Publishable Summary for 19NRM07 HV-com²
Support for standardisation of high voltage testing with composite and combined wave shapes

Overview

The reliability of high voltage electricity grids depends on the adequate testing of grid components. The aim of this pre-normative research was to realise the necessary metrology required for the standardisation of high voltage testing with composite and combined wave shapes. In order to address the current lack of traceability, traceable measurement systems and calibration services were developed for composite and combined wave shapes and the relationship between impulse voltages with High Voltage Alternating Current (HVAC) or High Voltage Direct Current (HVDC) measurements were determined. Input was provided to IEC TC 42 'High-voltage and high-current test techniques' which revises relevant standards, in particular the IEC 60060 series. Most of the recommendations, developed in this project, were adopted by the standardisation committee and used as a basis for the currently published 42/414/CDV and 42/416/CDV. In order to build up a reliable measuring technique, a modular wideband high-voltage divider was built. Furthermore, digital recorders with new software and a reference generator for the measuring devices were developed. In this project, the state of the art in measurement technology and standardisation in the field of combined and composite high-voltage forms was reviewed internationally and incorporated into the needs of the testing industry. In addition to the normative development, measuring equipment and calibration facilities were set up at the National Metrology Institutes, so that at the end of the project the basis for a new metrology field was created. The industrial partners and research institutes have successfully used this new metrology area in initial field tests.

Need

The reliability of high voltage electricity grids and their ability to support renewable energy sources crucially depends on the adequate testing of grid components. One of these tests involves the application of composite and combined wave shapes. At the beginning of the project there was a lack of traceability for these wave shapes which could have led to incorrect test results. This need was reflected in objective 3.

As part of the production of equipment for high voltage electricity grids, dielectric testing is performed to verify that the equipment can withstand the operational environment. Such tests are performed using composite and combined waves, where lightning impulses (LI) or switching impulses (SI) are superimposed on HVAC or HVDC. The IEC 60060-1 standard specifies separating measurements of HVAC or HVDC and LI or SI for either combined or composite wave shapes. This means that depending on the blocking element, for the applied impulses, the stress on the equipment under test and the generating components can differ. Therefore, there was an urgent need for traceable measurement systems for composite and combined wave shapes that can be directly attached to the device under test. This need is reflected in objectives 1 and 2. As an example, there are phenomena that occur especially when testing gas insulated high voltage systems with combined wave shapes. These phenomena result in a reduced breakdown voltage. Insulation systems like gas insulated substations and transmission lines will likely play an important role in the application of HVDC transmission and the integration of renewables within the energy grid. This need was reflected in objective 4.

The new versions of IEC 60060-1 and IEC 60060-2 are almost finished and will be published in the next few months. At the moment, they are still at the same level as before the project. There, the qualification of the voltage dividers and measuring systems that are used in test laboratories can be performed by separate calibrations with HVAC, HVDC, LI and SI. However, these separate calibrations do not provide evidence for the ability of such voltage dividers and measuring systems to measure composite and combined wave shapes. Furthermore, there is currently no scientific evidence that HVAC/HVDC and LI/SI generation circuits do not interfere with one another. Thus, their relationship was determined, traceable calibration services were provided and input to the revision of the IEC 60060 series of standards were given. This need was reflected in objectives 1 and 4. Additionally, there was a need for the qualification of the existing voltage dividers and measuring systems that were used for measuring composite and combined wave shapes. This led to the need to set up traceable measurement systems in order to verify the performance of the existing systems. This need was reflected in objective 2.

Objectives

The overall objective of the project was to support the standards being developed by IEC TC 42 'High-voltage and high-current test techniques', in particular the IEC 60060 series.

The specific objectives of the project were:

1. To reliably determine the relationship between impulse voltages with HVAC or HVDC measurements, and related detrimental effects due to combining wave shape tests.
2. To accurately determine the uncertainty of existing voltage dividers and measuring systems used in tests with composite and combined wave shapes. In addition, to relate the results to the requirements of current IEC 60060 standards.
3. To develop traceable measurement systems and calibration services for composite and combined wave shapes, with a target amplitude uncertainty of less than 2 %.
4. To provide input and contribute to a revision of the IEC 60060 series by providing the data, methods, guidelines and recommendations, for the questions raised in IEC TC 42. Outputs will be in a form that can be incorporated into the standards at the earliest opportunity and communicated through a variety of media to the standards community and to end users (e.g. industry and manufacturers of high voltage testing instruments).

