304 resistive divider.

Fig. 2. HAEFELY R600 damped capacitive divider

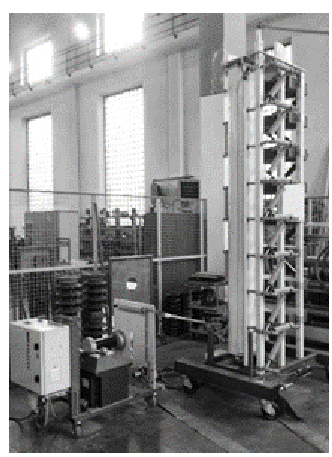

Fig. 3. HAEFELY SGSA 800/40 impulse generator.

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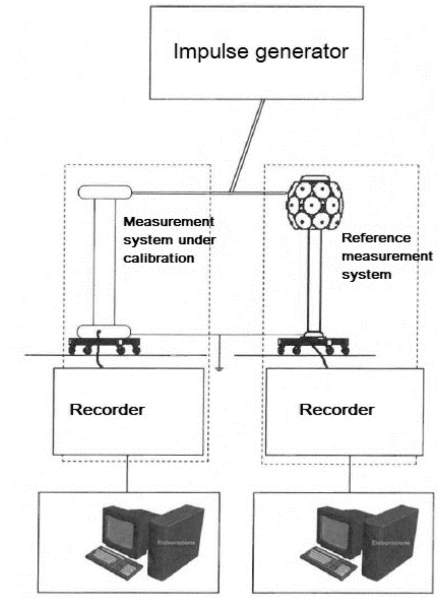

Fig. 4. Block scheme of the systems for LI voltages measurements at LATFC.

The calibration of a LI measurement system consists of the:

- Determination of the Scale factor (at a test voltage) and of its dynamic behavior by comparison with a reference measurement system, both submitted to the same waveform (Fig. 4);
- Determination of the time deviations of the time parameters between the two systems. The evaluation of these time parameters is carried out according to [14]. The analysis is performed on at least ten impulses for each voltage for the evaluation of the standard deviation of the measurements [15].

III. Convolution and Deconvolution method

A. Convolution Method

The convolution, as described in [14], is used to evaluate the dynamic behavior of a measurement system from the step response measurements. This method is outlined in the standard to assess the uncertainty contribution of the dynamic behavior of measurement systems for impulse voltages. The output waveform, calculated from a known input waveform and the step response of the measurement system, allows the evaluation of errors due to a non-ideal system. [14] gives the following equation for the convolution:

$$V_{out}(i) = \sum_{k=0}^{i} V'_{in}(k) \cdot g(i-k) \cdot \Delta t \quad i = 0,1,2,\dots,n-1 \qquad (1)$$

Where:

- $V_{out}(i)$ is the convolution output in the point i;
- $V'_{in}(k)$ is the input first derivative in the point k;
- $g(i)$ is the step response array;
- n is the number of samples of input array;
- Δt is the sampling interval.

B. Deconvolution Method

The deconvolution is the inverse of the convolution. The output of the deconvolution closely approximates the input waveform. The discrete form of the deconvolution was derived by inverting the (1) and analyzing the Fourier algorithm used in [4]:

$$V_{dec}(i) = \sum_{k=0}^{i} \frac{V'_{ac}(k)}{g(i-k)} \cdot \Delta t \quad i = 0,1,2,\dots,n-1 \qquad (2)$$

where:

- $V_{dec}(i)$ is the deconvolution output in the i point;
- $V'_{ac}(k)$ is the acquired waveform first derivative in k.

IV. Effects of the Deconvolution

The deconvolution helps to minimize undesired effects due to non-ideal behavior of a LI measurement system as in [8] where, by starting from an acquired waveform, the effects of a non-ideal measurement system are reduced. In our work, the deconvolution was applied to the INRiM measurements of the most demanding waveforms of the comparison [2] to assess whether our capabilities could be improved. To do this, the step responses measured during the comparison were analyzed. A discrete deconvolution method was applied as the sampling time of the input waveform and the step response were the same. Table 1 shows the INRiM results of U_t, (test voltage), of T_1 and of T_2 (rise time and time to the half-value of the impulse respectively) for [2] for the short positive impulses at 400 kV and 600 kV. Table 1 also includes the deconvoluted values obtained by applying eq. (2) and the mandatory algorithm of [1, Annex B], which is integrated into our software. The same procedure was applied for the deconvoluted values of Table 2.

