OVERVIEW OF TEST REQUIREMENTS ON HV DC APPARATUS AND RESULTING IMPACTS ON UHV DC TEST SYSTEMS

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Abstract: The growing demand for reliable and environmental friendly energy has led to an increased number of High Voltage DC transmission systems. Researchers and manufacturers worldwide are pushing the limits further to meet tomorrow's demand. At the same pace that the HV DC equipment is advancing, the testing equipment for HV DC equipment have to advance as well so that manufacturers can prove the performance and quality of their components and researchers have the tools to further investigate the insulation systems at increased voltage levels. This paper provides a brief overview of the different HV DC test requirements and procedures according to IEC standards as well as Cigre recommendations. The peculiarities for HV DC cables, DC bushings, converters, etc as well as general purpose testing will be introduced and discussed. An alternative to the common Greinacher cascade UHV DC generators will be presented in detail.

1. INTRODUCTION

Today, UHV DC installations become more and more common to provide reliable and environmental friendly energy all over the world. Installations with voltage levels up to 800 kV are being planned [1-2] or are being built in all parts of the world. Distances up to 3700 km and power ratings up to 3150 MW are being realized. Future UHV DC installations will push these limits even further with voltage levels of 1000 kV and above being considered.

For manufacturers and researchers to be able to exceed todays limits, test equipment has to stay ahead. For system voltages exceeding 1000 kV, test voltage levels for the UHV DC apparatus of approx. 2000 kV are required.

This paper focuses on UHV DC testing requirements according to today's standards and their impact on test equipment and gives an overview of other test requirements. Detailed information regarding Partial Discharges can be found in [3].

2. WITHSTAND TESTING

2.1. Converter Transformers, Smoothing Reactors and Bushings

The requirements of withstand testing are similar in respect to duration and pass criteria [4-6]. Withstand voltage is applied for a period of 2 hrs with positive polarity. The acceptance criteria consist of a no flashover/failure requirement as well as PD specification.

Bushings for converter transformers have a 15 % increased test voltage level compared to converter transformers. There are no discrete test voltage levels. All test voltages have to be defined under consideration of the component layout of the UHV DC system like number of valve bridges.

2.2. Valves for LCC and VSC

Testing of valves is different for thyristor based Line Coupled Converter (LCC) valves [7], and IGBT or Diode based Voltage Sourced Converter (VSC) valves [8]. All test voltage levels have to be derived from service conditions, etc.

For LCC valves, "valve support d.c. voltage test", "multiple valve unit d.c. voltage test to earth" and "valve d.c. voltage test", have to be performed. These tests follow the same procedure. From 50 % of test level U_{1min}, the voltage is raised within 10 s to 100 %. After 1 min the voltage level is reduced to U_{3h} and maintained for 3 h, then it is reduced to 0. The tests differ with respect to connection of the terminals and ground. All tests are to be done at both polarities, starting with pos. polarity. Between the tests, the valve has to rest for at least 2 h. For this reason these tests are not considered to be Polarity Reversal (PR) tests.

For VSC valves, testing is more extensive. The "maximum continuous operating duty test" (≥ 30 min) and "maximum temporary over-load operating duty test" (10 min) require a test voltage based on the "maximum continuous d.c. voltage". Switching frequency and modulation pattern are to be based on service conditions.

The "minimum voltage test" (≥ 10 min) is for proving performance of IGBT valves which derive the necessary operating power from the voltage between the terminals. Valve support d.c. voltage test and multiple valve unit d.c. voltage test to earth follow the same scheme as LCC.

2.3. Power Cables

At present, no mandatory IEC standard covers DC cables. Only recommendations are available from CIGRE [9-11]. They differentiate between polymer cable, typically used up to 250 kV and oil-paper/mass-paper/gas pressure cables up to 800 kV. For polymeric cable the recommendations differ according to the converter configuration.

The test voltage level is slightly increased for polymeric cables with $1.85 * U_0$ compared to $1.8 * U_0$ for routine and type test and $1.45 * U_0$ to $1.4 * U_0$ for after installation test (on-site test). Although test duration per CIGRE recommendation is 15 min for routine and after installation test, a considerable amount of time is needed for charging/discharging of the cable so that the DUT can be exposed to voltages above U_0 for several hours [12].

Development tests apply for polymeric cables, with a test voltage level of $1.45 * U_0$. The recommendation respects the intended use of the polymeric cable. When used with VSCs, no PR will occur during standard operation. For this reason the number of PR test cycles is evenly distributed over positive and negative withstand test cycles so that the total amount of withstand cycles is the same as with polymeric cables used with LCCs.

