The Usage of High Voltage Amplifiers to Set up Reference Calibrators for Combined and Impulse Voltages up to 1 kV.

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Abstract

An approach to set up reference calibrators to generate combined voltages, using voltage amplifiers, has been demonstrated. Four high voltage amplifiers were tested and studied. Measurements and experiments have shown that this approach could be used to set up calibrators for combined voltages, at least up to 1 kV. The advantage is the flexibility to generate separate or combined wave shapes (combination of AC, DC, distorted shapes, double exponential impulses such as lightening and switching impulses). This method could be beneficial to the fields where impulses, combined or not with DC or AC voltages, need a reference calibrator to calibrate digitizers. This method, relatively cheaper and simple to develop, reaches high metrological performance. For example, for lightning impulses up to 900 V, the uncertainties are lower than 0.2 % for the peak voltage, 1 % for the front time and 0.5 % for the time to half value . The traceability to the international system of units can be ensured by characterizing the gain using a step response, followed by the convolution technique.

1. Introduction

The apparatus designed to be installed on medium and High Voltage (HV) electrical grids should be tested to verify its performance under faulty conditions according to IEC 60060-1 [1] and IEC 60060-2 [2]. Some examples include: Lightening Impulses (LI) ranging from 0.84/40 µs to 1.56/60 µs, Switching Impulses (SI) ranging from 20/1000 µs to 300/ 4000 µs, current impulses ranging from 8/20 µs to 10/350 µs and combined waveforms (DC or AC combined with LI and SI). During routine calibrations, impulses are applied to the test object and measured at the same time with reference dividers (or reference current sensors). The output voltage is transmitted across a coaxial cable towards a Low Voltage Measuring Instrument (LVMI), a storage oscilloscope or a digitizer is used to acquire the signal. The divider has to be periodically calibrated by comparing it to a reference voltage divider. The LVMI has to be calibrated, usually before and after each measurement campaign, using an adequate standard calibrator, which is able to generate stable impulses similar to those acquired during the measurements campaign [3].

Commercial calibrators already exist in the market. Most of them are based on the principle of capacitor charging and discharging [4]. Charging and discharging resistors are usually adjusted, taking into account the input impedance of the LVMI, to obtain the desired wave shape. This kind of calibrator could be calculable if precautions are taken to set up the electrical design and its components are carefully chosen and characterized [5]. They can reach high metrological performances but need a separate electrical block for each wave shape type. The number of electrical blocks rise quickly and more effort to characterize them is made to cover all the industrial needs. In fact, during LI testing, the front time ranges from 0,84 µs to several µs and the duration of the pulse ranges from 40 µs to 60 µs. For SI testing, the time to peak ranges from 20 µs to 300 µs and the duration of the pulse ranges from 1 ms to 4 ms. For current testing, the front time ranges from 8 µs to 10 µs and the duration ranges from 20 µs to 350 µs.

During HV testing with composite and combined wave shapes according to [1] and [2], LI and SI could be combined with AC or DC. For these specific tests, reference calibrators do not exist in the market nor at National Metrology Institutes (NMIs). Great effort has been made by NMIs in order to set up reference calibrators for composite and combined tests. One of the NMI has developed a series arrangement of two calibrators, the first one used to generate the DC or AC voltages and the second one, which operates at floating mode, is used to generate the impulses,. Both generators can be calibrated separately. The influence of DC or AC voltages, which are applied to the front resistor of the impulse calibrator, has been studied. When the impulse is superimposed to AC voltage, a synchronization system was used to trigger the impulse but difficult to establish with high accuracy. This method needs an additional impulse calibrator for any additional impulse shape. Another NMI has developed a parallel arrangement of two calibrators, an impulse calibrator and a DC or AC calibrator. Blocking and coupling elements were used to ensure the isolation and to protect each source from the other. With this approach, the blocking elements are adapted for each wave shape. When SI is superimposed to AC, the input impedance of the LVMI (1 MΩ) becomes a problem because the impedance of the blocking elements is also high, consequently, produces a significant voltage drop. This method works well when impulses are superimposed to DC, when the blocking element on the impulse calibrator side is a capacitor. This method needs also an additional impulse calibrator for any additional impulse shape.

