Comparison of Partial Discharge Behavior with Alternating Current and Damped Alternating Current at Different Frequencies

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***Abstract*—This article presents investigations of partial discharges (PD) in a high voltage cable system using different voltage shapes and frequencies. The two voltage 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 consisting of coupling capacitor and coupling device with digital signal processing. With the help of an artificial PD source, the PD level is compared for AC and DAC and also 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. The measurements with the DAC source were performed at three different frequencies. Changing the resonant frequency is handled by adding capacitors in parallel to the cable system to increase the overall capacitance.**

Keywords—partial discharge, high voltage cable, PD detection, damped AC, artificial PD, PD measurement

I. INTRODUCTION

To verify the correct installation and PD performance of a cable system, medium and high voltage cables are tested by means of 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.

Nowadays various voltage shapes and measurement techniques have been defined for on-site testing [1-4]. 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. This confirms that applying AC electrical stresses is suitable for the recognition of all types of failures related to insulation and it can be also combined with diagnostic measurements [5], 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 has also become accepted since several years for on-site testing and PD measurements of medium and high voltage cables [7-9].

The investigations in this paper focus on the comparison of PD behavior for energizing a high voltage cable with 50 Hz AC compared to energizing with damped AC at different resonant frequencies. For this test a cable system, installed in the high voltage laboratory at the University of Stuttgart, is used [5]. This cable circuit consists of three joints with an overall cable length of 205 m. Energizing the cable with 50 Hz AC is done by a high voltage test transformers with sufficient power to support the high amount of reactive power. The damped AC voltage excitation is performed with a damped AC test system[6]. Different resonant frequencies can be adjusted by changing the capacitance of the resonant circuit. Switching discrete capacitors in parallel to the test circuit brings down the resonant frequency of the sinusoidal damped high voltage.

The 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) for different frequencies
- PD level at PDIV for different frequencies

II. TEST SETUP

A. *Cable system*

The cable system under investigation is a 205 meter long high voltage cable with three joints and two air terminations. The arrangement of the line exists of four sections of cable which has the length 30 m, 50 m, 120 m and 5 m. The type of cable is 64 / 110 kV with XLPE insulation. The screen of the air terminations and the joints can be connected in different ways, so it can be connected straight or with a screen handling like in cross-bonding links. Fig. 1 shows the connection of the cable sections.

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. All joints are filled with SF6 gas and have a rated voltage up U_m of 145 kV. The end termination is connected over the third joint with a 5 m long cable to the 120 m cable part. The shield of the end terminations can be grounded or open. PD defects can be attached to all joints. 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.

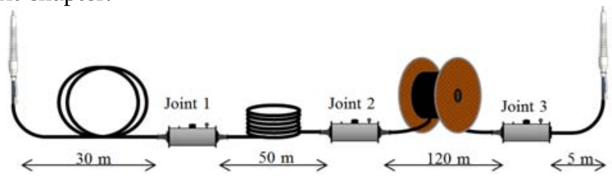


Fig. 1. Test setup with air terminations, 4 sections of high voltage cable and three joints.

B. *Partial discharge defect model*

For the investigation of different partial discharge measurement techniques, a reliable and defined PD source was developed. The requirements of the artificial defect were to be non-destructive to the cable or equipment and to be able to switch the PD on and off [5]. 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 Fig. 2.

The stray capacitance C_p together with the capacitance of the gas discharge tube (C_{tube}) represents a capacitive divider with the voltage ratio:

$$\frac{U_{tube}}{U_0} = \frac{C_{tube} \cdot C_p}{(C_{tube} + C_p) \cdot C_{tube}} \qquad (1)$$

Where U_{tube} is the voltage across the gas discharge tube and U_0 is the actual operating voltage (1). 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.

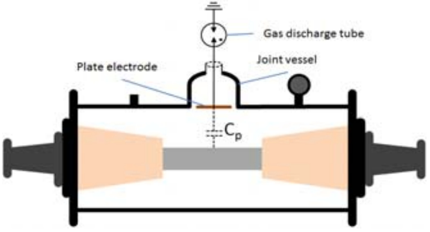


Fig. 2. Schematic view on the artificial PD source placed in a joint. The cable is connected through a cable socket to the inner conductor of the joint.

The defect model developed for these investigations fulfils the requirements: Different PD magnitudes can be produced with different inception voltages. By removing the gas discharge tube, the PD can be switched off. 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 this artificial PD source, with the possibility to select the PD level and the location, it is possible to perform further investigations in view of different kind of PD measurements and comparison of different PD detection techniques. 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 behavior it is necessary to use a PD source which is constant over the whole test and not influenced by aging, temperature, pressure or humidity.

C. *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 digital storage oscilloscope. Fig. 3 shows the arrangement for the 50 Hz measurement.

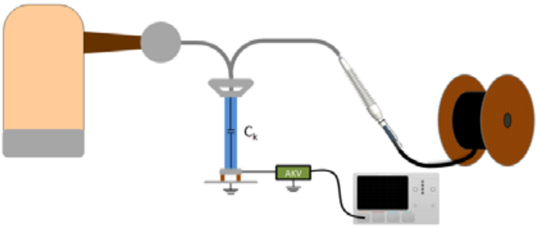


Fig. 3. Test setup for the 50 Hz AC measurement.

