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 will realise metrology solutions for grid component testing and condition monitoring required for successful implementation of future UHV transmission grids.

Specifically, the project will create 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.

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 are needed to secure availability and quality of supply.

Calibration services for UHVDC are not available above 1000 kV. There is 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.

Methods for linear extension of lightning impulse (LI) calibration, for dielectric testing of UHV grid equipment, urgently need 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 is an urgent need to provide recommendations to high voltage testing techniques standardisation.

New methods for calibration are 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 are largely limited by the voltage dependence of capacitance. The current methods used for determination of the voltage dependence are very time-consuming, highlighting the need for methods allowing faster assessment, especially for on-site calibration where planned interruption periods need to be minimised.

With new HVDC transmission grids and associated components, novel methods are needed for detection, classification and localisation of partial discharge (PD) under d.c. stress. The industry needs 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.

Objectives

The overall aim of the project is 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 are:

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 will be upgraded to 1200 kV with a 40 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 target measurement uncertainty of 200 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 is lacking to confirm 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 will extend metrology by developing and validating methods for linear extension up to 3500 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 will extend beyond the state of the art by developing new methods for on-site determination of linearity errors in HV capacitors with a target uncertainty of 80 µV/V 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, currently exist. Going beyond the state of the art, a calibration procedure will be 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.

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. Two complete sets of HVDC dividers are now available for calibration with traceability to 1200 kV in Europe from RISE and PTB. An expanded measurement uncertainty of 20 µV/V for 1200 kV will be claimed.

In total three measurement systems were set up in the lab of RISE in March 2022 for calibration. Prior to the HV calibration a LV calibration of all collected system components was done in the precision lab of 16 HV modules and six LV arms. 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 from RISE and PTB and an 800 kV configuration combining the dividers from TUBITAK, VSL and VTT.

Field modelling to avoid corona discharge in the 1200 kV divider design showed additional corona rings need to be added to joints between the HV modules. During the campaign at RISE the diameter of the connecting tubes needed to have a minimum of 250 mm diameter with smooth surface for corona free measurements at 1200 kV.

Two divider designs have been developed for UHVDC operation. The first shielded RCRC divider has been designed and assembled by PTB with support from RISE and VTT. Five 400 kV UHVDC divider modules have been built to reach 2000 kV. The second design is an unshielded RCR divider that has been designed and calibrated by RISE with support from PTB and VTT. Two 500 kV modules were built for the RCR divider to reach 1000 kV.

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 100 µV/V was reached at 1600 kV for the RCRC divider and 80 µV/V at 1000 kV for the RCR divider.

Lightning impulse linearity extension (objective 2)

A draft of a good practice guide is in its final stage. VTT and LNE has modelled signal cable effects. Simulation models based on telegraphers' equations and Schelkunoff equations embedded into circuit simulator show good correspondence with practical measurements. In parallel to modelling, a literature study has been carried out by PTB and TUBITAK, and in-depth PhD work by FFII and PTB, to investigate the influence of the attenuation, cable quality and length in the coaxial cable between the high voltage hall and control room. Further experimental work at RISE has indicated possible origins of front oscillations. A collaborator [10] has also been engaged to practical experimental work on this subject. It has been decided to implement the results from the measurement campaign taking place in October 2022 in the guide.

Nine different dividers have been selected to take part in the intercomparison in October 2023, with various designs and properties, i.e., resistive and mixed capacitive dividers. These dividers have been modified and characterised to fine-tune the performance. There are three categories of reference measurement systems to be used for the campaign; the first is 400-600 kV, the second is 1200 kV and the third is 2000-3600 kV.

Collaborations were established with 1) NIM, China, to support the work on front oscillations; 2) Haefely AG, Switzerland, to support the work on front oscillations, the cable effect, and to provide a measurement system for the measurement campaign; and 3) NMIA, Australia, to support the work on linearity extension methods.

Voltage linearity of UHVAC references (objective 3)

Information has been collected by TUBITAK on gas-capacitors accessible to project partners and their voltage dependencies based on which the best references as well as the measurement bridges have been selected. The influence of high-level harmonic distortion up to 10 % at 50/60 Hz on the uncertainty of HV capacitor measurements in a traditional capacitance bridge has been determined and published by LNE [6].

Latzel's method has been repeated by LNE on a high-voltage capacitor to review the technique. The resulting measurements have been published [6]. The new design of an 800 kV high-voltage capacitor has been upgraded by VETTINER after testing of the first version and is being prepared for a measurement campaign at PTB in January 2023.