LNE (The NMI in France) has explored a hybrid calibrator able to generate any wave shape - separate impulses or combined wave shapes. The calibrator is based on the use of HV and high-speed amplifiers. When they are connected to a high speed Digital to Analogue Converter (DAC), it is possible to generate any wave shape. To explore this approach , four commercial high voltage amplifiers were tested and studied. The results are presented in this paper.

2. Description of the approach

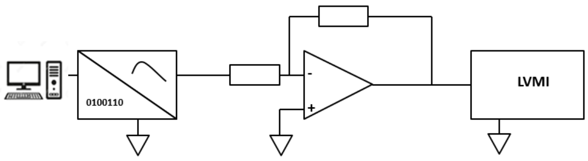

Fig. 1 - Reference calibrator structure based on the use of HV amplifier

The approach is based on the use of a HV amplifier, the principle is presented in figure 1. Software was used to generate numerical reference data according to the desired wave shape. For combined wave shapes, voltage impulses are generated independently and numerically combined. Equation 1, double exponential impulse, was used to generate impulses, by choosing the right parameters a, b and A. Table 1 shows an example of non-exhaustive parameters used to generate LI.

$$V_{impulse}(t) = V_{peak} \times A(e^{-at} - e^{-bt}) \qquad (1)$$

Table 1 - Example of parameters used to generate LI

Wave shape type	a (1/µs)	b (1/µs)	A
0.84 µs/40 µs	0.018188	3.55977	1.03275
1.2 µs/50 µs	0.014660	2.46898	1.03720
1.56 µs/45 µs	0.016618	1.92140	1.05141

DAC was used to generate all the desired wave shapes. It has a vertical resolution of 16 bits and a maximum sampling frequency of 160 MS/s. The output voltage is ± 6 Volts into 50 Ω and ± 12 Volts into 1 M Ω. The lowest voltage level is 1 mV. The bandwidth is 20 MHz, which is enough to generate impulses properly with a fast rise time. To avoid undesirable noise during the DAC operation, the sampling frequency was limited to 100 MS/s for LI, 10 MS/s for SI and 100 kS/s for AC or DC voltages.

Four amplifiers have been selected, tested and studied. The objective is to check their metrological performance in order to use them as accurate standard calibrators. The main amplifier characteristics are presented in Table 2. According to voltage requirements, a first selection has been made. It was observed that there are very few amplifiers with high bandwidth, which can operate for voltages up to 1 kVpp. Some of them could operate up to 4 kVpp but with limited bandwidth. High slew rates are needed to generate impulses with fast rise time. The value of slew rates given in the table 2 are obtained at favorable conditions, namely under a capacitive load less than 20 pF and a working temperature around 23 °C. In general, the slew rate decreases drastically with increasing temperatures and capacitive loads. The open loop gain is at least equal to 100 dB in order to reach high accuracy when the voltage is amplified (accuracy of 0.1 % for a gain of 100). The DC offset is chosen to be as low as possible in order to obtain a linear voltage dependence and a small wave shape distortion in the front. Each amplifier was tested on their capabilities to generate DC, AC, LI, SI and combined wave shapes.

Table 2 - Main characteristics of selected HV amplifiers.

