PD measurements on a DC gas-insulated transmission line (DC GIL) conducted in the frame of the Prototype Installation Test according to recommendation of CIGRE JWG D1/B3.57

TE-Messungen an einer DC gasisolierten Übertragungsleitung (DC GIL) im Rahmen des Prototype Installation Tests gemäß Empfehlungen der CIGRE JWG D1/B3.57

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Abstract

There is a growing demand for DC long distance transmission, as the power generation increasingly takes place far away from the load centres. In many countries the transmission lines in question have to be installed underground, due to environmental concerns and political decisions. Besides DC cables DC gas-insulated lines are an option. To gain long-term experience with this type of technology, CIGRE JWG D1/B3.57 suggests a Prototype Installation Test with a test duration of one year, by which the dielectric DC and overvoltage stress under real service conditions are reproduced and investigated. The gas-insulated line considered in this paper is designed for a rated DC voltage of ±550 kV and a current carrying capability of 5000 A. It is installed at a HVDC test facility at the Technical University of Darmstadt. For a long-term test with sufficient significance the insulating conditions of the test arrangement before and during long-term testing have to be monitored to observe the insulation performance. For this purpose an ultra-high-frequency partial discharge (UHF PD) monitoring system is installed, which is adapted for recording of PD under DC voltage stress. This system shall also be proven for condition monitoring of future DC GIL installations.

With this regard, the UHF PD monitoring system installed and the method to detect and identify possible PD defects under DC voltage will be discussed. The measuring sensitivity of the installed UHF monitoring system was tested according to the recommendations given in CIGRE TB 654. As the DC GIL under consideration is a new design, sensitivity verification step 1 had to be performed first on a typical test assembly. The sensitivity verification step 2 was carried out within the frame of the commissioning tests of the test arrangement. The UHF PD signal attenuation and the sensitivity obtained between two adjacent sensors will be given. By means of the attenuation profile the sensor distance for future DC GIL installations can be estimated.

During commissioning of the 100 m DC GIL prototype with DC test voltage a probable PD defect was detected by the monitoring system. Time of flight measurements were carried out in order to localise the defect. As no phase correlation of the PD pulses exists at DC voltage, pulse sequence analysis (PSA) had to be applied for PD defect identification. For this purpose investigations on the 100 m long DC GIL installation were performed using PSA methods at rated voltages. Based on pre-investigations of typical PD defects under DC voltage, briefly given in this report, the PD defect detected onsite could be identified by PSA analysis. The analysis of the measured PD signal showed a good agreement with one reference signal analysis gained in the pre-investigations.

1 Introduction

As the power generation increasingly takes place far away from the load centres, DC long distance transmission is of special interest. Due to environmental concerns and political decisions, in many countries the transmission lines in question have to be installed underground. Besides DC cables DC gas-insulated lines are an option. Up to now, only a few gas-insulated HVDC systems are in operation worldwide. In consequence, little service experience and only few information about the long-term capability of this type of technology are currently available.

