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Dielectric Testing of Ultra High Voltage Equipment

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SUMMARY

This paper presents the status of the CIGRÉ Working Group D1.36 - *Special requirements for dielectric testing of Ultra High Voltage (UHV) equipment*. The increase of the voltage level of transmission systems up to 1200 kV AC and ±1100 kV DC requires an adaptation of high voltage testing procedures. Individual users, manufacturers and laboratories have largely developed the technical requirements for dielectric testing of equipment exceeding a rated voltage up to 1200 kV since there is limited worldwide standardization. Therefore, the scope of this working group is to collect experiences, data and calibration practices in testing UHV equipment at these high voltage ranges. Particular areas of focus are the following ones: Lightning impulse voltage tests up to 3 MV, particularly with respect to front time and overshoot, switching impulse tests, combined and composed voltage tests, wet testing and atmospheric corrections.

Experiences have shown, that dielectric testing of UHV equipment has already reached, in many cases, the limits of most test facilities regarding test voltages, test currents, test power and hall dimensions. One major reason is simply the size of the test equipment and the test object itself, which leads to very high inductances due to connection length and stray capacitances due to proximity.

Due to these boundary conditions, a questionnaire was formulated and circulated worldwide to test laboratories and research centers. With the results of the questionnaire together with existing literature, the WG is able to show the applicability and the limits of the existing standards when applied in the UHV voltage range. Some results and first conclusions for future testing standards revisions and test equipment characteristics, including the calibration of measuring systems is given.

Lightning impulse testing can be done on light capacitances like circuit-breakers but relaxation needed for the front time for cables, transformers and UHV DC thyristor valves. Switching impulse testing seems to be achievable for UHV with existing standards for all apparatus. AC testing can be done, but care must be taken on electrodes, connections and streamers to avoid voltage drop during tests. Combined tests can be done with the same restrictions as for plain impulse tests AC on AC combined or AC on SI combined standards need to consider source "stiffness" to avoid one source influencing the other dramatically. Tolerances need to be discussed further.

KEYWORDS

UHV, ultra-high voltage equipment, transformer, GIS, circuit-breaker, bushing, dielectric testing, AC, LI, SI, DC, atmospheric correction, wet tests

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INTRODUCTION

The current international standards for dielectric testing of high-voltage equipment are optimized for voltage ranges below Ultra High Voltages (UHV) that is often defined as above 800 kV. The worldwide testing experience has shown that some requirements of the standards cannot be fulfilled completely for the dielectric testing of UHV equipment, due to their huge overall dimensions and subsequent problems.

CIGRÉ D1 has established working group D1.36 *"Special requirements for dielectric testing of UHV equipment"*, to collect the present state-of-the-art of testing experiences, to identify the problems and to derive consequences for standardization. The deduced recommendations of the CIGRÉ working group to IEC TC 42 (IEC 60060-1) should be based on practical test experiences.

Based on these working items, Working Group D1.36 was in close contact to IEC TC 42-WG19 (Adaption of TC 42 Standards to UHV Test Requirements), CIGRÉ WG C4.306 (Insulation Coordination for UHV AC Systems) and to CIGRÉ A3.28 (Switching phenomena and testing requirements for UHV & EHV Equipment).

With the start of this WG D1.36, the first task was the collection of literature and experiences of testing in the UHV range. The results were sorted into different topics like testing with LI/LIC, SI and AC, atmospheric correction and wet tests. Next step was and still is the evaluation of all collected information. Nevertheless, some special aspects and data are and were missing in performing tests on UHV equipment. To get up to date information, a questionnaire was formulated and circulated to manufacturer's test laboratories and research centers all over the world to collect the available experience in testing UHV equipment. Even though the following work refers to the UHV range being the target of the WG, in many cases the observations are also be valid for the upper range of EHV.