Progress beyond the state of the art

This project went beyond the state of the art as new reference voltage dividers for superimposed voltages have been designed and set up. The developed modular voltage dividers are based on RCR structure. These new dividers were used to qualify existing voltage dividers and measuring systems at testing laboratories. Furthermore, the uncertainty of the measuring systems for composite and combined wave shapes were determined. This was undertaken through measuring campaigns at TUG and TUD. The ability of existing voltage dividers to measure composite and combined voltages was investigated. The calibration methods with universal dividers were recommended to the standardisation bodies.

In this project new measuring systems and calibration capabilities for the wideband calibration of the composite and combined voltage test systems with a targeted uncertainty of less than 2 % were created. Herewith, references and calibration services for these superimposed wave shapes were created. New modular voltage dividers as well as measuring instruments were developed and characterised. Furthermore, a measuring campaign between the NMIs for composite and/or combined wave shapes will be arranged to validate the new systems and methods.

Tests of transformers or high voltage cables, for example, are currently carried out using composite and / or combined wave shapes. The measuring equipment used has to be traceable and it consists of voltage dividers and measuring instruments. However, IEC 60060-1 did not provide guidance for the calibration of the voltage dividers and measuring instruments that are used for testing with composite and combined wave shapes at the beginning of the project. The guidance was only given for separate calibration with d.c., a.c., lightning impulse and switching impulse voltages. This project made recommendations for TC 42 about the definitions and methods needed to standardise the measurement systems for composite and combined testing. The research and developments made in this project, were adopted by the standardisation committee and used as a basis for the currently published 42/414/CDV and 42/416/CDV.

Results

To reliably determine the relationship between impulse voltages with HVAC or HVDC measurements, and related detrimental effects due to combining wave shape tests.

The current practices used for generating and measuring superimposed voltage shapes were discussed in several web meetings to facilitate the coordination and development of the measurement principles. In order to investigate detrimental effects, LV generators, which are able to generate combined and composite voltages up to 1 kV, have been built. These LV generators were designed to generate combined and composite voltages higher than 500 V, with an achieved uncertainty of better than 0.5 % over a large bandwidth, so that they can be used for lightning impulses. Two proposed LV generators for composite and combined wave shapes were investigated: one using HV amplifiers and the other using a calculable calibrator. The performance of these calibrators was evaluated in a round robin test. With the help of stakeholders and industrial organisations, existing reference waveforms of combined and composite measurements, were collected in order to develop evaluation software. The consortium carried out a comparison where several developed items of software were tested with the collected reference waveforms. Within this comparison test, it was found that the measuring systems and software of the participating NMIs showed agreement below the set targets for all waveforms. During the comparison measurements in Braunschweig, Graz and Dresden, the high-voltage circuits were set up and tested before the comparison measurements. The influences of the high-voltage circuits on each other were investigated. Detrimental effects could be avoided by using the coupling elements. Thus, the objective was successfully achieved.

To accurately determine the uncertainty of existing voltage dividers and measuring systems used in tests with composite and combined wave shapes. In addition, to relate the results to the requirements of current IEC 60060 standards.

Data about the voltage dividers and measurement systems that are available from within the consortium, and at the newly developed modular universal divider, was collected for characterisation. A voltage generation setup, for HVDC and LI as well as for HVDC and SI up to 300 kV using a coupling capacitor and a resistor, was designed, developed and tested as part of a published PhD thesis during a measurement campaign at PTB.

After the setup of reference measuring systems, two high voltage campaigns were undertaken at TUD and TUG. The performed investigations conclusively demonstrated that commercially available measurement systems based on universal voltage dividers are capable of analysing the applied DC+LI/SI superimposed voltages with the accuracy required for high voltage testing. All systems retained their high overall accuracy during all superimposed voltage tests, especially regarding their dynamic behaviour. A DC component, which was considered to be particularly critical, did not have any negative effect on the performance of the investigated measurement systems. Moreover, the collected results suggested that it is sufficient to calibrate a measurement system based on universal voltage dividers for use with composite voltages with the respective individual voltages. For this, however, the scale factors for the different voltage waveforms should agree within ±1 %. Furthermore, it should be ensured that the deviation between the individual voltage component and the composite voltage with respect to the time parameters does not exceed ±2 %. Current measurement systems on the market for high superimposed voltage wave forms are mostly based on a universal divider and a transient recorder with the characteristics described in the IEC 61083 series. The industrial partners participating in this project provided such measurement systems for comparison measurements. In the context of the comparison measurements at Graz and Dresden described above, these systems achieved the targets, in terms of the measurement accuracy, and are suitable for the measurement of superimposed voltage waveforms.

