SOME REMARKS CONCERNING TESTING OF ULTRA HIGH VOLTAGE EQUIPMENT

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Abstract: The increase of voltage level for AC and DC transmission systems requires some changes in testing of high voltage equipment for Ultra High Voltage (UHV) systems. After a short description of the coordination work in the standardization bodies the requirements for UHV equipment are mentioned. The main points concerning high voltage testing of UHV equipment are the impulse shape of standard lightning impulse voltage, the evaluation of the test voltage for impulses with oscillations or overshoot near the peak and the time parameter of switching impulses. The linearity check of the measuring devices, the proximity effect and the wet tests are further points to be discussed concerning testing of UHV equipment.

1 INTRODUCTION

The increase of the demand for electric power requires the transportation of higher power. Even if the decentralisation of the energy generation via wind energy, solar energy, bio mass and coupling of thermal and electrical power will reduce the amount of power to be transported the generation of power will be very often far from the consumer of electric power. Therefore the electric power has to be transported over long distance which means in some countries over several thousand km. To prevent losses in the transportation the system voltage increases with increasing power and has reached levels of 1100 or 1200 kV for AC systems and 800 kV for DC systems. These system voltages are named Ultra High Voltage (UHV).

The introduction of higher system voltages led to numerous actions within the research community like International Council of Large Electric System (CIGRE) and the standardization body like International Electrotechnical Commission (IEC) in order to prepare a scientific basis for new or additional standards and to implement the knowledge in the standardization frame work.

2 IEC - CIGRE COORDINATION

The first reaction of the increasing system voltage was the foundation of an international coordination group with members from CIGRE and IEC, the Joint IEC - CIGRE Coordination Group (JICCG), where all the relevant Technical Committees from IEC and Study Committees could present their problems concerning UHV [1]. The main task of this group was to provide guidance to IEC and CIGRE in the development of standards regarding the possible special requirements for components in UHV systems in the different technical directions. The outcome of the work of JICCG was the following, that in the field of AC systems the existing standards need in most cases only an extension up to the highest system level, but in the field of DC voltage a lack of relevant standards exists. Therefore a road map of Standardization on UHV AC Technologies was created with a list of tasks for IEC as well as for CIGRE groups. Furthermore the creation of a new Technical Committee within IEC, named TC 115 “High Voltage Direct Current (HVDC) transmission for DC voltages above 100 kV” was proposed due to the fact that new standards in the field of DC voltage systems were required and that it is not sufficient to extend the existing standards up to the UHV level. There was also realized that the new Technical Committee TC 115 should coordinate the work with existing IEC working bodies in the field of DC a systems. The JICCG was disbanded after the definition of the required tasks within IEC and CIGRE and the future coordination will be done separately within CIGRE and IEC, in case of CIGRE by the Technical Committee of all Study Committee chairmen and in case of IEC by the Standardization Management Board (SMB) supported by some Strategic Groups (SG).

Within CIGRE a number of Study Committees started to investigate the consequences concerning UHV namely the committees A3 High Voltage Equipment, B3 Substations, A2 Transformers, B3 Overhead Lines, C4 System Technical Performance and D1 Materials and Emerging Test Techniques. The following contribution will therefore be limited to the consequences of UHV systems on the test and measuring techniques [2].

3 INSULATION CO-ORDINATION

The Technical Committee TC 28 Insulation co-ordination has the scope to prepare standards for power systems with nominal voltages above 1000 V AC and 1500 V DC regarding amongst
others the specification of a series of standard insulation levels (without regard to any particular type of equipment), a full statement of the tests to be included in the specification of the equipment to meet the insulation levels to be used in relation to the possibilities of overvoltage protective devices and recommendations for the minimum clearance distance in air between live parts. Therefore the work of this Technical Committee will influence the requirements on the necessary tests for high voltage equipment. The existing standards were extended from former 765 kV system voltages up to 1200 kV in respect to the UHV systems and the recommended parameters are shown in table 1.