VTT and VSL reviewed linearity extension techniques used in industry utilising electrical field probes. A new prototype field probe designed by VSL to further develop the probe technique and the expected uncertainty, was manufactured and tested with good results. The field probe has been used as input to the work by VTT and TAU. VTT has performed direct measurements up to 180 kV to determine the non-linearity and also using a field probe up to 240 kV with good results.

PTB has measured the temperature dependence of their eight capacitors, which will be used in the development of a new calibration method. This method is based on the comparison of three high-voltage capacitors at a small and constant AC voltage and a variable high DC voltage. First tests show promising results and have been submitted for publication. The new method will be evaluated during the measurement campaign in January 2023.

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 has been carried out. This study includes attenuation tests in AC cable samples (MV and HV) and theoretical determination for AC and DC cable systems.

Attenuation is much lower in HV cable systems than in MV cables. Real data have been supplied from on-site tests.

Test cells of representative defects have been used for aging (floating electrode, cavity, corona and surface) in two different testing facilities, one site focused on corona, surface and on floating charge and the other is focused on cavity defects. A comparison between real data and laboratory test cells has been performed with a small number of PD trains, and the conclusion is positive: 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 1000 PD pulse trains was supplied by a collaborator (DIAEL) to be used for 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 has been developed for tests in a lab by UPM with support from FFII and discussed with RISE, TAU and TU Delft. A review of the bibliography about the state of the art of failures in DC and HVDC converters has been presented together with a test plan.

Real data of noises were obtained from grid installations (wind plants, PLC from MV substations and DC Plants). Several time series have been incorporated in a synthetic PD generator for a round-robin test, using noise data to be mixed with real PD pulses through data analyses to reproduce such noises by a synthetic generator, FFII has developed three software tools for characterisation of PD analysers for AC: a) PD sensitivity vs noise, b) PD pattern recognition, c) PD clustering. These tools allow the determination of the capabilities of PD analysers and are now extended to include DC PD patterns. Validation of the calibration procedure to qualify PD analysers working in the frequency range between 1 MHz and 30 MHz developed in EMPIR project 15NRM02 UHV has been completed.

An adjustable synthetic calibrator has been designed and built for representative PD defects and noises, i.e., a versatile reference PD source. This calibrator will use adjustable parameters (PD amplitude and PD repetition rate) to simulate the four defects. A round-robin test assessing HF PD analysers using the developed adjustable PD calibrator is performed between FFII, RISE, TAU, TU Delft and UPM. The following performances will be evaluated: PD sensitivity for reference PD pulses, PD pattern recognition, PD clustering, noise rejection and PD location.

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

The magnetic antenna design for PD measurements in GIS has been improved extending the bandwidth above 300 MHz. A modification in the design has been introduced to minimise the effects of resonances. A mathematical model of the antenna frequency response has been developed that will be instrumental for the charge estimation of the partial discharges, which was published [4] by TU Delft. Analysis on the GIS PD signal attenuation is done in the working frequency range of the magnetic antenna.

A testing workbench, with dimensions similar to a real GIS, has been built, in which calibration of the charge estimation in GIS has been verified to prepare a full-scale laboratory GIS for calibration [5]. Preliminary work on charge estimation error calculation shows positive results and will be extended with theoretical developments and laboratory experiments to demonstrate the suitability of the proposed method based on the double time integral of the measured signal. An improved design of the magnetic antenna which shows better sensitivity is under research. A calibration procedure has been proposed where the calibration constant for the charge estimation method was found for the electric and magnetic antennas. A combination of the magnetic and electric antennas has been studied, resulting in a method to discriminate backward reflections and PD power flow in the GIS [7,8,9].

A HV characterisation set-up has been built. The validation of the high voltage and low-voltage methods are under test. The collaboration with SuperGrid Institute has focused on testing the magnetic antenna under noisy conditions and testing artificial defects under SF_6 and alternative gases.

Impact

The dissemination activities have focused on interaction with standardisation organisations by taking active part at several standardisation meetings in revision of standards, namely revision of IEC 60060-1, IEC 60060-2, and IEC 60270 and providing guidance on measurement uncertainties in the revision of 61869-11 and in impulse testing of instrument transformers in IEC 61689-1. Active interaction is performed concurrently with industrial stakeholders through update in progress during on-site calibrations, collecting new needs, describing project outputs and providing measurement guidance and calibration capabilities.

