Contribution to the standardisation of measurement of composite and combined high voltages

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SUMMARY

Besides the typical test voltages like DC, AC, lightning impulse (LI) and switching impulse (SI), combined and composed test voltages are of increasing interest. Combined test voltage is typical for disconnector tests where on both sides of the open contacts AC and impulse voltage will be applied. The elements between the two voltage sources and the test object are at the same time coupling and blocking elements which means that in one case they should transfer the voltage from one source and block the voltage from the other source. The use of high-voltage DC cables for transmission of power over long distances requires voltage tests with composite test voltage, where again coupling and blocking elements are very important components of the test circuit. The voltage measurement should be done with approved measuring systems which consist of converting devices and recording devices. For DC, AC, LI and SI voltages traceable reference divider are available, but for combined and composite test voltages not. Therefore, a European research project 19NRM07 HV-com² was established to develop traceable high-voltage reference dividers for combined and composite test voltages and also calibrators for approving digital recorders used in such a test circuit. The outcome of this project will be proposals for the revision of IEC 60060-1 and IEC 60060-2 whereby for part 1 some proposals are already available and will be taken into account in the discussion of the revision.

KEYWORDS Composite and combined test voltage, coupling/blocking elements, measurement of composite and combined voltages, calibrator for digital recorder

1 Introduction

High voltage equipment should be tested with voltages which simulate the voltage stress under service conditions, whereby the tests can be divided in type tests, routine tests (usually acceptance tests) and on-site tests. Depending on the voltage system these tests will be carried out with AC or DC and independent of the voltage system with lightning and switching impulse voltage. The last two voltage types should simulate the voltage stress at lightning activities, which is independent of the voltage level of the system and the voltage stress at switching operations, which depends on the performance of the switches, the system configuration and the distance between the switch and the stressed equipment. The insulation coordination defines the amplitude of the test voltage for the different types of test voltage and depending on the system voltage the surge arrestors for limiting the overvoltage can be evaluated [1]. The test voltage parameter relating amplitude, frequency, general test duration and time parameters are defined in a horizontal standard IEC 60060-1 including the allowed tolerances [2]. In order to evaluate the performance of high-voltage equipment one of the main tests is the withstand test, which means that a test is passed if no breakdown or a limited number of breakdowns within a given of voltage tests happens. However, the breakdown behaviour of insulation systems depends on physical parameters like air pressure, air temperature and air humidity. This should be noticed in the determination of the test voltage at the actual test procedure and the evaluation procedures are also defined in [2]. For the measurement of combined and composite test voltages are at the moment no reference measuring systems available which should also be traceable to national calibration laboratories.

2 Simple test voltages

The parameters for DC voltage are the amplitude of the test voltage with a ripple less than 3 % where the ripple is defined as half of the difference between the maximum and minimum voltage values. The measured values of the test voltage shall be maintained within ± 1 % of the specified level throughout the test if the test time is equal or less than 60 s, or within ± 3 % of the specified level throughout the test if the test time exceeds 60 s. The use of an approved measuring device is required, and attention is drawn to the requirements on the response characteristics of converting devices regarding ripple, transients or voltage stability [3].

The parameters for AC voltage are the frequency between 45 Hz and 65 Hz, the peak value (average of the magnitudes of the positive and negative peak values) and the root-mean-square (RMS) value of the voltage, the sinusoidal shape of the voltage, defined by the ratio of the peak to RMS value by $\sqrt{2}$ within ± 5 %. The measured values of the test voltage (peak value divided by $\sqrt{2}$) shall be maintained within ± 1 % of the specified level throughout the test if the test time is equal or less than 60 s, or within ± 3 % of the specified level throughout the test if the test time exceeds 60 s. The measurement of the value of the test voltage, the RMS value, and the transient drops shall be made with an approved measuring system [3].

The parameters for lightning impulse voltage (LI) are the extreme value, the evaluated test voltage including overshoot, and the time parameters as front time, time to half-value and time to chopping. The standard LI has a front time of 1,2 µs and a time to half-value of 50 µs. The tolerances are ± 3 % for the test voltage value, ± 30 % for the front time, and ± 20 % for the time to half-value. These tolerances shall be separated from the uncertainty of the measurement of the parameter. In the actual discussed revision of IEC 60060-1 the positive tolerance of the front time will be increased to 100 % for lightning impulse tests on equipment with a highest voltage for equipment Um above 800 kV [4]. The measurement of the value of the test voltage and the time parameters shall be made with an approved measuring system [3].