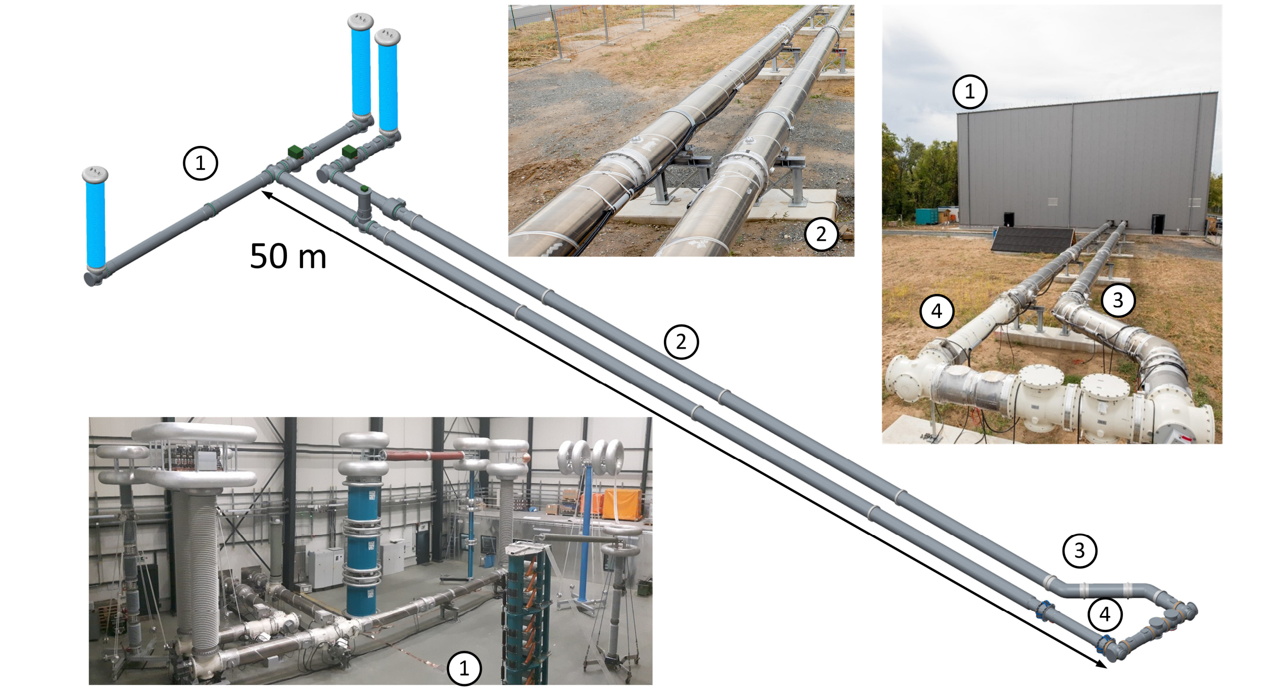


Figure 1: Test arrangement [2]

Before the installation in the grid, customers might desire a proof of a stable long-term performance under real service conditions of the total gas-insulated system to ensure the required technology readiness level. As no standards for (dielectric) testing of HVDC gas-insulated systems are currently in place, CIGRE Joint Working Group JWG D1/B3.57 has established the first testing recommendations [1]. Among others, a Prototype Installation Test is suggested to gain long-term experience with this type of technology. During the test duration of one year the dielectric DC stress and overvoltage stress under real service conditions are reproduced and investigated. To ensure a test with a sufficient significance the insulating conditions of the test arrangement is monitored before and during long-term testing by partial discharge (PD) measurements.

Much experience has been gathered with PD testing of gas-insulated AC systems. Therefore, CIGRE JWG D1/B3.57 recommends to apply AC voltage for PD measurements at routine tests and onsite tests. PD measurements under DC voltage are of interest, e.g. after commissioning before putting into service or during service.

The following report describes the test arrangement and the PD monitoring system installed based on the UHF method. Furthermore, various measuring results and their analysis under AC and DC voltage are presented.

2 Test arrangement

The DC GIL test arrangement (Figure 1) is constructed of eight straight modules (2) and two 45° DC GIL angle modules (3). The total current loop is approximately 100 m long, installed above ground and mostly outdoor. Approximately 35 insulators plus several insulating rods in switching devices are installed in the overall test assembly [2].

The test equipment for feeding the DC GIL with current and voltage is installed in a high voltage hall (1). The current loop of the test setup is connected by ±550 kV DC GIS modules and a lateral compensation module (4). The test arrangement is equipped with UHF PD sensors, optical light sensors and temperature measurement systems for monitoring of the conductor and the enclosure temperatures (pyrometers and PT100 sensors), besides the mandatory monitoring systems such as gas density meters. More details about the basic test circuit are reported in [2].

The locations of the UHF sensors are given in Figure 2. The GIL section is fitted with the sensors nos. 4…8. Sensors nos. 1…3 are installed in the connecting modules to the current and voltage source.

