Untersuchung von Teilentladungsverhalten mit Wechselspannung und gedämpfter Wechselspannung
Investigation of partial discharge behaviour with alternating current and damped alternating current

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Kurzfassung

Dieser Beitrag stellt die Untersuchung von Teilentladungsverhalten eines Hochspannungskabelsystems vor, unter der Verwendung von unterschiedlichen Spannungsformen. Die beiden Spannungsquellen die hierfür untersucht wurden, sind die Wechselspannung (AC) erzeugt von einem Hochspannungstransformator mit einer Frequenz von 50 Hz und die gedämpft oszillierende Wechselspannung (DAC). Beide Systeme können für die Teilentladungsmessung mithilfe eines standardisierten Messverfahrens eingesetzt werden. Der Messkreis besteht hierbei aus einem Koppelkondensator und einem Ankoppelnetzwerk mit digitaler Signalverarbeitung. Beide Versuchsaufbauten werden hierfür beschrieben und sind in der Lage den Kabelaufbau mit einer Spannung von über 110 kV (> 1.7 U_0) zu versorgen. Das in dieser Untersuchung verwendete Kabelsystem besteht aus einem 200 m langen Hochspannungskabel mit zwei Verbindungsmuffen. Defekte die eine Teilentladung verursachen, können an beiden Verbindungsmuffen und an den Endverschlüssen angebracht werden. Hierzu wurde eine künstliche Teilentladungsquelle verwendet. Der TE Pegel für AC und DAC sowie die Phasenlage wurden für beide Spannungsformen untersucht. Zusätzlich wurde die TE Einsetzspannung (PDIV) für beide Spannungsquellen untersucht.

Abstract

This article shows investigations of partial discharge (PD) in a high voltage cable system using different voltage shapes. The two sources which were used for energizing the cable system, are 50 Hz alternating current (AC) generated by a high voltage transformer and damped alternating current (DAC). Both systems can be used for PD detection with use of a standard PD measurement circuit existing of coupling capacitor and coupling device with digital signal processing. The both test circuits are described and can be used for energizing the cable to a voltage over 110 kV (greater than 1.7 U_0 for the cable used in this investigation). The cable system which is used for the investigations in this work is a 200 meter long high voltage cable with two joints. PD defects can be attached to both joints and the far end termination by using an artificial PD source. PD level for defects are compared for AC and DAC. The phase relation of PD for both methods is shown. Moreover comparison of partial discharge inception voltage (PDIV) for both energizing methods is described and measurements are shown.

1 Introduction

To verify the correct installation and PD performance of the whole cable system, high voltage cables are tested by applying partial discharge measurements. This provides a verification of an accurate installation of new energy cable links or a condition assessment during maintenance tests. The occurrence of PD shows defects in the cable insulation or incorrect installed joints or terminations of the cable system. The knowledge about local condition is very important to determine the reliability of a particular cable circuit [1]. Small damages or bad installation work on transmission power cables may deteriorate and can lead to failures as a result of the normally applied operational voltage stresses or during a transient voltage, such as lightning or switching. These failures can occur at localized electrical or thermal stresses and if the dielectric field in the insulation material is greater than the dielectric field strength of the material.

Factory routine tests are performed to ensure the defect freeness of the cable itself. After installation of the whole cable circuit, including assembling of joints and terminations, the reliability of HV power cables may further be improved by on-site testing.

Nowadays several voltage shapes and measurement techniques have been defined for on-site testing [2-5]. Applying AC voltages has a long history in laboratory testing of all types of cable insulation and a moreover 10 year's history in on-site testing. These confirmed that applying AC electrical stresses is applicable for the recognition of all types of failures related to insulation and it can be also combined with diagnostics measurements [6], e.g. partial discharge measurements or dielectric measurements.

As a consequence of experience in on-site AC testing on the one hand and the technological progress in power electronics and advanced signal processing on the other hand, damped AC voltage have become accepted since several years for on-site testing and PD measurements [7], [8].

