FINAL PUBLISHABLE REPORT

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RMG: -		

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1. Overview

This project aimed at making a significant contribution to the pre-normative research required for measuring and testing Ultra High Voltage (UHV) equipment, which was required for measurement of composite direct current (d.c.) wave shapes, very fast transients (VFT), and fault detection in equipment under d.c. stress. New methods have been developed for medical applications and for improving the reliability of future high voltage grids. The project provided input to standardisation committees e.g. the International Electrotechnical Commission (IEC) and Technical committees (TC), in particular IEC TC38, IEC TC42 and IEC TC62C, therefore improving standards for i) medical x-ray equipment, ii) correct measurement of VFT, iii) transmitted overvoltages and iv) partial discharge (PD) measurements under d.c. stress.

2. Need

Before this project, pre-normative research was required to support the standardisation of UHV transmission measurement techniques and provide guidance for High Voltage (HV) metrology. In medical applications, traceable methods were needed for d.c. switching measurements, which are used in the measurement of x-ray acceleration voltage for the calibration of medical x-ray equipment. Instrument manufacturers needed new improved and standardised methods, both for medical staff safety and more accurate x-ray dosing for the patients. There was a need to provide a unified view between the instrument manufacturers and the users.

New methods were required for the calibration of equipment used in measurements of VFT in grid components. Traceable measurement techniques were lacking, which are critical for correct assessment in the detection of failures in the grid, especially in insulation coordination for Gas Insulated Switchgear (GIS) equipment used in densely populated areas. For energy measurement, correct designs with limited transmitted overvoltages were also essential for correct metering and for avoiding failures. Therefore, manufacturers of instrument transformers and GIS need traceability and new methods for the measurement of VFT, which are now covered by National Metrology Institutes (NMIs).

New methods for the detection and prevention of insulation failures by PD measurement techniques for equipment under d.c. stress was required by power grid operators and manufacturers of equipment for d.c. grids. Additionally, traceability for low level PD was limited and new techniques with noise suppression were needed.

3. Objectives

The project focussed on the metrology research which was needed to support standardisation in ultra-high voltages and fast transients relevant to the electrical power industry, for use in the standards being developed by IEC TC42 and TC62C and related groups. The project had the following scientific and technical objectives:

- To provide a substantial contribution to TC62C work. This will contribute to the revision of IEC 61676 (Medical electrical equipment – Dosimetry instruments used for non-invasive measurement of x-ray tube voltage in diagnostic radiology). The project will deliver calibration procedures, including a statement of uncertainty, for invasive dividers for different x-ray equipment applications.
- To provide a substantial contribution to TC38 and TC42 work (via task-force D1.63). This will contribute to the development of measurement techniques relating to transmitted overvoltages in terms of VFTO, thereby supporting the pre-normative International Council on Large Electric Systems (CIGRE) working group D1.60 (Traceable measurement techniques for very fast transients), which in turn will report it to TC42. The project will deliver calibration procedures and Calibration and Measurement Capabilities (CMC entries for VFTO to 100 kV, 10 ns, with a target uncertainty of 1 %.
- To provide a substantial contribution to TC42 work (via task-force D1.63). This will be achieved by contributing to the revision of IEC 60060 series (High-voltage test techniques), IEC TC42 MT17, and thereby supporting the pre-normative CIGRE working group D1.63 (Partial discharge measurements). The project will deliver a calibration procedure and CMCs will be updated to include low-level PD down to 0.1 pC with a target uncertainty of 0.01 pC.
- To work closely with the European and International Standards Developing Organisations, and the users of the Standards they develop, to ensure that the outputs of the project are aligned with their needs, communicated quickly to those developing the standards, and in a form that can be incorporated into standards at the earliest opportunity.

4. Results

4.1. X-ray equipment voltage measurement – Objective 1

4.1.1. Motivation

Many countries put substantial efforts into quality control programmes in diagnostics since x-rays are extensively used in medicine for the diagnosis of injuries and diseases. This represents the largest man-made source of public exposure to ionising radiation. One very important set of x-ray equipment performance characteristics involves the determination of the measurement uncertainty and the reproducibility of the high voltage level and the exposure time according to IEC 60601-1. Because of the diversity of the high voltage pulses supplied by x-ray high voltage tubes (and of the ripples and spikes usually superposed on the high voltage pulse), it is impossible to establish test procedures for the performance requirements of instruments for the measurement of the x-ray high voltage without the definition of the quantity under consideration.

The IEC has recently adopted a new quantity named PPV (Practical Peak Voltage) for the calibration and adjustment of x-ray high voltage tubes. This quantity is related to the spectral distribution of the emitted x-radiation and the image properties. X-ray generators operating at the same PPV value will produce the same low level contrast in the radiograms, even when the waveforms of the tube voltages are different. The traceability to the SI of this new quantity is necessary to guarantee the accuracy of the invasive and non-invasive instruments used in diagnostic applications such as radiology, mammography, dental, fluoroscopic and others. A traceable system for the measurement of the PPV and the exposure time, i.e. pulses that can have time durations from 200 µs to a few seconds, will ensure a better control of the x-ray dose. A reference invasive divider calibrated for every type of pulse was needed.

For technical reasons non-invasive instruments are usually used for the on-site calibration of x-ray high voltage tubes. In IEC 61676 it is noted that problems exist associated with non-invasive measurements, in particular the influence quantities, have not been resolved in diagnostic applications. A substantial number of measurements are still necessary to improve the physical understanding of these influence quantities.

In this work there were two major challenges;

- The first challenge was to develop a reference high voltage measuring system traceable to the SI for the measurement of high voltage X-ray pulses for voltages up to 150 kV and for all type of pulses with duration between 200 µs and few seconds. It would include a validated algorithm for waveform processing, time parameter calculations, and PPV measurements. Other quantities such as average peak value and mean peak value, and measurements of current under high voltage, would be studied..
- The second challenge was to develop a method for on-site calibration of non-invasive instruments by comparison with the reference system developed in the first challenge. A test procedure would be provided for the evaluation of the influence quantities, and a comparison between several non-invasive instruments would be performed to check that non-invasive instruments can supply results that are comparable to those obtained by invasive instruments.

4.1.2. Research undertaken

In order to check the linearity of commercial invasive dividers, high voltage waveforms for voltages typically used by x-ray machines were generated, which is d.c. voltage with 30 – 100 μs rise and a time duration of between 200 µs and a few seconds (Figure 1). High voltage measurements have been performed at d.c, a.c and at switching impulse in order to validate that the voltage dividers are fast enough to measure possible transients for the shortest pulses, i.e. 200 µs. This gives input to calculating of correction factors of the invasive divider for the used waveforms. Calibration procedures, including a statement of uncertainty, for invasive dividers for different x-ray equipment applications are now available.

A traceable system has been developed for the measurement of the PPV and the exposure time for calibration of the dose in X-ray machines and to make comparative measurement with the presently used kilovolt peak (kVp) meter (Figure 2). The high voltage (HV) acceleration voltages from the generator often has superimposed ripples (Figure 1).

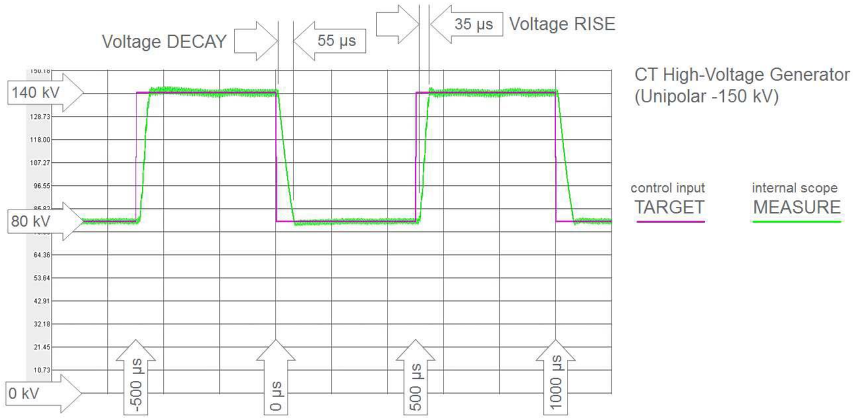


Figure 1: Pulses generated by the generator.

The first step was to develop a reference high voltage measuring system traceable to the SI units for the measurements of X-ray high voltage pulses for voltage up to 150 kV. The reference system is composed by two paired resistive and compensated invasive dividers with 10 MHz bandwidth. The first one is for the anode voltage up to 75 kV and the second one is for cathode voltage down to -75 kV. They are combined with a storage calibrated digitizer with a bandwidth of at least 100 MHz, 12 bits resolution and 2 GS/s sampling frequency.

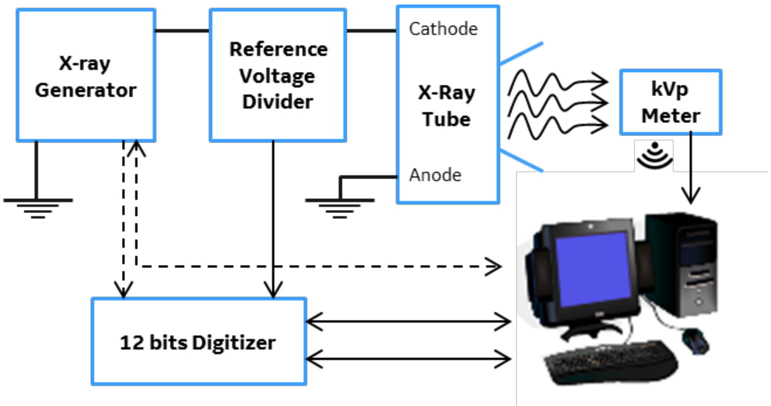


Figure 2: The kVp comparative measurement setup.

4.1.2.1 Selection and characterisation of HV dividers

Two voltage dividers from ROSS Engineering were selected from 4 candidate types, with 8 models of each. Routine characterisations were performed to verify the dividers' ability to carry out the measurements without causing significant errors. These errors are essential for the calculation of the uncertainty of measurements. Proximity effects, load impedance effects, temperature effects, frequency effects and the self-heating have been determined. The results show that the proximity effect is important, a distance of at least 60 cm has to be respected for both dividers to minimise this influence at least lower than 0,15 %. The influence on the scale factor of the load impedance is found for both dividers to be 44·k – 46 ppm/pF for capacitive loads and -0.016 – 0.024 %/kΩ for resistive loads. Temperature dependence has been determined at 1000 V at frequencies of 60 Hz, 1 kHz and 10 kHz, the relative deviation from 10 °C to 40 °C is less than 0.1 % for both dividers. The frequency linearity has been determined by measuring the scale factor at low voltage (1000 V) for frequencies up to 100 kHz. The results show that the relative change against frequency from d.c to 100 kHz is about 1 % especially observed at low frequencies (d.c. to 300 Hz). For the self-heating, this effect is usually determined at d.c voltage by increasing the voltages from 0 V to the nominal voltage and applying the nominal voltage for a large time (for example 30 minutes to one hour) and after that by decreasing the voltage to 0V. It was found that this effect is less than 0,05 %.

The dividers were further characterised at LNE for frequency response, proximity effect, frequency linearity, d.c and a.c linearity, influence of output impedances, temperature effect. Both dividers have been characterised at FFII (Figure 3) at high voltage for different waveforms; a.c., d.c, LI, SI, square waveform with duration from 200 µs to two seconds (Figure 1).

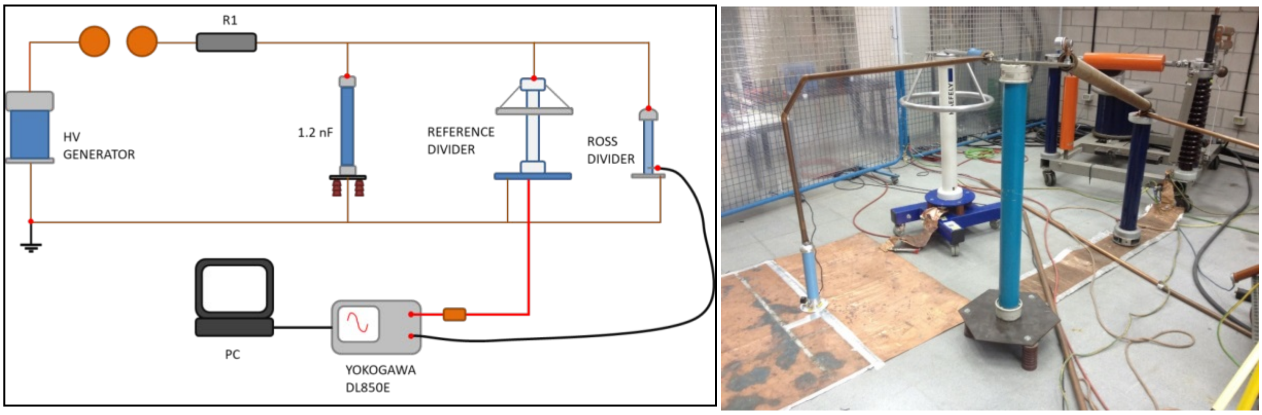


Figure 3: Calibration set up at FFII for lightning impulse, switching impulse and rectangular impulse measurements.

4.1.2.2 HV linearity

High voltage techniques described in IEC 60060-1 and -2, have been used to determine the linearity of the reference system for a known, traceable and a standardised waveform. The reference system is calibrated for lightening impulse (1.2/50 µs), switching impulse (250/2500 µs), chopped impulse, rectangular impulse, AC voltage and d.c. voltage. Every calibration is performed by comparison to a high voltage reference system traceable to SI, which is shown in Figure 3.

The lightning impulses have been carried out in eleven voltage levels up to 120 kV and ten repetitions for each voltage level. The switching impulses 250/2500 µs have been carried out in six voltage levels up to 75 kV, ten impulses for each level and for each polarity (positive and negative). The front time was modified in order to apply two other different switching impulse waveforms, i.e. 134/2760 µs and 70/2760 µs. The switching chopped impulse technique was used for the calibration points for 0.2 ms, 1 ms, and 10 ms duration. For d.c. chopped impulse technique , the calibration points for 100 ms; 500 ms; 1 s; 2 s duration has been used.