To develop traceable measurement systems and calibration services for composite and combined wave shapes, with a target amplitude uncertainty of less than 2 %.

Voltage generators were created, for superimposed voltages in the voltage range below 1000 V, along with the required evaluation software. Initial results led to two approaches being pursued. Two different types of low voltage generators were built. A calibrator-based solution combining an a.c.-d.c. calibrator with a calculable impulse calibrator has been set up and tested. An amplifier-based approach was also built. Both generators were tested in a comparison campaign by the consortium. These two calibrators with different approaches agreed within the measurement uncertainty. Therefore, no choice can be made between these two approaches for accuracy reasons. Rather, the reliability of both calibrators could be confirmed in this way. For the intercomparison, the amplifier-based calibrator was chosen as the reference system, as it was provided by the leading laboratory LNE.

The consortium developed lightweight RCR divider modules based on SMD components placed on printed circuit boards. After the tests with prototypes, this kind of design was suitable for composite and combined voltage measurements. In total 10 pieces of the 100 kV divider modules have been built and probably more will be built by the partners after the project. Four modules were characterised and prepared for the measurement campaigns where a comparison of two existing reference level universal dividers provided by two participating NMIs were done. The characterisation showed a measurement uncertainty for the new reference system of 0.5 % for amplitudes and 2 % for time parameters. This was also confirmed in the measurement campaign at PTB, so that measurement capabilities are now given at the NMIs for combined and composite high-voltage forms. Both commercially available systems had deviations below the measurement uncertainty. With this result, the objective was not only achieved but undercut.

To provide input and contribute to a revision of the IEC 60060 series by providing the data, methods, guidelines and recommendations, for the questions raised in IEC TC 42. Outputs should be in a form that can be incorporated into the standards at the earliest opportunity and communicated through a variety of media to the standards community and to end users (e.g. industry and manufacturers of high voltage testing instruments).

Time parameter and combined and composite waveshape values/results were collected in recommendation reports. Discussions with the standardisation bodies of IEC TC 42 as well as with the corresponding national mirror committees were done and will continue after the project. A finalised proposal to include additional parameters for the revision of the IEC 60060-1 was submitted to MT4 of IEC TC 42 and for the IEC 60060-2 to MT3 of IEC TC 42. The revision of IEC 60060-1 and 60060-2 is in a final state. The research and development work performed in this project, was adopted by the standardisation committee and used as a basis for the currently published 42/414/CDV and 42/416/CDV. Therefore, the objective was fully achieved.

Impact

To promote support for the standardisation of high voltage testing with composite and combined wave shapes, and to share insights generated throughout the project, the results were shared broadly with scientific and industrial end-users. Sixteen papers were published, one at the international conference VDE High Voltage Technology Symposium 2020, two at the 22nd International Symposium on High Voltage Engineering, one at Springer's MAPAN-Journal of Metrology Society of India, three at the 27th Nordic Insulation Symposium on Materials, Components and Diagnostics, NORD-IS 2022 and one at "Congreso de Alta Tensión y Aislamiento Eléctrico". Furthermore, one at the 2022 IEEE 12th International Workshop on Applied Measurements for Power Systems (AMPS), one at the CPEM 2022, one at Cigré Session in 2022 and one at IEEE Transactions on Instrumentation & Measurement are published. Seven papers await publication at the 23rd International Symposium on High Voltage Engineering. One papers await publication at the Cigré Cairns Symposium 2023 and one was published at Highvolt Kolloqium 2023.

One presentation was given at the 20th International Congress of Metrology 2021, one at ALTAE and respectively two at the 22nd International Symposium on High Voltage Engineering (ISH), three at the 27th Nordic Insulation Symposium on Materials, Components and Diagnostics and one at the international conference VDE High Voltage Technology Symposium 2020. Three presentations were given at the 27th Nordic Insulation Symposium on Materials, Components and Diagnostics, NORD-IS 2022, one at the CPEM 2022, one at IEEE 12th International Workshop on Applied Measurements for Power Systems (AMPS 2022) and one at "Highvolt Kolloquium 2023". Furthermore, the project was presented three times within PTB's scientific community.

