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1 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.

2 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.

3 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).

4 Results

The overall objective of this 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.

Objective 1

There are several standards with reference to combined and composite voltage forms. The aforementioned IEC 60060 series on high voltage and high current testing technology defines the setup for combined and composite voltage shapes as shown respectively in Figure 1 and 2. This standard series also describes the measuring instruments for high voltages and the measuring processes for different voltage forms. Unfortunately, only the circuit setups for composite voltage tests and combined voltage tests are given in this standard. To illustrate the metrological and normative challenge, Figure 1 and Figure 2 of the test circuits are used. The combined voltage *U* appears between two high voltage terminals of a three-terminal test object, while the third terminal is grounded (see Figure 1). The single voltage sources are guarded by a protection element in case of a breakdown of the test object. However, coupling of the different voltages via the equipment under test should be considered. Typical test objects are disconnectors, circuit breakers, gas insulated switchgears (GIS), etc. Direct measurement of combined voltage is difficult because there is no earth potential involved. Therefore, it is allowed to calculate the combined test voltage *U* from the separate measurement of its two voltage components U_1 and U_2. The reference measuring devices, here named "converting devices", are only calibrated for the individual voltage forms (e.g. LI or HVAC). As a result, if the other circuit is coupled, both the reliability of the measurement and that of the reference measurement system itself are insufficient. Therefore, the calculated combined voltage can also be incorrect. To solve this problem, reliable measuring systems calibrated for superimposed voltage waveforms are required in addition to reliable protective elements of the test circuits. This ensures the ability of these measuring systems to measure the applied voltage correctly and reliably even in the case of disturbed (superimposed) voltage waveforms.

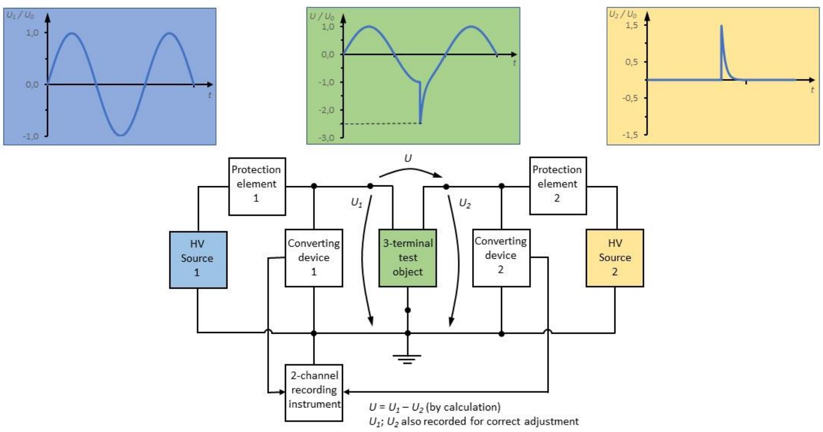


Figure 1: Test circuit for combined voltage tests

The composite voltage $U^*=U_1^*+U_2^*$ is the superimposed voltage on the test object, where test voltage is applied on the one terminal of the test object. The test circuit for composite wave shapes contains a measuring device which directly measures the voltage across the equipment under test. Coupling and blocking elements and further measuring devices for the adjustment of the single components of the composite wave shape are on both sides (see Figure 2). This means that depending on the coupling and blocking elements the stress on the equipment under test and the generating components can differ. The coupling and blocking element should have a low impedance for the coupling purpose of the relevant kind of voltage and a high impedance for the other kind of voltage of the composite test voltages.

From a metrological point of view, the composite wave shape is even more challenging. Here the converting device is used to measure the superimposed high voltage. Calibration of this converting device or better called measurement system using individual voltage waveforms HVAC, HVDC, LI and SI does not guarantee the correct measurement of a superimposed curve. In addition, the calibration factors of each individual wave form are often different, so it is not clear during tests which scale factor to use for superimposed waveforms. The 60060-2 specifies how approved measuring systems must be calibrated. Here, the necessary instruction for calibrating these measuring systems with superimposed voltage wave forms is missing. Finally, an incorrect test of equipment can lead to the failure of this equipment in the event of a real fault in the grid and thus reduce the reliability of the electrical grid.

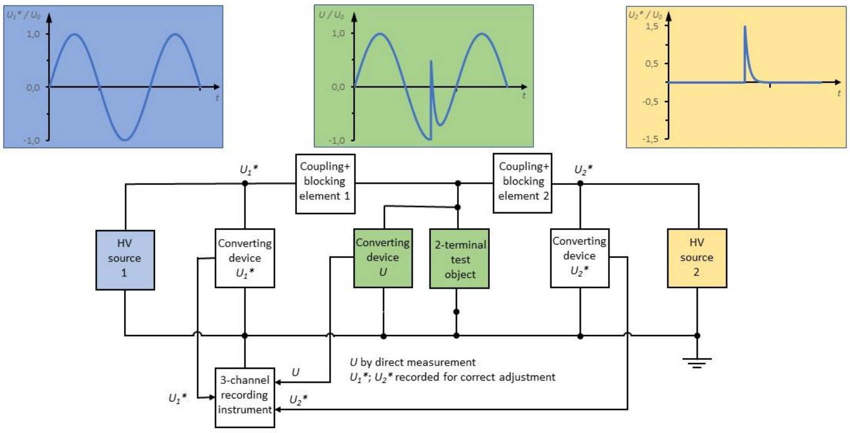


Figure 2: Test circuit for composite voltage tests

The IEC 61083 series describes the low voltage measuring instruments and software of high voltage measuring equipment. The American counterpart to these high voltage standards is the IEEE-4 standard for high voltage testing. And finally, there is the IEC 62271 standard, which describes the specification for AC voltage switches. In the IEC 61083 series, there are standardised voltage curves for AC voltages equal to voltages and pulse voltages. Evaluation software are typically qualified using a test data generator (TDG), which provides datasets with known reference values. Unfortunately, there are no data sets for superimposed voltage waveforms. The consortium has therefore collected data sets from industry. In a collaborative effort, data sets for all necessary superimposed voltage combinations were defined as standard voltage waveforms. These standard voltage waveforms, for example LI voltage of negative polarity superimposed on a DC voltage of positive polarity, are used both for the determination of the parameters and as the standard data set for the standard. During this project new definitions for measuring amplitude and time parameters were determined through scientific research. At the beginning of the project low voltage instruments (digital recorders) and software that are used for the evaluation of HV composite and combined tests have been developed and set up. Furthermore, calibrators for superimposed voltage shapes have been setup. Several types of calibrators were built in this project for use in calibrations of commercial low-voltage measuring instruments for combined and composite voltages up to 1 kV by LNE, VTT, PTB, INRIM and TUBITAK. One of the calibrators is based on the series arrangements of two sources. It consists of combining an existing DC or AC calibrator with a calculable impulse voltage calibrator. This kind of calibrator will be used for composite wave shapes generation. Another calibrator is based on the parallel arrangements of two sources. It can generate composite wave shapes using blocking elements and combining an existing DC or AC calibrator with an impulse voltage calibrator. In addition to the combination of existing calibrators for the single voltage waveforms, a novel approach based on linear high-voltage amplifiers was also investigated. A reference calibrator was developed that can generate both, fast waveforms such as LI and slow waveforms such as SI, AC, DC and combined or composite waveforms from them. Based on this technique, the reference calibrator achieves high metrological performance. Figure 3 shows the reference calibrator in the experimental setup for the calibration of digital recorders.

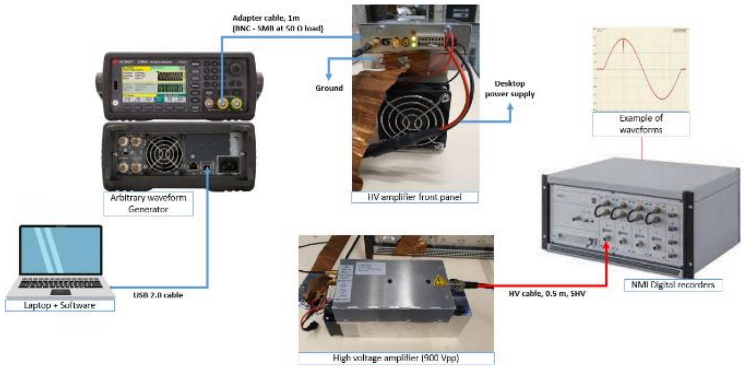


Figure 3: Reference calibrator structure based on the use of a linear high-voltage amplifier (LNE)

To ensure the HV amplifier's traceability to the international system of units (SI), four methods have been investigated. The first method consists of using a direct comparison by calibrating the gain for a specific wave shape. The principle is to measure the input and the output voltages using a reference digital recorder that was characterised before and after performing the measurements. In this case, the influence of the load impedance is evaluated. The second method is to use the convolution technique to characterise the gain. A calibrated DC voltage is applied to the input of the amplifier and shortened to ground using a high-quality mercury relay. The aim is to calculate the gain errors for a specific wave shape. In the third method, the gain frequency response at several voltage levels up to 250 V RMS and frequencies from DC to 50 kHz was characterised. This method is needed to calculate the wave shapes' parameters and apply the required correction factors for each frequency and voltage component. The fourth method is to use a combination of traditional DC calibrator together with a calculable, passive impulse voltage calibrator. The combination was used to generate a traceable waveform, which was compared with the output of the new reference calibrator with the substitution method using a stable digital recorder.