The investigations in this paper focus on the comparison of PD behaviour for energizing a high voltage cable with 50 Hz AC compared to energizing with damped AC. For this test a cable system, installed in the high voltage laboratory at the University of Stuttgart, is used [8]. This cable circuit exists of 2 joints with an overall length of 200 m. Energizing the cable with 50 Hz AC is done by high voltage test transformers with sufficient power to support the high amount of reactive power. The damped AC voltage excitation is performed with an damped AC test system, a so called oscillating wave test system (manufacturer Seitz Instruments, Switzerland).
The main goals of these experiments should show the following aspects:

- Calibration of the test setup in accordance to IEC 60270
- PD measurement according to IEC 60270
- PD inception voltage (PDIV)
- PD level at PDIV

2 Test setup

2.1 Cable system

The cable system which is used for the investigations in this work is a 200 meter long high voltage cable with two joints, one air termination and one gas filled SF6 Termination. The arrangement of the line exists of three sections of cable which has the length 30 m, 50 m and 120 m. The type of cable is 64 / 110 kV with XLPE insulation. The screen of the air termination the two joints and the gas filled termination can be connected in different ways, so it can be connected straight or with a screen handling like in cross-bonding links. **Figure 1** shows the connection of the cable sections.

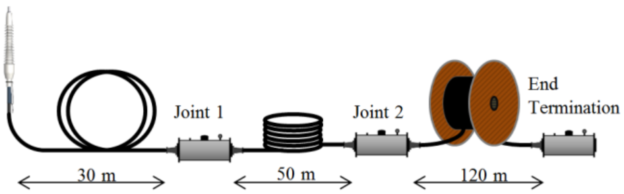

Figure 1 Test setup with air termination on the left side, 3 sections of high voltage cable, two joints and one SF6 filled termination.

On the left side the air termination is connected to the 30 m part of the cable. The termination is of dry insulation outdoor type with a rated voltage U_m of 123 kV. The other side of the 30 m long cable is connected to the first joint. Between the first and the second joint, the 50 m long cable section is arranged. Both joints are filled with SF6 gas and have a rated voltage up U_m of 145 kV. The end termination is connected to the second joint with a 120 m long cable. The shield of the end termination can be grounded or open.
PD defects can be attached to both joints and the far end termination. The defects can be placed only at one, at two or at three positions. The PD defects used for this investigation are shown in the next chapter.

2.2 AC 50 Hz measurement setup

A high voltage transformer provides the feasibility to energize the high voltage cable with a 50 Hz voltage up to 120 kV_{RMS}. This corresponds to a test voltage of over 1.8 U_0 for this cable. The high voltage connector of the transformer is directly connected to the termination of the cable circuit. In parallel to this connection a PD free coupling capacitor is placed to measure the partial discharges out of the circuit under test. Therefore the coupling device in the base point of the coupling capacitor C_k is connected to a digitizer card in a measurement computer. **Figure 2** shows the arrangement for the 50 Hz measurement.

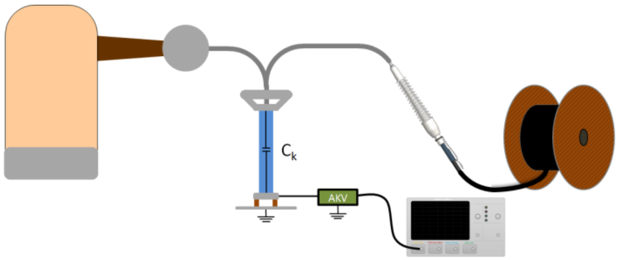

Figure 2 Test setup for the 50 Hz AC measurement. The high voltage transformer is connected to the cable system and in parallel the coupling capacitor with the PD detection unit is connected. The coupling capacitor is connected in the base point to a digitizer card by a coupling device.

The digitizer card samples the output of the coupling device with a rate of 100 MSample/s. A software was written to filter the signal and integrate the data numerical to provide a measurement result according to the IEC 60270. The software filter allows to band pass the measured signal in a range which could be defined by the user. In the case of a wide-band measurement according to IEC 60270 the corner frequencies of the filter must be between 30 kHz and 500 kHz, and the filter bandwidth must be at least 100 kHz [9]. In this measurement a frequency range from 100 kHz to 500 kHz was used. After this filter the peak detector computes step by step with a window of 50 µs the maximum value at the filter output. This result would be normalized and calculated with a factor. This factor can be determined in a calibration measurement with a standard PD calibrator.

