FINAL PUBLISHABLE REPORT

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RMG: -		

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1 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.

2 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.

3 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.

4 Results

4.1 Objective 1 – Extend traceable calibration of Ultra-High Voltage Direct Current (UHVDC).

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. Therefore, the first objective was 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**.

4.1.1 Extension of the modular 1000 kV divider to a 1200 kV UHVDC divider

For calibration of UHVDC metering with instrument transformers at least 40 µV/V is needed. RISE, PTB and TUBITAK with support from VTT redesigned, and upgraded an existing shielded RCRC modular HVDC divider to meet this objective up to 1200 kV. An RCRC divider consists of a precision and a shield stack in parallel, where the parallel shield capacitance is used to protect the precision resistors during a calibration from switching or lightning events.

4.1.1.1 Review of the modular 1000 kV UHVDC divider

The performance of the existing modular voltage divider designed in EMRP project ENG07 HVDC was reviewed. A need for additional corona rings from 800 kV in the original design was identified using field modelling. Input from experience in on-site calibrations to 1000 kV also indicated this. This was validated in lab experiments on RISE 1000 kV modular HVDC divider. Field modelling was done by RISE to identify critical field strengths and avoid corona discharge in the 1200 kV divider design. RISE as discussed with PTB and TUBITAK, decided to support the calculations by HV lab tests at RISE. The conclusion was to use additional corona rings to two joints between HV modules at 800 and 1000 kV. The top toroid design for 1000 kV used since 2013 by RISE proved to withstand 1200 kV.

Information about the performance of the existing modular voltage divider designed in EMRP project ENG07 HVDC has been monitored by RISE with support from PTB, TUBTAK, VSL and VTT. A paper was written on the stability of the original HVDC divider systems from 2013 – 2021, presented at CPEM 2022 and published. The performance of these modules was studied in a campaign at RISE.

4.1.1.2 Components for the new HVDC divider modules

Suppliers for the components were contacted by RISE and support was given by the old supplier Trench, even though the factory had been moved to another country, to produce the needed special shield capacitors. In the picture to the right a 50 kV sub-module is shown, where the three green blocks are the Trench capacitors. In the centre the precision resistors are mounted around a rod made from MACOR, which gives a larger stray capacitance than e.g., plastic materials.

Plans were made by RISE, PTB and TUBITAK for assembly and complete purchase lists for seven more HV modules. The original specification of precision resistors was used to order the needed amount for the TUBITAK module. RISE still had some in stock from the old project. PTB choose a lower temperature coefficient and purchased these for the HVDC divider as well as the new UHVDC divider. PTB performed measurements to find deviations of the voltage and temperature coefficient. The shield resistors proved to be hard to obtain with a close enough resistance compared to the od design. An estimate was made by RISE from these deviations of the new modules from the existing ones which resulted in a redistribution of shield blocks with the old divider modules.

All components for the seven new HVDC divider modules were purchased and delivered, with a delay for the shield capacitors to January 2022. This delayed the planned intercomparison from December 2021 to March 2022. Using the earlier field modelling, two corona rings per 1200 kV system were purchased, delivered in 2021 and assembled for the intercomparison at RISE.

4.1.1.3 Assembly and calibration of the HVDC divider modules

In total, seven HV modules, bottom support, and corona rings for the 1200 kV dividers were assembled by RISE. The plan was to make this a joint effort between RISE, PTB and TUBITAK, but COVID stopped it. The time slot for an intercomparison at RISE could not be moved further and would cause a knock-on effect on the final intercomparison at PTB in June 2022.

In total, seven HV modules for the 1200 kV divider were built in February 2022. One was added to the existing 1000 kV modular divider of RISE for 1200 kV, five were added to an existing 200 kV modular divider of PTB for 1200 kV, and one was added to an existing 200 kV modular divider for 400 kV.

The other 200 kV divider systems from PTB, TUBITAK, VSL ant VTT were sent to RISE in January 2022 for low voltage calibration of all 16 HV arms and 6 LV arms in preparation for the coming intercomparison.

4.1.1.4 Intercomparison of five 200 kV dividers

As a bonus having all the 200 kV divider configurations from the five NMIs, built 2010 – 2013, it was decided to perform a supplementary intercomparison for BIPM. The performance of five 200 kV HVDC dividers from RISE, PTB, TUBITAK, VSL and VTT was intercompared before the 1200 kV measurement campaign at RISE in March 2022. The results of this supported the history of the stability and was used as part for the publication at CPEM 2022. The set-up at RISE is shown in the figure to the right.

This intercomparison is registered at BIPM as two intercomparisons EURAMET.EM-S46 as “Supplementary Comparison - High voltage comparison of high resistance” and EURAMET.EM-S47 as “Supplementary Comparison - High voltage comparison of DC ratio”. Publication is expected at the end of 2023.

4.1.1.5 Intercomparison to 1200 kV

Preparations and a detailed planning for the calibration procedure was made for an intercomparison between two 1200 kV dividers from RISE and PTB, and one 800 kV mixed stack using the modules from TUBITAK (one old and one new), VSL and VTT.

An intercomparison took place in March 2022 between the two 1200 kV systems and one 800 kV system using HV modules from all involved NMIs. The picture to the right shows the comparison of the two complete 1200 kV systems from RISE and PTB. A calibration procedure was established using a step-up method from LV calibration to 200 kV, 600 kV and finally to 1200 kV. Using proper HV connections a corona-free measurement at 1200 kV gave excellent results. An expanded measurement uncertainty of 20 µV/V was claimed.

The preparation of a journal paper about the results on designing, building and calibrating the modular dividers is in writing. Due to an unexpected amount of data and the complex analysis this activity is delayed beyond the end of the project and will be submitted to a peer-reviewed journal by the end of 2023.

4.1.1.6 Result, measurement uncertainties and new CMC entries

The result from the intercomparison at RISE supports an expanded measurement uncertainty of 20 µV/V at 1200 kV. New CMCs have been claimed for RISE, PTB and TUBITAK for the precision UHVDC divider systems. This is a factor of 2 better than the project target of 40 µV/V which fulfils the first part of objective 1.

4.1.1.7 Early impact to industry

Seven full on-site UHVDC calibrations to 1200 kV were delivered by RISE to Swedish HV industry during 2022 and at least seven more calibrations have been ordered for Q3 2023. About 20 calibrations to 200 and 400 kV have been performed by PTB with their two UHVDC dividers.

4.1.2 Extension of traceability to 1600 kV

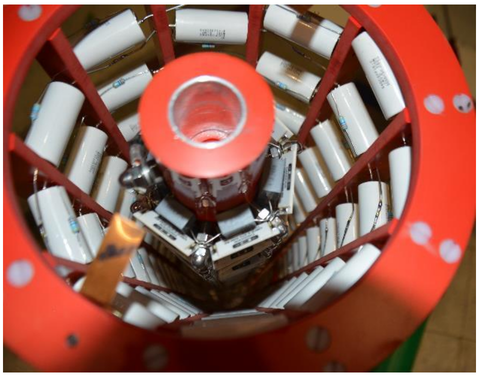
For calibration of UHVDC testing up to 1600 kV and beyond traceability to at least 200 µV/V is needed. Within the project a new RCRC divider was designed and built, based on the shielded RCRC divider principle as the precision 1200 kV modular divider. The discussions, led by PTB with support from LNE, RISE and TUBITAK, presented a simpler design based on off-shelf components only. In the 1200 kV precision divider described in section 4.1.1 the shield stack has unique capacitor stacks.

A new simpler design was developed, explored and internally funded by RISE using the design of a modular RCR divider. The idea was to use precision resistors, so called bleeder resistors parallel to the capacitors, which are very suitable for precise UHVDC calibration, and with the same divider solving the metrology for composite/combined wave traceability in a parallel EMPIR project 19NRM07 HV-com[2]. The latter divider was built with 500 kV modules to 1000 (1100) kV UHVDC in a separate project at RISE. This divider can be extended by stacking further modules to 1500 (1650) and 2000 kV.

4.1.2.1 Design of the RCRC 1600 kV UHVDC divider

The divider is based on the shielded RCRC divider principle as the precision modular divider for metering calibration and was designed by PTB to reach the targeted 1600 kV in four 400 kV modules. To further support testing as high as 2000 kV, a fifth 400 kV module was planned for.

The image to the right shows the mounting of the precision stack in a 400 kV module in the middle, adding capacitors in parallel with the precision resistors, to give more immunity to stray fields. In the 1200 kV precision divider these are not present to avoid possible leakage currents.



Shield components are surrounding the precision stack, which are mounted in two counterpropagating branches to reduce inductance (figure to the right). The shield capacitors are from Cornell-Dubilier, and the bleeder resistors are standard metal film resistors. This makes a cheaper solution than for the HVDC divider.

The structure is encased in a polypropylene tube with flanges, sealed and backfilled with protective gas to avoid drift of resistance from humidity and increase the dielectric strength. These HV modules are rated 400 kV and about 2.3 m tall and weigh 80 kg, to be compared with the HVDC design sustaining 200 kV in FRP tubes, 1.5 m tall and 150 kg.

4.1.2.2 Characterisation of precision components for the divider

As already mentioned, PTB choose a lower temperature coefficient for the precision resistors from Caddock. The temperature coefficient was found to be 0.2 – 0.3 µΩ/Ω/K, compared to the resistors on the old design having 1.1 µΩ/Ω/K. The voltage coefficient was the same as for the other batches, i.e., ca 9 µV/V/kV. PTB performed measurements to characterize the voltage and temperature coefficient.

4.1.2.3 Assembly and calibration of the UHVDC divider modules

In total five HV modules for the 1600 kV divider were built at PTB. Field modelling was performed by RISE to avoid corona discharge for the 1600 kV divider design. A double toroid with larger dimensions than for 1200 kV is needed and was purchased. Further corona suppression at 800 and 1200 kV and 1600 kV are needed and must be retrofitted to reach 2000 kV which the divider is designed for. This goes beyond the project.

4.1.2.4 Calibration

The 400 kV modules were calibrated at PTB as voltage dividers against their primary reference at 100 kV. The LV arms were calibrated and by calculation the resistance of each HV arm was determined. The scale factor was calculated when stacking several HV arms and by comparison with the other 1200 kV HVDC divider, also traceable to RISE.

4.1.3 Design of a 2000 kV UHVDC generator

A UHVDC generator was designed to 2000 kV by PTB with support by RISE. The generator is designed as modular to be able to adapt to the size of different laboratories. Preliminary test of the generator up to 1600 kV was undertaken in August 2021 at the open-air test field.

The 2000 kV generator is of type Greinacher/Cockroft-Walton, which was specifically designed and built for calibrations of the UHVDC divider systems. The generator and a 1600 kV UHVDC divider configuration were tested successfully in August 2021, and measurements were planned for at an outdoor open field test range that took place in May-June 2022.

