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Pulsed X-ray Induced Partial Discharge: Phase and Time-Resolved Measurements

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***Abstract-* The use of short x-ray pulses (duration 50 ns) has shown to eliminate the statistical time lag by providing start electrons for the partial discharge (PD) development in a void, which makes it possible to detect very small voids at low electric field levels. In this paper a predefined measurement procedure which includes both a conventional (CONV. PD) and pulsed x-ray induced partial discharge (PXIPD) measurement, allows the comparison of the quantitative parameters and phase resolved partial discharge (PRPD) patterns of self-produced transparent epoxy samples, each containing a single void of spherical shape naturally developed during the casting process. Additionally, to study the PD mechanism by analyzing the shape of the discharge pulse a time-resolved partial discharge (TRPD) detection circuit was developed. These triggered-fast-pulse measurements allow the comparison of the shape of the first PD induced artificially by the x-ray pulse and conventionally by natural radiation. The development of the partial discharge with time is also shown and compared.**

I. Introduction

The absence of partial discharges (PD) in the insulating material of high voltage equipment is one key criterion for its dielectric strength quality. The source of these PD is mostly imperfections and voids in the insulating material. By means of the conventional PD measuring technique it is difficult to detect very small voids (< 2 mm) due to the large statistical time lag that depends on the void size and can last hours or days. In [1] the theoretical statistical time lag for PD inception of voids with diameter 0.1 m to 10 mm in a pressure range of 50-100 kPa is given. For voids of 1 mm diameter is shown to be in the order of 30 minutes and is in the order of one day for smaller voids with 0.25 mm diameter. This statistical time lag is due to the absence of a start electron in the void. This start electron is usually provided by natural radiation. Under the influence of an electric field it would initiate a PD and make the void detectable.

Conventional PD measurements make use of high AC overvoltage to activate PD by releasing additional electrons, but in this way irreversible insulation damage can be initiated at highly stressed parts of the insulation.

In order to eliminate an inception delay and avoid applying an overvoltage to the test equipment, in the last decades it was tried to artificially provide a start electron in a void during a PD measurement, e.g. by using the ionizing radiation of x-rays [2-5]. However, in [3] a strong influence of continuous x-ray irradiation on the partial discharge mechanism and pattern was observed. High continuous x-ray doses even inhibited PD in voids.

To minimize the influence of x-rays on PD, a new method of PD measurement which uses pulsed x-rays offers a possibility of ionizing a void and detecting the PD activity at different times, so that the interaction of a continuous x-ray beam with the PD can be avoided [4,5].

In more recent experiments even ultra-short pulses of x-rays with 50 ns duration have been used successfully to detect voids of very small size [5, 6]. In [6] it was shown that spheroidal defects with a metallic contact of diameter ~0.3mm could be detected without any statistical time lag at the expected theoretical discharge inception level. The measured phase resolved PD patterns did not alter compared to naturally triggered ones.

In this work, PXIPD and CONV. PD measurements on self-produced single spherical void containing transparent epoxy samples are shown. There were 30 samples that had spherical voids from 0.1 mm to 2.6 mm diameter. The voids were quasi centered, i.e. had no contact to an electrode.

The measurements were performed according to a pre-defined measurement procedure (MP, see also section II). The aim of these measurements was mainly to see (i) how reliable x-ray pulses can be used for PD detection, (ii) what the smallest void size is that can be detected and (iii) if there is a difference between an x-ray induced and naturally induced PD pattern. Further, it should show if and how a first x-ray PD inception of a void has an effect on a later natural PD inception of the same void and vice versa. Additionally, to study the PD mechanism by analyzing the shape of the discharge pulse, a time-resolved partial discharge detection circuit was developed. These triggered-fast-pulse measurements allow the comparison of the shape of the first PD induced artificially by the x-ray pulse and conventionally by natural radiation.

