STAKEHOLDERS WORKSHOP

EUROPEAN RESEARCH PROJECT 19NRM07 HV-com²

"support for standardisation of high voltage testing with composite and combined wave shapes"

WP1 - Definitions, software and instrumentation

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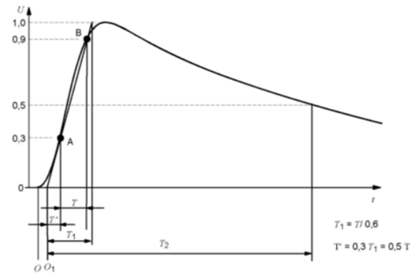
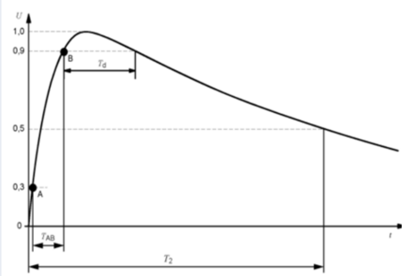
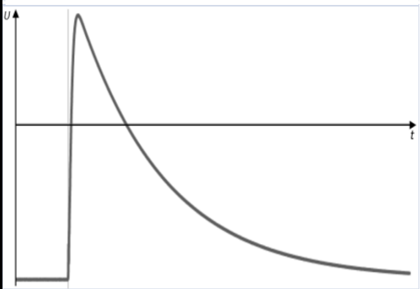
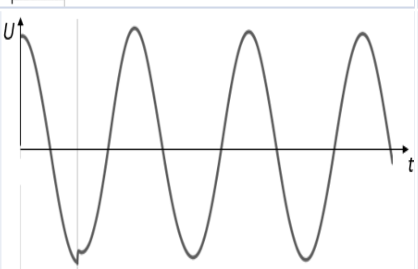
LABORATOIRE NATIONAL DE MÉTROLOGIE ET D'ESSAIS

HIGH VOLTAGE WAVES TRACEABILITY

Wave shape	Type	Requirements acc. to IEC 60060	Traceability status	Application domains
	**Lightning impulse** (LI)	0.84 µs < T1 < 1.56 µs 40 µs < T2 < 60 µs	- Traceability ensured for voltage and time parameters in HV and LV - Standard measurement systems used for the equipment calibration	- Testing of equipment for high voltage electricity grids **to qualify it can operate safely during rated electrical conditions** - etc.
	**Switching impulse** (SI)	10 µs < TAB < 300 µs 1000 µs < T2 < 4000 µs	- Traceability ensured for voltage and time parameters in HV and LV - Standard measurement systems used for the equipment calibration	- Testing of equipment for high voltage electricity grids - etc.
	**Composite wave shape** (superimposed HVAC/ HVDC with LI/SI)	- No enough regulations in international standards - Lack of standardized definitions - No sufficient requirements - No evaluation routines	- No traceability - No reference measuring systems - No standard LV calibrators	Withstand test of: - HVDC cable systems - Cable accessories - Gas Insulated HV systems GIS (Gas Insulated Switchgear) **to verify it can withstand specified voltage stresses**
	**Combined wave shape** (superimposed HVAC/ HVDC with LI/SI)	- No enough regulations in international standards - Lack of standardized definitions - No sufficient requirements - No evaluation routines	- No traceability - No reference measuring systems - No standard LV calibrators	Withstand tests for: - Transformers - Circuit breakers - Phase to phase insulation - Longitudinal insulation of switching equipment - etc.

NEEDS

Composite and Combined wave shapes tests

- Industry and test laboratories
- International standards
- NMIs

- Need for reliable HV testing of equipment

- Need for necessary metrology to be developed for the standardization of HV composite and combined wave shapes for the IEC 60060 series

  -> Review ongoing

  -> Review as decided at the meeting of TC 42, held in Toronto in October 2017)

- Need for traceable measurement systems for the calibration of combined and composite voltages with high accurate uncertainty

- Need for calibration capabilities

- Need for traceability to the SI of the systems measuring composite and combined voltages

WP1 OBJECTIVES

To determine the relationship between impulse voltages with HVAC or HVDC measurements and related detrimental effects due to combining wave shape tests

To realise the necessary metrology for the standardisation of high voltage testing with composite and combined wave shapes.

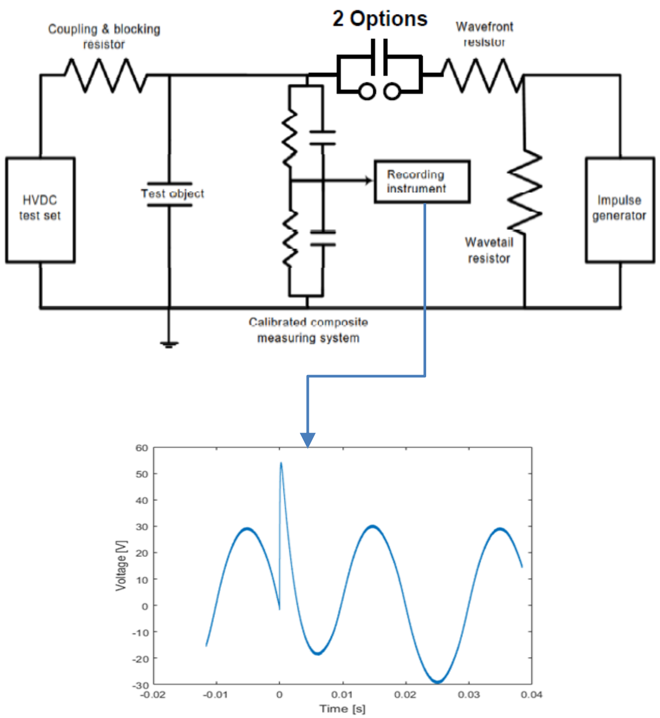
- Target voltage level: > 500 V
- Target uncertainty: better than 0.5 % for the amplitude
- Target bandwidth: up to 20 MHz

To provide input to contribute to the ongoing revision of the IEC 60060 and IEC 61083 standards , which are currently in preparation in TC 42

Definitions | Instrumentation | Software

WP1 OVERVIEW

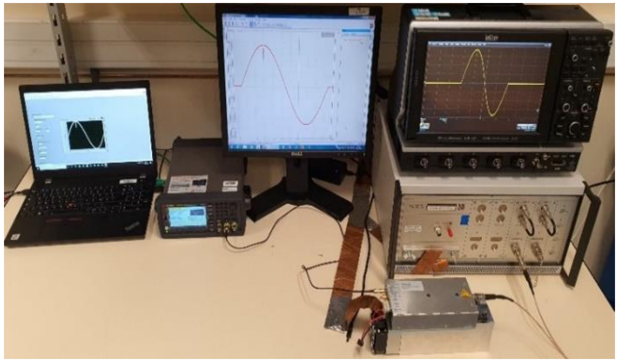
Definitions



- Review existing work
- Provide a proposal for the review of the Standard IEC 60060-1
- Provide standardised definitions and new parameters

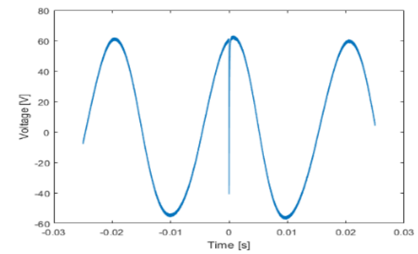
Instrumentation

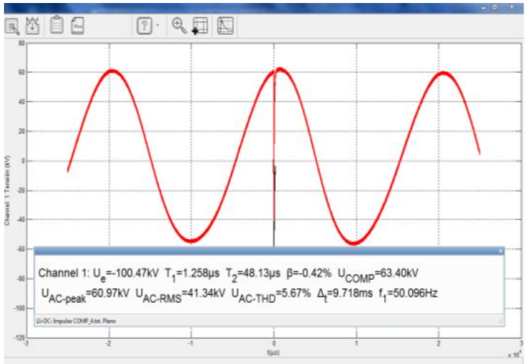
- LV calibrators/generators up to 1 kV for digitizers' calibration
- LVMI (scopes, attenuators, DMM or digital recording instruments, etc.)



- Calibrate the digitizers' up to 1 kV
- Develop characterization methods
- Support the next revision of the IEC 61083-1 regarding LV instruments

Software





- Evaluate composite and combined wave shapes parameters
- Prepare waveform data for future test data generators (IEC 61083 series)

WP1 SUMMARY

1) State of art: Standards and existing work
2) Definitions for combined voltage test
3) Definitions for composite voltage test
4) Standard LV calibrators/generators
5) LVMI characterization methods
6) Waveforms collected from industry
7) Project comparison of evaluation software
8) Interlaboratory comparison of LVMI using a standard calibrator

STATE OF ART

Standards related to the combined and composite voltage testing:

- **IEC 60060-1**, *"High-voltage test techniques – Part 1: General definitions and test requirements"* **provides definitions of the parameters to be evaluated from combined and composite test waveforms. IEEE 4**, *"IEEE Standard for High-Voltage Testing Techniques"* **is in line with IEC 60060-1.**

  Revision ongoing

- **IEC 62271-1**, *"High-voltage switchgear and controlgear - Part 1: Common specifications for alternating current switchgear and controlgear"* **provides only test voltage levels for superimposed voltage tests. However this version does not set specific requirements for the measurement systems.**

- **IEC 61083-1**, *"Instruments and software used for measurement in high-voltage and high-current tests - Part1: Requirements for instruments for impulse tests"* **provides requirements for the performance of recorders used for high-voltage and high-current impulse tests. However, no included requirements in the current version for the systems that are used to measure combined and composite voltages.**

- **IEC 61083-2**, *"Instruments and software used for measurement in high-voltage and high-current tests - Part2: Requirements for software for tests with impulse voltages and currents"* **provides test waveforms for validating software for impulse voltage and current testing. However, no combined and composite voltage waveforms are included in the current version.**

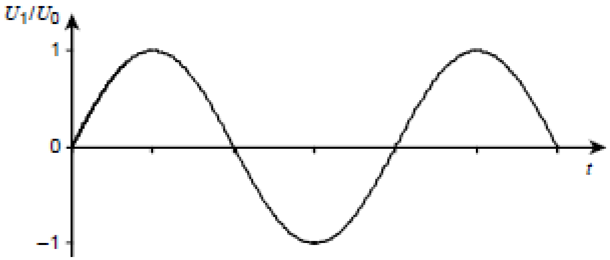
  Revision ongoing

- **IEC 60060-2**, *"High-voltage test techniques - Part 2: Measuring systems"* **provides requirement for measurement systems, but the current version does not set specific requirements for measurement systems for combined and/or composite voltage testing.**

