Publishable Summary for 19ENG02 FutureEnergy
Metrology for future energy transmission

Overview

Driven by the need for increased efficiency, transmission grid voltages have been pushed to ultra-high voltages (UHV), beyond 1000 kV. This project has realised metrology solutions for grid component testing and condition monitoring required for successful implementation of future UHV transmission grids.

Specifically, the project has created critical metrology infrastructure in four areas: reliable and traceable lightning impulse measurements above 2500 kV; extended traceability of Ultra-High Voltage Direct Current (UHVDC) up to 1600 kV; improved High Voltage Alternating Current (HVAC) traceability via linearity determination of HV capacitors up to 800 kV; development of partial discharge measurement techniques in support of equipment testing under High Voltage Direct Current (HVDC) stress.

The project has reached all its objectives and beyond. The traceability for UHVDC up to 1200 and 1600 kV is already in use, the linearity extension of UHVLI is now in use with a good-practise guide, a new method for non-linearity of HV capacitors is available and implementation of PD measurements is now requested from the industry and grid operators.

Need

Society’s increasing demand for electrical energy, along with the increased integration of remote renewable generation has driven transmission levels to ever higher voltages in order to maintain (or improve) grid efficiency. Consequently, high voltage testing and monitoring beyond voltage levels covered by presently available metrology infrastructures were needed to secure availability and quality of supply.

Calibration services for UHVDC were not available above 1000 kV. There was a need to extend the calibration capabilities for voltage instrument transformers up to 1200 kV and for factory component testing capabilities up to 2000 kV. On-site calibration up to 1200 kV is conducted since 2022 in several HV manufacturer laboratories.

Methods for linear extension of lightning impulse (LI) calibration, for dielectric testing of UHV grid equipment, urgently needed revision. Research performed by CIGRE, a non-profit power system expertise community, and a recent EMPIR project 14IND08 ElPow, has raised questions regarding the validity of the current linearity extension methods for voltages beyond 2500 kV. There was an urgent need to provide recommendations to high voltage testing techniques standardisation. These were now provided.

New methods for calibration were needed for the 0.2 class HVAC voltage instrument transformers for system voltages up to 1200 kV. Compressed gas capacitive voltage dividers used for such HVAC calibration were largely limited by the voltage dependence of capacitance. Recent methods used for determination of the voltage dependence were very time-consuming, highlighting the need for methods allowing faster assessment, especially for on-site calibration where planned interruption periods needed to be minimised. A new method is now available to fulfil these needs.

With new HVDC transmission grids and associated components, novel methods were needed for detection, classification and localisation of partial discharge (PD) under d.c. stress. The industry needed methods for reliably monitoring critical components such as cables (both HVAC and HVDC) and gas insulated substations (GIS), and techniques for addressing new challenges introduced by HVDC technologies, such as the ability to distinguish PD signals from switching transients in converters and other sources of noise. In 2023 there are requests from two TSOs in Europe to test and implement the new PD detection technique in HVDC cable transmission links.

Objectives

The overall aim of the project was to provide traceability for metrology in testing and calibration of components for future electricity grids, and to provide improved means for HVDC grid condition monitoring. The specific objectives were:

1. To extend the traceable calibration of Ultra-High Voltage Direct Current (UHVDC) **up to at least 1600 kV possibly 2000 kV** by developing new methods and hardware. In addition, to facilitate on-site measurements by developing two modular voltage dividers, one with an expanded measurement uncertainty better than **200 µV/V at 1600 kV,** and one better than **40 µV/V at 1200 kV**.
2. To extend and research methods for **lightning impulse voltage calibration** for testing of UHV equipment. The target is to provide new input to IEC 60060-2 for time parameters and voltage measurement on ultra-high voltages above 2.5 MV, with an uncertainty for peak voltage better than 1 %. To resolve unexplained effects on measurements from front oscillations, corona, proximity and signal cable.
3. To develop a new method(s) for linearity determination of HV capacitors with **a target calibration uncertainty** for HVAC of **80 µV/V at 800 kV**.
4. To develop and **demonstrate implementation of partial discharge (PD) measurement** techniques for testing of equipment under d.c. stress, with specific emphasis on detection and prevention of insulation failures in HVDC cables, GIS and convertors. To develop special PD calibrators of representative PD pulses associated with insulation defects and a new characterisation setup up to 100 kV for a HVDC gas insulated substations (GIS).
5. To facilitate the take up of the technology and measurement infrastructure developed in the project, by the electrical power industry and to make recommendations to standards covered by IEC TC38, TC42, TC115, TC122 and TC22F.