It is shown from the results that for d.c chopped impulses or switching impulses (impulse duration ≥ 1 ms) the divider reaches its ratios for d.c. and a.c. voltages. Results for the scale factors of chopped switching impulses at 0,2 µs, full switching impulses and full lightening impulse are comparable to each other within the uncertainty of measurements. The linearity of the dividers against voltage has been found at maximum equal to 0,3 % for the scale factor, 1,6 % for the rise time and 0,7 % for the duration of the pulse. Results for time parameters present small error, for the rise time of about 1 % and are in accordance within the uncertainty of measurements. A significant error for the duration of the pulse of about 3 % has been observed; switching impulse is a double exponential waveform with a slow decreasing after the peak voltage. Error of 3 % is then evident for the duration of the pulse because the dividers are not linear at low frequencies and that affect the tail of the waveform.

Table 1: Results of the high voltage characterisation.

Waveform type:	Scale factor	Error for time parameters	
		Front time	Duration
d.c. voltage, 70 kV d.c. chopped up to 2 s, 70 kV d.c. chopped at 100 ms, 70 kV	999.97 999 999		
a.c. voltage (50 Hz). 50 kV	998.1		
Switching impulse 70 /2760 µs, 70 kV Switching impulse 134 /2760 µs, 70 kV Switching chopped at 0,2 ms, 70 kV Switching chopped at 1 ms, 70 kV	992 992 995 998	-0.2 % -0.9 % -0.1 %	0.1 % -3.0 % -3.2 %
Lightning impulse 1.2 /50 µs, 70 kV	995.0		

Table 2: Linearity of the divider from 10 kV to the maximum voltage.

Waveform type:	Scale factor	Front time	Duration
d.c voltage	0.03 %		
a.c. voltage	0.10 %	0.4 %	0.4 %
Switching impulse 70 /2760 µs	0.20 %	1.2 %	0.5 %
Switching impulse 134/2760 µs	0.30 %	1.6 %	0.7 %
Lightning impulse 1.2 /50 µs	0.10 %		

4.1.2.3 Technical procedure

From the results of characterisation, it was decided to implement a calibration procedure, valid for the calibration of a large high voltage X-ray units available in the market (Dynalyser IIIU from Radcal manufacturing, GiCi-PMI Model H1049 from bleeder manufacturing etc). For waveforms with pulsed width above 1 ms, the frequency linearity could be measured at low voltage for example at 1000 V from d.c. to 10 kHz before the main calibration to avoid environment effects. The maximum deviation of the scale factors against frequency is kept for uncertainty of calculation. The linearity against voltage could be done at d.c. chopped impulse or at d.c. voltage for large pulses one time a year.

For waveforms with pulse width from 200 µs to 1 ms, the linearity frequency could be performed from d.c. to 100 kHz before the main calibration. The linearity against voltage could be done at switching impulse (for example 20/1000 µs, 250/4000 µs) or at lightening impulse for very fast pulses. Linearity at d.c. chopped impulse at 0.2 ms could also be checked every year.

For the measurements of time parameters, the linearity against high voltage is difficult to establish because they are usually correlated with the uncertainty of the voltage. Relationships could be identified by experience between the uncertainty of the voltage and its impact on the uncertainty of the rise time and duration of the pulse. Coefficients of 4.1 and 1.4 have been identified respectively for the rise time and the duration of the pulse.

Time parameters are also affected by the frequency non linearity. At low frequency it produces errors for the measurement of the duration of the pulse. At high frequency it affects the rise time. When the frequency non-linearity is higher than 1 % and in order to enhance the uncertainty of measurements for non-ideal high voltage dividers presenting very high frequency non-linearity, fast Fourier transform (FFT) and an inverse FFT based method could be used to correct this non-linearity. An ideal step voltage is injected to the HV divider. The step response of the clamp meter (or dividers) is measured by using its digitiser in order to minimise its effect on the result.

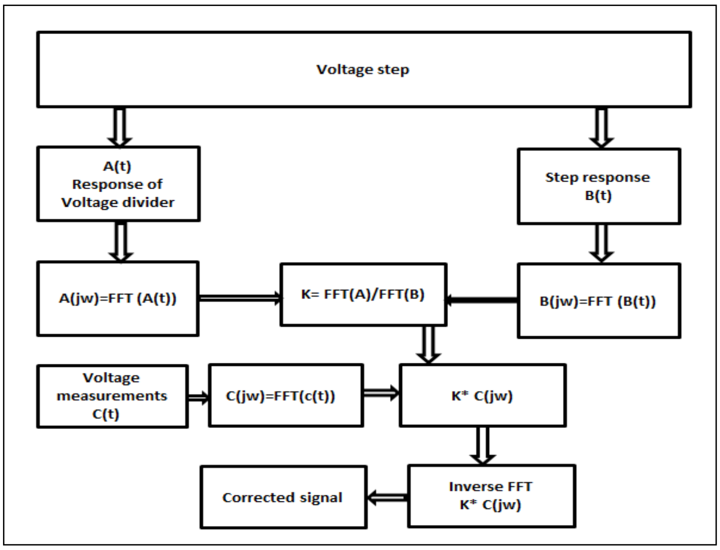


Figure 4: FFT and Inverse FFT technique.

Both FFT of the input and output steps are calculated (Figure 4), after being improved by some signal processing for a best FFT calculation; Sweeping, balancing, zero-padding, normalisation, filtering, to determine the errors for each frequency component. During the measurements the same signal processing is performed, the correction is applied to obtain the corrected signal in time domain. The frequency non-linearity could be reduced by this technique down to 0,5 %.

4.1.2.4 Measurements of the current under high voltage

A method of measurement of current under high voltage has been developed by LNE and CEA with support from GEMS using a commercial clamp meter, involving an FFT technique for the determination corrections of the clamp meter using step response measurements. Inverse FFT is used for the calculation of the waveform parameters after being corrected. The uncertainty for the measurements of this current (from 100 mA to 2 A up to 150 kV) is < 0.5%.

4.1.2.5 Correction factors from kVp to PPV

In diagnostic radiology clinical x-ray units, the measurement of the tube voltage is usually performed with non-invasive, portable, electronic devices, often called kV-meters. Very few commercial kV-meter models measure the PPV with the requirements of IEC 61676. The kV-meter errors increase with the percentage of ripples (Figure 5). A method for PPV determination from measurements with a kV-meter, that measures only the average or the average peak voltage, is needed.

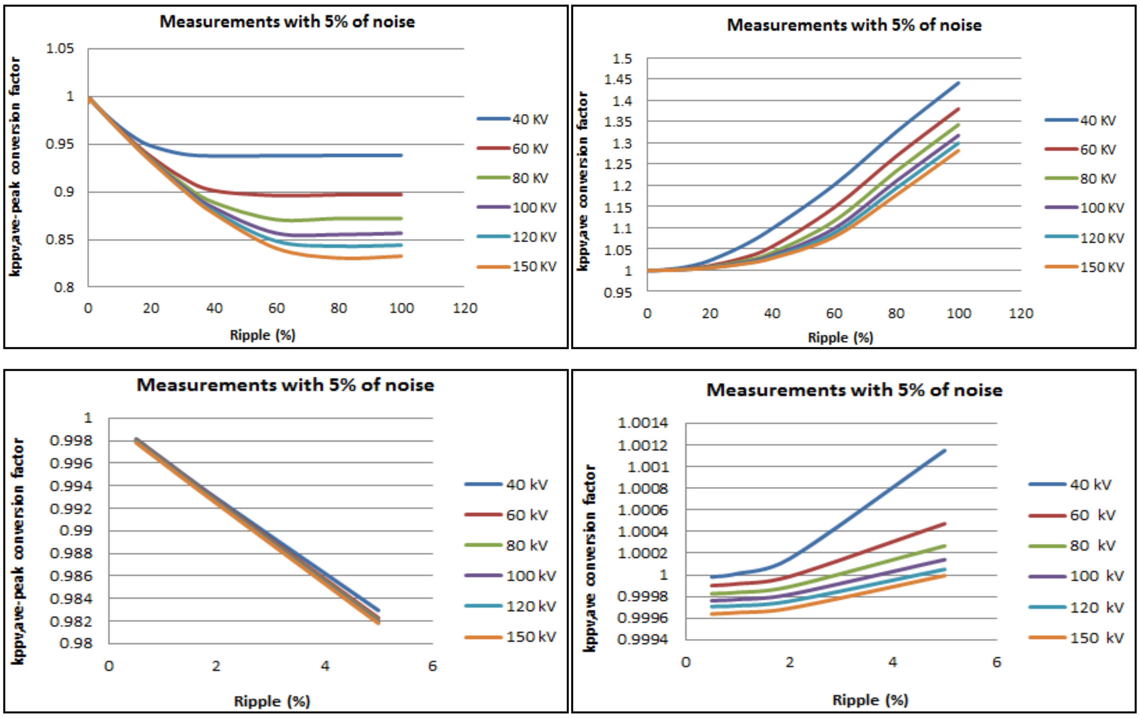


Figure 5: Example of correction factors from average peaks and mean value to the PPV.

LNE has determined correction factors for the conversion kVp quantity (average peaks and mean value) to PPV quantity by simulation and validated by a measurement with the CEA generator. It was demonstrated that the conversion factor is proportional to the ripples, the level of voltage, the rise time and the fall time.

4.1.2.6 Uncertainty of measurements

The uncertainties of measurement are calculated according to the GUM within the contributions coming from the reference high voltage dividers, the digitizer and the software. Table 2 presents the uncertainty budget for the voltage, the rise time and the duration of the pulse. The obtained uncertainties without using the FFT and inverse FFT technique are 0,64 % for the PPV (Table 3), 3 % for the rise time and 2 % for the duration of the pulse.

Table 3: Uncertainty budget for the PPV, the rise time and the duration of the pulse.

Uncertainty sources For the voltage	**Contribution (k=1)**
Frequency linearity	1 % ÷ 2√3
Influence of temperature	0,04 % ÷ 2√3
Self-Heating	0,1 % ÷ 2√3
Calibration at low voltage	0,2 % ÷ 2
Digitizer	0,3 % ÷ 2√3
Influence of software	0,1 % ÷ 2√3
Voltage linearity	0,3 % ÷ 2√3
Uncertainty for the voltage (k=2)	0,64 %
Uncertainty sources for the rise time	**Contribution (k=1)**
Influence of the uncertainty of the voltage	4×0,64 % ÷ 2
Dividers linearity	1,6 % ÷ 2√3
Maximum observed error	0,9 % ÷ 2√3
Determination of particular points (times at 10 % and 90 %)	0,15 % ÷ 2√3
Influence of the digitizer	0,0 %
Uncertainty for the rise time (k=2)	3 %
Uncertainty sources the duration	**Contribution (k=1)**
Influence of the uncertainty of the voltage	1 ×0,64 % ÷ 2
Dividers linearity	0,7 % ÷ 2√3
Maximum observed error	3,1 % ÷ 2√3
Determination of particular points (times at 50 % or at 90 %)	0,15 % ÷ 2√3
Influence of the digitizer	0,0 %
Uncertainty for the duration (k=2)	2,0 %

When the FFT and inverse FFT technique are used the frequency, non-linearity is reduced to 0.5 %. In this case, the uncertainties are enhanced to 0,4 % for the PPV, 2 % for the rise time and 1 % for the duration of the pulse.

4.1.3. In-situ measurements and non-invasive calibration set-up

Instruments using the X-ray beam to measure kVp (aka kVp-meters) are qualified as “non-invasive”, as they do not modify the X-ray equipment configuration – equipment behaviour remains unchanged. In comparison, external reference high-voltage dividers which are physically connected to the X-ray equipment modify the equipment behaviour, therefore they are qualified as “invasive”. Reference divider and connection cable to the equipment bring additional high-voltage capacitance, which slows down voltage rise time and fall time, and filters the ripple. Because rise time, fall time and ripple contribute to PPV calculation, a “minimally-invasive” configuration has been used for comparison between kVp-meter measure and reference divider PPV.

To perform short X-ray exposures (below 100 ms) with 10 µs range voltage rise and fall time, the X-ray source used comes by-design with a low capacitance: 330 pF total, spread in high-voltage transformer 210 pF, X-ray tube and high-voltage cable 120 pF (hv cable is very short, 70cm only). The source is unipolar, anode grounded, operating up to -140 kVp. In the following experiments exposures are limited to -75 kVp to be compatible with reference divider selected by LNE for the project. ***Note: both negative voltage and relative voltage (absolute value) are used in this document to express high-voltage – on some records kV “rise” may go down and “decay” up.***

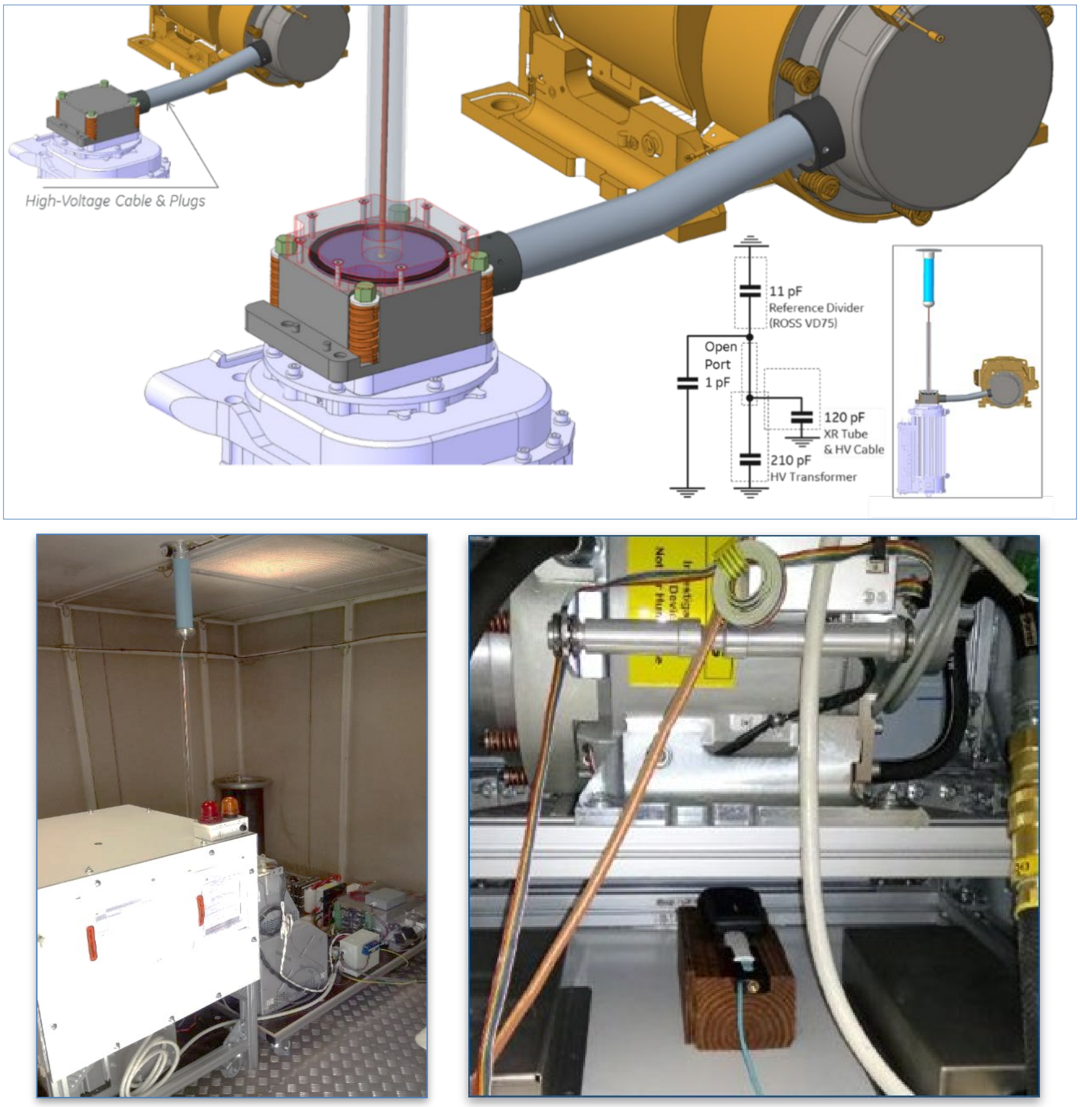


Figure 6: In-situ calibration with two reference dividers, Ross and North Star PVM-5.