TABLE 1
Deconvolution applied to the short P400 kV and P600 kV impulses

Short P400 (kV)	U_t (kV)	T_1 (µs)	T_2 (µs)
Comparison	408.31	0.850	42.15
Deconvolution	408.40	0.822	41.80
Deviation (%)	-0.013	1.887	0.487
Short P600 (kV)	U_t (kV)	T_1 (µs)	T_2 (µs)
Comparison	599.63	0.869	42.70
Deconvolution	599.70	0.841	42.36
Deviation (%)	-0.007	1.897	0.46

For both impulses, the first two rows show the INRiM results for the comparison and the same results after deconvolution, respectively. The third row reports the relative deviation between the first two data sets. The deconvolution mainly affects the time parameters by reducing their duration. Since the highest voltage variation (*dV*/*dt*) occurs on the rising edge of the waveform, the parasitic parameters of the divider have a higher impact on the measurements during this time. As a result, T_1 shows the highest deviation. This is observable in Table 1, where the deviation is higher for the Short P600 kV impulse than for the Short P400 kV one where *dV*/*dt* is lower. The deconvolution, has instead opposite effect on T_2 since the deconvolution, by modifying T_1, shifts the virtual origin (more

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when dV/dt is lower), from which T_2 is calculated. For this reason, T_2 measurements are not usually deconvoluted. The test voltage U_t remains instead approximately unchanged confirming the correctness of the deconvolution method for U_t as the used divider is suitable to measure these voltages. Table 2 shows the results of the applied deconvolution for the long positive impulse at 400 kV.

TABLE 2

DECONVOLUTION APPLIED TO THE LONG P400 kV

Long P400 (kV)	U_t (kV)	T_1 (µs)	T_2 (µs)
Comparison	400.17	1.585	43.97
Deconvolution	399.04	1.550	43.84
Deviation (%)	0.163	1.293	0.175

Also, for this waveform, T_1 has the largest deviation.

V. RECALCULATION OF THE COMPARISON

The same recalculation method of the comparison results up to 200 kV applied in [3], consisting in the updating the INRiM values and uncertainties for each result for [2], was used in the range 200 kV÷600 kV where the LATFC used the measurement system with the Haefely R600 divider. Tables 3 and 4 show in the second column the INRiM declared uncertainties for the comparison, while the following columns show the updated INRiM uncertainties of the measurements, with deconvolution in Table 3 and without deconvolution in Table 4, for more and less critical measurements, respectively. In both tables the expanded uncertainties are with a coverage factor k = 2 corresponding to a confidence level of 95 % [15]. In Table 3, the U_t uncertainties for voltages up to 400 kV and up to 600 kV are splitted. For more details concerning the new uncertainties of the time parameters, see Tables 9, 10.

TABLE 3

EXPANDED UNCERTAINTIES FOR THE COMPARISON AND NEW EXPANDED UNCERTAINTIES FOR MEASUREMENTS WITH DECONVOLUTION

Voltage range	Comparison	200 ÷ 400 kV short	400 ÷ 600 kV Short	200÷600 kV Long
Parameter	**Expanded uncertainties** (%)			
U_t	1	0.7	0.9	0.5
T_1	5		2	
T_2	5		1	

TABLE 4

EXPANDED UNCERTAINTIES FOR THE COMPARISON AND NEW EXPANDED ONES FOR MEASUREMENTS WITHOUT DECONVOLUTION

Voltage range	Comparison	200 ÷ 600 kV Short	200 ÷ 600 kV Long
Parameter	**Expanded uncertainties** (%)		
U_t	1	1	0.5
T_1	5		3
T_2	5		1

Tables 5-7 show the comparison results of U_t, T_1 and T_2 for the short P600 kV impulse (from the second to the fourth column) and the recalculated results after deconvolution (from the fifth to the eighth column). In these tables, the degree of equivalence (normalized error E_n) [15, 10. 4.3.2] was considered to assess the agreement of the results with the CRV. To assess also the comparison consistency, the χ^2 (chi-squared) test was evaluated. This test is satisfactory if Pr(χ^2) > 5% [2]. The short P600 kV impulse was the most challenging waveform for the INRiM measurement system due to the high voltage change within a short time period. The other participants to the comparison in the tables are anonymized. The CRV was determined considering the measurements of all the participants. The values are expressed as relative deviations (Δx_i) from the measurements of the transfer reference measurement system (TRMS)[1] along with the expanded uncertainties $U(\Delta x_i)$ of these deviations.

