Research Project EMPIR 19ENG02 Future Energy

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Abstract

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 Ultra-High Voltage Direct Current (UHVDC) presently are only available up to 1000 kV. There is a need to extend the DC calibration capabilities for voltage instrument transformers up to 1200 kV and for factory component testing capabilities up to 2000 kV. Also, methods for linear extension of lightning impulse calibration, for dielectric testing of UHV grid equipment, urgently need revision. Recent research has raised questions regarding the validity of the current linearity extension methods for voltages beyond 2500 kV. Furthermore, new methods for calibration are needed for the 0.2 class HVAC voltage instrument transformers for system voltages up to 1200 kV. The current methods used for determination of the voltage dependence are very time consuming, raising the need for methods allowing faster assessment. Finally, with new HVDC transmission grids and associated components, novel methods are needed for detection, classification and localisation of partial discharge (PD) under DC stress. The industry needs methods for reliable monitoring of critical components such as cables, for 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.

1 Introduction

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. In the production of equipment for high voltage grids, dielectric testing is a crucial step to verify that equipment can withstand their operational environment, including abnormal stress in the form of high voltage and high current impulses. Methods and schemes for calibration have been identified primarily in IEC 60060-2, High-voltage and high-current test techniques. The system voltages are however increasing to levels higher than those covered by this standard, and there is a strong need to extend test methods reliably into the ultra-high voltage range. Currently, traceability is needed up to 2000 kV for d.c. and 2800 kV for LI measuring systems. When traceability is lacking, a linear extension of a factor of 5 is accepted in the standard for a.c. [2]. However, the established methods and schemes [1] do not yet cover UHV voltage levels. Working group 19 of IEC TC42 [3] has been given the task to make recommendations for this extension, with support from a CIGRE group [4]. For power grid energy measurements, a revision of the IEC 38 standard IEC 61869 is on-going for d.c. voltage instrument transformers [5]. The MT23 maintenance team of IEC TC42 has been given the task to revise and upgrade IEC 60270 [6] describing PD measurements, traditionally developed for a.c. systems, and a CIGRE working group [7] has been tasked to recommend changes to encompass PD measurements under d.c. stress.

The “Future Energy” European metrology R&D project, which started in June 2020, will provide new traceability for metrology in testing and calibration of components for future electricity grids and to provide improved means for HVDC grid condition monitoring.

2 Project objectives

The first project objective is to extend the traceable calibration of 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.

The second objective is to develop 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 voltage above 2.5 MV, with an uncertainty for peak voltage better than 1 %, and to resolve unexplained effects on measurements from front oscillations, corona, proximity, and measurement cable.

The third objective is to develop new time-efficient method(s) for linearity determination of HV capacitors with a target calibration uncertainty for HVAC of 80 µF/F at 800 kV.

The fourth objective is to develop and demonstrate implementation of PD measurement techniques for diagnostics of equipment under DC stress, with specific emphasis on detection and prevention of insulation failures in HVDC cables, GIS, and convertors. Special PD calibrators of representative PD pulses will be developed associated with insulation defects and a new characterization setup up to 100 kV will be developed for a HVDC GIS.

3 State of the art and progress beyond

3.1 UHVDC calibration and testing

Traceable calibration of HVDC dividers is available today up to 1000 kV, with an expanded measurement uncertainty of 20 µV/V. This was achieved by designing a modular voltage divider in EMRP JRP ENG07 HVDC [9]. For d.c. voltage instrument transformers used for energy measurements in the grids with accuracy class 0.1 [5], a factory reference is needed at 1200 kV with at least a measurement uncertainty of better than 200 µV/V.

This project will therefore extend the calibration capabilities for UHVDC voltage instrument transformers up to 1200 kV with an expanded measurement uncertainty of 40 µV/V. Already at 1000 kV unwanted effects like corona have become apparent, which makes linearity investigation and validation of the reference systems inevitable.