The entire source is placed in a large faraday cage to allow required free air volume around the reference divider (Figure 6). Its connection to the source is provided between the X-ray tube and the high-voltage generator. High voltage connector has been modified to receive a long open port receiving a copper wired up to the reference divider. This port is not shielded, resulting in around 1 pF additional capacitance. Insulation is provided by plastic parts filled with high-voltage oil.

In a first measurement session kVp-meter outputs are compared to reference voltage divider and generator analog output “base” value reported by the digitizer. Base value is defined as “the value of most probable lower state” of the signal (excluding rise and fall sections). Six exposures are recorded: 10 ms, 100 ms and 1000 ms at 70 kV – 100 mA, and 10 ms, 100 ms, 1000 ms at 75 kV – 100 mA. Results show around 1% difference between reference divider base value and RTI Black Piranha (old generation kVp-meter), and around 0.5 % between reference divider base value and RaySafe X2 (new generation kVp-meter).

In a second step serval series of measurements have been performed. Close to the kVp-meter full scale reading limits, significant divergences with reference PPV have been observed at high current short exposure duration before saturation, and at low current short exposure before losing reading capability. Limits may vary between manufacturers and between technologies. PPV calibration based on reference divider measurements should allow to better define usage limits without being too much restrictive.

For KVp meter probe positioning, only center positions give a good correlation with PPV reference. Also, when located too close to the source (~20 cm), kVp-meter saturates at high mA (550 mA, 75 kV, 100 ms). In confined environment, when significantly shifted from central position kVp-meter sometimes reports misleading values (mainly at high mA), underestimating PPV by around 30 %.

In PPV calibration procedure based on reference voltage divider records and PPV computation, quality and integrity of the voltage measurement are critical to set accurate PPV reference. Voltage measurement should not be truncated (integrality of the signal should be recorded above 20 kV PPV voltage limit). Entire mA range and short exposure durations should be considered. Dynamic records highlight response time limitation of the kVp-meter measure chain. Intended use of kV-meters is actually non-invasive PPV measurement, they should not be used for real-time voltage acquisition, until new technologies bring them this capability.

4.1.4. Progress beyond the state of the art

In-situ calibration of the acceleration voltage and emission current in X-ray machines has been achieved and is now available for implementation for manufacturers. Further, a new method for dose calibration, the practical peak voltage (PPV), has been developed to support the earlier used dose calibration by the kVp meter, supported by an uncertainty analysis for the PPV (Table 3). A reference system for the calibration of pulsed X-ray high voltage tube has been developed, characterised according to the IEC 60060-1, and the uncertainty of measurements has been evaluated according to IEC 60060-2. A technical procedure has been proposed to IEC TC62C for amendment of IEC 61676 to simplify the characterisation of X-ray high voltage units. This procedure includes an FFT and inverse FFT technique to be used to correct the frequency non-linearity of the high voltage measuring unit. A procedure for the calibration of an X-ray system is shown in Figure 7.

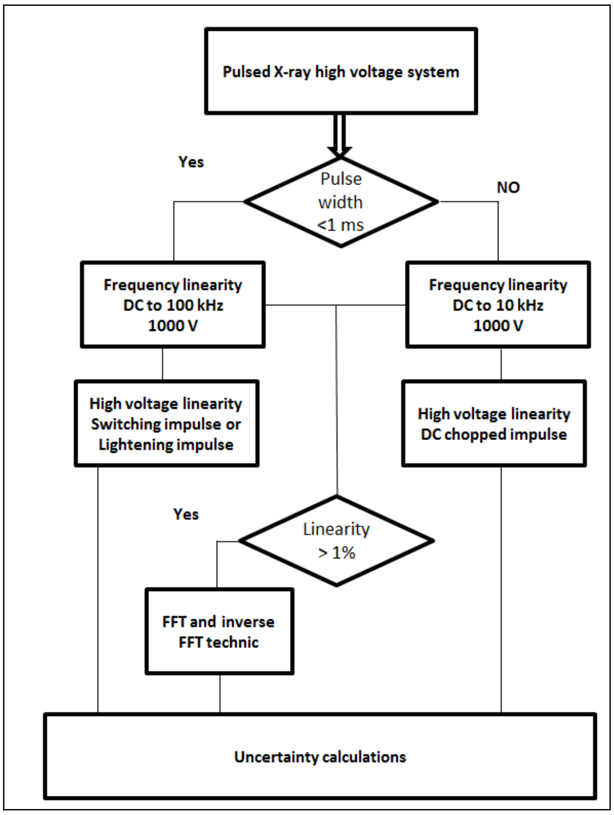


Figure 7: Procedure for the calibration of X-ray systems.

4.1.5. Recommendations to IEC TC62C

The following recommendations of amendments of standards have been sent to IEC TC62 committee:

- An overview of the new reference system for the measurements of PPV,
- Recommended procedure and performance for the qualification of invasive measuring systems for the measurements of PPV,
- Example of uncertainty calculation for the measurements of the Practical Peak Voltage using invasive technique,

- Convolution and Deconvolution techniques to enhance the frequency response of invasive high voltage measuring systems for the measurement of the Practical Peak Voltage,
- Recommended correction factors for the conversion of kVp (average peak and mean value) to PPV,
- Description of the reference system for the calibration of non-invasive instrument and study few kVp meters by comparison to the invasive reference system,
- Recommended limits of the use of kVp meters for the measurements of the PPV.

4.1.6. Summary

Reference system for the calibration of pulsed X-ray high voltage tube has been developed by LNE, FFII, GEMS and CEA. Available and traceable high voltage techniques according to IEC 60060-1&2 have been used to characterise the reference system for in-situ measurements. The evaluation of the uncertainty of measurements has been discussed. A technical procedure has been proposed to simplify the characterisation of any X-ray high voltage units. This procedure includes an FFT and inverse FFT technique to be used to correct the frequency non-linearity of the high voltage measuring unit (Figure 7). The reference system includes also a reference method for the measurements of the current under high voltage up to few amperes for voltage up to 150 kV.

A set-up for the characterisation of non-invasive instruments has been developed at GEMS with support from LNE. The set-up includes very fast high voltage X-ray generators associated with its internal measuring systems, high voltage X-ray tube and several kVp meters. The measurements are performed by comparison with the invasive reference standard. The set-up is installed in Faraday cage, different precautions have been considered in order to carry out accurate measurements and special adaptations have been made in order to avoid stray capacitances which could affect the performance of the generators.

Several kVp meters have been studied and results have shown a good agreement with the internal measuring system of the generators and with reference external voltage dividers. For 100 ms X-ray exposure standard duration, PPV was found within the reference measurement uncertainty, while for faster pulses the kVp meters have shown both good and inappropriate results depending on beam intensity (mA) and kVp meter probe positioning.

A paper on a reference system for the Practical Peak Voltage calibration in Radiology and diagnostic applications was published at CPEM2018 [3]. A paper at ISH2019 [11] on how to characterise invasive dividers for X-ray equipment has been accepted for publication in springer journal. A third paper at CIM 2019 on the results of characterization of several kVp meters [17]

A recommendation report to TC62 has been written and shared, describing the equipment, recommended test procedure for the characterisation of X-ray invasive dividers, how to calculate the uncertainty of measurements, the techniques to improve the uncertainty of measurements, recommended conversion factors for non-invasive instruments and recommendations for the use of kVp meters.

Table 5: PPV Capabilities for the partners after the project

NMI	Peak Value	Expanded uncertainty	Front time range		Front time	Expanded uncertainty	Tail time	Expanded uncertainty
	kV	%					µs	
LNE	150 (PPV)	0.4	30-100 µs		30 µs	2 %	> 30	1 %

4.2. Methods for testing with very fast transients (VFT) – Objective 2

4.2.1. Motivation

The aim of this objective was to provide support for the study of very-fast transients in collaboration with CIGRE D1.60, specifically by developing new calibration techniques for the measurement of very fast transients in Gas Insulated Systems (GIS) and by providing traceability for the measurement of transmitted over-voltages in instrument transformers.

Measurements of fast transient phenomena are routinely performed for the purposes of equipment testing, system condition monitoring and system performance assessments. The very fast transient overvoltage (VFTO) is a major concern for equipment connected to high voltage GIS because of the risk of damage to instruments and control systems connected to the low voltage side. Efforts to determine the effects of VFTO on equipment require sufficiently accurate measurements of the peak and time parameters of the transient pulses.

During switching operations or earth faults in SF_6 gas insulated switchgear, very fast transients (VFTs) occur and stress the equipment in GIS, adjacent equipment and secondary circuits connected to current transformers. To measure the VFT overvoltage, wideband sensors like B-dot probes or capacitive probes are used. In order to assure the reliability of corrective actions intended to reduce VFT over-voltages, wideband sensors had to be calibrated and traceability was required. A calibration SF_6 set-up would be developed to generate 100 kV, 10 ns rise time voltages including a reference measuring system (uncertainty 1 %) to calibrate the wideband sensors used in GIS.

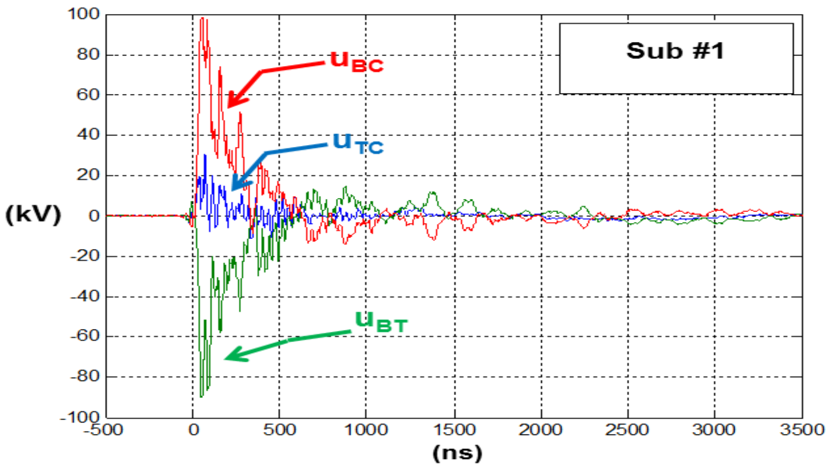


Figure 8: Recorded transients in a GIS system.

In the present version of IEC 61869-1, the test conditions for both GIS and air-insulated systems are given, but there is no guidance on the measurement methods that are used to assess the uncertainty of measurements because of a lack of traceability for HV transients with 10 ns and 500 ns rise times. The traceability for this measurement would be established, and methods would be proposed for the uncertainty estimation. The target measurement uncertainty is 2 % for the front time and 1 % for the peak value.

This calls for specific metrological solutions to apply new measuring procedures for traceable measurements of transients. This work package was split into two tasks:

- The first challenge was to develop hardware and methods for the creation and calibration of VFTO in GIS. A new reference measuring system for voltages up to 100 kV and a rise-time smaller than 10 ns would be developed and characterised.
- The second challenge was to develop a reference measurement system and a traceable measurement method for transmitted over-voltages in instrument transformers. A low-voltage method in IEC 61869-1 would be validated at full voltage in an instrument transformer. The target expanded measurement uncertainty for the system for an impulse wave shape of 0.5/50 µs duration, was set to be better than 1 % for the amplitude and better than 2 % for the time to peak and tail time.

4.2.2. Reference measurement systems

Measurement systems for HV were developed for both the VFT application, i.e. front times <10 ns, and transient overvoltages in instrument transformers, with front times <0.5 µs. A new digitizer was needed to make a major contribution to this project, with a fast enough settling time combined with an effective dynamic range exceeding 10 bits. New wideband attenuators between the HV dividers and also new HV dividers with a settling time well below 10 ns were needed. A special effort was therefore put into finding new design solutions for the system components and characterising the response of the digitizer, attenuators and HV dividers especially when working together. For the VFT calibration of GIS sensors a completely new system also with a new generator had to be designed.

4.2.2.1 Design and characterisation of a transient recorder

The design of a set-up for in-situ calibration of GIS sensors for VFT measurements up to 100 kV within 10 ns described in the next section needs a digitizer which settles faster than 6 – 7 ns within 0.5 % when applying a voltage step using a 50 Ω input impedance. The application in the second section for traceable HV measurement of overvoltages in instrument transformers uses the recorder with 1 MΩ input impedance.

