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Paper 4.2

Challenges on the measuring and testing techniques for UHV AC and DC equipment

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SUMMARY

After an introduction of the actual IEC Publication concerning high voltage test and measuring techniques with the relation between the lightning and switching impulse voltage to the highest voltage for equipment (AC or DC) the generation and measurement of the different types of test voltages are described.

The required AC test voltages in the range of 1200 to 1800 kV could be generated by transformer cascades or by resonance test systems, where the resonance conditions could be reached by variable inductance for a fixed frequency or by variable frequency for a fixed inductance. AC measurements are combined with partial discharge and dielectric measurements and therefore suitable coupling and standard capacitors are required.

Switching impulse voltages in the range of 1800 to 2400 kV and lightning impulses in the range of 2800 – 3500 are generated with Marx generators. Due to the large test circuits for UHV apparatus and the limited space in the test field the electrical field stress should be controlled by proper design of the electrodes; concerning the impulse shape oscillations are expected and should be handled. The main parameter for impulse voltage measurements are the influence of the proximity effect, the linearity of the voltage divider ratio and the new proposal for the evaluation of impulse voltage with superimposed oscillations near the peak.

The required DC voltages in the range of 1500 to 2000 kV are generated by rectification of a high AC voltage and multiplying the output DC voltage of a single stage by a cascade arrangement. The DC measurement is done by a resistive voltage divider with a capacitive grading to prevent damages in case of a test object flashover or breakdown.

Test voltage generators and measuring systems for UHV apparatus are available or could be manufactured and here the experience from the seventies and eighties could be used.

KEYWORDS

High Voltage Test Technique, High Voltage Measuring, Technique, Voltage Generator, AC Voltage, DC Voltage, Impulse Voltage

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1 Introduction

The IEC Publications 60060-1 [1], 60060-2 [2] and 60060-3 [3] are the generic standards for high voltage measuring and testing techniques and valid for the testing of all high voltage equipment. The required high voltage tests include type test, routine test, performance test and check as well the test procedure for on-site tests. At the moment a draft for high current testing and measurement is under discussion, which will not be discussed in the following contribution [4].

Furthermore IEC Publication 61083-1 [5] describes the requirements on the recording devices for high voltage measurements, mainly for impulse voltage measurements. The evaluation of the impulses is also important and therefore a software was developed in order to generate various impulse shapes for the qualification of the evaluation software according IEC Publication 61083-2 [6].

The required test voltages are based on the IEC Publication 60071-1 [7] in which all the different test levels are given depending on the highest AC voltage for equipment U_m and the requirements of the insulation co-ordination. Fig. 1 shows the highest required lightning and switching impulse test voltages as function of the voltage U_m. Lower impulse voltages are allowed depending on the insulation co-ordination and the correction factors. For voltage levels up to $U_m \leq 245$ kV AC voltage and lightning impulse voltage are required as test voltage, for voltages up to $U_m \geq 300$ kV switching impulse and lightning impulse voltages are required as test voltage. For tests of UHV components higher AC test voltages could be required than shown in Fig. 1.

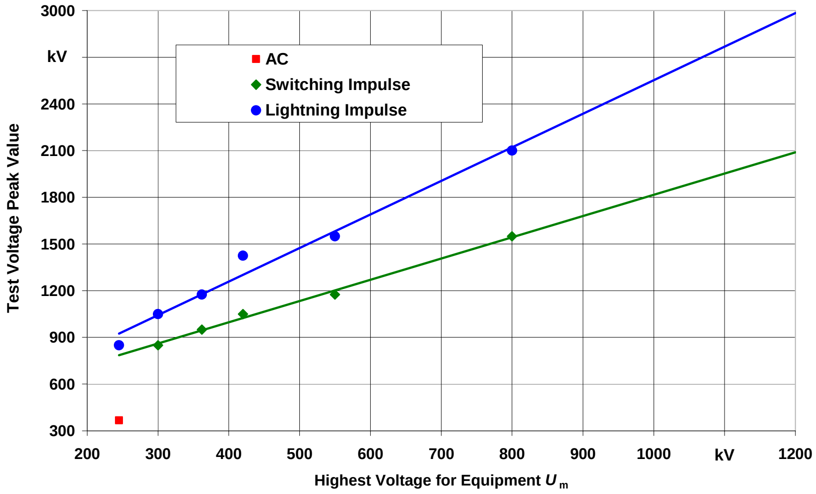


Fig. 1: Lightning and switching test voltage values as function of U_m [7]

The extrapolated lines should only give an idea about the expected test voltages, which depends on the insulation co-ordination. Assuming also tests with chopped lightning impulses with a peak value of 1.1 of the full lightning impulse test voltage and taking into account the levels for development tests the following table shows the figures for the expected voltage ranges to be generated and measured.

Table 1: Expected test voltage ranges for development and quality assurance

AC in kV	Switching impulse in kV	Lightning impulse in kV	DC in kV
1200 - 1800	1800 – 2400	2800 – 3500	1500 - 2000

The relation between the peak value of lightning or switching impulse test voltages and the AC voltage is shown in Fig. 2, where the AC voltage is defined as $U_m/\sqrt{3}*\sqrt{2}$, in order to use in both cases the peak value.

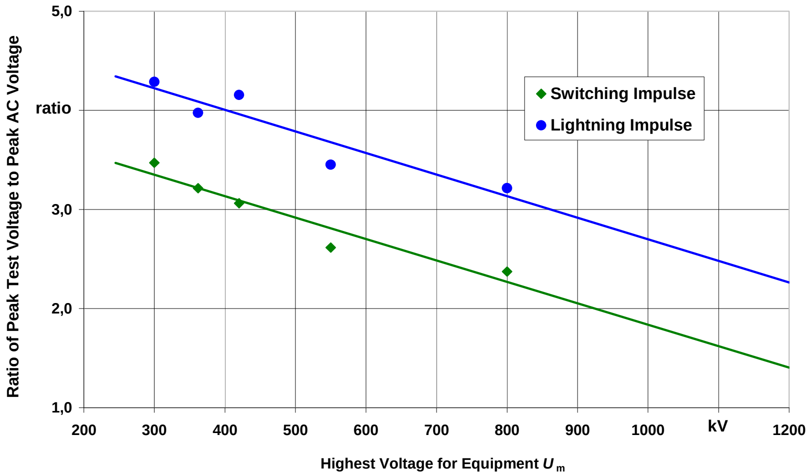


Fig. 2: Ratio of lightning and switching test voltage to AC voltage as function of U_m

Fig. 2 reveals that the ratio between impulse test voltage and highest AC voltage decreases with increasing AC voltage U_m from 4,3 at U_m = 300 kV down to about 3,1 at U_m = 800 kV for lightning impulses. For switching impulses the same tendency can be observed, only the absolute values change from about 3,5 to 2,2. An extrapolation to UHV voltages in the range of 1000 or 1100 kV would result in a further reduction to the ratio 2,5 for lightning impulse test voltages and about 1,7.