Progress beyond the state of the art

1. Building on the d.c. voltage traceability obtained in EMRP project ENG07 HVDC for on-site calibration up to 1000 kV, capability has been upgraded to 1200 kV with a 20 µV/V uncertainty for calibration of reference measurement systems. Two lower echelon measuring systems have been constructed with capability up to 1600 kV (possibly 2000 kV), which will satisfy the need for calibration of UHVDC measuring systems, with a measurement uncertainty of 40 µV/V.
2. For calibration of large LI measurement systems in industrial laboratories, linear extension is needed to support approved measurements up to 3500 kV. Scientific proof has confirmed this extension’s validity above 2000 kV. Typical errors of 1 % for test voltage values were observed at 2700 kV in EMPIR project 14IND08 ElPow, and more than 3 % errors above 3000 kV. This project has extended metrology by developing and validating methods for linear extension up to 3000 kV.
3. Voltage traceability for a.c. is typically provided by using inductive voltage transformers or capacitive voltage dividers with an uncertainty of around 50 µV/V at 200 kV, and 500 µV/V at 800 kV. This project has extended beyond the state of the art by developing new methods for on-site determination of linearity errors in HV capacitors with an uncertainty of 20 µV/V at 800 kV. It has furthermore developed a new generation of gas-capacitors with a non-linearity lower than 10 µF/F at 800 kV.
4. HVDC systems have recently been modelled, and a PD waveform generator developed, to study insulation under d.c. stress. However, neither specific methods, nor any PD calibrators for measurements under d.c. stress, existed up to now. Going beyond the state of the art, a calibration procedure has been developed to qualify PD analysers working in the frequency range between 1 MHz and 30 MHz, for measurement of PD in HV cables and converters, and PD charge in the 30 – 300 MHz range HVDC GIS. The new PD generator is now available for on-site assessment.

Results

UHVDC traceability (objective 1)

For the traceability to 1200 kV **with the target measurement uncertainty of 40 µV/V**, in total seven new 200 kV HV modules have been built. One HV module increases the 1000 kV modular divider to 1200 kV for RISE. Five HV modules increase the 200 kV modular divider to 1200 kV for PTB. One HV module increases the 200 kV modular divider to 400 kV for TUBITAK. In total three measurement systems were set up in the lab of RISE in March 2022 for calibration. The 1200 kV calibration was performed in a step-up procedure with 200 kV, 600 kV, 800 kV to 1200 kV. An intercomparison took place between two 1200 kV dividers. Two complete sets of HVDC dividers are now available and used for on-site calibration with traceability to 1200 kV in Europe from RISE and PTB. **An expanded measurement uncertainty of 20 µV/V for 1200 kV** has been claimed.

For the traceability to at least 1600 kV two divider designs have been developed for UHVDC operation. The first shielded RCRC divider has been designed and five 400 kV modules were assembled by PTB with support from RISE and VTT and 2000 kV was reached. An alternative design is an unshielded RCR divider built by RISE with support from PTB and VTT where 1000 kV was reached.

An UHVDC generator was designed by PTB and set up for 2000 kV at an outdoor open area field test range in May-June 2022. During a campaign two 1200 kV HVDC dividers were intercompared with the 2000 kV RCRC divider and the 1000 kV RCR divider. An **expanded measurement uncertainty of 40 µV/V was reached at 1600 kV** for the RCRC divider and 40 µV/V at 1000 kV for the RCR divider.

Objective 1 for traceable UHVDC reference measurement systems with an expanded measurement uncertainty of 40 µV/V was met with 20 µV/V at 1200 kV, and 200 µV/V was met with 40 µV/V at 1600 kV.

Lightning impulse linearity extension (objective 2)

Nine different dividers took part in an intercomparison in October 2023 at TU Delft, with various designs, i.e., resistive and mixed capacitive dividers. Five existing impulse voltage measuring systems from VTT/TAU, PTB, RISE, TUBITAK and VSL/TU Delft, with nominal voltages ranging from 1000 kV up to 4000 kV, were characterised in preparation for the campaign. The voltage linearity of these systems was characterised in the three-week campaign. Included in this campaign were dividers from collaborator NIM (China) and Haefely AG (Switzerland). NMIA (Australia) supported to the work on linearity extension methods.

The charging voltage method for linear extension relies on a corona-free set-up to achieve 1 % measurement uncertainty as given by the standard. Working beyond 2 MV on positive polarity puts demands on practically everything to be corona-free, i.e., the divider and generator conditions as well as the HV connections. The linearity test against charging voltage of the generator can be used to prove the linearity. However, as stated in IEC 60060-2, failure to prove linearity does not necessarily mean that the measuring system is non-linear.