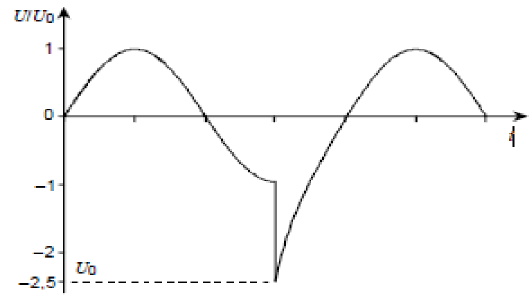
  Revision ongoing

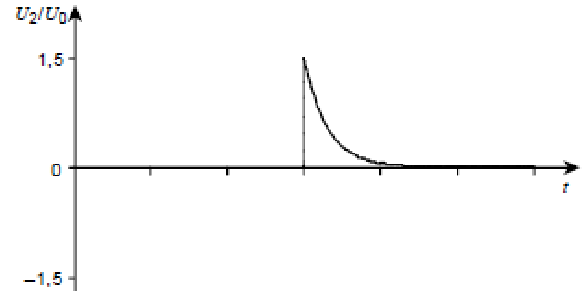
DEFINITIONS FOR COMBINED VOLTAGE TESTS

Combined HV generation and measurement acc. to the IEC 60060-1: 2010, chapter 9:



$U = U1 - U2 = -U_0 - 1{,}5\ U_0 = -2{,}5\ -U_0$



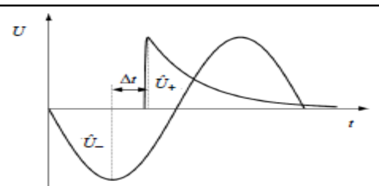


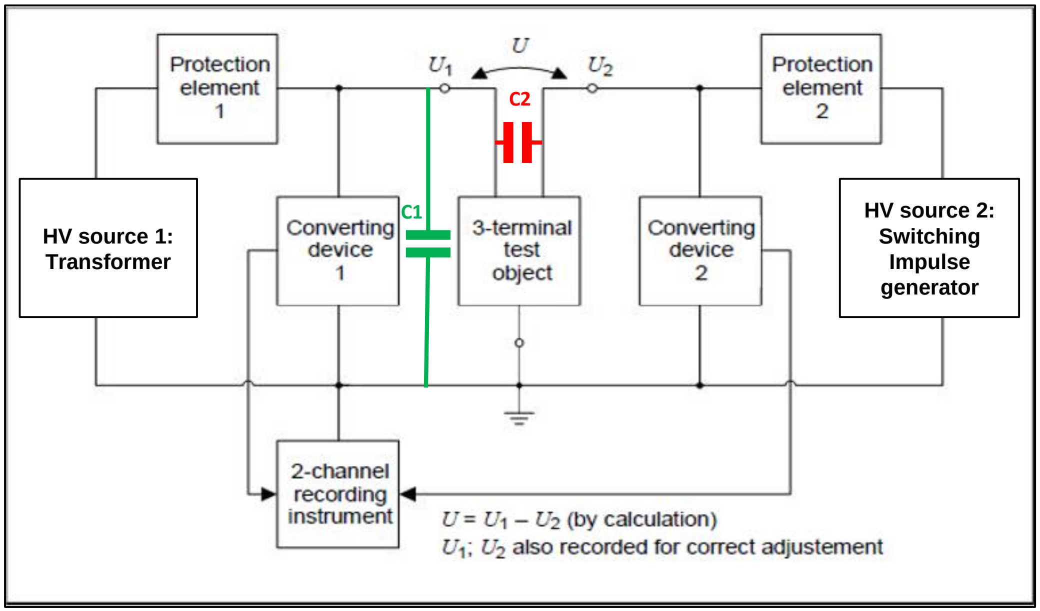
Schematic example for combined voltage (AC + positive impulse) between two HV terminals and earth

Combined test voltage

Shall be characterized by the following parameters:

- ✓ Its voltage value ***U***;
- ✓ Time delay ***Δt***;
- ✓ Parameters of its **two components**





Test circuit for combined voltage tests with two energized HV terminals

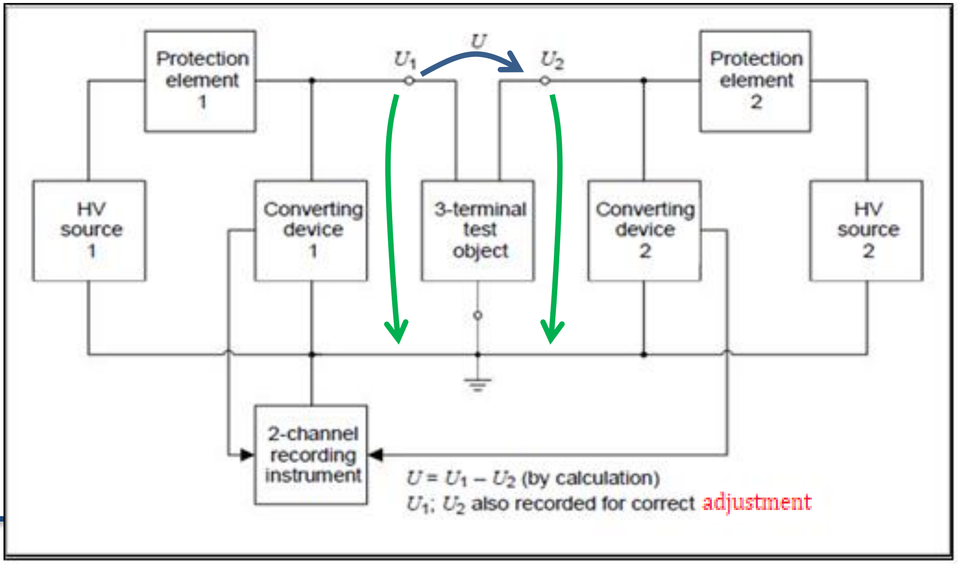
Requirements

- ✓ Circuit described the voltage test
- ✓ No requirements for the voltage test
- ✓ No requirements for the voltage drop
- ✓ No enough requirements for time parameters

DEFINITIONS FOR COMBINED VOLTAGE TESTS

Proposal for specific clauses for the ongoing revision of the IEC 60060-1:

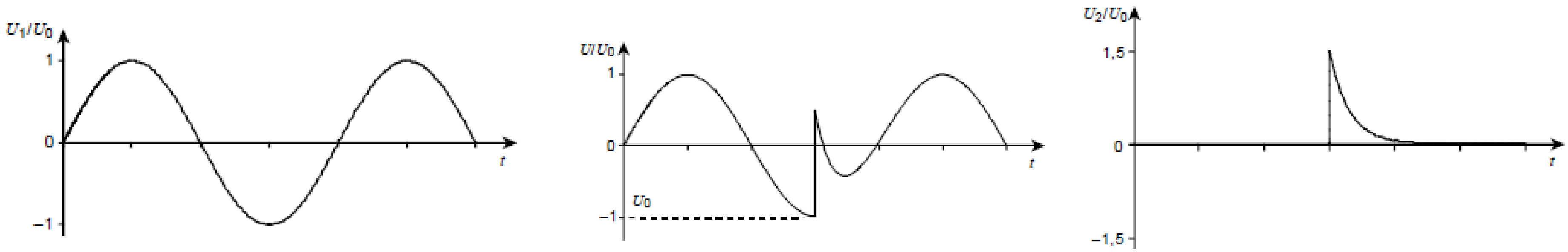
- Create a new structure of combined voltage test by splitting the clauses for combined and composite voltages
- Improve text passages and figures and overwrite the tolerances for the test voltage and the time delay
- Define and report the polarity of the test voltage. The term "value of combined voltage" shall be replaced by "test voltage"
- Describe more examples of the combined voltage test. Only one example with AC and impulse voltage is described
- Add a definition for the peak value of the impulse voltage $U_{peak\text{-}to\text{-}ground}$ measured against the earth's potential
- Describe the voltage drop (increase or decrease) on AC or DC voltage terminal. The measurement data immediately before the impulse occurs can be used to determine the DC and AC parameters. This can be done by pre-acquisition
- Define the time delay. The Δt is negative if the impulse peak occurs before the nearest positive or negative AC peak



Tolerance for	Parameters	Tolerances
Combined voltage test	Test voltage value	± 5 %
	Time delay	± 5% of the front time of an impulse or the quarter of a cycle of an alternating voltage; whichever is longer
	Parameters of the two voltage components	Acc. to the relevant clauses of the standard

DEFINITIONS FOR COMPOSITE VOLTAGE TESTS

Composite HV generation and measurement acc. to the IEC 60060-1: 2010, chapter 9:



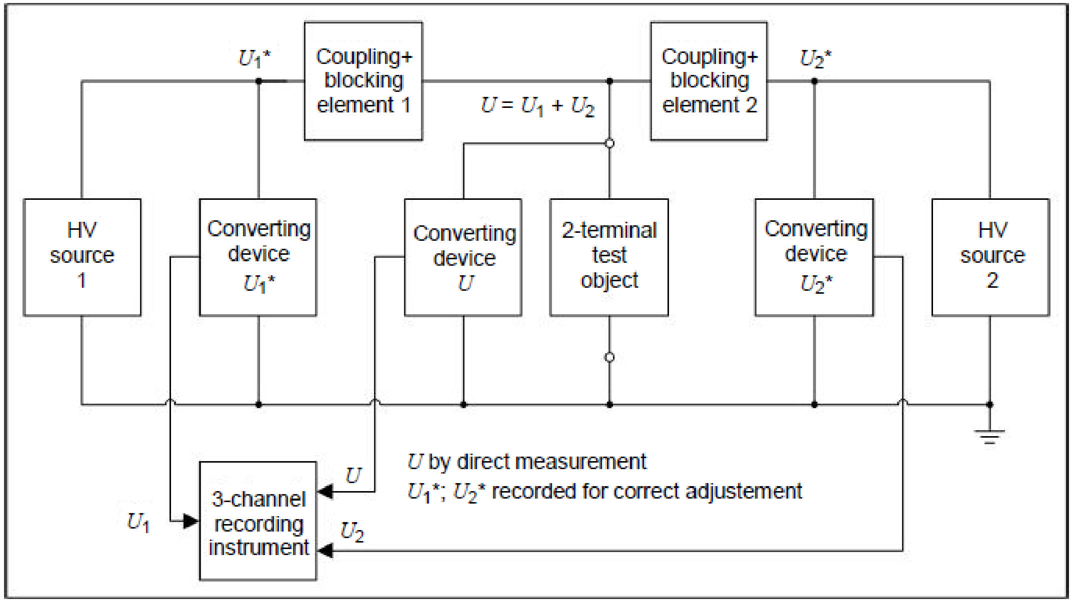
$U = U1 + U2 = -U_o + 1,5\ U_o$

Schematic example for composite voltage (AC + positive impulse) between one HV terminal and earth