One poster was presented at the 20th International Congress of Metrology 2021, another poster at the CPEM 2022 and three articles are published in a trade journal. Three master's theses titled: "Measuring system for composite and combined voltage tests" "Development and testing of software for evaluation of high voltage composite and combined waveforms" and "Testing and analysis of universal high voltage divider" have been published. One PhD thesis with the title "Metrological infrastructure for the measurement of superimposed impulse voltages in HVDC systems" has finished.

In a three-day workshop in April 2023 the achievements and measuring equipment of the research projects 19NRM07 HV-com² and 19ENG02 FutureEnergy have been shown. The participants of this workshop showed technical presentations and posters and visited high voltage, high current, wind energy and energy meter laboratories of PTB. More than fifty participants joined the workshop in Braunschweig, Germany.

Impact on industrial and other user communities

The newly acquired knowledge on the behaviour of the generating circuits for composite or combined wave shapes as well as the relationship between impulse voltages with HVAC or HVDC have been made available in open access journal publications and at conferences, workshops, training sessions, etc. This creates and will create impact as the testing industry and the manufacturers of testing equipment will use this knowledge to adapt their future activities and products e.g. new impulse generators, new software packages for evaluating superimposed wave shapes, new high voltage dividers and instrument transformers, and new calibration and testing services, at least for TSOs and DSOs. This will help the European electrical power industry to keep its competitive advantage with respect to lower-quality competitors. Furthermore, the results of this project, especially the reviewed standards will impact the competitiveness of the European HV manufacturing and testing industry by providing them with advanced measurement systems and new measurement techniques for unambiguously determining the quality of their products.

Manufacturers of HV testing and measurement equipment, testing laboratories and research institutes benefit directly from the evaluation of the existing universal dividers and measurement systems. These existing systems demonstrated the functionality of the new technology, in practice, to the target user group. Furthermore, it showed that the basic problems (e.g. the correct evaluation of the single overlaid wave shapes and the interaction between two generating circuits) have been tackled. For HV equipment manufacturers, the results of this project will generate impact by enabling them to improve their designs and equipment and this will boost their competitiveness by enhancing sales of their instruments. This benefits testing laboratories and HV instrumentation manufacturers (e.g. Haefely and HIGHVOLT). The industrial involvement in this project was of benefit by aligning it with industrial needs and furthermore it facilitated early industrial exploitation. The determination of the uncertainty of existing voltage dividers and measurement systems enables the establishment of a new area of metrology, together with the creation of traceability at the NMIs, and the standardisation of testing with composite and combined wave shapes.

Two partners in the project and manufacturers of high-voltage equipment, Highvolt and Heafely, have each developed a universal divider for combined and composite voltages up to at least 1100 kV peak voltage. These were compared with the reference system of PTB and VTT that was built in this joint research project in September and November 2022 during the measurement campaign at TU Graz and TU Dresden.

The new reference setups and systems that were developed for measuring high voltage composite and combined wave shapes generates impact by enabling the NMIs and the testing industry to keep up with the extended voltage range, up to the UHV range, in the transmission and distribution electricity grids. These developments lead to improvements in the quality of industrial measuring systems and allow the production of new measurement tools for these tests. The reference setups and systems include voltage generation and measurement capabilities, in both laboratory and industrial conditions, at voltages of up to 1100 kV. The best practise and uncertainty evaluation was explained in a workshop for collaborators and stakeholders. This guidance results in the testing institutes being able to apply their in-depth knowledge to their calibrations and to have the opportunity to undertake comparisons, thus it improves the quality of their measurements.

This outcome directly impacts the ongoing review of the high voltage standards IEC 60060-1 and IEC 60060-2. The national standardisation bodies, e.g. the German DKE K 124, as well as the international technical committee TC 42 benefitted directly during the project. The standardised evaluation routines and definitions make it possible for companies to develop and market measuring and test equipment for superimposed voltages. Most partners are also members of the relevant MTs (MT03, MT04, WG20) of IEC TC 42 and are involved in reviewing the standards.

The developed universal divider supported EMPIR JRP 19ENG02 FutureEnergy during the set up for lightning impulse measurements of the systems from VSL and TU Delft in preparation for the campaign at TU Delft in October 2022.

