# Publishable Summary for 15NRM02 UHV
# Techniques for ultra-high voltage and very fast transients

## 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.

## 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.

## 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.

**Progress beyond the state of the art**

Methods of validation and calibration of x-ray high voltage tubes, using invasive equipment, are often considered vague and of difficult interpretation. This project went beyond the state of the art by developing and validating appropriate measurement methods for the calibration of x-ray units for all types of pulses, with time durations from 200 µs to a few seconds. The practical peak voltage (PPV), a new method for dose calibration, was recently adopted by the IEC as a new quantity for the calibration of x-ray high voltage tubes. In this project, we carried out the in-situ calibration of the acceleration voltage and emission current in x-ray machines and made this available to manufacturers. Furthermore, a method for the new PPV quantity was developed to support the earlier used dose calibration by the KVp meter. A reference system for the calibration of pulsed x-ray high voltage tube was developed, characterized and its traceability validated. A technical procedure was proposed to IEC TC62C for amending IEC 61676, to simplify the characterization of x-ray high voltage units.

This project developed new methods and calibration capabilities for testing with very fast transients. In GIS, wideband sensors can now be calibrated to measure internal Very Fast Transient Overvoltage (VFTO) events by the manufacturers and the users. For transmitted overvoltage in instrument transformer, traceability is now available for measurements at full voltage instead of resorting to low voltage characterisation and extrapolation.

A calibration set-up for VFT sensors for GIS has been built, resulting in new claims of traceability for VFT for 6 ns front times, reaching beyond the target of <10 ns, for peak values up to 100 kV, for front times >25 ns up to 200 kV and for front times >50 ns up to 400 kV. Further progress was achieved by the development of a new generation of transient recorders now on the market, a new traceability for 0.5/50 ns impulses and input to standardisation for transmitted overvoltages.

In high voltage direct current (HVDC) transmission systems, the project achieved a major improvement in the traceability of PD measurements at ultra-low levels. Low level PD calibration was lowered from 0.5 pC to 0.1 pC for three NMIs, and 0.01 pC with an expanded measurement uncertainty 0.005 pC was also achieved.

Metrological means are now available for PD measurement of the insulation condition in d.c. grid and systems, achieved by a procedure developed for the qualification of all types of PD analysers for the insulation condition of HVDC and HVAC cable systems. PD pulses can now be generated suitable for measurement in frequency up to 50 MHz, extending the standard PD pulse earlier limited to 30 MHz. This procedure provides noise rejection, PD localization, and the PD clustering of different PD sources, crucial for determining the origin of the PD.

**Results**

*To provide a substantial contribution to TC62C work.*

The work on x-ray charging voltage measurement led to new services at European NMIs and served as input in the revision of existing standards. The measurement uncertainty and the reproducibility of the peak voltage and exposure time of x-ray equipment have been investigated. Traceable calibration of x-ray equipment ensures better control of the x-ray dose. We characterised and calibrated two commercially available high voltage dividers and one current sensor. This resulted in a new service available at LNE, which can be used by manufacturers of medical x-ray equipment and other stakeholders.

Prior to the selection of voltage dividers for in-situ measurements of the acceleration voltage, a study of ionisation chambers was carried out. Two voltage dividers were selected from 4 candidate types, with 8 models of each. A method was selected to be used for the measurements, and two voltage dividers were purchased and characterized determining the frequency response, d.c. and a.c. linearity, proximity effects, influence of output impedances and temperature effects, using square waveforms with duration ranging from 200 µs to 2 s.

A method of low current measurements under high voltage was developed using a commercial clamp meter with an x-ray generator as the source, applying mathematical post processing for the determination of correction factors for specific waveform parameters. With the calculated correction factors, a conversion of the standardised KVp quantity to the new PPV quantity was validated by measurements using an x-ray generator [4].

High voltage waveforms were generated, providing d.c. for a time duration ranging from 200 µs to a few seconds. High voltage measurements have been performed at d.c., a.c. and at switching impulse to validate the use of the voltage dividers at the shortest pulses, i.e. 200 µs. Calibration procedures, including a statement of uncertainty for invasive dividers for different x-ray equipment applications, are now available [18]. Our project successfully reached the target and contributed to IEC TC62C.

*To provide a substantial contribution to TC38 and TC42 work (via task-force D1.60).*
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. 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.

A GIS sensor calibration setup was designed and built for the generation of very fast transient over-voltages. Traceability for VFT sensor calibration has now been established by one national laboratory, FFII, claiming a CMC for 100 kV and 6 ns with 1.1 % expanded uncertainty for the amplitude, which is lower than the targeted 1 % standard uncertainty, and 1.5 ns expanded uncertainty for the front time. This traceability was validated with an advanced transient recorder, developed by a partner, a 600 kV reference divider design, a study of optimization divider geometries and the complete GIS sensor calibration set-up. Based on the results from this system, FFII claims new CMCs for the complete calibration system, and RISE and VTT claim CMCs for traceability of VFT measurement.

The project completed this goal by providing new calibration capabilities for the measurement of transmitted overvoltages in instrument transformers where RISE shared the outcomes with IEC TC38 and provided new input to the revision of IEC 61869-1 to TC38/MT48 and task-force D1.60.

*To provide a substantial contribution to TC42 work (via task-force D1.63)*
This project's work on PD measurement techniques led to new 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 with a standardisation committee. A new characterization procedure for the evaluation of PD analysers was developed and presented to different working groups. This characterisation procedure for PD instruments working under d.c. stress (also applicable to a.c.) led to an improvement of existing calibration services.

The calibration of a low-level PD calibrator (0.1 pC) was evaluated in an intercomparison carried out within the consortium. New calibration services and procedures for level PD down to 0.1 pC have been introduced by four partners, and respective CMCs submitted to EURAMET. The target measurement uncertainty of 0.01 pC was 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.

Representative test cells for PD under d.c. stress was designed and built for creating a database of reference PD pulses in High Voltage d.c./a.c for detection of PD patterns, which were validated with noise from a grid operator [5], [13]. A characterization setup was developed to generate reference PD pulse trains associated to real insulation defects (e.g. cavity, floating corona and surface PD sources) and saved in an optimized digital format only keeping the samples associated with PD pulses. The setup reproduces the saved reference PD pulse trains by means of an arbitrary function generator. A proposed method defines a standard PD pulse to be used for calibration purposes. The characterization setup allows determination of 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 location of a PD source.

The experience on PD under d.c. voltage stress has been extensively discussed within the CIGRE working group D1.63.

**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 minimizing 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 characterized 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-LCOE, 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 organizations 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.

**List of publications**


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| Project start date and duration: | 1 May 2016, 36 months | |
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| Internal Funded Partners:<br>1 RISE, Sweden<br>2 FFII, Spain<br>3 LNE, France<br>4 TUBITAK, Turkey<br>5 VTT, Finland | External Funded Partners:<br>6 CEA, France<br>7 GEMS, France | Unfunded Partners: |
| RMG: - | | |