Amplifier :	A	B	C	D
Model	APEX	Newton	Trek	Adamietz
Type	LPA194	LPA400	PZD2000	HVAB-0.9-0.2A
Voltage Peak (Vpp)	900	800	4000	900
Slew rate (V/µs)	2000	350	750	2000
Peak current (mA)	200	50	400	100
Gain	-100	100	200	150
Bandwidth (kHz)	1400	100	60	500
DC offset (mV)	300	150	800	250
Operating temperature (°C)	0-85	0-40	0-40	20-30
Open Loop Gain (dB)	100	100	100	100
Input impedance (kΩ)	0.05	10	25	0.05

3. Results and discussion

3.1 Generation of separate impulses

To characterize the generated impulses, a reference LVMI from "DR Strauss" company, 14 bits resolution, 200 MS/s sampling frequency, 50 MHz bandwidth, 2000 V channel was used. The first results show that the generation of a fast rise time in the range of a microsecond at high voltage levels is difficult to obtain for amplifiers with low slew rates. The generation possibilities of the four amplifiers, in terms of rise time and voltage level, are summarized in figure 2.

With amplifier B, short impulses (about 1,0 µs rise time) are only obtained for voltage lower than 250 Vpp without any visible distortion in the front. Voltages up to 800 Vpp are possible, but for rise times higher than 4 µs. This limitation is only due to its limited slew rate (350 V/µs). The standard deviation of 30 successive LI is better than 0.04 % for the peak voltage (250 Vpp), better than 0.2% for the front time (1.2 µs) and better than 0.04 % for the duration (50 µs). For large impulses, the standard deviation of 30 successive SI is better than 0.01 % for the peak voltage (800 Vpp), better than 0.4 % for the time to peak (250 µs) and better than 0.02 % for the duration (2300 µs). The repeatability of amplifier B is very good and can be compared with that of traditional calibrators (KAL1000 from Dr Strauss Company has a standard deviation better than 0.02 % for the voltage, better than 0.04 % for the front time and better than 0.02 % for the duration). For combined wave shapes, it is possible to generate DC and AC voltages up to ± 400 V, combined with short or large impulses but taking into account the voltage limitation in figure 2.

With amplifier C, the slew rate has been found to be about 600 V/µs. It is higher than that one of amplifier B and better performance could be expected. On the contrary, it was not possible at all to generate short impulses due to the large distortions in the front and to the superimposed oscillations in the peak. The minimum rise time that was generated properly is about 5 µs obtained only for voltages higher than 300 V. This amplifier could not be used to generate LI but only SI. The repeatability of SI is very good, better than 0.1 % for the voltages from 300 V to 3.7 kV (Figure 3). The repeatability of the time to peak is better than 0.5 % when the voltage is higher than 500 V (figure 4). Indeed, frequency noise coming from the power supply and the DC offset were superimposed to the output impulses. They have a slight impact on the repeatability of the voltage and the duration of the pulse but have a strong impact on the repeatability of the time to peak. It was concluded that amplifier C cannot be used as a reference calibrator for voltages lower than 500 V.

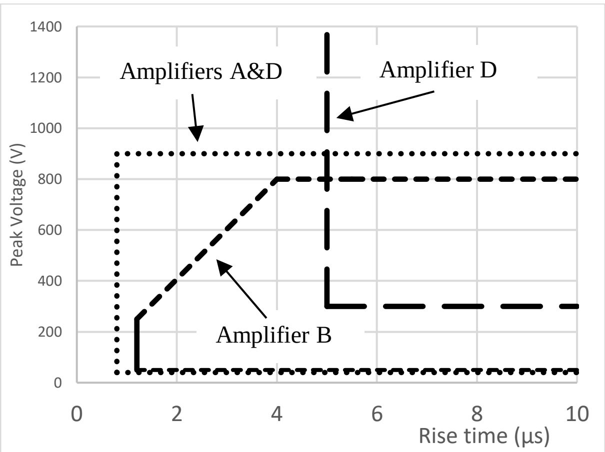

Fig. 2 - Area generation possibilities using voltage amplifiers.