Composite test voltage

Shall be characterized by the following parameters:

- ✓ Its voltage value ***U***;
- ✓ Time delay ***Δt***;
- ✓ Parameters of its **two components** " acc. to the relevant clauses of the standard "



Test circuit for composite voltage tests with one energized terminal

Requirements

- ✓ Circuit described the voltage test
- ✓ No specific requirements for the voltage test
- ✓ Does not deal with time parameters

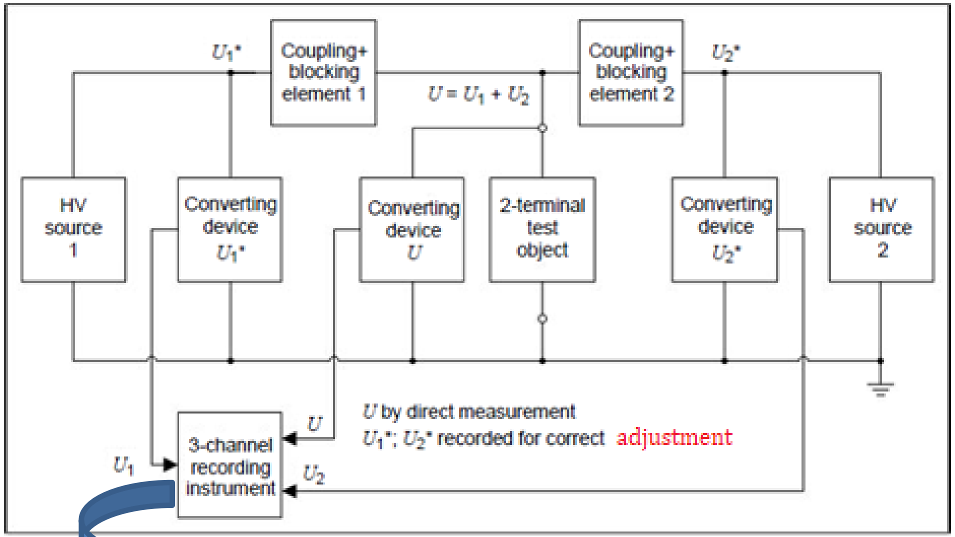
HV-com²

BUILDING TRUST LNE

DEFINITIONS FOR COMPOSITE VOLTAGE TESTS

Proposal for specific clauses for the ongoing revision of the IEC 60060-1:

- **Create a new structure of composite voltage test by splitting the clauses for combined and composite voltages**
- **Improve text passages and figures and overwrite the tolerances for the test voltage and the time delay**
- **Replace the term "value of combined voltage" by "value of the test voltage"**
- **Clearly define the behaviour of the coupling + blocking elements to accurately determine the voltages *U1** and *U2***
- **Describe more examples for the composite voltage test. Only one example with AC and impulse voltage is described**
- **Add a definition for the peak value of the impulse voltage $U_{peak\text{-}to\text{-}ground}$ measured against the earth potential**
- **Define how the time delay is calculated. Δt is negative if the impulse peak occurs before the nearest positive or negative AC peak**



Shall be characterized acc. to the IEC 61083 series

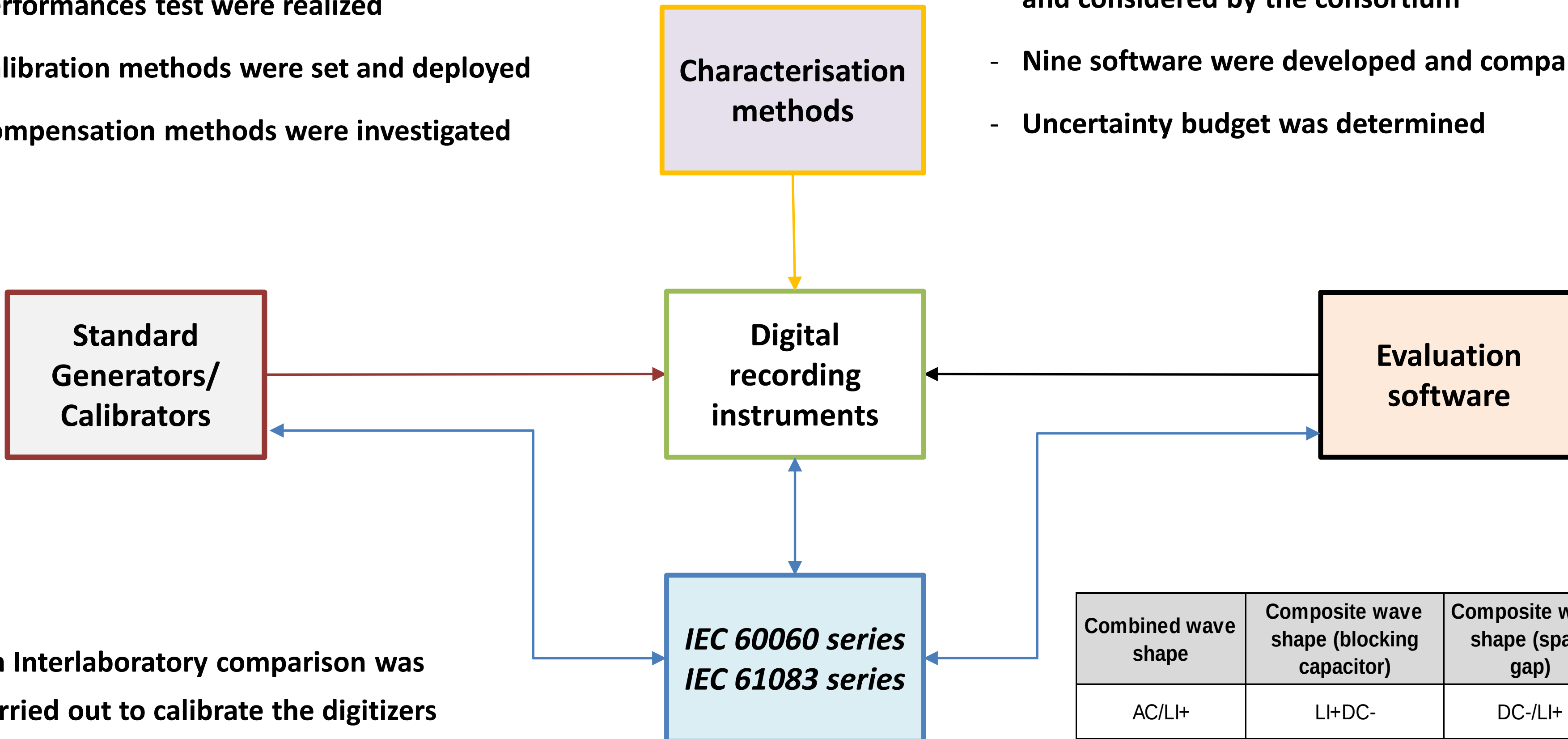
- **DC and AC parameters shall be determined by pre-acquisition immediately before the impulse occurs.**
- **U1 and U2 *are U1** and *U2** given that the behaviour of the coupling + blocking elements of the test circuit is known.**

Tolerance for	Parameters	Tolerances
Composite voltage test	Test voltage value	± 5 %
	Time delay	± 5% of the front time of an impulse or the quarter of a cycle of an alternating voltage; whichever is longer
	Parameters of the two voltage components	Acc. to the relevant clauses of the standard

INSTRUMENTATION AND SOFTWARE

- Three standard calibrators were developed
- Performances test were realized
- Calibration methods were set and deployed
- Compensation methods were investigated

- Waveforms were collected from Stakeholders and considered by the consortium
- Nine software were developed and compared
- Uncertainty budget was determined

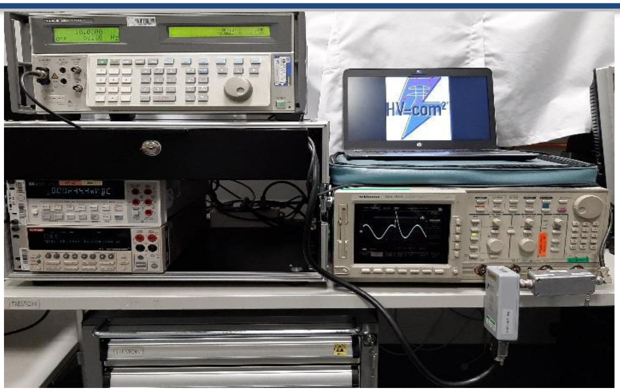


- An Interlaboratory comparison was carried out to calibrate the digitizers
- Calibration procedures were set up
- Uncertainty budget was determined for the calibration of LMVI up to 1 kV

Combined wave shape	Composite wave shape (blocking capacitor)	Composite wave shape (spark gap)
AC/LI+	LI+DC-	DC-/LI+
AC/LI-	SI+DC+	DC-/SI-
AC/SI+	AC/SI+	
AC/SI-	AC/LI-	

STANDARD GENERATORS/CALIBRATORS

1) VTT design for generating composite wave shapes

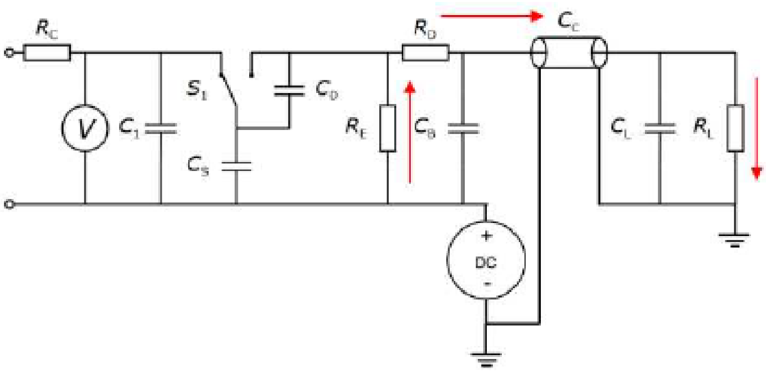


- Combining existing DC/AC calibrator (e.g. Fluke 5500 or 5700 series) and a calculable impulse voltage calibrator (keithley 2400 for charging a single stage impulse generator)

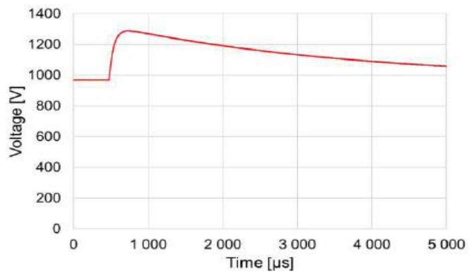
- Maximum impulse voltage peak is 330 V to high impedance load, whereas the DC/AC voltage can be within 1000 V.