A HV measurement system consists of a transient recorder, a divider and a generator. The geometries needed for the GIS system are quite different from the applications used for Lightning Impulse measurements (LI) with waveshapes (Figure 9 from IEC 60060-1) down to 0.84 µs front time T1 and 50 µs time to half value T2, where the latter waveshapes are used for the instrument transformer overvoltage measurement. The front times of the waveshapes in the GIS are about 100 times faster, which means that geometry and impedance matching the measurement set-up is of essence because propagation times in the set-up are not negligible. In fact, propagation is also detectable in LI, since that time domain is at the brink of needing such a description and is still treated with low frequency theory, i.e. lumped impedances.

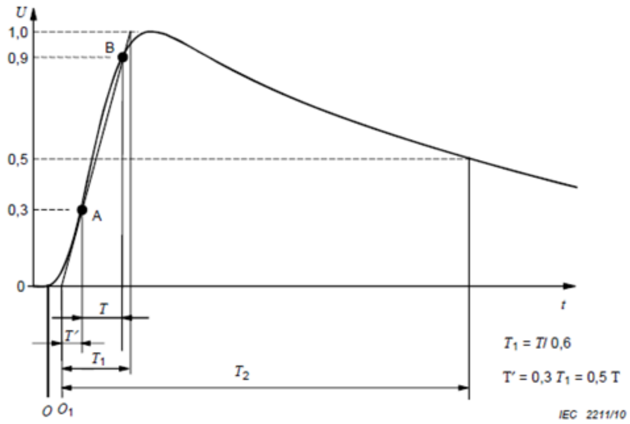


Figure 9: Definitions of lightning impulse parameters.

Many digitizers exist with bandwidths of several of GHz and tens of GS/s, but typically have only 8 bit resolution in single shot mode which is too low for the needs. There are examples of digitizers with higher dynamical range, but they do not qualify because of a limited settling time. Other digitizers with resolution up to 12 bits having a band width of 150 MHz, e.g. National Instruments PXI-5124, are specialised for LI measurements. The requirements of a recording instrument for lightning impulse defined in IEC 61083-1, have a much slower wave envelope than needed for VFT measurements. Several recorders on the market were studied for the LI application in the 14IND08 ElPow project, but none of these qualified for VFT in GIS.

After further survey of the market and testing of the step response of digitizers, a combination of the requirements for LI and the target uncertainties for VFT measurements led to the development of the digitizer the PXIe-5164 in collaboration with National Instruments (Figure 10). Design parameters were given, and a critical property of such a digitizer is a short enough settling time (Figure 10). This digitizer has 400 MHz bandwidth, a settling time <5 ns for 50 Ω termination, 14 bits dynamic range and >11.5 effective number of bits in single shot. Many digitizers used for LI measurements typically reach around 10 effective number of bits. Most of digitizers on the market offer higher bandwidths and sampling rates but are designed for repetitive signals where the dynamic range can be increased from 8 to 11 bits, but these are of no use for transient events.

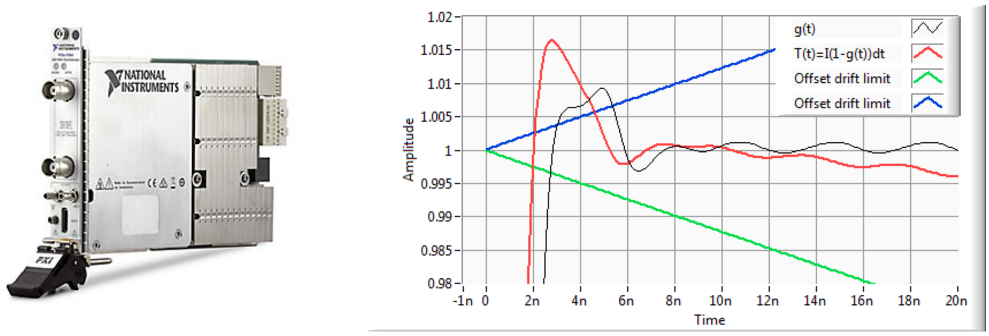


Figure 10: The transient recorder (left) and the settling time with 50 Ω termination (right).

The first step in qualifying or calibrating a transient recorder for measurements of fast transients, where the rise time of the signals can be around 10 ns, is to measure the step response. We had two modes of operation.

- For 50 Ω impedance the digitizer must settle within 0.5% well below 10 ns. Step generators were needed with proven rise times well below what we wanted to test, i.e. <1 ns. These generators were needed to be free from oscillations after the step, i.e. the signal needs to settle within at least 0.5% before 1 ns. A Fluke 9500 oscilloscope calibrator with a rise time of 170 ps was used for these measurements. The settling time of this device was not specified, but we had to rely on that for the moment.
- For 1 MΩ impedance a step generator was used based on a switch consisting of a mercury wetted relay to generate steps for 1 MΩ loads. This device has a 400 ps settling time and amplitude error thereafter less than 0.1 %.

The transient recorder has a 1.4 ns rise time and 4.5 ns settling time. Convolution with ideal wave shapes gives a front time error of 2.4% and peak value error of 0.2% at 5 ns front times.

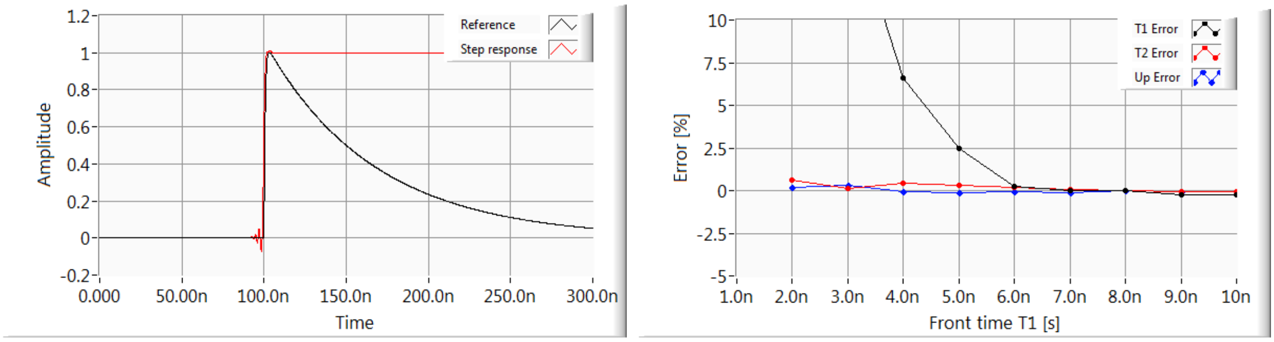


Figure 11: Convolution of step response (left) and errors for U_p, T_1 and T_2 (right).

4.2.2.2 Design of wideband attenuators

The voltage from typical HV dividers are several hundreds of volts up to 1.5 kV. For the VFT measurement in GIS, attenuators with 50 Ω impedance were needed to reduce the maximum voltage input below 5 V before the digitizer. One type of attenuator was found on the market with attenuation 50:1, but a two with attenuation 100:1 and one 14:1 of own design were built by RISE (Figure 12), one 100:1 attenuator was built by FFII, and all calibrated and used for the measurements.

Figure 12: Wideband attenuators for 50 Ω.

Attenuators for transient overvoltages with 1 MΩ input impedance were also needed and were designed using a concept developed for burst testing attenuation, where the attenuator is designed and adapted in order not to load high impedance HV dividers which are common on the market.

4.2.3. VFTO measurements and calibration of sensors in GIS

Wideband sensors like D-dot probes or capacitive voltage probes are used to measure very fast transient over-voltages, but the traceability for this kind of measurements is not recognised. In the present version of IEC 61869-1, the test conditions for both GIS and air-insulated systems are given, but there is no guidance on the measurement methods that are used to assess the uncertainty of measurements because of a lack of traceability for High Voltage (HV) transients. A calibration SF_6 set-up has been developed to establish the European traceability in this field.

The Very Fast Transients (VFT) calibration set-up is composed of a step voltage generator up to 200 kV with a rise time less than 10 ns, and a reference measuring system. The calibration setup is based on a cylindrical

SF_6 configuration, which uses a stainless steel duct with an outside diameter of 500 mm and an internal aluminium tube of 200 mm diameter as a high voltage conductor to have characteristic impedance around 50 Ω, as a representative figure of the SF_6 GIS. A spark-gap of SF_6 at 2 bars is used to achieve a pulse with a rise time of less than 10 ns. Conical elements allow a good impedance matching between different sections of the calibration setup. The probe of the measuring system under calibration is installed in an open window in the main duct of the calibration set-up. A fast resistive reference measuring system is installed at the end of the metallic duct. A wideband digital recorder described earlier, with 400 MHz bandwidth, is used to acquire and analyse the generated VFT pulses.

A HV step with a very fast rise time is achieved by closing an ideal switch to discharge a coaxial transmission line, previously charged by a HVDC source against a load resistor. Considering the transient wave propagation theory, if the internal resistance of the HVDC source is much higher than the characteristic impedance Z_0 of the transmission line, the voltage at the load resistor is a step voltage.

The calibration set-up in Figure 13 is composed of five blocks:

A. HVDC source with an external resistance
B. Transmission line composed of a high voltage bushing and a transmission duct using distilled water as dielectric medium
C. SF_6 Spark-gap (5)
D. Main duct that includes four D-dot probes (10) and one or two windows (11) on the envelope for the measuring system to be calibrated
E. Reference measuring system (13-15).

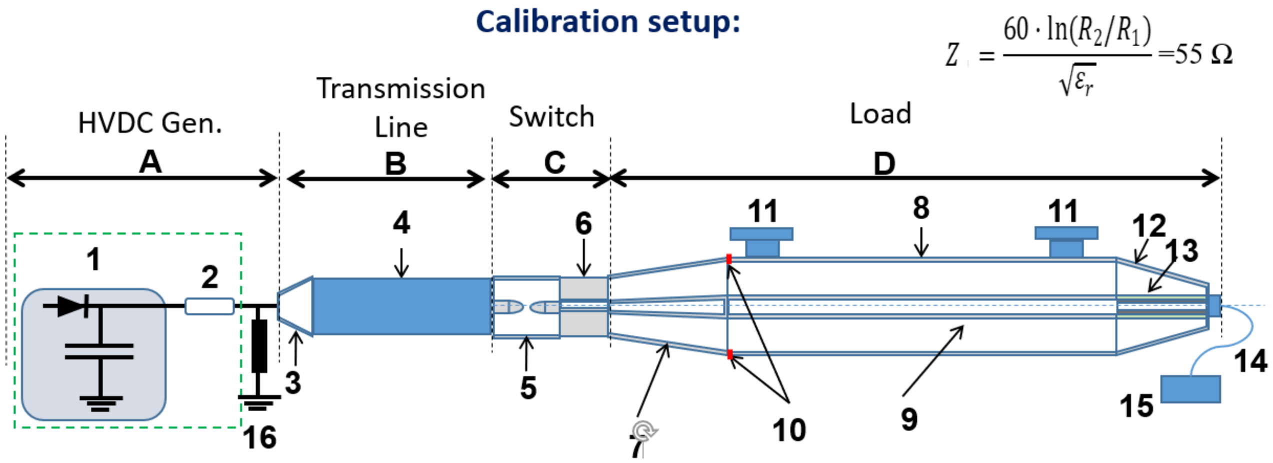


Figure 13: The GIS sensor calibration design; 1) HVDC generator, 2) Resistor, 3) Bushing, 4) Transmission line, 5) Spark-gap, 6) Cylindrical matching, 7) Conical matching, 8) Main Duct, 9) Conductor, 10) Control Dot probes, 11) Window for the sensor to be calibrated, 12) Matching resistor compartment, 13) Reference HV divider, 14) Measuring cable, 15) Digitizer, 16) HVDC Measuring System.

The three parts 13, 14 and 15 in reference measuring system in Figure 13 consist of a reference high voltage divider, a measuring cable including a wideband attenuator and a wideband transient recorder. Studies of alternate fast divider designs confirmed the advantages in characteristics in the selected resistive divider, which is composed of ceramic disc resistors. Fifteen resistor units are used for the high voltage arm to get 49.5 Ω, and one unit of 0.5 Ω for the low voltage arm. The output of the divider is connected to a resistive attenuator through a low-loss coaxial cable of 50 Ω with type N connectors.

A comparison between the four D-dot sensors and the reference divider signal, shown in Figure 14, was made to check for unwanted higher order Transverse electromagnetic (TEM) modes in the tube. D-dot sensor are mounted at the beginning and at the end of the main duct (8 in Figure 13).

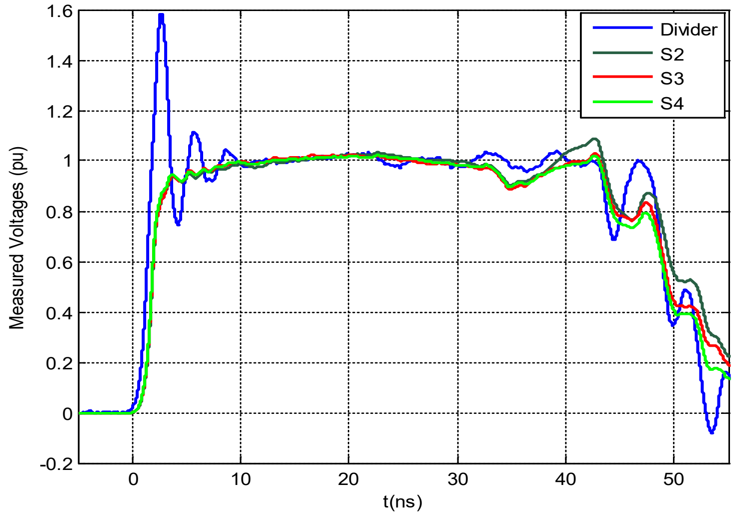


Figure 14: Comparison between Reference Measuring System and D-Dot sensors.

The output signals from the resistive divider and the integrated D-dot signal (which are sensing the relative electric field strength) are compared in Figure 15. These signals are used for the calibration.

