PD REQUIREMENTS FOR TESTING HV DC EQUIPMENT AND THEIR IMPACT ON HV DC TEST EQUIPMENT

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Abstract: The growing demand for reliable and environmental friendly energy has led to an increased number of HV DC transmission systems as well as increased HV DC distribution levels. Researchers and manufacturers worldwide push the limits further to meet tomorrows demand. At the same pace that the HV DC equipment is advancing, the testing equipment for HV DC equipment has to advance as well so that manufacturers worldwide push the limits further to meet tomorrows demand. While PD measurements are well accepted and commonly used within the High Voltage community to evaluate the performance of an insulation for HV AC applications, their behaviour and performance is not as well known for HV DC applications. This paper evaluates common standards for testing of HV DC equipment like converter transformers, bushings, valves, etc. Special emphasis is placed on the pass/fail criteria with respect to their appropriate PD acceptance values. Results achieved in practice vs. the required partial discharge limits in the appropriate standards are reviewed. An emphasis is placed on the necessary circuit components and design considerations required to achieve these results. The impact on the design and construction of the required test laboratory and the HV DC test equipment are detailed along with descriptions of the performance requirements necessary to achieve the desired results in factory tests.

1 INTRODUCTION

Emphasis today is put on environmental friendly energy. For the energy generation from water, wind or sun, geographical limitations have to be considered. While former power plants have been placed relatively close to the centers of energy consumption, this is not possible for renewable energies any more. As a consequence, energy has to be transported over long distances. To keep the losses reasonable, HV DC installations seem to be a suitable solution.

Although HV DC connections are existent for quite some decades, general interest and development was with HV AC. The changes in power generation as well as the advances in power electronics make the usage of HV DC more often an economical alternative to the classic HV AC. Besides the economical advantage there are also technical advantages as well.

With the growing demand for HV DC technology appropriate tools need to be provided to verify the quality of the insulation and components. The key value for describing the insulation quality for AC components is the widely accepted PD measurement.

Considering the acceptance and importance of this key value for AC equipment, it is not surprising that manufacturers and customers want to transfer their grown knowledge on DC equipment as well. The physics for partial discharges are the same under AC or DC condition. However, the behaviour and evaluation is different and the experience grown for AC PD measurement cannot be directly applied to DC conditions as well. It is astonishing, that, despite the importance for AC, relatively little research and publications are done on DC PD measurement and their interpretation. Only two books are known to the authors explicitly dealing with that topic. Even more astonishing: while cables have the highest requirements for AC PD measurement, there is no standard or recommendation yet even mentioning PD for DC cable testing [1-3].

2 PD ACCEPTANCE CRITERIA ACC. TO IEC STANDARDS

2.1 Converter Transformers, Smoothing Reactors and Bushings

PD have to be measured during withstand and polarity reversal (PR) testing [4-6]. While the test procedure is similar for converter bushings, smoothing reactors and bushings, the PD acceptance criteria vary slightly in respect to time and number of allowed pulses, see Table 1 for details.

Withstand testing is performed for a 2 h period at positive polarity. The PD level is measured only through the last 30 min of the withstand test. PR testing is done starting at negative polarity for 90 min, switching to positive polarity for 90 min followed by a 45 min period of negative polarity again. Transition times do not have to exceed 2 min between each reversal. Discussion is ongoing to extend the 2nd negative polarity period to 90 min as well. The differences between those 3 apparatus are with the number of allowed pulses and the time frames for measurement.

	Converter Transformers	**Smoothing Reactors**	**Bushings**
Withstand Testing			
Time frame	Last 30 min *(Last 10 min)*	Last 30 min *(Last 10 min)*	Last 30 min
Number / Amplitude of pulses	≤ 30 pulses ≥ 2000 pC *(≤ 10 pulses ≥ 2000 pC)*	≤ 30 pulses > 2000 pC *(≤ 10 pulses ≥ 2000 pC)*	≤ 10 pulses ≥ 2000 pC
PR Testing			
Time frame	30 min after PR *(Last 10 min of 30 min period)*	Any 10 min window without first 5 min of polarity	Any 30 min sliding window except reversal periods
Number / Amplitude of pulses	≤ 30 pulses > 2000 pC *(≤ 10 pulses > 2000 pC)*	≤ 10 pulses ≥ 2000 pC (≥ 500 pC shall be recorded)	≤ 10 pulses ≥ 2000 pC

Table 1: Details of acceptance criteria

Limiting the allowed number of pulses within the last 10 min of the 30 min period is to verify the pulse rate is constant or decreasing.