The voltage stress of the insulation in a DC system is a complex combination of fundamental and harmonic frequency component in addition to the DC voltage [8]. The test voltages for an HVDC bridge transformer should be used to demonstrate the requirements on the test voltages depending on the system DC voltage. Fig. 3 shows the switching and lightning impulse voltage values as function of the DC voltage in the relevant range between 500 and 800 kV.

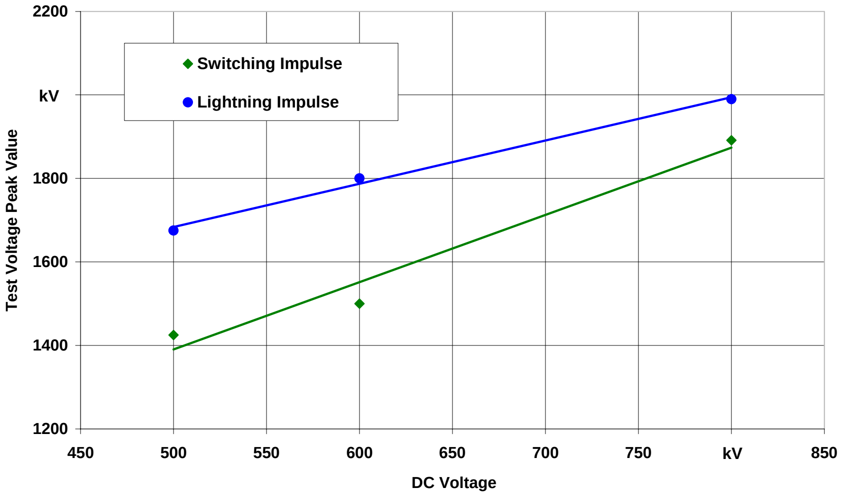


Fig. 3: Lightning and switching test voltage values as function of the DC voltage

With increasing DC voltage the switching and lightning impulse test voltage levels increase, but not linear with the DC voltage. For a 500 kV DC system the lightning impulse test voltage is 1675 kV, for an 800 kV DC system about 2000 kV. Fig. 4 shows the relation between the impulse test voltage values and the DC voltage as function of the DC voltage.

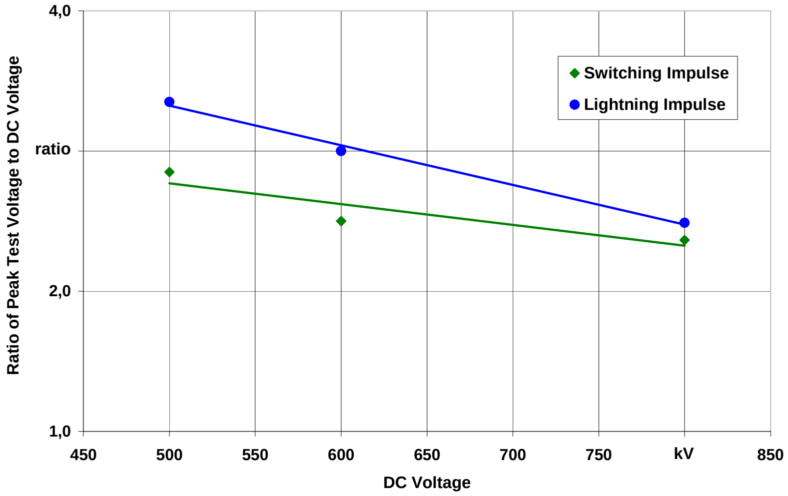


Fig. 4: Ratio of lightning and switching test voltage to DC voltage as function of DC voltage

It should be noted, that also for DC systems the test voltage level for impulse tests decreases with increasing DC system voltage. The reduction is comparable to AC systems but the extrapolation in the system voltage is for DC from 500 kV to 800 kV 60 % whereas for AC from 765 kV to 1000 kV only 30 %. This should be taken into account for the estimation of the failure probability and the required test voltages levels and test equipment [9].

Besides the generic requirements in the IEC Publications 60060 there are some more IEC Publications concerning different apparatus where the application and the requirements of the IEC Publications 60060 are not possible due to physical reasons. An example is the high voltage test on power transformers. IEC Publication 60076-1 [10] requires additional parameters at switching impulse tests like the impulse duration, which means the time above 90 % of the impulse peak value, and the time to zero crossing, because both parameters are strongly influenced by the transformer and should be taken into account on the design of the test circuit. Further detailed information are given in the IEC Publication 60076-3 [11] and 60076-4 [12] where the guide for switching and lightning impulse tests for transformers and reactors already demonstrate the difficulties in impulse tests.

The challenges on the measuring and testing techniques for UHC AC and DC equipment are based on the following assumptions. The ratio of the peak value of impulse test voltage to the peak AC voltage decreases with increasing U_m (see Fig. 2). The same behaviour could be observed for DC voltage (see Fig. 4). The safety margin for insulation is more expensive for higher voltage levels and therefore the requirements on the test voltage and the measuring uncertainty will be very important. The dimension of the apparatus will increase and in consequence the dimension of the test equipment and the test set-up. This is particularly important for the calibration of the measuring systems and may require reference measuring systems with a higher nominal voltage but at least accurate linearity tests for approved measuring systems. The increasing test circuit requires also a more attention of the earthing system and the influence of the electromagnetic disturbances, because such large test set-up will be very often realised in high voltage outdoor test fields [13].

2 AC test and measuring systems

2.1 General requirements

As most generation, transmission and distribution equipment is operating with alternating voltage, this voltage must be considered as the most important test voltage. It is not only used for development, type and routine testing, but also for energising complete UHV test lines. For that application also world's largest AC test system, a 3 MV transformer cascade [15], was installed in 1991 with approximate dimensions in 28 m height and 60 m length.