RETURN OF EXPERIENCE: DIELECTRIC TESTING OF UHV EQUIPMENT

Typical UHV equipment is of large overall dimensions, resulting in high capacitances and inductances. These large dimensions – compared to the typical high-voltage test lab size – are limiting the testability of the components' external insulation due to the required clearances to grounded objects. For switchgear, tests under combined alternating and switching impulse voltages require a minimum distance between bushings and between live parts and walls, which already exceed the limits of most high-voltage laboratories. Often larger electrodes than are used in service are required during works tests to prevent uncontrolled flashovers due to the non-linear nature of breakdown voltage vs. distance in the UHV range. The size of the test objects substantially increases the stray capacitance, the related internal capacitance of the test object and the inductance of the HV connection and ground connection; therefore a high power AC test source must be available which has low distortion and stable output voltage. For lightning impulse voltages, the technically feasible voltage shapes are limited due to the high capacitances and inductances of the test objects and the test circuits especially the inductance of the test loop. While modifications of impulse generating circuits can help with this problem, the fundamental physics determine wave shapes for a given set of circumstances. Under wet conditions, the uniformity of the precipitation distribution – in accordance with the standards – is challenging and often impossible for large-scale vertical test objects. Moreover, testability problems were reported for artificial pollution tests.

To achieve an overview about current experiences and problems of UHV equipment tests, a questionnaire was circulated worldwide to major high-voltage test labs. The questionnaire tried to figure out the typically applied test procedures and the testing parameters, which can be achieved from a physical and practical point of view in particular with respect to lightning impulse testing. In addition, dimensions and further parameters of test objects, test circuits and test labs were collected. The main questions were related to test experiences of large-scale equipment at

- Lightning impulse voltage (LI)
- Chopped lightning impulse voltage
- Switching impulse voltage (SI)
- Combined and composite voltages
- Wet conditions (artificial rain tests)
- Polluted conditions (artificial pollution tests).

Many test labs reported about testing of high-voltage products, e.g. bushings, circuit-breakers (CB), disconnector switches (DS), GIS, transformers, insulators of UHV DC equipment, as well as test setups of basic studies. Examples are shown in Figure 1, [1] - [3].
The data from respondents can be summarized as follows:
Lightning impulse voltage: In several cases the current requirements of IEC 60060-1 were fulfilled (front time $\leq$ 1.56 µs, relative overshoot magnitude $\leq$10 %). In these cases, the test loads were circuit-breakers or small switchgear assemblies-all devices with modest capacitance. Problems were indicated concerning large GIS assemblies, transformers and UHV DC thyristor valves. The test labs reported about some test cases with front times up to 2.5 µs and relative overshoot magnitudes up to 15 %. For such large-scale equipment, the requirements of IEC 60060-1 cannot be fulfilled in all cases (high capacitances and inductances). Modifications of the IEC are recommended. See Appendix 1 for calculation fundamentals.

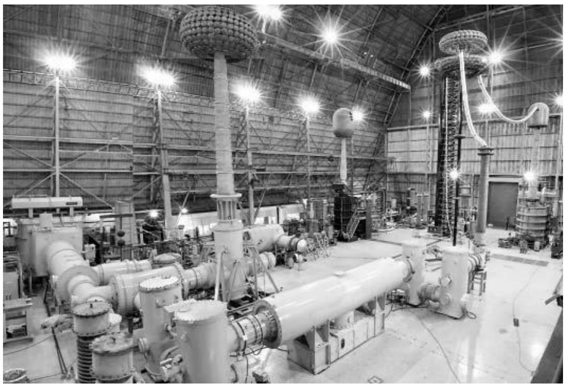


Figure 1 1200 kV mixed technology switchgear for new UHV grids in India, dielectric type tests (left), 1200 kV mixed technology switchgear for new UHV grids in India, on-site tests (right, at the top), dielectric test setups of 1100 kV CB in Japan (right, at the bottom)

Chopped LI voltage: No major deviations from IEC 60060-1 were reported, even though the problems of LI voltage should be the same at chopped LI voltage.
Switching impulse voltage: No major deviations from IEC 60060-1 were reported.
Combined and *Composite voltages:* A wide range of voltage drop was observed (5…30 %).
Artificial rain tests: Several problems with deviations from IEC 60060-1 were indicated, mainly related to the uniformity of the precipitation distribution at large-scale vertical test objects. Often the reproducibility of the tests is not given. Modifications of the IEC test procedure are recommended.
Artificial pollution tests: Pollution tests at complete UHV insulators are not common, only one lab reported about solid layer tests on complete insulator strings.