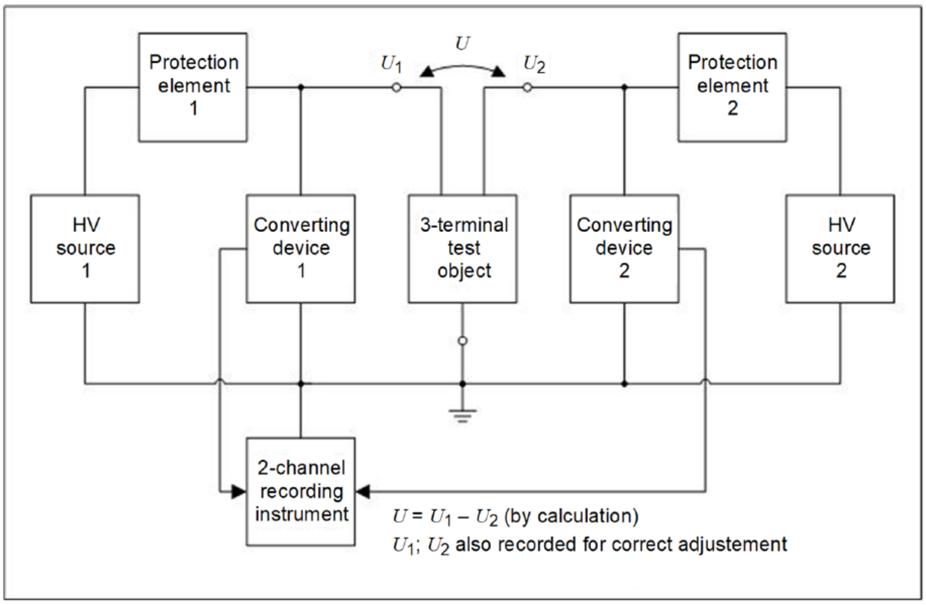
The parameters for switching impulse voltages (SI) are the test voltage and the time parameters as time to peak and time to half-value. The differentiation between LI and SI is the duration of the front time, a SI has a front time of 20 µs or longer. The standard SI has a front time of 250 µs and a time to half-value of 2500 µs. The basis for the front time is the knowledge that air gaps in the range of some meters show 3 a minimum of the breakdown voltage in this time range. The basis for the time to half-value is the simulation of a switching operation. The tolerance for the test voltage value is ± 3 %, same as for LI, and the tolerance for the time to peak is ± 20 % and for the time to half-value ± 60 %. Also, here the measurement of the value of the test voltage and the time parameters shall be made with an approved measuring system [3]. In the actual discussed revision of IEC 60060-1 is a proposal for the change of the time to peak parameter. Instead of time to peak the front time should be evaluated and used for the definition of a SI similar to the LI evaluation [4]. The measurement of the value of the test voltage and the time parameters shall be made with an approved measuring system [3].

3 Mixed test voltages

In [2] two mixed test voltages are described in one chapter, the combined and composite voltage. With both types it is common that two types of voltages are applied on the test object but the connection between the two sources and the test object is different and this has some consequences concerning the required elements in the test circuit and also in the connection of the measuring systems.

3.1 Combined voltage test

Combined voltages are applied for testing, for example, the longitudinal insulation of switching equipment and the phase-to-phase insulation of three-phase systems and equipment. The voltages are applied on different terminals of the test object. Relevant IEC recommendations are in [5] which is a collection of all recommendations under the number 62271 High-voltage switchgear and controlgear relevant for AC switching devices. Here the combined voltage test is used to check the performance of open contacts of a switching device where on one side e.g., an AC voltage is applied and on the other side an impulse voltage. Such a test arrangement is shown in Fig. 1.



IEC 2219/10

Fig. 1 Circuit for a combined voltage test [2]

Fig. 1 shows the two HV sources 1 and 2, the related protection elements 1 and 2, and the converting devices 1 and 2. The test object is a so called 3-terminal object, on two sides are the connected HV sources, and the third side is grounded. If no breakdown of the test object happens the two voltage sources are more or less separated depending on the character of the protection elements. In case of breakdown of the test object the opposite voltage source should be protected at least to an acceptable voltage stress. But which is not shown in Fig. 1 or mentioned in the recommendation is the function of coupling of the protection elements. The voltage from the protected voltage source should be transferred to the test object as much as possible and not limited by the protection element. These conditions are contrary and therefore an optimum for each test arrangement should be evaluated [6].

In [3] is determined that a measuring system shall be connected directly to the terminals of the test object, or in such a way that the voltage difference between test object terminals and the measuring system is negligible. The parasitic coupling between the testing and measuring circuit should be minimized. In Fig. 1 is clearly shown that the converting devices are behind the protection elements however the test voltages are not directly measured but calculated from the two voltages measured between high-voltage terminal and ground. Due to the mutual influences of the HV sources the combined test voltage across the test object has not the shape as expected from the single voltage sources and this should be taken into account and recorded by the converting devices. The following detailed description of the voltages in a combined voltage test with AC and SI is for an ideal circuit without coupling of voltages from one source to the other. Fig. 2a shows the signal from the AC HV source 1 recorded via the converting device 1. The amplitude of the AC voltage is U_0. Fig. 2b shows the signal from the impulse HV source 2 recorded via the converting device 2. The amplitude of the impulse voltage is 1,5 U_0. The impulse voltage is a SI for clarification of the combined test voltage. A LI would result in a thin vertical line if the same time scale would be used for both voltages.