Type and development testing is divided into load cycles. While the test voltage is applied permanently during a load cycle (LC), a current source is used to heat the cable to steady state conditions. The cycles can be than described as LC_{24}, LC_{48} and LC_{ZL} and LC_{HL}. Heating for LC_{24} is 8 h and 16 h of cooling, for LC_{48} 24 h heating and 24 h cooling apply. LC_{ZL} is zero load, with no heating at all and LC_{HL} with permanent heating. The heating influences the field distribution inside the cable. Depending on cable design and temperature of insulation, the maximum field strength can be achieved on the cable sheath under load conditions.

The test duration is significantly extended for Development tests with 30 and 40 LC_{24} cycles compared to 8 and 12 LC_{24} during Type Test for LCC and VSC cables respectively.

Between load cycle blocks with different polarity it is recommend to rest the cable for a minimum period of 8 h for non polymeric cables and 24 h for polymeric cable with the cable conductor connected to the cable sheath.

The long duration of testing is remarkable. For polymeric cable in development test, continuous neg. polarity is applied for as long as 160 days. As these are recommendations by CIGRE, differing test conditions can be negotiated.

3. POLARITY REVERSAL TESTING

3.1. Converter Transformers, Smoothing Reactors and Bushings

Requirements on PR testing are similar in respect to duration and pass criteria. The PR cycle consists of 90 min neg., 90 min pos. and 45 min neg. test voltage. Transition time for reversals is limited to a maximum of 2 min, shorter times preferred. The acceptance criteria consist of a no flashover/failure requirement as well as PD specification. In the future, the second neg. polarity might be extended to 90 min as well.

3.2. Power Cables

PR testing on cable is done for non-polymeric cables and polymeric cables used with LCCs. Polymeric cables used with VSCs are not exposed to PR and consequently not tested.

During PR testing, the cable is exposed to LC_{24} heating/cooling cycles. During this cycle, the polarity is reversed every 4 h for non polymeric and every 8 h for polymeric cables with an allowed transition time of 2 min. This procedure is repeated for 10 heat cycles at $1.4 * U_0$. For polymeric cables 8 heat cycles at $1.45 * U_0$ are applied for type test and 20 cycles at $1.25 * U_0$ during development tests

4. WET AND POLLUTION TESTING

4.1. Smoothing Reactors

The wet test is applied to the insulators of dry-type smoothing reactors with the insulators arranged in service condition. Since the wet test is done primarily on the insulators, an equivalent structure may be used to achieve the same position as in service.

The test voltage level is the same as the withstand test voltage level with $1.5 * U_{dmax}$, with U_{dmax} being the specified highest continuous dc voltage between the line terminals and earth. The test voltage level is applied for 1 h with the wetting of the insulator beginning 30 min before the test, no flashovers are allowed.

4.2. Bushings

Porcelain housed bushings may need to be tested according to artificial pollution test methods as described in [6]. Testing is performed at d.c. withstand test voltage level, typically of negative polarity. Testing is to be done in three consecutive tests. Outdoor bushings may be “even wet tested” for 1 h at $1.25 \times U_{dc.}$

Horizontal wall bushings may be “uneven wet tested” in a position resembling service condition. The voltage level is $1.25 * U_{dc}$. The test voltage is applied before wetting of the outside part of the bushing. Duration is until a flashover occurs. Otherwise it shall be maintained for at least 15 min from start of the rain.

Acceptance criteria are the same for all wet and pollution tests. In case of a puncture the DUT has failed. In case of flashover, the test is to be repeated once after a condition check. No additional flashover is allowed.

4.3. Isolators

For testing of isolators [14] has to be considered. Testing is requested according to salt fog test method and/or the solid layer method.

With a current of 100 mA driven through a resistive load, the ripple factor must be ≤ 3 %. Voltage drops ≤ 10 % are acceptable. As per the Technical Report, voltage drops between 10 % and ≤ 15 % can be tolerated.

Voltage overshoot shall not exceed 10 %. In case of flashover between 5 % to 10 % overshoot, the test is considered invalid and has to be repeated. Under salt fog test, the DUT is sprayed with a solution of defined salinity. Test duration is 1 h for salt fog test.

The solid layer method defines a pollution layer to be put on the DUT. When test voltage level is reached, even fog is generated to produce a defined wetting rate of the pollution layer. Test lasts until flashover occurs or the risk of flashover is negligible. The risk can be assumed by evaluation of the leakage current.

5. SUPERIMPOSED VOLTAGE TESTING

5.1. DC and Impulse Testing

Only cables are tested with impulse voltages superimposed on the DC voltage. Table 1 shows possible configurations of the combined voltages and the configurations. The indices used are “1” for lightning and “2” for switching impulse, while “S” stands for same and “O” for opposite polarity.

