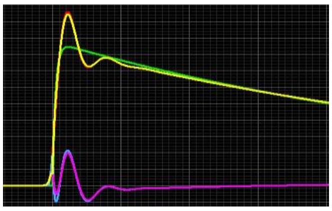

Publishable Summary for 14IND08 ElPow
Metrology for the electric power industry

Overview

This project focused on the research required to prove the quality of products developed for higher efficiency in electricity grids (i.e. with higher grid voltages and lower losses), which is key to maintaining competitiveness and the leading position of the European high-voltage electrical power industry. The project included traceability in testing at the highest voltages and fastest impulses as well as traceability in the quantification of losses in key grid components such as power transformers, cables, and High Voltage Direct Current (HVDC) converter stations. The project successfully developed new references and calibration methods for UHV testing as well as new and traceable calibration facilities for very fast transients. The project has also shown that losses in HVDC convertor stations can be measured as the difference between AC and DC power. Finally, the project developed the underpinning metrology for industrial measurements of loss for power transformers, HV capacitors, HV reactors, and power cables, with an uncertainty that is 3 to 10 times better than previously possible.

Need

Reliable electrical energy delivery is one of the prime needs in modern society and HV transmission grids are the backbone of our electricity grid infrastructure. However, the aging of this infrastructure combined with the stresses caused by integration of renewable energy sources affect the reliability of our daily electricity supply. This project supported the urgent need to develop the transmission grid infrastructure, through the provision of measurement tools needed for the reliable design and production of future grids.

In the production of equipment for high-voltage (HV) grids, dielectric testing is performed to verify that the equipment can withstand the operational environment, including high-voltage and high-current impulses. Methods and schemes for calibration have been identified primarily in IEC 60060-2. However, prior to the start of this project system voltages were increasing to levels higher than those covered by this standard, and there was an urgent need to extend the traceability of the test methods into the ultra-high voltage range, with test voltages that exceed 2500 kV.

Losses from major equipment used in high-voltage energy transmission represent a major cost and also CO_2 footprint. Therefore, correct measurements are needed to underpin efforts to reduce losses. Prior to this project, loss measurements on large transformers and reactors are performed using complex measuring systems that rely on extremely precise voltage and current transducers connected to advanced power meters. Especially for large power transformers, the demands on accurate calibration of these systems surpass the ability of calibration facilities in Europe.

Objectives

In response to these needs of the HV industry, the project had the following objectives:

1. To develop methods to extend the voltage range of traceable lighting impulse testing to the ultra-high level of 3500 kV with a targeted uncertainty of better than 1 %.
2. To develop hardware and methods for the traceable calibration of impulse voltages, such as those used in puncture testing on insulators (500 kV, 200 ns). As well as, to develop reference calibration circuits for impulse currents with ultra-fast rise times in the sub-microsecond range and peak value range of 50 A to several kA, with 0.5 % uncertainty.

3. To produce facilities for the loss measurement of large power transformers, reactors and power capacitors and AC cables. This will require the measurement of active loss power at low power factors in industrial conditions with the extreme accuracy of 10 µrad in phase and 50 µW/VA in power at voltages and currents up to 150 kV and 2000 A. Determination of skin effects for three-phase cables will also be studied with the aim to quantify losses incurred.
4. To develop a measurement system concept for the accurate determination of total HVDC converter station losses by simultaneous measurement of AC and DC power. The target is to measure a 1 % loss with a relative uncertainty of 3 %. In order to facilitate on-site measurements, a non-invasive current sensor will be developed with an uncertainty smaller than 50 µA/A in current and 50 µrad in phase angle.
5. The output of the JRP will be disseminated via publications in international journals, presentations at scientific and industry conferences, organisation of workshops, and by active participation in international standardisation committees. Together with an active JRP stakeholder committee, this will ensure that the JRP outputs are effectively disseminated to and exploited by the electrical power industry and it will facilitate an early take-up of the technology and measurement infrastructure developed by the project.

Progress beyond the state of the art

<u>Ultra-high lightning impulse voltage (UHV) testing</u>

Prior to this project, reference systems used for on-site work at the end-user's premises have generally been limited to 500 kV, which is not sufficient for proof of linearity up to full test voltage for UHV applications. This project has developed new references for UHV testing with operating voltage up to 1000 kV, as well as methods to prove linearity from the calibration level to full UHV and to characterise environmental and other on-site influences.

<u>Very fast impulse testing</u>

The project has produced new calibration facilities for very fast transients using traceable reference measuring systems in two areas: 1) measurement of fast transients at voltages up to 500 kV and with 200 ns rise-time, such as encountered in puncture testing of insulator strings, and 2) measurement of fast surge currents down to 10 ns rise-time.