4.1.4 Design of the RCR 1000 kV RCR divider

The second new UHVDC design is an unshielded universal RCR divider designed, separately funded and built by RISE. The RCR divider is based on 500 kV modules, extendable to 1500 and 2000 kV, was compared with the shielded divider up to 1000 kV. This universal RCR divider was also designed for composite wave measurements in the EMPIR project 19NRM07 HV-com[2].

As mentioned, each 500 kV HV module of the RCR divider has been built using off-shelf components. Precision resistors from Caddock was used for precision UHVDC components, also working as “bleeders” to control the potential over the capacitors in DC operation. The capacitors are from WIMA and are of pulse type FKP1. Damping for impulse operation in composite wave calibrations for EMPIR project 19NRM07 HV-com[2], Ohmite ceramic type OX resistors were used and mounted in series with the bleeder-capacitor pairs. In one 500 kV module 600 precision resistors in parallel with 600 capacitors and 300 ceramic resistors are mounted on 3D printed plastic disks. The module is then enclosed in a FRP tube and filled with SF_6 protective gas. The low-voltage arm is based on the same components.

A publication about the UHVDC performance up to 1000 kV of the RCR divider was accepted for presentation at ISH 2023 and will be published in IET Journal.

4.1.5 Validation of UHVDC reference voltage dividers

The UHVDC generator built in 2021 was set up for 2000 kV at the outdoor open area field test range at PTB in May-June 2022 for intercomparisons of the three UHVDC divider designs (figure to the right). At the test site, two RCRC HVDC 1200kV, from RISE and PTB, were compared with the new RCRC 2000 kV divider from PTB and the new 1000 kV RCR divider from RISE. Current leakage in the new divider modules of the PTB HVDC 1200 kV system was detected and eliminated. Subsequent calibrations up to 1200 kV showed that the modification was successful and gave an excellent agreement between the 1200 kV HVDC and the 1600 kV UHVDC system.

Analysis of the measurement results has led to the new CMC claim of 40 µV/V at 1600 kV for PTB. RISE abstained to file a CMC beyond the 1200 kV but is prepared to increase its traceability to at least 1600 kV in the near future given a need from the industry using the RCR divider.

A publication about the linearity and temperature dependence of the UHVDC divider modules was accepted for presentation at ISH 2023 and will be published in IET Journal.

4.1.6 Key results

The precision 1000 kV modular HVDC divider by RISE, was optimised and extended to 1200 kV. The HVDC divider by PTB was extended from 200 kV to 1200 kV. The HVDC divider of TUBITAK was extended from 200 to 400 kV. In total 7 new 200 kV HVDC modules were built, adding to the existing 9 HVDC modules built in the EMRP project ENG07 HVDC. In summary there are 6 HVDC modular precision measurement systems at five European NMIs to support the HV industry with calibrations up to 1200 kV.

- The project has achieved traceability for UHVDC precision on-site calibration of instrument transformers extended up to 1200 kV with a claimed extended measurement uncertainty of **20 µV/V at 1200 kV. The target was 40 µV/V**.
- The project has extended the traceability for on-site calibration of HV industry dividers for testing to 2000 kV with a claimed extended measurement uncertainty of **40 µV/V at 1600 kV. The target was 200 µV/V.** This was achieved by designs of two categories of modular UHVDC dividers, one 2000 kV modular shielded RCRC divider at PTB and one 1000 kV modular unshielded RCR divider at RISE, extendable to 2000 kV.
- This objective produced **seven on-site precision calibrations in 2022**, carried out by RISE to full 1200 kV using their precision UHVDC divider. The new RCR divider from RISE 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. Both dividers at PTB have been used in 30+ calibrations up to 400 kV.

A spin-off was achieved in measuring the stability of the precision HVDC dividers. The performance of five 200 kV HVDC dividers from RISE, PTB, TUBITAK, VSL and VTT were intercompared before the 1200 kV measurement campaign at RISE. This intercomparison is registered at BIPM as two intercomparisons EURAMET.EM-S46 as “Supplementary Comparison - High voltage comparison of high resistance” and EURAMET.EM-S47 as “Supplementary Comparison - High voltage comparison of DC ratio”. Publication expected end of 2023.

4.1.7 Conclusions

Objective 1 has been met with large margins and the power industry in Europe can now be supported with on-site calibrations.

- The project has produced two 1200 kV precision dividers for on-site calibrations by RISE and PTB, and claim an expanded measurement uncertainty of **20 µV/V at 1200 kV** compared to the targeted **40 µV/V.** The drift of the scale factors for the first five HVDC modules at RISE in the precision divider was found to be an unprecedented **0.7 µV/V/year**.
- The project has further developed one 2000 kV divider for PTB and claim an extended measurement uncertainty of **40 µV/V at 1600 kV** for a corona free set-up**,** compared to the targeted **200 µV/V**.

- The synergy with EMPIR project 19NRM07 HV-com[2] led to the development with RISE funding of a modular universal RCR divider, with an expanded measurement uncertainty of **40 μV/V at 1000 kV**. This modular design can be extended to 2000 kV and can likely fulfil the targeted **200 μV/V**.

4.2 Objective 2 – Extend and research methods for lightning impulse voltage calibration.

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.

Objective 2 was to extend and research methods for **lightning impulse voltage calibration** for testing of UHV equipment. In addition, the targets are 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 %, and to resolve unexplained effects on measurements from front oscillations, corona, proximity, and signal cable.

4.2.1 Characterisation of dividers

In preparation for the linearity measurement campaign in November 2022 (see chapter 4.2.2), five measurement systems were characterised by the partners.

VTT and TAU worked together to characterise VTT 1000 kV divider in 2021 - 2022. The divider construction was reviewed as a master's thesis work [17], and its low voltage arm was modified to optimise the system performance. VTT provided the digitiser and impulse analysis software for this system. This system took part on the linearity measurement campaign.

Instead of their original plan for preparing their 1000 kV divider, PTB characterized their 2000 kV divider. No modifications were deemed necessary for this divider. This divider took part in the linearity measurement campaign, and it was used with VTT backup digitiser and software.

VSL and TU Delft worked together to characterise and prepare the 4000 kV LI divider at TU Delft. The TU Delft divider construction was reviewed, and a proper damping resistor was prepared to optimise its performance. The complete TU Delft system was calibrated against VSL reference system in June 2022 in anticipation for the linearity measurement campaign. Both VSL reference system, and TU Delft 4000 kV system took part on the linearity measurement campaign.

Instead of their original plan for characterising their 1000 kV divider, TUBITAK characterised their 1000 kV and 1200 kV dividers and prepared them for series connection to reach 2200 kV. The series connection was successful, and the system was calibrated by TUBITAK, but unfortunately logistic problems prevented the shipping of the system in time to TU Delft, and they had to cancel their participation to the linearity measurement campaign.

Instead of their original plan for characterising their 1000 kV divider, RISE characterised their 3600 kV divider, which is used together with RISE digitiser and impulse analysis software. This system took part on the linearity measurement campaign.

4.2.2 Characterisation of voltage linearity

In a three-week measurement campaign the linearity methods were put to test, using ten voltage dividers with traceability starting at 400 kV and up to 3600 kV. Six dividers were of resistive type (R), with maximum voltages ranging from 400 kV to 2000 kV, three damped capacitive (RC) dividers with maximum voltages from 1000 kV to 4000 kV and one damped universal divider (RCR) up to 1200kV. The systems were prepared for comparison campaign by project partners (TU Delft, VTT, RISE, VSL, PTB and TAU) or by project's collaborators (National Institute of Metrology of China - NIM, and Haefely AG). From this campaign this project has extended metrology beyond the 2000 kV limit by developing and validating methods for linear extension up to 3000 kV, given proof for the determination of measurement uncertainties, and finding solutions for many cases in the large front time errors.

4.2.2.1 Measurement plan

The campaign was started by checking the step response of each divider, using the same digitiser for all measurements. Measured step responses have been saved for later analysis. The dividers of the measurement systems studied in this campaign are listed in Table 1.

Then impulse parameters (Ut, T1 and T2, and β') of each system, consisting of a divider and a digitiser, were calibrated at 400 kV against a reference divider (R400 in Table 1).

For the linearity measurement each system was connected in turn to the impulse generator, all the impulse parameters (Ut, T1 and T2, and β') and the respective charging voltage were recorded. No changes to the high voltage setup and generator configuration were made during the linearity test. Only the charging voltage of the generator, and input range of the digitiser were adjusted.

Finally, the two systems having dividers with highest voltage rating were connected in parallel to the generator, and their parameter readings were compared with each other, and against the charging voltage.

Table 1: Main characteristics of high voltage dividers used in the tested systems. Type R means resistive, RC damped capacitive and RCR universal divider.

Id.	**Type**	U_{max}	R_{in}	C_{in}	***Front resistor***
R400	R	400 kV	10 kΩ	-	250 Ω
R500	R	500 kV	10 kΩ	-	180 Ω
R600	R	600 kV	10 kΩ	-	300 Ω
R1200A	R	1200 kV	10 kΩ	-	330 Ω
R1200B	R	1200 kV	20 kΩ	-	300 Ω
R2000	R	2000 kV	12 kΩ	-	270 Ω
RC1000	RC	1000 kV	370 Ω	600 pF	270 Ω
RCR1200	RCR	1200 kV	180 Ω	700 pF	355 Ω
RC3600	RC	3600 kV	290 Ω	430 pF	820 Ω
RC4000	RC	4000 kV	256 Ω	400 pF	500 Ω

4.2.2.2 Calibrations at the 400 kV level

The reference in the 400 kV calibration was the system used by VTT for their participation in recent worldwide comparison (J. Hällström, A.-P, Elg, J. Havunen et al., 'Supplementary comparison EURAMET.EM-S42, comparison of lightning impulse (LI) reference measuring systems', 2020 Metrologia 58 01001, doi: 10.1088/0026-1394/58/1A/01001). Typical calibration setups are shown in Figure 1, and the calibration results are summarised in Figure 2.

Each point shown in Figure 2 is the average result of ten measured impulses. Standard deviation of the results was low in all cases, and the respective error bars would fit behind the points shown in the graphs.

The load to the impulse generator changed slightly when the divider under calibration was changed. Respective adjustments were made to keep the impulse shape close to nominal, 1.2/50 µs.