- Reference parameters are calculated based on the:
  - applied voltage,
  - charging voltage of the impulse calibrator,
  - internal impedance of the impulse calibrator,
  - input impedance of the device under calibration (C_L and R_L)

- Performances test were performed with DC voltage and LI/SI. The combined voltage with AC + LI/SI is under development.



Circuit diagram of VTT design based on a series connection



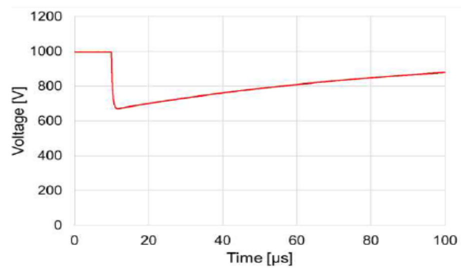


Table 2 - Calibration results with DC+LI.

Digitizer range [V]	DC [V]	LI [V]	DC error	U_t error	T_1 error	T_2 error
100	0	90	-	0.08 %	0.02 %	-0.02 %
100	-45	90	0.04 %	0.09 %	0.05 %	0.02 %
100	-90	90	0.01 %	0.11 %	-0.01 %	0.02 %

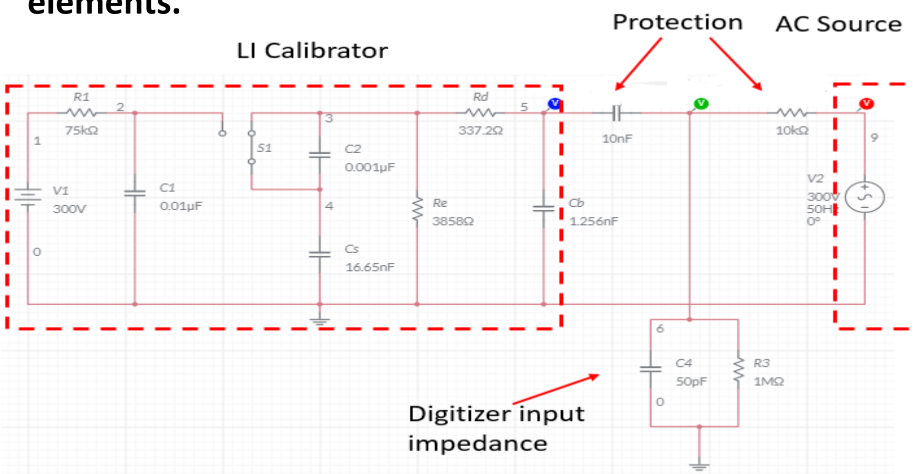
Table 1 – Uncertainty budget for composite DC+LI

Parameter	Expanded uncertainty (k=2)
DC voltage	0.01%
Test voltage Ut	0.05%
Front time T1	0.46%
Time to half-value T2	0.29%
Composite voltage value	0.06%

TÜBİTAK

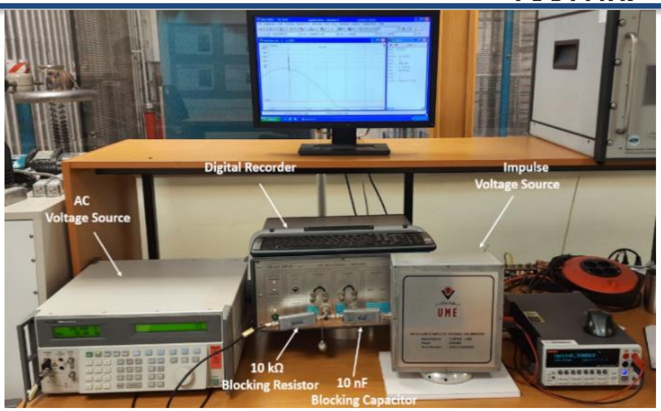
2) TUBITAK design for generating composite wave shapes

- Combining existing DC/AC calibrator and a calculable impulse calibrator to generate composite voltages (LI+AC or LI+DC).
- The sources have been protected from each other using blocking elements.



Circuit diagram of TUBITAK design based on a parallel connection

- Maximum impulse voltage peak is 300 V, whereas the DC and AC voltage can be within 1000 V.
- Performances tests were performed. Measurements results show that the blocking elements were performed properly and the calibrator generates properly LI+AC or LI+DC composite signals without damage.

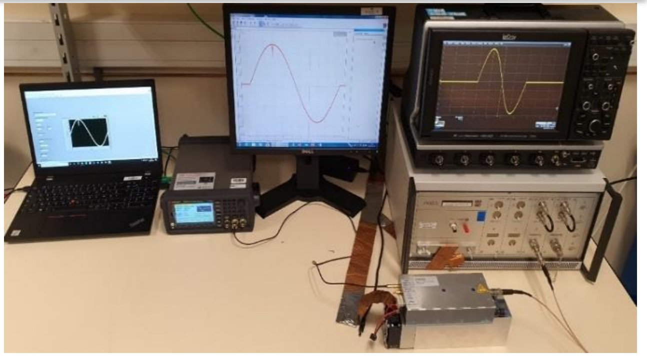


TUBITAK design based on a parallel connection

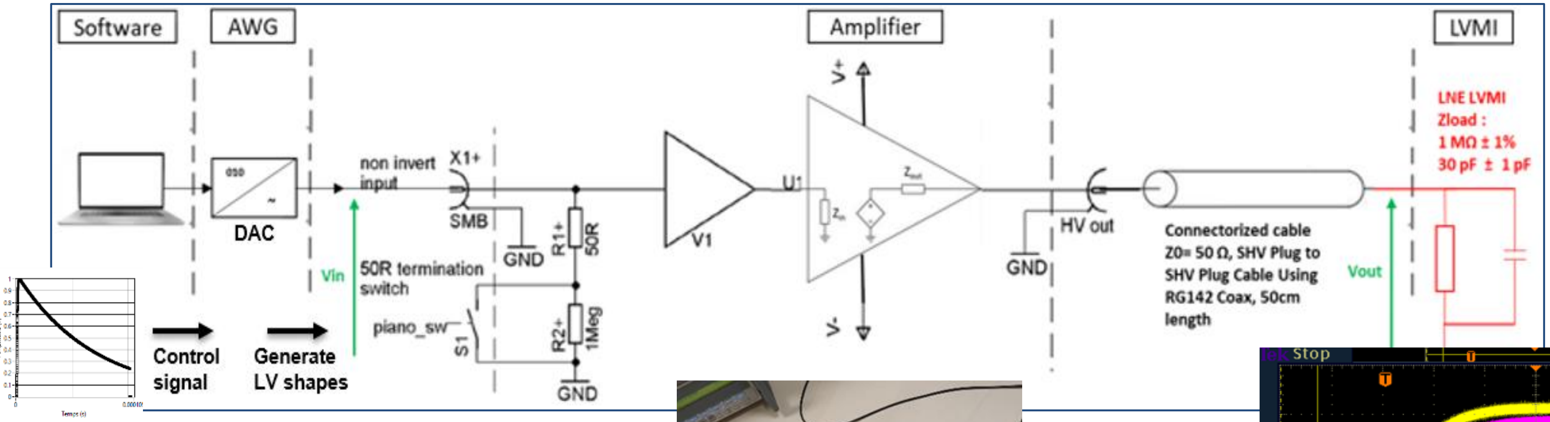
Table 1 – Uncertainty budget for composite LI/SI +AC/DC

Parameter	Expanded uncertainty (k=2)
LI/AC voltage value	10 µV/V
Test voltage	1 mV/V
Composite voltage value with LI+AC	0.25%
Composite voltage value with LI+DC	0.20%
Time parameters	10 ms/s

3) LNE design for generating composite and combined wave shapes



- Design is based on a linear HV and high speed amplifier to generate separate and superimposed wave shapes (AC, DC, LI, SI, combined and composite voltages) using only one electrical unit for all shapes.
- Both composite and combined voltages could be reached up to ± 900 V.
- No distortion shown even for fast impulses measured at the amplifier.



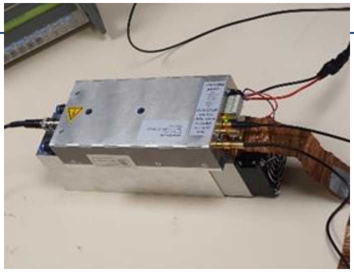
AWG specifications :
- Sample rate: 160 MS/s
- Vertical resolution: 14 bits
- Bandwidth: 80 MHz

Digitizer specifications :
- Sample rate: 200 MS/s
- Vertical resolution: 14 bits
- Bandwidth: 50 MHz
- Zload: 1 MΩ ± 1% & 30 pF ± 1 pF

Circuit diagram o

Table 1: Example of non-exhaustive parameters used to generate LI shapes acc. to IEC 60060-1

Wave shape type	a (µs-1)	b (µs-1)	A
LI 0.84 µs/ 40 µs	0.018188	3.55977	1.303275
LI 1.2 µs/ 50 µs	0.014660	2.46898	1.03720
LI 1.56 µs/ 45 µs	0.016618	1.92140	1.05141



Equation based on double exponentials:

$$V_{impulse}(t) = V_{peak} * A\,(e^{-at} - e^{-bt})$$

STANDARD GENERATORS/CALIBRATORS

3) LNE design based on HV amplifiers

Performances tests were performed regarding the accuracy for amplitude and time parameters.