The traceability study of the reference calibrator based on an HV amplifier has demonstrated that this kind of calibrator is able to calibrate the digital recorders with very good uncertainty for combined and composite wave shapes measurements. The generation of all-waveforms is guaranteed to have good accuracy using this calibrator. For example, for LI wave shapes up to 900 V, the uncertainties were estimated to be less than 0.2 % for the peak voltage value, 1 % for the front time and 0.5 % for the time to half value. Several reference digital recorders have been investigated by LNE, VTT, PTB, INRIM, TUBITAK, among which, three digital recorders and one digital multimeter have been selected and fully characterised for typical waveforms, such as AC, DC, LI, and SI measurements and for each range of the digital recorders up to their maximum range. In addition, two other reference digital recording instruments have been investigated, according to the IEC 61083-1, to be used in the measurement of composite and combined voltages. The digital recorders' performance test has led to the determination of characterisation methods, and the measurement uncertainty budget, while taking into account the AC, DC, and impulse voltages, which may play an important role in the calibration uncertainty of the digital recorders.

A comparison of the evaluation software was arranged between several NMIs (VTT, PTB, LNE, FFII, INRIM, TUBITAK), two universities (TUG, TUD), and one test laboratory (Haefely) to estimate the uncertainties related to the parameter evaluation of the combined and composite voltages. At first, the relevant waveshapes were chosen and the evaluated parameters were agreed. After that, each of the 9 partners developed their own evaluation software and evaluated the relevant parameters related to the specific waveform according to IEC 60060-1. The evaluated results were compared and analysed to understand what the achievable uncertainty is related to in the evaluation of certain combined and composite waveforms. During the software development, ideas for new parameters or better definitions were collected from the 9partners to support the revision of terms and definitions in IEC 60060-1. Waveshapes and the results of this comparison could also be utilised in the development of test data generators (TDG) of IEC 61083-2 or/and IEC 61083-4.

The work was started by defining which combined and composite waveshapes should be evaluated. In the case of combined voltage AC+LI/SI and composite voltage AC+LI/SI, DC+LI/SI were chosen. Composite voltage with AC is not a common test voltage but it is used at least when specific thyristor valves need to be energised with AC during impulse testing. The combination of two impulse voltages were not included in this comparison. Parameter evaluation was chosen to be according to IEC 60060-1:2010 where the parameters are calculated for the complete test voltage (combined or composite) and separately for each voltage component (AC/DC/LI/SI).

Recorded waveforms from actual combined and composite voltage testing were collected from industrial stakeholders. Since there are no recommendations in the standards regarding the recordings, some challenges occurred. At first, for combined AC only two files were used, see Figure 4. The problem related to this approach was that defining the time delay accurately is challenging due to the low sample rate of the AC signal. Also, the determination of AC values was complicated since there was only a half-cycle of AC and it was recorded after the impulse which might have an effect on the recorded AC signal. It was suggested to use 3 separate files with combined AC: The impulse with high sample rate, AC with high sample rate in the region where the impulse is applied, and AC with low sample rate. This allows the better evaluation of the time delay and the AC parameters. An example of using 3 files is presented in Figure 5.

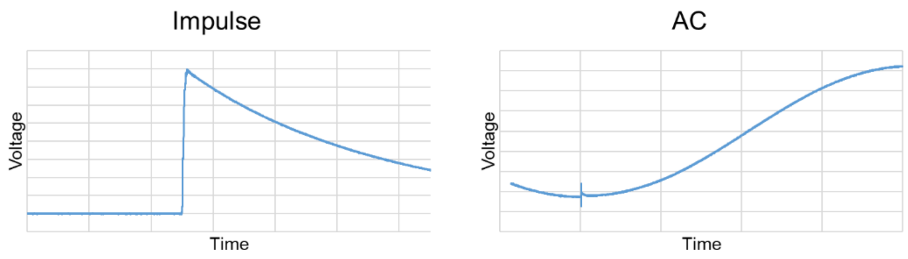


Figure 4: LI with high sample rate on the left, AC with lower sample rate on the right. This kind of file format was found to be insufficient

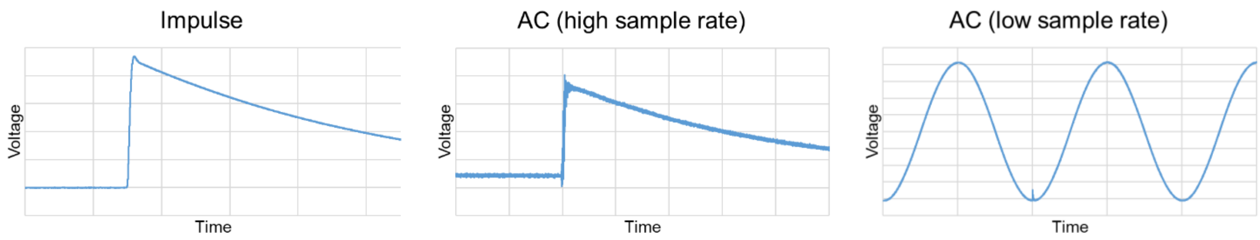


Figure 5: Preferred files for the evaluation of combined AC signals: LI with high sample rate on the left, AC with high sample rate on the region where the impulse is applied on the centre, and AC with low sample rate on the right

Second challenge related to file formats was composite AC voltages. These are typically recorded with only one channel using a high sample rate to record the applied impulse accurately as seen in Figure 6. This leads to a very high number of samples (up to 25 MS) when the AC signal is included in the recording. All developed software could not handle so many samples, so files were divided into two parts: First part LI/SI with high sample rate, and second part AC with lower sample rate. Some of the developed software were able to perform this process automatically from the one file with a high number of samples.

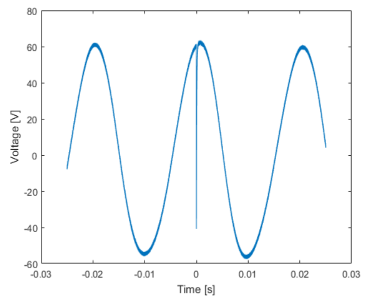


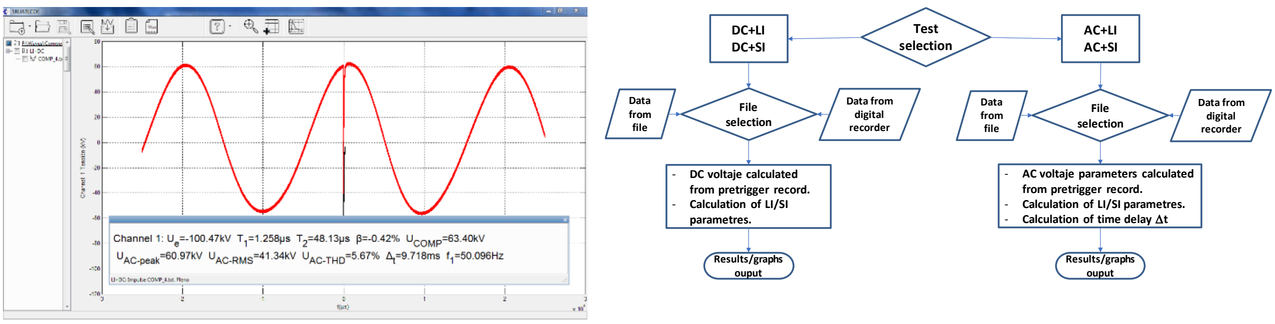
Figure 6: Composite AC with LI using 500 MS/s sample rate. Recording has 25 million samples

Finally, 4 combined and 7 composite voltages were chosen to be used as reference waveforms for the evaluation software. The waveshapes are summarised in Table 1. In total 7 different partners (PTB, LNE, VTT, TUBITAK, INRIM, FFII, Haefely) were working with their own evaluation software for combined and composite waveforms. Some of the developed or modified software were not able to evaluate all the different cases. An example of an evaluation software interface and operation is presented in Figure 7.

