Reference calibrator for combined and composite high voltage impulse tests

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REFERENCE CALIBRATOR FOR COMBINED AND COMPOSITE HIGH VOLTAGE IMPULSE TESTS

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Abstract

This paper describes the design and characterization of a reference calibrator, able to generate any type of reference wave shape, such as AC, DC, LI, SI, combined, or composite, up to 900 V. This reference calibrator has been developed at the French National Metrology Institute (LNE), using a novel approach, based on a linear high voltage amplifier. For combined and composite wave shapes, there are no reference or commercial calibrators available on the market nor at National Metrology Institutes. This reference calibrator will enable required calibration capabilities to be created to accurately determine the uncertainty in the calibration of combined and composite wave shapes, and fulfil the requirements of the IEC 61083-1 standard. Further experiments have been performed in order to evaluate the calibrator performances, for impulses as fast as LI, as slow as SI, and combined and composite wave shapes, during which LI or SI are superimposed on AC or DC voltages. Furthermore, two methods have been proposed to demonstrate the calibrator traceability to the international system of units, up to 900 V. This study will contribute to the preparation of voltage testing standardization with combined and composite wave shapes for the forthcoming revision of the IEC 61083-1 standard.

1 Introduction

As the use of high voltage applications rise in the area of electricity grids, and given the importance of having reliable electricity grids able to support renewable energy sources, there is an urgent need for adequate grid components testing to ensure their ability to withstand the instantaneous electrical surge that can occur in service and continue to operate reliably. Damage from the high voltage impulse can result in the power grid experiencing a partial failure or blackout, leading to dissatisfied consumers and potentially high repair costs. Therefore, metrological traceability in grid components testing and calibration is required for electrical power industry and high voltage instrument manufacturers to test the performances of their components, such as transformers, circuit breakers, high voltage cables, gas insulated systems, surge arrestors, isolators, switchgear, etc. The typical tests on electricity grid systems, as described in [2], [4], and [5], include the combined and composite voltage tests, during which lightning impulse (LI) or switching impulse (SI) are superimposed on the High Voltage Alternating Current (HVAC) or High Voltage Direct Current (HVDC). The superposition of these wave shapes is carried out by two separate generating circuits using blocking elements, such as a spark gap or a coupling capacitor [2] [3] [6]. Depending on these blocking elements, the stress on the equipment under test and the generating components can differ. However, at present, there are inadequate traceable measurement systems that can be directly attached to the equipment under combined and composite high voltage impulse tests, and no scientific evidence and sufficient technical understanding of the circuits interference in combined and composite wave shapes, which may result in unreliable test results.

The wave shapes evaluation on high voltage tests is performed with approved measurements systems by accredited institutes and test laboratories. The current IEC 60060 series [2] [3] allow the voltage dividers and measuring systems, that are used in test laboratories, to be qualified by separate calibrations of AC, DC, LI, and SI voltages. However, these separate calibrations do not provide evidence for the ability of such voltage dividers and measuring systems to measure correctly combined and composite wave shapes. In addition, the IEC 61083-1 [1] standard allows low voltage measuring instruments to be qualified by comparison to approved reference calibrators traceable to the international system of units. However, commercial and reference calibrators available on the market and at National Metrology Institutes (NMI) generate only separate AC, DC, LI, and SI voltages, with a separate block for each wave shape type. Indeed, in the case of impulse voltages, there are different types of generators, such as analog impulse voltage sources that can generate a resonance circuit with the help of changeable capacitors and resistors, and calculable impulse generators that can generate a calculable impulse curve considering the input impedance of the digitizers and resistive and capacitive elements measured beforehand. Currently, the IEC 61083-1 [1] standard is not applicable to those digital recording instruments used for the evaluation of combined and composite voltage tests, as there are no reference or commercial calibrators available on the market nor at National Metrology Institutes for those wave shapes.