2.3 Damped AC measurement setup

Damped alternating voltages are generated by the coupling of the charged test object capacitance with a suitable inductance. The test circuit basically consists of a unipolar HV voltage source, an HV inductor, a capacitor represented by the test object and a suitable HV switch. When the preselected maximum test voltage level is reached, the HV switch is closed. This is generating a damped alternating voltage at the test object, see **Figure 3**.

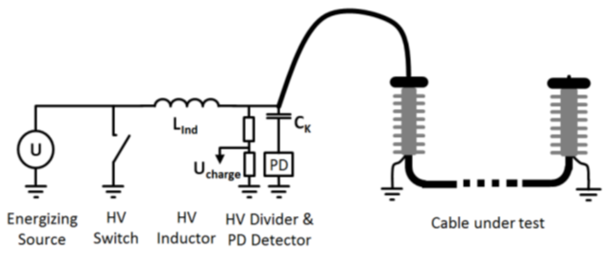

Figure 3 DAC test circuit connected to the cable under test.

This method is used to energize and to test on-site power cables with sinusoidal AC frequencies in the frequency range of 20 Hz up to 500 Hz. In addition this method can easily be used to measure and to locate on-site partial discharges in power cables in accordance with IEC 60270 recommendations. The system consists of a digitally controlled power supply to charge capacitive load of power cables with capacitive values of up to 10 µF. With this method, the cable under test is charged during the time t_{charge}:

$$t_{charge} = U_{\max} \cdot C_{cable} / I_{load} \tag{1}$$

The current I_{load} is constant over the charging time up to the selected maximum test voltage level. In this time the voltage on the test object is constantly increasing. If the test voltage is reached, a specially designed solid-state switch connects an air-core inductor to the cable sample in a closing time of < 1 ms.
Now a series of AC voltage cycles starts with the resonant frequency of the circuit f_{DAC}:

$$f_{DAC} = 1 \Big/ 2\pi\sqrt{L \cdot C_{cable}} \tag{2}$$

Where L represents the fixed inductance of the air core and C_{cable} represents the capacitance of the cable sample. In **Figure 4** a typical DAC voltage shape is plotted. On the left side, the voltage on the cable is increasing due to the charging current from the power source. In the moment when the desired charging voltage is reached, the solid state switch closes and the damped alternating voltage begins to oscillate.

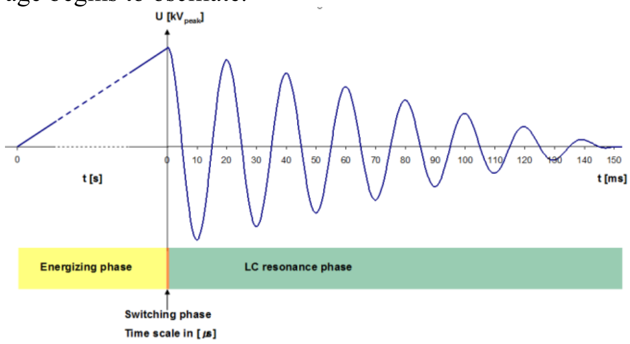

Figure 4 Typical DAC voltage shape. The RMS-value of the voltage is determined by $V_{DAC}/\sqrt{2}$ of the 1st cycle.

The test frequency of the damped AC voltage is the resonant frequency of the circuit. The air core inductor has a low loss factor design, so a slowly decaying AC waveform of test voltage is applied to the cable sample.
During a number of AC voltage cycles the PD signals are initiated in a way similar to 50 (60) Hz inception conditions [7]. By usage of digital signal processing of the PD signals, single PD pulses can be obtained and their origins can be localized in the cable. This method is the so called time domain reflectometry. After localization of the PD origin the cable system could be repaired at the specific position.