It has been defined that the evaluation of the AC and DC values from the superimposed test voltages must be carried out before the pulse is applied, in order to avoid subsequent interference caused by the pulse. However, all of the provided AC waveshapes didn’t have a full AC cycle before the impulse which led to a higher deviation in the AC parameters within the consortium. Therefore, it is recommended to have at least one full AC cycle before the applied impulse. It was also noted that the definitions of time delay, and the value of the combined voltage were not unambiguous. Both definitions should have a clear indication if the AC or impulse is used as a reference point. Because of the definitions, the consortium ended up providing results with disagreement if the value is positive or negative. One new parameter was proposed during the comparison. This parameter is for combined AC describing the voltage change in the AC measuring system caused by the impulse voltage application.

Table 1: Evaluated waveshapes

Name	Type	Component 1	Component 2	Additional information
A	Combined	AC	LI	Positive impulse applied at negative peak of AC.
B	Combined	AC	LI	Negative impulse applied at positive peak of AC.
C	Combined	AC	SI	Positive impulse applied at negative peak of AC.
D	Combined	AC	SI	Negative impulse applied at positive peak of AC.
E	Composite	DC	LI	Positive impulse applied to negative DC.
F	Composite	DC	SI	Positive impulse applied to positive DC.
G	Composite	AC	SI	Positive impulse applied at AC zero.
H	Composite	AC	LI	Negative impulse applied at positive peak of AC.
I	Composite	DC	LI	Positive impulse applied to negative DC. Use of sphere gap influenced the impulse tail.
J	Composite	DC	SI	Negative impulse applied to negative DC. Use of sphere gap influenced the impulse tail.
K	Composite	AC	SI	Positive impulse applied at AC zero. AC included a lot of transients.



a) b)

Figure 7: Software interface on the left side, flowchart for combined and composite voltage analysis on the right side

The easiest evaluation was the composite DC with LI since LI evaluation according to IEC 60060-1 can be used except for the additional DC parameters. Results have reasonable deviations, but the non-standard tail (Figure 8) probably influenced the algorithms. Evaluation of composite DC with SI was also straightforward. As seen from the results, the use of modified LI evaluation for SI can improve the time parameter agreement significantly.

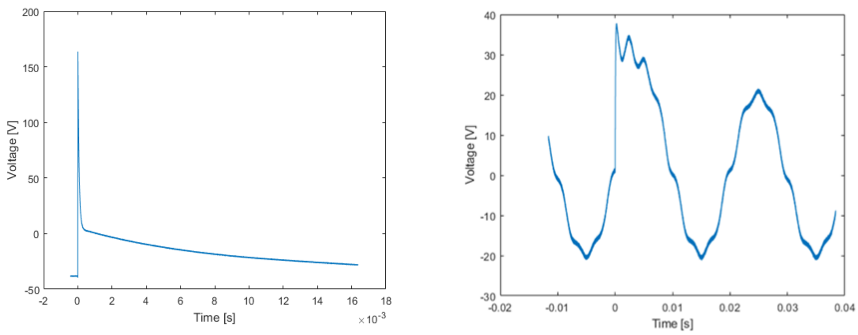


Figure 8: Curve I from Table 1 (left side), Curve K from Table 1 (right side)

Composite AC with impulses is more challenging since the AC and LI/SI signals are harder to be separated from each other. Typically, this is done by fitting an AC signal and removing this from the composite voltage resulting in the impulse. This procedure can increase the deviations with the AC parameters and the impulse parameters. The impulse parameter deviations are higher than with composite DC. One reason for higher results is the use of different input files due to downsampling. This might have caused the loss of some of the information. Also, the results would probably have been better if there had a been one full cycle of AC before the impulse. With SI, the parameters can be improved using the LI calculation. An exception to this is the composite AC with a high harmonic. This impulse form is very dependent on, if the AC signal is evaluated before or after the impulse. Even though it was recommended to fit the AC signal before the impulse, the recommended one full cycle is not available before the signal.

Combined AC with impulses has better agreement on AC parameters than the composite AC waveshapes. Also, the impulse parameters have better agreement than with composite AC. As also seen from these results, the use of a modified LI evaluation for SI can improve the time parameter agreement significantly.

Results show that using combined or composite test voltages typically increases parameter evaluation related uncertainties compared to the separate AC/DC and impulse waveform evaluation. This is because the voltage components might distort each other, or challenges related to using different sample rates. Comparison results and related files are available for IEC 61083-2 or/and IEC 61083-4. Improved combined test files with a full AC cycle before the impulse can still be recorded during the project and these were provided to the interested standardisation bodies.

The development of novel voltage generators, for superimposed voltages in the low voltage range, as well as the digital recorders and new evaluation software goes beyond the state of art and will create the prerequisite for the traceability of measuring instruments for superimposed voltages, which are part of the high voltage measuring system.

Summary

Objective 1 has been achieved, as real reference waveforms have been selected and evaluated with new test generators, new measurement instruments and new software, showing excellent agreement between the consortium. Furthermore, the Recommendation Reports for both standards were created from the experiences, which have also found their way into the current CDVs of IEC 60060-1 and IEC 60060-2. Calibration and traceability of measuring instruments and software can be offered by the NMIs.

Objective 2

To replicate the electrical stress occurring on power equipment, tests with superimposed voltages are used. During these tests, the components are simultaneously stressed with either an AC or a DC voltage and an impulse voltage (e.g. LI/SI). The measurement of the resulting voltage is only possible with universal voltage dividers (RCR dividers), which have not yet been standardised. To evaluate tests with superimposed voltages, this objective focuses on the performance of universal voltage dividers at different voltage combinations. The uncertainty of such existing voltage dividers and measuring systems was accurately determined in two measuring campaigns at TUG and TUD by TUD, TUG, PTB and the manufacturers. The preparation and the evaluation of the results of the campaigns was done by all partners. The results obtained have been used to investigate how universal voltage dividers can be calibrated and how this process can be standardised.

To assess the effects of the mixed voltage stress on measurement linearity and measurement uncertainty occurring during composite voltage tests, the measurement results of two commercially available measurement systems from different manufacturers, based on universal voltage dividers, were compared with a reference measurement system developed in this project, which is described in the next chapter “Objective 3”. In light of the increasing importance of HVDC equipment, the investigations focused on the combination of DC and lightning as well as switching impulse voltages (Figure 9). The dividers were tested up to a DC voltage of ±350 kV, superimposed with LI and SI voltage amplitudes of ±1100 kV and ±1000 kV respectively.

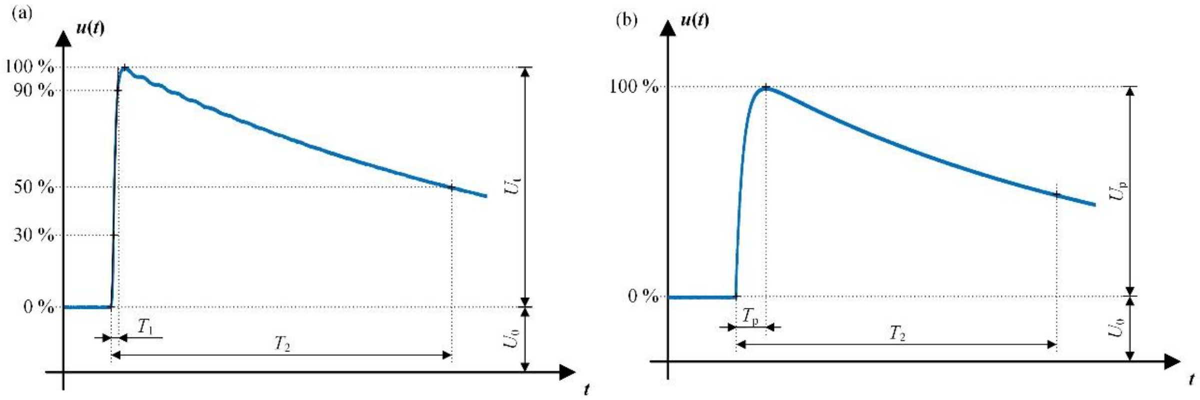


Figure 9: Exemplary voltage waveforms of a DC voltage superimposed with (a) a lightning impulse voltage and (b) a switching impulse voltage

The main goal of the high-voltage tests was to assess the effects of the superimposed voltage stress on the measurement linearity and measurement uncertainty of the measurement systems, based on universal voltage dividers, occurring during composite voltage tests. Two different series of tests were carried out for this purpose. In the first test series, two commercially available universal voltage dividers (Com1 and Com2) from European manufacturers were compared with the reference divider (Ref) developed in this project in order to be able to assess the basic linearity and measurement accuracy of the two commercial dividers. In the second test series, aimed at assessing the properties of the two commercial dividers at higher voltages, the reference divider was removed from the test setup due to its limited voltage range.