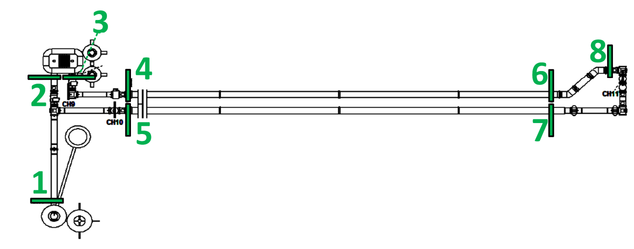


Figure 2: Locations of the UHF sensors

3 PD monitoring on the DC GIL prototype

For PD measurements at routine tests and onsite tests and for PD measurements under DC voltage, e.g. after commissioning before putting into service or during service an UHF PD monitoring system is installed. For recording of PD under DC voltage stress it is correspondingly adapted. This system shall also be proven for condition monitoring of future DC GIL installations.

3.1 Tests for sensitivity verification

As a charge calibration of the UHF method is not possible for gas-insulated systems, a two-step process is recommended to verify that the applied systems properly function at a requested level of sensitivity and are able to detect defects with an apparent charge of e.g. 5 pC [3]

In step 1, mostly carried out in in the laboratory, an artificial PD pulse magnitude is determined equivalent to e.g. 5 pC caused by a real defect. The same artificial PD pulse magnitude will be applied later on-site during step 2. The second step is carried out on-site on the installed gas-insulated system (same design and same type of sensors as used in the laboratory test). By injection of the determined artificial impulse magnitude, the test verifies, that the installed sensors, UHF measurement and monitoring system have sufficient sensitivity to detect signals from the real PD defect defined in step 1.

3.1.1 Sensitivity verification, step 1

As the DC GIL under consideration is a new design, sensitivity verification step 1 had to be performed first. It was conducted on a typical GIL structure presented in Figure 3.

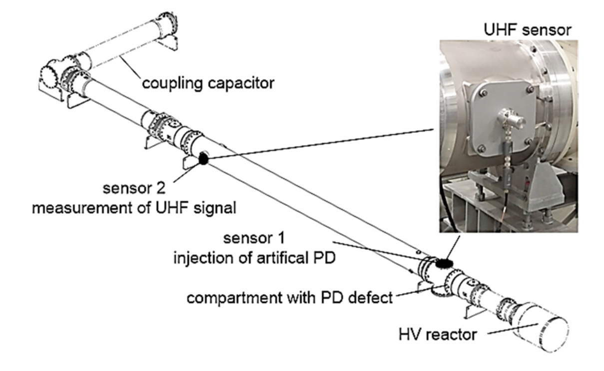


Figure 3: Test arrangement for sensitivity verification step 1

Two insulators and 10 m GIL were present between sensor 1 and sensor 2. As PD defect a mobile particle was chosen causing a PD magnitude of 5 pC according to IEC 60270. The UHF signal was acquired in the time domain as well as in the frequency domain.

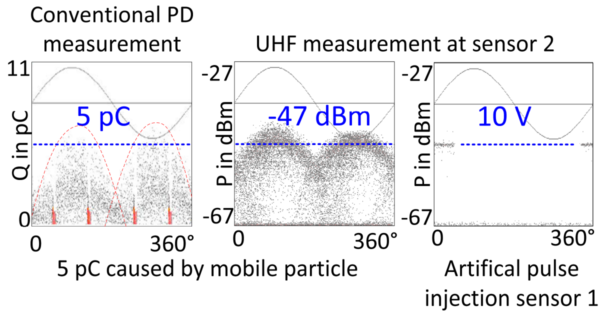
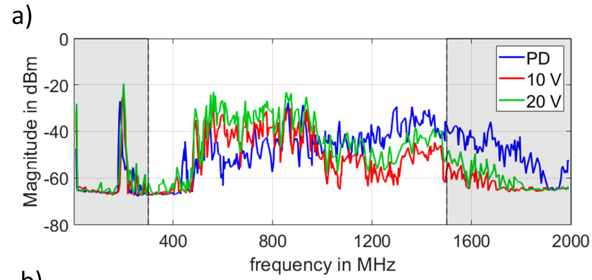


Figure 4: Test results of sensitivity step 1 in the time domain

The results in the time domain are shown in Figure 4. The PD signal of 5 pC measured by the conventional method (Figure 4, left) corresponds to a -47 dBm UHF signal (Figure 4, middle). The equivalent UHF signal generated by an artificial pulse amounts to 10 V (Figure 4; right).