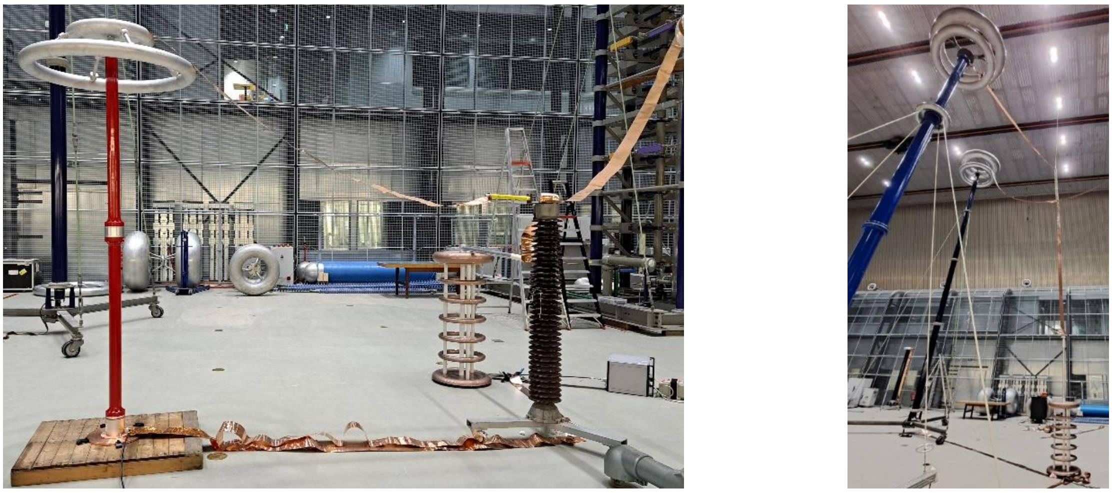


Figure 1: Setup for 400 kV calibration. Left: calibration setup for 1200 kV system (R1200A, red). Right: calibration setup for 3600 kV (blue, left) and 4000 kV (blue, in the middle).

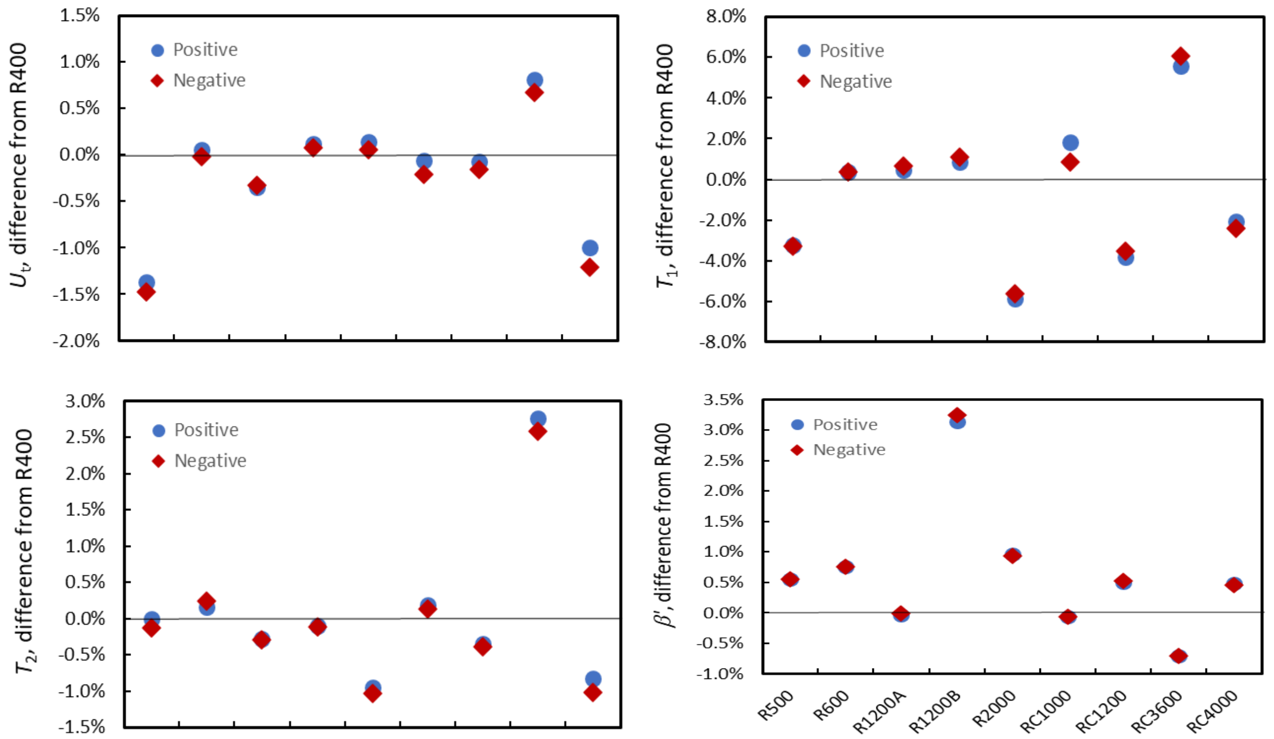


Figure 2: Results of the 400 kV calibration. R400 system links the calibrations to worldwide comparison (J. Hällström, A.-P, Elg, J. Havunen et al., 'Supplementary comparison EURAMET.EM-S42, comparison of lightning impulse (LI) reference measuring systems', 2020 Metrologia 58 01001, doi: 10.1088/0026-1394/58/1A/01001), and it is used as the reference. Vertical axis shows relative errors for U_t, T_1 and T_2, and absolute errors for β'.

4.2.2.3 Measurement of generator charging voltage

The maximum nominal charging voltage of the 14-m high 20-stage impulse voltage generator is 4000 kV, and the respective energy 200 kJ. The generator has secondary spark gaps in the discharge circuit; these gaps were shorted during this study to stabilise the impulse shape. Due to its old age, the generator was charged only up to 90 % of the nominal maximum value. With the loading by the dividers the final maximum voltage reached was 3000 kV.

The charging voltage of the impulse generator was measured with a universal voltage divider (see Figure 4). Charging voltage was logged continuously at a rate of 0.6 samples/s. The value for the charge voltage was taken as the last value before the generator was triggered. The generator was triggered manually, and the trigger time was decided by monitoring the charge voltage. The generator was triggered when charging had reached peak voltage and stabilised to a lower level after that. Typical charging voltage curves are shown in Figure 3. Voltage measurement system used was RISE RCR500-1 universal divider together with Keysight 34470 multimeter. The expanded uncertainty for the charging voltage measurement of the RISE measurement system was 0.02 %.

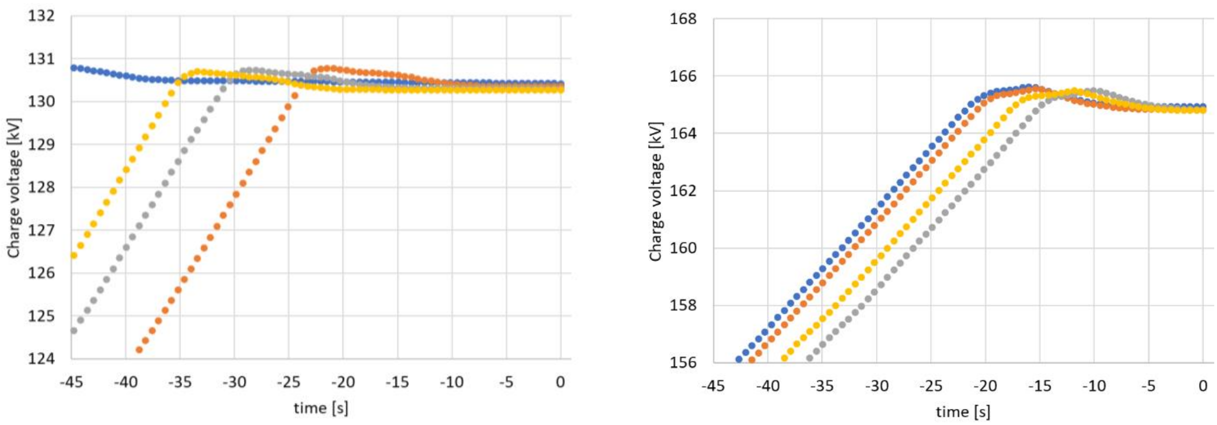


Figure 3: Typical stabilisation curves of the generator charging voltage. Four applications at 130 kV (top) and 165 kV charging. Generator was manually triggered at 0 s.

4.2.2.4 Linearity testing

Linearity tests from 400 kV to 3000 kV, both positive and negative, were performed on the systems. For generation of test voltages up to 2400 kV 16 stages of the generator were used, and full 20 stages were used for voltages up to 3000 kV. The 2400 kV level was measured using both configurations, and the results shown in following linearity graph were adjusted so that those two measurements match. Systematic errors of the systems, test voltage, front time and time to half-value were corrected, based on the comparison results at 400 kV with HUT 400 kV lightning impulse measuring system.

Changes of the ratios between test voltage and the charging voltage, using the newly developed RCR500 divider from RISE, are illustrated in Figure 5 for systems with maximum voltage above 1200 kV. For all the dividers with rated voltage less than 1200 kV, the test voltage nonlinearity was found to be less than ±1 %. For the RC3600 and RC4000 systems, the nonlinearity shows similar trend up to 3000 kV. This suggests that the non-linearity is caused by the generator or testing environment, rather than by the measuring systems, which mutually agree within ±1 % up to 3000 kV (Figure 6).

Figure 4: Setup for the linearity measurement up to 3000 kV. RC4000 divider (dark blue, left) and RC3600 (light blue, front). The damping resistor used with the RC3600 is supported from the ceiling. The RCR500-1 divider for charging voltage measurement (green) is in the background.

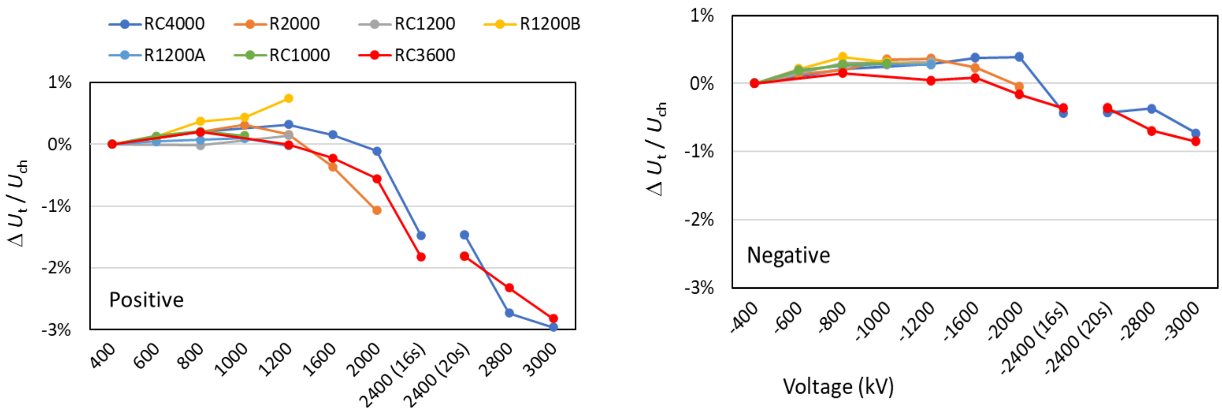


Figure 5: Change of the ratio between the measured test voltage and the charging voltage. Results are normalised to 400 kV reading; horizontal scale shows the test voltage.