Impact on the metrology and scientific communities

There is a significant amount of high-quality science behind the realisation of reference voltage dividers for composite and combined wave shapes and the setups required for calibrating them. This project tackled some of the most complex measurement problems known to the HV electrical metrology community and creates impact by significantly advancing the science in this field. The project’s impact is realised through the development of cutting edge HV measurement technologies, not only via the primary reference setups for NMIs (reflected in new CMCs), but also via traceable approved industrial measuring systems for the HV testing industry. This leads to new calibration capabilities and services at the NMIs.

The list of definitions and quantities to be measured for composite and combined wave shapes, as well as the methods and procedures required to measure these quantities, create impact by providing useful guidance to NMIs and industrial calibration laboratories.

Participating universities and NMIs complement their capacities to generate high voltage composite and combined voltages and provide testing facilities for calibrations, research and service to industry. TU Graz, TU Dresden, VTT and PTB start this as pioneers.

All NMIs in the project have carried out a measurement campaign for the low-voltage calibration of test generators and set up low voltage generators based on different systems for combined and composite voltages. Moreover, evaluation software was developed and tested at the NMIs, which enables the partners to investigate combined and composite waveforms and to evaluate them reliably.

Impact on relevant standards
This normative research project responds to the need expressed by IEC TC 42 “High-voltage and high-current test techniques” for traceable testing with composite and combined wave shapes. This TC was involved in the project in order to support its members. Furthermore, the partners had actively contributed to the review of the horizontal standard series IEC 60060 “High-voltage test techniques” as well as to the review of the standard series IEC 61083 “Instruments and software used for measurement in high-voltage impulse tests”. All related maintenance team conveners were involved in this project either through participation or as collaborators. The early impact on the IEC 60060-1 and IEC 60060-2 standards resulted from the input of scientific results and recommendations on how to measure composite and combined wave shapes. This was undertaken by the partners that are members of the IEC TC 42 maintenance teams.

After the finalisation of the review of both series of standards, IEC 60060 and IEC 61083, they will influence the testing industry by providing a clear method of testing and calibrating with composite and combined wave shapes. Furthermore, these standards will facilitate the creation of traceability at the NMIs and for the testing industry.

The results concerning the parameters of the combined and composite waveshapes were collected and published in several papers e.g. at CIM, ISH and Cigré. PTB, RISE and VTT are regularly in discussion with the standardisation bodies of IEC TC42. The revision of IEC 60060-1 and 60060-2 is in a final state. The research and development in this project, were adopted by the standardisation committee and used as a basis for the currently published 42/414/CDV and 42/416/CDV.

Longer-term economic, social and environmental impacts
This project will lead to closer cooperation between the NMIs, the European industry and experts in these fields. The results and standards will, in turn, improve the effective product testing that is critical to the development of next-generation power grids. A strong European power industry can assert its unique competitive advantage over competitors around the world.

Future HV transmission grids will be the backbone of our electricity supply chain, and its components will need to meet the highest quality standards. The development of the ultra-accurate measurement technology to meet the needs of industry and standards developing organisations will put European instrument and test equipment manufacturers at the forefront of industrial measurement systems and it will improve their standing. The new NMI measurement capabilities realised in the project, reflected in new CMCs, will provide a sound basis for accurate verification of their products.

The decentralisation of energy generation and the necessary change in Europe's transmission and distribution grids, in particular through the integration of HVDC, requires new test methods to guarantee the safety and reliability of these grids. Therefore, these new test methods need to be standardised using the results from this project. In addition to future grid reliability, it will be possible to use the largest renewable energy generators in the grid. This will make a decisive contribution to reducing CO_2 emissions.

A secure and affordable electricity supply is of utmost importance for our society and specifically for European industry. The lower cost of ownership of transformers for utilities will lead to more affordable customer bills and reduced fuel poverty. The project support to the European HV instrument manufacturing industry will enhance European competence in this important technology area, and it will secure jobs and employment in Europe.

List of publications
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https://oar.ptb.de/files/download/EMPIR.19NRM07.CA.20230119.pdf

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This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:		1 May 2020, 36 months
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Chief Stakeholder Organisation: IEC Technical Committee 42		Chief Stakeholder Contact: Heribert Schorn
Internal Funded Partners: 1. PTB, Germany 2. FFII, Spain 3. INRIM, Italy 4. LNE, France 5. RISE, Sweden 6. TUBITAK, Türkiye 7. VTT, Finland	External Funded Partners: 8. AME, Italy 9. TAU, Finland 10. TUD, Germany 11. TUG, Austria	Unfunded Partners: 12. Haefely, Switzerland
RMG: -		