Driven by the increasing demands on traceable reference calibrators and calibration services, being able to fully cover the required needs, the French National Metrology Institute (LNE) has studied a novel approach, based on linear high voltage amplifiers, to develop a reference calibrator to be used for generating in only one block any kind of wave shapes below 1 kV at full scale, in particular, those closely identical to the typical waveforms measured at the equipment under combined and composite high voltage tests. This study will enable required measurements to be performed for the preparation of the standardization of high voltage impulse testing with combined and composite wave shapes for the forthcoming revision of the IEC 61083-1 [1] standard in the IEC TC42 (High-voltage and high-current test techniques). In addition, the traceability demonstration to the international system of units of the designed reference calibrator will enable required calibration capabilities to be created for low voltage measuring instruments and attenuators used to acquire combined and composite wave shapes. This will lead to new CMCs statements being recorded in the BIPM Key Comparison Database (KCDB) and new services to be created in the branch “High voltage and current”. The European Metrology Programme for Innovation and Research (EMRP) supports this work through the normative Joint Research Project 19NRM07 HV-com², which started in 2020 and has received funding from the EMPR co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme [8].

2 Reference calibrator performances

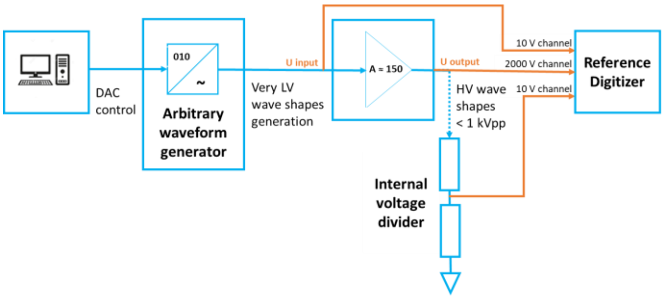

Fig. 1. Reference calibrator structure

The designed reference calibrator, described in figure 1, is mainly based on a linear high voltage amplifier that allows increasing inputs voltages to higher voltage levels. This linear high voltage amplifier, which the specifications are specified in table 1, was chosen for its excellent properties, such as a wide bandwidth, stable operation, a high gain of about 150, a fast slew rate of about 3.4 kV/µs at 20 pF, a stable output voltage with lower noise, which is suitable for generating the required wave shapes, as fast as LI with very short front times lower than one microsecond, as slow as SI, AC, DC, and combined or composite wave shapes. The maximum output voltage of the high voltage amplifier is about 900 Vpp. Therefore, it is restricted by the voltage at its input that should not exceed 6 Vpp over 50 Ω load. Moreover, the reference calibrator is equipped with an internal voltage divider, with a gain of about 1500 into 1 MΩ load and 150 into 50 Ω load, and suitable for use to demonstrate the reference calibrator traceability to the international system of units up to 900 V. The reference calibrator circuit shown in figure 2 involves the linear high voltage amplifier (a) associated with the internal voltage divider (b).

Table 1. Linear high voltage amplifier specifications

Parameter	Level
Output voltage	+/- 450 V
Output current	+/- 170 mA
Bandwidth (3 dB)	DC to 500 kHz at 20 pF DC to 300 kHz at 100 pF
Gain	150
Input	1 MΩ or 50 Ω load
Slew rate	3.4 kV/µs at 20 pF
Output offset	0.25 mV DC
HV monitor	1:10 voltage divider into 50 Ω load and 1500 into 1 MΩ load
Ambient conditions	Temperature 20-30°C, Humidity 70%