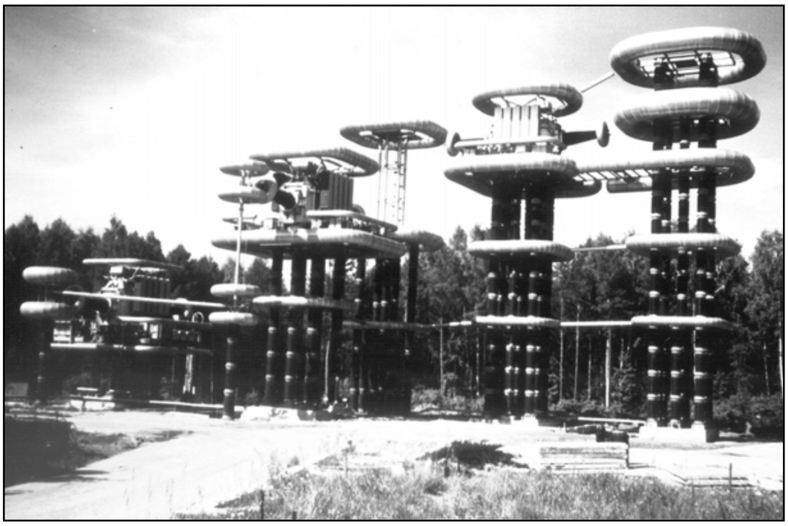


Fig. 5: Transformers cascade 3000 kV, 12.6 MVA for continuous operation (Manufacturer: HIGHVOLT Dresden GmbH, Germany)

The requirement to AC test voltages are specified in the generic IEC Standards [1-3] and no change is expected by the present revision [15]. The AC test voltages shall represent stresses in service considering both operating frequencies of 50 and 60 Hz. Therefore a frequency range of the test voltage between 45 and 65 Hz is required for quality testing in test fields, whereas for HV on-site testing [3] the much wider range of 10 to 500 Hz is accepted, but can be reduced by the relevant IEC Technical Committees for equipment.

The application of frequency converters for feeding AC test systems is connected with technical and economic advantages and therefore widely used for on-site testing [16]. A wider frequency range than 45 to 65 Hz, also for quality testing in UHV test fields, could reduce the cost for the necessary AC test systems remarkably, but requires research work on the influence of frequency on the insulation behaviour.

To guarantee a sinusoid wave shape, the present IEC Publication 60060-1 [1] requires a relation of ($\sqrt{2}$ (1 ± 0.05)) between the peak and the r.m.s. value of the AC voltage. The revision of IEC 60060-1[15] will introduce the total harmonic distortion

(THD) of up to 5% instead of that relation, but the difference in the requirements is small.

In many cases AC testing is connected with PD measurement, therefore the PD noise level of AC test systems must be specified. Values of 10 pC or even less can be reached by correct design and measured in well shielded UHV test laboratories.

The rated AC test voltages, available in a UHV test field, should be about 1.5 times higher than the test voltages specified for UHV AC transmission system (see Fig. 1) to enable research and development tests at 1000 kV equipment. It should also be mentioned that UHV AC test systems must be provided for combined and composite test voltage generation of AC with superimposed impulse or DC test voltages. Furthermore UHV AC test systems must be equipped with huge carefully designed electrodes [17] to avoid pre-discharges at the system components and the connections to test objects.

2.2 AC test voltage generation

UHV AC test voltages in the voltage range of 1200 to 1800 kV can be generated by transformer cascades or resonant circuits of modular reactors in series, but resonant circuits can only be used for capacitive test objects.

2.2.1 AC generation based on transformers

The well-known principle of transformer cascades enables UHV AC generators for all kind of tests (dry, wet, polluted) and test objects. They can be realised with cylindrical insulating case transformers (ICT) which are arranged in one column. ICT cascades are limited in current and only for short-term operation, because they are usually not equipped with additional separate coolers. Due to the insulating material and the shape of the insulating cylinder ICT cannot be recommended for outdoor test areas.

Metal tank transformers (MTT) are designed for higher currents, lower short-circuit impedance and continuous duty. The second and all the following transformers within the cascade have to be fed via the lower transformer(s) and arranged on insulating support(s) (see Fig. 5), because the tank of each transformer unit is on the output potential of the preceding transformer. Fig. 6 shows a general arrangement.

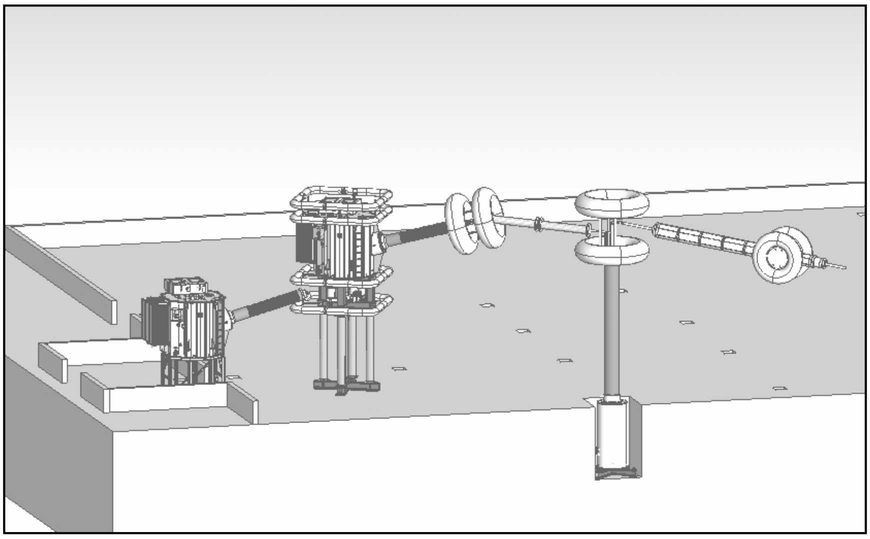


Fig. 6: MTT cascade 1200 kV / 2400 kVA with UHV filter and connection electrodes

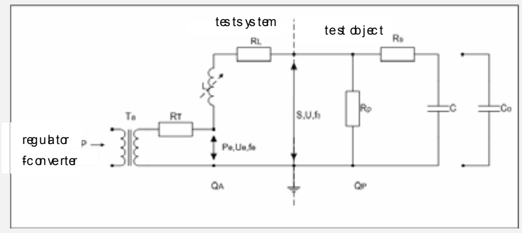
Usually it is assumed that MTT cascades require more space in the laboratory than ICT cascades. This is not correct, because the required space around the transformers is given by the breakdown behaviour of the air and the relevant distance. Only if the transformer cascade is not in use the space for storage the equipment is smaller for ICT than for MTT. MTT cascades are very well suited for outdoor application.

Fig. 6 gives also an impression about the size of the required electrodes in order to reduce the electrical field stress and to prevent partial discharges of the test equipment. The bushing itself can be considered as an additional part of the UHV filter consisting of blocking impedance and coupling capacitor.

Special single test transformers are designed for pollution testing (current of several Amps and very low short-circuit impedance) or for direct connection to an SF6–insulated test bus for testing of gas-insulated substations (GIS) which enables a very efficient testing of UHV GIS and its components.