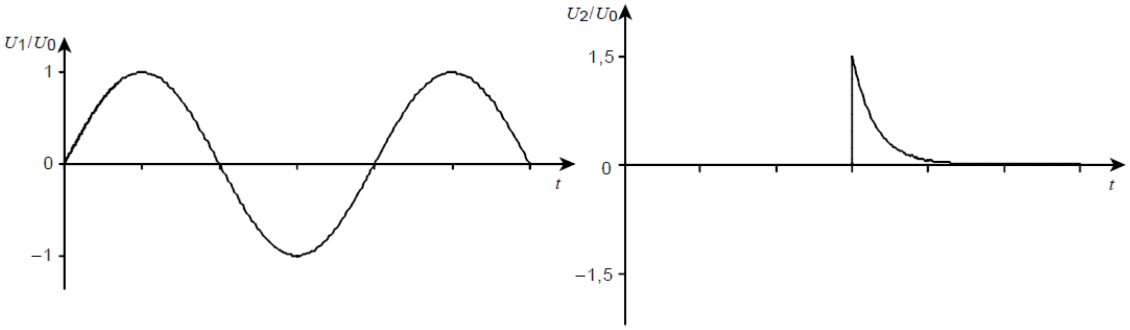


Fig. 2a **Fig. 2b**

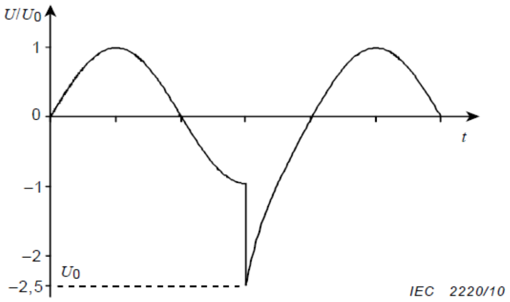
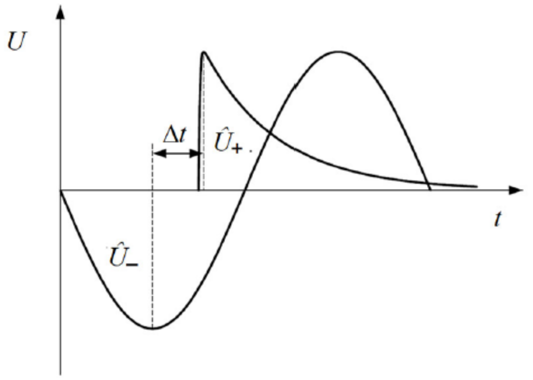


Fig. 2c

Fig. 2 Schematic example for combined voltage (AC + SI) [2]
a) AC voltage (HV source 1) b) - SI (HV source 2) – c) Test voltage

Fig. 2c shows the calculated combined voltage U which has a maximum value of - 2,5 U_0 according to the calculation $U = U_1 - U_2 = - U_0 - 1{,}5\ U_0 = - 2{,}5\ U_0$. The result of the calculation of the combined test voltage depends on the direction of the voltage arrow system. In the previous calculation is assumed that the voltage arrows start at the high voltage point and end at ground and that the calculation starts at point U_1 in Fig. 1. If the same kind of calculation starts at point U_2 the result will be $U = U_2 - U_1 = 1{,}5\ U_0 - (-U_0) = + 2{,}5\ U_0$. This means that the sign of the voltage can be misleading, but the voltage stress over the test object is 2,5 U_0: Another explanation is the direction of the change of potential. If the starting point is U_1 and the end point U_2 the potential will increase by 2,5 U_0, vice versa the potential will decrease by 2,5 U_0. This is also mentioned with the two heads of the voltage arrow in Fig.1.

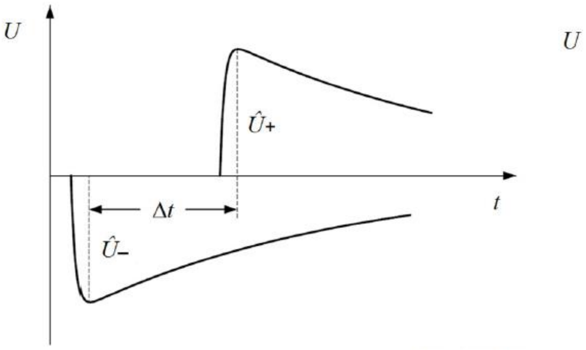
The combined test voltage generated by two voltage components shall be characterized by the following parameters, test voltage value, time delay and parameters of the two voltage components. Fig. 3 shows an example of the time delay of a combined test voltage with AC and SI. The reference voltage is again the AC voltage, because this in many test laboratories the reference value for the trigger of an impulse generator. Fig. 3 shows an example of a combined test voltage and again the reference voltage is the AC voltage.



IEC 2224/10

Fig. 3 Combination of SI and AC voltage [2]

The tolerances for the single voltage components should ± 5 % according to the proposal in [4]. The tolerance of the time delay is 5 % of the front time of an impulse or 5 % of a quarter of a cycle of an alternating voltage, which is the longer time of the two voltages involved. Another example for combined test voltages is the application of two impulses on both sides of the test object. This could be a special test for disconnector. Fig. 4 shows the voltage shape.