<u>Loss measurement on HV equipment</u>

The project has developed the underpinning metrology for industrial measurements of loss of power transformers, HV capacitors, HV reactors, and power cables, with an uncertainty that is 3 to 10 times better than previously possible. More specifically, for power transformers, an on-site calibration infrastructure is now in place that provides an uncertainty better than 0.005 % of apparent power at power factors down to 0.01; for a measurement that is made at high voltage (c. 150 kV) and high current (c. 2 kA). For losses of large (mF) capacitors and large (mH) inductors, a novel light-weight measuring system has been developed with an uncertainty of better than 0.01 % and 10 µrad. For losses in very low-loss power cables with insulated wires, a calorimetric measuring system has been realised to supplement electrical methods.

<u>HVDC converter station loss</u>

It has been shown that losses in entire HVDC convertor stations can be measured as the difference between AC and DC power. However, this requires very accurate measurement devices with approximately 0.01 % uncertainty on both AC and DC sides and hence the project identified possible technical solutions for this.

Results

<u>*To develop methods to extend the voltage range of traceable lighting impulse testing to the ultra-high level of 3500 kV with a targeted uncertainty of better than 1 %.*</u>

The project has developed capabilities for the calibration of measuring systems for UHV impulse testing. The targets for calibration capabilities (800 kV @ 0.5 % uncertainty) were met or surpassed and will be backed by Calibration and Measurement Capability (CMC) claims from PTB and RISE. An associated method for linearity estimation was also investigated and proven up to 2700 kV, (i.e. the maximum voltage in the laboratory), however the method is expected to be fit for use up to 3500 kV.

Unsuspected problems in attaining satisfactory performance of digital recorders for lightning impulse were encountered by the project and resolved and this led to important publications. For example, leading manufacturers of transient recorders and oscilloscopes have focused on very fast step response and neglecting stability after the step. The search for suitable instruments unveiled at least one good choice but did incur a substantial delay in the work.

Furthermore, it was discovered that the length of coaxial signal cables could have a decisive impact on errors of the measuring system. The experience gathered will be used in upcoming revision work on the standard IEC 60060-2 High-voltage test techniques - Part 2: Measuring systems, where partners RISE and VTT expect to play a major role.

To develop hardware and methods for the traceable calibration of impulse voltages, such as those used in puncture testing on insulators (500 kV, 200 ns). As well as, to develop reference calibration circuits for impulse currents with ultra-fast rise times in the sub-microsecond range and peak value range of 50 A to several kA, with 0.5 % uncertainty.

An improved measuring system for very fast voltage transients up to 500 kV and 200 ns rise-time has been developed and successfully calibrated. The measuring system divider has been proven and replicas have been built both for project partners RISE and ABB (formerly STRI) and for external parties such as Verescence La Granja (Spanish insulator manufacturer). A presentation of the measuring system was given at the ISH 2017 conference. New CMC's for such measurements are in preparation by VTT and RISE.

A "cable generator" for step current was developed using a high-quality radio frequency coaxial cable with a length of more than 100 m, permitting a pulse length of 1 µs and rise-time less than 5 ns at 100 A pulse current. Tests by the project have highlighted the need for a very short distance between generator and current sensor. Several precision, high bandwidth current sensors were tested, but full verification of their stated characteristics (rise-time < 2ns) could not be achieved. The project concluded that this was predominantly caused by unavoidable physical limitations such as unavoidable series resistance of the cable that led to degradation of the generated current pulse. New CMC's for transient currents re in preparation by PTB and VTT.

To produce facilities for the loss measurement of large power transformers, reactors and power capacitors and AC cables. This will require the measurement of active loss power at low power factors in industrial conditions with the extreme accuracy of 10 µrad in phase and 50 µW/VA in power at voltages and currents up to 150 kV and 2000 A. Determination of skin effects for three-phase cables will also be studied with the aim to quantify losses incurred.

Two different sampling systems for measurement of loss of capacitors and reactors were built by partners VTT and PTB, The first sampling system uses direct measurement of voltage and a Rogowski coil to capture the current and the other uses electronically aided voltage and current transformers. These systems have been intercompared with good results and the first system has also been successfully demonstrated on-site.

Two accurate and stable phantom power sources rated for 100 kV and 1500 A at any power factor have been developed at VSL and PTB for use in the calibration of transformer loss measuring systems. One phantom power source can be used in-house and generates both voltage and current with power amplifiers and step-up transformers, while the other phantom power source phase-locks an amplifier to on-site high voltage signal to control the high current. Both phantom power sources exhibit excellent stability. Two reference measuring systems were also developed and an intercomparison between them resulted in agreement well within 20 µW/VA. The work has resulted in new CMC claims from PTB and VSL.