2.2.2 AC generation based on series resonant circuits

The schematic diagram for a principle circuit diagram of a resonant circuit and the basic equations and parameters are given in Fig. 7 for the two types of resonant test circuits, the fixed frequency circuit with a tuneable inductance and the fixed inductance circuit with tuneable frequency.



natural frequency $f_o = 1/(2\pi\sqrt{LC})$

quality factor $Q = S/P \approx U/U_e$ for series resonance

$Q = Q_A{*}Q_P/(Q_A+Q_P)$

fixed frequency: inductance-tuned	fixed inductance: frequency-tuned
$f_0 = f_e = f_N = 50$ Hz	$f_W = f_e = f_0$ ($f_W = 20 \ldots 300$ Hz)
$C_{max} = C_{min}\,(L_{max}/L_{min}) \approx 20\,C_{min}$	$C_{max} = C_{min}\,(f_{max}/f_{min}) \approx 225\,C_{min}$
Q = 40 … 60	Q = 80 … 100
p = 3 … 5 kg / kVA	p = 0.8 … 1.2 kg / kVA

Fig. 7: Principle circuit diagram of a resonant circuit and basic equations and parameters

The total capacitance is given by the test object, the coupling and divider capacitors and forms with the HV inductance an oscillating circuit with a characteristic natural frequency f_o (see Fig. 7). For a continuous AC voltage, only the losses P must be compensated via an adaptation transformer. The quality factor Q of the circuit is the relation between the reactive power S and the power losses P and, for series resonant circuits, the relation between the voltage at the test object U and at the exciter transformer U_e.

For fixed frequencies (50 or 60 Hz) as used for factory testing, the loss power is supplied from the usual power supply and the natural frequency f_o must be adapted by tuning the variable inductance (see Fig. 7). This is done by an adjustable gap between the fixed and the moveable part of the magnetic core of the reactor and it causes a limited load range of about $C_{max}/C_{min} = 20$. To generate a voltage without test object, a basic load must be provided.

Resonant circuits of fixed frequency are the optimum test systems for factory testing of capacitive UHV equipment as GIS, power and voltage transformers (applied voltage tests) and especially for cables. They might be applied for wet testing, if large capacitors are in parallel to the test object, but they cannot be used for pollution testing and are not recommended for outdoor use. Fig. 8 shows a resonance test set with a fixed frequency with an output voltage of 1200 kV and a current of 2A.

Fig 8: Reactor cascade and basic load of a resonant circuit of fixed frequency 1200kV/2A (Manufacturer: HIGHVOLT Dresden GmbH)

The second possibility to reach resonance is to supply the power losses with natural frequency f_o via a frequency converter. Such resonant systems of variable frequency have a much wider load range, a better quality factor, a lower power consumption, a lower weight and usually a remarkably lower price than inductance tuned systems. But the frequency depends on the capacitance of the test object and the frequency range for factory testing (45…65 Hz) can only be reached with a large basic load. Therefore the current main application is at the moment HV on-site testing. A wide application of frequency tuned test systems in UHV equipment testing could be expected, if the standards allow a wider frequency range (e.g. 25…100 Hz) also for factory testing, but for commissioning testing of UHV AC equipment on site, resonance test systems with variable frequency will play an important role.

2.3 AC voltage measurement

There are no additional problems when UHV AC measurements [2] are done: The usual converting device is a voltage divider with sufficiently large electrodes to avoid any pre-discharge in the surrounding air. The measuring instrument is a comfortable peak voltmeter or even a digital recorder, which enables to measure the test voltage value (defined as half of the peak-to-peak value divided by √2, [15]), the r.m.s. and the average value, the test frequency, the relation between test voltage and r.m.s. values, the total harmonic distortion and the dynamic test characteristics.

UHV AC testing will be connected with PD measurement, as for many UHV equipment no partial discharges up to the test voltage are acceptable. This means that an extremely low PD noise level must be guaranteed requiring the filtering of the power supply, a perfect shielding and grounding system of the UHV test field, high voltage filters and an extremely low PD noise level of the components of the test system itself. The components for PD measurement, coupling capacitor, measuring impedance and PD detector, have to follow the principles of PD measurement and calibration of IEC 60270 [18]. The huge circuits (see Fig. 5) act as antennas for radiated noise signal. If the shielding is not good, a remarkable noise signal can appear and therefore the circuits should be as compact as possible and of low impedance.

It is expected that the conventional methods must be completed by non-conventional methods, especially by VHF/UHF and acoustic methods [19] and the UHV equipment to be tested should be prepared for such measurements.

For some UHV equipment, e.g. measuring transformers and bushings, also C and tan δ-measurements must be performed. For these measurements standard capacitors of ≥ 1200 kV are a challenge whereas the instruments are conventional. For a UHV application of 1200 kV a solution was found, which combines the compressed gas standard capacitor with the coupling capacitor and the voltage divider. Fig. 9 shows the standard capacitor which is inside a SF_6-filled steel tank.

The cylindrical measuring electrode surrounds the HV electrode which is connected to a capacitive resin impregnated bushing, used also as coupling capacitor for PD measurement.

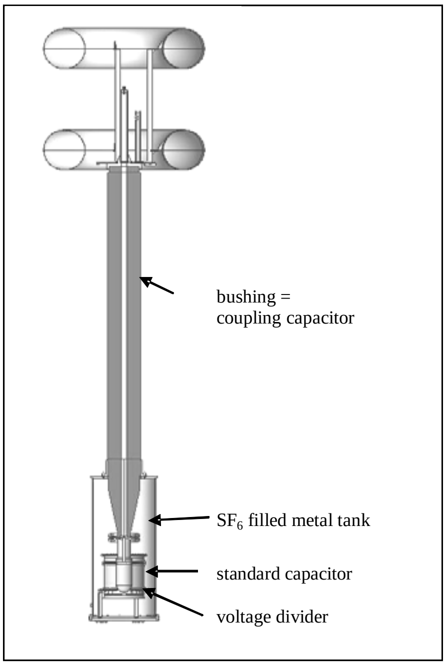


Fig. 9: Combination of standard capacitor, voltage divider and PD coupling capacitor for 1200 kV

3 Impulse test and measuring systems

3.1 General requirements

As most generation, transmission and distribution equipment is subjected to fast transients such as lightning and switching impulses, this voltage is also an important test voltage used for development, type and routine testing. The requirement for lightning and switching impulse voltages are specified in the generic IEC Publication 60060-1 [1], but for some apparatus the relevant Technical Committees has changed or added some requirements [10]. The actual revision of the IEC Publication 60060-1 [15] will introduce new evaluation procedure for lightning impulse voltages due to a test voltage factor, which takes into account the contribution of oscillations near the peak on the breakdown performance of insulating materials [20, 21]. The evaluation of the time to peak for switching impulses will be adapted to the procedure for the front time of lightning impulses in order to have only one procedure for the time parameters of impulse voltages. An important point, particularly for impulse tests on UHV equipment, will be the definition and evaluation of the oscillations or overshoot near the peak of a lightning impulse, because due to the large dimension and the associated inductance of the test circuit the test impulses are subjected to oscillations. The engaged parties, manufacturer and customer, have to decide whether they accept the oscillations or a longer front time, both are determined by the inductance and resistance in the test loop. Fig. 10 shows an outdoor test field with an impulse generator of 6000 kV charging voltage and a 4800 kV voltage divider in order to get an impression of the size and dimension.