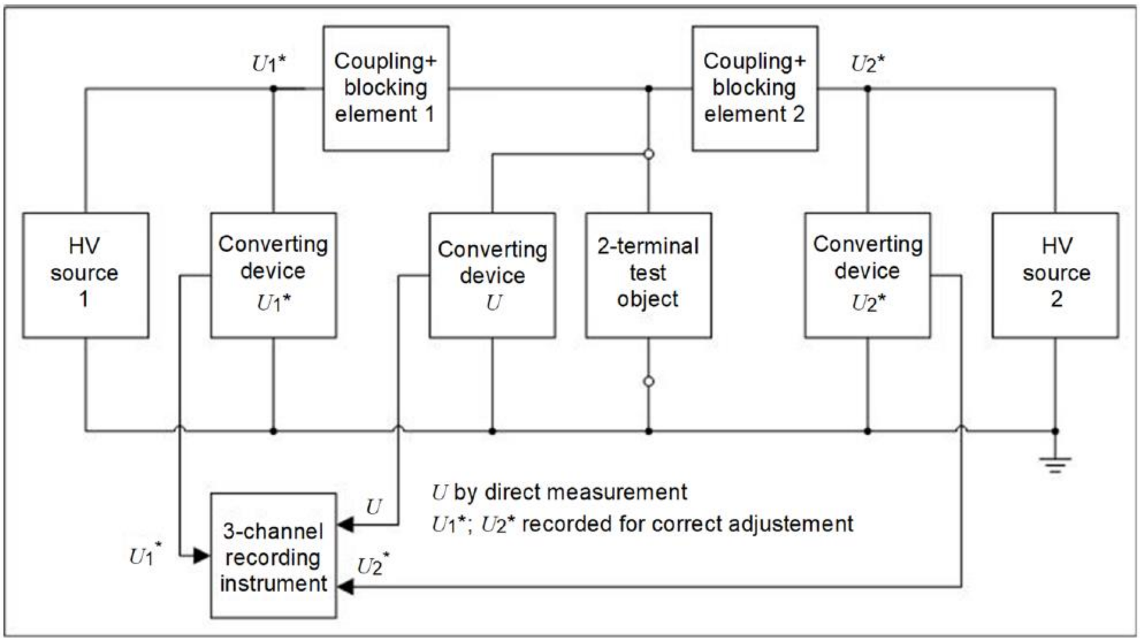
IEC 2223/10

Fig. 4 Combination of two impulses voltages [2]

Here is the peak of the first applied impulse voltage the reference point for Δt. Concerning the influence of one voltage source to the other the coupling of the two sources influences the shapes and amplitudes of the two voltage components and they will differ from those generated by the same sources used separately. The permitted limits for voltage dip on the other component shall be specified by the relevant Technical Committee.

3.2 Composite voltage tests

Composite voltage tests are applied on test objects where the two voltage sources are connected to a single high-voltage terminal point. A typical example is the composite voltage test on a high-voltage cable. This type of test is of increasing interest because cables are more and more used also for electric power transmission and here particularly the HVDC transmission systems with cables exists or are in planning up to voltages of 800 kV [7, 8]. Fig. 5 shows the test arrangement for a composite test. Here is already mentioned in the figure that the blocking elements have also the task of coupling of the relevant voltage source. The two voltage sources are permanently connected with each other and this requires a careful selection of the blocking/coupling elements. The relevant parameter is the impedance of these elements. In [6] are some information available concerning the selection of the locking/coupling elements and therefore only one example will be mentioned here. A capacitor between the impulse generator as one voltage source and the test object will transfer the impulse voltage more or less without any influence on the impulse voltage due to the low impedance of a capacitor at high frequencies. The voltage distribution depends on the capacitance of the coupling capacitor and the capacitance of the test object. If the other voltage source is a DC generator the coupling capacitor will block the DC voltage from the impulse generator due to its nearly infinite impedance for DC voltage. With an inductor as a coupling element between the DC voltage source and the test object the DC voltage is transferred to the test object without any influence as the impedance of an inductor at DC is nearly zero, but the impulse voltage will be blocked due to the high impedance of an inductor at high frequencies.



IEC 2222/10

Fig. 5 Circuit for a composite voltage test [2]

Concerning the voltage measurement on the test object the main difference to the combined voltage test is that the voltage across the test object can be directly measured and should not be calculated, but more recording channels are required for adjustment purposes. Fig. 6a shows the AC voltage which represents the voltage from HV source 1. Fig. 6b shows the SI generated by HV source 2. These two voltages are the original voltages generated by the HV sources without connection to the test object via coupling elements 1 and 2. For such a case the voltage U_1* and U_2* are identical with the voltages shown in Fig. 6a and 6b. The measured voltages U_1* and U_2* are very close to the voltages U_1 and U_2, shown in Fig. 6a and 6b assuming that the coupling and blocking elements have negligible influence on the AC and SI voltage.

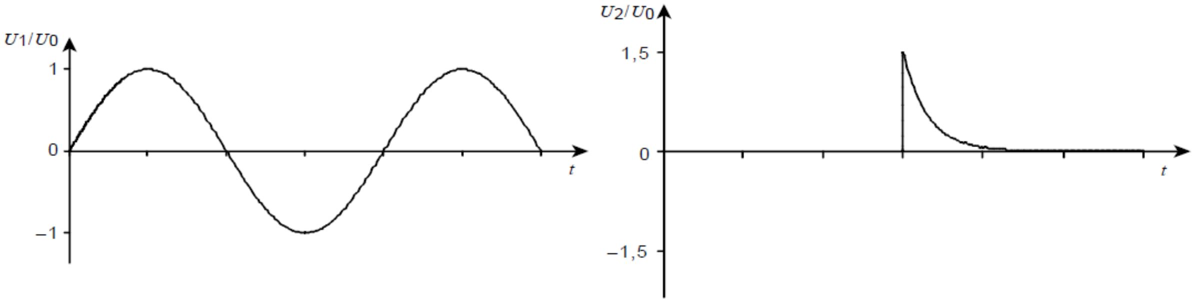


Fig. 6a **Fig. 6b**

Fig. 6 Schematic example for composite voltage (AC + SI) [2]
a) AC voltage (HV source 1) b) - SI (HV source 2)

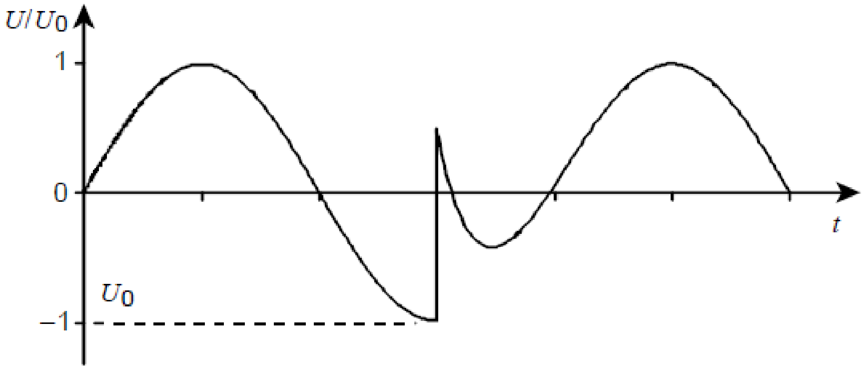


Fig. 7 Schematic example for composite voltage (AC + SI) [2]