The maximum impulse voltage levels are 1950 kV switching impulse and 2700 kV lightning impulse. Such voltage levels require distances in the range of 13 m and loops of a test set up in the range of 50 m or more. Such dimensions may be not available in high voltage test laboratories of equipment manufacturer and therefore outdoor test fields or new test facilities are necessary.

4 UHV REQUIREMENTS

The test voltages for UHV equipment are according table 1 very high and this requires test voltage sources with high rated voltage. The increase of the test voltage is combined with the increase of the physical size of the equipment even for gas insulated equipment. The increase of the equipment and test voltages leads to an increase of the whole test set-up and its inductance. Particularly for the generation of a standard lightning impulse the inductance of the complete test circuit is very important relating overshoot and front time of the impulse.

The large dimension of the equipment influences also the wet tests, because the generation of an artificial rain according to the requirements in the standards is very difficult. The water jet should not be concentrated in order to prevent a flashover but the large distance between the rain equipment and the equipment under test could not be coped with a sprayed jet. Here some solutions are required taking into account the feasibility of the tests, the costs of the test equipment and the reliability of the test results. A solution could be a component test may with a little bit higher requirements in order to increase the safety margin because an extrapolation from component behaviour to system behaviour is necessary.

Another subject is the impulse shape of standard switching impulse voltage. The increase of the voltage level and the limited ratio between rated power frequency voltage and required switching impulse voltage asks for a careful evaluation of the switching impulse shape, because the breakdown voltage of large air gaps depends on the time to peak of the applied switching impulse voltage.

Finally in some countries UHV lines should be installed in high altitude. The influence of the altitude and the atmospheric conditions are taken into account in different ways depending on the relevant recommendations. Furthermore in some cases the recommended test values are only valid up to 1000 m and for higher altitudes a correction factor should be applied which is not validated for such high altitudes. Therefore IEC as well as CIGRE have established working bodies like IEC Joint Working Group TC 42 WG 22 "Atmospheric and altitude correction" where the Subcommittee 17A and 17C, "High-voltage switchgear and controlgear" and "High-voltage switchgear and controlgear assemblies" the TC 28, "Insulation Co-ordination", the TC 36 "Insulators" and the TC 115, "High Voltage Direct Current (HVDC) transmission for DC voltages above 100 kV" were engaged. CIGRE has established Working Group D1.36 “Special requirements for dielectric testing of ultra high voltage (UHV) equipment”, WG D1.50 “Atmospheric and altitude correction factors for air gaps and clean insulators” and WG D1.35 “Performance of high-voltage and high-current measurement systems for high voltage testing” also with respect to requirements on tests of UHV equipment.

5 SWITCHING IMPULSE VOLTAGE

The peak time of a standard switching impulse was defined according to the breakdown voltage of air gaps. According to [3] the high voltage tests for equipment up to the highest voltage for equipment $U_m$ of 245 kV were power frequency and lightning impulse tests, above $U_m$ equal 300 kV switching and lightning impulse tests were required. The following experimental results were the basis for the determination of the standard time to peak for switching impulses [4].

It can be clearly recognized that according to Figure 1 for a distance up to 7 m the standard time to peak of 250 μs is very close to the time of the minimum flashover $In$ [5] the distances for rated

<table>
<thead>
<tr>
<th>High voltage for equipment $U_m$ (kV)</th>
<th>Standard rated switching impulse withstand voltage</th>
<th>Standard rated lightning impulse withstand voltage</th>
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</thead>
<tbody>
<tr>
<td>Voltage (kV)</td>
<td>(peak value)</td>
<td>(ratio to the phase to earth peak value)</td>
</tr>
<tr>
<td>1100</td>
<td>1178 (1)</td>
<td>1.10</td>
</tr>
<tr>
<td>1450</td>
<td>1377</td>
<td>1.10</td>
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voltages above 800 kV are much larger and therefore the actual time to peak for standard switching impulses does not correspond with the minimum flashover voltage of air gaps. The consequence could be the extension of the time to peak for testing of UHV equipment with switching impulses.