Figure 5 presents the results in the frequency domain. Figure 5 a shows the UHF spectrum caused by the mobile particle generating 5 pC and the spectra generated by an artificial pulse of 10 V and 20 V, respectively. For a better assessment which artificial pulse fits best, the spectra are evaluated with the aid of statistical tools (Figure 5 b). The evaluation of the spectrum's average amplitude (AA), average power (AP) and maximum power (MP) is carried out in the frequency range between 300 and 1500 MHz.

a)



b)

	Average Amplitude AA in dBm	Average Power AP in dBm	Maximum Power MP in dBm
5 pC PD	-47.1	-39.8	-27.5
Calibrator 10 V	-49.9	-41.3	-28.5
Calibrator 20 V	-44.3	-35.1	-23.0

Figure 5: Sensitivity check step 1 (frequency domain)

a) UHF spectra caused by a mobile particle generating 5 pC and an artificial pulse of 10 V and 20 V

b) Evaluation of the spectra by statistical tools

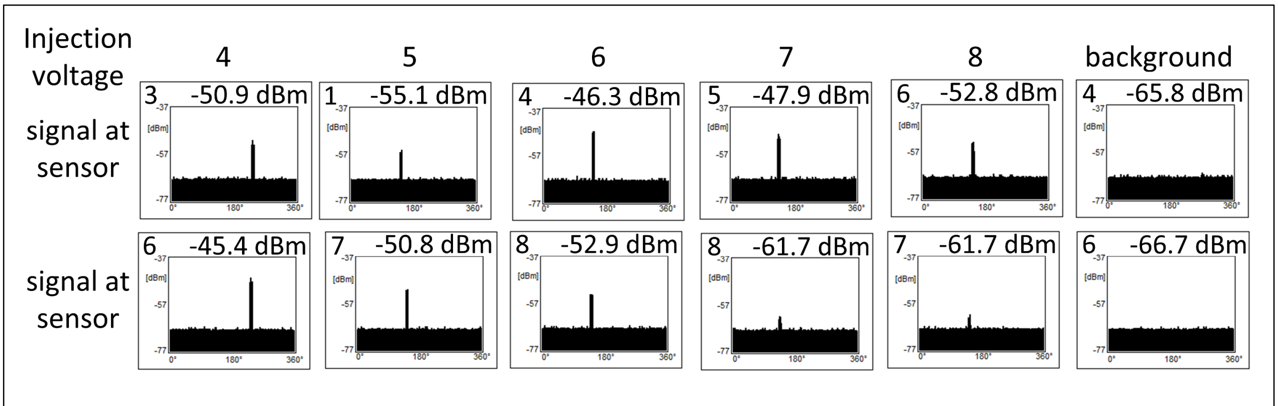


Figure 6: Results of Sensitivity verification, Step2

The ranges below 300 MHz and above 1500 MHz are disregarded. Below 300 MHz the spectrum is affected by external noise. Above 1500 MHz the injected artificial pulse is not steep enough to generate signal amplitudes comparable to those of the real PD pulse. In the case under consideration the 10 V pulse magnitude fits quite well.

The injection voltage for sensitivity verification test step 2 is therefore 10 V, to prove that a 5 pC mobile particle PD defect can be detected between two adjacent sensors.

3.1.2 Sensitivity verification, step 2

The sensitivity verification step 2 was carried out within the frame of the commissioning tests of the test arrangement. The positions of the UHF sensors are illustrated in Figure 2. The artificial pulse of 10 V was injected into one sensor, and the corresponding PD signal was recorded at the adjacent sensors. The acquired signals are shown in Figure 6.