Further to this, a measuring system was designed and built for the calorimetric characterisation of AC-DC difference for large power cables. The measuring system has been successfully used for the characterisation of large power cables, both for single phase and three-phase modes/cables.

To develop a measurement system concept for the accurate determination of total HVDC converter station losses by simultaneous measurement of AC and DC power. The target is to measure a 1 % loss with a relative uncertainty of 3 %. In order to facilitate on-site measurements, a non-invasive current sensor will be developed with an uncertainty smaller than 50 µA/A in current and 50 µrad in phase angle

The project has shown that direct measurement of HVDC converter station losses, measured as difference of AC- and DC-power, is achievable with sufficient accuracy. The project has shown with state-of-the-art equipment that 1 % converter losses indeed can be measured with 3 % relative uncertainty. This result is being fed into the relevant CIGRÉ group Study Committee B4, DC systems and power electronics, for consideration to contribute to their Working Group 75, Feasibility Study for assessment of lab losses measurement of VSC valves.

Supplementing this is the development of a readout system for a reference current transformer intended for on-line live connection to grids up to 400 kV. The reference current transformer is intended for calibration purposes and surpasses the expectations of uncertainty smaller than 50 µA/A in current and 50 µrad in phase angle

Impact

Impact on industrial and other user communities

The project has improved, and extended, the high-voltage metrology infrastructure in the fields of loss determination and high-voltage testing. In particular the following project outputs are already providing benefits to industrial end-users and stakeholders:

- Development of calibration and linearity extension for lightning impulse measurements for future UHV transmission (in response to needs expressed by IEC). End users will benefit from better quality control of high voltage transmission system components, which will lead to more cost-effective solutions for UHV power transmission. (objective 1)
- Improved test setups for puncture test on high-voltage line insulators. This supports the compatibility of testing between different test organisations and enables accurate measurements via development of calibration services. End users such as ABB (formerly STRI) and Verescence La Granja (Spanish insulator manufacturer) benefit from better quality control of high voltage transmission system components, leading to more cost-effective solutions. (objective 2)
- Reference measuring systems and calibration methods for very fast current transients have been made available to industry e.g. and furthermore provide support for standards development, e.g. for IEC 62475, from the metrological community. (objective 2)
- Enhanced loss measurement capabilities to support procurement of new systems or components for electricity transport as required in the EU Ecodesign Directive (2009/125/EC). Target beneficiary groups are transmission system operators (TSO) and major manufacturers of high voltage equipment such as phase correction capacitors, air core reactors and power transformers. (objective 3)
- A metrological infrastructure and traceable calibration service for loss measurement on large power transformers and converter valves. Beneficiaries are manufacturers and purchasers of such equipment. (objective 3)
- A calorimetric measuring system for measuring the ratio between AC and DC resistance of the conductor of high voltage power cables has been developed and used to measure the ratio of the AC resistance relative the DC resistance, R_{AC}/R_{DC}, of a cable of low loss design. An uncertainty analysis predicted that the ratio R_{AC}/R_{DC} at 90°C of a 2500 mm^2 cable of low-loss design can be measured with an uncertainty of 1.0 %. (objective 4)
- Long term non-intrusive calibrations and an in-situ determination of a non-linear response in current transformers in substations for 400 kV power grids by an improved non-invasive current sensor. This will be beneficial for TSOs and legislators. (objective 4)
- The enhanced capabilities created for measurement of ultra-high lightning impulses ensures that production margins for the tested equipment can be reliably established, leading to more economic designs where optimised usage of materials is supported. The outcome will be that resources for construction are optimally used, with lowered energy used in manufacturing. (objective 1)
- The enhanced capabilities in measurement of loss has a twofold impact, firstly it enables optimisation of e.g. transformers with respect to materials usage, and secondly it provides a quality assured verdict of the actual efficiency of the high-voltage equipment, promoting the choice of low-loss equipment.

Again, the outcome will be that resources are optimally used in construction, and that equipment with consistently lower losses can be deployed into the electrical transmission system. (objectives 2 & 3)

Early uptakes have been achieved by

- project partner RISE with Energimyndigheten (the Swedish Energy Agency). RISE has evaluated an industrial loss measurement on a large transformer (100 kVA, 11 kV) to support Energimyndigheten's investigation of its conformance to the Ecodesign Directive.
- partners VTT and Aalto have developed a new voltage divider for fast transients and a test system for puncture testing of cap-and-string insulators. This has been purchased by two commercial laboratories ABB (formerly STRI AB), Sweden and Verescence La Granja, Spain, both involved in insulator testing.
- PTB has provided feedback to Amotronics, a manufacturer of transient recorders for lightning impulse, especially regarding interference suppression.
- RISE has provided feedback to National Instruments, a manufacturer of fast transient recorders for general use, especially regarding step performance and stability of recorded level after the step. A step generator developed in this project has been a central tool in this endeavour.
- Use of the new VSL Calibration and Measurement Capability (CMC) related to calibration of power transformer loss measurement systems in an on-site calibration at the premises Smit Transformatoren, a major manufacturer of power transformers and reactors.