3 Defect model

For the investigation of different partial discharge measurement techniques a reliable and defined PD source was developed. The requirements to the defect were to be non-destructive to the cable or equipment and to be able to switch the PD on and off. Also an arbitrary but defined PD magnitude was required to ensure same conditions for the measurements. Therefore the PD source should be independent from external influences like temperature, relative humidity and pressure.
With these requirements a PD source was developed which is connected from the outside of the joint. A conducting plate is placed near the high voltage conductor of the joint. A wire connects the plate with a gas discharge tube which is grounded on the second lead, see **Figure 5**.
The parasitic stray capacitance C_p together with the parasitic capacitance of the gas discharge tube (C_{tube}) represents a capacitive divider with the voltage ratio:

$$\frac{U_{tube}}{U_0} = \frac{C_{tube} \cdot C_p}{(C_{tube} + C_p) \cdot C_{tube}} \tag{3}$$

Where U_{tube} is the voltage across the gas discharge tube and U_0 is the actual operating voltage (3). If the voltage U_{tube} reaches the ignition voltage of the gas discharge tube, it conducts the charge on the plate electrode to ground. This amount of charge is directly measureable and corresponds to the charge detected by the PD measurement device.

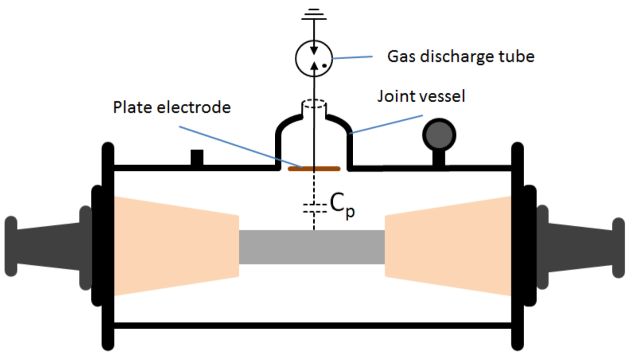

Figure 5 Schematic view on the artificial PD source placed in a joint. The cable is connected through a cable socket to the inner conductor of the joint.

The plate electrode is located over the high voltage conductor in the inner of the joint vessel. Figure 5 shows the setup and the placement of the plate electrode. In **Figure 6** the measurement of the partial discharge phase resolved pattern (PRPD) is shown for an operating voltage of 16 kV. This voltage is near to the inception voltage for this gas discharge tube in this setup. As can be seen, there is one PD event in each half of the 50 Hz cycle.

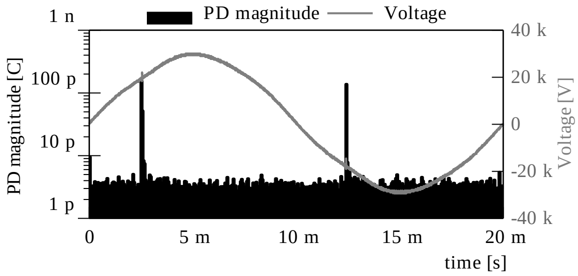

Figure 6 Phase resolved PD pattern at 16 kV and AC 50 Hz voltage. There is one ignition of the artificial PD source with a magnitude of about 150 pC. The PD source is located at Joint 1 without cable system.

By increasing the test voltage the number of partial discharges in each cycle increases. In **Figure 7** the test voltage is 45 kV. As can be seen, the PD occurrence is increased. Now there are four PD events in each half cycle of the 50 Hz voltage shape because of the higher dU/dt. Another characteristic phenomenon is that the PD magnitude does not increase with the test voltage. The PD level is still 150 pC.

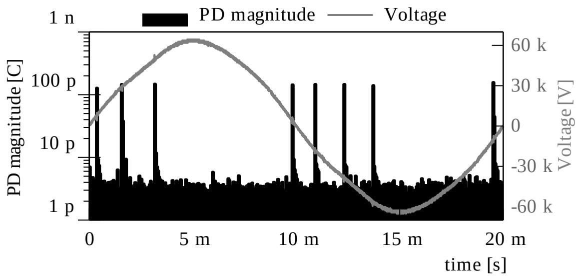

Figure 7 Phase resolved PD pattern at 45 kV and AC 50 Hz voltage. There are four ignitions of the artificial PD source with a magnitude of about 150 pC. The PD source is located at Joint 1 without cable system.