Table 1 – HV amplifier specifications

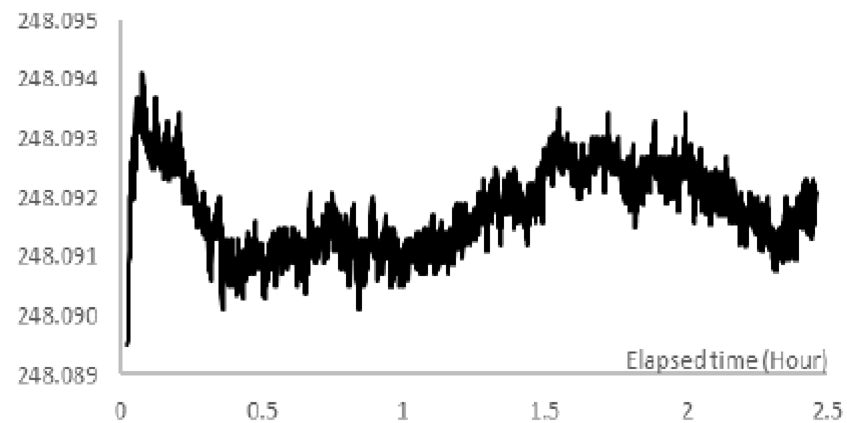
Model	Adamietz HVAB-0.9-0.2A	Shapes	Adamietz HVAB-0.9-0.2A
Voltage Peak (Vpp)	900	DC and AC voltage	900 Vpp
Slew rate (V/µs)	2000	Short LI (0.84 µs)	50 V – 900 V
Peak current (mA)	100	Long LI (1.56 µs)	
Gain (V/V)	150	SI	
Bandwidth (kHz)	500	Combined	900 Vpp
DC offset (mV)	250	Composite	900 Vpp
Operating temperature (°C)	20-30	Fast rise time	0.8 µs
Open Loop Gain (dB)	100	Accuracy of voltage	0.2% 50V<LI & SI<900V
Input impedance (Ω)	50	Accuracy of time	1% T1>0.8µs; V>50

Output stability	Frequency		
	DC	60 Hz	10 kHz
Voltage coefficient	< 0.01% over 2.5 hours application < 20 ppm after 10 min stabilization		

Table 2 – Output voltage stability (Repeatability of 30 impulses)

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%

For 50 V, the presence of an offset and high frequency ripples at the amplifier output were considered but no major influence on measurements from 100 V to 900 V.



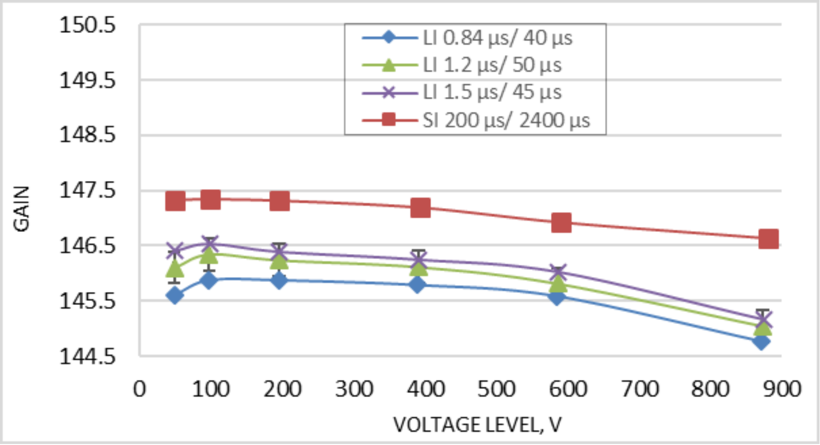
250 VDC over 2.5 hours of voltage application to test the output voltage

STANDARD GENERATORS/CALIBRATORS

3) LNE design based on HV amplifiers

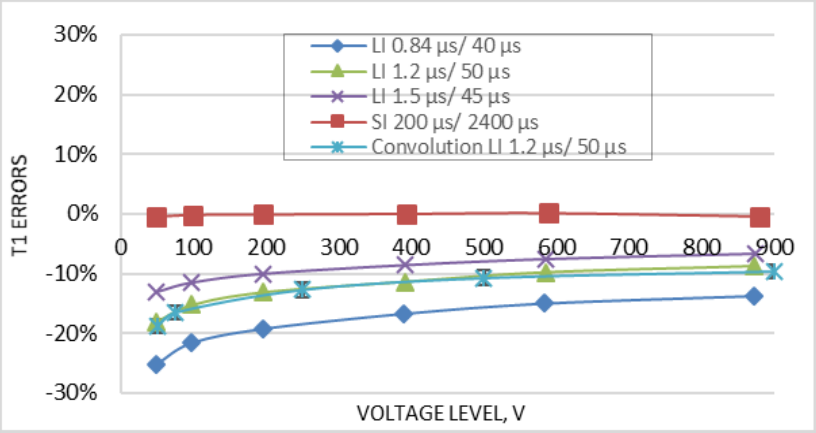
Three traceability methods:

1) Direct comparison method to calibrate the gain



Gain of the amplifier at different impulse shapes (between the output and input voltage of the amplifier)

2) Convolution technique to characterize the gain



T1 / Tp errors of the amplifier for specific impulse using convolution technique

3) Gain frequency response characterization

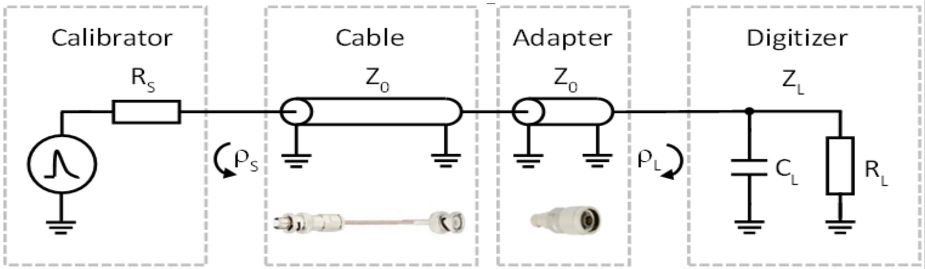
Wave shapes parameters calculation require the correction factors application for each frequency and voltage component.

Table 1 – Uncertainty budget for the amplifier based-calibrator Adamietz HVAB-0.9-0.2A up to 900 V

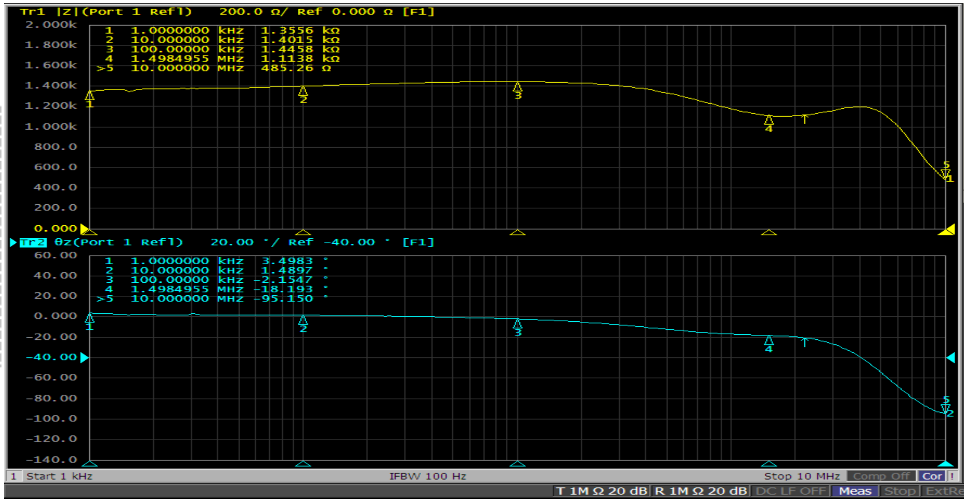
Parameter	Expanded uncertainty (k=2)
DC and AC voltage	≈ 0.2%
Test voltage Ut	≈ 0.2%
Front time T1	< 1%
Time to half-value T2	< 0.5%
Composite voltage value (LI/SI + AC/DC)	0.28%
Combined voltage value (LI/SI + AC/DC)	0.28%

STANDARD GENERATORS/CALIBRATORS

Two compensation methods:



A simple model defined by the output impedance of an amplifier-based calibrator, the characteristic impedance of the measuring cable and adapters and the digitizer



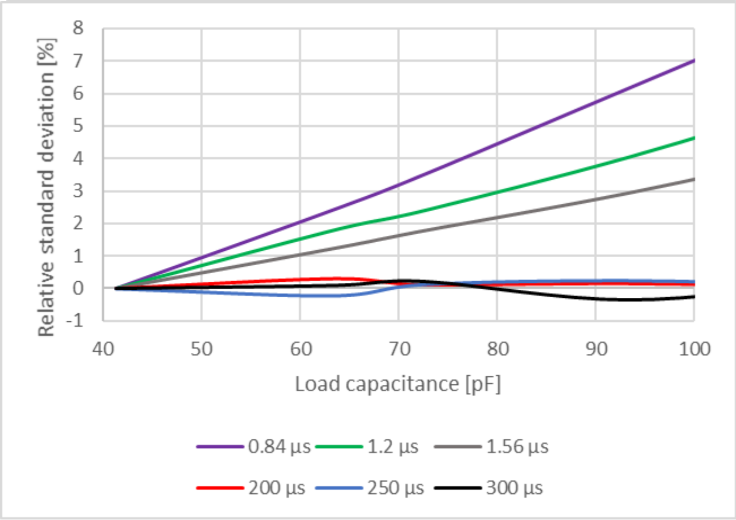
Output resistance of the LNE calibrator Rs=1.446 kΩ at 100 kHz (amplitude response on the top and phase response on the bottom)

1) Direct compensation method

- ✓ Performed on recorded raw data
- ✓ Measured correction factors of the wave shapes parameters of each waveforms

2) Digital compensation method

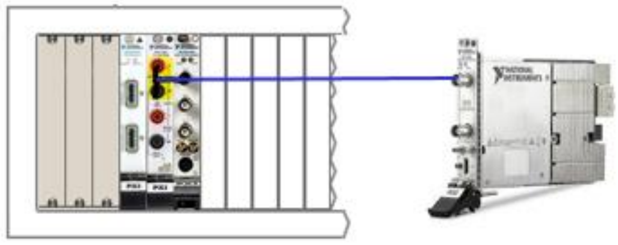
- ✓ Performed on simulated data using digital processing of the recorded raw shapes data



➡ A poster was prepared by HAEFELY AG on this topic " Towards a Traceable Step Calibration of High Voltage Impulse Digitizers "

CHARACTERISATION METHODS FOR LVMI

- **Characterization of scope cards such as NI-5122 and NI-5124 for DC, AC, LI (1.2/ 50 µs) and SI (250/ 2500 µs) voltages and NI 5164 and NI 5124 with composite wave shapes (DC+LI and DC+SI)**
- **Characterization of a DMM 4081 for DC and AC voltages for slow phenomena measurements**