Fig. 7 shows the voltage U across the test object which is more or less the sum of the U_1* and U_2*. Voltages U_1* and U_2* can be used for the adjustment of the single voltage components of the composite voltage, but they are not necessary for the evaluation of the voltage U across the test object, because this is directly measured by the recording system. The combination of the two voltages, AC and SI or two impulse voltages is similar to the combined tests and therefore they will not be discussed here. Also, the definition and the tolerances for the single voltage components and the delay time are the same as for combined tests (see Fig. 3 and 4).

Due to the increasing application of high-voltage DC cables two CIGRE Technical Brochures (TB 852 and TB 853) have been edited [7, 8]. Fig. 8 shows the different possibilities for a composite test with DC and impulse voltage, furthermore the variation of the impulse shape depending on the blocking/coupling elements, sphere gap or blocking capacitor. Fig. 8 shows the composition of a DC voltage and a lightning impulse with opposite polarity to the DC voltage.

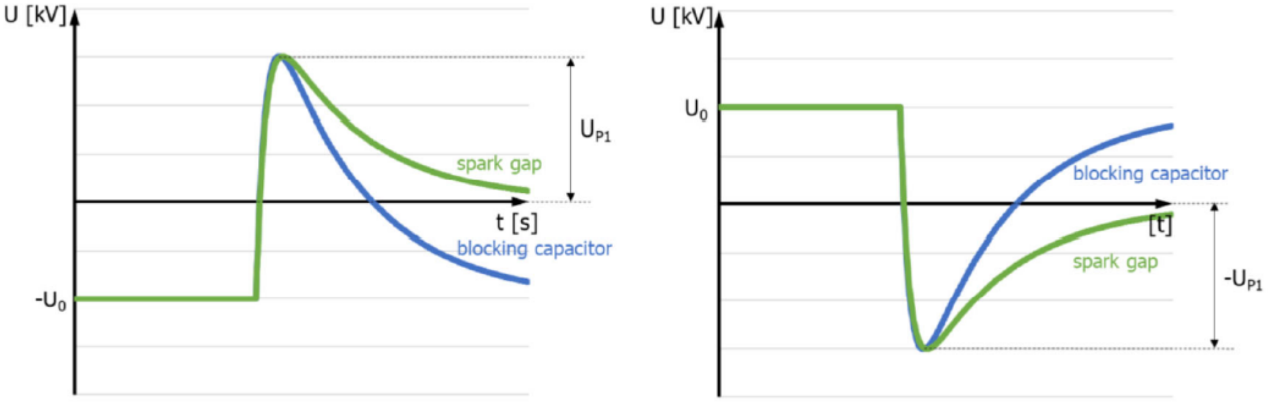


Fig. 8 Composite voltage with DC and LI [7]

The peak of the impulse voltage to ground is named as U_{p1} with a sign for positive or negative impulse polarity. The type of the converter technology, Line Commutated Converter (LCC) or Voltage Source Converter (VSC) has no influence on the composite test voltage.

Fig. 9 shows the composition of DC and SI for VSC with an SI of the same polarity and for LCC and VSC for an SI with opposite polarity. Here the peaks of the SI voltages are named as $U_{p2,S}$ for the same polarity (index S) and $U_{p2,O}$ for the opposite polarity (index O). A question could arise, which voltage is the test voltage. In left part of Fig. 9 the test voltage could be defined as DC plus SI. However, in the right part of Fig. 9 the applied voltage is DC minus SI and this results in - $U_{p2,O}$ which could also be the test voltage, but requires some explanations.

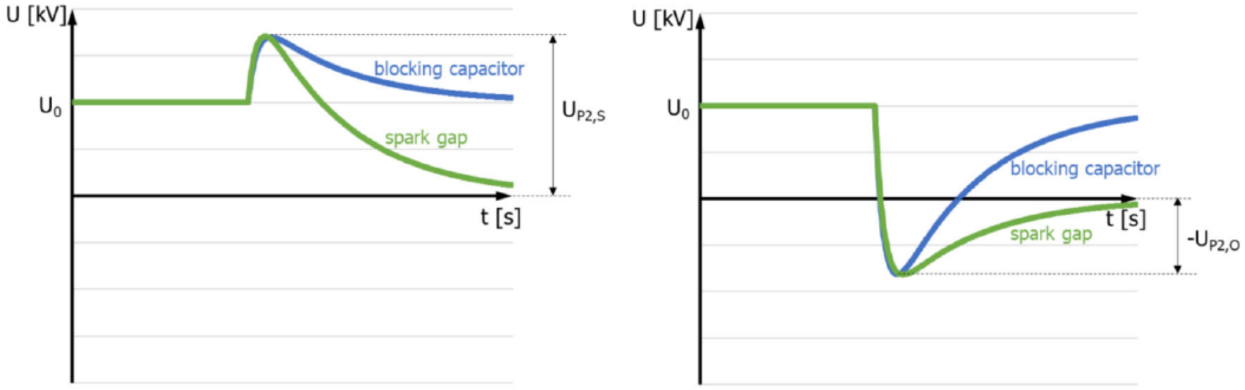


Fig. 9 Composite voltage with DC and SI [7]

Finally, the polarity of the DC voltage can be changed and the superimposed SI can be positive or negative. The results are similar with results in Fig. 9 only the signs of the voltages U_{p2} will change.