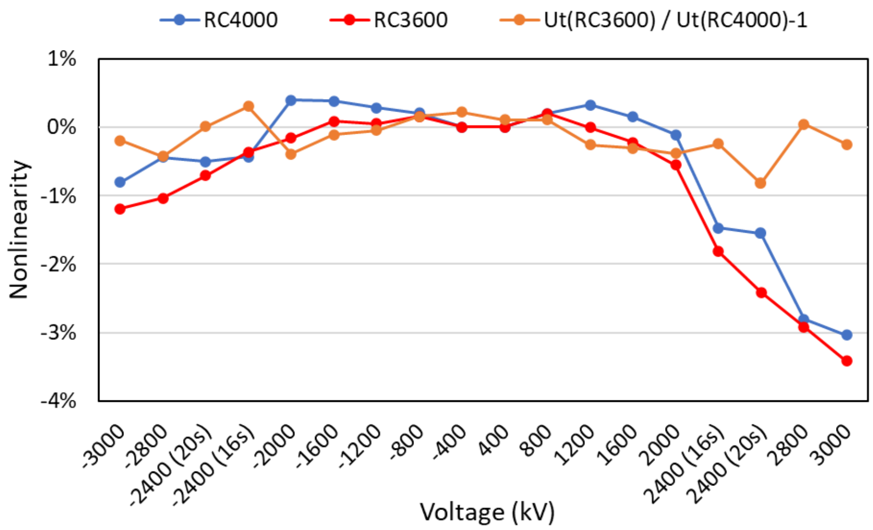


Figure 6: Change of the ratio between RC4000 and RC3600 U_t readings and the charging voltage (blue and red), and comparison of RC4000 and RC3600 U_t readings after gain correction based on their 400 kV calibration (orange). Horizontal scale shows the test voltage.

4.2.3 Influence factors

The good practices for measurement of Ultra High Voltage (UHV) impulse voltage measurement were studied. The topics of these studies were:

- Convolution & deconvolution
- Linearity extension methods
- Principle of linear extension
- Influence of front oscillations
- Influence of corona
- Proximity effect
- Signal cable effect.

Special emphasis was put on the linearity extension, and the specific methods that were studied were:

- Comparison with impulse generator charging voltage
- Comparison with field probe
- Comparison with measurement system with a higher voltage rating.
- Evaluation of linearity
- Uncertainty estimation of linearity test
- Using linearity results in measurement.

Another topic with special emphasis was the influence of front oscillations on the generated impulse voltage. The specific items were:

- Examples of front oscillations
- Sources of oscillations
- Damped capacitive divider as load capacitor
- Influence of measurement set-up
- Countermeasures.

Finally, two simulation methods for modelling the impulse deformation in the signal cable were developed. Both models are based on using telegrapher’s equations. Practical solutions differ, one of the models is implemented using Matlab, and the other is based on using circuit simulation software.

4.2.4 Key results

Five existing impulse voltage measuring systems were characterised. Their nominal voltages ranged from 1000 kV up to 4000 kV.

The voltage linearity of ten impulse voltage measurement systems with nominal voltages from 500 kV to 4000 kV was characterised in a three-week campaign.

Partners’ experience with impulse voltage measurement techniques was collected to the Good Practice Guide on characterisation methods for UHV lightning impulse (LI) dividers.

4.2.5 Conclusions

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.

Objective 2 was successfully met in proving 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.

4.3 Objective 3 – Linearity determination of HV capacitors

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. The 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 need to be minimised.

Objective 3 was 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.

4.3.1 Review and selection of methods

Investigation efforts were initiated to provide a comprehensive overview of existing methodologies employed in determining the voltage dependence of high voltage capacitors. Prominent institutions, namely PTB, VSL, TUBITAK, and VTT, collaborated on a report that extensively reviewed past approaches. The primary source of information for this analysis was Latzel's thesis (1987), which proved to be an invaluable reference.

Several notable methods were identified and examined through direct comparisons of capacitors (Schering, 1920), the voltage doubling method (Zinkernagel, 1976), the direct voltage method (Kusters, Petersons, 1963) extended for high voltage measurements (Wang, Latzel, 1986), the voltage doubling method with capacitive divider (Latzel, 1987), tilting of a high voltage compressed gas capacitor to a horizontal position (Kusters, Petersons, 1963), applying external forces to the top of the capacitor to displace the electrodes (Rungis, Brown, 1981), and periodic displacement of the electrodes of high voltage compressed gas capacitors caused by electrical or mechanical forces (Kusters, Petersons, 1963), (Latzel, 1987).

Additionally, the potential of electric field measurement as a means to predict the behaviour of high voltage capacitors was explored. This approach is a well-known technique employed in determining the charge voltage for lightning impulse measurement.

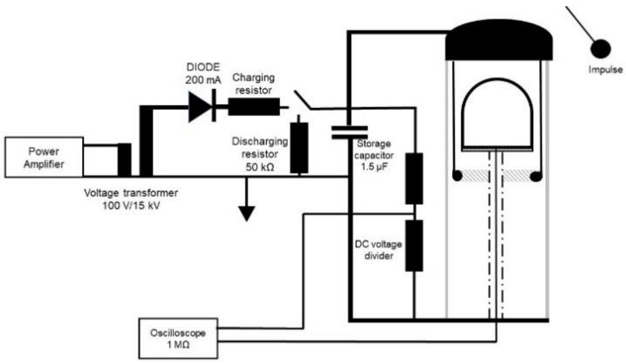
Following a thorough evaluation, five methods were selected for further development and refinement. These methods include the well-known **kinetic method** (LNE from Latzel), the **field sensor approach** (TAU, VTT, VSL), the new “**three equations method”** (PTB), and the “**simplified tilt”** and “**CCD method”** (both NIM, collaborator). These chosen methods hold significant promise in advancing the understanding and accurate measurement of voltage dependence in high voltage capacitors.

4.3.1.1 Kinetic method

A typical compressed gas capacitor based on coaxial cylindrical electrodes structure is shown in Figure 7. The main elements are the high voltage electrode (HVE) mechanically attached to the upper part of the capacitor, external insulating envelope of the capacitor, and the low voltage electrode (LVE), mechanically attached to the lower part of the capacitor via its guard electrode and their support foot. Their common mechanical link is made through the base of the external insulating case of the capacitor. The kinetic method is based on vibrating the capacitor in order to determine its resonant frequency. The electrodes are made to oscillate by mean of mechanical impulse given at the top of the capacitor. Taking into account that the mass of the HVE-attached set is in a much higher mass proportion than the LVE-attached set, it is assumed that only the LVE is being moving.

The voltage dependence of a 100 kV capacitor and a 300 kV capacitor has been studied in LNE using kinetic method. The capacitors have been charged by mean of charging capacitor (1,5 µF/20 kV DC). The charging capacitor is charged by mean of a power source, high voltage transformer and high voltage rectifier circuit (high voltage diode, high voltage charging and discharging resistors). It is very important to avoid disturbances and interferences because the measured current is very low (in the range of Nano-amperes). The signal to noise ratio is improved by putting the capacitor inside a faraday cage. The charging circuit is disconnected in order to avoid any alternating components.

The LVE oscillates by mean of the mechanical impulse applied at the top of the capacitor. The current flowing though the capacitor is measured across the input impedance of the oscilloscope (1 MΩ ± 1 %) in parallel with the capacitance of the shielded coaxial cable (about 0,5 nF).

a) 

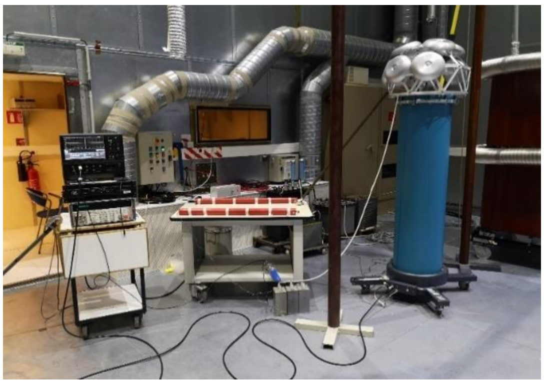
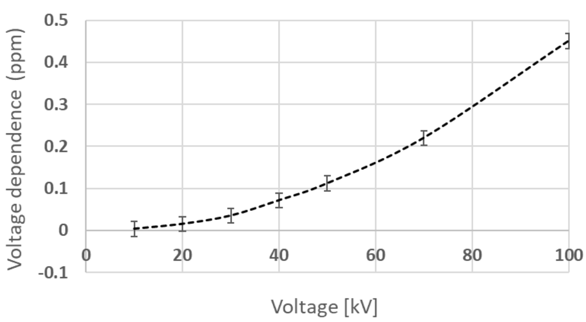
b) 

Figure 7: (a) Experimental set up used for Kinetic method measurements, (b) Measurement of the 300 kV capacitor in LNE Faraday cage to avoid any interferences.

a) 

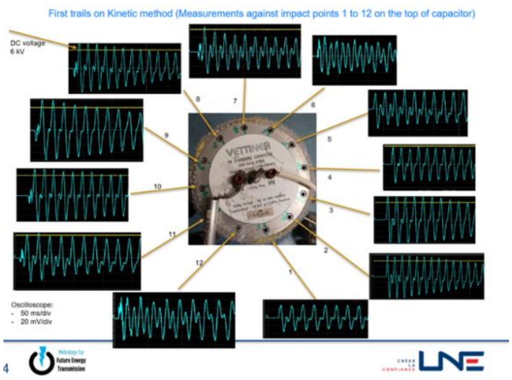
b) 

Figure 8: a) Voltage dependence of capacitance for the 100 kV capacitor from VETTINER. b) Readout from mechanical impulse excitations in different directions.

The voltage dependence up to 100 kV is given in Figure 8. At maximum voltage it is equal to 0,45 µF/F with an uncertainty of 0,10 µF/F. This low level of uncertainty is difficult to obtain with other methods. Note that, the relative uncertainty with kinetic method is high (about 25 %). It may be concluded that the kinetic method is particularly suitable for use with capacitors with very low voltage dependence of capacitance. For capacitors with large voltage dependence of capacitance, the traditional methods could be employed. This method was used to support the development of the new 800 kV gas capacitor by VETTINER described in section 4.3.1.5.