Table 2: Characteristics of investigated measurement systems

	Ref	**Com1**	**Com2**
R in GΩ	2,4	1	0,8
C in pF	205	700	375
R_D in Ω	480	180	800
$R_{D\text{-ext}}$ in Ω	529	355	207.5
max. U_{DC} in kV	± 300	± 600	± 400
max. U_{AC} in kV	300	400	400
max. U_{LI} in kV	±300	±1200	±750
max. U_{SI} in kV	±300	±1000	±650
Scale Factor F	820729	850	967
Δt_{LI} in ns	5	4	4
Δt_{SI} in ns	20	240	100

Table 2 gives an overview of the characteristics of the measurement systems used and the permissible voltage ranges (voltage to ground). In the case of bipolar voltage combinations, the theoretical maximum peak to peak voltage may be fully utilised (e.g. $-U_{\text{DC-max}} + U_{\text{LI-max}}$). In the case of homopolar combinations, the addition of the DC and LI/SI voltages must not exceed the LI/SI limits. Due to the RCR divider design, the scale factors F are independent of the type of test voltage (DC/AC/LI/SI).

The composite test voltages were generated according to the circuit proposed in IEC 60060-1 (Figure 10). A 1.5 MV GREINACHER cascade generated the DC voltage, while a 3.2 MV MARX generator provided the impulse voltages. A protection resistor R_{protec} = 15 MΩ was used to protect the DC source. On the MARX generator side, it is theoretically possible to either use a spark gap or a blocking capacitor to avoid constant DC stress.

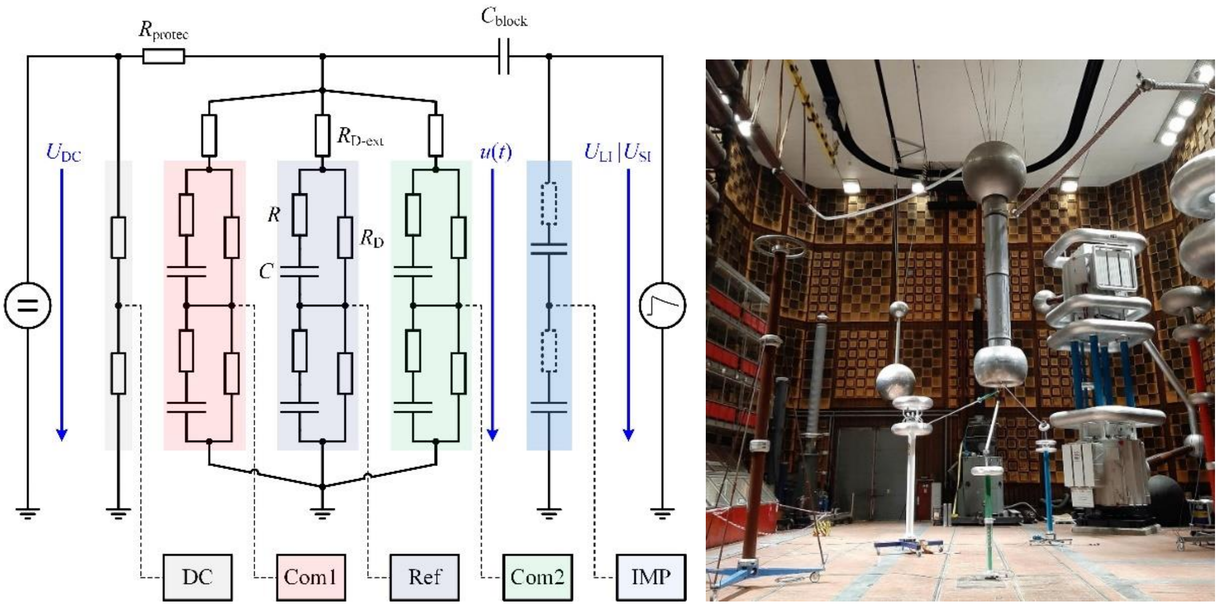


Figure 10 : Test circuit for composite voltages (left) and laboratory setup (right)

However, a blocking capacitor was chosen, due to the numerous disadvantages associated with spark gaps. A series connection of three external capacitors with a total capacitance of C_{block} = 67 nF was used. Figure 12 visualises all DC/impulse voltage combinations realised during the investigations. Each combination was applied n = 10 times. The tests were divided in a part with limited test voltages, where the commercial dividers were compared against the reference divider and a part with higher test voltages, where the commercial dividers were compared against each other.

Every investigated universal divider was used in combination with its respective transient recorder and corresponding evaluation software, thus forming a complete measurement system. For test voltages consisting of DC+LI the evaluated parameters include the DC voltage at the DUT U_0, LI amplitude U_t, front time T_1 and time to half-value T_2. For test voltages consisting of DC+SI, the evaluated parameters include the DC voltage U_0, SI peak voltage U_p, time to peak T_p and time to half-value T_2 (Figure 11). The mean error for each evaluated quantity (ΔU_0, ΔU_t, ΔT_1 etc.) was then calculated as the average over n = 10 test voltage applications.

As the result both commercial measurement systems exhibit a slight deviation from the reference system with regard to all mean errors investigated. However, for test voltages consisting of DC+LI as well as for DC+SI, the mean errors are on average nearly constant (Tables 3 and 4) and rarely exceed the limit of 1 % with respect to the voltage parameters and the limit of 2 % with respect to the time parameters.

Table 3: Average mean errors in % (DC+LI)

	ΔU_0	ΔU_t	ΔT_1	ΔT_2
Com1 – Ref	n. a.	-0.38	-1.51	0.08
Com2 – Ref	0.53	-0.76	0.55	1.75
Com1 – Com2	n. a.	0.18	-3.60	-1.32

Table 4: Average mean errors in % (DC+SI)

	ΔU_0	ΔU_p	ΔT_p	ΔT_2
Com1 – Ref	n. a.	-0.5	-1.14	0.12
Com2 – Ref	0.39	-0.07	-1.08	0.21
Com1 – Com2	n. a.	-0.43	-1.37	-0.09

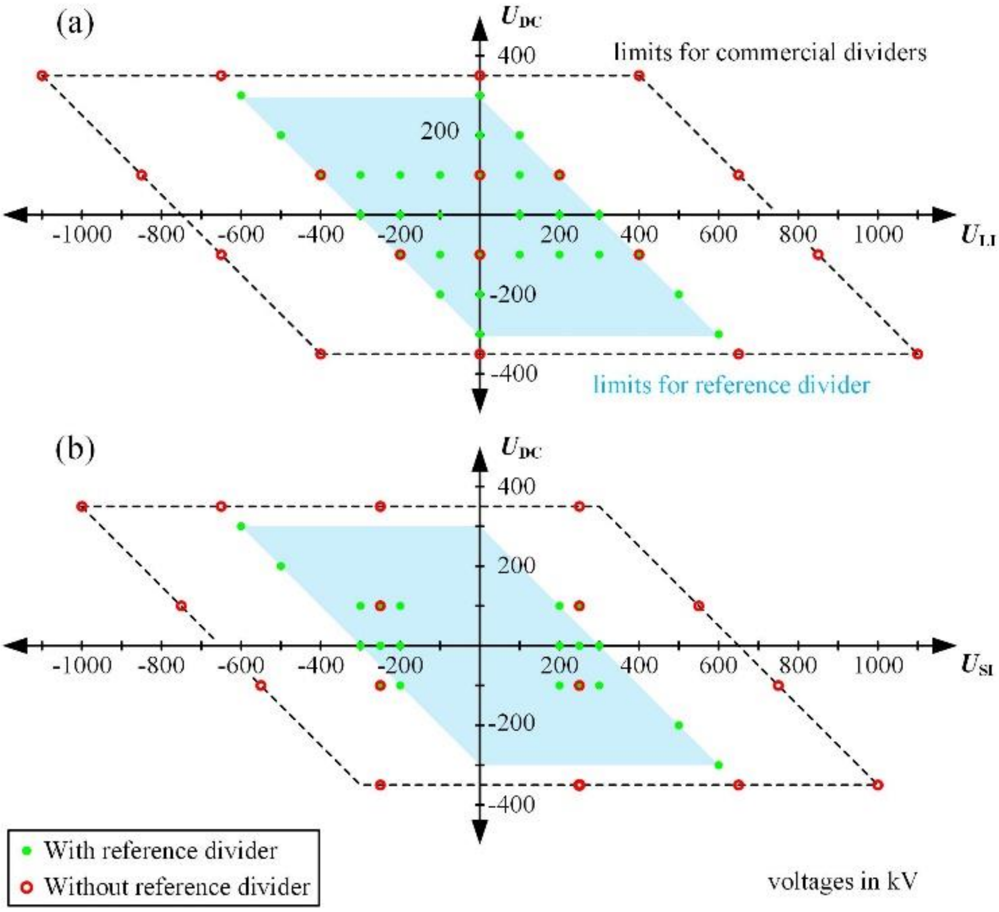


Figure 11: Applied voltage combinations

Similar results were obtained when comparing the commercial dividers with each other in the extended voltage range. Only the deviations concerning U_0 and T_1 are slightly higher. With regard to ΔU_0 the increased deviation can be explained by a differing time synchronisation of the measurements. With regard to ΔT_1, the influence of the temporal resolution on the error calculation must be taken into account, e.g. a difference of 20 ns already leads to a deviation of 1.7 %.