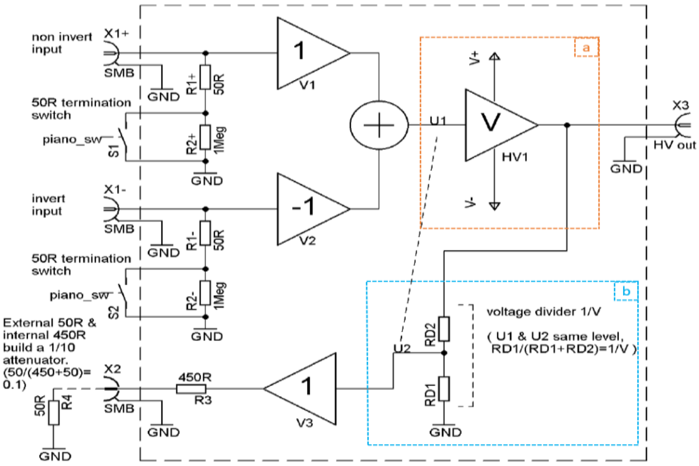

Fig. 2. (a) Linear high voltage amplifier circuit, (b) Internal voltage divider circuit

The reference calibrator performances have been investigated regarding the accuracy for both amplitude and time parameters, in particular, the output voltage stability, self-heating, output offset, and high frequency ripples. Further experiments have been performed to ensure the reference calibrator traceability up to 900 V. In addition, using a software, low voltage wave shapes have been simulated using an arbitrary waveform generator (sample rate up to 160 MS/s, vertical resolution of 16 bits, bandwidth of 20 MHz which is enough to generate properly fast rise time impulses), consisting of a high-speed digital-to-analog converter (DAC), and used to convert the numerical reference data to standard and arbitrary signals which the voltage levels are adapted to the high voltage amplifier input. From figure 1, the used arbitrary waveform generator is linked to the high voltage amplifier input of the reference calibrator with an adapter cable of 1 m (BNC - SMB over 50 Ω load). Using this technic, any type of wave shape can be simulated and amplified to higher voltages up to the maximum output voltage of the high voltage amplifier. Examples of low voltage wave shapes that can be measured at the reference calibrator output are shown in figures 3 and 4.

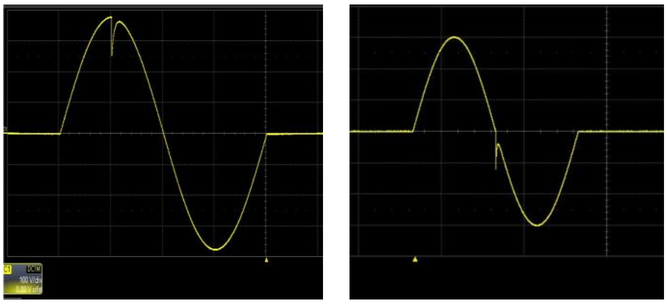
Fig. 3. Example of a LI superimposed with an AC voltage

In the case of a superposition of an AC voltage with LI, as shown in figure 3, this causes the occurrence of a drop voltage when the superimposition has to be at the peak value of the AC voltage. This wave shape has been simulated and measured at the reference calibrator output, while changing the position of LI on the AC signal whatever the polarity, and also varying the time delay (Δt) between the instant when AC and LI reach their maximum values. More details about combined and composite wave shapes definitions and evaluation routines are described in [2], [3], and [6]. Furthermore, it is planned to adapt the chapter structure in the current standards by developing standardized parameters and adequate evaluation routines for the combined and composite wave shapes. Subsequently, the revised standards will serve as a basis for the revision of the IEC 61083-1 [1] standard.

Fig. 4. Example of a 900 V LI superimposed on a - 450 V DC

In figure 4, the wave shape on the left side corresponds to the voltage at the high voltage amplifier input and the amplified wave shape on the right side corresponds to the voltage at the high voltage amplifier output. As the reference calibrator slew rate is very fast, of about 3.4 kV/µs, calculated from step response measurements at 900 V, this curve of a 900 V LI superimposed on a - 450 V DC voltage proves that the amplified wave shape follows the input wave shape and does not present any deformation even if the impulse voltage with a very short front time is as high as 900 Vpp.

