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 is 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 will be 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 will be determined. Input will be provided to IEC TC 42 'High-voltage and high-current test techniques' which revises relevant standards, in particular the IEC 60060 series.

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. However, at present, there is inadequate traceability for these wave shapes which may result in incorrect test results. This need is 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 is 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. At present there is no standard to test the dielectric behaviour of HVDC gas-insulated systems, which will be the foundation for satisfactory reliability. This need is reflected in objective 4.

The current IEC 60060 standard also permits the voltage dividers and measuring systems that are used in test laboratories to be qualified 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 needs to be determined in order to provide traceable calibration services and input to the revision of the IEC 60060 series of standards. This need is reflected in objectives 1 and 4. Additionally, there is a need for the qualification of the existing voltage dividers and measuring systems that are used for measuring composite and combined wave shapes. This leads to the need to set up traceable measurement systems in order to verify the performance of the existing systems. This need is reflected in objective 2.

Objectives

The overall objective of the project is 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 are:

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

Composite and combined wave shapes are generated using two separate generating circuits, e.g. one for d.c. voltage generation and the other one for lightning impulse voltage generation. The superposition of these voltage forms is either carried out by a spark gap or a coupling capacitor. This project will go beyond the state of the art as new definitions for measuring amplitude and time parameters will be determined through scientific research. These definitions will allow new evaluation routines to be generated. Current practices will be discussed to enable measurement principles to be coordinated and developed. Both the definitions and the evaluation procedures will be passed on to TC 42 for use in standardisation and, if approved by TC 42, they will be added to the current revision of the IEC 60060 series of standards. The scientific findings in this project on the interaction of the impulse voltages, superimposed with d.c. or a.c. voltages, will enable optimised test setups to be created for superimposed voltages. This will create the prerequisite for the traceability of measuring instruments for superimposed voltages, which are part of the high voltage measuring system.

This project will go beyond the state of the art as new reference voltage dividers for superimposed voltages will be designed and set up. The developed modular voltage divider will be based on RCR structure. When finished, these new dividers will be 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 will be determined. This will be undertaken through measuring campaigns at TUG and TUD. The ability of existing voltage dividers to measure composite and combined voltages will be investigated. Finally, a statement will be made on whether the previous calibration method is practical or whether it will need to be completely revised.

The scale and correction factors of the measuring systems are currently given separately for each type of voltage (HVAC, HVDC, LI and SI), and these factors can differ significantly. At the moment, there are no references and no calibration services for these combined wave shapes. Therefore, this project will go beyond the state of the art by creating 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 %. New modular voltage dividers as well as measuring instruments will be 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 does not provide guidance for the calibration of the voltage dividers and measuring instruments that are used for testing with composite and combined wave shapes. The guidance is only given for separate calibration with d.c., a.c., lightning impulse and switching impulse voltages. This project will go beyond the state of art by making a recommendation for TC 42 about the definitions and methods needed to standardise the measurement systems for composite and combined testing. This research and development will be used in the ongoing review of the IEC 60060-1 and 60060-2 standards that started recently (as decided at the meeting of TC 42, held in Toronto in October 2017).

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, are built. These LV generators are being designed to generate combined and composite voltages higher than 500 V, with a target 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 are being investigated: one using HV amplifiers and the other using a calculable calibrator. The performance of these calibrators will be evaluated with an ongoing 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 software were tested with the collected reference waveforms. Comparison results will be used to improve the current definitions of the parameters and to estimate the uncertainties related to the parameter evaluation.

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 are being 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 a part of a published PhD thesis.

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

The work on the development of voltage generators, for superimposed voltages in the voltage range below 1000 V, and evaluation software has started. Initial results have 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 are tested and the comparison campaign by the consortium is ongoing until October 2022.

After agreeing the design principles, simulations, and component testing, the consortium ended up developing a lightweight RCR divider modules based on SMD components placed on printed circuit boards. After the first tests with prototypes, this kind of design will be suitable for composite and combined voltage measurements. Totally 10 pieces of 100 kV divider modules have been built and probably more will be built by partners later on the project. So far, four modules have been characterized and prepared for the upcoming measurement campaign where they will be compared to two existing reference level universal dividers provided by two participating NMIs.

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 a draft report. Discussions with the standardisation bodies of IEC TC 42 as well as with the corresponding national mirror committees are ongoing. A finalized proposal to include additional parameters for the next revision of the IEC 60060-1 is submitted to MT4 of IEC TC 42. Revision of IEC 60060-1 and 60060-2 has started. Due to the large complexity of the combined and composite waveshape part for IEC 60060-2, a separate document will be prepared to the IEC 60060-2

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. Eight 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 peer reviewed open access journal "Electrical Engineering", 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". Six papers, one at the 2022 IEEE 12th International Workshop on Applied Measurements for Power Systems (AMPS), two at the CPEM 2022, two at Cigré Session in 2022 and one at Springer's peer reviewed open access journal "Electrical Engineering" are waiting for publication.

Furthermore, 2 presentations were given at the 20th International Congress of Metrology, one at ALTAE and respectively two at 22nd International Symposium on High Voltage Engineering (ISH), three at 27th Nordic Insulation Symposium on Materials, Components and Diagnostics and one at the international conference VDE High Voltage Technology Symposium 2020. Furthermore, the project was presented three times within PTB in a scientific community.

One poster was presented at the 20th International Congress of Metrology and one article is published in a trade journal. Three master's thesis 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" are published. One PhD thesis with the title "Metrological infrastructure for the measurement of superimposed impulse voltages in HVDC systems" has finished.