TABLE 5

U_t COMPARISON RESULTS FOR THE SHORT P600 kV IMPULSE BEFORE AND AFTER THE DECONVOLUTION OF THE INRiM MEASUREMENTS

	Comparison results			Recalculated with results deconvoluted		
Lab	Δx_i %	$U(\Delta x_i)$ %	E_n	Δx_i %	$U(\Delta x_i)$ %	E_n
INRiM	0.55	1.03	0.53	0.53	0.87	0.60
Others	0.16	0.56	0.29	0.15	0.56	0.27
	-0.26	0.56	-0.46	-0.27	0.56	-0.48
	-0.42	0.39	-1.09	-0.44	0.39	-1.11
	0.63	0.56	1.13	0.62	0.56	1.10
	CRV %	U(CRV) %	Pr (χ^2) %	CRV %	U(CRV)%	Pr χ^2) %
	0.30	0.28	6	0.32	0.27	5

TABLE 6

T_1 COMPARISON RESULTS FOR THE SHORT P600 kV IMPULSE BEFORE AND AFTER THE DECONVOLUTION OF THE INRiM MEASUREMENTS

	Comparison results			Recalculated with results deconvoluted		
Lab	Δx_i %	$U(\Delta x_i)$ %	E_n	Δx_i %	$U(\Delta x_i)$ %	E_n
INRiM	-3.83	5.19	-0.74	-0.62	2.44	-0.25
Others	–1.68	2.43	–0.69	-1.78	2.49	-0.72
	1.16	2.26	0.51	1.06	2.32	0.46
	2.56	2.45	1.04	2.46	2.50	0.98
	-1.35	2.77	–0.49	-1.45	2.82	-0.52
	CRV %	U(CRV) %	Pr (χ^2) %	CRV %	U(CRV) %	Pr (χ^2) %
	3.1	1.36	8	3.2	1.25	17

[1] The explanation of the TRMS role is given in the next paragraph.

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TABLE 7
T_2 COMPARISON RESULTS FOR THE SHORT P600 kV IMPULSE BEFORE AND AFTER THE DECONVOLUTION OF THE INRiM MEASUREMENTS

	Comparison results			Recalculated with results deconvoluted		
Lab	Δx_i %	$U(\Delta x_i)$ %	$\boldsymbol{E_n}$	Δx_i %	$U(\Delta x_i)$ %	$\boldsymbol{E_n}$
INRiM	0.62	5.28	0.12	1.16	1.99	0.58
Others	-0.59	1.96	-0.3	-0.86	2.01	-0.43
	0.34	1.91	0.18	0.08	1.97	0.04
	-0.49	1.76	-0.28	-0.76	1.82	-0.42
	0.89	2.26	0.39	0.62	2.30	0.27
	CRV %	U(CRV) %	Pr (χ^2) %	CRV %	U(CRV) %	Pr (χ^2) %
	-0.82	1.10	89	-0.55	1.00	65

Fig. 5 and 6 show respectively the results of T_1 in the comparison and the same results after the deconvolution of the INRiM measurements. The graphs show dT_1/T_1 calculated for each laboratory as percentage difference between the values of the measurement system of the laboratory and of the TRMS. From Tables 5÷7 and Fig. 5, 6, it can be observed that the INRiM measurements are always in agreement (compatible) with the CRV and with the other participants. After deconvolution and recalculation, the comparison consistency for T_1 is improved and E_n (degree of equivalence) of INRiM is lower than before which means that the result is more trustworthy. From Table 5, it can be also observed that, after deconvolution and recalculation of the INRiM measurements, the U_t results were mostly unchanged. This is because the INRiM divider used was suitable therefore the deconvolution and recalculation had a negligible effect on the U_t values. For T_1 the deconvolution improved the INRiM measurements bringing them closer to the CRV and to the results of the other participants. The measurements, uncertainties and the degrees of equivalence of the other laboratories were negligibly affected and all laboratories maintained the agreement with the CRV after both operations. Instead, the deconvolution and recalculation moved the T_2 INRiM measurements further from the new CRV (Table 7) and the degree of equivalence increased also for the uncertainty reduction. The agreement of the other participants was slightly affected, worsening in some cases and improving in others. This is because only five laboratories performed these measurements, thus the insertion of the new INRiM measurements and uncertainties had a higher impact, which, coincidentally, slightly worsened the INRiM results. In addition, as said, in par. IV, the deconvolution has opposite effects on T_2 shifting the virtual origin from which T_2 is calculated. Nevertheless, all participants maintained fully the agreement with the CRV for T_2 after deconvolution and recalculation.