**Figure 1:** Flashover voltage at switching impulses as function of time to peak (former time to crest) [4]

It should be mentioned that the research results of Figure 1 have been achieved for a rod-rod configuration, which represents a strong non-uniform electrical field configuration. The electrical field configuration however in real UHV equipment is much more uniform and the minimum breakdown voltage at switching impulse is less influenced by the time to peak.

Within the discussion of the relevant IEC Working Group TC 42 WG 19 [6] the opinion of the experts was not to change the time to peak for tests of UHV equipment.

### 6 LIGHTNING IMPULSE VOLTAGE

The actual version of IEC 60060-1 [7] will introduce a test voltage function which considers the influence of the overshoot on the test voltage level. The former version of the same IEC standard defines only a frequency or a time duration concerning the overshoot as parameter for the evaluation of the test voltage and the basis was a so-called mean curve evaluated by drawing the mean curve through the recorded curve as shown in Figure 2 [8].

**Figure 2:** Overshoot evaluation according to IEC 60060-1:1989, Figure 10 “Mean curve” (dotted curve) shall be drawn by experienced engineers.

The introduction of the test voltage function allows now to evaluate the test voltage as function of the frequency or time duration of the overshoot without this former sharp frequency limit and with a clearly defined base curve, close to the former mean curve, but with a high reproducibility. The test results of a European Research Project were the basis for this test voltage function as shown Figure 3 [9]. However the discussion was going on concerning the allowed overshoot value. The former value was 5% and now is changes to 10% [7], but for UHV equipment this limits are mainly not achievable due to the large circuit and its inductance.

**Figure 3:** Experimental results of the k-factor, describing the relation between breakdown voltage and overshoot frequency.

The revision of IEC 60060 also includes a description of the evaluation procedure for the test voltage taking into account that nowadays more or less all recording instruments are based on digital recorders. Now instead of a “mean curve” as shown in Fig. 2 a well-defined base curve could be calculated, based on the assumption that the standard lightning impulse shape is given by the superposition of two exponential functions. The test voltage can then be calculated taking into account the influence of the test voltage function in
such a way, that the superimposed oscillations is removed from the recorded curve $U(t)$, filtered according to the test voltage function and the filtered resulting curve added to the base curve according to the following equation:

$$U_{\text{test}}(t) = U_{\text{base}}(t) + k(f) \cdot (U(t) - U_{\text{base}}(t))$$  \hspace{1cm} (1)

The test voltage $U_{\text{test}}$ will be determined by the maximum of the base curve $U_{\text{base}}$ which is determined by a well-defined procedure according to the actual recommendation IEC 60060-1:2010 and by the contribution of the overshoot depending on the frequency. This second part in Equation (1) can be calculated by multiplying the difference between the maximum value of the recorded curve $U$ and the maximum of the calculated mean curve $U_{\text{base}}$ with the frequency dependent factor $k$, shown in Figure 3. The physical background of this proposal is the fact, that overshoot or oscillations contribute to the breakdown behaviour of material as function of the frequency. As higher the frequency as lower is this contribution and therefore the factor $k$ changes from 1 for low frequencies to 0 for high frequencies. Fig. 4 shows an example of a simulation of a test circuit [10].

The large dimensions of UHV equipment and the relevant test circuits asked again for a compromise between front time and overshoot value. Due to the increasing physical size of the test circuit the inductance increases and then the required front time of a standard lightning impulse can in many cases only be reached by acceptance of a higher overshoot value. Here the new established Working Groups within IEC and CIGRE propose a change in the time parameters for the lightning impulse voltage for tests of UHV components. The standard front time of 1,2 µs will be kept as well as the negative tolerance of $-30 \%$, but the positive tolerance will be increased up to $+150 \%$ which leads to a maximum front time of 3,0 µs. The recommendation in the apparatus standards may differ from these values depending on their particular interest. However a compromise between acceptable overshoot value and extension of the front time should be find because the relation between overshoot and front time is given by the inductance and the resistance within the test loop and is based on physics.