In case of testing transformers or reactors the impulse shape is also strongly influenced by the test object and minor by the test loop. These so called non conventional impulse shapes need further attention.

For air insulation some test laboratories are performing the impulse tests by reducing the test level with increasing number of impulses. This may be acceptable for particular test objects, but not in general if no further investigations of the statistical flashover behaviour of the tested apparatus are available. This should be discussed in CIGRE and in IEC.

Fig. 10: Outdoor test field with an impulse generator [13]

3.2 Impulse test voltage generation

The generation of lightning and switching impulse voltages is usually done by an impulse generator, called Marx generator, which consists of a number of capacitor charged in parallel via a charging resistor and discharged in series trough front and tail resistors. The connection between the capacitors is done by sphere gaps in the different stages of the impulse generator, where only the bottom stage needs a trigger impulse. Switching impulse voltage may be also generated by an impulse excitation of a transformer.

Due to the natural triggering of the stages within the generator the output voltage of an impulse generator is generally not restricted, but the size of the generator and its mechanical limits as well as the required dimension of the electrode due to the limited electrical field strength of the air determine the maximum output voltage. The output voltage across the test object is mainly a double exponential function assuming that the influence of the inductance could be neglected. In large test fields this assumption is not any more valid. Fig. 11 shows a typical lightning impulse with oscillations due to the inductance in the test circuit and the relative low damping resistance in order to reach the required front time. In this figure a fitted double exponential curve is also included, which is used according the standard [1] as the basis for the calculation of the overshoot ß and the determination of the test voltage depending on the frequency of the superimposed oscillation. Furthermore the difference between the recorded curve and the fitted double exponential curve is also shown to have an idea about the amplitude of the oscillation and the frequency.

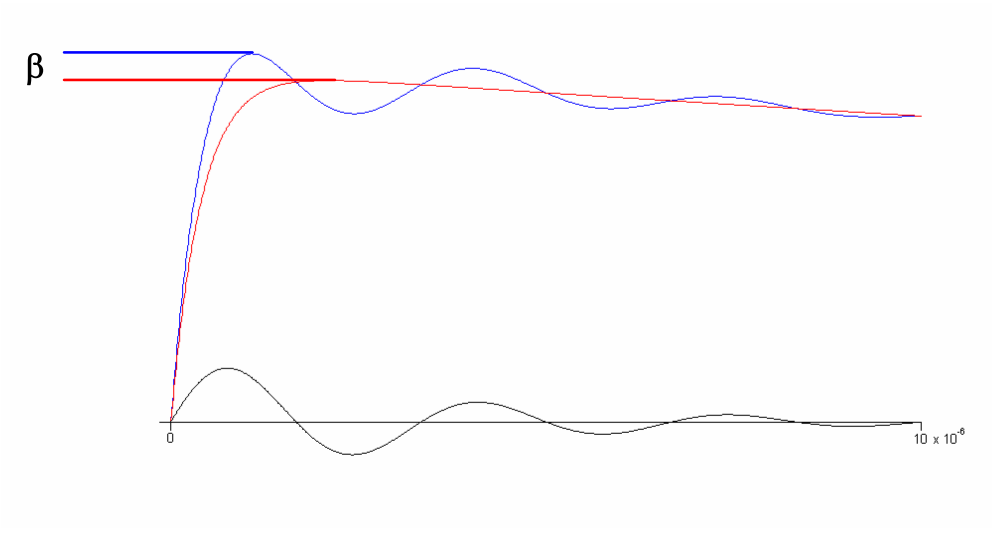


Fig. 11: Recorded lightning impulse with an oscillation and fitted double exponential impulse together with overshoot β and the difference curve between the recorded and the fitted impulse on the bottom

In large test circuits for UHV equipment the limits concerning front time and allowed overshoot, specified in [1], can be easily reached because the inductance of the complete test circuit is usually high and the capacitance of the test object can also be high. Then a decision is required to tolerate either a larger overshoot or to have a longer front time. Fig. 12 gives an example for the range of the load capacitance C_l as function of the front time parameter and the allowed 5 % or the additional proposed 15 % overshoot for a specific impulse generator and test circuit.

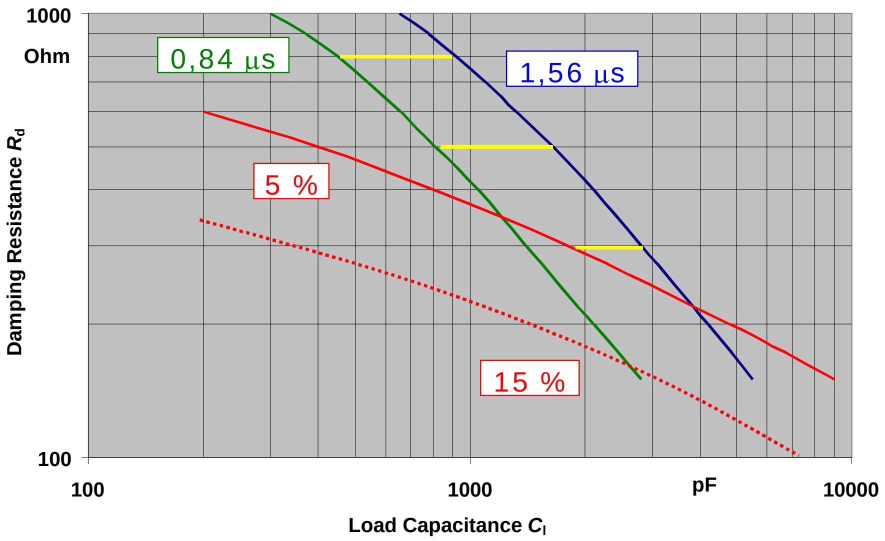


Fig. 12: Load diagram of an impulse generator with the tolerances of the front time and two values of overshoot 5 % and 15 %

The lines at 800, 500 and 300 Ohm representing a constant value of different damping resistors R_d and it can be clearly seen that for this test arrangement the load capacitance is limited to 4000 pF for standard lightning impulses with an overshoot < 5 % or 8000 pF for an overshoot < 15 %. Above these values the impulse will have a higher overshoot than the values shown in Fig. 12 or a longer front time (> 1,56 µs) depending on the damping resistance.