II. Experimental Setup and the Measurement Procedure

Two independent measurement setups were used, one for the PRPD and one for the TRPD measurements (Figure 1). For the PRPD measurements, an LDS-6 System by Lemke Diagnostics was used with a bandwidth of 100 – 400 kHz and a capacitance of the coupling capacitor of 1000 pF. With this setup, PD amplitudes down to 0.3 pC can be measured. This classical PD detection system makes use of a relatively small bandwidth and records the discharge magnitude and its phase position. To be able to study the discharge mechanism of a PD its apparent current pulse shape i(t) has to be recorded. This was done with a wideband detection system (digitizing oscilloscope) of 1 GHz where the transient voltage over the 50 ohm transmission line is connected over a 50 Ohm resistor to the oscilloscope (see Figure 1 right part, TRPD).

Both measurements were done independently at 50 Hz AC voltage. For the PXIPD measurement a pulsed x-ray source was integrated in the setup. The x-ray beam irradiates only the sample containing a single void while simultaneously the AC voltage is applied. This x-ray source emits short pulses of 50 ns duration with maximum photon energy of 150 kV and with an adjustable number of pulses to be triggered at a repetition rate of 15 Hz.

To study PXIPD and compare it to a CONV. PD measurement first a measurement procedure (MP) for the PRPD measurements (see Figure 2) was defined and transparent epoxy samples of rod-rod geometry containing a single spherical void were prepared (see Figure 3). The gap distance between the rod electrodes was 3 mm. For the MP there were 2 groups of samples each containing 15 test samples with voids of diameter range from 0.1 to 2.4 mm, i.e. each void diameter was produced twice. Three measurement sessions were made with a waiting time of 2 weeks in between, during which the samples were short circuited and kept in a dark dry place.

The aim of the MP was to see how a first PD inception with x-ray in a void affects a later conventional PD inception and its development in the same void and vice versa. Further, this MP allows us to see if the PD inception levels and PRPD patterns are reproducible at different sessions.

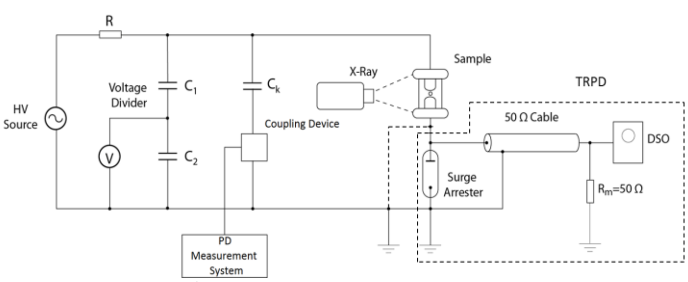

Figure 1: Diagram of the phase resolved and time resolved pulsed x-ray PD measurement circuit

For the PXIPD measurement (Figure 2 X1, X2 and X3) the AC voltage was brought to 3 kV and then increased by 1 kV steps. At each voltage level 5 x-ray pulses were applied. If there was a PD inception within 10 seconds at the current voltage level the PRPD pattern was recorded for 60 seconds and the inception voltage was registered as the "PXIPD inception voltage". After recording the PRPD pattern the voltage was decreased slowly and the PD extinction voltage was registered. In case of no PD inception the voltage was increased in steps of 1 kV (up to 33 kV) and the procedure was repeated. At the CONV. PD measurement (Figure 2 C1, C2 and C3) the main difference is that there was no x-ray pulse applied and at every voltage level the waiting time was 60 seconds before the voltage was increased by 1 kV. Here, if there was a natural PD inception at a certain level the PRPD pattern was recorded for 60 seconds and the inception voltage registered as the "apparent PD inception voltage". After recording the PRPD pattern the voltage was decreased slowly and the PD extinction voltage was registered.

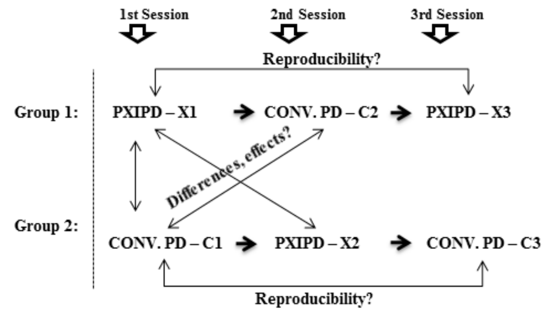

Figure 2: The measurement procedure (MP)