4.3.1.2 *Field sensor method*

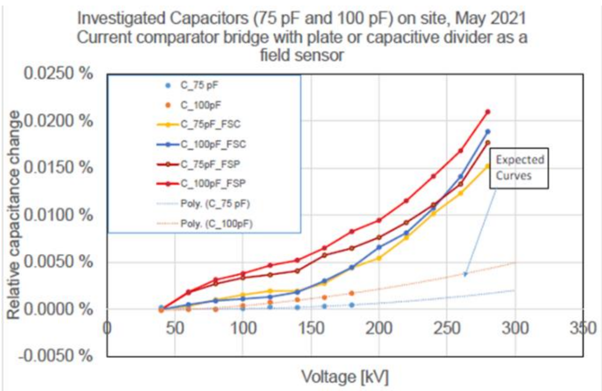
VTT, VSL and TAU studied in cooperation the applicability of a field sensor for investigation of high voltage capacitor voltage nonlinearity of up to its maximum voltage. The work was done using two different approaches: by comparison with the field sensor output current using capacitance bridge and by comparison with field sensor output voltage using two synchronised sampling voltmeters. In the experiments, two kinds of field sensors (plate electrode and capacitive divider) were used to study the linearity of five different compressed gas capacitors (Table 2).

Table 2: Gas capacitors used and voltage ratings.

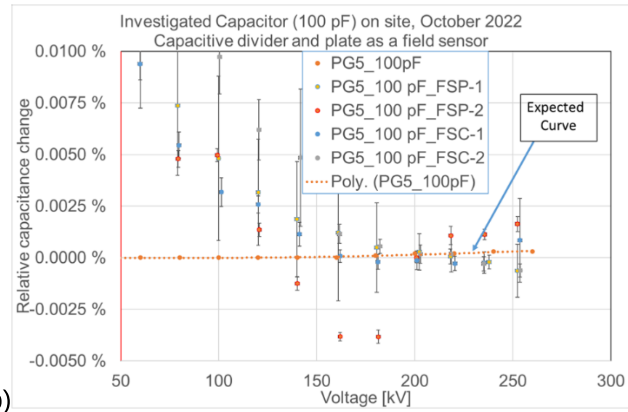
Type	Capacitance [pF]	Voltage rating [kV]
MWB CP 0.11	37	100
Micafil PG1	100	150 (200)
Highvolt MCP300	100	300
TuR MCF 75	75	350
Micafil PG5	100	500

The first measurements were performed at VTT, where the two capacitors MWB CP 0.11 and Micafil PG1 were investigated up to 100 kV and 175 kV. Results with field sensor agreed very well up to 100 kV. The agreement was within the estimated uncertainty, about 30 µF/F. The measurement on Micafil PG 1 up 175 kV was also good within the estimated uncertainty 30 µF/F except for the highest voltage 175 kV. Corona discharges were affecting this voltage level. Result deviated about 80 µF/F from expected value.

A second set of measurements were performed at TAU. Two capacitors, HIGHVOLT MCP300 and TuR MCF 75, were investigated up to 270 kV using capacitance bridge and field sensor. With both methods the results agreed well up to 200 kV within the estimated uncertainty 50 µF/F. It was suspected that diameter of one high voltage tube was too small and there existed some corona discharges affecting the results. Deviation from the expected curves was less than 150 µF/F (Figure 9a). These results were published in CPEM 2022, Wellington (*Esa-Pekka Suomalainen & Jari Hällstöm & Kari Lahti: Field sensor for linearity measurement of high voltage capacitor)*.



a)



b)

Figure 9: Relative capacitance changes for the second and third measurement campaigns.

A third measurement was performed only with field sensor for the Micafil PG5 capacitor up to 270 kV. An ultrasonic corona detector was used to measure corona discharges. No corona was detected. Below 150 kV the results were not good because of the small signal levels with noise. Above 150 kV the result agreed well, within the estimated uncertainty 50 µF/F (Figure 9b). These results were published in the poster presented in CPEM 2022.

In conclusion the field sensor is a simple device for studying voltage linearity of reference capacitors. However, field sensor is sensitive to corona discharges and the measuring setup must thus be carefully constructed. The non-linearity measured using the field sensor was typically about one order of magnitude higher than expected, but if the setup is carefully constructed very good results can be achieved. The uncertainty estimate for this method is in the order of 50 µF/F in a corona-free set-up.

4.3.1.3 Three equations method

The method proposed by PTB for determining voltage non-linearities of capacitors relies on the utilisation of three capacitors, namely C1, C2, and C3. Initially, none of these capacitors have known voltage non-linearities. In order to assess their characteristics, the relative change in AC current ($\Delta I_{n,m}$) is measured, at various DC voltages, induced by each pair of capacitors (Figures 10 and 11).

For every combination of capacitors, the alteration in AC current is carefully measured across a range of DC voltages. The objective is to validate that the method satisfies the desired target uncertainty of 80 µF/F at an operating voltage of 800 kV. To ensure accuracy, three 800 kV capacitors are employed, with two sourced from PTB and the remaining capacitor designed and built by VETTINER. The method was presented at CPEM2022 conference.

Two measurement campaigns were used to test the method. In the first campaign three 200 kV gas capacitors of type HIGHVOLT MCP200 were used. One of the capacitors had been repaired but not adjusted to minimise the voltage dependence, which was intentionally not done to have a unit with a higher voltage dependence to test the method. In the second campaign, where three 800 kV capacitors were to be tested, one 500 kV gas capacitor replaced the VETTINER capacitor in this assessment (see 4.3.1.5). Lacking a proper corona ring in the 500 kV capacitor the voltage was limited to 240 kV because of corona on-set. The results from these two campaigns were used to determine the expanded measurement uncertainty for this method to 20 µF/F. A reduction of the measurement uncertainty is planned for, where it is imperative to improve the current measurement technique and maintain a stable temperature during the measurement. By refining these aspects, the overall measurement uncertainty can be further reduced to 10 µF/F.

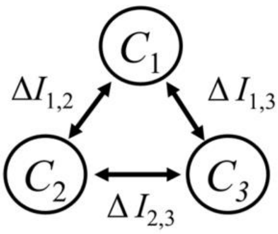


Figure 10: Three equations method.

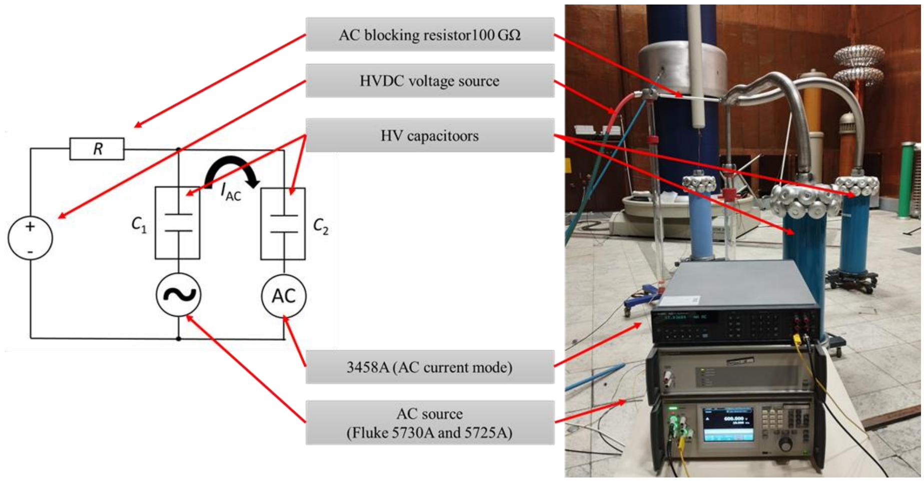


Figure 11: Measurement set-up.

$$\Delta I_{1,2}(U_{DC}) = \frac{U_{AC}}{\frac{1}{j\omega\Delta C_{1,DC}}+\frac{1}{j\omega\Delta C_{2,DC}}} \quad (1)$$

$$\Delta I_{2,3}(U_{DC}) = \frac{U_{AC}}{\frac{1}{j\omega\Delta C_{2,DC}}+\frac{1}{j\omega\Delta C_{3,DC}}} \quad (2)$$

$$\Delta I_{3,1}(U_{DC}) = \frac{U_{AC}}{\frac{1}{j\omega\Delta C_{3,DC}}+\frac{1}{j\omega\Delta C_{1,DC}}} \quad (3)$$

$$\Delta C_1(U_{DC}) = \frac{2\cdot\Delta I_{1,2}\cdot\Delta I_{3,1}\cdot\Delta I_{2,3}}{U_{AC}\cdot\omega\cdot(\Delta I_{1,2}.\Delta I_{2,3}-\Delta I_{1,2}\cdot\Delta I_{3,1}+\Delta I_{3,1}\cdot\Delta I_{2,3})} \quad (4)$$

Figure 12: Solving the three coupled equations (1-3) gives the change in capacitance in (4).

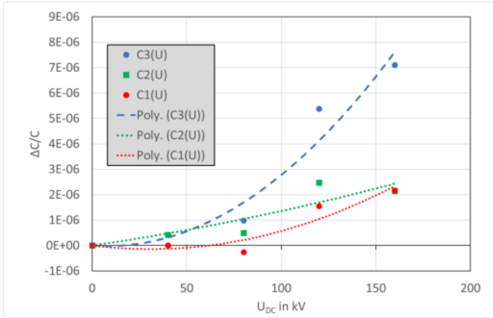


Figure 13: Voltage dependence of the capacitance for three 200 kV gas capacitors.

The three-equation method can be used for rapid determination of non-linearity in high-voltage capacitors without prior knowledge of the capacitance with a measurement uncertainty better than 30 µF/F. This result was proven by a comparison between two 800 kV and one 500 kV gas capacitor at PTB.

The clear benefit of this method is since neither the capacitance of the gas capacitors nor the absolute voltages or currents have to be measured, only the relative change in current. The only requirement is that the AC source remains stable throughout the entire measurement of relative current change as a function of the applied DC voltage, as is shown in equation in Figure 12.

Additionally, all capacitor types can be tested, unlike the tilting method, which is only suitable for capacitor types with a cylindrical central electrode. The drawbacks are that always three capacitors are required, which should have the same order of magnitude of voltage dependency. In the future, this method will be compared with the existing methods, e.g., the tilting of compressed gas capacitors.

4.3.1.4 CCD and simplified tilt methods

A collaborator in the project (NIM) proposed a method where detection and monitoring of electrode movements are facilitated by a camera utilising a charge-coupled device (CCD). This camera system plays a crucial role in capturing and analysing the intricate motions of the electrodes due to the applied voltage. By continuously observing a designated target pattern visible through a window, the CCD camera effectively tracks and records any variations in the electrode positions.