The space in test fields is usually limited and therefore the electric field stress at the high voltage electrode of the impulse generator should be controlled by the suitable electrode dimension. Fig. 13 shows an impulse generator in a test laboratory with a voltage divider in front of the generator. The field control is particularly important for switching impulses where the breakdown in air is combined with the formation of leader.

The generator and the voltage divider have a large electrode at the top to control the local electrical field. The voltage limit is given either by the charging voltage of the generator or by the gap distance between the top electrode and the neighbouring grounded parts like building walls, ceiling or tank of the test object.

Fig. 13: Impulse generator, 16 stages, maximum charging voltage 3200 kV, energy 240 kJ (Manufacturer: Haefely AG, Basel, Switzerland)

3.3 Impulse Voltage Measurement

Impulse voltages are measured using a measuring system, comprising dividers suited for these types of voltages such as resistive or damped capacitive dividers as converter unit, transmission cables, low voltage attenuator and a digital recorder [22]. Special attention has to be paid to the proper grounding of the test circuit and the digital recorder as well as on the shielding of it. In case of a flashover of the test object, high and steep voltages might cause problems with the digitizers.

For UHV equipment the dimensions of the test object are usually very large which requires large distances between the test object and the grounded parts of the test field and large test loops with a high inductance. For practical reasons this inductance could not be reduced by means of low-inductive connections between e.g. impulse generator and test object or voltage divider. Furthermore in indoor test fields the available space is limited and therefore proximity effect has to be taken into account.

The calibration of an approved measuring system requires comparative measurements with a reference measuring system as the recommended procedure [2], but the rated voltage of reference measuring systems is limited and the test could be done at 20 % of the nominal voltage of the voltage divider. According to Table 1 test voltages of above 2400 kV for switching impulse voltage and about 3500 kV for lightning impulse voltage are necessary taking into account a certain margin for development tests and quality assurance. This requires reference measuring systems for 500 kV or 700 kV which are at the moment not everywhere available but could be manufactured. Fig. 14 gives an idea about the distances for comparative measurements with two different reference measuring systems.

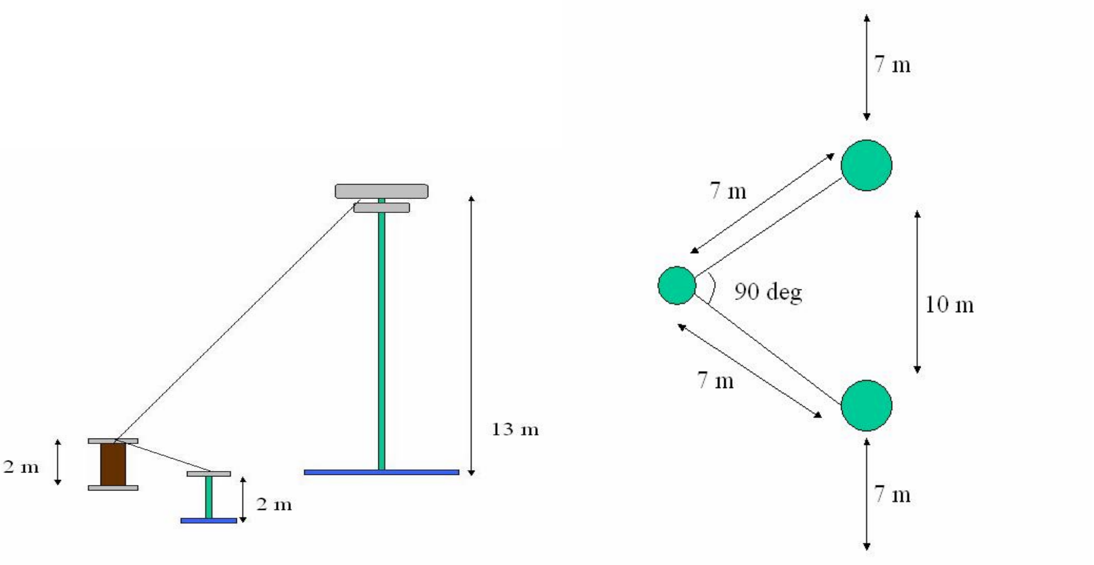


Fig. 14: Schematic diagram of a measurement with a reference divider for lightning and switching impulse measurements
- dimension of the dividers (left side) – height of the dividers
- top view of the arrangement (right side) – distances to wall and between apparatus

The maximum voltage for reference measurements is given by the nominal voltage of the reference divider. In order to use the voltage divider up to its nominal voltage the IEC Publication 60060-2 requires a linearity tests on the complete system under the condition which represents the real situation in the test field. One possibility to check the linearity is the comparison between the output voltage of an impulse generator, measured with the system under test and the charging voltage of the single stages of the impulse generator. Fig. 15 shows the results of the linearity test at switching impulse and lightning impulse voltages. The deviation from the ratio 1 is a measure for the non-linearity of the measured output voltage.

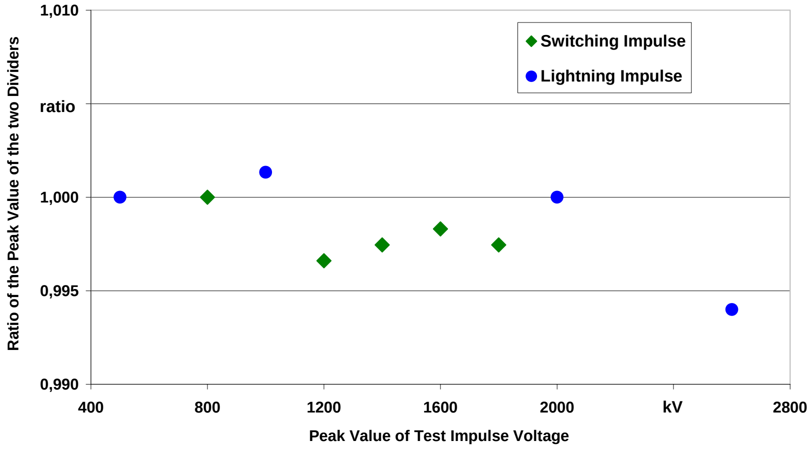


Fig. 15: Linearity check for lightning and switching impulse voltage

From the components in an impulse measuring system the linearity of the impulse voltage divider is the most critical, all the other, transmission system, voltage attenuator and digital recorder, could be assumed to be linear. Both tests show clearly the good linearity of the measuring system which is less than 0,75 %. It could be assumed that the measurement of the DC charging voltage of the impulse generator up to the maximum charging voltage per stage of 200 kV is correct and has no linearity effect.