The oscilloscope samples the output of the coupling device with a rate of 100 MSample/s. This signal is filtered and numerically integrated to provide a measurement result according to the IEC 60270. In this measurement a frequency range from 100 kHz to 500 kHz was used according to an IEC 60270 wide-band measurement. 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 will be normalized and scaled with a factor. This factor can be determined in a calibration measurement with a standard PD calibrator.

D. *Damped AC measurement*

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 [1]. This is generating a damped alternating voltage at the test object, see Fig. 4.

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 300 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.With this method, the cable under test is charged during the time t_{charge}:

$$t_{charge} = U_{\max} \cdot C_{cable} / I_{load} \tag{2}$$

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 < 5 µs. Now a series of AC voltage cycles starts with the resonant frequency of the circuit f_{DAC}:

$$f_{DAC} = \frac{1}{2\pi\sqrt{L \cdot C_{DUT}}} \tag{3}$$

Where L represents the fixed inductance of the air core and C_{DUT} represents the capacitance of the cable sample and optionally a support capacitor. The arrangement with support capacitor is shown in Fig. 4. The support capacitor has to be connected by an inductor in series to avoid the PD pulse disappear and flow through it to earth.

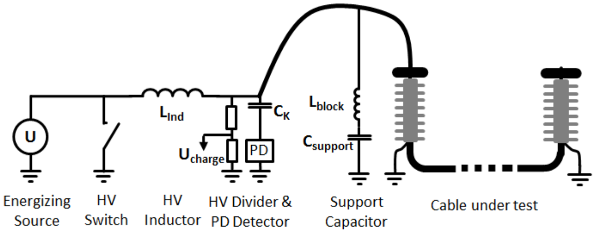


Fig. 4. DAC test circuit connected to the cable under test.

E. Calibration

To determine the calibration factor of the PD detector, a calibration measurement without high voltage is applied. A 1 nC PD pulse generated by a standard PD pulse calibrator is injected to the near end termination of the cable. After calculating the calibration factor, the output of the PD detector is scaled with this value. After every change of the support capacitor, the setup was calibrated again. It was noticed that the noise level increased due to the low impedance connection of the 200 nF capacitor. Resonances in the connection tend to higher background noise in the measurement. If needed, this could be prevented by use of a higher decoupling inductance L_{block} in series to the support capacitor.

III. MEASUREMENT RESULTS

A. Comparison at different frequencies for DAC voltages

The behavior of the artificial PD source under different frequencies is shown in the following measurements. Three different frequencies were applied to the cable system with the same PD defect for all measurements.

Comparing the partial discharge inception voltage (PDIV) for different frequencies, it shows that the voltage is at the same level for all three frequencies. The frequencies used, were 66 Hz, 109 Hz and 241 Hz. Also the PD level is in the same range and changes only slightly with the frequency. The phasing of the PD pulses is in the region of the voltage zero-crossing. This pattern corresponds to a cavity within the dielectric or surface discharges between external metal or carbon and dielectric surfaces [11].

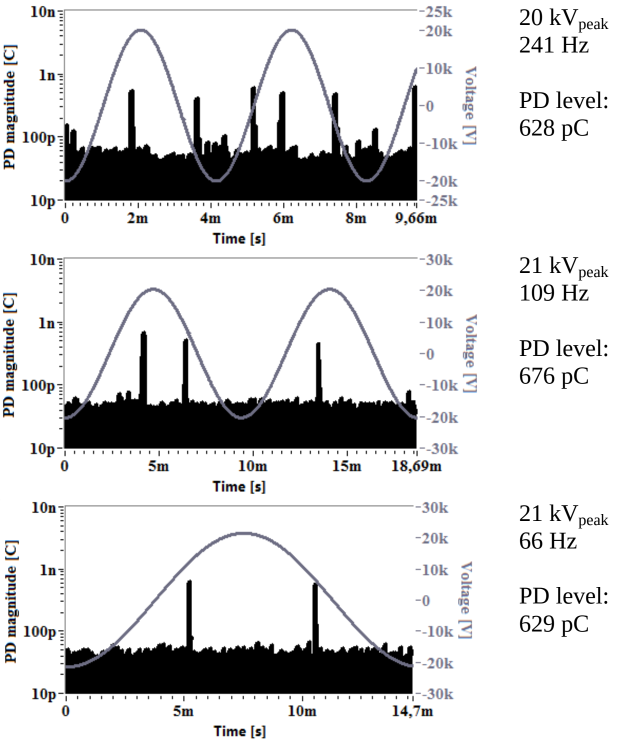


Fig. 5. DAC measurement with different frequencies at PDIV (20 kV)

B. Comparison of different voltage levels and frequencies for DAC voltages

To investigate the PD behavior of the artificial PD source under higher voltages, the measurements with the frequencies of 241 Hz and 66 Hz were performed at 35 kV$_{peak}$. For this purpose the same setup of the artificial PD source was used, as for the measurements in Fig. 5.