Experimental setup for the digitizers characterization for the resolution check in time and amplitude

NI 5124 parameters	AC [%]	+/- DC [%]	+/- LI [%]	+/-SI [%]
Voltage (peak)	0,77	0,77	0,77	0,90
T_1 or T_p	-	-	0,56	3,1
T_2	-	-	0,096	1,6

NI 4081 parameters	AC [%]	+/- DC [%]	+/- LI [%]	+/-SI [%]
Voltage (peak)	0,46	0,26	-	-

NI 5122 parameters	AC [%]	+/- DC [%]	+/- LI [%]	+/-SI [%]
Voltage (peak)	0,37	0,50	0,37	0,36
T_1 or T_p	-	-	0,94	3,1
T_2	-	-	0,082	1,6

NI 5164 parameters	AC [%]	+/- DC [%]	+/- LI [%]	+/-SI [%]
Voltage (peak)	0,40	0,50	0,10	0,10
T_1 or T_p	-	-	0,5	0,7
T_2	-	-	0,3	0,3

- **Performances test of 12commercial digitizers (TR-AS 200/12 from Dr. Strauss, HiRES from HIGHVOLT) for AC, DC, LI (1.2/ 50 µs) and SI (250/ 2500 µs)**

HIRES 250/14 parameters	AC [%]	+/- DC [%]	+/- LI [%]	+/-SI [%]
Voltage (peak)	0,1	0,2	0,12	0,12
T_1 or T_p	-	-	0,6	0,6
T_2	-	-	0,4	0,4

TR-AS 200/12 parameters	AC [%]	+/- DC [%]	+/- LI [%]	+/-SI [%]
Voltage (peak)	0,1	0,1	0,12	0,12
T_1 or T_p	-	-	0,6	0,6
T_2	-	-	0,4	0,4

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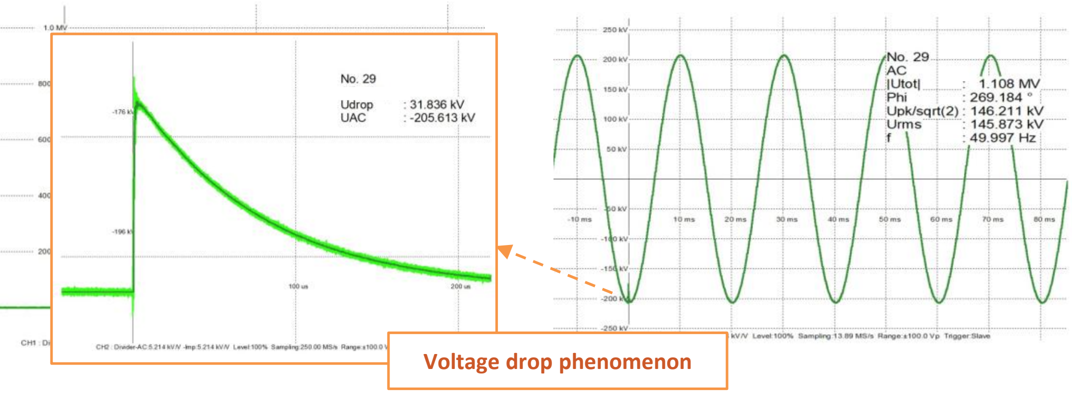
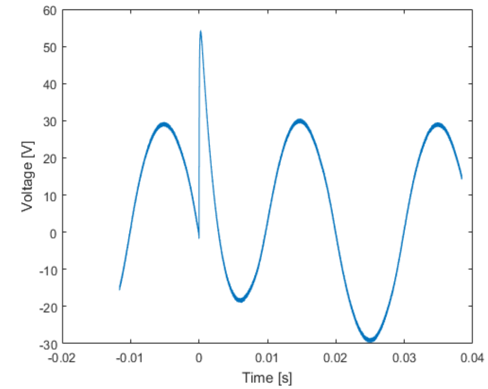
WAVEFORMS COLLECTED FROM INDUSTRY

- ✓ **Waveforms correspond to real measurements were collected from test laboratories to cover the possible combinations**
- ✓ **8 different combined (AC+LI/SI) and 7 different composite (DC+LI/SI, AC+LI/SI) wave shapes were chosen to be evaluated**
- ✓ **Raw data were used for the software development and uncertainty for combined and composite voltages.**

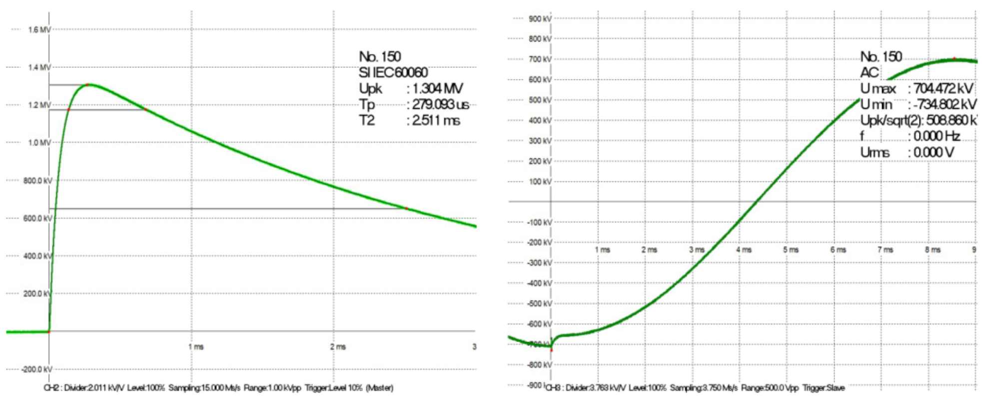
Combined voltage test (AC with superimposed LI)



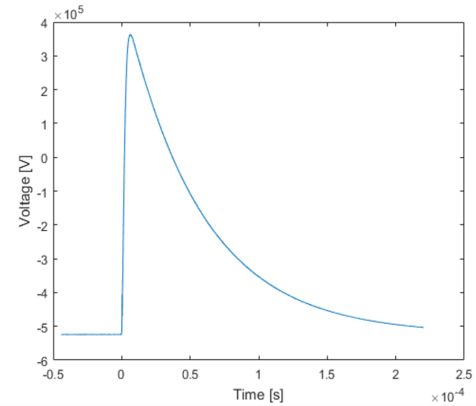
Composite voltage test (AC with superimposed SI)



Combined voltage test (AC with superimposed SI)



Composite voltage test (DC with superimposed LI)



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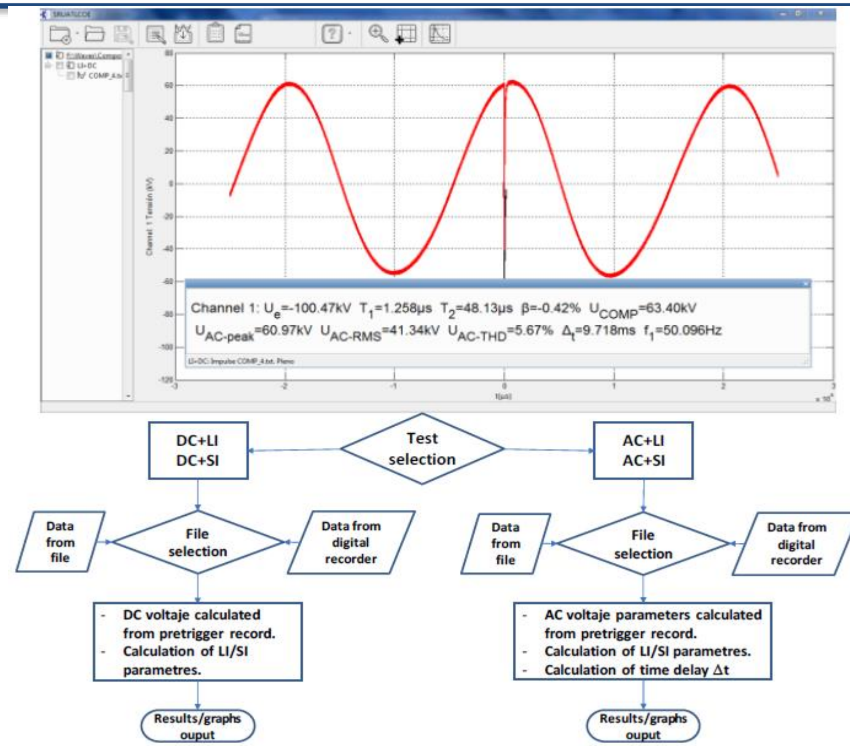
EVALUATION SOFTWARE

- ✓ **9 different evaluation software developed by 10 participating partners were compared**

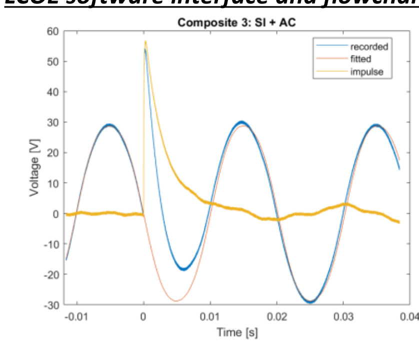
- ✓ **Agreements for combined voltages:**
  - **Preferred file formats (3 files per test)**
  - **AC/DC value should be defined before impulse (requirement for the recordings)**
  - **Value of a combined voltage and Δt need more accurate definitions**

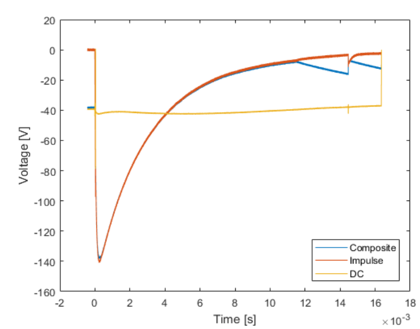


LCOE software interface and flowchart for combined and composite voltage analysis

- ✓ **Agreements for composite voltages:**

During the high-voltage calibrations, blocking capacitors should be preferred instead of sphere gaps (avoid crocodile tails in the impulse data)





A poster was prepared by LCOE – FFII regarding the universal measuring system developed in this project: low voltage measuring instrument + software (including composite and combined wave shapes) + HV-com2 divider

COMPARISON OF SOFTWARE

- ✓ **Evaluation results of the comparison show the standard deviation between the evaluated values for the given wave shape.**
- ✓ **Results are presented only if two or more partners were able to evaluate the parameters.**
- ✓ **The obtained uncertainties estimate related to the parameter evaluation are typically higher than with separate AC/DC/LI/SI.**