Impact on the metrology and scientific communities

The outputs of the project includes several important additions and extensions to CMC statements recorded in the BIPM key Comparison Database (KCDB), and as such provide a significant impact to the worldwide electrical power metrology community. Specifically, new and extended CMCs are, or will be, submitted for

1. Measurement of losses at high voltage, high current and low power factor (150 kV, 2 kA, PF=0.01). PTB, VSL
2. Measurement of fast current transients (rise-time of 10 ns at currents of at least 50 A) PTB, VTT
3. Calibration of lightning impulse voltage measurement systems at UHV levels, i.e. above 2100 kV, RISE, PTB. VTT

The high-voltage scientific community will significantly benefit from these new or enhanced measurement capabilities in areas where scientific information has been previously scant or lacking.

Another major scientific impact has also been provided by publication of key project results in peer reviewed journals and via presentations at key conferences in the electrical power industry field. A total of 15 peer reviewed contributions have been published.

The project hosted a workshop in cooperation with EMRP project ENG61 FutureGrid in August 2016 in Braunschweig, Germany. Altogether 40 people representing project partners, standardisation organisations, industry and academia attended the workshop, and 12 presentations and 23 posters were presented. A second workshop was held in Haarlem, the Netherlands in April 2018 and attendees also included graduate students, TSOs and stakeholders. The workshop was attended by 23 delegates, who benefited from 27 presentations and 14 posters during the workshop.

Impact on relevant standards

The project has generated results that are valuable to standardisation work within IEC and CENELEC. Liaisons have been accomplished by project partners, who are active in standardisation committees, such as CENELEC and IEC TC14 (power transformers), IEC TC20 (Electric cables), IEC TC42 (High-voltage and high-current test techniques), IEC TC22F WG25 (Determination of power losses in voltage source converters for HVDC systems), and CIGRÉ D1 WG60 (Traceable measurements of very fast transients). The consortium is involved in an IEC Working Group on "Rules for the determination of uncertainties in the measurement of losses in power transformers and reactors", which has been charged with aligning two existing Technical Specifications; one from CENELEC and one from IEC. The project coordinator is the convenor of this Working Group with project partner VSL a member.

Findings both for lightning impulse and for fast transients have also been presented to plenary meetings of IEC TC42. Further contributions will be presented to IEC TC42 for consideration of amendments to international standardisation, especially in the upcoming revision of IEC 60060-2, where project partners RISE and VTT expect to take part.

Longer-term economic, social and environmental impacts

The electricity grid is by necessity a long-term asset, where reliability and efficiency need to be built in from the start. The output of this project will decisively aid these efforts as exemplified below.

- The project has helped major HV grid component manufacturers to remain at the forefront of competition, thus supporting their long-term prospects, which in turn insures future job opportunities
- The developed metrology infrastructure, as evidenced by the new CMCs, will provide a long-term traceability infrastructure to both HV grid component manufacturers and to instrument manufacturers to assure the accuracy of their products
- Broader impact is via supporting higher grid voltages and the better measurement of losses of grid components. This means lower grid losses in the longer term, and overall reduced costs.
- Better tests of HV components will increase grid reliability and thus reduce the immense costs and society disruptions of brown-outs and blackouts
- The environment will benefit from better measurement of losses from grid components and the development of higher efficiency grid components. Higher efficiency means less CO_2 emission and hence long-term support of the implementation of the Ecodesign Directive with its corresponding CO_2 aims, as well as the 20/20/20 aims of the EU.
- Finally, HV grids have a large indirect environmental impact; without them it would not be possible to integrate large-scale renewable generation, such as off-shore wind farms, into the European electricity system. Reliable measurements are essential for the reliability of the European transmission grids. This project has provided the measurement tools and infrastructure to help design and realise efficient and reliable HV grids, thus enabling the timely integration of distributed renewable generation into electricity networks.

List of publications

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<table>
<tr><td colspan="2">Project start date and duration:</td><td>2015-05-01, 36 months</td></tr>
<tr><td colspan="3">Coordinator:
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Project website address: http://GridMeas.eu</td></tr>
<tr><td>Internal Funded Partners:
1 RISE, Sweden
2 CMI, Czech Republic
3 PTB, Germany
4 VSL, the Netherlands
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