Table 1: Combined voltage tests

Polarity DC	Lightning Impulse U_{P1}	Switching Impulse U_{P2}
Pos.	Pos.	Pos. U_{P2S}
	Neg. $-U_{P1}$	Neg. $-U_{P2O}$
Neg.	Pos. U_{P1}	Pos. U_{P2O}
	Neg.	Neg. $-U_{P2S}$

Depending on the type of cable and the intended use, only some of the impulses have to be considered for testing. For non polymeric cables and polymeric cables for LCC converters this is $–U_{P2O}$; U_{P2O}; $–U_{P1}$; U_{P1}. For VSC cables U_{P2S} and $–U_{P2S}$ apply additionally. Polymeric cables do not have to be tested with superimposed lightning impulse if the cable will not be exposed to lightning due to installation.

The amplitude of the superimposed impulse depends on the overvoltage the cable can experience. For same polarity of DC voltage and impulse, the maximum voltage is often limited by surge arresters installed in the converter station while the peak amplitude for opposite polarity may be limited by the converter itself. Testing is to be done with at least 1.15 * the highest possible amplitude.

5.2. DC and AC Testing

Valves for VSC converters have to be tested with DC and AC test voltage superimposed. Testing is split into a short term (10 s) and long term (30 min) test. For short term testing, an energy storage capacitor might be sufficient. Eventually this can be the inherent capacitance of the DUT itself. For long term testing a separate DC power source is mandatory.

The test levels are defined by the valve and converter station design. The voltage is brought up to the 10 s test level, reduced to the 30 min test level and is switched off.

6. IMPACT ON TEST EQUIPMENT

Testing of DC equipment is very demanding and very special compared to AC or impulse testing. The following points have to be considered:

6.1. Long term testing

Typical test systems are designed for short term testing, i.e. some hours. For non polymeric DC cables, test duration is up to 10 days continuous at one polarity and 30 days of voltage with polarity changes, rest times are not considered. For development testing of polymeric cable the durations are as high as 160 days of continuous negative test voltage, the complete development test procedure lasts for a minimum of 360 days with only very short interruptions on the test voltage level.

Thermal design: Test equipment is designed for application testing under consideration of test durations and cycles as required by standard and customer request. Keeping the on-time to a minimum gives the advantage of higher output ratings or more compact designs at reduced costs.

Electrical design: For shorter testing durations, higher electrical stress can be accepted to reduce size, weight and cost of the system.

Controls and regulators: According to [15], the test voltage has to be within ± 1 % for test durations below 60 s and ± 3 % for test durations exceeding 60 s. As changes of the input voltage are typically rather slow within some hours, over a testing period of 160 days it can be assumed that the input voltage will vary within the ± 10 % limit for the power grid. The regulator of the test equipment has to compensate for this deviation or additional measures to stabilize the input voltage have to be taken.

6.2. High current testing

For DUTs with large capacitances, the charging current has to be sufficiently high to reach the test voltage in a reasonable time. Considering 2 min for PR, charging time has to be less than 1 min. As the DUTs have capacitive characteristic, the charging current decreases and should reach steady state current within this 1 min. While PR is also required for type and development tests on dc cables, especially cable parts, routine tests and after installation tests are done on the complete cable installation with length well above 100 km. Even with a high current power supply, charging can take several hours under these conditions. The DC equipment must also be compact and mobile to bring it on-site especially for after installation tests.

For testing insulators, electrodes, etc. pollution and wet tests maybe required. Because of the reduced insulation resistance and discharges, power sources capable of large currents are necessary to reduce feedback effects on the discharges. Currents of up to 2 Amperes are considered to be necessary [13].

6.3. Stored energy

As mentioned above, time for PR is limited to 2 min for most applications. As DC testing involves charging of large capacitances, they also have to be discharged in a reasonable time. This is true not only for standard testing like PR, but also in case of emergencies like failures of DUT, testing equipment, etc. and for undefined conditions like power outages.

With impulse generators and AC systems earthing of the complete system is rather easy. Under DC conditions, earthing of a fully charged DUT might cause arcing over a considerable time endangering not only the test equipment and the DUT but also personnel operating the system. For this reason, additional bleeding resistors might be necessary for testing DUTs with large capacitances. They help to discharge the DUT to safe levels within acceptable time. The bleeding resistor will increase the leakage current making a power source with higher current rating, for charging and steady state current, necessary.