In **Figure 8** the PRPD pattern for a gas discharge tube with a rated voltage of 5 kV is shown. Because of the higher ignition voltage as compared to the measurements before, the amount of charge displaced is higher as compared to the gas discharge tube used in Figure 6 and Figure 7.

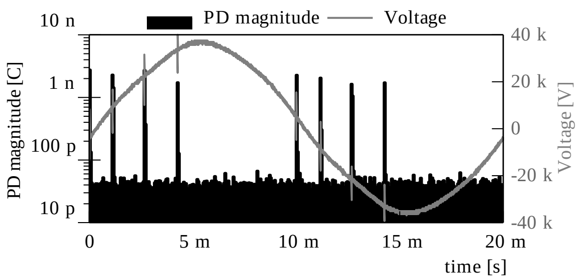

Figure 8 Phase resolved PD pattern at 20 kV and AC 50 Hz voltage. The magnitude of PD is about 2 nC. The PD source is connected to the cable system located at near end.

The defect model developed for these investigations fulfils the requirements noted above. Different PD magnitudes can be produced with different inception voltages. By removing the gas discharge tube, the PD switched off without anything be left. The artificial PD is stable in respect to the phase relation and magnitude. Increasing the test voltage also increases the number of PD per cycle.
Based on these artificial PD sources, with the possibility to select the PD level and the location at the two joints and the end termination, it is possible to perform further investigations in view of different kind of PD measurements. In particular the further investigations in this paper engage with the comparison of the different voltage excitation with alternating current (AC) and damped alternating current (DAC). For the direct comparison of PD behaviour it is necessary to use a PD source which is constant over the whole test with no influences by aging, temperature, pressure or humidity.

4 Results AC 50 Hz

The AC measurement with a voltage of 50 Hz was realized with the setup described in the chapter above. The voltage shape and the PD measurement for a voltage of 90 kV_{RMS} are shown in **Figure 9.** The partial discharges are symmetrical for both half of voltage cycle. The first ignition begins at the zero crossing of the voltage and the second pulse can be detected about 1.5 ms after the first pulse. This condition is stable over the time at a constant voltage.
The background noise level of the measurement is about 30 pC at a test voltage of 90 kV_{RMS} (1.4 U_0). The voltage shape is not perfect sinusoidal, because of the used energy source for the test transformers. A motor-generator combination is used, which is not being able to deliver a harmonic wave in this strong capacitive load. Hence the measured RMS value is higher than the $\hat{U}/\sqrt{2}$ value. This is of importance for the compare measurement in the next chapters.

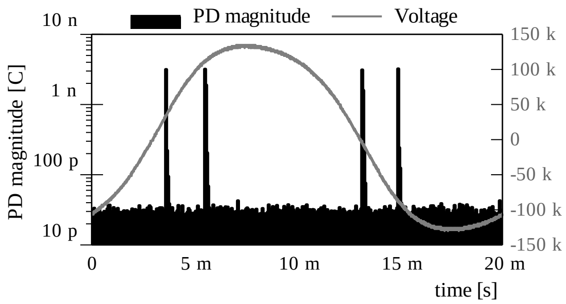

Figure 9 PD measurement with the artificial PD source and 50 Hz voltage excitation. The phase relation of the PD is at the zero crossing of the voltage.

It could be concluded that the phase relation of the PD pulses is located to the first and third quadrant of the sine wave voltage shape. This behaviour is the same as in defects like voids or cavities.

5 Results DAC

For a direct comparison of 50 Hz AC PD behaviour and damped AC PD behaviour the same artificial defects for both methods were used. As can be seen in **Figure 10** the voltage shape of the damped AC is sinusoidal with a frequency of about 300 Hz, which corresponds to the equation 2.

For this measurements the same coupling capacitor, PD detector and voltage measurement, was used for the damped AC voltage. This leads in the same performance for PD detection and voltage measurement as for the alternating current test, which is necessary for a proper comparison of both energizing methods.