The characterization of the output voltage stability is crucial in order to qualify the reference calibrator as a reference. Therefore, short-term stability has been tested for impulses up to 900 Vpp, and voltage levels up to 700 V in the frequency range from DC to 10 kHz. For impulse voltages up to 900 Vpp, each voltage level has been evaluated by averaging 10 impulses. The results for LI and SI measurements are summarized respectively for Vc, T1, and T2, in figures 5, 6, and 7. The maximal standard deviation obtained for LI measurements is about 0.13% for Vc, 0.9% for T1, and 0.3% for T2. For SI measurements, the maximal standard deviation obtained is about 0.03% for Vc, 0.2% for T1, and 0.14% for T2. The important standard deviations seen at 50 Vpp are explained by the presence of an offset value and high frequency ripples at the reference calibrator output, of about - 0.25 mV DC, but has no major influence on the measurement from 100 Vpp to 900 Vpp. The only difficulty is to find a way to compensate this offset value, which may be performed using the DAC to download programmed waveforms with compensated offset value into the arbitrary waveform generator.

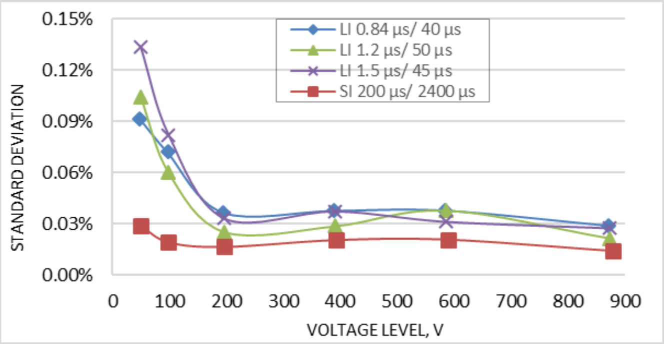

Fig. 5. Output voltage stability of 10 impulses for Vc

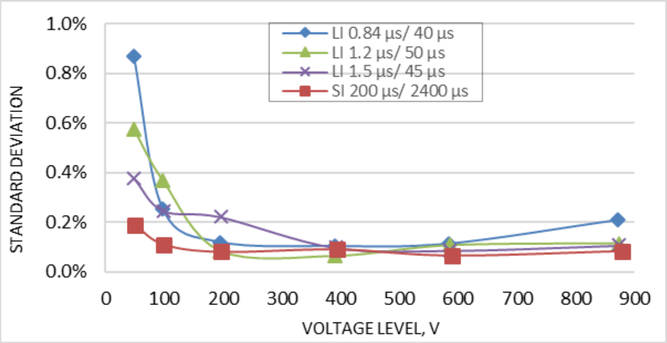

Fig. 6. Output voltage stability of 10 impulses for T1

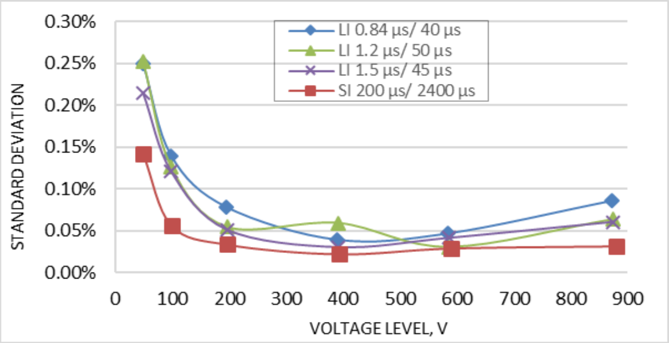

Fig. 7. Output voltage stability of 10 impulses for T2

For the frequency range from DC to 10 kHz at 250 V, the output voltage stability of the reference calibrator has been tested over a time period of 2 hours of voltage application for temperature and self-heating drifting testings, as shown in figure 8. By stabilizing the DC voltage over 2 hours of voltage application, the temperature of the internal components of the reference calibrator increased due to the flow of current, as shown in figure 9.