6.4. Long term stability

The considerations on thermal and electrical design for long term testing also apply for the measuring equipment. Stressing the equipment with heat and electrical field over a long time will affect the aging of the components and impact the long term stability of the measuring device.
Long term stability can be estimated from experience and material parameters of the used components, mainly capacitors and resistors for the high voltage dividers and the low arm.

6.5. Ripple measurement

Although the ripple factor is as important for describing a DC voltage as the frequency is for AC voltages, its measurement was often not realized. This is due to the fact that a separate measurement system had to be used for the ripple measurement. For most DC generators, the ripple frequency is the power frequency or a multiple of it. In praxis, the limit requires a bandwidth of approx. 7 times of the ripple frequency. For Greinacher cascades the bandwidth must be 350/420 Hz and 700/840 Hz for symmetrical voltage doubler circuits for power supplies with 50/60 Hz mains frequency.

HVDC dividers realized as resistive dividers have very limited bandwidth and may produce unacceptable measuring errors for frequencies of a few Hz already: Capacitive compensated dividers are mandatory for ripple measurement.

Modern digitizers provide sufficient resolution and capabilities to measure the arithmetic mean value and ripple with the required uncertainties within one measurement device.

7. DESIGN OF UHV DC TEST EQUIPMENT

Generation of HVDC voltages for test purposes is well known for several decades. Typical designs implement a Greinacher cascade. Here, a different approach is presented.

Our modular DC generators were originally designed for powering industrial electron beam systems which are operated 24 hours per day. The main requirements for these applications include uninterrupted operation in the presence of continuous flashovers and a mechanically compact package. Additionally, very high voltages are required with stable voltage regulation and small voltage drop during transient or steady state changes in load impedance. These requirements are similar to those required for HV testing and a line of modular test systems has been developed employing the best features of the industrial designs. Systems up to 1800 kV have been delivered and installed to date. A system with 2200 kV and 30 mA continuous current is projected. For increased current ratings, the modules can be configured in parallel. 200 mA short term and 150 mA continuous current have been realized for a 1000 kV outdoor system.

Up to date, the design has been applied to a 1 stage 3 phase system. The current rating is 2 A at an output voltage of 300 kV for pollution and icing testing.

7.1. Theory of Operation

Fig. 1 shows the electrical diagram for a 1 phase 200 kV single stage DC power supply.

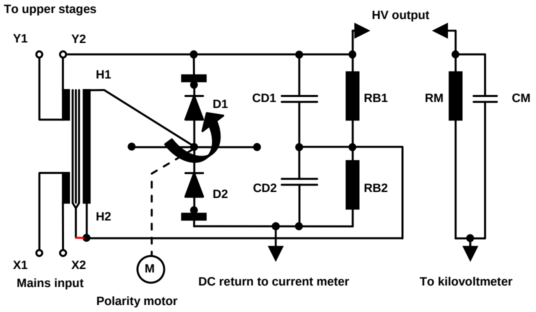


Fig. 1: 200 kV single stage doubler circu*it*

Each stage of the system has a transformer feeding a symmetrical voltage doubler circuit. The tertiary winding on each transformer supplies voltage and power to upper stages in the cascade. The HV transformer core is electrically connected to the midpoint of the DC voltage doubler capacitors. The H2 terminal of the step up transformer is also connected to the mid DC potential point. The result of this connection technique is the establishment of a uniform DC voltage division in the HV transformer while maintaining a compact design.

The diodes are connected on a rotary switch which mechanically enables the system to change from positive to ground to negative polarity within seconds. The control will reduce the grounding and reversing speed for normal test conditions to reduce stress on the switch. For easy handling, modules rated 400 kV and 600 kV are available. The height for a 600 kV module is approx. 2.8 m.
The compensated divider is located inside the module for the measurement of the arithmetic mean value and the ripple factor of the DC voltage. The divider can be connected/disconnected on the outside of the module for calibration purposes.

Fig. 2 shows a 1000 kV DC system with a 15 min current rating of 45 mA and a continuous current rating of 10 mA for testing of converter transformers. The system consists of the damping resistor (A), the DC cascade (B), the bleeding resistor (C) and a coupling capacitor (D) for PD measurement. The bleeding resistor is not necessary in most applications. While it supports the damping resistor and makes connections of the DUT a little easier, its main purpose is to fast discharge the capacitance of the system of converter transformer and coupling capacitor for PR times in less than 2 min. The damping resistor protects the DC cascade in case of failure or flashover by limiting the current through the cascade and the diodes. It acts also as a filter for blocking the switching noise of the diodes for PD measurements.