For component testing and development purposes, the 1000 kV traceability is not enough for testing of grid components for grids up to 1200 kV as these systems need to be tested up to 2000 kV. For development and testing purposes an expanded measurement uncertainty of 1 % is enough, and many UHV class labs would preferably have their own reference systems with an uncertainty of 0.2 %. To calibrate these references in turn, the uncertainty requirement approaches 200 µV/V. Such services are not available at this voltage level.

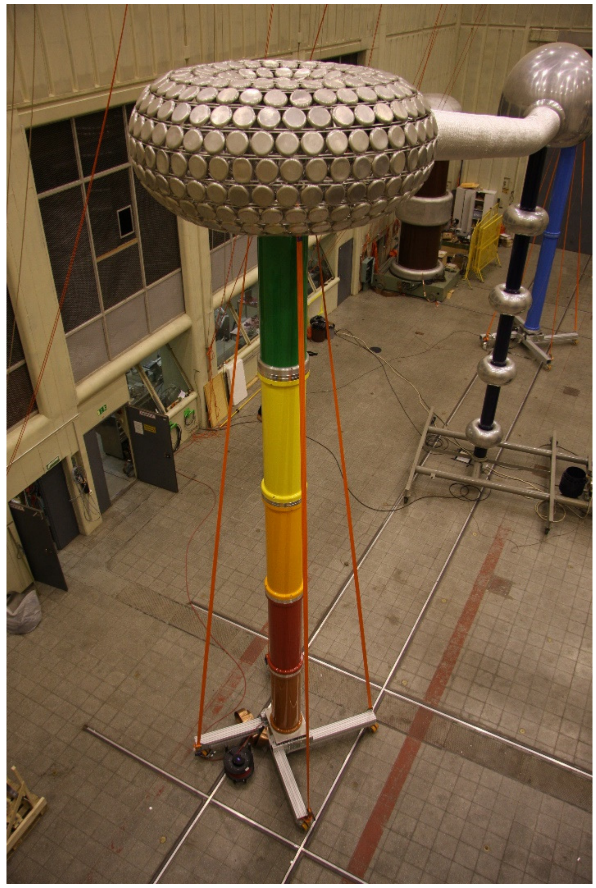

Figure 1 The HVDC 1000 modular divider from the EMRP ENG07 HVDC project [9]

As a first target, this project will develop a simplified UHVDC reference divider, compared to the reference divider for energy metering calibration, up to at least 1600 kV, and possibly 2000 kV. Research and validation of the linearity for these reference systems, also addressed in this project, will be an even more difficult research challenge.

3.2 Lightning impulse voltage calibrations for UHV testing

Lightning impulse calibrations are routinely performed onsite owing to the sheer size of the impulse dividers. Reference measurement systems suitable for transportation to the customer laboratories reach about 700 kV, which makes a linear extension of up to a factor of five for UHV

systems inevitable [2]. However, the required proof of linearity up to full test voltage for UHV applications still needs to be given. This is particularly relevant given the proximity effects in often cramped test laboratories. The uncertainty of linear extension above 2500 kV has been found to deviate more than 3 % [8], whereas for useful test results it is required to be better than 1 %.
Research in EMPIR JRP 14IND08 ElPow [10] raised serious questions regarding the validity of the current linearity extension methods for LI to voltages beyond 1500 kV. The effects discovered include the unexpectedly large influence of the divider distance to the test point, corona and generator source impedance. A measurement set-up for linear extension determination is shown in Figure 2.

Figure 2 Linearity extension measurements in EMPIR 14IND08 ElPow [10]

The new Future Energy project will progress beyond the state of the art by developing methods for extension of the validity of scale factor determination from the 800 kV level up to a UHV level of 3500 kV based on earlier standards and findings. Studies will be both experimental and theoretical.
Furthermore, front oscillations in impulse measurements have been discovered to affect the front time determination. Such oscillations are resolved by smaller fast responding reference measurement systems but are not usually detected by test systems capable of handling higher voltage levels. The outcome is that the uncertainty for front time determination, often claimed for CMCs to be within 1 % of the expanded measurement uncertainty, is often questioned as to whether it is even within 2 %. This project will determine the origin of the oscillations, whether these are truly present in the measurement system, or are artefacts from the HV circuit setup, or possibly depend on the UHV class divider design. The findings and recommendations will be reported to IEC TC42 for future amendments to the standards.