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 will be made available in open access journal publications and at conferences, workshops, training sessions, etc. This 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, this project 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 will directly benefit from the evaluation of the existing universal dividers and measurement systems. These existing systems will be very effective in demonstrating the functionality of the new technology, in practice, to the target user group. Furthermore, it will show 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 will also benefit testing laboratories and HV instrumentation manufacturers (e.g. Haefely and HIGHVOLT). The industrial involvement in this project will be of benefit by aligning it with industrial needs and furthermore it will facilitate early industrial exploitation. The determination of the uncertainty of existing voltage dividers and measurement systems will create impact by enabling 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.

The new reference setups and systems that will be developed for measuring high voltage composite and combined wave shapes will generate 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 will lead to improvements in the quality of industrial measuring systems and will allow the production of new measurement tools for these tests. The reference setups and systems will include voltage generation and measurement capabilities, in both laboratory and industrial conditions, at voltages of up to 750 kV. The creation of traceability and calibration services at the NMIs will enable the establishment of a new area of metrology together with the determination of the uncertainty of the existing voltage dividers and measurement systems and the standardisation of testing with composite and combined wave shapes. The best practise and uncertainty evaluation will be explained in a workshop for collaborators and stakeholders. This guidance will result 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 will improve the quality of their measurements.

This outcome will directly impact the ongoing review of the high voltage standards IEC 60060-1 and IEC 60060-2. The national standardisation bodies, e.g. the German VDE K 124, as well as the international technical committee TC 42 will benefit directly during the project. The standardised evaluation routines and definitions will 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.

Impact on the metrology and scientific communities
There is 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 tackles some of the most complex measurement problems known to the HV electrical metrology community and it will create impact by significantly advancing the science in this field. The project's impact will be 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 will lead to new calibration capabilities and services at the NMIs.

The realisation of the HV reference measuring systems at the NMIs will lead to new CMCs statements being recorded in the BIPM Key Comparison Database (KCDB). At present there are no CMCs related to superimposed high voltages, which means that the project will also enable the establishment of new sub-services in the branch "High voltage and current".

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

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 will get involved in the project in order to support its members. Furthermore, the partners will actively contribute 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 will be involved in this project either through participation or as collaborators. The early impact on the IEC 60060-1 and IEC 60060-2 standards will result from the input of scientific results and recommendations on how to measure composite and combined wave shapes. This will be undertaken by the partners that are members of the IEC TC 42 maintenance teams.

The two standard series IEC 60060 and IEC 61083 are the most likely to provide a route to impact. After the review of both series of standards, 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.

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

Johann Meisner et. al., “Support for standardisation of high voltage testing with composite and combined wave shapes”, in VDE Hochspannungstechnik, Berlin, Germany, November 2020
https://doi.org/10.7795/EMPIR.19NRM07.CA.20210215;
https://oar.ptb.de/resources/show/10.7795/EMPIR.19NRM07.CA.20210215

Stefano Caria, “Sistema di misura per prove di tensione composite e combinate (Measuring system for composite and combined voltage tests)”, Master Thesis - Politecnico di Torino, October 2020
https://webthesis.biblio.polito.it/15631/

Paolo Roccato, “Towards a traceable divider for composite voltage waveforms below 1 kV”, Springer’s peer reviewed open access journal “Electrical Engineering”, Suisse, August 2021
https://doi.org/10.1007/s00202-021-01368-5

Hanane Saadeddine, “Reference Calibrator for Combined and Composite High Voltage Impulse Tests”, 22nd International Symposium on High Voltage Engineering ISH 2021
https://doi.org/10.5281/zenodo.6993921

Jiang, H. et. al., “Prequalification of capacitors for high-precision voltage dividers”, 22nd International Symposium on High Voltage Engineering (ISH), Xi’An, China, 2021
https://zenodo.org/record/6073729#.YgtSCZYxmUk

Abderrahim Khamlichi, “Universal Measuring Unit for High Voltage Measurements”, 27th Nordic Insulation Symposium, NORD-IS 2022
https://www.ntnu.no/ojs/index.php/nordis/article/view/4898/4501

Oskari iisakka, “Development and testing of software for evaluation of high voltage composite and combined waveforms”, Tampere University publications archive TREPO
https://urn.fi/URN:NBN:fi:tuni-202110287941

Simon Boonants, “Testing and analysis of universal high voltage divider” Tampere University publications archive TREPO
https://trepo.tuni.fi/bitstream/handle/10024/140641/BoonantsSimon.pdf?sequence=2&isAllowed=y

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Stephan Passon, “Metrological infrastructure for the measurement of superimposed impulse voltages in HVDC systems”, Technische Universität Braunschweig publications archive
https://publikationsserver.tu-braunschweig.de/receive/dbbs_mods_00070624

Mohamed Agazar, “The Usage of High Voltage Amplifiers to Setup Reference Calibrators for Combined and Impulse Voltages up to 1 kV”, 27th Nordic Insulation Symposium, NORD-IS 2022
https://www.ntnu.no/ojs/index.php/nordis/article/view/4875/4500

Abderrahim Khamlichi, “Universal high voltage recorder for testing laboratories”, Congreso de Alta Tensión y Aislamiento Eléctrico (ALTAE) 2021
https://doi.org/10.18845/tm.v34i7.6008

This list is also available here: https://www.euramet.org/research-innovation/search-research-projects/details/project/support-for-standardisation-of-high-voltage-testing-with-composite-and-combined-wave-shapes/