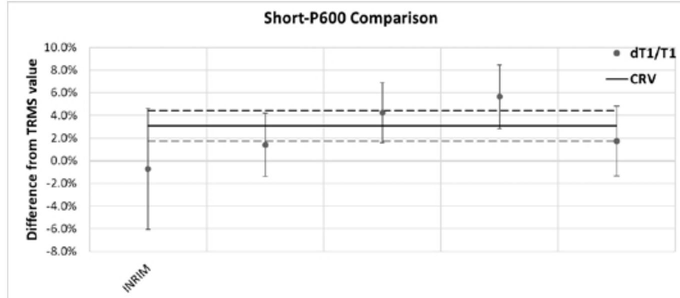

Fig. 5 T_1 comparison results for the short impulse at 600 kV. The bars correspond to the relative expanded uncertainties.

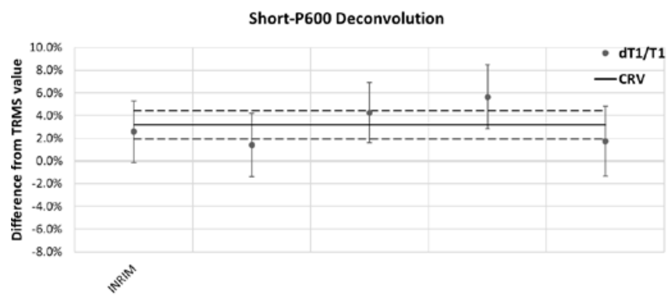

Fig. 6. T_1 comparison results for the short impulse at 600 kV after the deconvolution and the recalculation with the new uncertainties.

Also the consistency of the comparison for the short impulse at 600 kV after deconvolution and recalculation for U_t and T_2 is maintained (Tables 5, 7). The same considerations apply for the other waveforms. The results are available at https://zenodo.org/records/10926139.

VI. INSIGHTS ON THE NEW UNCERTAINTIES

The reliability of the new uncertainties is enforced by analyzing the deviations of the deconvoluted values from the corresponding CRVs shown for the two most critical waveforms. These deviations can be considered as measurement uncertainties (type B rectangular distribution [15]) of the deconvoluted INRiM measurements at a 2σ confidence level. Applying a restrictive criterion, these deviations were compared (Table 8) with the new INRiM uncertainties at the same confidence level reported in Table 1. All of them were within the new INRiM uncertainties except only for T_2 for the Short P600 kV impulse for the reasons given in the previous paragraph. Anyway, the deviation from the CRV of the INRiM T_2 measurement for this impulse remains well within the uncertainty $U(\Delta x_i)$ of this deviation (Table 7). This analysis can represent an additional validation of both the new uncertainties of the INRiM deconvoluted measurements and of the discrete application of the deconvolution.

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TABLE 8
COMPARISON BETWEEN THE DEVIATION OF THE RESULTS WITH DECONVOLUTION FROM THE CRV AND THE NEW EXPANDED UNCERTAINTIES FOR THE SHORT P600 kV AND P400 kV IMPULSES

Impulse	Parameter	Δx_i %	New expanded uncertainties %
Short P600 kV	U_t	0.53	0.9
	T_1	-0.62	2
	T_2	1.16	1
Short P400 kV	U_t	-0.013	0.9
	T_1	1.887	2
	T_2	0.487	1

Tables 9 and 10 report the uncertainty components at $k = 1$, [15], of the measurements of U_t, T_1 and T_2 of the INRiM system for short time impulses, with and without deconvolution respectively from 200 kV to 600 kV.

TABLE 9
NEW UNCERTAINTIES COMPONENTS FOR U_t, T_1 AND T_2 FOR THE SHORT TIME IMPULSES WITH DECONVOLUTION

Component	$u(U_t)$ %	$u(T_1)$ %	$u(T_2)$ %
Scale factor	0.22	0.44	0.22
Linearity	0.25	0.15	0.15
Dynamic behavior[2]	0.15	0.75	0.35
Short time stability	0.15	0.15	0.15
Long-time stability	0.20	0.2	0.2
Temperature effect (10 °C)	0.08	0.16	0.16
Proximity effect	0	0	0
Software	0.02	0.43	0.08
RSS	**0.45**	**1.0**	**0.5**

At k =2 the uncertainties of the three parameters are therefore $U(U_t)$ = 0.9 %, $U(T_1)$ = 2 % and $U(T_2)$ = 1 % respectively.