Good practices for measurement of Ultra High Voltage (UHV) impulse voltage measurement were studied by VTT, LNE, PTB, RISE, TUBITAK and NIM (China), which was summarised in a good practice guide. This guide contains Convolution & deconvolution method, Linearity extension method, Principle of linear extension, Influence of front oscillations, Influence of corona, Proximity effect, and Signal cable effect.

Special emphasis was put on the linearity extension, using comparison with impulse generator charging voltage, with a field probe, with measurement systems with a higher voltage rating, evaluation of linearity uncertainty estimation of a linearity test and using linearity results in measurement.

Objective 2 successfully proved that a measurement uncertainty of 1 % is possible beyond 2500 kV. This work was demonstrated up to 3000 kV with recommendations on criteria to meet to go beyond.

Voltage linearity of UHVAC references (objective 3)

Information on gas-capacitors was collected by TUBITAK and made accessible to project partners. The influence of high-level harmonic distortion up to 10 % at 50/60 Hz on the uncertainty of HV capacitor measurements was studied by LNE in a traditional capacitance bridge. Latzel's method was used on a high-voltage gas capacitor as reference for other techniques.

Following a thorough evaluation, five methods for non-linearity measurement of gas capacitors were compared and two of these selected for further development to be used for determination of the voltage coefficient of capacitors up to 800 kV, to significantly advance the applicability in an on-site characterisation. These were the "Field sensor method", developed by TAU, VTT and VSL, and a new method "Three equations method" developed by PTB. Two alternative methods, the "simplified tilt" and a new "CCD method" were studied by

NIM (China, collaborator). A design and development of an entirely new standard 800 kV gas capacitor by VETTINER was supported by characterisations by LNE.

The field probe method was studied by VTT and TAU in two campaigns. The three equations method was evaluated in two measurement campaigns at PTB. The study on field sensors for voltage nonlinearity in high voltage capacitors highlighted their potential but also their sensitivity to corona discharges limited the expanded uncertainty to < 30 µF/F @ 250 kV. The “Three equations method” reached an expanded measurement uncertainty of < 20 µF/F @ 800 kV. The new design of an 800 kV high-voltage capacitor by VETTINER has provided an estimated non-linearity of < 30 µF/F @ 800 kV for the first prototype.

Objective 3 successfully developed a new method for HV capacitor non-linearity determination within < 80 µF/F @ 800 kV and produced two methods where the best can reach an uncertainty of < 20 µF/F @ 800 kV.

HVDC grid condition monitoring (objective 4)

PD procedure for qualifying PD analysers used for d.c. measurement in the 1 – 30 MHz range

An attenuation study in HVAC and HVDC cable systems included attenuation tests in AC cable samples (MV and HV) and theoretical determination for AC and DC cable systems in the 1 – 30 MHz range. Test cells of representative defects have been used for aging (floating electrode, cavity, corona and surface) in two different testing facilities. A comparison between real data and laboratory test cells concluded that test cells represent real defects. Further comparisons are ongoing using a larger number of PD pulse trains for improvement of the test-cells in preparation of ageing experiments.

A set of PD pulse trains was supplied by a collaborator (DIAEL, collaborator) and used for development of an artificial intelligence (AI) tool. The results from the laboratory set-up using test cells have fed into setting up a neuronal network for DC PD pattern recognition by UPM. An HVDC converter test cell was developed for tests in a lab by UPM with support from FFII and discussed with RISE, TAU and TU Delft. Real data of noises were obtained from grid installations and time series have been incorporated in a synthetic PD generator for a round-robin test. FFII has developed three software tools for characterisation of PD analysers for AC which now also include DC PD patterns.

An adjustable synthetic calibrator was designed and built for four representative PD defects and noises with adjustable parameters. A round-robin test assessing HF PD analysers using the PD calibrator was performed by FFII, RISE, TAU, TU Delft and UPM. The round-robin results were very good.

PD charge evaluation in HVDC GIS using magnetic sensors measuring in the 30 MHz – 300 MHz range

A method for partial discharge (PD) charge evaluation in HVDC gas-insulated substations (GIS) was developed at TU Delft using a magnetic sensor using the following procedure: First, the propagation characterisation of PD in a GIS in the 30 – 300 MHz range was studied to understand the attenuation of the PD along the GIS. Secondly, the characteristics of the most common defects in GIS were investigated; with this, the bandwidth of the measuring system was selected. Thirdly, a test bench for characterising the sensor and the calibration method was developed, which was used for design of a magnetic sensor to cover the VHF range. Finally, the measuring system was tested using artificial defects in a low-voltage and high-voltage set setup.