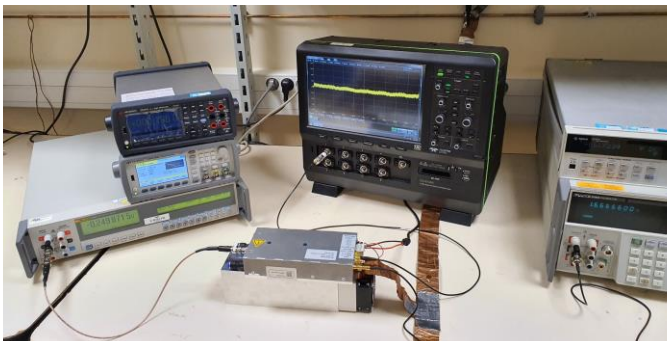

Fig. 8. Experimental set up for DC measurements to characterize the calibrator output stability at LNE

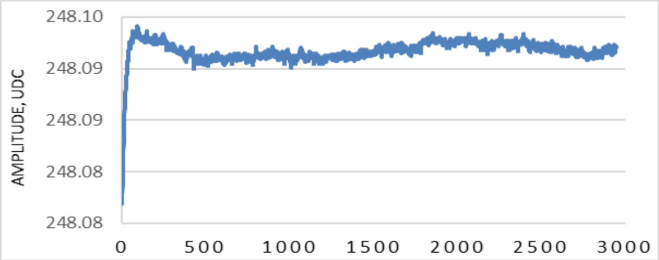

Fig. 9. Output voltage for 250 VDC over 2 hours of voltage application

The curve described in figure 9 shows that the output voltage stability obtained for DC at 250 V is better than 0.01% over a time period of 2 hours application. However, after a stabilization time of 10 minutes, this voltage stability is better than 20 ppm. Furthermore, it is applicable not only for power frequencies but also for frequencies up to 10 kHz. Thus, the associated voltage stability obtained over a time period of 2 hours application does not exceed 0.01%.

The output stability of the reference calibrator has not yet been tested over the long term. Normally, it will be checked every year to observe the possible deviations due to the reference calibrator self-heating. In addition, the characterization in temperature of the reference calibrator has not yet been performed but the calibrator is equipped with an adequate cooling system, what avoids the deterioration of the internal components through overheating, by keeping the temperature lower than 28 °C. The temperature effect is considered negligible so far, therefore, there is no need to apply corrections.

The major drawback of the voltage amplifiers concerns their output offset and high frequency ripples. The output offset value, of about - 0.25 mV DC, has been measured over several hours, and it seems that the maximal fluctuation of the value is slight. In addition, the frequency of the ripples is in the range of tens of MHz. Normally, this measured offset value and high frequency ripples have no major influence on the measurement of voltage levels between 100 V and 900 V. For the compensation of the output offset value of the high voltage amplifier, a DAC program will be improved and used as a practical solution to obtain the output offset value at the initial zero point. Unfortunately, no solution has been found so far for the ripples compensation. The performances of the reference calibrator have been tested and the results of this study are considered at least equivalent of what can be achieved with those traditional calibrators excising in the market. The designed reference calibrator has better features and a good output voltage stability, since the front time of the wave shapes do not present any deformation or oscillations even if the voltage levels are as high as 900 Vpp, thanks to the internal filtration of the high voltage amplifier.

3 Traceability and uncertainty

In order to demonstrate the traceability of the designed reference calibrator to the international system of units, several methods have been studied, among which, two methods have been selected and are described in this paper. The two considered methods are the calibration of the gain and internal voltage divider of the reference calibrator. The principle is to measure the input and output voltages using a reference digitizer. In this case, the influence of the load impedance has to be evaluated. In this study, it was demonstrated that an impedance of 1 MΩ ± 2 % and a load smaller than 100 pF is necessary to avoid any distortion caused by the load impedance.