Impact on industrial and other user communities

The project currently has 34 stakeholders, ranging from TSOs, HV instrument manufacturers, standards development organisations, national metrology institutes and universities. These stakeholders will benefit from the project's outputs, which will boost the development of strong backbones for both HVDC and HVAC transmission networks by enabling more reliable, sustainable, and lower loss solutions. The methods and hardware developed (including on-site applications) improving uncertainty and enabling traceable calibration of metering to the highest voltage levels, will 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 European power industry, with vast experience in both a.c. grids and d.c. transmission, has a leading position in producing and testing of high voltage components. The improved traceability and quality of measurement developed in this project allows for more precise (reduced) safety margins and thereby increased operability of manufactured products and systems. For example, the industry will benefit from the new methods of creating traceability for instrument transformers at the highest voltages and thereby for power loss measurement systems for e.g., reactors. One of the early impacts so far is that seven calibrations to 1200 kV with RISE HVDC reference measurement system have been ordered by the HV industry.

New offshore renewable energies and extensive electrical links between islands and countries require very large submarine cables and GIS in HVDC. Unexpected dielectric failure in these critical HVDC facilities due to dielectric degradation has serious consequences for the continuity of power supply and the stability of the power grid. Partial discharge measurements have proven to be effective in preventing such risks in HVAC. By extending this approach to HVDC, this project will support the metrological base to improve and verify reliability of HVDC networks (cables, GIS and convertors). Development of methods, equipment, and interpretation of PD data under d.c. stress advances the ability to detect and prevent insulation failures, providing means for grid condition monitoring and fault detection largely impacting the TSO's ability to also handle d.c. grids.

Transparency of the project's work will facilitate the uptake of its outcomes by the stakeholders and will enable end-results to be fed into the metrology network created by EMPIR project 18NET03 SEG-net (EMN-SEG). Close co-operation between NMIs and European industry will lead to better control and prevention of losses and damage mechanisms crucial for the next generation transmission grids.

Impact on the metrology and scientific communities

The HV scientific community will benefit 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. Collaboration and consultations with these organisations have been key for addressing the developments needed as voiced by the metrology and scientific communities. Project outputs will include several important additions and extensions to NMI/DI Calibration and Measurement Capabilities (CMSs) related to the calibration of UHVDC voltage instrument transformers and testing equipment, calibration of lightning impulse voltage measurement systems, linearity determination of reference measurement systems for a.c., and PD measurements under d.c. stress for cables and GIS.

Impact on relevant standards

This project has a major impact on IEC standardisation committees and working groups with new methods and an improved measurement traceability. The consortium generates results that will be very valuable to standardisation work within IEC and CENELEC, namely revision of several standards, IEC 60060-1, IEC 60060-2, IEC 60270, which is covered by IEC TC42 and IEC 61869-1, 61869-7,8,9 and IEC61869-105, standards covered by IEC TC38. Within TC115 and TC22F a number of revisions is ongoing and TC122 will be informed after the measurement campaigns. Results are also fed into pre-normative bodies of CIGRE SC D1 working groups D1.63 and D1.66. In WG D1.50 the writing of a technical brochure is concluded, which foremost feeds into IEC TC99 but has important impact on several standardisation bodies by a joint working group JWG22 coordinated by IEC TC42. Another example is supporting the pre-normative and standardisation work in d.c. PD, currently discussed in depth within CIGRE D1.63, that has fed into the revision of IEC 60270 and a future new standard has been discussed. Harmonisation of test voltage curves and extending calibration methods to UHV levels above 2.5 MV will help to shape new input to measurements and time parameters defined by IEC 60060-2 for lightning impulse voltages. New methods for the determination and correction of a.c. voltage non-linearity in HV capacitors which are used as references for calibration of UHVAC systems will enable more efficient testing and development of system components and support standardisation within IEC TC122.

Longer-term economic, social and environmental impacts

All the areas of emphasis within the project aim to improve grid stability and operability, to ensure a sustainable and affordable energy supply for European society. Electric power interties (transmission lines that connect separate electric grids) between continents and demands for reduced energy losses over long distance transmission 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 primary aim for this project is to contribute 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, will give 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.