4 Measuring systems

As shown in Fig. 1 and 5 the measurement of the voltage components and the voltage across the test object is done by a converting device and a recording instrument, usual a digital recording instrument. The required performance of the measuring system depends on the voltage type or wave shape and should be carefully evaluated. In general, it can be stated that the measuring systems of the voltage components should be able to measure both components because in any case a part of the voltage will be coupled from one voltage source to other voltage source resp. measuring system. The converting devices should convert both types of voltages with the required uncertainty and the recording devices should be able to record both types of voltages with a required resolution in time and amplitude. Furthermore, the usually included software for the evaluation of the test voltage should also be able to evaluate the test voltage parameters with the required uncertainty. The requirements for approved measuring systems, mainly the converting device, reference measuring systems and its calibration are described in IEC 60060-2 [3], but limited to the most 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 [9], IEC 61083-2 describes the requirements for software for tests with impulse voltages and currents [10] and here a revision is under preparation. The part 3 of IEC 61083 describes the requirements for hardware for tests with alternating and direct voltages and currents [11]. 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 [12].

For the combined and composite test voltages no adequate traceability of these wave shapes exists and therefore the research project 19NRM07 HV-com² “Support for standardisation of high voltage testing with composite and combined wave shapes” within EMPIR was established.

5 Research project 19NRM07 HV-com²

The project will investigate the interaction of impulse voltages superimposed with AC and DC voltages enabling optimised test setups to be created. The uncertainty of existing measuring systems will be determined, and new systems and calibration capabilities will be created and validated through measurement campaigns. At the end of the project in 2023 the results will input into revision of existing standards, generate new European capabilities and improve the robustness of power grids to adverse operational events. The project is divided in three working parts, WP1 Definitions, software and instrumentation, WP2 Traceable reference systems, WP3 Existing measuring systems at testing laboratories.

In WP1, the consortium of the project has put a great effort on the development of standardized 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 described in chapter 3 are defined in a horizontal standard IEC 60060-1 including the allowed tolerances [2]. Some definitions found in this project are already transferred to the relevant MT 04 of TC 42 and will be taken into account within the comments of the National Committees to the CD [4]. Project results have already been incorporated into the review processes of IEC 60060-1 and IEC 60060-2. The structure of the future IEC 60060-1 should contain two new chapters, one for tests with combined voltages and one for tests with composite voltages.

The WP1 includes also solutions and measurement techniques for the generation of low voltage reference combined and composite wave shapes. Fig. 10, 11, and 12 shows circuit diagrams examples of low voltage calibrators developed in WP1 in order to be used to check the performance of digital recorders used for measurements of combined and composite voltage wave shapes.

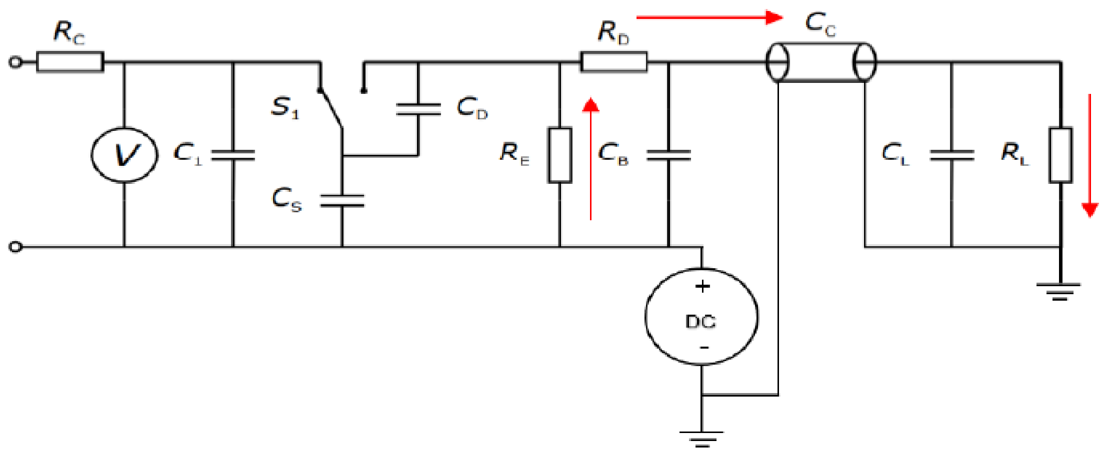


Fig. 10 Circuit diagram of a DC and an impulse voltage calibrator (series connection)

Fig. 10 shows a calculable impulse voltage calibrator design based on combining existing DC or AC calibrator with a calculable impulse voltage calibrator [16] to provide composite voltage wave shapes.

The capacitor C_S is charged to known voltage, and is discharged into the pulse-forming network by closing the relay S_1. The peak value and the time parameters are calculated from the measured values of the capacitors C_S and C_B and the resistors R_E and R_D of the impulse circuit. In addition, the charging voltage together with the input capacitance C_L and resistance R_L of the device under calibration have to be known. For the equivalent circuit, the charging resistor R_C, the voltmeter and filter capacitor C_L can be ignored because they are disconnected from the circuit when the relay is energized. The capacitor C_D, which dampens the switching surges, is shorted. The red arrows marked the relevant voltages.

Currently, the design has been tested with DC and LI/SI. Working with AC calibrator is currently underway due to work needed for synchronization of AC and impulse peaks.