3.3 Voltage dependence at HVAC

Reference measurement systems for a.c. phase-to-neutral voltage provide traceability in HVAC is typically provided by using inductive voltage transformers or capacitive voltage dividers up to the current 1200 kV system voltage level. The factory reference should have a measurement uncertainty of around 50 µV/V at 200 kV, and 500 µV/V at 800 kV. Using capacitive voltage dividers, the higher uncertainty at higher voltage levels is due to the lack of voltage linearity in the HV capacitors (often compressed gas capacitors), but also due to increasing corona. The existing voltage linearity determination methods for high voltage capacitors are better than 10 µF/F and are used for trimming compressed gas capacitors [13, 14]. However, for a quick assessment and adjustment of the linearity error of any type of HV capacitor, especially for tall factory references which are not easily transportable, the current methods are not very practical.
The project will make a major step 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 µF/F at 800 kV.
In this work the consortium combine NMI measurement capabilities with the development of a new compressed gas capacitor by the industrial partner VETTINER to verify and compare new and existing methods for voltage linearity determination. The new methods shall applicable on any reference capacitor and validated using mechanical-based methods on the new 800 kV reference [13, 14].
A 230 kV compressed gas capacitor from VETTINER shown in figure 3 has a voltage dependence of 4 µF/F.

Figure 3 HV capacitor with 4 µF/F voltage dependence up to 230 kV.
Scaling of this design to 800 kV with V^2 would give an approximate expanded uncertainty below 50 µF/F. A new

capacitor developed in the Future Energy project has a target voltage dependence better than 10 μF/F at 800 kV.

3.4 HVDC grid condition monitoring

PD measurements have a long tradition in a.c. systems and are described in IEC 60270 [6] maintained by IEC TC42. Traditional PD measurement methods are based on the integration of analogue signals, or digitisation using fast digitisers. However, for the expanding d.c. transmission grid, methods or traceability of PD measurements under d.c. stress is not yet established.

The rate and amplitude of the PD pulses are small under HVDC stress. Therefore, noise suppression techniques are implemented in recent measuring instruments to measure small PD pulses under d.c. stress. However, no standard procedure exists to determine the error caused by measuring instruments when these noise suppression techniques are applied. In addition, most of the measuring systems used for online PD measurements give voltage readings from the output of PD sensors related to apparent charge. However, no clear correlations between the measured signals and the charge are given for d.c. Furthermore, PD pulses must be discriminated depending on their waveform in order to distinguish the type of defect (corona, cavity defect, surface PD, etc.), but at present, no measuring procedures are given in the standards for d.c. stress.

The CIGRE expert group D1.63 are currently working on a review of existing methods and metrology principles which might be used for monitoring under d.c. stress. Metrological support to new measuring instruments for insulation condition analysis and methods for distinguishing PD sources has recently been initiated in EMPIR JRP 15NRM02 UHV [11]. Four test cells were developed to register corona signatures in the 1 – 30 MHz, shown in Figure 4.

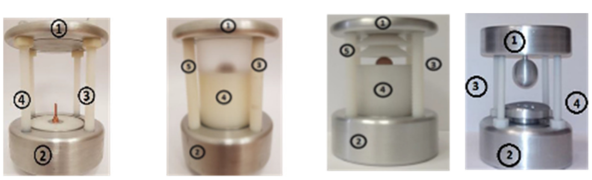

Figure 4 PD test cells for recording of representative defects, from left corona, floating PD, surface PD and cavity

The present project will apply the knowledge developed in 15NRM02 UHV to the validation of measurement systems used for partial discharge (PD) measurements for HVDC transmission systems. It will further provide metrological support for new measuring instruments to analyse the insulation condition in both a.c. and d.c. grids applied to the detection of PD under d.c. stress in HV cables and develop monitoring techniques for GIS with regards to new insulating materials and gases.

The PD methods and equipment for GIS application will also be further used for collecting data for detection and future analysis of PD in HVDC convertors, where traditional methods cannot distinguish between PD and switching transients in converters. The outcomes will be fed to maintenance team MT23 of IEC TC42 for revision and updating the PD measurement methods described in IEC 60270 [5].