7 TEST TECHNIQUES

The points related to test techniques of UHV equipment are mainly related to the large dimensions of the UHV equipment. The generation of the test voltages are not difficult, however for combined and composite tests, e.g. switching impulse and lightning impulse on open contacts of a circuit breaker, the mutual influence of the different voltage sources may be taken into account.

One of the most critical test is actually the wet test. The standardized wet test procedure requires a rain with 45 ° deg, so that rain equipment fixed on the ceiling will not be sufficient. Besides the required large dimension the generation of the correct water amount may be very difficult. The water should not be supplied in a jet, but in droplets. However the generation of droplets with an angle of 45 °deg related to the equipment under test over a large distance which is required due to the high voltage is very difficult. Fig. 5 shows a DC disconnector as an example to give an impression about the size and the required area which should be supplied by the rain test equipment.

According to Fig. 5 the area for the rain will be about 500 m² if the complete disconnector should be tested. A possible solution could be to test each insulator alone but again the test of the moving part of the disconnector requires at least the length of the rain equipment of more than 30 m. The problem with the distance between equipment under test and the generation of standardized rain within such large distance remains.
8 MEASURING TECHNIQUES

The test of UHV equipment requires according to [4] lightning impulse voltages up to 2700 kV and switching impulse voltages up to 1950 kV. Assuming a certain safety margin and development margin the UHV manufacturers should be able to measure lightning impulse voltages up to about 3000 kV and switching impulse voltages up to about 2300 kV. The preferred calibration method for voltage measuring devices is the comparison method [11]. The voltage divider to be calibrated is connected in parallel with a reference divider, but the rated voltage of the reference divider could be only 20 % of the rated voltage of the voltage divider under test. Today reference divider with a rated voltage up to 500 kV are available and therefore a voltage divider with a rated voltage of 3000 kV could not be calibrated according the relevant standard. The small difference may be acceptable, but a larger problem is the check of linearity of such a large divider. This problem is not now, but became again a point of interest with the testing of UHV equipment.

In former times a solution was proposed by comparison the charging voltage of the impulse generator with the output voltage of the generator measured with the voltage divider under test. This ratio is usually named efficiency factor and if this factor will be constant over the up to the rated voltage of the voltage divider it can be assumed that the voltage divider is linear. This is only valid if the impulse generator output voltage depends linear on the charging voltage within the required uncertainty of the voltage divider. Another possibility is the calibration of the single components of a voltage divider up to its full rated voltage. But here again the linearity should be checked on the complete assembled device. The use of a field probe may be a solution for the linearity check. The field measures the electric field and the field changes linear with the applied voltage assuming that no discharges influence the electric field distribution in the area of the electric field probe. In [12] such a device was used to check the transfer behaviour of a voltage divider, but it can also be used for a linearity check of a voltage divider up to the rated voltage.

The proximity effect on high voltage measuring equipment is well known and mentioned in the standard [11]. However due to the large dimension of the UHV equipment and the related generators and measuring devices it may be necessary to take the proximity effect into account in such a way, that the measuring device will be calibrated at a certain position in the laboratory and should be fixed in this position in order to take care of this proximity effect. In addition the equipment under test should have a distance from the measuring devices which is high enough to prevent an influence on the measuring uncertainty. These requirements could be not fulfilled in all laboratories, particularly if UHV equipment like transformers or disconnectors have to be tested. For DC equipment the voltage divider should be designed without any metallic flanges to prevent surface leakage.

9 CONCLUSION

Higher test voltage levels require larger test setup with higher inductance which leads to higher overshoot or with higher damping to longer front times. The test voltage factor leads to higher reproducibility of the test results taking into account the influence of the overshoot on the breakdown behaviour. The uncertainty of the measuring devices should be carefully checked up to the rated voltage. The wet test procedure is still difficult and reasonable and feasible solutions are required.

10 REFERENCES

[6] IEC TC 42 WG 19 Adaptation of TC 42 standards to UHV test requirements, IEC website