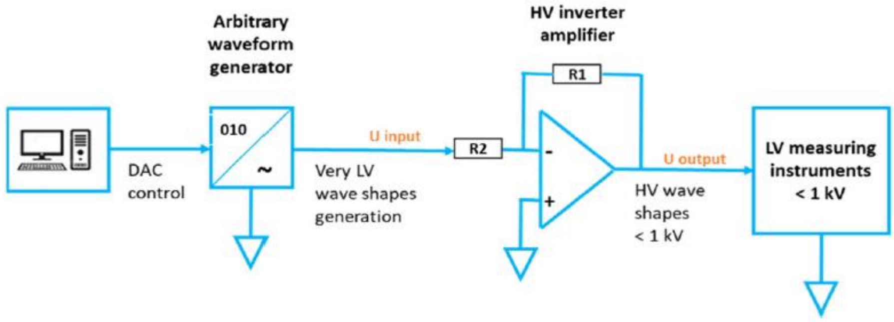


Fig. 11 Structure based on a HV inverter amplifier

Fig 11 shows a reference calibrator design based on a linear high voltage and high-speed amplifier [14] to be used to generate in only one block 900 V standard voltage wave shapes. Several methods have been investigated to ensure the calibrator traceability. Based on the test results, high metrological performances have been reached for both composite and combined voltage wave shapes.

Fig 12 shows a calibrator circuit diagram based on the combining existing DC or AC calibrator with an impulse voltage calibrator and using blocking elements. Currently, the design has been tested for composite voltage wave shapes. A further task will be a comparison of the developed low voltage calibrators in order to find requirements for their use. This comparison will be performed using an approved measuring instrument traceable to national calibration laboratories.

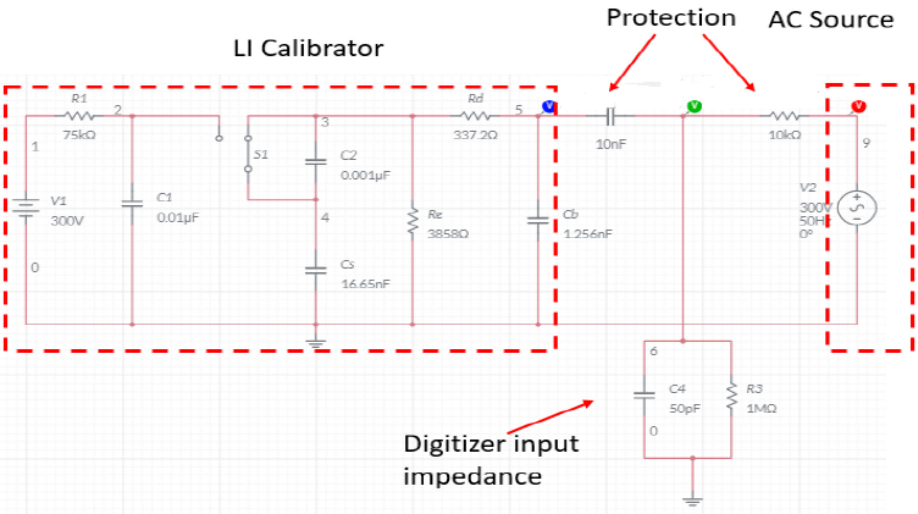


Fig. 12 Circuit diagram of an AC and an impulse voltage calibrator (Parallel connection)

For the combined and composite voltage measurement, several measuring instruments from national laboratories have been characterized in this project, following requirements defined in IEC 61083-1. The measuring instruments characterization led to methods and measurement uncertainty budget that can be used in the calibration uncertainty determination of the digital recorders. The next step will be a comparison of the characterized measuring instruments using one reference low voltage calibrator. The results will input into the forthcoming revision of IEC 61083-1 [9]. In addition, developed evaluation software are ready to be used with approved digital recorders for combined and composite wave shapes evaluation.

Fig. 13 shows an example of evaluation software interface developed in this project. A further task will be a comparison of the developed evaluation software to define the uncertainty related to parameter evaluation of combined and composite voltages. This comparison is based on actual recorded test voltages from different test laboratories. The evaluation results will input into the forthcoming revision of IEC 61083-2 [10]. 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 [10].

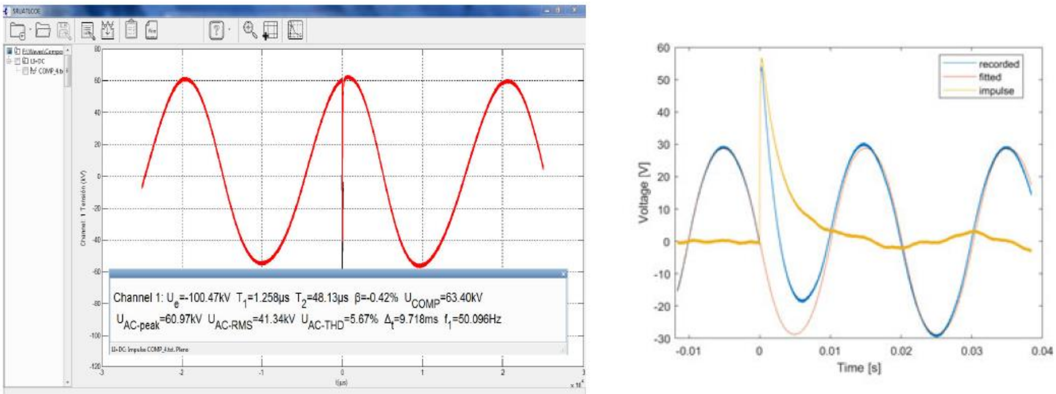

Channel 1: U_e=-100.47kV T_1=1.258µs T_2=48.13µs β=-0.42% U_{COMP}=63.40kV
$U_{AC\text{-}peak}$=60.97kV $U_{AC\text{-}RMS}$=41.34kV $U_{AC\text{-}THD}$=5.67% Δ_t=9.718ms f_1=50.096Hz