2.2 Valves for LCC and VSC

For valve testing, the test acceptance criteria for PD measurement are the same [7-8]. For these components the acceptance criteria is graduated, see Table 2 for details.

PD pulse level	**Number of pulses per min**
> 300 pC	Max. 15
> 500 pC	Max. 7
> 1000 pC	Max. 3
> 2000 pC	Max. 1

Table 2: Details of acceptance criteria

During testing with superimposed AC and DC voltages, additionally the periodic peak value has to be monitored. The allowed value is < 200 pC.

3 PHYSICS OF PD UNDER DC ELECTRIC FIELD

3.1 General considerations

The physical processes for PD are the same for AC and DC electric fields. Due to the electric field and voltage distribution inside the insulation, the breakdown voltage is exceeded for a part of the insulation and the partial discharge eventually occurs. The long time scale under DC requires the consideration of processes which can be neglected under AC conditions.

Testing with DC voltage can be divided into 4 stages according to the electric field distribution inside the insulation [9].

1. Capacitive stage
2. Transition stage
3. Resistive stage
4. Relaxation stage

3.2 Capacitive stage

A change in voltage can be considered as charging / discharging of capacitances. In this stage, the voltage and electric field distributions inside the insulation are defined by the permittivity of the involved insulation materials. Considerations for AC PD apply and the repetition rate can be estimated:

$$n \approx \frac{C_{insulation}}{C_{void}} \cdot \frac{du}{dt} \cdot \frac{1}{u_{br}} \qquad [1]$$

With n repetition rate, $C_{insulation}$ and C_{void} being the capacitance of the insulation and the void, du/dt being the voltage rise and u_{br} the breakdown voltage of the void. As the capacitances and the breakdown voltage are defined by the geometries and material of the insulation, the repetition rate is dependent on the voltage rate of rise.

3.3 Transition stage

During transition stage, the voltage rate of rise decreases. The field distribution gradually changes from capacitive to ohmic field distribution.

3.4 Resistive stage

In this stage, the field is defined by the conductivities and the current flowing inside the insulation. One must consider that the conductivity is largely depending on temperature, moisture content, etc. For this reason, the field distribution inside the insulation is completely different than from AC condition. This is not only true for insulations involving two or more different materials like oil paper insulation in transformers, but might also apply for insulation made of one homogenous material. For example the maximum field strength inside a polymeric cable insulation does not have to be on the inner conductor. Under load condition, the heating of the inner conductor enhances the conductivity of the insulation end the electric field is pushed into the cooler insulation. The maximum field strength can than be found in the area of the sheath.

Additionally, high insulation resistance help build up space charges inside the insulation. Under steady state conditions these space charges help to reduce electric stress on voids. However, in the case of a discharge, a large quantity of charges is stored in close vicinity to the void. As a consequence, discharge levels are typically high for DC PD.

The time dependent voltage across a void can be described as:

$$u_{void} = \frac{R_{void}}{R_{insulation} + R_{void}} \cdot (1 - e^{\frac{-t}{\tau}}) \cdot U \qquad [2]$$

With u_{void} voltage over void, R_{void} and $R_{insulation}$ being the leakage resistances and U the voltage across the insulation. The time constant τ can be calculated according to:

$$\tau = \frac{R_{void} \cdot R_{insulation}}{R_{void} + R_{insulation}} \cdot (C_{void} + C_{insulation}) \quad [3]$$

From these considerations it follows, that the inception voltage is hard to define under DC condition. If the voltage is gradually increased, the voltage above the void increases until breakdown. If the voltage rate of rise is low, it can take up to an infinite amount of time to recharge the void to breakdown voltage. For this reason an inception voltage can only be defined for a certain, defined repetition rate.