3.1 Gain calibration

The gain has been determined for voltage levels up to 900 V using a reference digitizer (sample rate up to 200 MS/s, 14 bit, bandwidth DC to 70 MHz, two channels with 24 ranges each one for voltage measurements up to 2000 V) mainly used for LI and SI measurements and has been fully calibrated and validated at LNE by comparison to a standard high voltage peak detector for the peak voltage determination [7], according to the IEC 61083-1 [1] standard, for all typical waveforms such as lightning impulses, chopped impulses, oscillating impulses, switching impulses, rectangular impulses, etc.

Based on the hardware set up in figure 1, the high voltage amplifier input is connected to a 10 V channel of the reference digitizer, while the 2000 V second channel is dedicated to the measurement of the high voltage amplifier output. Both digitizer channels have an input impedance of about (1 MΩ ± 0.01%) in parallel with a capacitance of about (20 ± 0.4) pF. The coaxial cable used to connect the high voltage amplifier output to the reference digitizer has low capacitance of 50 pF. Before performing the measurements, both channels of the reference digitizer have been characterized using a step response followed by the convolution technique application.

The gain characterization has been performed for three types of LI (0.84 µs/ 40 µs, 1.2 µs/ 50 µs, and 1.5 µs/ 45 µs), and one type of SI (200 µs/ 2400 µs), and led to the results of figure 10, which corresponds to the ratio between the peak voltages of the high voltage amplifier output and input, for voltage levels from 50 V to 900 V.

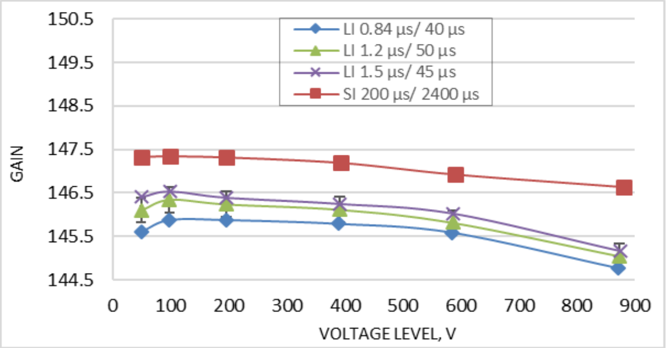

Fig. 10. Gain between the output and input voltages

Table 2. Voltage and frequency coefficients determination

Vpp	DC	60 Hz	1 kHz	10 kHz	50 kHz
70	148.15	147.69	147.38	147.43	146.81
280	148.56	147.65	147.32	147.36	146.89
560	148.80	147.46	147.06	147.11	146.74
707	148.87	147.35	146.90	146.96	146.60
Mean	148.59	147.54	147.17	147.21	146.76
Std	0.5%	0.2%	0.3%	0.3%	0.2%

The results of figure 10 clearly show that the gain decreases when the speed and voltage of the impulses increase. These results are in accordance with the results obtained with AC measurements for different frequencies as shown in table 2. Indeed, the gain has also been determined for AC voltages up to 707 Vpp and frequencies up to 50 kHz, and the output and input voltages have been measured by two reference voltmeters in RMS mode (load impedance is quite different for AC measurement and less than 150 pF). The results of table 2 confirm that the gain decreases when the frequencies and voltages of the impulses increase, except for DC measurements, which can be explained by the presence of a negative offset leading to the gain increase against voltage. The gain linearity shown in both figure 10 and table 2 allows the use of accurate corrections for each waveform depending on the speed of the impulses or the frequency components. Whereas for the time parameters evaluation of the impulses, the deformation introduced by the high voltage amplifier shown between the time parameters of its output and input has been determined and the results obtained for the front time and time to half value are presented in figures 11 and 12.