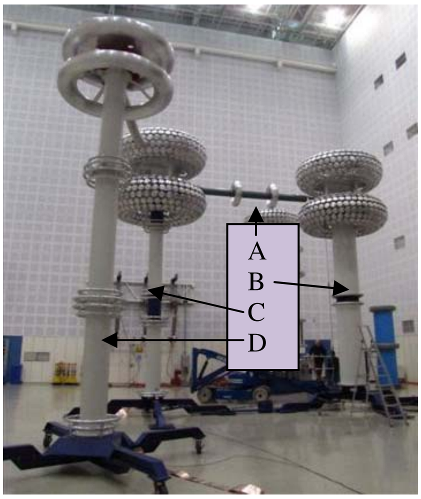
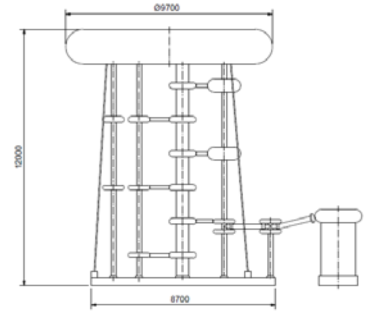
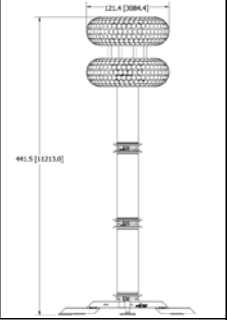


Fig. 2: UHV DC system during commissioning

7.2. Advantages

The generator, as well as the coupling capacitor and the bleeding resistor, is made of stacked FRP cylinders. Together with the compactness of the generator modules, it leads to a light and modular design. Fig. 3 visualizes the space requirements for a classic Greinacher cascade and the modular design with comparable technical specification.





	Greinacher Cascade	Modular Cascade
Height [m]	12	11.2
top electrode [m]	9.7	3.1
Voltage [kV] @ ripple < 3 %	1500	1600 1800 (@ 5 mA)
Current [mA]	20 cont.	10 cont. / 20 (4 hr ON)

Fig. 3: Greinacher cascade 1500 kV 20 mA left
Modular cascade 1600 kV 20 mA right

Thanks to this design, it is easy to move the test system in the test lab with help of air cushions. The compact modular design allows also easy on-site testing under fair weather, e.g. of cables, with very short set-up time. Generators with outdoor design are also available.

Expansion to higher voltages can be done by simply adding modules to an existing system, without reducing the current rating of this system.

With an additional front end, it is even possible to split a system into two independent test systems, for example for bipolar operations.

Dust is a major problem for DC test equipments. As the active parts of our generators are inside a limited number of FRP cylinders, the test system is easy to clean and requires less maintenance than a Greinacher cascade.

High outputs currents can be achieved by parallel connection of modules.

7.3. Influences on Voltage Stability

The changes in mains voltage, usually less than 10% and rather slow, cause the DC output voltage to change proportionally. The control unit keeps the test voltage within 1 % of the target value. In case of an instantaneous change in the mains voltage of 10 %, the automatic voltage control will readjust the output voltage in approximately 1 s. When a test object is subjected to DC voltage, the equivalent load resistance can change due to heating effects, dielectric absorption, glow corona discharges or other phenomena. When the DC output current changes instantaneously from no-load to full resistive value, the output voltage will drop linearly as long as the mains voltage is fixed. The typical value of the voltage drop from no load to full load current is < 15 %. During testing, the transition between no load and full load appears rather slow and will be compensated by the static control to ≤ ± 1 % of target value.

Corona, surface discharges, intense streamers, etc, cause transient changes in the load resistance and capacitance. Due to system limitations in power supply and regulation, these transients cannot be compensated by the control and voltage regulator. Their influence can be reduced with systems with higher current rating or by increasing the HV capacitance.

The voltage drop can be approximated by:

$$\Delta U_{DC} \approx \frac{\text{peak DC current} \times \text{time duration}}{\text{"Capacitance" of DC generator}}$$

For example, with a 1200 kV generator for an output voltage drop of < 10 %, a transient streamer drawing a current of 100 mA can burn up to 2 ms before the voltage drop exceeds 10 %. With an increased capacitance the arc could last longer.

8. CONCLUSION

The current standards for HV DC testing have been analysed and requirements for testing equipment have been derived. An additional solution for UHV DC generators to the common Greinacher cascade has been presented.

Although generation of DC voltage is well known for decades, development is still ongoing. Recently, the measurement of the ripple factor has been implemented into the system without the need for additional external measuring equipment. Further improvements will be done to reduce the PD level of the DC cascades. Another area of research is to increase the current capabilities of the generator while keeping the compact, modular design with all its advantages.

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