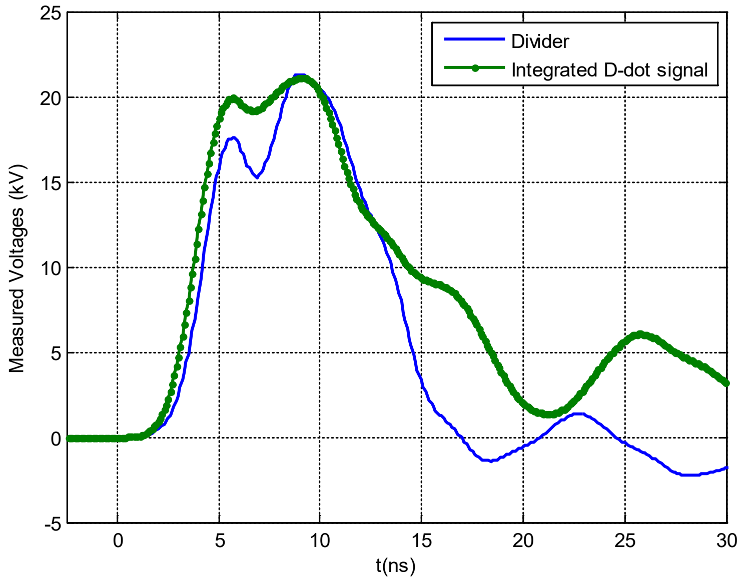


Figure 15: Recorded waveform by resistive divider and integrated D-dot sensor signal.

Based on uncertainty analysis new CMC entries have been claimed for calibration by FFII, which has the full calibration set-up with generator (Figure 16), for 6-25 ns front times and 100 kV peak voltage, and by RISE and VTT for measurement capabilities of waveshapes >25 ns up to 200 kV and >100 ns up to 400 kV respectively.

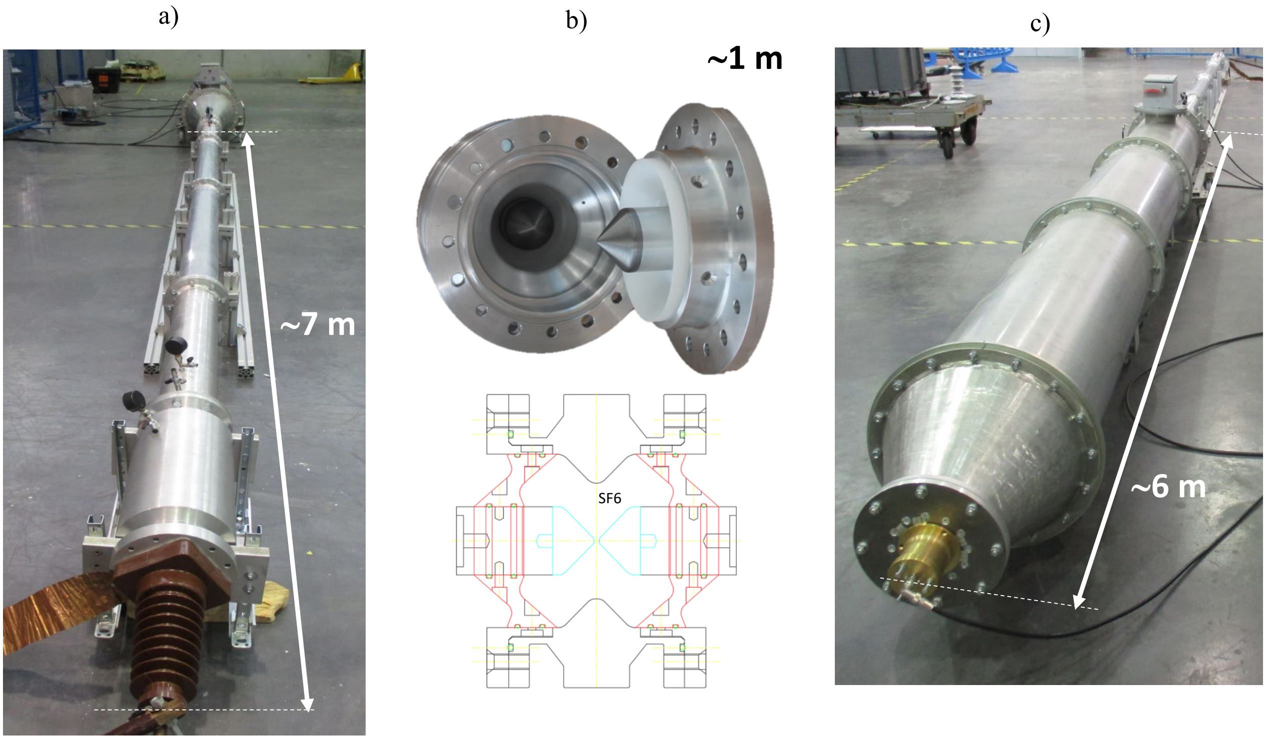


Figure 16: The GIS sensor calibration set-up: a) transmission line to be charged, b) spark gap, c) Main duct in which the reference divider and the VFT sensor under calibration are installed.

4.2.3.1 Progress beyond the state of the art

A clear progress beyond the state of the art has been made by introducing a calibration set-up for VFT sensors for GIS. Measurements with this set-up have been undertaken to support new claims of traceability by FFII for 6 ns transient impulses with peak values up to 100 kV. Also, RISE and VTT have in this context made claims for new CMC beyond the state of the art.

4.2.4. Traceable Measurement of Transmitted Over-voltages in Instrument Transformers

VTT has designed and built a calibration head for the specific waveshape of 0.5/50 μs for an existing impulse voltage calibration system CalHUT. The transient recorder PXIe-5164 developed together with National Instruments described above was calibrated by the voltage calibration head and now has a traceability for this wave shape.

Several wideband attenuators (Figure 12) with response times better than 4 ns, were jointly designed by RISE, FFII and VTT, and built by RISE and FFII, to reduce the voltage from HV dividers from < 2 kV to voltages acceptable to the selected transient recorder. This was done in preparation to enable full voltage measurements to be performed on the secondary winding of instrument voltage transformers of type VT (inductive), CVT (mixed capacitive/inductive) and CD (capacitive divider).

RISE and FFII planned and constructed a low voltage measurement set-up for the determination of transmitted over-voltages for air insulated voltage transformers as prescribed by the standard IEC 61869-1 and shown in Figure 17. The applied 0.5/50 μs impulse on the primary winding was measured using different set-ups. A measurement system from FFII consisted of a voltage divider of type ASEA YDSA 600 kV connected to one channel of an oscilloscope of type Yokogawa DL350 with 10 GS/s sampling rate and 1.5 GHz bandwidth (Figure 17). The second channel simultaneously sampled the VFTO from the secondary winding of the DUT. A second measurement system from RISE used fast resistive divider developed by VTT for the 14IND08 ElPow project and the NI PXIe-5164 transient recorder, and the second channel simultaneously sampled the transmitted overvoltage.

Measurements of transmitted over-voltages on an ASEA 145 kV VT took place, using a Marx-generator on the primary side with a 1.6 kV pulse, and simultaneously sampling the transmitted over-voltage on the second channel of the transient recorder using the wideband attenuators. High-voltage measurements were then conducted up to full 189 kV on the VT for comparison of transmitted over-voltages on the VT (Figure 18). The inductive voltage transformer overvoltage could be linearly scaled from 1.6 kV to 189 kV which confirms the use of the method in IEC 61869-1.

Figure 17: The VFTO measurement set-up. Left a schematic, middle (FFII) and right (RISE) reference measurement systems.

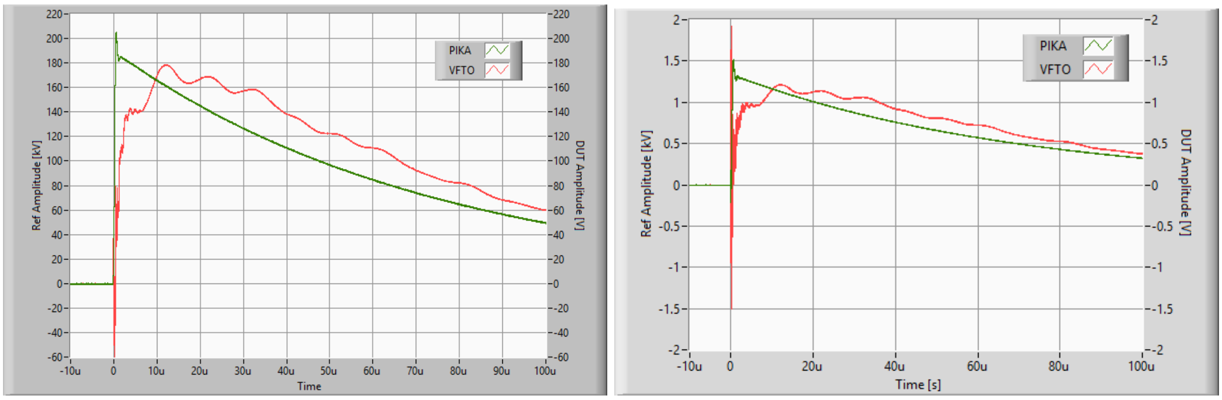


Figure 18: Applied impulse on the HV (green, left scale) and measured transmitted overvoltage (red, right scale). HV test left figure and 1.6 kV test in right figure.

Several other types of instrument voltage transformers were the tested at RISE. One Capacitive Voltage Transformer (CVT) for the 400 kV, which shall withstand peak voltages $U_p = 1.6 \cdot \sqrt{2}/\sqrt{3} = 516$ kV, failed the test. Another CVT for 132 kV grid voltage showed a factor of two times higher overvoltage in the prescribed LV test (IEC 61869-1) than when tested at HV. In the test of a Capacitive Divider (CD) the voltage was overestimated by a factor of 2.5.

FFII and RISE have jointly prepared an uncertainty budget for the measurement set-ups. The target uncertainties were <1% for the peak voltage U_p and <2% for the front time T_1 and the time to half value T_2. The resulting uncertainties are <1% for U_p, <2% for T_1 and <1% for T_2.

A presentation of the measurement was made by RISE at a general meeting of IEC TC38. A recommendations report on the methods and required measurement uncertainties has been submitted to IEC TC38, and proposal for changes in the current revision of IEC 61869-1 has been submitted. A report was submitted to EURAMET as D4: ‘Recommendations report proposing new or improved international standards on transformer over-voltages to TC38’. The findings are that the present standard allowing for LV tests of VFTO in instrument voltage transformers have in one case showed overestimate of a factor of 2.3 at 25 kV compared to full voltage at 189 kV [10].

4.2.5. Progress beyond the state of the art

A clear progress beyond the state of the art has been made with a new generation of transient recorders, claims of traceability for 0.5/50 μs impulse, with 1% for U_p, <2% for T_1 and <1% for $T_{2;}$ and input to standardisation with new HV measurement technique for transmitted overvoltages.

4.2.6. Recommendations to IEC TC38

The following recommendations of amendments of standards have been sent to IEC TC38 committee:

- Performing the measurement at full voltage leads to much lower uncertainty for testing of transmitted overvoltage measurement transformers instead of relying on an estimate based on a linear behaviour in the tested object. Recommend a revision of the IEC 61869-1 standard accordingly.
- Use the standard the short front of LI, i.e. 0.84/50 µs instead of LV testing of transmitted over-voltages.
- Traceability now exists in Europe for HV testing of the shorter front 0.50/50 µs
- In defining the transmitted overvoltage test using LI impulse wave shapes, better guidance would be at hand and references could be made to the existing standards IEC 60060-1, -2 for HV measurement and IEC61083-1 for transient recorder qualification and uncertainty estimates

4.2.7. Recommendations to IEC TC42

The following recommendations of amendments of standards have been sent to IEC TC42 committee:

- Metrology and a new calibration procedure are now available for VFT sensors used in GIS for future amendment of e.g. IEC 60060-1.
- New metrology for burst testing will be presented for possible revision of IEC 61211

4.2.8. Summary

Work on VFT Overvoltages (VFTO) has provided new calibration methods for fast transient sensors installed in GIS, which is critical for development and insulation coordination of GIS equipment. Therefore, different techniques, most of them used in grid installations, are used to monitor VFTO under service conditions. In order to assure the reliability of corrective actions to reduce VFTO, wideband sensors can now be calibrated, and a traceability chain is proposed and new Calibration and Measurement Capability (CMC) are claimed.

A GIS sensor calibration setup was designed and built for the generation of very fast transient over-voltages. This calibration rig consists of a co-axial GIS generator fast reference divider developed in the 14IND08 ElPow project. Traceability for VFT sensor calibration has now been established by one national lab. This traceability is validated with an advanced transient recorder, developed by guiding an unfunded partner and published at the conference CPEM2018 [1], the 600 kV reference divider published at ISH2019 [9], a study of optimisation divider geometries at ISH2019 [6] and the complete GIS sensor calibration set-up also published at ISH2019 [7]. Based on the results from this system one lab claims new CMCs for the complete calibration system, and two labs for traceability of VFT measurement.

Input to IEC TC42 on the project's development was presented in Toronto 2017, the results are used in writing the technical brochure on VFT techniques within CIGRE D1.60 and the calibration system and traceability will be reported and discussed at the IEC42 general meeting in Shanghai 2019.

New calibration capabilities are available for measurement of transmitted overvoltages in instrument transformers as new input to revision of a standard IEC 61869-1 by IEC TC38. Results have been presented at a general meeting, a recommendation report with advantages of switching from using low voltage measurements to using high voltage traceable techniques was submitted to TC38. RISE has submitted input via the national committee and is actively taking part int the revision of IEC 61869-1. New updated low-level PD entries have been submitted by RISE of the Calibration and Measurement Capability (CMC) to BIPM for review. A paper on these measurements was published at ISH2019 [10].

4.3. New procedures for partial discharge testing – Objective 3

4.3.1. Motivation

The aim of this objective was to improve the traceability of partial discharge (PD) measurements by extending the sensitivity range (0.1 pC and a target uncertainty of 0.01 pC) of calibration services available from NMIs, and to give metrological support to the new measuring instruments that are used to analyse PD phenomena in the d.c. grid.

In addition to causing outages, insulation failures lead to human health and safety risks, inducing catastrophic fires or emissions of toxic gases. In the case of a catastrophic fire on an oil rig, a replacement could cost around 2.5 M€. The probability of such accidents increases when HV cable systems are used. Additional risks appear in the grid voltage when outages occur in high power offshore generation systems. Fall-out on a large offshore wind park could probably be handled in-land. However, in the case of a failure in a HVDC cable, the installation cost is 1 M€/km – 2.5 M€/km. Surveillance of electrical cable insulation can avoid these critical situations. Diagnosis of the insulation condition of cable systems requires on-site PD measurements using non-conventional methods. Traditional PD measuring technologies used in AC high voltage grids are currently being adapted for new HVDC cable system requirements.