LIGHTNING IMPULSE TEST WAVEFORM

For the lightning impulse withstand voltage (LIWV) test, the IEC 60060-1 “High-voltage test techniques” as revised in 2010, specifies a test waveform with its value of test voltage U_t within ± 3 %, front time T_1 = 1.2 µs ± 30 %, time to half-value T_2 = 50 µs ± 20 %, and overshoot rate β’ of

10 % or less. T_1 and β’ are in a contradictory relationship to each other, making it important to understand the relationship between T_1 and β’ to discuss whether or not a waveform that meets the standard is generated. Figure 2 summarizes the values of the front time and the overshoot rate presently available for LI voltage test waveforms for actual UHV class equipment based on both Japanese and Chinese test experiences and Japanese calculation results [4].
In the UHV class, the increasing capacitance of the equipment to be tested associated with increasing inductance of a HV connection and the ground return contribute to extend T_1 of the test waveform, which is not in conformance with IEC 60060-1. The phenomenon is characterized by T_1 becoming longer and the introduction of an oscillatory element.

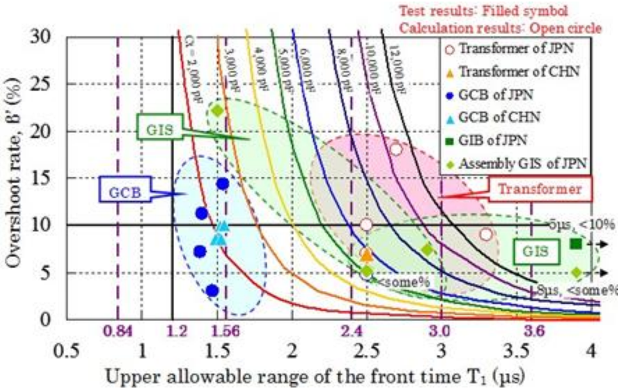


Figure 2 LI parameters as tested with available UHV equipment; both experimental and calculated results are shown

As a consequence, β’ gets larger when T_1 is made shorter. It is often seen that the test conditions specified in the present standard cannot be fulfilled particularly for GIS assemblies and transformers. These situations are summarized in Table 1.

Table 1 Relation between the front time and the range of equipment to be covered

Upper-limit tolerance of Front time, T1		1.56 µs (+30%)	2.4 µs (+100%)	3.0 µs (+150%)	3.6 µs (+200%)
Capacitance range covered under the condition of β’<10%. [Ls=150 µH]		< 2300 pF	< 6000 pF	< 11000 pF	Larger than 12000 pF
Equipment	GCB	Almost OK	OK	OK	OK
	GIS	No	Partially OK	Almost OK	OK
	Transformer	No	Partially OK	Almost OK	OK
	Other apparatuses	OK	OK	OK	OK

In order to study the possibility to extend the front time T_1, breakdown tests were conducted for LI waveforms with longer T_1 using the largest possible models assuming UHV class equipment such as GIS, a transformer, and an air insulation part. The change in the 50 % breakdown voltage (BDV) with a T_1 up to 3.0 µs is within 3 %.
Superimposed oscillations on the crest of lightning impulses appear also when UHV equipment is tested (GIS, GIB, transformers, etc.). Although, increasing the front time of lightning impulses reduces the overshoot amplitude, relative overshoots up to 10 % are expected during UHV tests in practice. Therefore, extension of the k-factor approach introduced in the present IEC 60060-1 might also be convenient for UHV equipment.
For air insulation, e.g. insulator strings, SI and AC overvoltage under contaminated conditions are dominant factors. Therefore, air insulation is not an essential issue for UHV equipment. Consequently, the behavior of SF_6 and the oil used for the internal equipment insulation must be prioritized.
Tests to determine experimental k-factor values for high voltages in large models have been carried out in recent research projects developed by TEPCO (Japan) and LCOE (Spain). Frequency dependency is relatively similar to the existing k-factor function, see [5] - [7]. For higher frequencies, smaller k-factor values are obtained, but smaller k-factor values are determined for UHV equipment. In principle, the large formative time lag of discharges due to long gap lengths is considered to cause these smaller values, compared with the results obtained in the EU project referred in IEC 60060-1

standard. Since the acceptable relative overshoot β' is limited also to 10 % as in the present IEC 60060-1, k-factor values with β' around 10 % are shown in Figure 3.