The sensitivity verification demonstrates that PD defects distinctly lower than 5 pC can be detected in the sections between two adjacent sensors at all GIL parts.

Additionally, the attenuation performance of typical GIL sections were investigated. E.g. by injection of artificial impulses in the range of 30 V at sensor 3 or 4 respectively, the signal attenuation between sensor 4 and 6 and between 6 and 8 was measured. The attenuation of these two sections is mainly determined by the insulators, which are of different types in both sections. In case of a star-shaped tripod insulator the attenuation is mainly caused by changes in the geometry of the inner conductor and the enclosure, respectively. The attenuation of disc-type insulators is determined by the changes in permittivity of the epoxy resin compared to that of the pure gas. Both effects lead to changes in the surge impedance of the transmission line and to a reduced transfer of the UHF signal. The attenuation of the coaxial gas-filled arrangement is comparatively low.

The measuring results are shown in Figure 7. The section between sensor 4 and 6, 40 m in length, contains three insulators of type 1. The attenuation amounts to about 8 dB, i.e. the attenuation of this type of insulator is about 2 dB. The attenuation of the section between sensor 6 and 8 containing four insulators of type 2 amounts to about 10 dB, i.e. 2.5 dB per insulator. From this, one can conclude that at the DC GIL design under consideration, comprising about eight insulators per 100 m, a sensor distance in the range of 200 m would still be sufficient to detect 5 pC defects caused by a mobile particle, which represents the most common PD defect in gas-insulated systems.

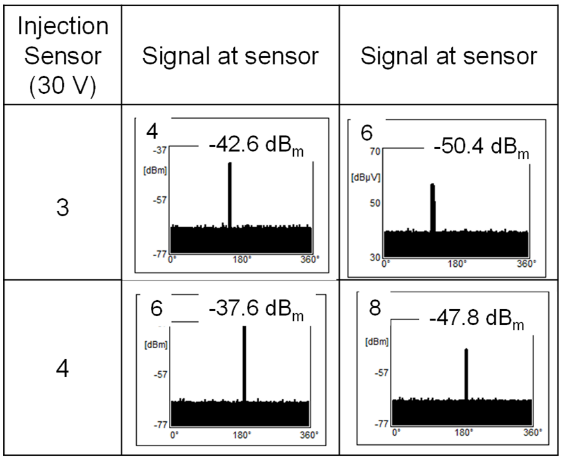


Figure 7: Attenuation between sensor 4 and 6 and between 6 and 8

3.2 Commissioning test with AC voltage

As recommended by CIGRE JWG D1/B3.57, the commissioning test of the DC GIL prototype installation was carried out with AC voltage. The AC test voltage was generated by a mobile resonant unit. During the first AC voltage stress, the DC-GIL is conditioned by a defined step-by-step AC voltage increase. At the different voltage steps particles of different sizes might be activated. The particle movement can be observed by the UHF monitoring system to ensure that all potential particles are captured by

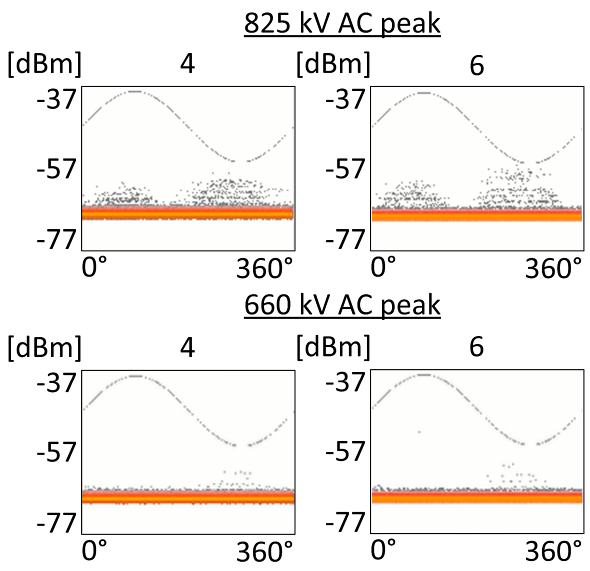


Figure 8: PD activity at 1-min-AC test voltage (825 kV_{peak}= 583 kV_{rms}) and at PD test voltage (660 kV_{peak}= 467 kV_{rms})

the particle traps. This process is of special importance for gas-insulated DC GIL assemblies, because free moving particles could directly trigger flashovers under DC voltage stress [6].