Proximity effect

An additional test in the indoor test field shows, that a move of a divider in the range of about 3 m influence the transformation ratio of the impulse voltage divider due to the proximity effect by about 1 %. Due to the large dimension of the test system components and the test object the proximity effect should be taken into account during the calibration and the measurements.

Linearity

A linearity check of the measuring system is absolutely necessary, because due to the high test voltages, the relative low voltage of the reference measuring system and the possible discharges within the voltage divider may lead to a change of the voltage divider ratio. The requirements in the IEC Publication are to check the impulse voltage measuring system under real test conditions up to the nominal measuring voltage.

Evaluation of the recorded impulse

The actual discussion concerning the introduction of a test voltage factor k which takes into account the influence of the oscillations near the peak of a lightning impulse is particularly important for impulse testing of UHV equipment due to the large dimension of the test objects and the test circuit. The IEC document [15] shows a proposal for the future evaluation of lightning impulse voltages with oscillations near the peak. Extensive investigations on the behaviour of the different materials [21] have shown, that with the introduction of a frequency dependent test voltage factor k, a test voltage impulse could be evaluated where the peak value of this impulse is equivalent to the peak value of a double exponential lightning impulse. Fig. 16 shows a recorded and evaluated impulse with the test voltage U_t. as peak of the test voltage impulse.

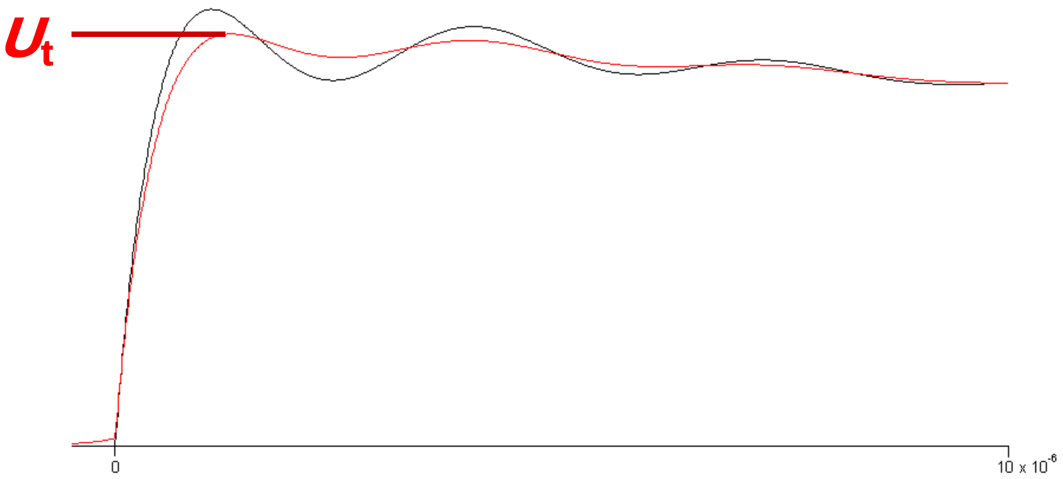


Fig. 16: Recorded and evaluated lightning impulse voltage for the determination of the test voltage

The evaluation procedure can be described in five steps:

- Determination of a double exponential function which fits the best in the recorded curve (details are under discussion) and which represents the mean curve
- Calculation of the differences between the recorded curve and the mean curve which represents the residual curve
- Filtering the residual curve with a filter which characterise the k factor influence on the breakdown voltage
- Calculation of the test voltage curve by addition of the mean curve and the filtered residual curve
- Evaluation of the test voltage as peak value of the test voltage curve

The proposed procedure should be checked by the relevant Technical Committees of IEC concerning the validity of the procedure and the reliability and reproducibility [23]. From the available information from different test laboratories it could be assumed that the determination of the test voltage and time parameters will not be a problem. The definition of the overshoot, taking into account the new evaluation procedure, and the allowed limit for the overshoot amplitude, 5 % in the actual IEC Publication, and proposed 15 % in the revision draft [15], should be discussed and the consequences could be seen e.g. in Fig. 12.

4 DC test and measuring systems

4.1 General requirements

There are no general standards for testing of high DC equipment, but only for bushings and capacitors. IEC Publication 62199 is valid for bushings [24] and the test voltages are given by equations, which are also valid for smoothing chokes and converter transformers as already mentioned in chapter 1.

In IEC Publication 60871-1 [25] for capacitors the DC voltage test level is given with 4 times the rated DC voltage, but this test could be done on single elements and will not be a challenge for DC test equipment. The reason of this high test voltage is, that special attention to the parallel resistive control of the capacitors must be given for DC voltage stress.

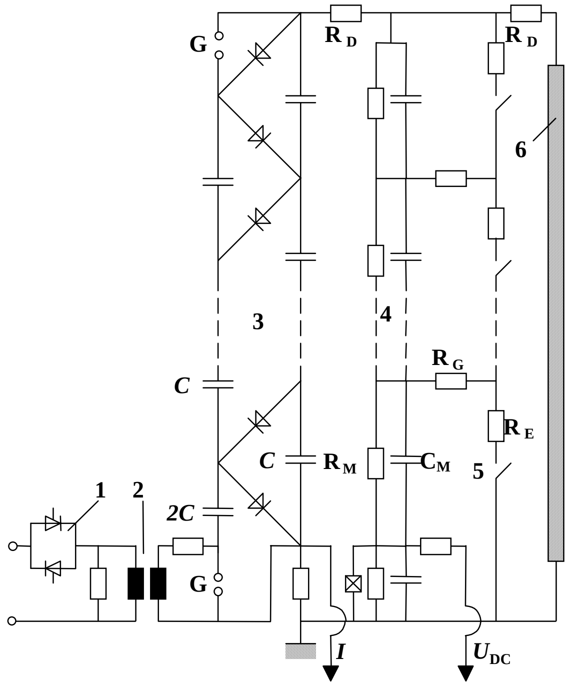
For all further elements (post insulators, switchgears, etc.) there are no special standards concerning DC test voltage levels. The test voltage levels were usually agreed between manufacturer and user. In most cases test levels of earlier agreements were taken with the peak value of the highest AC nominal voltage or 1.5 times the rated DC voltage.

4.2 DC test voltage generation

It is possible to generate DC voltages „directly “ by means of band-generators (Van-de-Graaff-generator), but this type of generator can be generate only small currents and is therefore not very useful for high voltage tests for UHV DC equipment.