TABLE 10
NEW UNCERTAINTY COMPONENTS FOR U_t, T_1 AND T_2 FOR THE SHORT TIME IMPULSES WITHOUT DECONVOLUTION

Component	$u(U_t)$ %	$u(T_1)$ %	$u(T_2)$ %
Scale factor	0.22	0.44	0.22
Linearity	0.30	0.15	0.15
Dynamic behavior	0.20	1.3	0.35
Short time stability	0.15	0.15	0.15
Long-time stability	0.20	0.2	0.2
Temperature effect (10 °C)	0.08	0.16	0.16
Proximity effect	0	0	0
Software	0.02	0.43	0.08
RSS	**0.5**	**1.5**	**0.5**

Again, at k =2, the uncertainties of the three parameters are respectively $U(U_t)$ = 1.0%, $U(T_1)$ = 3 % and $U(T_2)$ = 1.0 %. The uncertainties in Tables 9 replace those declared by INRiM for [2], Annex D. In that case, the uncertainty components were based on the previous calibration measurement capabilities (CMCs). The proposal for the uncertainty reduction was mainly due to the further characterization of the INRiM LI measurement system with the R600 divider, using a higher-voltage step generator (up to 1 kV output voltage), improving the measurement resolution beyond the tens of millivolts level due to the large scale factor of the entire conversion system which exceeds 60000.The analysis of the new data provided a deeper understanding of the divider behavior showing that the step response data were suitable for deconvolution. The inverted unit-step response $g(t)$ of the acquired data is shown in Fig. 7, while the processed data in the form of the step response integral $T(t)$, as required by [14], are shown in Fig. 8. In this figure, the last point of contact of the curve with either tangent is the settling time of the divider in response to the impulse. This is the time it takes for the divider's response to stabilize with the input signal. Table 11 shows the results of the step response of the INRiM system for LI measurements.

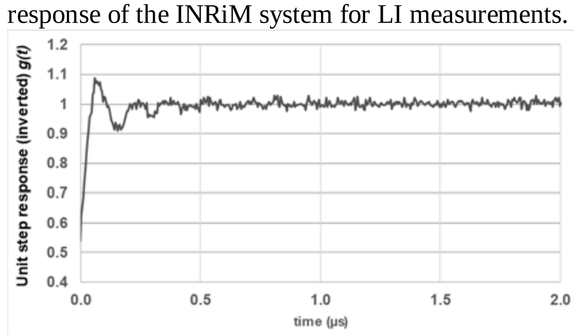

Fig. 7. Unit step response (inverted) $g(t)$ with the 1 kV step generator.

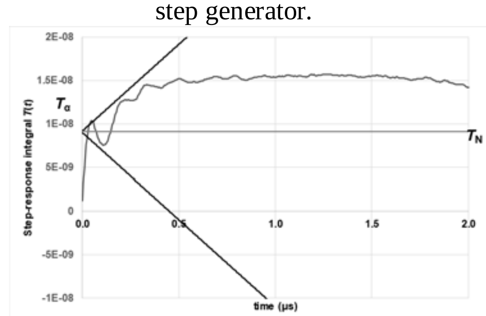

Fig. 8. Step-response integral $T(t)$.

TABLE 11
STEP RESPONSE PARAMETERS FOR FULL LI REFERENCE MEASURING SYSTEMS

	INRiM with R600	RECOMMENDED
Experimental response T_N	7.9 ns	≤ 15 ns
Settling time t_s	75 ns	≤ 200 ns
Partial response T_α	15 ns	≤ 30 ns

[2] Although the deconvolution introduces its own uncertainty component, as it minimizes the error due to the dynamic behavior of the measurement system, this component is negligible with respect to the overall uncertainty of the dynamic behaviour of the entire measurement system.

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T_N, T_α, and t_s are defined in [14, c.2.5,6,9]. The values of Table 11 demonstrate that the INRiM system with the R600 divider complies with the standard recommendations of [14, 10.4] for the response and settling times of a reference measurement system. This means that the system responds quickly enough to accurately capture the behavior of the measured impulse and settle to the correct value without introducing any drift. As a result, the behavior of the divider does not significantly affect the measurement of the impulse voltage during calibrations. The fulfilment of these recommended parameters can further justify the uncertainty reduction at the same level of the INRiM system for LI voltages up to 200 kV. While for [2], the uncertainty component due to the Scale factor of the reference system was the same for T_1 and T_2, in Tables 9, 10 this value for T_2 is lower. This is due to the new step response characterization with which it was observed that, around T_2, the INRiM system with the R600 divider reaches a satisfactory stabilization, and the voltage of the input waveform decreases smoothly. Instead, since T_1 is much shorter and corresponds to the time when the input waveform rises rapidly, the measurement system may not be fully stabilized, which could affect the reliability of the T_1 measurement. Table 12 reports the relevant uncertainty components of U_t of the system when submitted to the deconvolution for long impulses.