For a successful discharge not only the voltage has to be sufficiently high, but a start electron must be present. Secondly, the voltage across the void will not drop completely to 0 but to some statistical value. For this reason, the starting conditions vary from discharge to discharge even under a constant DC voltage. It can be shown, that the error is < 10 % for a ratio of voltage over the sample to inception voltage of sample of ≥ 5.

The repetition rate is proportional to the current inside the insulation. During the transition stage the current steadily decreases until the resistive stage is reached. To verify this behavior, the standards for converter transformers and smoothing reactors define a different number of pulses for the last 10 min during the 30 min testing period.

3.5 Relaxation stage

During relaxation, the applied voltage is gradually reduced and the device under test eventually earthed. During this phase, the rate of PD decreases. Due to high resistive values of the insulation, space charges have been build up inside the insulation. As a matter of fact, discharging of large capacitive loads like cables may take even longer for discharging than for charging.

3.6 Polarity Reversal

During PR the polarity of the applied external voltage is changed within 2 min. The considerations regarding capacitive, transition and resistive field apply. The space charges inside the insulation have a great influence on the transient field distribution inside the insulation. The superposition of external field and internal field due to space charges can cause very high local field strength with amplitudes above 100 % of normal conditions for paper-oil insulation [10].

4 CONSIDERATIONS FOR DC TEST EQUIPMENT

The DC PD performance of the test equipment is very much influenced by the surroundings. It is most important, that DC generators are kept clean.

During operation, the housings but also objects in close vicinity will build up electric charge on their surface due to electrostatic charging. Unfortunately, this causes dust particles and dirt to be attracted to the charged up surfaces, including the DC generator and the system components. Therefore, external discharges are a very common problem during DC testing.

The only solution to address this problem is to keep the laboratory and the generator very clean. One might think that using an outdoor housing could help reduce the external PD. While the outdoor housing does not necessarily reduce the field strength along the surface, the horizontal sheds will help dust to settle and stay on the surface. Therefore it is expected that the long term PD performance of an outdoor housing is reduced compared to an indoor housing due to contamination.

Therefore small compact DC generators shall be preferred to the larger Greinacher cascade with approx. 60 % more electrode surface [11], see Fig. 1.

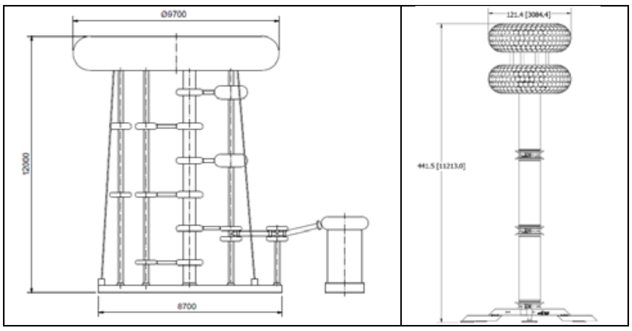

Fig. 1: Greinacher cascade 1500 kV 20 mA (left)
Modular cascade 1600 kV 20 mA right

According to [12], the background noise level is recommended to be less than 50 % of the permissible PD magnitude. Considering the acceptance criteria on HV DC apparatus, a DC PD level of the generator of up to 150 pC is suitable for all withstand testing. The ground noise level including the

DC generator for PR testing can be as high as 1000 pC.

Fig. 2 shows a typical stacked voltage doubler HV DC system with the DC generator, the series damping resistor and the coupling capacitor connected.

Fig. 2: Stacked voltage doubler system for 1.2 MV during erection

4.1 DC generator

In the common types of HV DC generators for test purposes, like Greinacher cascade or stacked voltage doubler systems, diodes are used for rectification. The switching of the diodes generates noise which will be detected by the measuring device as PD. The noise can be gated under the following conditions: The gating is set on a voltage level well below test voltage level and is not to be altered. The gating time shall be less than 2 % of the accumulated test time. In case of several mains coupled pulses the gating window may be extended to < 10 %.