One notable advantage of this approach is its accessibility to users with limited mechanical expertise. The reliance on the CCD camera eliminates the need for intricate mechanical systems or complex mechanical knowledge to monitor and detect electrode movements. Instead, the visual input provided by the camera offers a straightforward solution. The need for an optical window in the gas capacitor makes this an unconventional method.

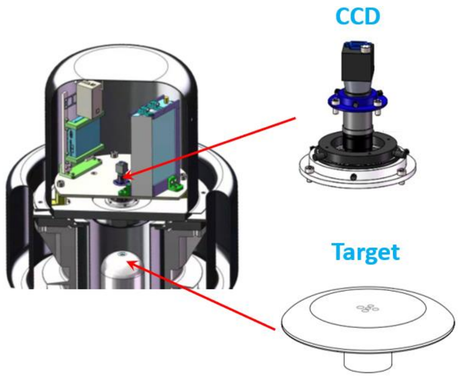
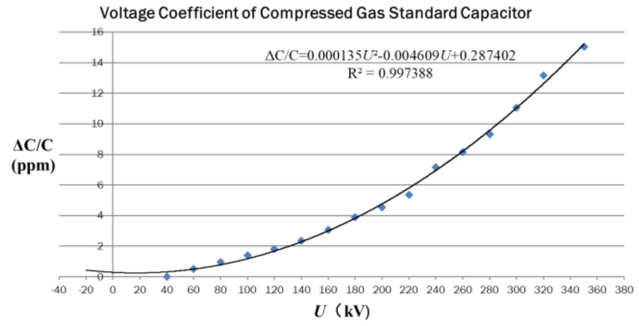
	

Figure 14: CCD method with a camera looking through the top flange of a modified gas capacitor	**Figure 15:** Voltage coefficient of compressed gas standard capacitor

A simplified version of the existing tilt method was also explored by NIM.

4.3.1.5 Development of a new HV capacitor

In parallel, a new 100kV-100pF standard capacitor design by VETTINER was tested at LNE (see section 4.3.1.1) and gave very good linearity results with very low voltage dependence (dC/dV) within the measurement uncertainty. Based on these experiences VETTINER developed a new 800 kV capacitor with target voltage non-linearity of < 10 µF/F at 800. The first 800kV standard capacitor prototype was tested in Q1 2022. The results were encouraging with an estimated < 30 µF/F but not yet at target for the nonlinearity. However, other improvements were achieved such as very low PD levels.

From the experience and insight with the prototype, the decision was made to build a second final capacitor for a measurement campaign at PTB in Q2 2023. A design review was conducted with the Engineering school INSA Lyon in Q2 2022, to improve the 800kV standard capacitor initial design. As a result, several parts were improved, suppliers were changed, and the assembly process improved. In Q3 2022, all parts were then ordered for the final prototype which was initially scheduled to be built at the end of 2022. Some suppliers were experiencing minor delays, except the German insulator manufacturer Reinhausen which defaulted and generated a critical 12-month supply delay. Hence, this second improved version was too late for the measurement campaign at PTB. As of today, there still has not been any delivery, However, new suppliers have been found and contacted. The final HV tests planned for at PTB, initially scheduled in January-February 2023, were moved to September 2023, but no new delivery schedule has been received from Reinhausen at the time of this final report. In the lack of the new VETTINER capacitor, measurements using the new “Three-equations method” were completed at PTB in April 2023, replacing the VETTINER capacitor with a 500 kV gas capacitor of PTB. Final testing of the VETTINER design after the end of the project is possible at PTB and RISE and is yet to be determined.

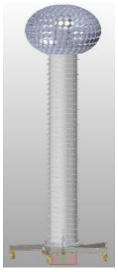
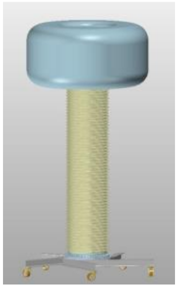
			
Previous 800kV-50pF standard capacitor			New 800kV-50pF standard capacitor

Figure 16: Old gas capacitor design of VETTINER and the prototype new capacitor.

4.3.2 Key results

In recent developments, novel approaches have emerged to accurately determine the voltage coefficient of capacitors operating up to 800 kV. For calibration a factory reference should have a measurement uncertainty of better than 400 µV/V, and the NMI references better than 80 µV/V. Standard methods used for determination of the voltage dependence are very time consuming. To meet the need for easier methods for assessment of this voltage dependence, and to verify the existing model-based methods, advancements have led to the creation of two key results, and extended calibration procedure for UHVAC calibration capability of 800 kV with an expanded measurement uncertainty of < 20 µV/V

Two new methods present the key results:

- The field sensor – simple but sensitive to corona, applicable to any capacitor, can achieve an uncertainty of 50 µF/F at 800 kV in a corona-free set-up.
- The new "three equations method" – no prior knowledge of capacitance needed, applicable to any capacitor but in total three capacitors are needed, has an uncertainty of 20 µF/F at 800 kV.

In addition, supplementary findings have contributed to the completion of these results. Throughout the project's duration, numerous attempts and investigations were conducted to achieve the desired objective. Notably, two distinct capacitor methods were developed, accompanied by the design and development of an entirely new standard 800 kV gas capacitor. These combined efforts have significantly advanced the understanding and measurement of voltage coefficients for capacitors operating at 800 kV.

PTB, RISE, and VTT have submitted new CMC claims in 2022 for UHVAC calibration which will be available in the BIPM CMC database.

4.3.3 Conclusions

In conclusion, the research has significantly contributed to enhancing high voltage testing and monitoring for UHV transmission grids. The development of new methods improved the determination of the voltage coefficient at 800 kV, while the evaluation of field sensors highlighted their potential and sensitivity. These findings address measurement accuracy gaps and overcome challenges in UHV grid monitoring.

In summary:

- Five different methods have been studied and two methods have been selected for development for determination of the voltage coefficient of capacitors at 800 kV, leading to significant advancements in measurement accuracy.
- Extensive investigations and development of the methods for determination of the voltage dependence in high voltage capacitors provided valuable insights for the development of the proposed methods.

- The three equations method, utilising relative changes in AC current by applying different DC voltages, has an expanded measurement uncertainty of 20 µF/F @ 800 kV, which is four times better than the target uncertainty of 80 µF/F @ 800 kV.
- The study on field sensors for voltage nonlinearity in high voltage capacitors highlighted their potential but also their sensitivity to corona discharges.

The developed methods contribute to improving high voltage testing and monitoring for ultra-high voltage transmission grids. These advancements address measurement accuracy gaps, enhance metrology resources, and overcome challenges in UHV grid monitoring. The five methods with uncertainties, pros and cons are listed in Table 3.

Table 3: The five studied or developed methods and uncertainties.

	Method	**Exp. unc. @ 800 kV**	**Pros**	**Cons**
1	Kinetic method	< 0.2 µF/F	Lowest unc.	Only gas capacitors, time consuming
2	Field sensor	< 50 µF/F	Simple, on-site	Very sensitive to corona
3	Three equations	< 20 µF/F	no prior info of C, applicable on-site	Three capacitors needed
4	Simplified tilt	< 10 µF/F		special mechanical arrangement, only gas capacitors
5	CCD method	< 10 µF/F	sensitive	Intrusive, rebuild top of capacitor, only gas capacitor

Objective 3 was successfully met with the “three-equations method” the measurement uncertainty of which is independent of test voltage. Testing at full voltage will only be possible with proper corona rings, as is always the case.

4.4 Objective 4 – Develop and demonstrate implementation of partial discharge (PD) measurement.

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.

This objective was divided into two parallel paths, one developing PD procedures in the 1 – 30 MHz range, applicable to HVDC cables, and one on development of metrology for PD charge evaluation applicable to HVDC GIS and converters in 30 MHz – 300 MHz range.

4.4.1 PD procedure for validation of PD analysers for HVDC cables, 1 – 30 MHz range

4.4.1.1 Validation of the PD procedure for qualifying PD analysers

To validate the PD procedure for qualification PD analysers working between 1 MHz and 30 MHz a set of activities were developed: analysis of the PD pulse propagation through HVDC cable systems considering the differences between HVDC and HVAC cable systems, aging for four representative defects representative of HVDC cable systems and failure modes of converters in HVDC stations by means of high voltage tests. In addition, representative standard noises from converters and electronic power sources were collected from real HVDC and HVAC grids. Using a collection of the representative PD pulse trains related to the four insulation defects in cable systems and impulsive noises, a first validation of the procedure developed in EMPIR project 15NRM02 UHV was carried out to improve the qualification procedure. A new adjustable synthetic calibrator capable to play PD pulse trains representative of insulation defects and impulsive noises was developed to be used in round robin test. This new calibrator is an improved implementation of the patent achieved in the previous EMPIR project 15NRM02 UHV. In parallel to these activities an artificial intelligence tool for PD pattern recognition of insulation defects in HVDC grids was developed using the database of PD pulse trains acquired during the aging process of the four insulation defects. A round robin test was performed assessing HF PD analysers of each partner involved, using the developed PD calibrator in order to analyse the robustness of the improved qualification procedures.

4.4.1.2 PD pulse propagation differences between HVDC cable systems and HVAC cable systems

FFII collected PD pulses from real a.c. cable systems supplied by DIAEL collaborator to analyse the amplitude attenuation (dB/km) versus frequency range and performed an analysis of the most representative standard pulses in a.c. cable systems and artificial pulses from EMPIR project 15NRM02 UHV. FFII worked with UPM to extend this study to HVDC cables considering the differences between HVDC cable systems and HVAC cable systems. Attenuation of a PD pulse when PD pulse travels along a HVDC cable system of 320 kV was compared with the attenuation caused by HVAC cable systems from 20 kV to 220 kV. This study allowed to know representative PD pulse widths in HVDC cable systems to be used in qualification of PD analysers.

4.4.1.3 Aging of representative defects

Four insulation defects under HVDC stress (internal void, floating electrode in air, corona in air, and surface discharge in air) were analysed by UPM with FFII support using test cells developed for this project. HVDC voltage was applied for more than 1 year to reproduce aging process. More than a thousand of PD pulse trains from real defects of AC cable systems were supplied by DIAEL collaborator to be compared to the PD pulses measured under HVDC stress (see Figure 17).

a)

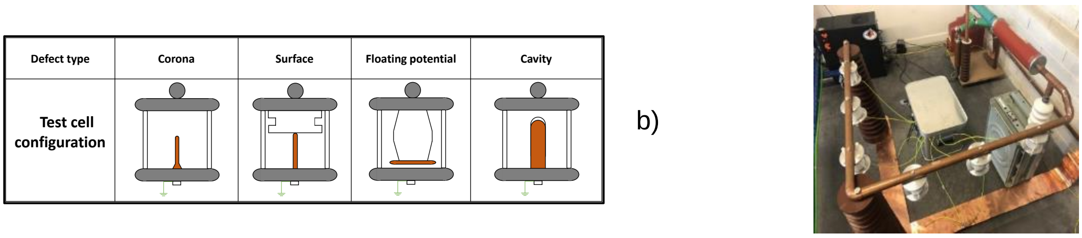


Figure 17: a) Test cells of the four representative insulation defects, b) Testing setup for aging under HVDC.