TABLE 12
COMPONENTS OF THE NEW UNCERTAINTIES OF U_t FOR LONG TIME IMPULSES

Component	$u(U_t)$ %
Scale factor	0.11
Linearity	0.10
Dynamic behavior	0.10
Short time stability	0.10
Long-time stability	0.10
Temperature effect (10 °C)	0.08
Proximity effect	0
Software	0.02
RSS	**0.25**

At k =2, the expanded uncertainty of U_t is $U(U_t)$ = 0.5 %.

The uncertainties in Table 12 consider that, for long-time impulses, the measurement system is fully responsive to the input waveform. This allows a reduction of the uncertainty components compared to those for short-time impulses. Tables 13 and 14 show the recalculated results without deconvolution of the INRiM measurements for T_1 for the Short P400 kV impulse (representing all the short impulses) and for the Long P600 kV impulse (representing all the long impulses). The χ^2 test values are also given. Analyzing these tables, it can be concluded that the new uncertainties are consistent as the recalculation gave a satisfactory agreement of the INRiM measurements with the CRV with no participant at [2] being incompatible with the CRV. The results of T_2 and U_t without deconvolution are reported in the repository. These results also confirm the agreement with the CRV of the INRiM measurements with the claimed uncertainties with no impact on the other participants.

TABLE 13
COMPARISON RECALCULATION INTRODUCING THE INRiM T_1 RESULTS WITHOUT DECONVOLUTION FOR THE SHORT P400 kV IMPULSE

Lab	Δx_i %	$U(\Delta x_i)$ %	E_n
INRiM	-3.01	3.35	-0.90[3]
Others	-0.90	2.54	-0.36
	0.86	2.39	0.36
	3.01	2.56	1.18
	-0.05	2.17	-0.03
	-1.09	2.54	-0.43
CRV %	U(**CRV**) %	**Pr**(χ^2) %	
2.36	1.13	11	

TABLE 14
COMPARISON RECALCULATION INTRODUCING THE INRiM T_1 RESULTS WITHOUT DECONVOLUTION FOR THE LONG P600 kV IMPULSE

Lab	Δx_i %	$U(\Delta x_i)$ %	E_n
INRiM	–1.48	2.89	-0.51
Others	-0.13	1.95	-0.07
	0.53	1.89	0.28
	-1.10	1.89	-0.58
	0.70	1.76	0.40
	3.17	1.23	2.57
	-0.88	2.74	-0.32
	0.68	1.90	0.36
	-0.26	2.31	-0.11
CRV %	U(**CRV** %	**Pr**(χ^2) %	
0.84	0.91	66	

VII. CONCLUSION

The results submitted by INRiM to the EURAMET.EM-S42 comparison were consistent with the CRV and whit those of the other participants but with higher uncertainties. Following a more in-depth analysis of the dynamic behavior of the reference measurement systems for LI measurements of the LATFC, smaller uncertainties for the INRiM measurements in the comparison were proposed. The aim of the present work was, in fact, to reduce the uncertainties and verify if, with reduced uncertainties, the agreement with the CRV was maintained. The INRiM measurements of critical waveforms were subjected to deconvolution and the measurements of the comparison were then recalculated introducing the new uncertainties. These two

[3] Although for the comparison [2], a satisfactory agreement with the CRV was considered up to E_n =1.5, also this not fully satisfactory result, led us to the improvement of the measurement by means of the deconvolution.

operations maintained the INRiM measurements in agreement with the CRV with a minimal impact on the equivalence of the other participants, all of which maintained the agreement with the CRV. Therefore, the INRiM revised uncertainties can be supported by the EURAMET.EM-S42 comparison. Although the deconvolution allows for a more accurate reconstruction of input LI waveforms from the output, it requires advanced computational skills and additional time during calibrations due to the deconvolution process itself. For this reason and according to the required uncertainties of our calibration activities, also the measurements without deconvolution were recalculated to verify their agreement with the CRV. The results were acceptable (improvable with deconvolution only for the most demanding waveforms) justifying the improvements of both uncertainties and system capabilities.

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