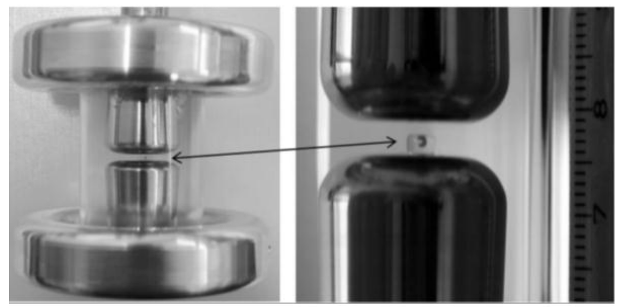

Figure 3: Design of the transparent epoxy samples with rod-rod geometry electrodes and the single spherical void between

III. THE PHYSICSAL BACKGROUNG OF PARTIAL DISCHARGES

A PD in a spherical void with a diameter d causes a voltage breakdown in the void and deploys the charge ±q on the walls of the void. This charge can be measured as an apparent charge on the electrodes of the sample. Two types of discharges can occur in voids, Townsend discharges and streamer discharges [8]. Streamer discharges have higher charge pulses and are easier to detect with a conventional measurement system. In [1] the electric field is given, which has to be exceed for a streamer inception to occur, given that an initiatory electron is available:

$$fE_0 > E_{str} = \left(E/p\right)_{crit} p\left[1+\frac{B}{(pd)^n}\right], \qquad (1)$$

where E_0 is the applied background field and for air: $(E/p)_{crit}$ 25 V/(Pa*m), B 8.6 $m^{1/2}$ $Pa^{1/2}$ and n = 0,5. *f* is a factor that quantifies the field enhancement in the void and is ~1.33 for spherical voids in epoxy (ε_r=4). *p* is the pressure in the void and is typically assumed to be in the range of *p*=50-100 kPa.

For a PD to occur the electric field E in the void must exceed the discharge inception field E_{inc} (E_{str} in (1)) and a start electron must be available. At PXIPD the first electron to start the avalanche is provided by the x-ray irradiation. After a PD has started it then runs by itself without any further x-ray pulse. The start electrons for the consequent PDs are the deployed and trapped electrons from a previous discharge on the void walls. Big voids have a bigger effective surface area into which electrons are trapped than small voids. For this reason big voids show a high rate of PD, i.e. start electrons are abundantly available.

IV. PRPD MEASUREMENTS

A. Results

Figure 4 shows Session 1 of group 1 (X1), i.e. PXIPD measurement of virgin voids. It can be clearly seen that PD are detected at electric field strengths close to the streamer inception field calculated with Eq. (1). E_{inc} increases with increasing void diameter. In the diameter range ~ 0.5 mm the x-ray inception fields are much higher than the theoretically expected ones but the PD extinction fields (E_{ext}) of these 0.5 mm voids are close to the theoretical inception curve (see Figure 4).

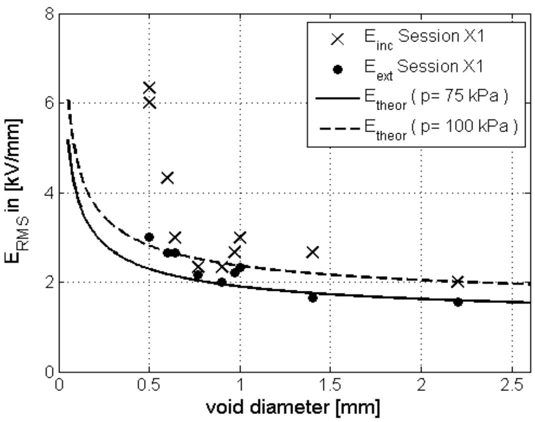

Figure 4: Measurement procedure of group 1, session 1 (X1)