Fig. 13 Evaluation software interface example and composite voltage example with AC and SI

In WP2 a modular universal voltage divider will be developed and tested by the participating national calibration laboratories. The main design principles and component values have already been agreed based on simulations. Different types of components have been characterized to find the most suitable ones. Several divider prototypes using different types of capacitors have been built and characterized. Based on the test results four 100 kV voltage divider modules (Fig. 14) have been built and are currently under characterization to find their accuracy limits with AC, DC, LI, and SI.

The complete 400 kV voltage divider based on the four 100 kV modules will also be characterized. In parallel, existing universal voltage dividers used by the national calibration laboratories are characterized. Comparison campaign between the new and existing universal voltage dividers will be performed up to 300 kV using composite and combined test voltages. The dividers will be used together with the characterized digitizers and developed evaluation software from WP1. Comparison results will provide knowledge on accuracy limits of reference measuring systems used in combined and composite voltage measurements.

Fig. 14 One 100 kV voltage divider module

To ensure long-term stability of the divider performance, it is important to qualify capacitors used in high-precision voltage dividers. Different film and foil capacitors were tested with charge and discharge cycles (repetitive impulse stress, Fig. 15). The performed experiments aimed a simulation of the electric stress associated with high-voltage tests in a laboratory. The applied test procedure considers parameters like magnitude of test voltage, number of impulses, series resistor, test circuit geometry, cooling period, self-heating, and temperature [15]. The results shown in Fig. 15 indicate that the change of capacitance C caused by repetitive impulse stress can be significant (unit 1 – 3: change of capacitance ΔC up to 700 ppm).

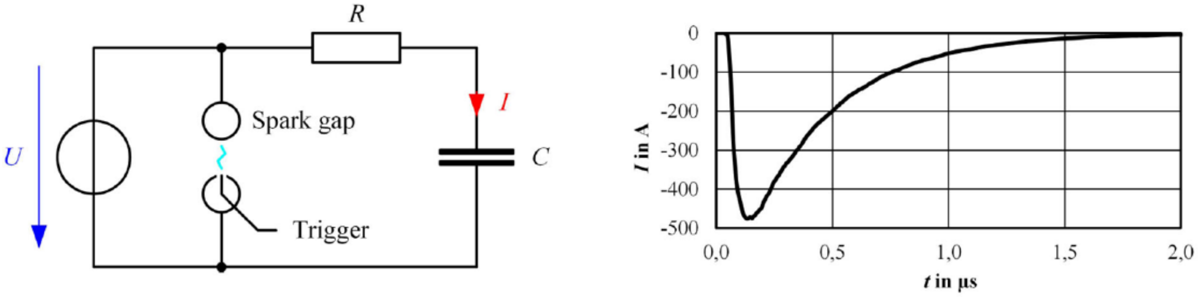


Fig. 15 Impulse stress test circuit with triggerable spark gap and typical discharge current [15]

However, this effect will be smaller when there is a natural cooling period between test cycles. In this case, the best-suited capacitors showed a variation of less than 200 ppm. However, capacitance testing of a control group (unit 4 – 6) demonstrate the influence of ambient temperature to the test results as shown in Fig. 16. The developed divider will be used as a part of a traceable reference system for high voltages.

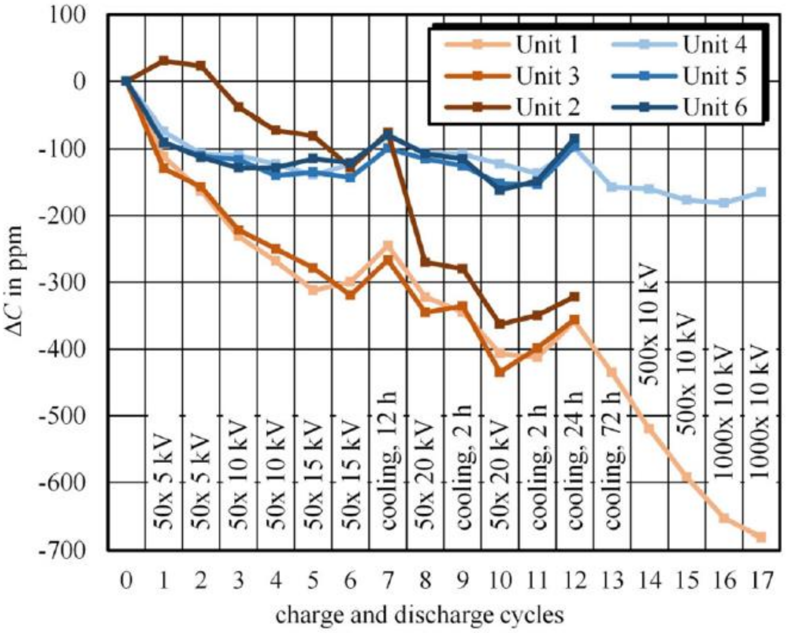


Fig. 16 Relative change (ΔC) of capacitance C
(Unit 1 – 3: DUT, Unit 4 – 6: control group) [15]

In WP3 a comparison between the traceable reference system and the measuring systems in the participating high voltage test laboratories will be carried out.

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