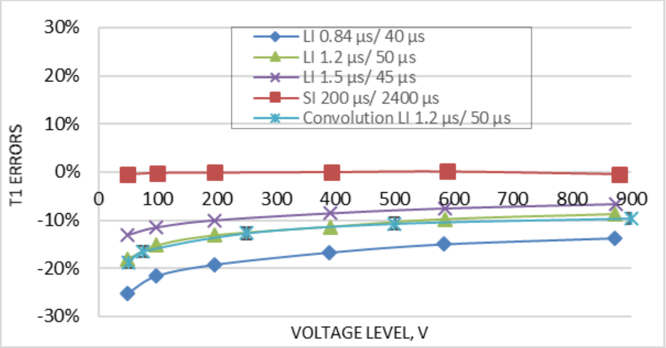

Fig. 11. Front time (T1) errors between output voltages and input voltages

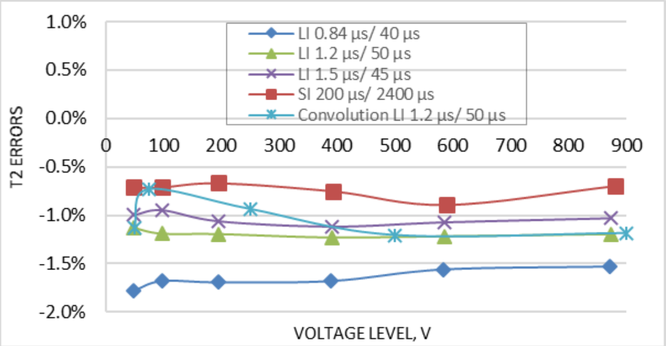

Fig. 12. Time to half (T2) errors between output voltages and input voltages

The front time (T1) errors obtained especially for fast impulses are significant, up to 25%, as shown in figure 11. The faster the impulses and the larger the errors. Additionally, the errors are more visible for lower voltages due to the output offset and frequency of the ripples that affect the conventional zero of the impulse and, in particular, the time at 30% of Vc. Even if the offset is considered too small, it will produce big errors at high frequency. For the SI front time errors, there are no significant errors between the output and input impulses (the errors are less than 1%). Similar observations apply to time to half (T2). The faster the impulses and the larger the errors. These errors are also due to the output offset and frequency of the ripples. Therefore, in order to evaluate the reference calibrator behaviour, complementary tests have been performed to determine time parameters errors of the LI using an ideal step voltage of a rise time of a few ns, followed with the convolution technique application, according to the requirements of the IEC 60060 standard [2] Annexe D. The aim of using this convolution technique is to correct the time parameters errors of any type of impulse wave shape introduced directly by the reference calibrator while taking into consideration the reference digitizer corrections. In addition, the results obtained with the convolution technique for LI measurements are promising. Complementary traceability could the verified using the internal voltage divider of the reference calibrator.

3.2 Internal voltage divider calibration

Following the same procedure for the gain determination, the hardware set up described in figure 1 has been used to determine the scale factor and time parameters errors of the internal voltage divider for three types of LI (0.84 µs/ 40 µs, 1.2 µs/ 50 µs, and 1.5 µs/ 45 µs) and one type of SI (200 µs/ 2400 µs) for output voltages up to 900 V. The reference calibrator output voltage is acquired by a 2000 V channel of the reference digitizer and the internal voltage divider output is acquired by a second 10 V channel. The nominal scale factor of the internal divider is about 1500 into 1 MΩ load (150 into 50 Ω load). The results regarding the internal voltage divider linearity for LI and SI measurements are summarized respectively in figures 13, 14, and 15. From figure 13, the obtained scale factor shows a slight impact of the offset voltage at low voltages (of about 0.3% from 50 V to 100 V and less than 0.4% from 100 V to 900 V). It is also noted that the scale factor decreases with fast impulses but very slightly (less than 0.1% from T1=1.2 µs to T1=0,84 µs).