To generate the needed superimposed voltages in the laboratory at Technische Universität Dresden (TUD) a twelve-stage Marx generator and a three-stage Greinacher cascade are connected to the reference and two commercial voltage dividers. The Marx generator is divided in two parts. The upper six stages constitute the blocking capacitor with $C_{bl} \approx 83.3$ nF (Figure 12). While the other six stages are configured to generate the impulse voltages according to the standard. The voltage forming stages have a total impulse capacitance of $C_D \approx 83.3$ nF. The capacitive voltage divider at the impulse voltage generator, which also forms the external load capacitance, measures the impulse voltage at the impulse voltage generator with an effective capacity of $C_{LIG} \approx 1.8$ nF. The Greinacher Cascade has in the first stage a booster capacitance of $C_{B1} \approx 72$ nF. The other smoothing and booster capacitances have $C_S \approx C_B \approx 35$ nF. An ohmic voltage divider with an effective resistance $R_{DC} \approx 2.4$ GΩ measures the DC voltage at the Greinacher cascade. The DC voltage is connected via a protection resistor $R_W \approx 7$ MΩ to the test object, in this case the reference and commercial voltage dividers. The measurement campaign at TUD was carried out by TUD, TUG and PTB.

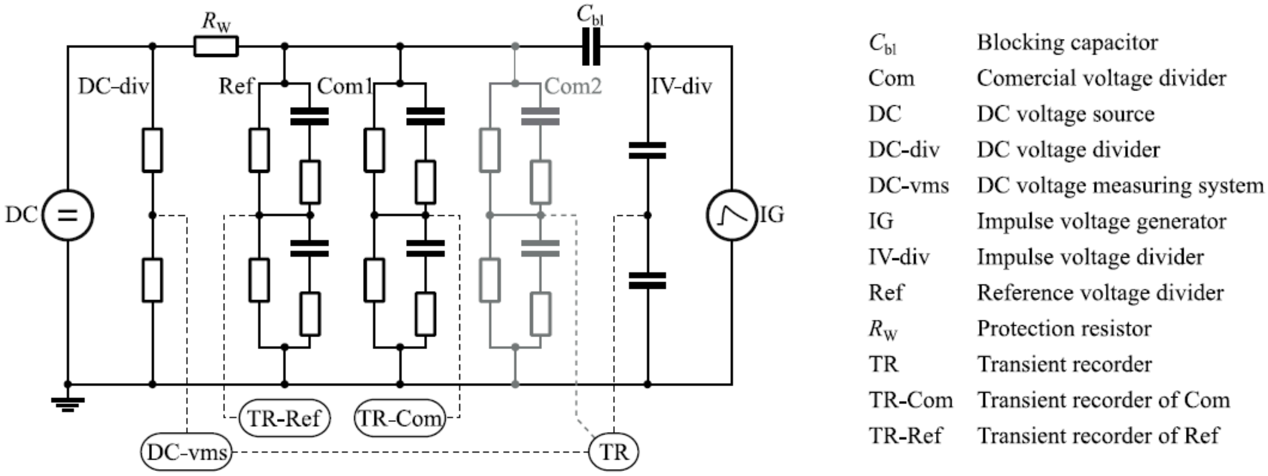


Figure 12: Test circuit according to IEC 60060-1 to superimpose impulse and DC voltage (TUD)

The first commercial voltage divider Com1, also a universal voltage divider, was utilised in the high-voltage laboratories at the Technische Universität Graz (TUG) and Technische Universität Dresden (TUD). The second commercial divider Com2 that was used was different at Graz and Dresden. The measurements of this divider are not relevant for this investigation. Additionally in Graz the values of the blocking and coupling elements were $R_W \approx$ 15 MΩ and $C_{bl} \approx$ 66.6 nF. Also, a different Marx Generator and DC voltage supply were used. A central electrode distributes the voltage to ensure that all universal voltage dividers receive the same voltage (Figure 13).

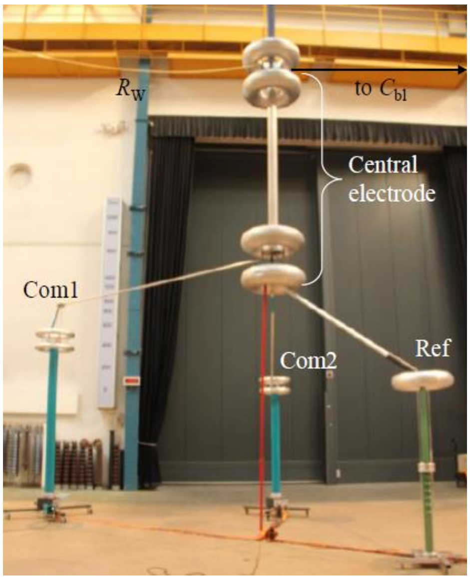


Figure 13: Arrangement of the voltage dividers (TUD)

The performed investigations conclusively demonstrate 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. 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 %. The major outcome of this work is the verification of the capability of commercial measurement systems for use in composite and combined testing. Based on the comparison of the new reference measurement systems of the NMIs and the systems already available on the market, additional procedures for future calibrations could be defined and handed over to TC42 in the form of the revision of the IEC60060 series of standards. This objective has thus been optimally fulfilled.

Summary

Objective 2 was achieved, as 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. 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 %. These results have been included in the ongoing revision of IEC 60060-1 and IEC 60060-2. Current measurement systems on the market for high superimposed voltage wave forms are mostly based on a universal divider and a transient recorder with characteristics described in IEC 61083 series. In the context of the comparison measurements described above, these systems achieved the targets in terms of measurement accuracy and are suitable for the measurement of superimposed voltage waveforms.

Objective 3 (D4)

The current IEC 60060 series standards allow voltage dividers and measuring systems used in testing 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 combined and composite wave shapes. Furthermore, the AC/DC and LI/SI generation circuits do interfere with one another. For qualification of the existing voltage dividers and measuring systems described above the development of traceable measurement systems for composite and combined wave shapes was necessary. Therefore, a universal divider with bandwidth ranging from DC up to approx. 10 MHz was designed and constructed by PTB, VTT, TUG, FFII, RISE, LNE, TUBITAK, INRIM, TAU, HAEFELY. The obvious solution presented in the literature is the parallel RC divider, with additional damping in the capacitive branch. In practice, both damped capacitive and resistive dividers are in the same unit, with their scale factors matched with each other. Large capacitance is preferred in order to minimise the inevitable proximity effect typical for high voltage dividers. Contradicting requirements come from the fact that excessive loading of the test transformer should be avoided, and from the need to keep the size and cost of the divider reasonable. The current for high voltage DC divider resistive branch is typically limited between 100 µA and 1 A, which keeps the self-heating effect at a reasonable level. Lower current might lead to problems with displacement or leakage currents. To match the output voltage level with the digital recorders commonly used for high voltage calibration, a nominal scale factor of 1000 was chosen, which leads to a maximum output voltage of 100 V. The low-voltage arm of the divider also includes a series matching resistor to prevent excessive distortion due to reflections on the measuring cable. The main design parameters of the divider are shown in Table 5 and the principal schematic diagram in Figure 14. This design is in principle that of a damped capacitive divider with an additional parallel branch to handle the DC component.