COMBINED AC+LI										
Combined voltage	AC peak	AC rms	THD	f	dt [μs]	Ut	T1	T2	β' [%]	Udrop
0.10 %	0.14 %	0.0 %	0.2 %	0.06 %	22	0.01 %	0.5 %	0.02 %	0.1	3.1 %

COMBINED AC+SI													
Combined voltage	AC peak	AC rms	THD	f	dt [μs]	Up	Tp	T2	Udrop	Ut	T1	T2	β' [%]
0.4 %	0.4 %	0.8 %	2.0 %	0.5 %	74	0.3 %	1.4 %	0.1 %	2.5 %	0.02 %	0.1 %	0.3 %	0.2

COMPOSITE DC+LI							
Composite voltage	DC	Ripple amplitude	Ripple frequency	Ut	T1	T2	β' [%]
0.5 %	0.1 %	26 %	-	0.1 %	1.1 %	0.2 %	0.1

COMPOSITE DC+SI										
Composite voltage	DC	Ripple amplitude	Ripple frequency	Up	Tp	T2	Ut	T1	T2	β' [%]
0.2 %	0.04 %	30 %	-	0.3 %	6.7 %	0.8 %	0.2 %	0.3 %	0.4 %	0.9

COMPOSITE AC+LI									
Composite voltage	AC peak	AC rms	THD	f	dt [μs]	Ut	T1	T2	β' [%]
0.7 %	1.9 %	0.9 %	2 %	0.2 %	1.7	0.8 %	8.8 %	12.9 %	2.8

COMPOSITE AC+SI													
Composite voltage	AC peak	AC rms	THD	f	dt [μs]	Up	Tp	T2	Ut	T1	T2	β' [%]
0.3 %	6.3 %	2.5 %	9 %	1.8 %	0.4	0.7 %	11.7 %	3.9 %	0.62 %	1.8 %	3.1 %	-

COMPOSITE AC (harmonics) +SI												
Composite voltage	AC peak	AC rms	THD	f	dt [μs]	Up	Tp	T2	Ut	T1	T2	β' [%]
0.6 %	4.5 %	15 %	4 %	1.7 %	0.5	2.3 %	1.8 %	8.9 %	1.9 %	2.5 %	4.2 %	-

HV-com²

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LVMI COMPARISON

Interlaboratory comparison

Experimental setup for the LVMI calibration using an amplifier based-calibrator

- **To compare several digital recording instruments using a travelling standard in order to qualify the digitizers**
- **To check the capabilities of the participating institutes in the area of combined and composite in LV fields**
- **To validate new calibration test procedures for the systems measuring composite and combined wave shapes through the Interlaboratory comparison**
- **To determine the comparison reference value (CRV), the degrees of (DoEs), and equivalent measurement uncertainty associated to the reference value**
- **To set up the traceability to the SI of combined and LV composite measurements by validating methods**
- **To check the IEC 61083-1 standard requirements for composite and combined voltage measurements**

LVMI COMPARISON

Comparison organization

Comparison measurements program

Composite LI/SI + DC				Combined LI/SI + AC				Composite LI/SI + AC			
Wave shape N°	T_1/T_p [µs]	T_2 [µs]	U_t [V]	Wave shape N°	U_p [V]	Δ_t [ms]	U_{drop} [V]	Wave shape N°	U_p [V]	Δ_t [ms]	U_t [V]
1	1.2	50	200	13	200	0 ms	10	25	200	0 ms	400
2	1.2	50	500	14	200	0 ms	20	26	200	+ 1 ms	400
3	1.2	50	800	15	200	0 ms	40	27	200	+ 2 ms	400
4	1.2	50	-800	16	400	- 1 ms	150	28	200	+ 3 ms	400
5	0.84	40	-800	17	400	+ 1 ms	150	29	200	0 ms	400
6	1.56	45	-800	18	400	+ 2 ms	150	30	200	+ 1 ms	400
7	250	2500	200	19	200	0 ms	10	31	200	+ 2 ms	400
8	250	2500	500	20	200	0 ms	20	32	200	+ 3 ms	400
9	250	2500	800	21	200	0 ms	40				
10	250	2500	-800	22	400	- 1 ms	150				
11	200	1000	-800	23	400	+ 1 ms	150				
12	300	3000	-800	24	400	+ 2 ms	150				

✓LVMI shall be with input impedance of 1 MΩ and < 50 pF.

✓LVMI shall be documented (load impedance (R//C) of the whole system, bandwidth, sampling rate, resolution).

- ❑ LNE calibrator was used as the travelling standard to generate the shapes from N°1 to N°32 following the comparison program.
- ❑ Technical protocol and experimental setup was provided by the pilot laboratory.
- ❑ 7 participating partners took part among the comparison. They used their own LVMI to measure the wave shapes. They had to report on the measurement results and uncertainties.

Parameters	Quantities to be measured
DC	Direct voltage (*Vdc*)
AC	AC peak (*Vp*)
LI	*Ut, T1, T2*
SI	*Ut, Tp, T2*
Composite DC+LI/SI	*Vcomp* = Vp (impulse peak) + Vp (AC) Time delay (*ΔT*) = t (impulse peak) – t (AC peak)
Composite AC+LI/SI	*Vcomp* = Vp (impulse peak) + Vdc
Combined AC+LI/SI	*Δt* = t (impulse peak) – t (AC peak) *Udrop* = Vp (AC) – Vp (impulse peak)

LVMI COMPARISON

Preliminary results

- ✓ Comparison reference value was determined from the weighted mean of all reported results.
- ✓ Results were evaluated according to the degree of equivalence (DoE) value.

Consistency test for U_{dc}

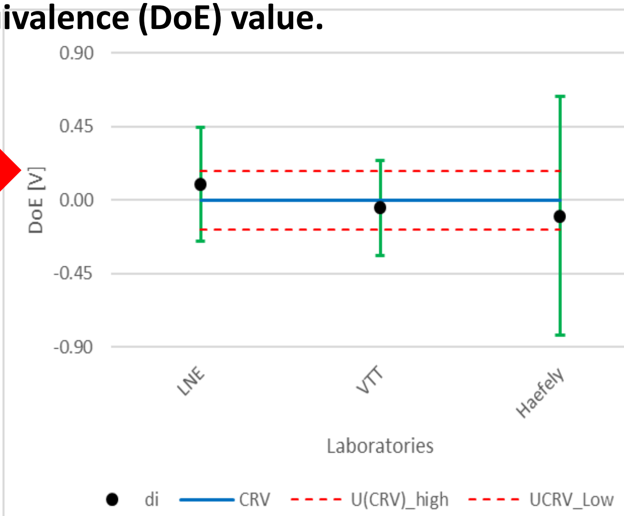
Wave shape N°	CRV [V]	U (CRV)	Consistency test, χ^2	P [%]	Excluded Y/N
1	- 102,49	0,17	4,2	12	N
2	- 100,36	0,17	13	0,15	Y
3	- 412,04	0,70	3,5	17	N
4	+ 412,07	0,70	3,5	17	N
5	+ 412,79	0,70	1,9	39	N
6	+ 411,72	0,70	1,8	41	N
7	- 101,96	0,17	4,0	14	N
8	- 100,43	0,17	5,6	6,1	N
9	- 408,66	0,69	1,9	39	N
10	+ 408,17	0,68	2,1	36	N
11	+ 407,95	0,68	1,1	57	N
12	+ 407,87	0,68	1,7	43	N

0.17%

$U_{composite}$

Wave shape N°	CRV [V]	U (CRV)	Consistency test, χ^2	P [%]	Excluded Y/N
1	+ 98,60	0,18	0,66	72	N
2	+ 402,33	0,73	2,0	38	N
3	+ 392,35	0,72	8,1	1,7	Y
4	- 392,68	0,71	3,5	17	N
5	- 392,03	0,72	2,0	38	N
6	- 393,46	0,72	6,8	3,4	Y
7	+ 99,18	0,19	0,55	76	N
8	+ 401,48	0,76	0,39	82	N
9	+ 393,24	0,75	4,3	12	N
10	- 393,68	0,75	1,7	43	N
11	- 393,86	0,75	1,1	59	N
12	- 394,14	0,75	1,1	57	N

0.19%



Degrees of equivalence of wave shape N°1 $U_{composite}$ with respect to the CRV at 100 V

Consistency test for U_t

Wave shape N°	CRV [V]	U (CRV)	Consistency test, χ^2	P [%]	Excluded Y/N
1	+ 201,09	0,30	0,42	81	N
2	+ 502,82	0,75	0,40	82	N
3	+ 804,6	1,2	0,38	83	N
4	- 804,7	1,2	0,11	94	N
5	- 805,0	1,2	0,012	99	N
6	- 805,4	1,2	0,88	64	N
7	+ 201,12	0,32	0,73	69	N
8	+ 501,89	0,79	0,36	84	N
9	+ 801,9	1,3	0,27	87	N
10	- 801,8	1,3	0,12	94	N
11	- 801,9	1,3	0,044	98	N
12	- 802,0	1,3	0,24	89	N

0.16%

T_1 / T_p

Wave shape N°	CRV [V]	U (CRV)	Consistency test, χ^2	P [%]	Excluded Y/N
1	1,370	0,008	1,0	59	N
2	1,320	0,008	0,59	75	N
3	1,316	0,008	0,33	85	N
4	1,330	0,008	0,33	85	N
5	0,985	0,007	3,3	19	N
6	1,615	0,008	0,33	85	N
7	250,1	1,3	1,6	45	N
8	250,6	1,3	0,22	90	N
9	250,4	1,3	2,5	29	N
10	250,4	1,3	1,3	53	N
11	201,2	1,0	0,13	94	N
12	300,6	1,4	3,6	17	N

0.7%

T_2

Wave shape N°	CRV [V]	U (CRV)	Consistency test, χ^2	P [%]	Excluded Y/N
1	50,41	0,12	2,7	26	N
2	50,64	0,12	6,2	4,4	Y
3	50,26	0,12	6,1	4,4	Y
4	50,37	0,12	2,2	34	N
5	40,49	0,10	2,1	35	N
6	45,28	0,11	3,6	16	N
7	2525,5	5,8	0,22	90	N
8	2546,1	5,8	1,3	53	N
9	2532,6	5,8	1,6	44	N
10	2532,9	5,8	0,80	67	N
11	1004,0	2,3	0,23	89	N
12	2997,1	6,8	0,0046	100	N

0.2%

LVMI COMPARISON

Discussions and first analysis

Uncertainties taken into account for the CRV and U(CRV) calculation:

Travelling standard calibrator; Calibrator drift behaviour; Load capacitance correction; Measurements uncertainty of each participating partner.