At the 1 min AC test voltage with $1.5 \cdot U_{rdc}$ = 825 kV_{peak} (583 kV_{rms}.) some PD activity was initiated in a certain section of the prototype installation. The PRPD patterns acquired indicate that some mobile particles were activated in the section between sensor 4 and 6 (Figure 8, top).

According to the recommendation of CIGRE JWG D1/B3.57 the PD measurement was performed at $\hat{U}_{pd\ test\ AC} = 1.2 \cdot U_{rdc}$ = 660 kV_{peak} (467 kV_{rms}) after a pre-stress with $1.5 \cdot U_{rdc}$ = 825 kV_{peak} (583 kV_{rms}).

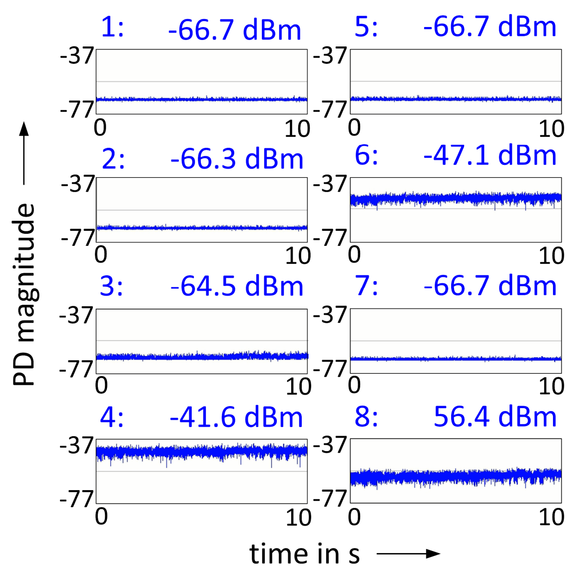


Figure 9: PD activity at -660 kV DC

This AC test voltage also corresponds with the test voltage of the DC long-term test. As to be seen from Figure 8, bottom, the PD sources are no longer active. The mobile particles seem to be captured by the particle traps.

3.3 Pre-test with DC voltage

After the AC voltage test further pre-tests were conducted, among others a DC voltage test. When increasing the DC test voltage up to 1.2 U_{rdc}, PD activity started at about -660 kV in one GIL section (Figure 9). According to the measured PD magnitudes the PD source was assumed to be located in the section between sensor 4 and 6.

For localisation and identification further measurements were initiated. The localisation was carried out by time of flight measurements. According to the measuring result presented in Figure 10 the probable PD source could be localized to be 7 m away from sensor 4.

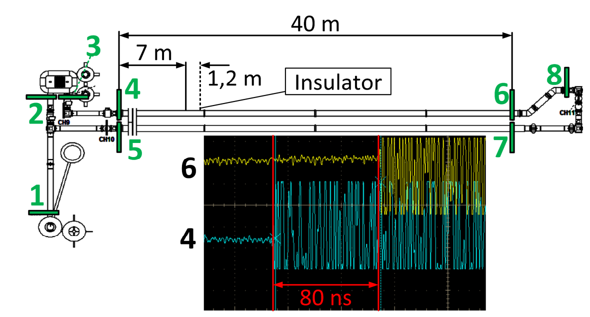


Figure 10: Time of flight measurement for localisation of a probable PD defect

Identification of the type of defect by PRPD pattern analysis, well known from PD measurements at AC voltage, is not possible, since a phase correlation does not exist at DC voltage. Therefore, pulse amplitude and pulse sequence have to be applied for characterization of typical PD defects.