Table 5: Nominal characteristics of the divider module

Withstand voltage:	100 kV
HV capacitance (*C*in):	850 pF
HV resistance (*R*in):	600 MΩ
Output voltage (*U*out):	100 V
Load impedance (*R*meter):	1 MΩ
Insulation:	Air

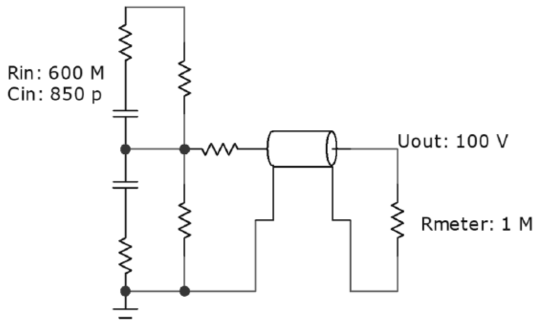


Figure 14: The principal schematic of the universal divider showing the parallel damped capacitive and resistive branches. The divider assumes a measuring instrument with 1 MΩ input resistance (R_{meter})

The main requirements for the reference divider capacitor are low temperature and voltage coefficient. The capacitor should also have a high dV/dt rating to cope with impulse voltages; it should withstand repeated charging from zero to full voltage in approx. 1 µs without degradation. Losses of the capacitor should also be low enough, so that long time application of the high voltage AC does not lead to degradation due to self-heating. Selection of high voltage NP0 ceramic capacitors with a large enough capacitance value is not as wide as that of PP foil capacitors. However, their low dissipation factor and low temperature coefficient ($\pm 30\ 10^{-6}\ K^{-1}$) together with a smaller size for the same capacitance-voltage product led us to go for this solution, regardless of its slightly higher price. Surface mount capacitors with a 1 kV nominal voltage were chosen and connected massively in series and parallel. Such capacitors are available off-the-shelf. The damping resistance has a twofold purpose. On one hand it damps the oscillations in the high-voltage circuit, and on the other hand it limits the current surge on the capacitors in case of sparkover. The main requirements for this resistance are that it should be able to absorb the energy stored in the capacitor, without overheating, temporarily (for approx. 100 ns) withstand the full voltage applied to the divider during sparkover, and withstand continuous application of a nominal AC voltage. In our case the consortium ended up looking for an approx. 1 Ω resistance with a 100 mJ energy capability to be connected in series to each 1 kV capacitor section. Again, suitable bulk metal foil resistors in a surface mount package were found to be available off-the-shelf. The main requirement for the DC resistor was again its low temperature coefficient. The possible voltage coefficient, which is typical for film resistors, can be corrected for. Series coupling of 200-V surface mount film resistors with nominal TC of $\pm 25\cdot 10^{-6}$ K-1 was found to be a good compromise between price and performance. The high voltage PCB boards are shown in Figure 15.

The low-voltage arm is built into a small box, which is connected to the high voltage arm with an N-connector. The nominal output voltage is 100 V, and the capacitive branch components have a coaxial structure to minimise the inductance and interference pickup. The low-voltage arms are shown in Figure 16.

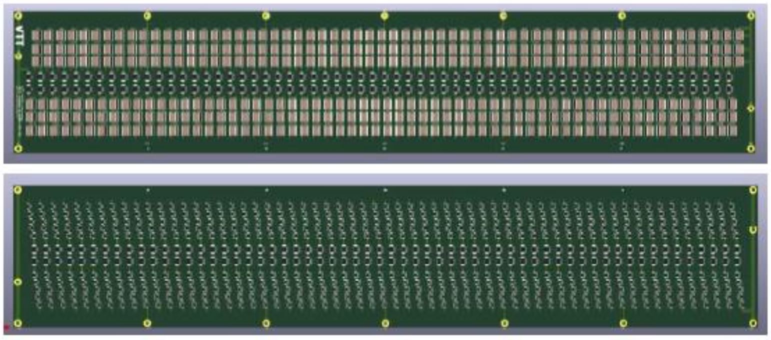


Figure 15: The top and bottom sides of the 500 mm long PCB board. Nominal maximum voltage of the board is 100 kV.

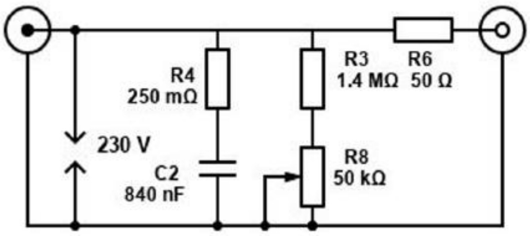


Figure 16: Low voltage arm of the divider. R8 is used to adjust the DC scale factor until it is equal to the AC scale factor.

The number of capacitors on one board is 360. Some early failures have been observed, c. 1 out of 1000 capacitors, during initial energising of the boards. However, as the system is air insulated it is easy to find the failing component and replace it. Two adjustments are needed for optimising the divider frequency response. After selecting the measurement cable type and length, the capacitive ratio is fixed. The damped capacitive branch time constant in the low voltage arm is slightly larger than that of the high-voltage arm, and the resistance of an additional damping resistor in the high voltage circuit needs to be adjusted for the best response in <1 µs range. The resistive ratio is then matched with the capacitive ratio, measured e.g. at 50 Hz, by using the trimmer resistor in the low voltage arm to set the DC ratio to match with the measured AC ratio. In addition to DC, AC, LI and SI voltage measuring systems, the divider can also be used for the calibration of the universal dividers used during combined and composite voltage testing. First characterisation tests show that the measurement uncertainty is lower than 0.1 % for the test voltage value for all voltage types, when two modules are used to build a 200 kV system. For a full characterisation of the new reference universal divider a comparison campaign was scheduled, where reference measuring systems of VTT, PTB, INRIM, TUBITAK, TAU, RISE, FFII, TUG and Haefely for single voltage shapes were used as references in a superimposed circuit. These single shape reference measuring systems were characterised before. After the characterisation of the entire new modular universal voltage divider, comprising 4 modules, the system was ready for the measuring campaign. In parallel, the design of the setups for the generation and measurement of both combined and composite wave shapes at PTB was completed.

From the 27th of June until the 8th of July 2022 the measurement campaign was carried out at PTB's high-voltage laboratory. PTB, VTT, RISE, FFII and TUG took part in it. An example test setup is presented in Figure 17. Our main interest was to compare the parameters of the two voltage components of the composite or combined voltages since the value of the test voltage is based on addition or subtraction of these values. The used test voltages are a combination of AC/DC and lightning impulse (LI) or switching impulse (SI).

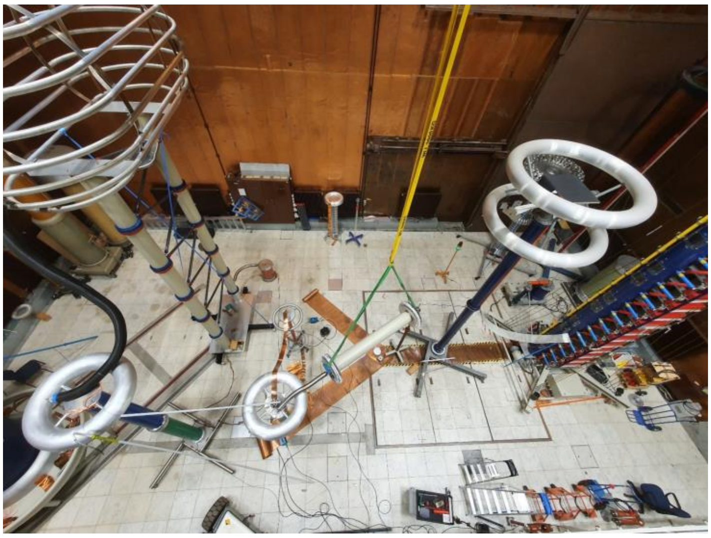


Figure 17: Test setup for composite voltage measurements (DC+impulse). Coupling capacitor hanging from the ceiling is used to protect the impulse generator (right) from the DC voltage (left).

Three measurement systems were used in this comparison campaign. Measurement system based on the new modular universal voltage divider is called System I. The measurement system based on the existing RISE voltage divider is called System II, and the system based on the existing PTB voltage divider is called System III. All the systems were placed in the test setup parallel so that they were all measuring simultaneously (see Figure 18).

Figure 18: Test setup for combined testing (AC+LI). Left in the front: New modular universal voltage divider, New modular universal voltage divider consisting of four 100 kV modules. FFII digitizer is located next to the divider (right side)

Besides the systems under comparison, the above-mentioned single shape measuring systems were used to measure the impulse voltages, AC/DC, and the voltage across the blocking element. These systems were used only for informative purposes to adjust the voltage components according to the test plan. The voltage divider of system I consisted of four 100 kV RCR divider modules that were built in this project. Each tube has two 100 kV modules inside, as seen in Figure 19. Two of the modules were tested and characterised in Finland before the campaign by TAU and VTT. Two other modules were tested and characterised by PTB. The voltage divider was used with a digitizer and software developed by FFII. This universal measurement system can measure DC voltages up to 400 kV, AC voltages up to a 400 kV peak and LI/SI voltages up to 400 kV.