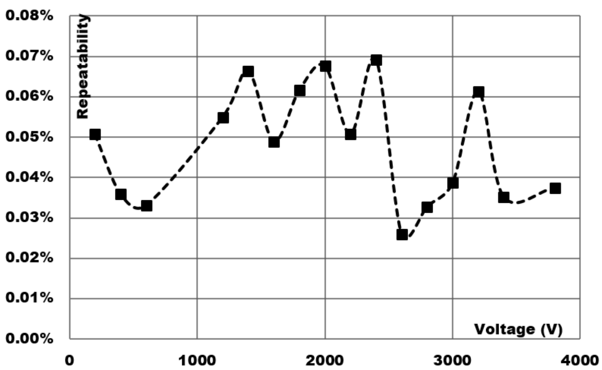

Fig. 3 - Voltage repeatability (in %) of amplifier C.

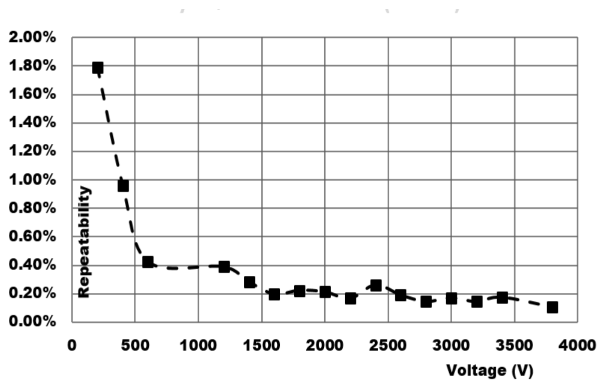

Fig. 4 - *SI time to peak repeatability (in %) of amplifier C.*

Amplifiers A and D have almost the same characteristics. The slew rate was measured by applying a step voltage of a few nanoseconds rise time at its input. The slew rate, measured at 23 °C and with a capacitive load less than 100 pF, was found to be higher than 2500V/µs for amplifier D and was about 1800 V/µs for amplifier A. Both amplifiers are able to reach LI up to 900 Vpp, even for short LI (0.84/50 µs).

For impulses up to 900 Vpp, the repeatability was evaluated by averaging 30 impulses. The maximal repeatability obtained for LI is about 0.12% for the voltage (Vc), 1.1 % for the front time (T1) and 0.26% for the duration (T2). For SI, the repeatability obtained is about 0.03% for voltage (Vc), 0.23% for time to peak (Tp), and 0.09% for the duration (T2). Large errors were observed at 50 V especially for the front time, the lowest voltage has the largest repeatability. Indeed, high frequency noise, of about ± 100mV and several tens of MHz, affects the repeatability of the fast impulses at low level but has no major influence above 100 Vpp. It was concluded that good performance could not be obtained for voltages lower than 100 V, especially for LI. For other levels, the obtained performance is as good as traditional calibrators. The results for LI and SI measurements are summarized in Table 3, the last two columns are the performance of a traditional calibrators at 600 V (respectively Kal1000 from Dr Strauss Company and RIC422 from Haefely Company).

Table 3 - Repeatability of 30 impulses obtained by amplifier D.

Voltage Peak	LI			SI		
	Vc	T1	T2	Vc	Tp	T2
50 V	0.12%	1.10%	0.26%	0.03%	0.23%	0.09%
100 V	0.05%	0.18%	0.12%	0.01%	0.16%	0.07%
200 V	0.03%	0.09%	0.05%	0.01%	0.08%	0.03%
400 V	0.03%	0.13%	0.05%	0.01%	0.08%	0.02%
600 V	0.04%	0.12%	0.04%	0.02%	0.09%	0.02%
900 V	0.02%	0.13%	0.04%	0.07%	0.11%	0.03%
KAL1000 600 V	0.02%	0.02%	0.02%	0.01%	0.04%	0.02%
RIC22 600 V	0.04%	0.2 %	0.05%	0.02%	0.10%	0.03%

3.2 Generation of AC and DC combined with LI and SI.

For combined testing, usually the DC or AC voltages are applied a few hours before applying the combined impulses [6], the LVMI has to be tested under the same condition. The influence of self-heating, when applying the DC or AC voltages for a long duration, is an important parameter on the increase of temperature and the decrease of the slew rate. It was then necessary to reach high AC/DC voltage output stabilities at least for a few hours of voltage application. Adequate cooling systems to keep the temperature below 30 °C was used (for example, a fan for amplifiers A and D). The influence of this self-heating has been determined at 250 V DC and AC. To characterize the generated DC and AC voltages, a precision voltmeter fluke 8508A and a reference calibrator Fluke 5520A were used as shown in figure 5 using amplifier D.