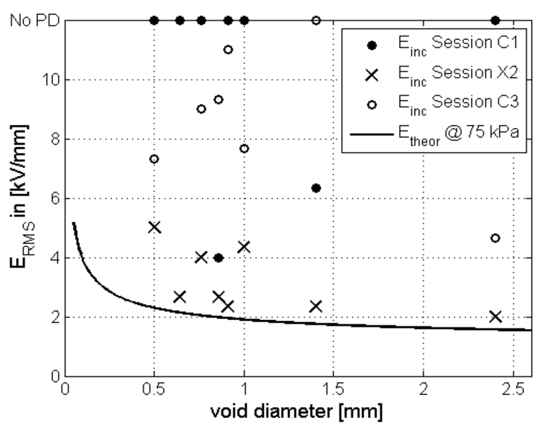

Figure 5: Measurement procedure of group 2, all sessions (C1, X2, C3)

Voids < 0.5 mm showed PD activity at the time instant of x-ray pulse application but PDs were not stable thereafter. For this reason these voids are not plotted in Figure 4 since no stable PXIPD inception occurred.

Figure 5 shows C1, X2 and C3, i.e. all three sessions of group 2. At C1, the CONV. PD, only 2 of 8 voids showed natural inception at very high electric fields, which corresponds also to long statistical time lags. The second measurement with x-ray (X2) incepted PD in every void at fields very close to the theoretical level. At C3 most of the voids incepted naturally but at very high electric fields, i.e. the statistical time lag is also high.

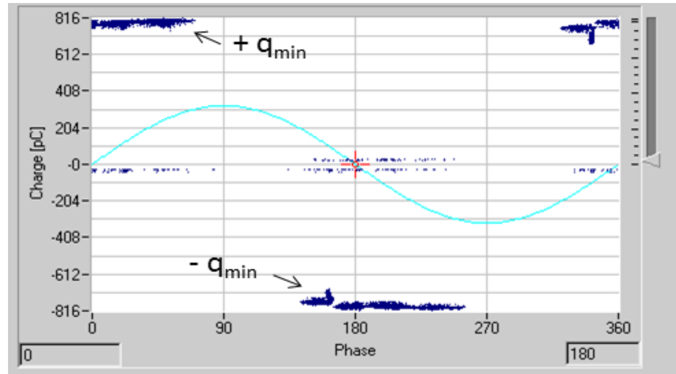

Figure 6: PRPD pattern of a 2.4 mm void at 4.6 kV/mm showing the typical bar structure for q_{min} in pC. (PXIPD inception at 2 kV/mm).

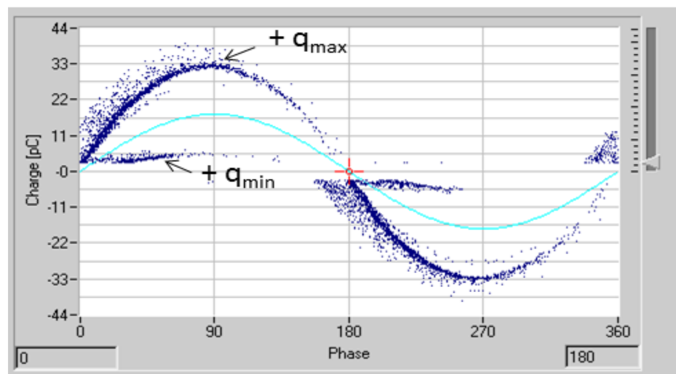

Figure 7: PRPD pattern of a 0.5 mm void at 6.3 kV/mm showing both the bar structure with q_{min} and the bow like structure with q_{max}. (PXIPD inception at 6.3 kV/mm).

Figure 6 shows the typical Hn(φ) distribution of a big void (2.4 mm). For voids of this size start electrons for consequent PDs are abundant each time the electric field in the void exceeds E_{inc} i.e. the theoretically expected horizontal pattern at q_{min} can be seen (PRPD pattern characteristics described in [2]). Figure 7 shows the PRPD pattern of a 0.5 mm void and here additionally the typical arc structure can be seen showing both q_{min} and q_{max}. For voids of this size start electrons for consequent PDs are scarce i.e. there is not always immediately a PD when the field in the void exceeds E_{inc}. PDs occur randomly at any field between E_{inc} and E_{max}. Since the PD magnitude (here in pC) is directly proportional to the electric field in the void at the time instant of the PD event, the PRPD pattern follows the electric field curve in the void.