The attenuations of the most representative PD from GIS discontinuities were collected in a database and SF_6 test cells were developed. A balanced magnetic loop antenna was developed and characterised. A magnetic and electric sensors model was tested using a test bench, where with two available mounting holes to admit sensors was used for comparison of the calibration method. This setup is for measuring the sensors' frequency response and time domain response against calibrated pulses. The charge was calculated in the time domain and by a method from FFII using the frequency domain, and it was found that the charge determination using the frequency domain obtained the best results.

After characterising the PD propagation, the PD defects, the sensors, and the calibration method, the measuring system was validated in two setups. A LV setup consisted of the test bench and the HV method validation consisted of a full-scale GIS with artificial defects PD, and additionally to TU Delft and FFII, SuperGrid Institute (collaborator) participated, increasing the interoperability of the method.

Objective 4 was successfully met by development and demonstrated the implementation of partial discharge (PD) measurement techniques and special calibrators for d.c. stress, with specific emphasis on detection and prevention of insulation failures in HVDC cables, GIS and convertors.

Impact

The output of the project was disseminated via presentations at international conferences (CPEM2020, CPEM2022, ISH2021, ISH2023, EIC2021, EIC2023, JICABLE2021, ALTAE2021, VDE2020, ICD2022, Norprd-IS22, CMD2022), with 29 peer-reviewed publications submitted into international journals (22 published), by active participation in three CIGRE working groups and general meetings, and by active participation and sharing of results in newsletters on the project web page.

Two stakeholder workshops were arranged, one at PTB in Braunschweig and one at FFII/LCOE in Madrid. One course was held on "Metrology for future HV transmission: HV measuring techniques" at LCOE/FFII in Madrid for HV industry, power grid operators and university students. Several courses were held at TU Braunschweig, UPM (Madrid), and Chalmers (Göteborg) for university students. Two good news stories were published on the EURAMET and the project webpages. In addition, a very important contribution to the HV community was the publication of the CIGRE brochure TB 888.

Impact on industrial and other user communities

The project has 38 stakeholders around the world, representing 14 countries, ranging from TSOs, HV instrument manufacturers, standards development organisations, national metrology institutes and universities. All stakeholders have benefited from the project's outputs and boosted the development of strong backbones for both HVDC and HVAC transmission networks by enabling more reliable, sustainable, and lower loss solutions. Transparency of the project's work has facilitated the uptake of its outcomes by the stakeholders and enabled end-results to be fed into the metrology network 18NET03 SEG-net (EMN-SEG).

The methods and hardware developed (including on-site applications) improving uncertainty and enabling traceable calibration of metering to the highest voltage levels, allow grid operators to minimise losses and improve monitoring of critical assets. The realisation of necessary metrological infrastructures for testing ensures improved quality control of high voltage transmission system components, thus benefiting manufacturers, suppliers, and users alike.

The UHVDC dividers built in this project can now calibrate instrument transformers and test equipment to 1200 kV and 2000 kV respectively, where in total fourteen on-site calibrations to full 1200 kV were carried out in 2022 and 2023. The modular RCR divider has been used in over 30 on-site calibrations in 2022 and several on-site assessments of non-standardised wave shapes up to 800 kV. Traceability for the latter wave shapes in advanced testing has a huge impact and a potential for rapid growth of service in the industry.

The on-site calibrations if UHV lightning impulse measurement systems have benefited from the practical guide and foremost the linear extension methods developed in the project. Industry is now better served with on-site calibrations of lightning, switching impulse and composite waves. A new guidance is at hand for linear extension metrology for correct measurement of lightning and switching impulse testing of e.g., power transformers.

With the new methods for determination of non-linearity in HV capacitors, new services are available. NMIs performing on-site calibrations of HVAC systems can now quickly assess customer systems with the new methods. Improvement of the traceability for HV capacitor calibrations, increasing the capability to 1000 kV, will also give improved services to calibrate AC measuring systems in HV industry.

New services for partial discharge in a.c. but foremost new d.c. grids, e.g., the north-south intertie in Germany now being built for energy transports, will significantly enhance the monitoring of the European power grids. The project has provided new tools for PD detection are being exploited with tight collaboration with HV industry, DSOs and TSOs. With the new HVDC transmission grids, the electric insulation is subjected to more critical stresses, demanding novel methods for detection, classification and localisation of PD.