4 Project progress

In June 2020 the Future Energy project was initiated in a meeting with 22 participants from all eleven partners. Work is underway to establish possible collaboration with five different entities, comprising of a mixture of companies and NMIs, for additional research or development and impact to the project.

During the project the results will be published in open-access papers, many connected to conferences such as the bi-annual International Symposium of High Voltage Engineering (ISH, odd-numbered years), the bi-annual International Conference on High Voltage Engineering and Application (ICHVE, even-numbered years), CIGRE sessions and IEEE conferences.

At least one stakeholder workshop is planned at the end of the project in spring 2023. The workshop will be open to industry, national metrology institutes, universities, instrument manufacturers and accredited laboratories. The workshop will present the results achieved by the project and will allow time for discussion of the results with all the participating stakeholders and instrument manufacturers.

Training sessions will be arranged where PhD students will take part in the scientific work.

5 Impact

5.1 Impact on industry and user communities

Initially 15 stakeholders were in support to the project, in mixture of HV manufacturers, grid operators, standardisation and pre-normative bodies. The list is growing and is now encompassing 25 stakeholders. A recent example is the interest from the SuperGrid Institute in France, which aims to become "tomorrow's European champion for large electrical networks" in competition with China's multiterminal connection plans with Europe.

These stakeholders will benefit from the project's outputs, which will boost the development of strong backbones for both UHVDC and UHVAC 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 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.

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 JNP 18NET03 SEG-net (EMN-SEG) [12]. Close co-operation between NMIs and European industry will lead to better control and prevention of losses and monitoring of damage mechanisms crucial for the next generation transmission grids

5.2 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 perform. 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.

The outputs of the project will include several important additions and extensions to NMI/DI Calibration and Measurement Capabilities (CMCs) statements recorded in the BIPM key Comparison Database (KCDB), and as such, provide a significant impact to the worldwide electrical power metrology community. Specifically, new and extended CMCs are foreseen for:

1. Calibration of UHVDC of voltage instrument transformers with uncertainties better than 40 µV/V for energy metering up to 1200 kV.
2. Calibration of UHVDC of testing equipment with uncertainties better than 200 µV/V up to 1600 kV, possibly 2000 kV.
3. Calibration methods in terms of linear extension of lightning impulse voltage measurement systems at UHV levels up to 3500 kV.
4. Measurement methods for linearity determination of reference measurement systems for a.c. calibrations up to 800 kV.

5.3 Impact on relevant standards

This project will have a major impact on IEC standardisation committees and working groups with new methods and improved measurement traceability. The consortium is expected to generate results that will be very valuable to standardisation work within IEC and CENELEC, namely the IEC 60060 series, IEC 60270, and the IEC 61869 series, and standards covered by IEC TC38 and TC42. The project will have a tight collaboration with the standardisation bodies IEC TC42 and CENELEC TC38 for HV metrology, and HV applications regulated by TC22F, TC115 and TC122. Project partner contacts and active work are also tying into several CIGRE D1 working groups. The project will provide input to ongoing revisions of IEC 60060, IEC 61083, IEC 60270 and IEC 61869 series.

6 Summary

The society and industrial needs and objectives have been presented for the project 19ENG02 FutureEnergy, funded by the European Metrology Programme for Innovation and Research (EMPIR). Several metrological areas will establish new and extended traceability for measurements, tests and calibrations with UHVDC, UHVLI including linear extension to 3500 kV, voltage linearity of HV capacitors and metrology for PD detection under d.c. stress.

Providing transparency of the project's work will facilitate uptake of its outcomes by the stakeholders and will enable end-results to be fed into the metrology network created by EMPIR JNP 18NET03 SEG-net (EMN-SEG) [12]. A close co-operation between NMIs and European industry will lead to better control and prevention of losses and monitoring of damage mechanisms crucial for the next generation transmission grids. This metrology provide means for reliably building a European super grid for exchange of bulk energy with other continents.

7 Acknowledgement

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8 Literature

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