The combination of four modules, the used cable, and the input impedance of the digitizer/attenuator used will affect the AC scale factor of the divider. Therefore, the resistance of the low-voltage arm needed to be adjusted to match the DC scale factor to AC scale factor. The RC time constant of the high-voltage arm was also changed due to the combination of four modules. Therefore, the external damping resistor was adjusted to get a proper step response. Both modifications were performed during a PTB campaign before starting the measurements. Based on the characterisation of the new modular universal voltage divider the estimated uncertainty (k = 2) for the two composite voltages DC+LI and DC+SI is 0.5 % for all voltage parameters and 2 % for all time parameters. Measurements with composite DC and LI was carried out with the test plan presented in Table 6.

Table 6: Test plan for composite DC and LI

Case	Nominal DC [kV]	Nominal LI [kV]	Results
1	100	100	Mean value for each parameter was calculated based on the results of the three systems. Each system's deviation from the mean value was observed. The highest observed deviations from the mean values were 0.5 % for DC voltage (system I), 0.7 % for U_t (system II), 3.6 % for T_1 (system I) and 0.7 % for T_2 (system II). Systems II and III showed better agreement with DC while having the largest difference below 0.2 %. All the measuring systems agreed with the mean value within the uncertainty requirements of DC and LI reference measurement systems given in IEC 60060-2:2010. The uncertainty requirements for test voltages are 1 % and for time parameters it is 5 %.
2	0	300	
3	0	-300	
4	150	-300	
5	150	150	
6	300	-300	
7	300	-300	

Measurements with composite DC and SI was carried out with the test plan presented in Table 7.

Table 7. Test plan for composite DC and SI

Case	Nominal DC [kV]	Nominal SI [kV]	Results
8	0	270	Mean value for each parameter was calculated based on the results of the three systems. Each system's deviation from the mean value was observed. The highest observed deviations from the mean values were 0.1 % for DC voltage (system II), 0.7 % for U_p (system III), 1.8 % for T_p (system I) and 0.3 % for T_2 (system II). All the measuring systems agreed with the mean value within the requirements of DC and SI measurement systems given in IEC 60060-2:2010. The uncertainty requirements for test voltages are 1 % and for time parameters 5 %.
9	150	150	
10	150	-270	

Measurements with composite AC and LI was carried out with the test plan presented in Table 8. System III was not used in this comparison.

Table 8. Test plan for composite AC and LI

Case	Nominal AC [kV]	Nominal LI [kV]	Results
11	50	100	Mean value for each parameter was calculated based on the results of the three systems. Each system's deviation from the mean value was observed. The highest observed deviations from the mean values were 0.6 % for AC rms voltage, 0.2 % for U_t, 0.8 % for T_1 and 0.9 % for T_2. All the measuring systems agreed with the mean value within the requirements of DC and LI measurement systems given in IEC 60060-2:2010. The uncertainty requirements for test voltages are 1 % and for time parameters 5 %.
12	50	200	
13	50	-200	

Measurements with composite AC and SI was carried out with the test plan presented in Table 9 9. System III was not used in this comparison. Results are presented in Annex 2.

Table 9. Test plan for composite AC and SI

Case	Nominal AC [kV]	Nominal SI [kV]	Results
14	30	100	Mean value for each parameter was calculated based on the results of the three systems. Each system's deviation from the mean value was observed. The highest observed deviations from the mean values were 0.6 % for AC rms voltage, 0.5 % for U_p, 1.0 % for T_p and 0.6 % for T_2. All the measuring systems agreed with the mean value within the requirements of AC and SI measurement systems given in IEC 60060-2:2010. The uncertainty requirements for test voltages are 1 % and for time parameters 5 %.
15	30	200	
16	30	-200	

Combined measurements were carried out to test the measuring systems for combined voltage measurements. A commercial vacuum interrupter was used as a test object. AC voltage was measured using the voltage divider from system III and the LI voltage was measured using the voltage divider from system I. Both dividers were used together with the digitizer from system I. System II was used to monitor either the AC or LI terminal. Measurements with composite AC and SI was carried out with LI voltages from -100 kV to +100 kV and an AC voltage of 30 kV. The measurement systems worked with combined testing without any issues.

Summary

With the results from the newly developed measurement systems including a wideband modular reference divider, low voltage measuring systems and software, objective 3 is successfully completed. The characterisation of the new measurement systems enabled both the measurement campaigns at TUG and TUD (objective 2) and the development of calibration capabilities at the NMIs. The development of the new measurement systems was thus the basis for the achievement of all project objectives.

Objective 4

The definitions and parameters of high voltage tests are described in 60060-1 as mentioned in objective 1. The requirements for approved measuring systems, mainly the voltage dividers, reference measuring systems and their calibration are described in IEC 60060-2, but limited to the most commonly used types of test voltages like DC, AC, LI and SI. In addition, the digital recording devices are described in the series IEC 61083 and here, the differentiation is made between the hardware and software. IEC 61083-1 describes the requirements for instruments for impulse tests, IEC 61083-2 describes the requirements for software for tests with impulse voltages and currents and here a revision is under preparation. Part 3 of IEC 61083 describes the requirements for hardware for tests with alternating and direct voltages and currents. As an analogue to part 2, the part 4 will describe the requirements for software for tests with alternating and direct currents and voltages and this document is under consideration within the Working Group TC 42 WG 20. For the combined and composite test voltages no adequate traceability of these wave shapes existed before this project.

During the project and the technical elaboration of the objectives, all project the consortium participated in meetings of the working groups and maintenance teams of IEC TC42 and reported the results obtained. Additionally, the consortium prepared two recommendation reports, one for the ongoing revision of IEC 60060-1 and one for the ongoing revision of IEC 60060-2. These recommendation reports were provided to MT04 and MT03 of IEC TC 42 for the ongoing revision of the standard. The results were reviewed together with both conveners and the obtained information including the existing and new composite and combined wave shapes' parameters and how to measure them properly were included in the revision of the standard. In order to create new standardised parameters, the consortium discussed with experienced industrialists in the field of high-voltage testing to understand well some phenomena related to the superposition of waveforms. Based on the consortium's knowledge, and results from tasks related to the evaluation software, new parameters were studied and new phenomena were explained. In 2022, a new version of the recommendation report for both 60060-1 and 60060-2 was finished and more relevant project results were incorporated into it. These reports were provided to TC42 in time for the next review processes of the standards. Now both revisions are in the CDV status and are expected to be published soon.

The consortium put great effort into the development of standardised definitions for combined and composite test voltages. As there is no adequate traceability of these wave shapes, the technical understanding of the generation and measurement in such voltage test circuits has been provided. The test voltage parameters of the voltage components and the combined and composite voltages across the test object are defined in a horizontal standard IEC 60060-1 including the allowed tolerances. Some definitions found in this project are already transferred to the relevant MT 04 of TC 42 and have been taken into account within the comments of the National Committees to the CD. The structure of the future IEC 60060-1 will contain two new chapters, one for tests with combined voltages and one for tests with composite voltages.

For the combined and composite voltage measurement, several measuring instruments from national laboratories have been characterised in this project, following requirements defined in IEC 61083-1. The measuring instruments characterisation led to methods and a measurement uncertainty budget that are used in the calibration uncertainty determination of the digital recorders. A comparison of the characterised measuring instruments using one reference low voltage calibrator will give input into the forthcoming revision of IEC 61083-1. In addition, the evaluation software that were developed are ready to be used with approved digital recorders for the evaluation of combined and composite wave shapes.

A comparison of the developed evaluation software to define the uncertainty related to parameter evaluation of combined and composite voltages was based on actual recorded test voltages from different test laboratories. The evaluation results have been used for the input into the forthcoming revision of IEC 61083-2. The evaluated recordings were defined as the standard voltage wave shapes for the standard and can be used as a basis for the future versions of Test Data Generators (TDG), for example, the one delivered with IEC 61083-2.

Recommendation Report for the Review of IEC 60060-1

In Recommendation Report I, a new structure of combined and composite related clauses was given. Additionally, a similar structure for LI and SI clauses was suggested. Furthermore, the following definitions have been updated or suggested:

- A new circuit diagram for the combined voltage setup
- A new circuit diagram for the composite voltage setup
- Calculation of the value of the test voltages
- Definition of the value of the test voltage

- Definition of impulse peak to ground $U_{\text{peak-to-ground}}$
- Definition of the time delay Δt
- Definition of the voltage change
- Tolerances for the test voltage
- Measurement of AC with impulse
- Measurement of DC with impulse

Most of the recommendations were adopted by the standardisation committee and used as a basis for the currently published 42/414/CDV. For this reason, the objective has been optimally completed and the goals set have been achieved.

Recommendation Report for the Review of IEC 60060-2
In Recommendation Report II, two new clauses for combined and composite were proposed. Both new clauses are similar in their structure to the clauses for LI and SI. Th following is the proposal for two new chapters of combined and composite related clauses.