3.4 Identification of PD defects by pulse sequence analysis (PSA)

3.4.1 General description and pre-investigations

One method of representation of PD data apply statistical distributions of basic quantities for defect classification, such as PD magnitude A_i and A_{i+1} of PD pulse i and subsequent pulse i+1 or differences of PD magnitude ΔA_i and ΔA_{i+1} between subsequent pulses respectively, and time difference Δt_i and Δt_{i+1} between subsequent pulses i and i+1 (Figure 11) [4][5][6]. The objective is to develop characteristic PD sequence patterns under DC stress for various defects by pulse sequence analysis (PSA). The PSA data can be recorded by the conventional or UHF measuring method [6][7].

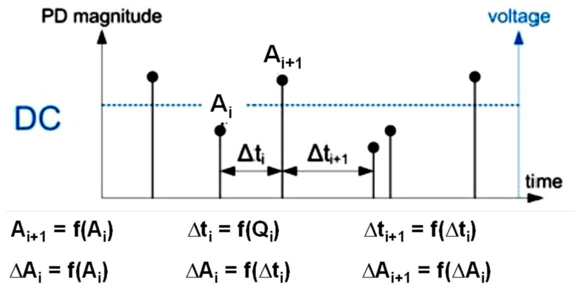


Figure 11: Defect identification by pulse sequence analysis (PSA) [4][6]

Different kinds of PSA analyses are published in literature, in which the defect identification is based on the PD quantities according to equation (1a) to (1c) [4][5] or (2a) and (2b) [6].:

$$\Delta A_{i+1} = f(\Delta A_i) \quad (1a) \qquad \Delta t_{i+1} = f(\Delta t_i) \quad (1b)$$

$$\Delta A_i = f(\Delta t_i) \quad (1c)$$

$$A_{i+1} = f(A_i) \quad (2a) \qquad \Delta t_i = f(\Delta A_i) \quad (2b)$$

In further pre-investigations of typical PD defects in a gas-insulated DC arrangement by means of the UHF method the before mentioned approaches were modified [8]. Using further PD quantities and a logarithmic scaling for normalizing the PD quantities a better characterisation of the defect in question was achieved. The modified approach makes use of the PD quantities according to equation (3a) to (3f) [8]:

$$\Delta A_{i+1} = f(\Delta A_i) \quad (3a) \qquad \Delta t_{i+1} = f(\Delta t_i) \quad (3b)$$

$$\Delta A_i = f(\Delta t_i) \quad (3c) \qquad \Delta A_i = f(A_i) \quad (3d)$$

$$\Delta A_{i+1} = f(\Delta A_i) \quad (3e) \qquad \Delta t_i = f(\Delta A_i) \quad (3f)$$

Examples of PSA patterns gained in the pre-investigations based on the PD quantities in (3a) to (3f) are shown in Figure 12, bottom.

3.4.2 PD defect detected at pre-test with DC voltage

As described in section 3.3, PD inception was observed at negative DC polarity at about -660 kV. The PD extinction voltage was below about -550 kV. For defect identification the method developed in the pre-investigations and the knowledge gained with some typical PD defects were applied. The PSA pattern acquired at -660 kV and -550 kV for 1 min are presented in Figure 12, top.

The Figure shows that the PSA pattern slightly changes with the voltage. Therefore, a comparison with reference signals recorded at similar test voltages and testing time is recommended for an efficient identification.

However, at the time of the commissioning tests a limited number of reference signals was available, e.g. some signals recorded at lower test voltages. A comparison with the reference signals available shows a good correspondence of the pattern acquired on-site with reference patterns caused by mobile particles at the inner conductor. In any case, it distinctly differs from a reference pattern caused by a 5 mm protrusion (Figure 12, bottom).