This called for specific metrological solutions to apply new measuring procedures. Consequently, this work package was split into two challenges:

- The first challenge was to develop calibration procedures for very low-level PD calibrators. More sensitive devices have been developed mainly to fulfil the needs of the HVDC cable industry.
- The second challenge has concentrated on the development of procedures for the qualification of the PD analysers used for d.c. cable systems. For its successful execution, this second task would make use of the traceability developed in the first challenge.

4.3.2. Research for partial discharge traceability below 1 pC

VTT, FFII, TUBITAK and RISE have designed and built calibration systems for low-level PD calibration, choosing different approaches with different emphasis. One method is based on analogue integration and the other is numerical integration. VTT has found a solution to increase the sensitivity of the PD measurement below 0.1 pC with a target uncertainty of 0.01 pC using a Charge Sensitive Preamplifier (CSP). It is known that for low PD levels, i.e. below 10 pC, the use of a low-noise electronic integrator will significantly amplify the voltage and improve the signal-to-noise ratio. Charge-sensitive preamplifiers (CSPs) are integrating devices, and they can be used in order to convert the charge into the voltage (Figure 19). Both methods are shielded from external electromagnetic interference to reduce the measurement uncertainty. Two papers on these methods were presented and published at CPEM 2018 [5] and an extended paper at IEEE TIM [16].

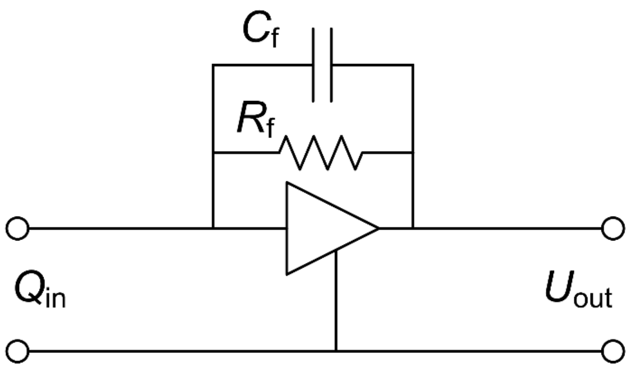


Figure 19. Basic configuration of a CSP.

Numerical integration method is based on the impulse voltage measurement over the shunt resistor as shown in Figure 20. A traceability scheme described in the IEEE TIM publication by VTT is shown in Figure 21, comparing the analogue CSP integration traceability path to the numerical method. VTT has developed a procedure, including guidance for shielding practices, for calibrating low-level PD calibrators. This will be submitted to working group 23 of IEC TC42 in October 2019.

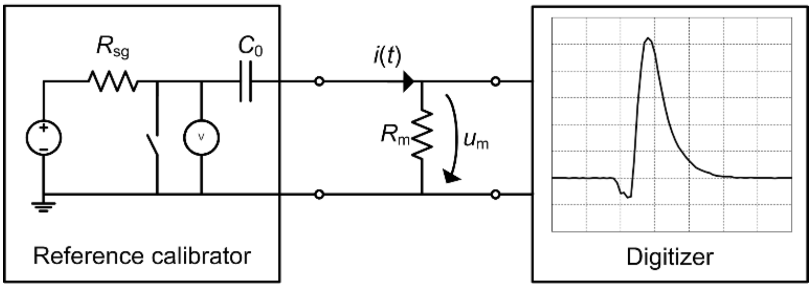


Figure 20. Numerical integration method is based on the impulse voltage measurement over the shunt resistor. Charge from the calibrator can be calculated from the voltage with the numerical integration.

A reference partial discharge measurement system was designed and built at TÜBİTAK for providing traceability of partial discharge measurements <2 pC with <1 % expanded measurement uncertainty. The measurement uncertainties of PD calibration at National Metrology Institutes up to now range between in 6 % and 20 % for the lowest level 0.5 pC.

For the characterisation of PD measurement system, a reference partial discharge generator (PDCAL) has also been designed and built for PD up to 1000 pC within 1 % expanded measurement uncertainty. In this system, the input voltage is limited up to 10 V and output capacitors are exchangeable between 1 pF, 10 pF and 100 pF for the generation of partial discharges up to 1000 pC. This limited voltage decreases the uncertainty of the measurement system.

A quad-lateral intercomparison of ultra-low PD was launched between four labs, FFII, RISE, TUBITAK and VTT. New updated Calibration and Measurement Capability (CMC) entries to include low-level PD down to 0.1 pC (and below by VTT) with uncertainties as low as 0.001 pC have preliminary been submitted by three labs to EURAMET as deliverable D6 and to BIPM for review. The lowest level results are shown in Figure 22.

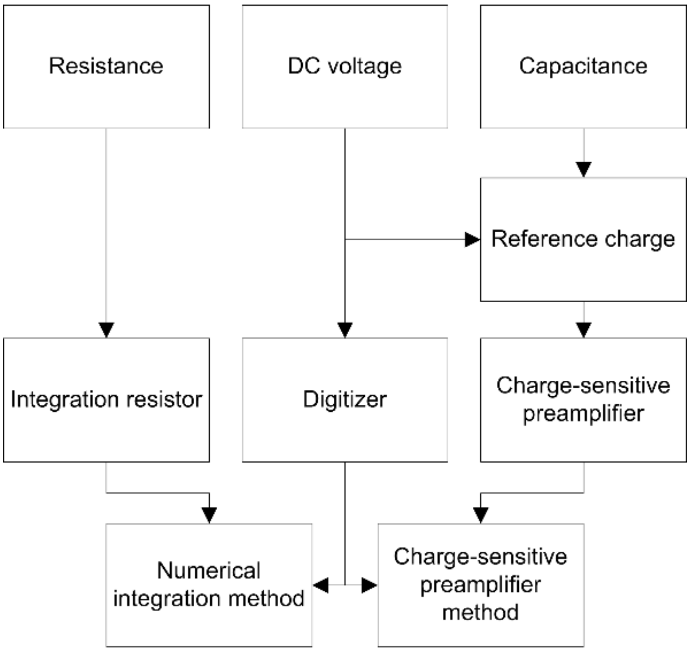


Figure 21: Traceability of the numerical integration method and the proposed method using CSPs.

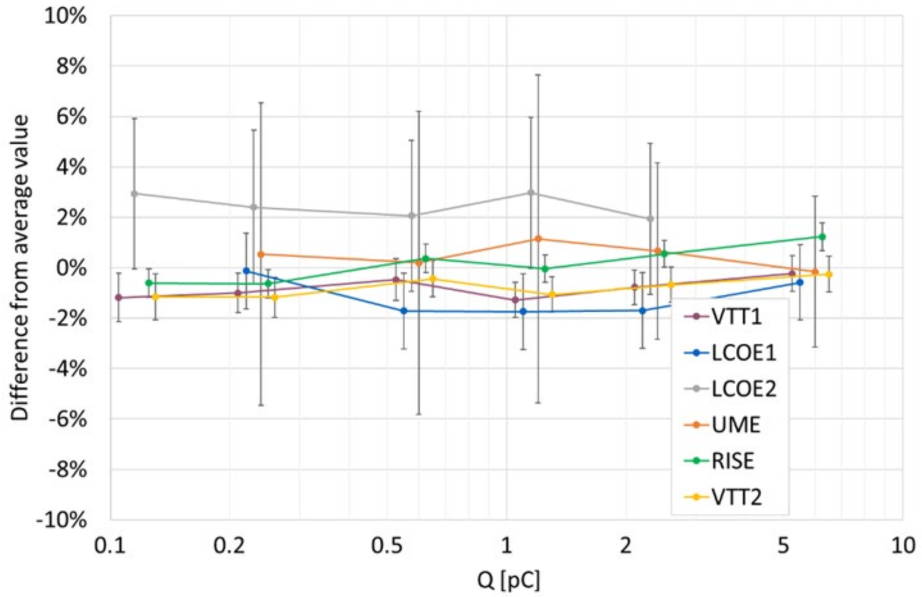


Figure 22: Comparison results from 0.1 pC to 5 pC.

4.3.3. Procedures to qualify the PD measuring instruments for systems under d.c. stress

FFII has designed and built a specific testing set-up for PD patterns for generation of a digital file database of reference PD-pulses for d.c. testing and of representative noise in HVDC grids (see Figure 23 and 25). It also includes power electronic noise due to controlled semiconductors, sinusoidal modulated noise and random noise. The characterisation set-up was developed to generate reference PD pulse trains associated to real insulation defects (cavity, floating corona and surface PD sources). These patterns (Figure 24) are sampled in an optimised digital format, only saving the samples associated to PD pulses and removing the samples associated to the time intervals between PD pulses.

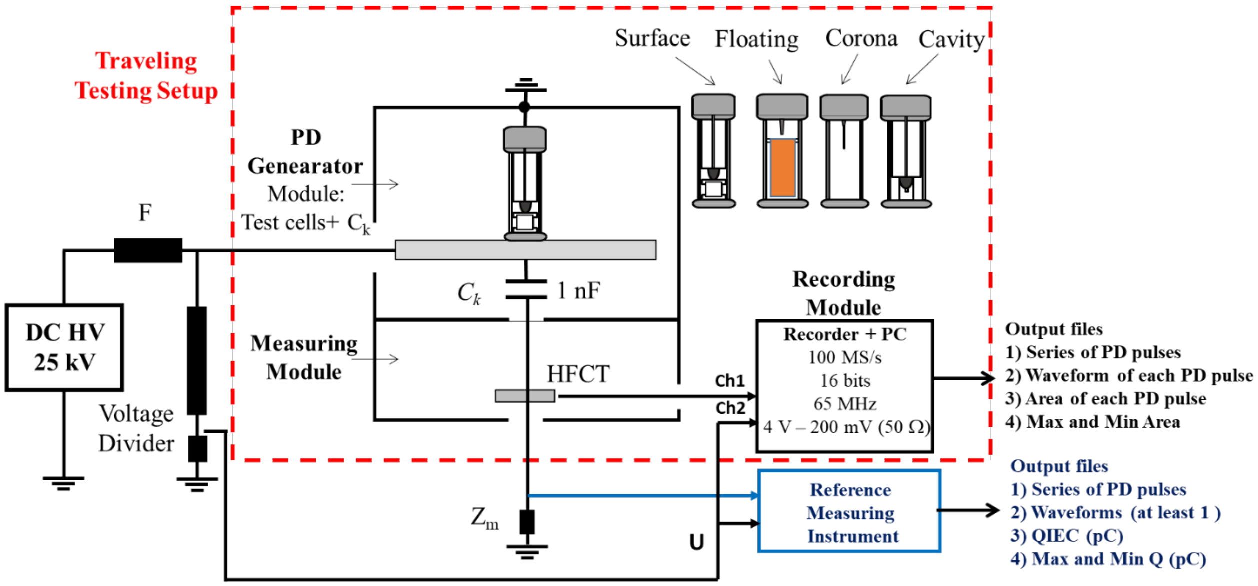


Figure 23: Testing set-up and PD pattern generation.

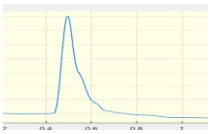
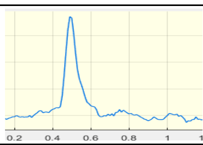
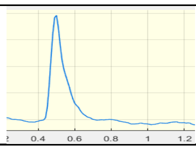
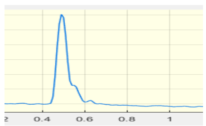
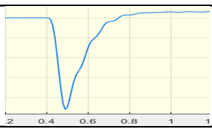
The characterisation set-up reproduces with a good stability the saved reference PD pulse trains in analogic format by means of an arbitrary function generator. The proposed method defines a standard PD pulse to be used for calibration purposes. The characterisation set-up allows to determine the transfer impedance of a HFCT PD sensor, the scale factor of a PD analyser, the sensitivity for detecting PD pulses under electrical noise, the capability of the PD analyser to discriminate different overlapping PD sources and to locate where a PD source is placed (e.g. in a metal enclosed switchgear or in the cable system connected to the it).

FFII, with support from RISE, TUBITAK and VTT, has developed a test data generator software for use in the qualification of PD analysers. The software modes are a) a generator of single standard PD-pulses whose amplitude and PD rate can be regulated; b) a series of reference PD pulses; c) series of multiple PD sources that are superimposed; c) a series of reference PD pulses + representative noises. A complementary software for modelling of attenuation in cable systems considering different semiconductor performances was developed that allows qualification for location of PD-pulses along a cable system.

The software application generates PD pulses specified in the qualification procedure. The software application allows for mixing of individual reference PD pulse sources associated to different defect types with superimposed artificial noise. The characterisation software is available as an executable, with data files containing the required waveforms.

The qualification procedure enables the characterisation of PD instruments with: a) sensitivity to pulse signals immersed in electrical noise, b) uncertainty of the PD source location along a cable system, c) clustering capability of the measuring instrument under checking to separate different PD pulses and d) location capability of the analyser to identify a PD source location.

The system uses an arbitrary waveform generator with the test data generator to produce the waveform. This arbitrary waveform generator has a bandwidth of ≥100 MHz; an analogic output between 5 mV and 1 V, and digital sampling rate of 1 GS/s, a 14 bit resolution and a memory depth >100 MS. The system uses an arbitrary waveform generator with the test data generator to produce the waveform. This arbitrary waveform generator is with bandwidth up to 40 MHz (-3dB attenuation) and with -4dB attenuation up to 50 MHz; and has an analogic output between 4.4 mVp and 6 Vp with a 50 Ω load, and digital sampling rate of 0,8 GS/s, a 16 bit resolution and a memory depth of 128 MS = 2 x 64 MS.