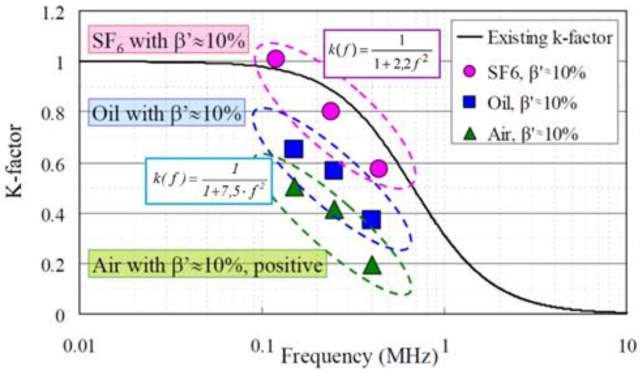


Figure 3 k-factor values for large-sized models of SF_6, oil and air dielectric media, up to -1 MV for SF_6 and oil and up to +1.8 MV for air gaps

For the time being, if SF_6 and oil results are taken as the reference for internal insulation of UHV equipment, a slightly different k-factor function for UHV-class equipment can be proposed

In future, a complete revision of the k-factor function is suggested to improve the present IEC 60060-1. Because test experiences are limited, further investigations at higher test voltages and for different insulating materials are desirably to clarify any possible influence on k-factor function.

SWITCHING IMPULSE TEST WAVEFORM

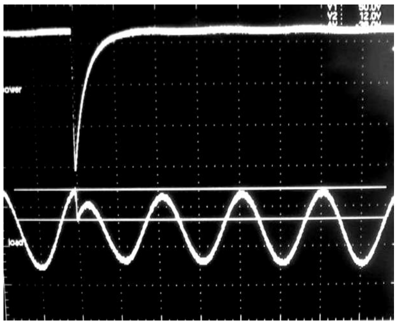
According to the switching surge data of Japanese and Chinese grids, it could be concluded that the T_p of waveforms generated in the actual field, which should be verified by the apparatus switching impulse voltage test, ranges from around 100 µs – 1000 µs.

The breakdown voltage of typical industrial insulation systems is almost constant within the time domain of 100 µs to 1000 µs. This applies to both GIS and transformers [8]. For air insulation, the critical front time ranges from 350 µs to 550 µs for a long air gap of rod-plane electrodes under basic conditions [9]. Using more practical conditions and realistic designs, the critical front time for air insulation tends to lower values between 100 µs and 300 µs. Summarizing, the need to change the requirements for switching impulse voltages seems to be very low since the current standard front time is 250 us and the time to half value is 2500 us.

COMBINED AND COMPOSITE TEST VOLTAGES

Testing with combined and composite voltages requires higher voltages and power ratings for the test equipment. The most common applied test combines an AC with an impulse voltage or an AC with an AC test voltage. In the case of UHV components, the relatively high switchgear capacitance causes a dip on the alternating voltage transformer due to the applied impulse during the combined voltage tests. This situation has been seen with cascade transformers but could be alleviated by using a series resonant system with a suitable preload capacitance. The voltage drop can also be compensated by a voltage increase or by additional lumped capacitances C_a on the alternating voltage side (see Figure 4). It is clear that very high voltage test transformer cascades with the resulting high impedances are not the best solution for combined tests especially where streamers from undersized test electrodes are present.

Since the supporting capacitor increases the load of the test circuit, a more powerful AC voltage source may be required. In that case, the application of a resonant AC test system with variable inductivity is recommended. If such a system is not available, the combination of a switching and a lightning impulse can be considered as an equivalent test. In addition, the divider both suitable to LI and AC voltage measurement is significant for the purpose of the determination of the voltage drop at the AC side.