10 Measurement of combined voltage
10.1. Requirements for an approved measuring system
10.1.1 General
The general requirements are:

- to measure the voltage components from the two energised terminals with relevant parameters according to IEC 60060-1 with an expanded uncertainty that is relevant to the applied test voltage described in the relevant clauses of this standard;
- to measure the value of the test voltage according to IEC 60060-1 with an expanded uncertainty $U_{M1} \leq 5$ %;

  HV-com²-consortium comment: Here we measure the difference of the two voltages. If we combine two 3 % components we get 4.2 % that can be rounded to 5 %.

- to measure the value of the impulse peak to ground according to IEC 60060-1 with an expanded uncertainty $U_{M2} \leq 3$ %;
- if applicable to the test, to measure the voltage change according to IEC 60060-1 with an expanded uncertainty $U_{M3} \leq 3$ % relative to the applied AC or DC voltage;
- if applicable to the test, to measure the time delay Δt according to IEC 60060-1 with an expanded uncertainty $U_{M4} \leq 10$ µs;

  HV-com²-consortium comment: see 9.3.1.2 of CD2 60060-1 Ed. 4.0 Version 2022-07-28.

10.1.2 Uncertainty contributions
For the used measuring system, the expanded uncertainty of measurement U_M shall be evaluated with a coverage probability of 95 %; according to the relevant clauses of this standard. Other contributions can be important in some cases and so shall be considered in addition.

10.1.3 Requirement for measuring systems
10.1.3.1 Requirement for measuring instruments
The measuring instrument shall comply with relevant parts of IEC 61083.
It is recommended to record the two voltage components by a two or three channel recording instrument according to IEC 61083-1 that enables the direct evaluation of the combined voltage from its two voltage components.

10.1.3.1.1 Measurement of AC with impulse

Two records on different sampling rates are recommended on the divider that is connected to terminal with applied AC test voltage. One record with low sampling rate, grabbing preferably a number of more than one full period before applied impulse for measurement of AC characteristics. Another record with fast sampling rate synchronized with impulse side recording, to enable correct measurement of voltage drop and evaluation of test voltage.

10.1.3.1.2 Measurement of DC with impulse

Two records on different sampling rates are recommended on the divider that is connected to terminal with applied DC test voltage. One record with low sampling rate, grabbing preferably one second before applied impulse for measurement of DC characteristics. Another record with fast sampling rate synchronized with impulse side recording, to enable correct measurement of voltage drop and evaluation of test voltage.

10.1.3.2 dynamic behaviour (use of universal divider)

The scale factors for AC or DC on one hand, and SI or LI on the other hand, shall match within 3 %.
HV-com²-consortium comment: This requirement is given for discussions, any comments are welcome.

10.1.4 Connection to the test object

If impulse voltages are applied, please follow the relevant guidance described in this standard on how to connect to the test object.
It is recommended to connect the converting devices as far as possible from the test circuit related to the opposite voltage terminal to reduce coupling through stray capacitances.

10.2 Tests on an approved measuring system

The measuring systems on both sides of a set up for combined voltage tests shall fulfil the requirements given in the respective clauses as shown in table 10 below.

Table 10. Requirements for test systems combined voltages

	Requirement for DC or AC side measurement				Requirement for impulse side measurement			
	DC clause 6	AC clause 7	LI clause 8	SI clause 9	DC clause 6	AC clause 7	LI clause 8	SI clause 9
DC + LI	X		X				X	
DC + SI	X			X				X
AC + LI		X	X			X	X	
AC + SI		X		X		X		X

HV-com²-consortium comment: This table is given for discussions, any comments are welcome
Note: Interference from the impulse generator on the AC or DC measuring system and/or from the AC generator on the impulse measuring system may have significant influence on the measured voltage drop.
HV-com²-consortium comment: Test should be made to enable reliable measurements, e.g. by energizing terminals one at a time keeping the other terminal de-energized and measuring the crosstalk signal from the de-energized terminal simultaneously. However, a good procedure is still missing.

10.3 Performance checks and tests on measuring systems

The performance checks and tests shall be performed ass shown in table above for different wave forms or voltage types.

11 Measurement of composite voltage

11.1 Requirements for an approved measuring system

11.1.1 General

It is generally recommended to use universal dividers as part of approved measuring systems. Calibration of approved measuring systems can be done in the form of separate calibrations for the necessary waveforms.
The general requirements are:

- to measure the composite voltage with relevant parameters according to IEC 60060-1 with an expanded uncertainty that is relevant to the applied test voltage described in the relevant clauses of this standard;
- to measure the value of the test voltage according to IEC 60060-1 with an expanded uncertainty U_{M1} ≤ 5 %;

  HV-com²-consortium comment: Here we measure the difference of the two voltages. If we combine two 3 % components we get 4.2 % that can be rounded to 5 %.

- to measure the value of the impulse peak to ground according to IEC 60060-1 with an expanded uncertainty U_{M2} ≤ 3 %;
- if applicable to the test, to measure the voltage change according to IEC 60060-1 with an expanded uncertainty U_{M3} ≤ 3 % relative to the applied AC or DC voltage;
- if applicable to the test, to measure the time delay Δt according to IEC 60060-1 with an expanded uncertainty U_{M4} ≤ 10 µs;

  HV-com²-consortium comment: see 9.3.1.2 of CD2 60060-1 Ed. 4.0 Version 2022-07-28.

11.1.2 Uncertainty contributions

For the used measuring system, the expanded uncertainty of measurement U_M shall be evaluated with a coverage probability of 95 %; according to the relevant clauses of this standard. Other contributions can be important in some cases and so shall be considered in addition.

11.1.3 Requirement for measuring systems

11.1.3.1 Requirement for measuring instruments

The measuring instrument shall comply with relevant parts of IEC 61083.

11.1.3.1.1 Measurement of AC with impulse

The evaluation of the DC characteristics can be done by using preferably a number of more than one full period of the recorded waveshape before applied impulse.

11.1.3.1.2 Measurement of DC with impulse

The evaluation of the DC characteristics can be done by using preferably one second of the recorded waveshape before applied impulse.

11.1.3.2 dynamic behaviour

If the individually calibrated scale factors of the separate wave forms vary more than the measurement uncertainty of the voltage parameters, the user of the system must make the necessary corrections.
HV-com²-consortium comment: This requirement is given for discussions, any comments are welcome.

11.1.4 Connection to the test object

If impulse voltages are applied, please follow the relevant guidance described in this standard on how to connect to the test object.
It is recommended to connect the converting devices as far as possible from the test circuit related to the opposite voltage terminal to reduce coupling through stray capacitances.

11.2 Tests on an approved measuring system

The measuring systems for composite voltage tests shall fulfil the requirements given in the respective clauses as shown in table 11 below.

Table 11. Requirements for test systems composite voltage tests

	Requirement for an approved measuring system			
	DC clause 6	AC clause 7	LI clause 8	SI clause 9
DC + LI	X		X	
DC + SI	X			X
AC + LI		X	X	
AC + SI		X		X

HV-com²-consortium comment: This table is given for discussions, any comments are welcome.

11.3 Performance checks and tests on measuring systems

The performance checks and tests shall be performed ass shown in table above for different wave forms or voltage types.

12 Measurement of composite voltage

12.2.2 Reference method: Comparative measurement

Add: In case of measuring systems with a universal divider for composite or combined wave forms, the calibrated scale factors for all necessary test voltage types should not differ more than 1 %, otherwise corrections shall be done.

Summary

Two recommendation reports were given to IEC TC 42 for the ongoing reviews of IEC 60060-1 and IEC 60060-2. Most of the recommendations were adopted by the standardisation committee and used as a basis for the currently published 42/416/CDV and 42/414/CDV. For this reason, the objective 4 has been optimally completed and the goals set have been achieved.

5 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.

6 List of publications

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https://doi.org/10.1007/s00202-021-01368-5

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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

Abderrahim Khamlichi, "Universal Measuring Unit for High Voltage Measurements", 27th Nordic Insulation Symposium, NORD-IS 2022
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https://oar.ptb.de/files/download/EMPIR.19NRM07.CA.20230119.pdf

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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://doi.org/10.5324/nordis.v27i1.4875

Serkan Dedeoglu/Ahmet Merev, "Realization of the reference composite voltage waveforms for lightning impulse (LI) voltages superimposed over DC and AC signals" Springer MAPAN-Journal of Metrology Society of India, 2023
https://link.springer.com/article/10.1007/s12647-023-00634-0
DOI: 10.1007/s12647-023-00634-0

Jari Hällström, "Design of a modular wideband high voltage reference divider", Conference on Precision Electromagnetic Measurements, CPEM 2022
https://doi.org/10.5281/zenodo.8131452

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/repository/research-publications-repository-link/

7 Contact details

The address of the project public website: https://www.ptb.de/empir2020/hv-com2/home/

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