4.4.1.4 Representative impulsive noises

Representative noises from converters and electronic power sources were analysed by FFII and UPM for both d.c. and a.c. systems from the data supplied by FFII and DIAEL collaborator. Noise samples obtained from real installations in a.c. and d.c. grids (wind plant, converter stations and PLC) were collected. A set of adjustable parameters were defined to enable reproduction of these representative noise signals. Three different impulsive noise were studied in the time and in the frequency domain, one coming from a wind plant, another from a PLC system in an MV grid, and the last one from a DC converter station.

4.4.1.5 Artificial Intelligence tool for PD pattern recognition of insulation defects in HVDC

An automatic processing tool on artificial intelligence (AI) for defect recognition was developed by UPM (see Figure 18). This automatic AI system classifies the type of insulation defect that affects the grid. This AI recognition tool combines know-how retrieved through previous data analysis with Support Vector Machine (SVM) models in a methodology that allows for the automatic classification of isolated partial discharge samples. The software indicates the probability of success in the recognition. The recognition tool processes the trains in several steps. First, it divides each train into sub-trains. Then, it classifies each of the remaining sub-trains into a class (corona, surface, void, floating, or noise), giving a vote to the assigned class. Moreover, it provides the probability of a sub-train belonging to each of the classes. Finally, the train is classified into the class with the largest number of votes in the sub-trains and a probability of the train belonging to that class is obtained considering the average of the probabilities of the sub-trains for the class selected.

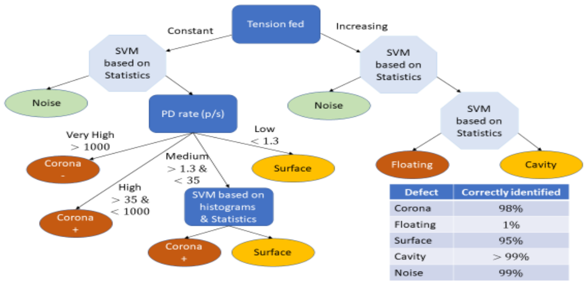


Figure 18: Schematic structure used for the AI tool for insulation recognition of HVDC defects.

4.4.1.6 *Validation of procedure for qualification of PD analyser developed in EMPIR project 15NRM02 UHV*

The procedure developed in EMPIR project 15NRM02 UHV was validated by FFII with support from UPM. In addition, complementary functional tests were analysed, using the testing workbench shown in Figure 19.a and a first version of PD synthetic calibrator (Figure 19.b) to inject PD pulse trains and noise signals in different sites of a **testing workbench**: (1) in the cable splice, (2) in the GIL input, and (3) in the AIS end. A conventional PD measuring system consisting of a coupling capacitor and a measuring impedance was also available to perform PD measurements according to IEC 60270. The test consists of superimposing two PD pulse trains related to different insulation defects with two different pulsating noises.

a) b)

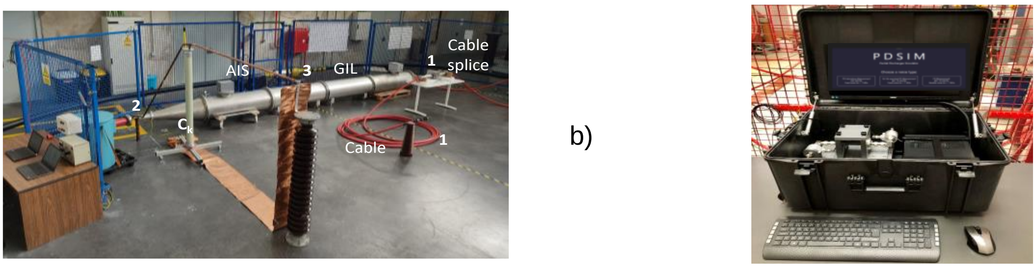


Figure 19: a) Testing workbench for complementary performance tests; (b) Synthetic PD calibrator.

4.4.1.7 *New PD Calibrator to reproduce representative PD pulse trains*

A new PD synthetic PD calibrator that plays current PD pulse trains representative of insulation defects was developed by FFII with UPM collaboration. This synthetic PD calibrator was used for qualification of PD analyser used for HVDC and HVAC grids (see Figure 19.b). PD current pulses are generated by arbitrary Wave Generator (AWG). Then they are acquired and measured by means of a new HFCT sensor (also developed for this project), whose transfer impedance was characterised in the frequency domain up to 0,5 GHz. The current signal at the input of each HFCT sensor is reconstructed by means of a software developed ad hoc using a state variable model. The charge quantity of each PD pulse, q, is determined by applying the final value property of the Laplace transform to the function I(s), obtained from the reconstructed current signal i(t). In conclusion, the developed synthetic PD calibrator can generate PD pulse trains of stable charge values from 2 pC to 7 nC (improving the initial objective: around 1.5 pC to 3 nC) with an uncertainty of less than ±2 % or ±1 pC, whichever is greater (uncertainty requirements were not defined in the initial objective), and with a time resolution down to 5 µs (improving the initial objective at least 1 pulse per 20 µs). The PD amplitude of the PD pulses generated by the PD calibrator can be regulated between 0,4 mV and 4 V improving the initial objective (from 1 mV to 2 V). This Synthetic PD calibrator can also reproduce PD pulse trains of the same sequence as actual representative defects from an insulation defect database, and representative impulsive noises which were previously recorded in high voltage tests. This calibrator is a useful tool for qualification of PD analysers addressed to insulation diagnosis of HVAC and HVDC grids.

4.4.1.8 *Failure modes of converters in HVDC*

Online PD measurements in HVDC plants were supplied by DIAEL collaborator to analyse the impulsive signals acquired in real conditions. No significant conclusions were achieved, for this reason external and internal failure modes of converters in HVDC were analysed by UPM and FFII in collaboration with TU Delft. The most representative internal failure model happens when the voltage blocking is stressed due to the local electric field between the silicone gel and the metallised ceramic, to the sharp edges of the copper metallisation, or to the internal defects in the substrate. To obtain representative PRPD patterns related to aging conditions, a PD analysis was performed in a semiconductor junction under a repetitive overvoltage. The charge and PD repetition rate values were analysed during overvoltage cycles when the semiconductor temperature changes. The higher the temperature, the greater the number of PD pulses, but the average charge value of the PD pulses, q, remains nearly constant. The main PD pulse activity appears once the maximum repetitive peak reverse voltage is overpassed.

4.4.1.9 Round robin test assessing PD analysers of each partner, using the synthetic PD calibrator

A round-robin test in which participated five partners (RISE, FFII, TU Delft, TAU and UPM) proved the robustness of the improved qualification procedure using the developed synthetic PD calibrator. This improved procedure for the metrological qualification of PD analysers was developed by FFII with support from UPM, RISE, TAU and TU Delft. A set of metrological tests was defined along with specific acceptance requirements. These tests were defined considering all possible applications of PD analysers, which were classified into three categories: off-line PD measurements, sporadic on-line PD measurements and continuous PD monitoring. The measurement conditions and acceptance requirements were adapted to the type of application of the analyser. The allowable errors for each test were selected considering the IEC 60270 standard requirements, the Technical Specification IEC 62478 and the inherent noise conditions of off-line and on-line sporadic measurements and continuous monitoring. The results for metrological tests carried out for continuous PD monitoring during round robin tests are shown in [19].

To achieve a complete qualification of PD analysers, the metrological tests were complemented with functional tests for diagnostic tools. An improved procedure for the functional qualification of PD analysers was developed by FFII with support from UPM, RISE, TAU and TU Delft. For the qualification of PD analysers diagnostic tools (PD recognition, PD clustering and PD location) three functionality tests were developed and validated. This procedure has been implemented in a synthetic PD calibrator that plays PD pulse trains of representative insulation defects and noise signals for qualification of PD analyser functionalities. The results for functional tests carried out during round robin tests are shown in [20]. Applying this qualification procedure, two PD methods for the detection and prevention of insulation defects were approved, one for HVAC and the other for HVDC grids.

4.4.1.10 Validation of the PD method in a d.c. grid for detection and prevention of insulation failures

From the results derived from the round robin test FFII, with support from UPM, RISE, TAU and TU Delft, a quantitative qualification procedure for PD analysers was established. Three papers related to this work were submitted to peer-reviewed journals. One of them [24] is related to the synthetic PD calibrator, other [19] is related to the results of the round robin tests and the last one [20] is related to the validation of partial discharge (PD) method in d.c. grids for detection and prevention of insulation failures in HVDC cables, GIS and convertors.

The qualification procedures proposed will be useful for improving the features of PD analysers used for insulation diagnosis of HVAC and HVDC grids and supporting the development of the future versions of PD standards for online PD measurements.

4.4.2 PD charge evaluation in HVDC GIS, 30 MHz – 300 MHz range

To develop a method for partial discharge (PD) charge evaluation in HVDC gas-insulated substations (GIS) using a magnetic sensor, the following procedure was pursued: First, the propagation characterisation of PD in a GIS in the very-high frequency (VHF) range was studied; this is important to understand the attenuation of the PD along the GIS. Then, the characteristics of the most common defects in GIS were investigated; with this, the bandwidth of the measuring system was selected. Afterwards, a test bench for characterising the sensor and the calibration method was developed. This test bench is important to design the sensors and evaluate the calibration method correctly. With the test bench, the magnetic sensor was designed to cover the VHF range, and its charge estimation method was investigated. Finally, the measuring system was tested using artificial defects in a low-voltage and high-voltage set setup. These tasks were accomplished at different stages of the project.

4.4.2.1 PD pulse propagation in HVDC GIS

First, the PD pulse propagation in the very-high frequency range was studied for HVDC GIS. The attenuations of the most representative GIS discontinuities were collected. This provides information on the PD before it is affected by the GIS discontinuities and on the optimal sensor location selection. The transmitted PD through a "T" section is attenuated 66 %. The spacer attenuation is not critical for the pretended frequency range of the sensor. A sensor next to the bushing is nulled due to the total reflection of the signal. And straight sections and "elbows" do not affect the signal in the very-high frequency.

4.4.2.2 Developments of test cells

By knowing the most representative defects in a GIS, a surface discharge, floating electrode, protrusion and jumping particle SF_6 test cells were developed. A database was created, including each defect's PD amplitude, repetition rate, and wave shape. By knowing the frequency content of each defect, the bandwidth of the measuring system was selected. The bandwidth of the four defects is not affected by the ageing process and is above the measuring system's frequency range.