PD Sources for AC and DC voltages	Corona -a-	Floating PD -b-	Surface PD -c-	Cavity -d-
Standard pulse of the PD series DC^{+} 0,2μ/div				
Standard pulse of the PD series DC^{-} 0,2μ/div				

a)

b)

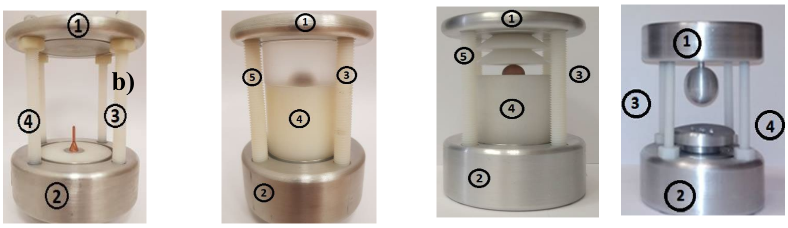
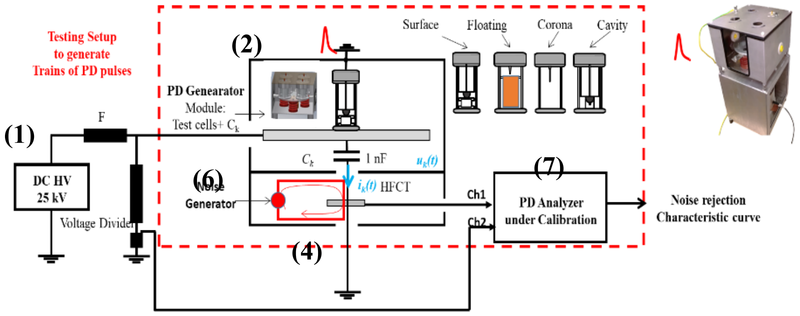


Figure 24: a) Typical PD patterns for the four different sources, b) PD test cells of representative defects.

FFII, with support from TUBITAK, has developed a procedure for the qualification of all types of PD analysers operating in the high frequency range using HFCT PD sensors, which are used to analyse the insulation condition of HVDC cable systems and of HVAC cable systems. This procedure uses the arbitrary waveform generator to generate analogic pulses on the basis of the set of reference PD pulses saved in the database. Although PD pulses suitable for measurement by PD measuring instruments can be generated for the frequency range from 0.1 MHz to 50.0 MHz, a standard PD pulse with a frequency content limited to 30 MHz was defined according to the Technical Specification IEC/TS 62478 (published 2016).

a)



b)

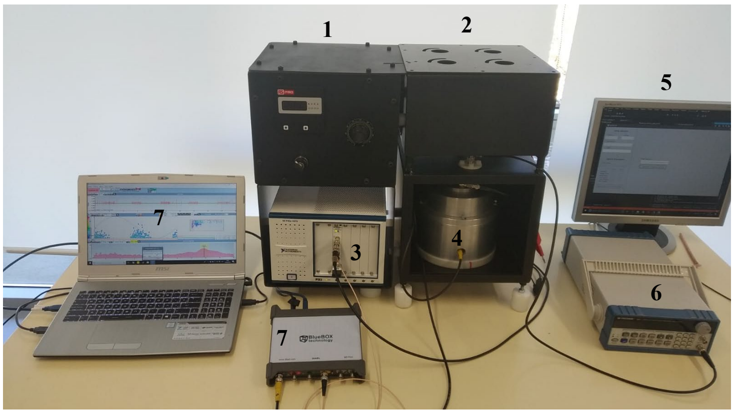


Figure 25: a) Characterisation set-up with a HV source and a PD generator, b) Prototype of the set-up: 1) HV module, 2) PD generator, 3) Arbitrary function generator to generate PD pulses, 4) PD Measuring module, 5) Monitor for user interface, 6) External noise generator, 7) Commercial PD analyser characterisation.

The amplitude uncertainty of the generated PD pulses is better than 0.1 %. This procedure also considers noise rejection, PD location, and the PD clustering of different PD sources, which is crucial for determining the origin of the PD. A patent was filed by FFII on this method.

FFII, TUBITAK, RISE and VTT have developed a set of recommendations on the use of PD analysers in determining the insulation condition of HVDC cable systems. This was submitted to IEC TC42/MT23. FFII with support from RISE has presented and discussed the results related to procedures for qualifying the PD analysers used for d.c. testing at several CIGRE D1.63 meetings and provided input to the writing of a CIGRE D1.63 technical brochure. A report has been submitted to EURAMET as D7 (Report on the input provided to CIGRE D1.63 on the procedures for determining the suitability of the PD analysers used for d.c. testing) which was titled as “Procedure for the qualification of PD analysers working in the high frequency range (0.1 MHz - 30 MHz) used to analyse the insulation condition of HVDC cable systems”.

In Figure 25a the circuit of the characterisation set-up using HV source and PD Generator module is shown and Figure 25.b depicts the characterisation set-up using either the HV source (1) and the PD generator module (2) or alternatively an arbitrary function generator (3) to inject PD pulses in the Measuring module (4) where electrical noise (6) is superimposed (4) to characterise a commercial PD analyser (7).

4.3.4. Progress beyond the state of the art

A clear progress beyond the state of the art for low level PD calibration, currently 0.5 pC, was obtained with a measurement uncertainty of 0.1 pC for several labs and one as low as 0.01 pC and with an expanded measurement uncertainty as low as 0.001 pC.

A procedure has been developed for the qualification of all types of PD analysers which are used to analyse the insulation condition of HVDC cable systems and HVAC cable systems. PD pulses suitable for measurement by PD measuring instruments can now be generated for the frequency range from 0.1 MHz to 50.0 MHz, extending the standard PD pulse which up to now was limited to 30 MHz in IEC/TS 62478. This procedure considers noise rejection, PD localisation, and the PD clustering of different PD sources, which is crucial for determining the origin of the PD. A patent was filed by FFII on this method.

4.3.5. *Recommendations to IEC TC42*

The following recommendations of amendments of standards have been sent to IEC TC42 committee:

- A new method for calibration of ultra-low PD calibrators will be recommended for the revision of IEC 60270.
- A new PD calibration procedure and qualification of PD analyser will be recommended for implementation in the present PD standard IEC 60270, for analysis of insulation condition of a.c. and d.c. cable systems. Specifically, d.c. applications will be discussed for revision of IEC 60270.

4.3.6. *Summary*

This project's work on PD measurement techniques now offers calibration services for the most sensitive PD measuring instruments. It has provided a new view and significant understanding of PD phenomena in HVDC systems and results have been submitted to and discussed in IEC TC42/MT23. This improvement of PD measurements under d.c. stress provides a better service continuity for d.c. transmission and distribution grids using cable systems, thereby reducing the risk of eventual explosion or blackouts due to a short-circuit fault.

VTT, FFII, TUBITAK and RISE have designed and built calibration systems for low-level PD calibration, choosing different approaches with different emphasis. A solution was found to increase the sensitivity of the PD measurement below 0.1 pC with a target uncertainty of 0.01 pC using a Charge Sensitive Preamplifier (CSP). An intercomparison of calibration of a low-level PD calibrator (0.1 pC) was performed by circulating a PD-calibrator in autumn 2018 between four NMIs. New calibration services and procedures for level PD down to 0.1 pC have been introduced by four partners, and respective CMCs submitted for EURAMET review. The target measurement uncertainty of 0.01 pC is by far reached and is now as low as 0.001 pC. This new metrology using a new PD measurement method will feed into the next revision of IEC 60270. Two papers on ultra-low PD measurements were published in 2018 to CPEM2018 [5] and IEEE TIM [16] and one paper published at the ISH2019 [8].

Representative test cells for PD under d.c. stress was designed and built for creating a database of reference PD pulses in High Voltage DC/AC for detection of PD patterns, validated with noise from a grid operator. A paper on this was published at CPEM2018 [4] and one at the ICHVE2018 [12]. A new method has been developed for evaluation and qualification of measuring and diagnostic instruments for PD measurements, which also has been filed as a patent. The proposed method allows for determination of sensitivity of the PD pulses under electrical noise, location of the defects, PD location under interference between two different equipment and the discrimination of different overlapping PD sources. Two papers were presented at ICD2018 [13,14]. A reference measurement system for PD was designed and presented at CPEM2018 [2] and published in a journal [15].

4.4. Overall results summary

4.4.1. *X-ray acceleration voltage*

In-situ calibration of X-Ray acceleration voltage and dose by LNE, FFII and GEMS, is now available for application by the medical equipment industry. A method was established for conversion of the standardised kVp quantity for calibration of the X-ray dose to a new quantity named Practical Peak Voltage (PPV).

- Reference system for the calibration of pulsed X-ray high voltage tubes has been developed by LNE, FFI, GEMS and CEA.
- An evaluation of the uncertainty of PPV measurements has been developed.
- A technical procedure has been proposed to simplify the characterisation of any X-ray high voltage units, which includes an FFT and inverse FFT technique to be used to correct the frequency non-linearity of the high voltage measuring unit
- The reference system includes also a reference method for the measurements of the current under high voltage up to a few amperes for voltage up to 150 kV.
- A set-up for the characterisation of non-invasive instruments has been developed at GEMS with support from LNE, which includes very fast high voltage X-ray generators associated with its internal measuring systems, high voltage X-ray tube and several kVp meters.

- The set-up is installed in Faraday cage, different precautions have been considered in order to carry out accurate measurements and special adaptations have been made in order to avoid stray capacitances which could affect the performance of the generators.
- Several kVp meters have been studied and results have shown a good agreement with the internal measuring system of the generators and with reference external voltage dividers. For 100 ms X-ray exposure standard duration, PPV was found within the reference measurement uncertainty, while for faster pulses kVp meters have shown both good and inappropriate results depending on beam intensity (mA) and kVp meter probe positioning.
- A paper on a reference system for the Practical Peak Voltage calibration in Radiology and diagnostic applications was published at CPEM2018 [3]. A paper has been accepted at ISH2019 [11] on how to characterise invasive dividers for X-ray equipment. A third paper at CIM2019 [17] describes the results of characterisation of several kVp meters.
- A recommendation report has been sent to IEC TC62, describing the equipment, recommended test procedure for the characterisation of X-ray invasive dividers, how to calculate the uncertainty of measurements, the technics to improve the uncertainty of measurements, recommended conversion factors for non-invasive instruments and recommendations for the use of kVp meters.
- New measurement capabilities for X-ray acceleration voltage and PPV were established. The traceable measurement capability is available and LNE, CEA and FFII for fast switching of d.c high voltage <150 kV, and for LNE and GEMS for PPV in X-ray equipment.

4.4.2. *Methods for testing with very fast transients (VFT)*

- A new transient recorder was developed in collaboration with National Instruments. The performance is state of the art combining a 14 bit resolution with 400 MHz bandwidth at 50 Ω, providing a 5 ns settling time within 0.5% amplitude. A paper on the qualification of this digitizer was published at CPEM2018 [1].
- New high bandwidth attenuators were designed and built with settling times from >5 ns.
- Several divider designs for U_p up to 200 kV were studied with settling times >8 ns. A paper on these fast dividers has been accepted for publication at ISH2019 [6].
- A resistive divider, originally designed in the 14IND08 ElPow project, was modified and housed in a co-axial GIS set-up. This was essential to reach the needed response time and for establishing traceability of VFT sensor calibration.
- The resistive reference divider was used in international comparison organised by CIGRE D1.60. A paper summarising the results was accepted to ISH2019 conference [9].
- A GIS sensor calibration setup was designed and built for the generation of very fast transient over-voltages. This calibration rig consists of a co-axial GIS generator fast reference divider, has a similar design as in EMPIR 14IND08 ElPow but is mounted in a coaxial symmetry. The complete GIS sensor calibration set-up and procedures was accepted for publication at ISH2019 [7].
- Calibration procedures for VFT sensors used in GIS were developed by FFII, RISE and VTT. Full calibration services for calibration of VFT sensors in GIS systems are now available at FFII. These new calibration methods are critical for development and insulation coordination of GIS equipment.
- A traceability chain for VFT measurement is proposed and new Calibration and Measurement Capability (CMC) are claimed by FFII, RISE and VTT. Traceability for VFT sensor calibration is claimed by FFII (Table 6) – **First in the world**.
- Input to IEC TC42 on the project's development was presented in Toronto 2017 and the final results will be presented at the coming general meeting in Shanghai 2019, where the calibration system and traceability will be further discussed for possible future standardisation.
- The results are used for the creation of the technical brochure on VFT techniques within CIGRE D1.60.

Table 6: VFT - Claimed Measurement Capabilities (CMC) for the partners after the project

NMI	Peak Value	Expanded uncertainty	Front time range	Front time	Expanded uncertainty	Tail time	Expanded uncertainty
	kV	%				μs	
FFII	100	1.1	6-25 ns	> 6 ns	1.5 ns		
RISE	200	2	> 25 ns	>25 ns	5 %		
RISE	400	5	> 25 ns	>25 ns	5 %		
VTT	400	5	> 25 ns	>100 ns	5 %		
RISE	400	1	0.45 – 0.55 μs	0.45 – 0.55 μs	2 %	40 – 50	1 %

4.4.3. Methods for measurements of transmitted overvoltages

- The transient recorder developed in collaboration with National Instruments has a performance comparable to the state of the art combining a 14 bit resolution with 300 MHz bandwidth at 1 MΩ, providing a 14 ns settling time within 0.5 % amplitude.
- Calibration set-ups have been designed at FFII and RISE for traceable HV measurement of transmitted overvoltages in voltage transformers.
- Traceability of HV transmitted overvoltages have been accepted for publication at ISH2019 [10].
- Results have been presented at a general meeting; a recommendation report with advantages of switching from using low voltage measurements to using high voltage traceable techniques was submitted to TC38.
- New calibration capabilities are available for measurement of transmitted overvoltages in instrument transformers as new input to revision of a standard IEC 61869-1 by IEC TC38. RISE has submitted input via the national committee and is actively taking part int the revision of IEC 61869-1.
- New updated lightning impulse entries have been submitted by RISE of the Calibration and Measurement Capability (CMC) to BIPM for review to claim uncertainties for the 0.5/50 μs wave shape up to 400 kV (Table 6).
- Traceability for transient overvoltages is now available for HV up to 400 kV. **First in Europe.**

4.4.4. Partial discharge traceability below 1 pC

- This project's work on PD measurement techniques now offers calibration services also for the most sensitive PD measuring instruments.
- VTT, FFII, TUBITAK and RISE have designed and built calibration systems for low-level PD calibration, choosing different approaches with different emphasis.
- A method based on analogue integration using a Charge Sensitive Preamplifier (CSP) has given a solution to increase the sensitivity of the PD measurement, to take traceability down to 0.01 pC with an uncertainty of 0.005 pC.
- An intercomparison of calibration of a low-level PD calibrator (0.1 pC) was performed by circulating a PD-calibrator in autumn 2018 between four NMIs.
- New calibration services and procedures for level PD calibration (<0.5 pC**)** have been established by four partners, and respective CMCs submitted for EURAMET review (Table 7), reaching the target measurement PD calibration capability and expanded uncertainty of 0.01 pC. - **First in the world.**
- A reference partial discharge measurement system built at TUBITAK is designed for providing a reference for traceability of partial discharge measurements. This reference enables measurements of partial discharge <2 pC with <1 % expanded measurement uncertainty.
- For the characterisation of PD measurement system, a reference partial discharge generator (PDCAL) has also been designed and built for PD up to 1000 pC within 1 % expanded measurement uncertainty.