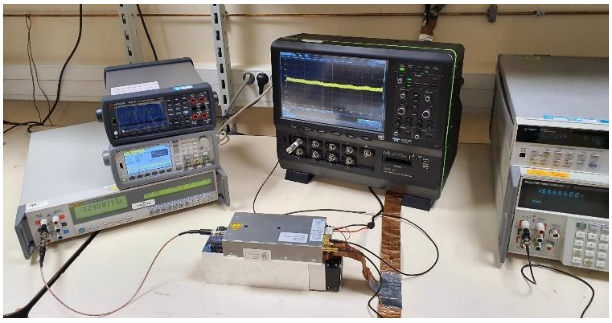

Fig. 5 - Testing amplifier D at DC/AC voltages

At DC voltage, a rapid voltage increase of about 50 µV/V is observed in the first minutes. After that, the voltage is almost stable, a slight fluctuation of about 20 µV/V has been seen in 2.5-hour voltage application (figure 6). This fluctuation is essentially due to variation of the ambient temperature (23 ± 1) °C. The influence of self-heating is is good enough to reach high accuracy. Any significant drift on LI and SI combined with DC voltage has been seen. The same procedure has been performed for AC voltages, deviation less than 0.02 % is observed after a 6-hour of voltage application, which is enough to reach high accuracy.

The generation of superimposed AC/DC voltages and impulses could be ensured with high accuracy, even if the DC voltage is applied within a few hours. Using amplifiers, it is easy to generate combined voltages, combining AC or DC voltage with LI or SI could be done at any time. Usually, during high voltage combined testing [7], LI or SI is applied in the AC peak, the time between AC peak and impulse peak Δt have to be less than 5 % of a quarter period.. Another quantity to be measured during combined testing (AC combined with LI or SI) is the difference between AC peak and impulse peak. Using the amplifiers, it is easy to fix both quantities at any value we need for the calibration (figure 7).