4.4.2.3 Magnetic loop antenna

A balanced magnetic loop was developed and characterised for PD measuring in the very-high frequency range. Compared to the previous sensor in the EU Horizon 2020 PROMOTioN project, the advantage of this design is that the balanced loops reject the common-mode noise produced by the induced electric field. This common-mode signal affects the charge estimation, the noise discrimination and the PD wave shape. A carbon black epoxy with aluminium grading shield was designed to shield the sensor from the power frequency electric field. The carbon black epoxy allows the penetration of the magnetic field required by the magnetic sensor, and the aluminium grants better shielding. This shield acts as an electric coupler, allowing the measurement of magnetic and electric fields at the same time. The combination of both fields enables the discrimination of the forward and backward components of the propagated PD pulse. This improves the charge estimation by eliminating the backward reflections and determining the PD propagation direction. The magnetic and electric sensors covered a bandwidth in the very-high frequency range (30 – 300 MHz) with a gain of around 10 mV/A. This sensor allows the estimation of a few pico Coulombs charges. This task resulted in the publication of two conference papers (CMD2022 and ISH2023) and two journal papers (IEEE Sensors and ELSEVIER IJEPES).

A magnetic and electric sensors model was built and tested using the test bench explained in the next paragraph. This model predicted the sensors' response in the very-high frequency range. Also, the charge estimation principle for these sensors was investigated; the narrow-band response allows the application of the double integration method. The calibration procedure using the double integration method was examined and tested in a full-scale GIS for real applications. This task resulted in the publication of one conference paper in ICD2022 and a journal paper in ELSEVIER IJEPES.

4.4.2.4 Test bench

A test bench was built to characterise the sensors and the calibration method. This test bench consists of a 50 cm GIS section with two available mounting holes to deploy the sensors. This setup is considered for measuring the sensors' frequency response and their time domain response against calibrated pulses. A transition cone was used to connect the required vector network analyser (frequency domain) and the oscilloscope and pulse calibrator (time domain), smoothing the connection from the GIS to the BNC connector. By matching the test bench to 50 Ω, it is possible to characterise the PD measuring system up to 1 GHz. This task resulted in the publication of a conference paper in the EIC2021.

At the same time, TU Delft adapted the magnetic and electrical sensor design to be used in the FFII setup. Following the procedure developed by TU Delft, FFII performed a sensor characterisation on its GIL installation, which was adapted for this purpose. The FFII test bench consists of a full-scale GIS 7 m long with a 50 Ω characteristic impedance. At the injection point, an impedance-matching cone adapted to the full-scale GIS was used in order to avoid pulse reflections.

a) b)

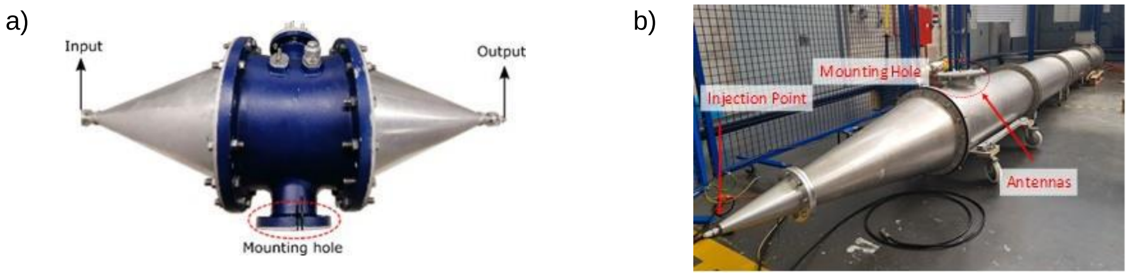


Figure 20: Setup for antenna characterisation and low voltage testing. a) TU Delft setup; b) FFII setup.

The integration constants of both antennas were obtained and tested by FFII by injecting sinusoidal signals of variable frequency. Moreover, FFII developed a complementary characterisation procedure for the VHF antenna PD sensor developed by TU Delft. By injecting UHF pulses with different amplitudes with a UHF calibrator, the calibration constants were determined by calculation of the pulse charge. The charge was calculated in the time domain (double integral method) and by a method developed by the FFII using the frequency domain. The charge determination using the FFII method working in the frequency domain obtained better results than those obtained working in the time domain. Finally, the rest of the antenna's electrical parameters was used in the synergy method and was determined in using a RLC bridge to measure both the self-inductance (Ls) of the magnetic antenna and the parasitic capacitance (C2) of the electrical antenna.

4.4.2.5 Low voltage validation of measuring system

After characterising the PD propagation, the PD defects, the sensors, and the calibration method, the measuring system was validated in two setups: a low-voltage and a high-voltage one. The LV setup consisted of the test bench (4.4.2.4) and the injection of calibrated pulses; with this, the uncertainty and the influence of noise were evaluated. The magnitude linearity, pulse width and signal-to-noise ratio uncertainties were evaluated by TU Delft and FFII, giving charge estimation errors of around 10 %.

4.4.2.6 Full scale HV validation of measuring system in GIS

The HV method validation consisted of a full-scale GIS with artificial defects PD. In this method, additionally to TU Delft and FFII, SuperGrid Institute participated, increasing the interoperability of the measuring method.

a) b) c)

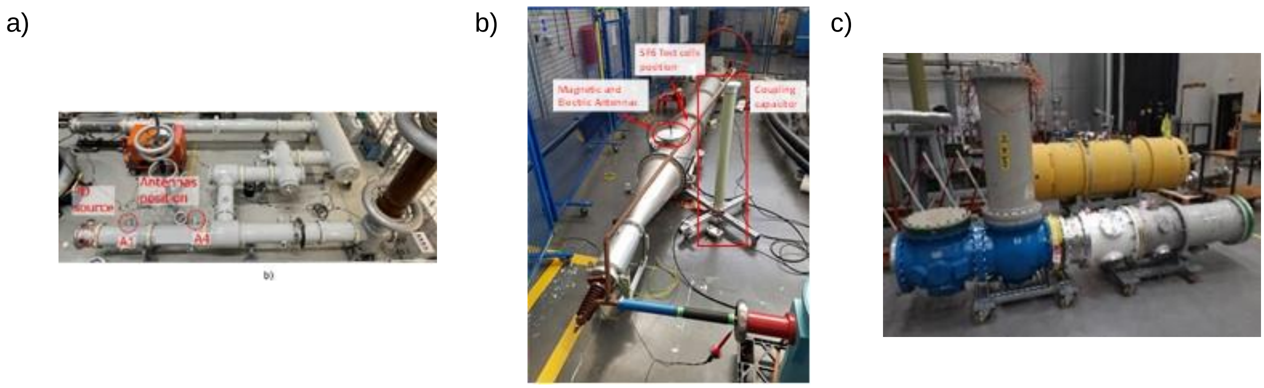


Figure 21: Setup for high voltage testing. a) TU Delft setup; b) FFII setup; c) SuperGrid setup.

TU Delft, with support from FFII, performed the analysis of the two validation methods including the uncertainty determination of each method and the influence of noise. Overall, the measuring system was able to detect PD below 5 pC and had an estimation error of 30 % for this order of charge magnitude. A conference paper for EIC2023 derived from these results.

Finally, the validation of the measuring method resulted in an article on the method for PD calibration in d.c. power grids in a 100 kV HVDC GIS published in IEEE Sensors Journal. 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. This result provides an alternative PD measuring system for online monitoring, with the capability of a calibrated measurement.

4.4.3 Key results

With the development of PD detection techniques, the key results are:

- New synthetic partial discharge calibrator for qualification of partial discharge analysers for insulation diagnosis of HVDC and HVAC grids
- Metrological qualification of PD analysers for insulation diagnosis of HVDC and HVAC grids
- Validation of a qualification procedure applied to the verification of partial discharge analysers used for HVDC or HVAC networks
- Methods for partial discharge calibration in gas-insulated substations for HVDC power grids and charge evaluation uncertainty.

4.4.4 Conclusions

Through a round robin test FFII, with support from UPM, RISE, TAU and TU Delft a quantitative qualification procedure for PD analysers was established using a synthetic PD Calibrator. This synthetic calibrator enables validation of partial discharge (PD) method in d.c. grids for detection and prevention of insulation failures in HVDC cables, GIS and convertors.

The qualification procedures proposed will be useful for improving the features of PD analysers used for insulation diagnosis of HVAC and HVDC grids and supporting the development of the future versions of PD standards for online PD measurements. Industry has contacted the consortium about exploring this technology for new HVDC cable interties.

A LV method and a HV method was used for validation in a full-scale GIS with artificial defects PD. Through collaboration between TU Delft and FFII with Super Grid Institute the interoperability of the measuring method was established. The developed measuring system was able to detect PD below 5 pC and had an estimation error of 30 % for this order of charge magnitude. This method is suitable for PD calibration in d.c. power grids in a 100 kV HVDC GIS.

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. This result provides an alternative PD measuring system for online monitoring, with the capability of a calibrated measurement.

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.

4.5 The collaborative approach

- Development of the traceability for UHVDC references to 1200 kV and 1600 kV found its strengths in collaboration of five NMIs, RISE, PTB, TUBITAK, VSL and VTT with experience using the modular RCRC divider developed in EMRP project ENG07 HVDC. RISE has since 2013 performed on-site calibrations to 1000 kV, which was important for the extension to 1200 kV. Using the same RCRC concept PTB with support from RISE led to the final design of a modular 2000 kV divider, and the RCR design by RISE built on collaboration between RISE, FFII, PTB, TUBITAK and VTT in the EMPIR project 19NRM07 HV-com[2].
- For the linear extension of UHV lightning impulse and a good practice guide, the 30+ year experience by RISE and VTT was fused with PTB and TUBITAK, the resources at TU Delft and the collaboration with NIM supported by VSL. The work was building on findings in EMPIR project 14IND08 ElPow, collaboration with NMIA (Australia) and HAEFELY, which gave a huge background experience.
- Led by VSL in the field of non-linearity determination of HV capacitors, PTB played a major role in development of methods. RISE and VTT have a long tradition in linear extension using the field sensor, not to forget the collaborator NMIA. Exploring many gas capacitors collected at PTB in collaboration with HIGHVOLT and driving development of a new generation gas capacitor by VETTINER was invaluable for the understanding on non-linearities.
- Using the long tradition and wide experience of PD metrology at FFII, this partner led the PD work for HV cables developed in EMPIR project 15NRM02 UHV (1-30 MHz). UPM laid the ground for test cells and advanced analysis of data obtained from the collaborator DIAEL. This research was expanded to

development of PD detection in GIS and converters (30-300 MHz) by TU Delft supported by FFII, and further expanded to full scale tests at the SuperGrid Institute.

5 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 CO2 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 SF6.

6 List of publications

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