Reliable and affordable energy delivery is the prime societal need. Europe needs a renewal of the electricity grid as a new backbone for the infrastructure, which is mirrored in the enormous interest in the bi-annual CIGRE meetings and the annual IEEE Power and Energy meetings. This project offers a unique opportunity for European NMIs to pool their collective strengths, and unique capabilities and facilities, to make a robust contribution to the realisation of the future grids.

Supporting higher transmission voltages will reduce losses, especially when using d.c. transmission, and even the smallest contribution to this improvement will result in a reduction in CO_2 emissions from energy transportation of many kilotons per year. Furthermore, PD, a key diagnostics tool, is an important measurement for preventing failures especially for GIS which are commonly filled with SF_6 (1 kg SF_6 has the ozone-depleting potential of 23 tons of CO_2). Today there are more than 10000 such installations, which if released would be the 15 % of the EU GHG equivalent in 2017.

List of publications

1. Elg, Alf-Peter, Garnacho, Fernando, Agazar, Mohamed, Meisner, Johan, Merev, Ahmet, Houtzager, Ernest, Hällström, Jari, Lahti, Kari, Escurra, Christian Mier, Platero, Carlos Antonio, Micand, Thierry, Steiner, Thomas, Voss, Andreas., “Research Project EMPIR 19ENG02 Future Energy”, ETG-Fb. 162: VDE Hochspannungstechnik, December 2020. https://doi.org/10.5281/zenodo.4769653
2. Joni Klüss, Alf-Peter Elg, Claes Wingqvist, “High-Frequency Current Transformer Design and Implementation Considerations for Wideband Partial Discharge Applications”, IEEE Transactions, IEEE Transactions on Instrumentation and Measurement 70, 1-9, 2021. https://doi.org/10.5281/zenodo.4772471
3. Abderrahim Khamlichi, Fernando Garnacho, Fernando Álvarez, “Error in the measurement of partial discharge pulses according to the frequency response of HFCT sensors”, 1257 - EIC2021, https://doi.org/10.5281/zenodo.5906679
4. Christian Mier Escurra, Armando Rodrigo Mor, Peter Vaessen, “Design and Characterization of a Magnetic Loop Antenna for Partial Discharge Measurements in Gas Insulated Substations”, IEEE Transactions on Instrumentation and Measurement 70, 1-9, 2021. https://doi.org/10.1109/JSEN.2021.3089084
5. Christian Mier Escurra, Armando Rodrigo Mor “Test Bench and Frequency Response of a Magnetic Antenna used in GIS PD Measurements”, 2021 IEEE Electrical Insulation Conference (EIC): Proceedings (pp. 269-272). [9612372] IEEE. https://doi.org/10.5281/zenodo.5815711
6. Mohamed Agazar, Hanane Saadeddine, Johann Meisner, Frank Gerdinand, Stephan Passon, Jean Marc Pillet, “Determination of voltage dependence of capacitance of 1000 kV and 300 kV compressed gas capacitors using the kinetic method”, ISH 2021. https://doi.org/10.5281/zenodo.7142256
7. Christian Mier Escurra, Armando Rodrigo Mor, Luis Castro, Peter Vaessen, “Partial Discharge Charge Estimation In Gas-Insulated Substations Using Electric and Magnetic Antennas”, ICD2022, https://doi.org/10.1109/ICD53806.2022.9863499

8. Christian Mier Escurra, Armando Rodrigo Mor, Peter Vaessen, André Lathouwers, “Magnetic and electric antennas calibration for partial discharge charge estimation in gas-insulated substations”, International Journal of Electrical Power and Energy Systems, VOL. 141. https://doi.org/10.1016/j.ijepes.2022.108226
9. Christian Mier Escurra, Armando Rodrigo Mor, Luis Castro, Peter Vaessen, "Magnetic and electric antennas synergy for partial discharge measurements in gas-insulated substations: Power flow and reflection suppression", International Journal of Electrical Power and Energy Systems, VOL. 144, https://doi.org/10.1016/j.ijepes.2022.108530

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Project start date and duration:	01 June 2020, 36 months	
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Internal Funded Partners: 1. RISE, Sweden 2. FFII, Spain 3. LNE, France 4. PTB, Germany 5. TUBITAK, Turkey 6. VSL, Netherlands 7. VTT, Finland	External Funded Partners: 8. TAU, Finland 9. TU Delft, Netherlands 10. UPM, Spain 11. VETTINER, France	Unfunded Partners: -
RMG: -		