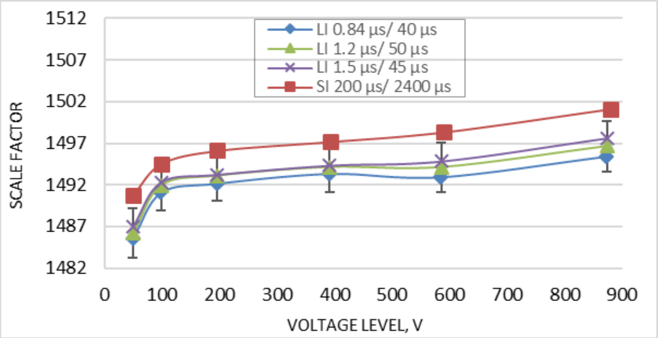

Fig. 13. Internal divider characterization for scale factor

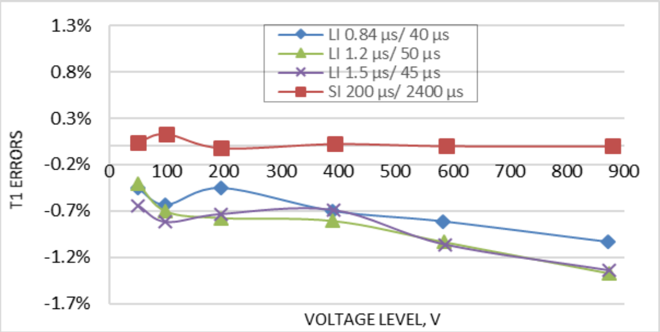

Fig. 14. Internal divider characterization for T1

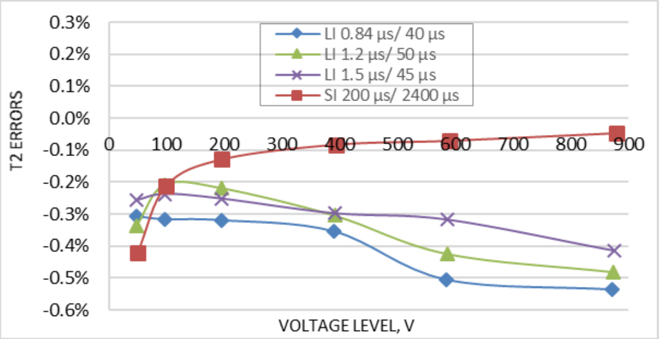

Fig. 15. Internal divider characterization for T2

From figures 14 and 15, the results of the time parameters for both LI and SI measurements have shown reasonable errors. For T1 they are less than 0.2% for SI and less than 1.5% for LI. For T2, they are less than 1.7%.

3.3 Uncertainty

According to this study, the uncertainty regarding the results of the reference calibrator characterization up to 900 Vpp have been estimated according to the GUM [9]. The uncertainty, as specified in table 3, are lower than 0.2 % for the peak voltage and lower than 1 % for the time parameters.

Table 3. Uncertainty for the reference calibrator (k=2)

Wave shape 100 V – 900 V	Peak voltage	Front time or time to peak	Time to half value
0.84 µs/ 40 µs	≈ 0.2%	< 1%	< 0.5%
1.2 µs/ 50 µs			< 0.5%
1.5 µs/ 45 µs			< 0.5%
200 µs/ 2400 µs			< 1%

4 Conclusion

The paper provides detailed insight into the design of a reference calibrator, based on a linear high voltage amplifier, to be used for generating, in only one block, any kind of reference wave shape in order to calibrate low voltage measuring instruments. This technic is relatively cheap and easy to develop. Based on it, the reference calibrator can reach high metrological performances at least equivalent to what can be achieved with the traditional calibrators excising in the market and will certainly reveal a great interest in fields where low voltage measurement systems are used to acquire impulses. Outcomes of this study will enable required calibration capabilities to be created and will contribute to the preparation of high voltage impulse testing standardization with combined and composite wave shapes for the forthcoming revision of the IEC 61083-1 standard in the IEC TC42 (High-voltage and high-current test techniques).

Future studies will consist of comparing this reference calibrator to others currently under development at National Metrology Institutes involved in the project. One of the proposals is based on the series arrangements of two sources (AC/DC calibrator and impulses calibrator), and another proposal is based on the parallel arrangements of two sources (AC/DC calibrator and impulses calibrator) using blocking elements.

5 Acknowledgements

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