Parameter	Comment
Test voltage Ut	Results are well within the consistency criteria, thus the scale factor should be correct.
T1/Tp	Results are within the criterion, but two weak points have been observed 1) Consistency of Waveform 5 is somewhat weak, but this was expected because of the shortest T1 of the LI+/-DC waveforms. This might be due to the input capacitance compensation since the amplifier is quite sensitive to the load (maybe not all additional load cables have considered; maybe this observed deviation is due to the measurement uncertainty of 1 %). 2) There is an issue observed with wave shape N°12. It can be explained by the error introduced by the used software for parameters evaluation, which has the major uncertainty contribution. In general, we recommend verifying the software evaluation of all participants for all selected reference waveforms prior to the hardware calibration. However, no TDG available to be used according to the IEC 61083-2 standard.
T2, U_{dc},$U_{composite}$	Results are not within the criterion. But when correcting the DC offset in the $U_{composite}$ using the difference of the DC result values then all $U_{composite}$ values, all participants' results are with criterion. It can be explained by a DC drift compensation that must be taken into account. The amplifier probably has an integrated DC compensation control loop, and this is very likely also the case for all high-speed analog-to-digital converters.

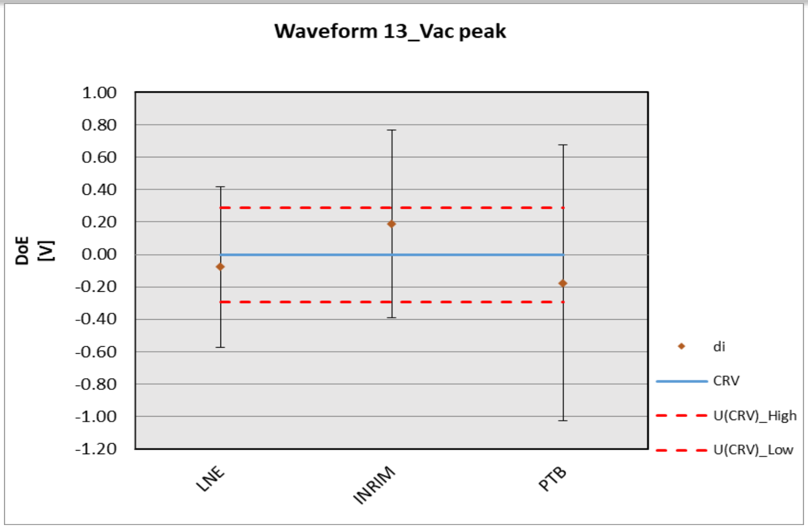
LVMI COMPARISON

Preliminary results and analysis

CONSISTENCY TEST FOR *AC peak (U_p)*

Wave shape N°	Std deviation				Up	
	U_p	Δ_t	$U_{composite}$	U_{drop}	CRV [V]	U(CRV)
13	0.18%			12%	199.95	0.29
14	0.28%			12%	200.01	0.29
15	0.40%			12%	199.92	0.29
16	0.28%	-7%		21%	400.03	0.58
17	0.26%	2%		15%	399.94	0.58
18	0.23%	3%		18%	400.11	0.58
19	0.48%			16%	199.92	0.29
20	0.48%			9%	199.72	0.29
21	0.47%			5%		
22	2.5%			4%		
23	0.43%			0.76%		
24	0.55%			0.92%		
25	0.54%		23%		197.73	0.29
26	0.48%	5%	24%		202.61	0.29
27	0.52%	2%	19%		198.78	0.29
28	0.62%	5%	12%		198.42	0.29
29	0.65%		34%		190.33	0.28
30	0.55%	24%	34%		202.42	0.29
31	0.46%	13%	28%		202.58	0.29
32	1.7%	7%	18%		202.80	0.30

0.15%



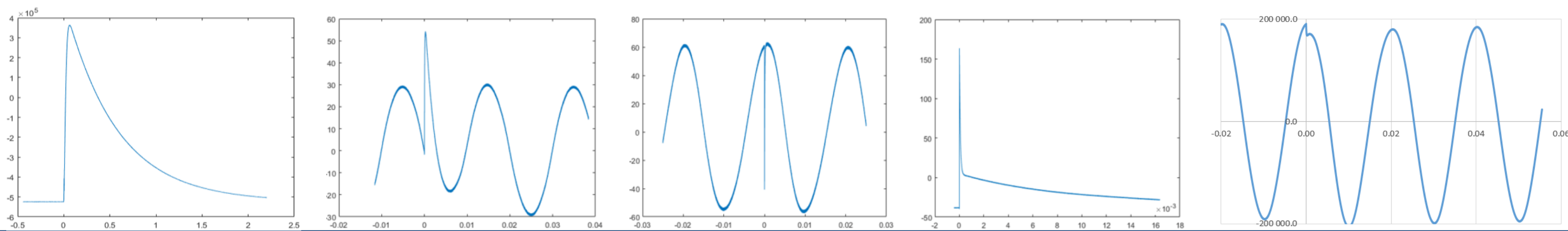
Parameter	Comment
U_p	Results are well within the consistency criteria.
Δt, $U_{combined}$	- Results are not within the consistency criteria. Significant deviations are observed between the participants' measurements, especially on the time parameters. - Further effort is needed for the parameters' evaluation to deal with complex phenomena such as Udrop determination. - Uncertainties are higher compared to the separate AC and impulse waveforms.

CONCLUSION

- **Proposal of recommendations and parameters was submitted to MT4 of TC 42 ‘High-voltage and high-current test techniques’ for the ongoing revision of the IEC 60060 series.**
- **Composite and combined wave shapes traceability to the International System of Units was ensured up to 1 kV using developed standard calibrators. One calibrator generates voltages up to 900 V with an uncertainty < 0.2% for the amplitude and 1% for the time parameters.**
- **Composite and combined wave shapes parameters were evaluated using the developed software.**
- **Requirements of the IEC 61083 were verified for LVMI through an Interlaboratory comparison.**
- **Calibration test procedures and uncertainty budget estimate were established for LVMI calibration.**

TRACEABILITY

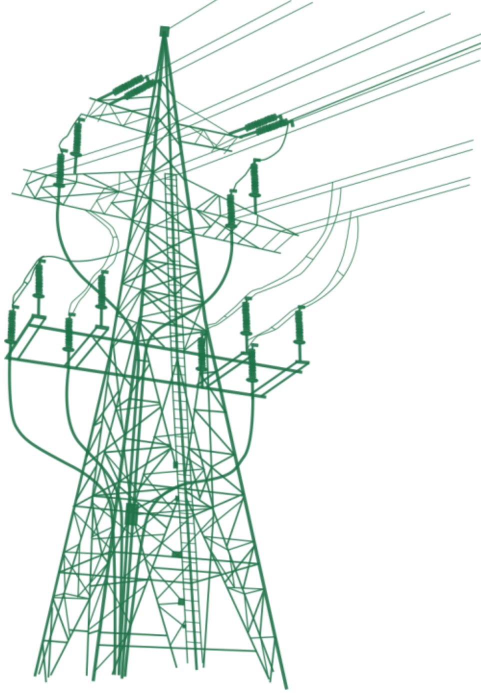
- Wave shapes
- Calibrators
- LVMI+Software



WP1 PUBLICATIONS

Proceedings	Johann Meisner	Support for standardisation of high voltage testing with composite and combined wave shapes	VDE High Voltage Technology 2020; ETG-Symposium	http+B4:F16s://oar.ptb.de/resources/show/10.7795/EMPIR.19NRM07.CA.20210215
Masters thesis	Stefano Caria	Sistema di misura per prove di tensione composite e combinate (Measuring system for composite and combined voltage tests)	Master Thesis -Politecnico di Torino	https://webthesis.biblio.polito.it/15631/
Article in peer-reviewed journal	Paolo Roccato	Towards a traceable divider for composite voltage waveforms below 1 kV	Springer - Electrical Engineering	https://doi.org/10.1007/s00202-021-01368-5
Proceedings	Hanane Saadeddine	Reference Calibrator for Combined and Composite High Voltage Impulse Tests	22nd International Symposium on High Voltage Engineering ISH 2021	https://doi.org/10.5281/zenodo.6993921
Proceedings	Abderrahim Khamlichi	Universal Measuring Unit for High Voltage Measurements	27th Nordic Insulation Symposium, NORD-IS 2022	https://www.ntnu.no/ojs/index.php/nordis/article/view/4898/4501
Masters thesis	Oskari iisakka	Development and testing of software for evaluation of high voltage composite and combined waveforms	Tampere University publications archive TREPO	https://urn.fi/URN:NBN:fi:tuni-202110287941
Proceedings	Jussi Havunen	Design and Verification of a Calculable Composite Voltage Calibrator	27th Nordic Insulation Symposium, NORD-IS 2022	https://doi.org/10.5324/nordis.v27i1.4491
Proceedings	Tim Christoph Schlüterbusch	Evaluation of composite voltage test parameters	2022 IEEE 12th International Workshop on Applied Measurements for Power Systems (AMPS)	
Proceedings	Ernst Gockenbach	SC D1 PS 1 / Testing, monitoring and diagnostics; Testing and experience with non-standardized, composite and combined voltages	cigré 2022	
PhD thesis	Stephan Passon	Metrological infrastructure for the measurement of superimposed impulse voltages in HVDC systems	Technische Universität Braunschweig publications archive	https://publikationsserver.tu-braunschweig.de/receive/dbbs_mods_00070624
Proceedings	Mohamed Agazar	The Usage of High Voltage Amplifiers to Setup Reference Calibrators for Combined and Impulse Voltages up to 1 kV	27th Nordic Insulation Symposium, NORD-IS 2022	https://www.ntnu.no/ojs/index.php/nordis/article/view/4875/4500
Article in peer-reviewed journal	Stefano Emilio Caria	D1: Development of standardized definitions for Combined and Composite High Voltage Tests	Springer - Electrical Engineering	
Article in peer-reviewed journal	Ahmet Merev	Realization of the Reference Composite Voltage Waveforms for Lightning Impulse (LI) Voltages Superimposed Over DC and AC Signals	Springer - Electrical Engineering	https://doi.org/10.1007/s12647-023-00634-0

THANK YOU FOR YOUR ATTENTION



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