The phase relation of the PD pulses is same as in the AC measurement, at the rising and falling slope of the voltage.

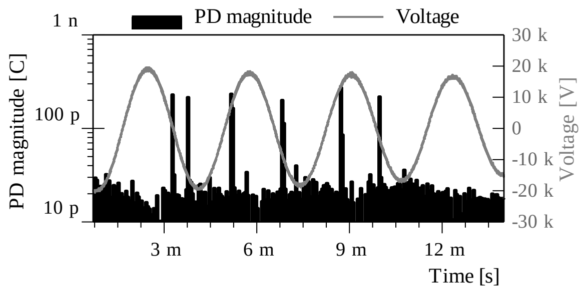

Figure 10 DAC measurement plot with PD detection. The PRPD pattern shows partial discharges from the artificial PD source near to the voltage zero crossing.

The charging voltage for the measurement in Figure 10 was 21 kV, what results in a RMS value of 15 kV for the first sine cycle. For each following cycle, the maximum voltage decreases due to losses in the insulation and the air core used for the resonant circuit. It can be seen in Figure 10 that the PD magnitude does not decrease with the voltage. Even if the voltage is too low to start the ignition of the PD, the pulses will expire complete. This effect is visible in the fourth voltage cycle of Figure 10.

6 Comparison AC and DAC

6.1 Partial discharge inception voltage

The partial discharge inception voltage (PDIV) is the applied voltage at which partial discharges become visible. The voltage therefore is gradually increased from a lower value at which no partial discharges are observed [9].

For different values of ignition voltage of the gas discharge tubes used in the artificial PD source, the PDIV was observed and its corresponding PD magnitude was analysed. Two examples plotted in **Figure 11** and **Figure 12** shows the PD behaviour at the voltage when the PD just incepts. For both measurements, the test voltage was increased with steps of 1 kV. Figure 11 shows the PD pattern for the excitation with 50 Hz alternating current and a voltage of 68 kV_{RMS}. One PD occurrence in each half cycle is detectable with nearly the same magnitude of 800 pC. Increasing the test voltage leads to more PD pulses in each half cycle (see Figure 7 and Figure 8).

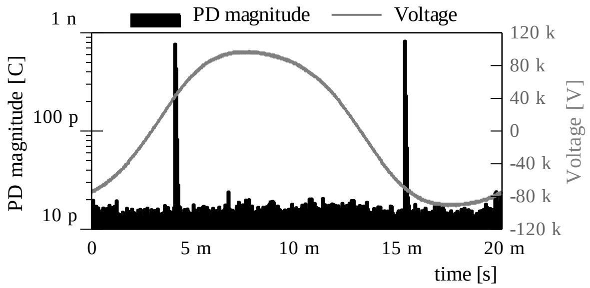

Figure 11 PD pattern by 50 Hz alternating current excitation with a voltage of 68 kV. The artificial PD source is placed at Joint 1 and the measureable magnitude is 800 pC.

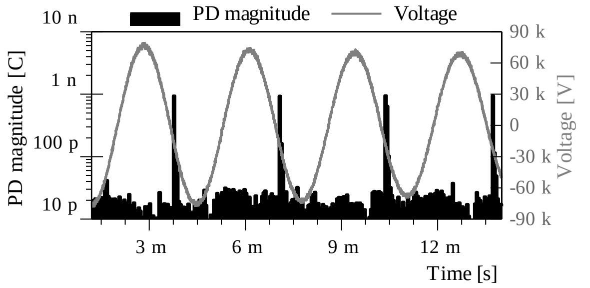

Figure 12 PD pattern with damped AC voltage shape and a charging voltage of 82 kV. The artificial PD source is placed at Joint 1 and has a magnitude of 950 pC.

Table 1 Partial discharge inception voltage and PD magnitude at specified voltage for different artificial PD sources.