The authors generally do not recommend gating. As there are tight restrictions on permissible pulses counts or pulse rates, gating of 2 % to 10 % of the test duration might be critical.

Instead it is recommended to use classic filtering of switching noise created inside the DC generator. Depending on the required PD level, the damping series resistor will provide 20 dB of damping. An additional filter choke can be installed as well.

4.2 Series damping resistor

The series damping resistor is for protection of the DC generator and limits the maximum current of the system under fault condition. Besides, the resistor acts as a filter for the switching noise of the diodes. For this reason it is important that no external pulses on the resistor itself occur. The same principles apply to reduce the field strength on the surface of the damping series resistor as under AC conditions. With double toroids, the resistor can be placed inside the field shadow between the electrodes.

4.3 Coupling capacitor

The PD performance of the coupling capacitor is critical for the performance of the complete system. It is placed behind the blocking impedance. For this reason any PD from the coupling capacitor will be recorded with the full level. In a test arrangement with a test object, PD coming from the coupling capacitor cannot be separated by filtering from PD of the test object. Both, the balanced circuit arrangement or polarity discrimination arrangement will detect it.

4.4 PD measurement

The characteristics of the PD under DC voltage are very different compared from those with AC voltage. The interpretation of PD under DC voltage is momentarily not that advanced as it is for PD under AC voltage.

Numerous discharges may occur when the applied voltage is changing, especially during a polarity reversal phase. After stabilisation of the applied voltage, the pulse repetition rate will decrease with the time. Then in steady state, the discharge pulse repetition rate can be very low, with less than one pulse per minute. Only pulses generated by the equipment under tests must be counted and their parameters recorded.

Therefore it is important to distinguish between internal partial discharges within the test object and external noise.

Different solutions can be used to perform the discrimination like, for example, the classic balanced method or the polarity discrimination method. These discrimination methods have to be implemented in the PD detectors.

Due to the blocking impedance between system and coupling capacitor, these methods are not suitable for verification of the generator performance.

4.5 Laboratory

For sensitive DC PD measurements, the quality of the test lab is essential and the same considerations as for AC test labs have to be applied. These include the following:

1. Shielding of test area via shielded cabin or complete shielded test lab for larger test objects
2. Low impedant ground insulated from the common factory ground
3. Filtering of all input powers via shielded isolation transformer and low voltage line filters
4. Sufficient spacing
5. Grounding of metal parts

The electric field charges surrounding objects. Due to the high insulation resistances, the time constants for charging can be very long. Together with long test durations this can lead to external impusles which disturb the PD measurement. As these pulses in general have a rather low repetition rate they are pratically impossible to locate by classical means.

5 PD PERFORMANCE OF STACKED VOLTAGE DOUBLER

For the stacked voltage doubler system [13] shown in Fig. 1, the PD rating has been defined between customer and producer according to Table 3. The measurement was performed with the system connected to a coupling capacitor. The system was calibrated to 50 pC with the ground noise level set to 40 pC. The PD measurement was performed for each polarity for 30 min after applying the test voltage level.

Configuration	Voltage [kV]	PD level [pC]	PD rate [/min]
2s	960	> 50	< 10

Table 3: System specification

Although the specification is not limited by a maximum PD level, no pulses above 80 pC have been observed.

6 CONCLUSION

As pointed out in this paper, the existing knowledge of AC PD measurement and interpretation cannot be directly applied to DC conditions. This is being considered in the fact, that the standards on apparatus testing do not define one maximum allowed PD level. Rather the time dependent behaviour of PD pulses and the distribution of pulses during the testing period is critical. Depending on the application, pulses up to 1000 pC from the test source and the coupling capacitor are acceptable for most test requirements.

A test system with stacked voltage doubler cascade could be realised for 960 kV with a maximum pulse count of 10 pulses per minute. The maximum PD level achieved is below 70 pC for both polarities. The system performance exceeds all requirements even for testing of the most demanding UHV DC equipment. It enables researchers to further investigate and understand PD under DC conditions to take on the next level of UHV DC distribution.

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