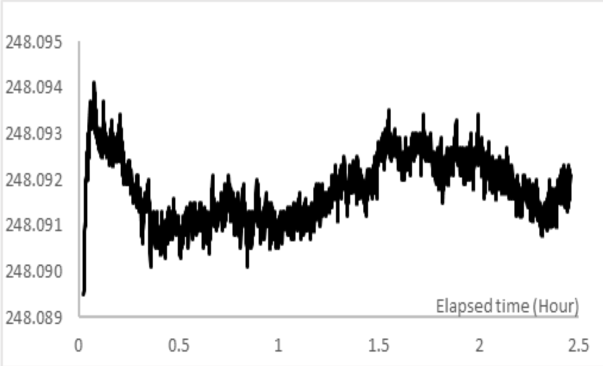

Fig. 6 - *self-heating of amplifier D up to a 2,5-hour voltage application.*

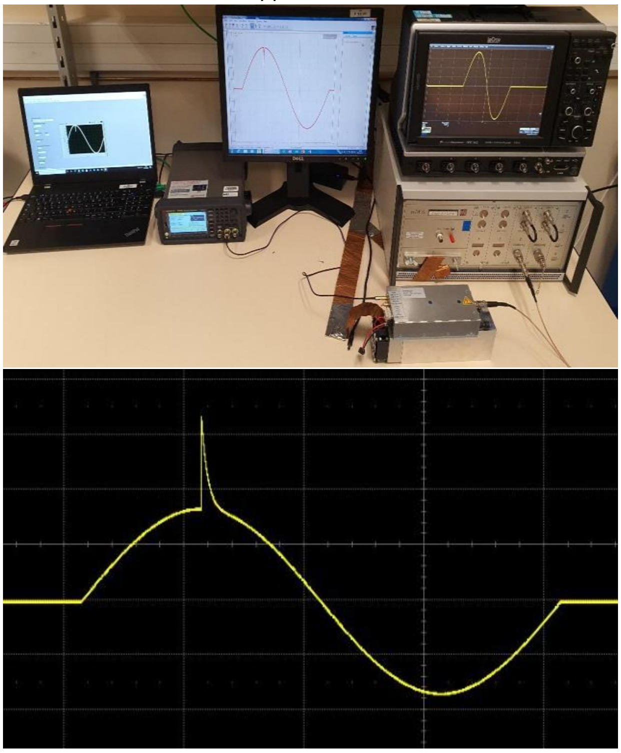

Fig. 7 –: Example of AC combined with LI using amplifier D

3. Traceability and uncertainty

Three methods have been used to calibrate the amplifiers.

The first method involves using the direct comparison method, namely calibrating the gain for a specific wave shape. The principle is to measure the input and the output voltages using a reference digitizer. In this case, the influence of the load impedance is evaluated. In our case, it was demonstrated that a resistance of 1 MΩ ± 2 % and a capacitance smaller than 100 pF is necessary to avoid such influence. This condition is generally met with the majority of LVMIs. The impulse is generated by the DAC and measured using a 10 V channel. A 1000 V channel is used to measure the output voltage of the amplifier. Before performing the measurements, both channels have been characterized. The calibration results are presented in figures 8, 9 and 10 respectively for the gain, the front time and the duration of LI and SI.

The second method is to use the convolution technique to characterize the gain. A calibrated DC voltage is applied to the input of the amplifier and shortened to ground using a high quality mercury relay. The output voltage is measured by a reference digitizer. The objective is to calculate the errors of the gain for a specific wave shape. The first and the second methods have been compared each other in Figures 9 and 10 for the measurements of the front time and the duration of the impulse.

From calibration results of the first and the second methods, the gain is given in figure 8 for each wave shape, we can see that the gain decreases with increasing the voltage and frequency. It is seen in figure 9 that front time errors obtained for short impulses are too large. They decrease with increasing the voltage and front time. They are especially due to the offset, which affects the conventional zero of the impulses and, in particular, the times at levels of 30 % and 90 % of the voltage peak, which are needed to calculate the front time. Similar observations were made in figure 10 for the duration of short impulses but not significant (less than 2 %). For large impulses, errors of the duration are very low.

The comparison between the direct method and the convolution method shows very good agreement for T1 and T2. The convolution technique can be used as a reference method because of its simplicity. It could be employed for any wave shape even for combined and combined shapes.

The third method is to characterize the gain frequency response at different levels of voltages and different frequencies including the DC. Depending on the frequency component of the wave shape, it is possible to calculate the parameters of the generated wave shape by applying correction factors for each frequency and voltage component. A good frequency and voltage linearity are needed to avoid complex corrections. The gain has been measured at frequencies up to 50 kHz and at voltage up to 250 V RMS (700 Vpp). The results are shown in Figure 11 for amplifier D, they are obtained with an uncertainty of 0.05 %. The voltage and frequency dependencies are clearly visible and could be used to correctly calculate the voltage peak. In order to calculate the output front time of short impulses, the gain of amplifiers has to be characterized for frequencies up to few megahertz.

Table 4 –. *Obtainable uncertainties of amplifier D (k=2)*

Wave shape 100 V-900V	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%
AC and DC	0,05 %	-	-

The obtainable uncertainties of amplifier D, for traditional wave shapes, are summarized in Table 4. The calculation was performed according to the GUM [8].