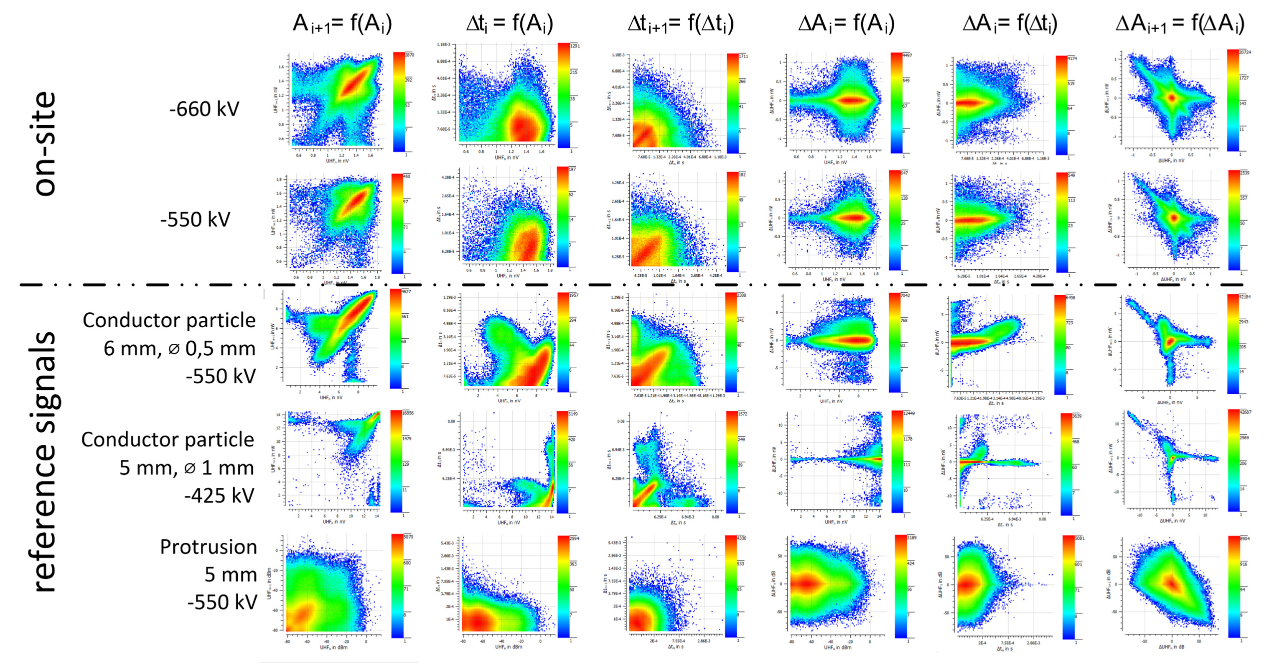


Figure 12: PSA patterns recorded on-site and reference patterns obtained in the laboratory

Thus it can be assumed that the PD defect recorded onsite is most probably caused by a mobile particle adhering to the inner conductor, and which was not yet captured by the particle trap. As the defect location was not in the vicinity of an insulator and a flashover across the insulator surface reducing the dielectric strength permanently was unlikely, further pre-test were conducted to capture the particle.

4 Conclusion

To gain long-term experience with DC GIL technology CIGRE JWG D1/B3.57 suggests a Prototype Installation Test with a test duration of one year, by which the dielectric DC and overvoltage stress under real service conditions are reproduced and investigated. For a test with sufficient significance the insulating conditions of the test arrangement before and during long-term testing have to be monitored. For this purpose, an UHF PD monitoring system is installed, which is adapted for recording of PD under DC voltage stress.

A sufficient sensitivity can be proven by the two-step sensitivity verification test according to CIGRE TB 654, which can also be used to determine the HF signal attenuation of the GIL system. The knowledge gained during the commission test with AC voltage and pre-test with DC voltage demonstrate that PD monitoring is suited for detecting imperfections in the test arrangement and to locate and identify probable PD defects. Probable PD defects are localised rather precisely by time of flight measurements. For identification of the type of PD defects PSA provides good results at the 100 m GIL arrangement. In total, PD monitoring helps to ensure long-term testing with a reliable validity with regard to the insulation performance. PD monitoring at gas-insulated DC systems is thereby also of interest for future DC installations.

Acknowledgments

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