Impact on the metrology and scientific communities

The HV scientific community has benefited from new and enhanced measurement capabilities in areas where scientific information has been lacking or measurements have been difficult to achieve. The needs addressed in this project resulted from explicit input from the HV industry and discussions with standardisation bodies, confirmed by experiences from on-site calibrations as well as from previous Horizon 2020 projects.

The project has produced two modular 1200 kV precision dividers for on-site calibrations by RISE and PTB with a claimed expanded measurement uncertainty of 20 μV/V at 1200 kV. The project has developed one 2000 kV divider at PTB for on-site calibrations with a claimed extended measurement uncertainty of 40 μV/V at 1600 kV in a corona free set-up, and a modular universal RCR divider with an expanded measurement uncertainty of 40 μV/V at 1000 kV also extendable to 2000 kV.

For UHV lightning impulse calibration the charging voltage method for linear extension relies on a corona-free set-up to achieve 1 % measurement uncertainty as given by the standard. The project has proof of this target up to 3000 kV on positive polarity. However, this puts demands on practically everything to be corona-free, i.e., the divider and generator conditions as well as the HV connections. Partners' experience with impulse voltage measurement techniques was collected to the Good Practice Guide on characterisation methods for UHV lightning impulse (LI) dividers.

Five methods have been studied and two further developed. Three methods are specialised for lab use, typically at NMI labs. Two methods for easy on-site assessment of HV capacitor non-linearity are now available for assessment of non-linearity, where a new method can provide an expanded uncertainty down to 20 μF/F at 800 kV in a corona-free environment.

New metrology is now available for enhanced PD detection, specifically for PD under d.c. stress, classification and localisation in HV cables, GIS and converters. Three NMIs and two universities now have the capability to detect and analyse PD particularly under d.c. stress applicable to HV cables, with key points for the analysis and classification where to use advance filtering, pattern recognition and artificial intelligence. New sensors, test benches and methods have been developed and qualified for PD detection in GIS and converters. Both LV and HV techniques were developed for this purpose and are now available for the scientific community.

Impact on relevant standards

This project had a major impact on IEC TC22F, TC38, TC42, TC99, TC115, TC122 and CENELEC TC38 adding new methods and an improved measurement traceability. The consortium generates results which has contributed to standardisation work, in e.g., revision of several standards, IEC 60060-1, IEC 60060-2, IEC 60270, IEC 61869-1,-7,-8,-9,-11 and -105. Within TC115 and TC22F a number of revisions is ongoing and TC122 has been updated with results from the measurement campaigns.

Results from new PD metrology contributed to the CIGRE SC D1 working groups D1.63 and D1.66, feeding into the revision of IEC 60270 and the technical specification IEC 62478 and a possible new standard. Harmonisation of test voltage curves and extending calibration methods to UHV levels above 3000 kV has given input to measurements and time parameters defined by IEC 60060-2 for lightning impulse voltages. The project has provided methods for the determination of a.c. voltage non-linearity in HV capacitors which will improve testing and development of system components and support standardisation within IEC TC122. In WG D1.50 work on the technical brochure on atmospheric corrections TB 888 has now been published, feeding into IEC TC99 and has impact on several standardisation bodies via JWG22 on IEC TC42.

Longer-term economic, social and environmental impacts

All the areas of emphasis within the project have provided means to improve grid stability and operability, to ensure a sustainable and affordable energy supply for European society, where electric power interties between continents and demands for reduced energy losses are driving grids to operate at ever higher voltage levels. Transmission losses can be sharply reduced by increasing the present transmission voltage levels leading to more affordable energy for customers and reducing the environmental impact of our electricity infrastructure. The project has in this context provided UHVDC traceability and monitoring of for long distance energy transports for the European and international interties.

This project has contributed to a reduction of European grid losses and prepare for a stable future UHV transmission grid. With the research and outputs from this project, highly competitive HV testing facilities, in particular new UHVDC calibration services and traceability and guides for UHVLI, has given a strong support for the European manufacturers to remain forerunners in grid innovation. This has a direct impact on the competitiveness of European power industry on the international market, leading to additional jobs, providing high quality and high reliability in equipment compared to low-cost and low-quality non-European manufacturers.

Supporting higher transmission voltages will reduce losses in a reduction in CO_2 emissions from energy transportation of many kilotons per year. Furthermore, PD as a key diagnostics tool, is an important measurement for preventing failures especially for GIS which are commonly filled with SF_6.

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