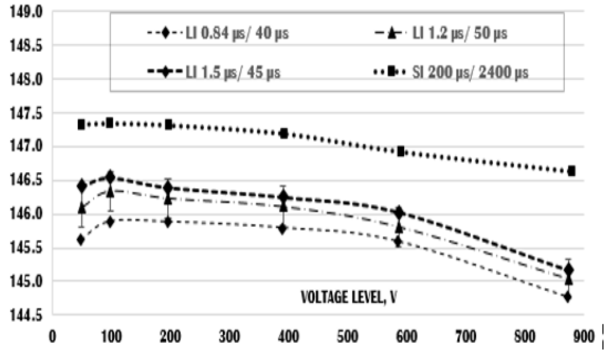

Fig. 8 – Gain of amplifier D at different impulse shapes.

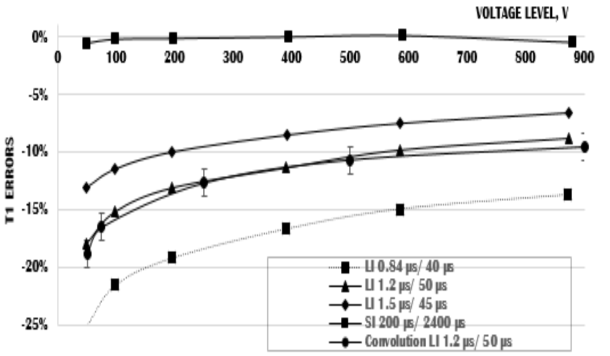

Fig. 9 – Front time errors of amplifier D at different impulse shapes and with the convolution technique.

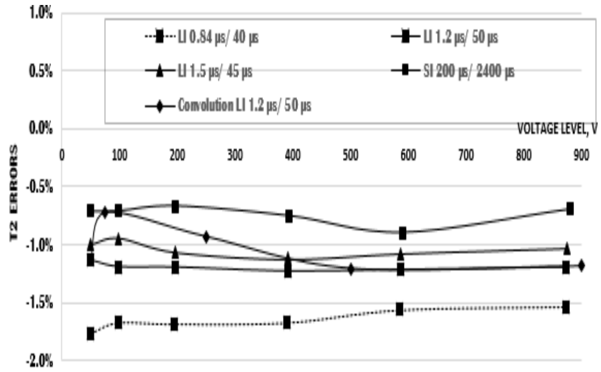

Fig. 10 – Duration time errors of amplifier D at different impulse shapes and with the convolution technique.

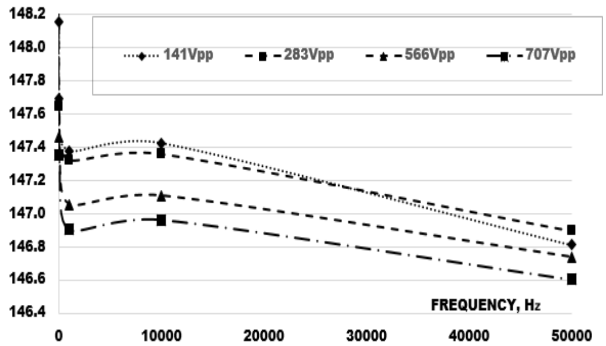

Fig. 11 – Scale factor of amplifier D obtained at AC voltage.

4. Acknowledgements

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6. Conclusion

The usage of voltage amplifiers for reference impulse and combined wave shapes calibrators, up to 1000 V, has been demonstrated in this study. As traditional calibrators, they can achieve high metrological performance. They are capable of calibrating, with very good uncertainty, low voltage measuring instruments used to acquire separate impulses as short as 1 µs rise time. They are also capable of being a reference calibrator for combined wave shapes, where the impulses are superimposed to AC or to DC voltage. They could be traceable to the International System of Units by characterizing the gain. In this study, LNE has proven that HV amplifiers are flexible enough to generate any waveform in only one block. They are as accurate as traditional calibrators and very cheap to develop.

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