Gas discharge tube	AC 50 Hz (PDIV / PD mag.)	DAC 300 Hz (PDIV / PD mag.)
800 V	19 kV / 260 pC	15 kV / 270 pC
1.4 kV	35 kV / 320 pC	30 kV / 410 pC
2.5 kV	68 kV / 800 pC	58 kV / 950 pC
3.5 kV	84 kV / 960 pC	79 kV / 1.1 nC

The partial discharge inception voltage in this compare measurement is for 50 Hz AC higher than for the DAC voltage. This is a result of the difference in the voltage steepness dU/dt in the region of the zero crossing. The higher steepness in the DAC measurement leads to a lower PDIV. The PD magnitude is for both voltage shapes in the same range. Measured with the DAC voltage the PD magnitude is slightly higher than for the AC 50 Hz, what can be caused by the higher test frequency.

6.2 Partial discharge magnitude

In this chapter the PD magnitude of different PD origin locations is described. Therefore at the both joints and the termination the artificial PD source was placed and the PD value at the same voltages of AC 50 Hz and DAC 300 Hz were measured. Both measurements were performed with the same coupling capacitor, same coupling device and the same measurement software. For each test setup the calibration was done by using the same PD calibrator.

The following tables show the results for a direct comparison of the two different voltage shapes. Four defect values have been attached to three different positions on the cable system. Table 2 represents the defect placed at joint 1, 30 m from the measurement equipment. For both voltages, AC and DAC, the PD magnitudes are displayed in the table. In Table 3 the same comparison for the defect placed at joint 2, 80 m from the PD detector is shown. Table 4 shows the results for the PD origin at the gas insulated far end termination.

Table 2 Comparison of PD magnitude for defects at Joint 1 (30 m from the near end) for 50 Hz AC and 300 Hz DAC voltage.

Gas discharge tube	Voltage (RMS)	AC 50 Hz (PD magn.)	DAC 300 Hz (PD magn.)
800 V	19 kV	260 pC	260 pC
1.4 kV	35 kV	320 pC	390 pC
2.5 kV	68 kV	800 pC	920 pC
3.5 kV	84 kV	960 pC	1.1 nC

Table 3 Comparison of PD magnitude for defects at Joint 2 (80 m from the near end) for 50 Hz AC and 300 Hz DAC voltage.

Gas discharge tube	Voltage (RMS)	AC 50 Hz (PD magn.)	DAC 300 Hz (PD magn.)
800 V	14 kV	120 pC	150 pC
1.4 kV	31 kV	150 pC	210 pC
2.5 kV	55 kV	600 pC	660 pC
3.5 kV	77 kV	300 pC	500 pC

Table 4 Comparison of PD magnitude for defects at far end termination (200 m from the near end) for 50 Hz AC and 300 Hz DAC voltage.

Gas discharge tube	Voltage (RMS)	AC 50 Hz (PD magn.)	DAC 300 Hz (PD magn.)
800 V	13 kV	500 pC	530 pC
1.4 kV	31 kV	600 pC	830 pC
2.5 kV	63 kV	2.1 nC	1.9 nC
3.5 kV	77 kV	2.2 nC	2n C

Because of the non-equal stray capacitance of defect at the particular locations, there is no attenuation of the PD pulse magnitude detectable with this measurement setup. It would be assumed that for both voltage shapes the same pulse attenuation occurs during travelling through the cable. As can be seen from the measurements in this chapter, the PD magnitude for the same defect arrangement is in good agreement for both voltage shapes. A slightly heightened PD magnitude with the DAC voltage is noticeable.

7 Conclusion

Regarding this research the following conclusions can be made:

1. The full size HV cable system used in this investigation is able to provide the measurements for the AC and DAC comparison. As a result all physical and technical aspects of different energizing methods and PD detection can be compared in a proper way.
2. The used measurement equipment for both energizing methods: continuous AC and damped AC; fulfil the IEC 60270 recommendations for PD detection. As a result the importance of using standardized PD detection for laboratory and on-site testing has been demonstrated.
3. An artificial PD source enables to compare the partial discharge inception voltage and PD magnitude for AC and DAC voltage shape, respectively. As a result the both energizing methods show good agreement in PDIV and PD magnitude for different voltage levels up to 1.7 U_0.

8 References

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