Therefore DC test voltages for testing UHV apparatus were mainly produced „indirectly“ by rectification of high AC voltage, where also currents can be generated which are limited by the power of the feeding AC transformer and the rectifying elements. In order to get a higher DC voltage than the peak of the AC supply voltage

DC generators for testing purpose are cascade rectifier, named as Greinacher or Cookroft-Walton cascade. Such generators consist mainly of a supplying transformer with a reasonable AC output voltage and two capacitor columns, connected with rectifier elements. Fig. 17 shows a principle arrangement of a DC cascade with the left capacitor column as so-called grading capacitors, the right capacitor column as smoothing capacitors, a resistive and in parallel capacitive voltage divider, an earthing resistor column and the test object. The general design of such a cascade rectifier is modular and the nominal output DC voltage for each stage, consisting of one grading capacitor, one smoothing capacitor and two rectifiers, is 2 times the peak voltage of the AC power supply voltage.



1	Thyristor controlled voltage regulation
2	High voltage transformer
3	Rectifier with diodes, charging and smoothing capacitors
4	Voltage divider with grading capacitors
5	Discharging and grounding device
6	Test object
C	grading, smoothing capacitors
C_{M}	grading capacitors of the measuring resistor
R_{M}	measuring resistor
R_{D}	damping resistor
R_{E}	earthing resistor
R_{G}	grading resistor of the earthing switch
G	protection spark gap

Fig. 17 Principle of a DC rectifier cascade

The large number of individual rectifier elements has the advantage that a polarity reversal is possible within a much shorter time than with one to single rectifier element.

Also for DC generators the electrical field strength at the head of the generator should be controlled by the dimension of the electrode. The limit of the allowed field stress is much more important for DC than for impulse voltage due to the long duration of the applied voltage, where the discharge processes can develop.

Attention should be paid that DC generators, in contrary to AC generators, do not have a galvanic connection between the high voltage electrode and ground. Therefore an installation for short circuit and grounding of each capacitor within the generator is necessary and should be integrated in the control system of the DC generator for safety reasons.

Furthermore during the assembling and dismantling of the test circuit it should be taken into account that capacitor elements may be still charged for a long time due its large time constant and therefore every capacitor element should be discharged, short circuited and grounded. Fig. 18 shows a DC generator for 1200 kV

Fig. 18 DC generator for 1200 kV output voltage (Manufacturer: HIGHVOLT Dresden GmbH)

The DC output voltage from a cascade rectifier is not a complete constant voltage, but shows some ripple due to charging and discharging times of the smoothing capacitor. The DC voltage should have a ripple smaller than 3% of the mean DC value according to the relevant IEC Publication [1]. The ripple is defined as half of the voltage difference between the highest value and lowest value and depends on the output current, the frequency of the supply AC voltage and the value of the capacitors, assuming that each stage has the same capacitor.

The output DC voltage is lower than the calculated output voltage given by the peak value of the supply AC voltage and multiplied by a factor 2 and the number of stages. This voltage drop is determined by the so-called impedance of the DC generator and depends also on the load current, the capacitors and strongly on the number of stages.

Usually a damping resistor is placed between the DC generator and the test object in order to protect the rectifier elements in case of a flashover of the test object. The voltage drop across this resistor should be small in order to have the full output voltage on the test object.

The DC test voltage is not only limited by the test object or the generator but also by the environment conditions. Humidity can have a large influence on the attainable output voltage, because the humidity at the surface of the DC components influences the voltage distribution and may lead to unacceptable conditions as well as to strong partial discharges.

For DC test voltages over +/-1200 kV attention should be given also to the contamination of the environment due to the high electrical DC field which acts as particle-attractive whereas particles mean also insects. These particles are accelerated toward the highest electrical field and generate partial discharges by hitting the electrode. For the same reason of electrical field stress smooth surfaces have a substantially better voltage distribution than rough surfaces and this should be considered in particular for connecting elements.

Electrical charges play a significant role for DC applications. Electrical charges get shifted by the stationary electrical field. These charges recombine again after switching off the DC test voltage, according to the time-constant R*C, where R represent the resistance and C the capacitance of the relevant element. Due to the high value of the resistance for DC components R the discharging time can reach from hours up to days for recombining all charges. With oil/board arrangements the discharging time lies in the range of hours, with plastics arrangements (composite insulators) it can takes days for a complete discharging. These charges change the original electrical field of the DC test voltage and should be taken into account for the design of DC apparatus [26].

Partial discharges affect also very strongly the original field distribution and lead with longer period to a breakdown or flashover as well as for internal and external insulation.

The IEC Publication 62199 [24] requires a partial discharge measurement during the DC test and furthermore a polarity reversal test with partial discharge measurement. The measurement of partial discharges at DC voltage is still not completely solved, because a distinction between internal and external partial discharge impulses is not simple due to the lack of a phase relationship as with AC partial discharge measurement. Furthermore the partial discharges distinguish at AC voltage due to the voltage shape which is not the case for DC voltage.

Finally for DC voltage tests with artificial pollution layer and under rain high power DC generators are necessary with output currents in the ampere range and with very high smoothing capacitance and fast voltage regulation.

Fig. 19 shows a DC test of a transformer bushing in the high voltage laboratory of the Technical University of Graz.

Fig. 19 DC test of an 800 kV transformer bushing

4.3 DC voltage measurement

For DC test voltage measurement usually a resistive voltage divider with high impedance is required. It should be taken into account that discharges at the flanges of the divider will influence the uncertainty of the divider because the surface current is increased. To reach an uncertainty of less than 3 % the IEC Publication 60060-1 requires a measuring current of at least 0,5 mA at rated voltage. For lower voltages the value of the leakage current should be evaluated in order to keep the required uncertainty. For high precision DC measurement the voltage and temperature coefficient of the resistor elements should be taken into account or compensated. During DC tests the test object may have a breakdown and this results in a fast voltage change. Usually this voltage change should not be measured accurately but the voltage distribution across the resistor of the voltage divider should be kept linear and therefore a capacitive grading of the resistive voltage divider is very important.

Also for DC measurements reference measuring systems are not available up to the rated voltage of the dividers or generators. Therefore a linearity check is required and this could be done with a rod-rod gap described in IEC Publication 60052 [27].

5 Conclusions

The challenges on the measuring and testing techniques for UHV AC and DC equipment could be accepted and solved.

The revision of the standards for high voltage testing and measuring techniques will take into account also the importance of the testing of UHV equipment.

The voltage generators for UHV equipment are partly available or could be manufactured. The adaptation to the required high output voltage will be not a problem for the design of the test equipment.

The measurement of such high voltages for UHV apparatus requires a careful check of the uncertainty particularly of the voltage divider as converting device, because this element would mostly contribute to the uncertainty budget of the voltage measurement.

The measuring and test technique is prepared for all kind of test voltages and could benefit from the experience of the seventies and early eighties of the last century at which test systems were built for voltage levels which were already sufficient for all tests of UHV apparatus.

The test voltage values however should de defined as soon as possible by the insulation co-ordination and the relevant Technical Committees and the test procedures should be carefully handled.

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