- This new metrology using a new PD measurement method will be discussed for the next revision of IEC 60270.
- Two papers on ultra-low PD measurements were published in 2018 to CPEM2018 [2] and IEEE TIM [16] and one paper will be published at the ISH2019 [8]. One paper has been published in Springer MAPAN-Journal of Metrology Society of India [15].
- New updated low-level PD entries of the Calibration and Measurement Capability (CMC) have been submitted by RISE to BIPM for review (Table 7).

Table 7: PD Capabilities for the partners after the project

NMI	PD Value	Expanded uncertainty	Method
	pC		
FFII	0.1 – 0.2	50 mC/C	Analogue integration
FFII	0.2 – 100000	15 mC/C	Numerical integration
RISE	0.1 - 50000	10 mC/C	Analogue integration
TUBITAK-	0.2 – 0.9	(0.01q+0.01) pC	Numerical integration
TUBITAK	0.9 – 4.9	(0.01q+0.05) pC	Numerical integration
TUBITAK	4.2 – 1000	(0.01q+0.1) pC	Numerical integration
VTT	0.01 – 0.05	0.005 pC	Analogue integration
VTT	0.05 - 100	10 mC/C	Analogue integration
VTT	100 - 10^7	20 mC/C	Numerical integration

4.4.5. Procedures to qualify the PD measuring instruments for systems under d.c. stress

- A characterisation setup for PD analyser working in the high frequency range used for d.c. and a.c. grids has been developed – **First in the world.**
- Representative test cells for PD under d.c. stress were designed and built for creating a database of reference PD pulses in High Voltage DC/AC for detection of PD patterns, validated with noise from a grid operator. A paper on this was published at CPEM 2018 [4].
- FFII, with support from RISE, TUBITAK and VTT, has developed a test data generator software for use in the qualification of PD analysers.
  - The system uses an arbitrary waveform generator with the test data generator to produce the waveform. This arbitrary waveform generator has a bandwidth of ≥100 MHz; an analogic output between 5 mV and 1 V, and digital sampling rate of 1 GS/s, a 14 bit resolution and a memory depth >100 MS.
  - The software modes for characterisation are the following:
    - **Conventional calibrator:** a generator of single standard PD-pulses which amplitude and PD rate can be regulated;
    - **PD source recognition and reference values:** a series of reference PD pulses is generated;
    - **PD clustering analysis:** series of multiple PD sources are superimposed;
    - **Noise rejection analysis:** a series of reference PD pulses + representative noises.
    - Complementary software with modelling of attenuation in cable systems with different semiconductor performances allows for qualification of PD analysers for location of PD-pulses.
    - This software is available as an executable, with data files containing the required waveforms.

- A new method has been developed for evaluation and qualification of measuring and diagnostic instruments for PD measurements. This procedure also considers noise rejection, PD location, and the PD clustering of different PD sources, which is crucial for determining the origin of the PD. A patent was filed by FFII on this method.
- FFII, with support from TUBITAK, has developed a procedure for the qualification of all types of PD analysers, which are used to analyse the insulation condition of HVDC and HVAC cable systems. This procedure uses the arbitrary waveform generator to generate analogic pulses, which conforms with the set of reference PD pulses saved in the database.
- FFII, TUBITAK, RISE and VTT have developed a set of recommendations on the use of PD analysers in determining the insulation condition of HVDC and HVACb cable systems (submitted to IEC TC42/MT23).
- FFII with support from RISE has presented and discussed the results related to procedures for qualifying the PD analysers used for d.c. testing at several CIGRE D1.63 meetings and provided input to the writing of a CIGRE D1.63 technical brochure.
- A report has been submitted to EURAMET as D7 (Report on the input provided to CIGRE D1.63 on the procedures for determining the suitability of the PD analysers used for d.c. testing) which was titled as “Procedure for the qualification of PD analysers working in the high frequency range (0.1 MHz - 30 MHz) used to analyse the insulation condition of HVDC and HVAC cable systems”.
- The project has provided a new view and significant understanding of PD phenomena in HVDC systems and results have been submitted to and discussed in IEC TC42/MT23.
- The improvement of PD measurements under d.c. stress provides a better service continuity for d.c. transmission and distribution grids using cable systems, thereby reducing the risk of eventual explosion or blackouts due to a short-circuit fault.

4.4.6. Key technical insights

- In-situ metrology was developed for calibration medical X-ray exposure to minimise patient dosing.
- A transient recorder with fast enough settling time and dynamics had to be developed for calibration of sensors used in GIS for measurements of very fast transients with front times < 10 ns .
- For calibration of VFT sensors, the effect of wave propagation and absence of transverse electromagnetic modes (TEM) in the GIS setup was checked and needed to be kept in control for VFT sensor calibration.
- A new method to solve the low-level PD calibration has been proposed by application of ultra-sensitive amplifiers designed for e.g. nuclear physics particle counting.
- Test cells were used for PD pattern generation and HFCT PD sensors were used in developing procedures for PD analysers working in the high frequency range (1-50 MHz).
- A patent has been filed on methods for PD diagnostic testing of instruments.

4.4.7. The collaborative approach

- Exploring and fusing specialities of traceable calibration of the national labs LNE and FFII, combined with expertise from manufacturer of medical equipment of GEMS and CEA, an in-situ calibration of X-ray equipment were successfully developed.
- For the design of the calibration set-up used for VFT sensors, criteria were discussed and equipment developed at FFII, jointly with RISE and VTT and other experts within CIGRE D1.60. To achieve this, also wave propagation expertise within the group was essential, using theory and practice from laser design (RISE) and microwave system design.
- The achievements in ultra-low level PD calibration and partial discharge measurement under d.c. stress benefited from using the experience and expertise from four NMIs. Amplifier development for particle physics research, the university of Madrid and the industry represented in CIGRE D1.63 were very successful.

5. Impact

A stakeholder committee was created with members from 23 organisations including BIPM, electric power grid equipment manufacturers, high voltage test laboratories, and national accreditation and legal metrology bodies. The members of the stakeholder committee represented a total of 12 countries.

The output of the project was disseminated via presentations at international conferences (e.g. CPEM, ISH, ICD and CIM), 17 peer-reviewed publications in international journals (e.g. IEEE Transactions on Instrumentation and Measurement), by active participation in CIGRE working groups and general meetings, and by active participation in international standardisation committees.

The project hosted a workshop for graduate students, stakeholders and NMIs. Training of graduate students is offered at the NMIs in all fields to disseminate the findings of the project to future scientists. Close cooperation between universities and NMIs support the transfer of knowledge to the metrological and scientific community.

A good news story of the digitizer, titled “Innovative instrument developed for electrical networks”, has been published on the EURAMET and the project webpages.

A patent on a method using the test cells has been filed under the name “Testing procedure on the basis of a Synthetic generator of PD patterns for checking PD diagnostic instruments to be used in HVDC and HVAC grids”.

Impact on industrial and other user communities

The methods developed in this project can be applied to existing or new x-ray equipment which require traceable calibration. this will ensure better control of the x-ray dose, therefore minimising the x-ray dose to patients and staff. Having in-situ control of the x-ray dose may also be explored to make more advanced imaging. Calibration services are provided by LNE, and were developed with support from GEMS, CEA and FFII. The methods used in these services are available and can be demonstrated by CEA and GEMS.

FFII, RISE and VTT have established calibration services for VFT sensors up to 400 kV, providing the shortest front time 6 ns at 100 kV. Further, traceability for transmitted overvoltages in voltage instrument transformers is available up to 400 kV. These will be official calibration services for the power industry with claimed new CMC entries on the BIPM webpage. In collaboration with the instrument manufacturer National Instruments, a new transient recorder for VFT measurements, the PXIe-5164, has been characterised and validated within the project and is now available on the market. This will improve the diagnostics of discharges in power grids, especially in GIS systems.

FFII, RISE, TUBITAK and VTT introduced new calibration services for ultra-sensitive PD calibrators down to 0.01 pC and submitted new claims for CMC entries on the BIPM web page. The methods for identification of PD sources in d.c. grids, are of major interest for grid operators. A patent was filed by FFII on a method for the correct assessment of source and position of PD in the grid, both of which will have impact on the reliability and failure prevention in grid operation. The power industry will be able to use the new methods for identification of PD under d.c. stress for monitoring of the systems. Grid operators supplied data to the project to validate methods for the identification of PD sources. The power industry will be able to use the new methods for identification of PD under d.c. stress for monitoring of the systems.

Impact on the metrology and scientific communities

The high-voltage scientific community will benefit from the new or enhanced measurement capabilities because now it has means for carrying out i) traceable measurement of x-ray voltages, ii) traceable measurement of VFT and transient voltage, iii) calibration of ultra-low PD and iv) qualification of all types of PD analysers measurement systems under d.c. stress.

The measurement of the fast front d.c. pulses, i.e. composite waves, for the x-ray medical system, has contributed to an ongoing discussion of similar measurement systems for the HV community. We have given the first steps towards solving the current need for traceability of measurement systems for composite waves, i.e. d.c. or a.c. with superimposed lightning impulse or switching impulse events, for HV testing up to voltages approaching 2000 kV.

Traceability for calibration of VFT is now available, extending the present limit for lightning impulse testing at 0.84 ns by two orders of magnitude, below 10 ns rise times for peak values of 100 kV.

Several NMIs have already acquired a PXIe-5164 transient recorder manufactured by National Instruments or VFT measurements, which was designed in cooperation with this project.This provides the community with new generation digitizers which combine increase in dynamic range with high bandwidth and excellent step response needed in measurement of transients.

The development of techniques for PD calibrators extending traceable low-level calibration of PD will have high impact on the metrology community. The design and construction of standard source equipment for studies of various corona sources, providing standardised typical PD patterns for d.c. systems, will also have high impact on this research field. A procedure is available for the qualification of all types of PD analysers working in the high frequency range using HFCT PD sensors to analyse the insulation condition of HVDC and HVAC cable systems.

The outputs of this project include several important additions and extensions to the CMC statements recorded in the BIPM key Comparison Database (KCDB), and as such provides a significant impact to the worldwide electrical power metrology community.

The project was active in metrology committees and has represented the project at the meetings of BIPM CCEM (Electricity and Magnetism) and EURAMET TC-EM (Electricity and Magnetism).

Impact on relevant standards

This project has generated results valuable to standardisation work within IEC and CENELEC. The calibration of x-ray systems and of the developed algorithms for improved calibration are being considered in the revision of IEC 61676 and will be taken into account by IEC TC62C when writing new standards prepared. LNE with support from FFII, CEA and GEMS has provided input on the measurement of x-ray acceleration voltage to this technical committee. Effects of dose reduction on imaging quality were reported to IEC TC62B.

FFII, RISE and VTT contributed to a technical brochure of CIGRE D1.60, to be published at e-CIGRE and concurrently reported to IEC TC42. Results and recommendations on VFT were submitted to the maintenance group IEC TC42/MT16, with the aim of being included in the revision of IEC 61083-1 and possibly in a new standard.

Following on from a request from IEC TC42, CIGRE initiated a working group D1.63 on “Partial discharge detection under d.c. voltage stress” to which FFII and RISE provided input. Further impact was created using the results and recommendations on PD under d.c. stress, disseminated in the maintenance groups for the new revision of IEC 60270 by IEC TC42/MT23 succeeding the work of IEC TC42/MT17.

RISE provided input to IEC TC38, for the new revision of the IEC 61869-1 standard by IEC TC38/MT48 and new parts or sub-standards for measurement uncertainties developed by TC38/WG55. RISE has taken part at several meetings of TC38/WG55, and presented results at the general meeting of IEC TC38 in 2018 and a recommendations report for transmitted overvoltages.

Longer-term economic, social and environmental impacts

The new calibration methods and services will support the development of better techniques, enhanced measurement capabilities for the calibration of x-ray equipment acceleration voltage provide more accurate diagnostics and dosing *e.g.* cancer treatment. This will improve patient safety by introducing improvements for x-ray control.

A metrological infrastructure has been created for the calibration of PD at low levels of apparent charge and the evaluation of the performance of PD measuring instruments under d.c. stress. Beneficiaries include manufacturers and users of PD detection equipment, and users of the power grid because greater reliability of electricity continuity will avoid blackouts. Additionally, the risk is reduced for explosions and catastrophic fires due to short-circuits caused by insulation failures. Measurement techniques for very fast transients now support the compatibility of testing between different test organisations and enable accurate measurements via the development of calibration services. Users of GIS and instrument transformers benefit from better quality control of the components for a high voltage transmission system, thus leading to more cost-effective solutions. More accurate and traceable measurement of transients will provide data for diagnostics and support development of new equipment for the prevention of failures on several scales.

Reliable electrical delivery is one of the prime needs in modern society; it is at least as important as water supply, since the latter depends on the supply of electricity. The progress in ultra-sensitive PD, methods for PD measurements in d.c. grids, and measurements of VFT in GIS and transmitted overvoltages will have a wide impact on power delivery, especially in the monitoring and stability of future local d.c. grids, but also for long distance bulk transmission systems such as UHVAC and UHVDC.

One of the European 20-20-20 targets is a 20 % reduction in CO_2 emissions compared to 1990 levels. The improved PD measurement techniques for existing and future d.c. grids and VFT diagnostics in GIS switchgear mounted in large infrastructure installations in densely populated areas and more reliable instrument transformers for energy metering has provided a new level of reliability to the power grid. With these diagnostic and metrological improvements, the grid can be used more efficiently to give an equivalent reduction in CO_2 emissions easily exceeding kilotons per year.

6. List of publications

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