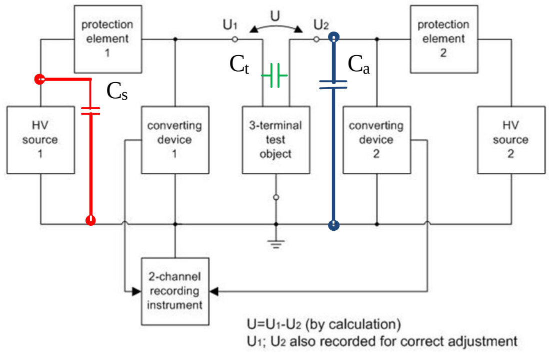


Figure 4 example of measured voltage drop u = 20 % (left) and Principle test circuit of combined voltage C_t capacitance of test object, $C_{a\,AC}$ - supporting capacitor, C_s supporting capacitor of impulse generator. $C_s >> C_t$, $C_a >> C_t$ (right)

ATMOSPHERIC CORRECTION

The different IEC and IEEE standards for insulation coordination and apparatus applications define different methods for atmospheric/altitude corrections, resulting in different correction factors for the same altitude resp. air pressure correction.

The analysis of atmospheric correction factors for UHV equipment using the calculation methods of IEC 60060-1, 60071-2, IEC 60044 showed differences for AC, lightning impulse and switching impulse to a varying degree. When comparing these calculated correction factors against the available test data, no good correlation could be found as can be seen in Figure 5. Figure 5 shows clearly the comparison of calculated vs. measured correction factors for switching impulse for 4 m and 5.1 m gaps. At this time, the majority of test data is available for this wave shape.

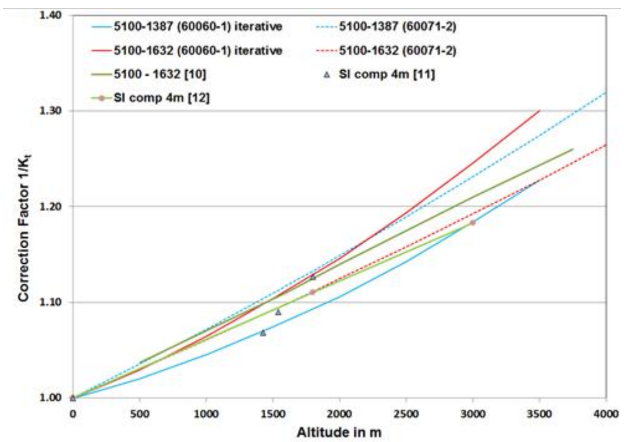


Figure 5 Comparison of tests vs. calculated correction factors for withstand and flashover values

The graphs for IEC 60060-1 and IEC 60071-2 show the results for the withstand (5100-1387) and 50 % flashover (5100-1632) in comparison to the 50 % flashover test results of the 5.1 m gap. The test results for 4 m gaps are included as reference because usually shorter gaps result in larger correction factors.

The general differences in atmospheric/altitude correction factors between the different standards and necessary tests to establish common correction factors will be analyzed and performed in the CIGRÉ WG D1.50 *“Atmospheric and altitude correction factors for air gaps and clean insulators”*.

APPENDIX 1

In the case of normal impulse generators using a basic Marx circuit, for the maximum allowable front time of a lighting impulse to be within the standards, the minimum front resistance and maximum capacitance load must meet the following criterion:

$$R_{FT} \geq 1.45\sqrt{\frac{L_S}{C_{LMax}}}$$

Where

R_{FT} = the minimum, total front resistance in [Ω]

L_S = the total circuit inductance in [µH]

$C_{L\,Max}$ = the total capacitive load in [µF]

Given the minimum front resistance to damp the circuit, the load capacitance for 1.56 µs front time can be calculated from:

$$C_L = \frac{624 \times 10^{-3}}{R_{FT}}$$

ACKNOWLEDGMENT

Figure 6 WG D1.36 Meeting in Brazil (2013)

The CIGRÉ Working Group D1.36 has more than 20 regular members. They are from Argentina, Australia, Austria, Switzerland, Japan, Spain, USA, Sweden, Russia, Brazil, Hungary, China, Italy and Germany.

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FURTHER PUBLICATIONS OF CIGRÉ WG D1.36

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Riechert, U.; Neumann, C.; Hama, H.; Okabe, S.; Schichler, U.: *Basic Information and Possible Counter Measures Concerning Very Fast Transients in Gas-Insulated UHV Substations as Basis for the Insulation Co-ordination*, CIGRÉ SC A2 & D1 Joint Colloquium 2011 in Kyoto, - Transformers, Materials and Emerging Test Techniques - Kyoto (Japan) September 11 – 16, 2011, paper PS3-O-5

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