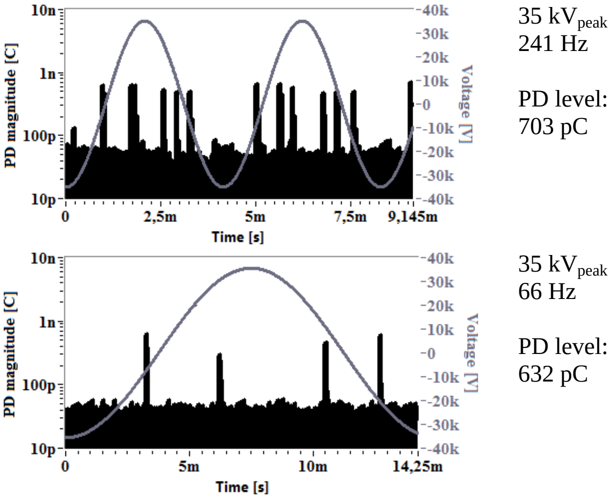
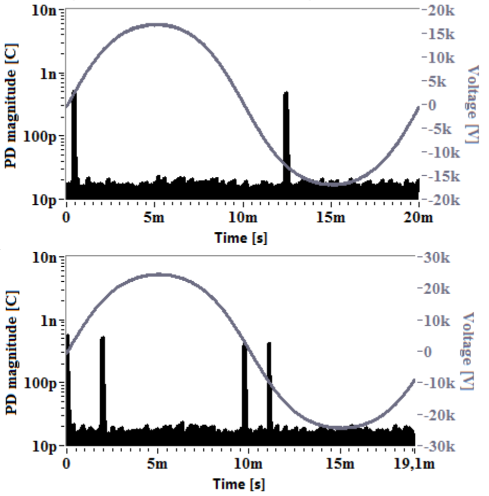


Fig. 6. DAC measurement with different frequencies at 35 kV

At 35 kV$_{peak}$ and a frequency of 241 Hz, the PD level is slightly increased and at 66 Hz the PD level is nearly unchanged. As can be seen in Fig. 6, the phase relation shows the same position of the PD pulses, but with an increased number of pulses per period.

C. Comparison of AC and DAC

The measurements of continuous AC voltage and damped AC have been compared. The AC voltage is generated with a high voltage transformer at a frequency of 50 Hz. The measurements in Fig. 7 are compared with the results of Fig. 5 and Fig. 6 for different voltage levels and frequencies.



17 kV$_{peak}$
50 Hz

PD level:
514 pC

24 kV$_{peak}$
50 Hz

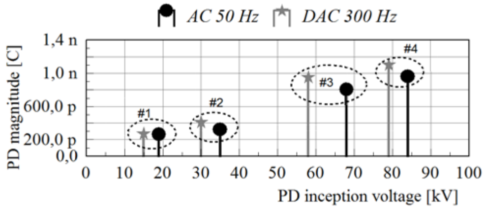
PD level:
548 pC

Fig. 7. AC 50 Hz measurement with different voltage levels

The phase relation of the PD pulses in the measurement at 50 Hz AC shows the same results as the measurements with DAC, for all frequencies. The PD pulses appear in region of the zero crossing of the voltage. Increasing the voltage level will also increase the number of PD pulses per period. The PD level is slightly lower than with DAC excitation, but also in the same region and comparable to damped AC.

D. PD inception voltage and magnitude of AC and DAC

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 analyzed. The PDIV vs. PD magnitude is plotted in Fig. 8.

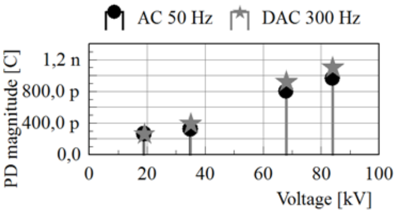


- PDIV with AC is slightly higher than with DAC
- PD magnitude is in same range for AC and DAC

Fig. 8. PDIV for AC with 50 Hz and DAC with 300 Hz for different PD defects (#1-4)

The partial discharge inception voltage in this compare measurement is for 50 Hz AC slightly higher than for the DAC voltage. This is a result of the difference in the frequency and therefore the voltage steepness dU/dt in the region of the zero crossing.

Fig. 9 shows the PD magnitude for different voltage levels with the same PD defect at the same location. 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



- PD magnitude for both voltage shapes is in good agreement
- A slightly heightened PD magnitude for the DAC voltage is noticeable

Fig. 9. PD magnitude for AC with 50 Hz and DAC with 300 Hz for different voltage levels

IV. CONCLUSION

A full size HV cable system is used to compare PD measurements at AC and DAC excitation. As a result all physical and technical aspects of different energizing methods and PD detection can be compared in a proper way.

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.

An artificial PD source allows the comparison of partial discharge inception voltage and PD magnitude for AC and DAC voltage shape, respectively. Both energizing methods show good agreement in PDIV and PD magnitude at different voltage levels.

The results of the measurements demonstrate the comparability of AC and damped AC, also for higher frequencies. PD behavior for both voltage shapes is similar and the PDIV can be compared.

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