B. Discussion

These measurements clearly proved that x-ray application eliminates the statistical time delay and incepts PD at low electric fields corresponding to the theoretical inception field. For voids with diameter ≥ 0.5 mm PDs incept with an x-ray pulse without any time delay and PDs run stable. Voids with diameter ≤ 0.5 mm showed PD activity at the time instant of x-ray pulse application but PDs were not stable after the x-ray pulse. These may be due to the relatively small effective void surface area which after the first PD initiated by the x-ray pulse supplies the consequent PDs with start electrons.

A previous PD inception (PXIPD or CONV. PD) has deployed charges on the walls of the void that later can be detrapped by the electric field and so start a naturally incepted PD (C3). These charges seem to be trapped at the void walls and be available for detrapping even after 2 weeks of waiting time.

A PXIPD at X1 seems to have changed the PD inception conditions in the virgin void. At X3 the same voids have a lower PXIPD inception field E_{inc} and also a lower PD extinction field E_{ext} (this plot is not shown in this paper). This is probably due to the pressure reduction in the void because of previous PD activity, in this case in the range of 10 min. This moderate aging seems to have consumed part of the oxygen and so the gas pressure in the void is reduced. PD and oxygen cause also oxidation of the void surface [7, 8].

The Hn(q) and Hn(φ) distributions of PD allow the comparison of important physical and statistical parameters like the PD phase angle φ, the PD magnitude q and the PD rate. It may be suggested that the change of these characteristic parameters of a PD pattern is due to the time effect of the PD activity and not because of x-ray irradiation. These measurements seem to prove the assumption that pulsed x-ray inception supplies only initial electrons by ionizing the gas volume and the further PD development shows no difference to a natural PD inception without x-ray application.

V. TRPD – MEASUREMENTS

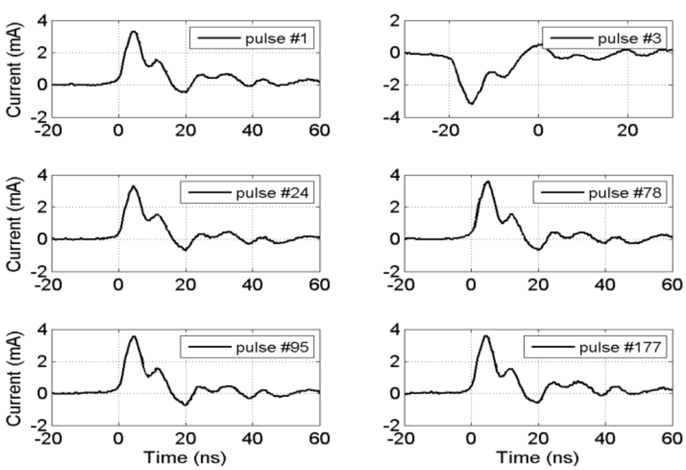

Figure 8: Example of time resolved discharge pulse shapes from a 0.9 mm void. Different pulses from a PD sequence of 200 PD pulses.

Figure 8 shows an example of TRPD pulses measured on a 0.9 mm virgin void. At each inception a sequence of 200 pulses was recorded and later analyzed.

TRPD measurements done by other researchers [7, 8] have shown that PDs have characteristic rise times of few nanoseconds and that there are mainly two different discharge pulse types seen. The so called streamer-like discharges are faster and the pulse magnitude is bigger, diffuse discharges (Townsend-like) are slower and the pulse magnitude is always under the magnitude of streamer-like discharges.

With our TRPD measurement setup (see Figure1 and Figure 8) individual partial discharge pulses with rise times of several nanoseconds can be recorded. However, the detected pulses oscillate which is an indication for the high self-inductance of the discharge path and the time constant of the setup seems to be high. To detect and compare the first PD in a void also noise coupled especially from the x-ray equipment needs to be filtered. Additionally, optical detection of the PD pulses during the TRPD detection will be done, since transparent epoxy samples are used. These improvements of the setup and further investigations are the next steps of this work.

VI. CONCLUSIONS

The PXIPD measurements of the self-made samples with single spherical voids confirmed that short pulsed x-ray application reliably incepts sustainable PD at low electric fields and without any statistical time delay. These measurements showed: (i) x-ray inception incepts PD at voids Ø ≥ 0.5 mm, (ii) for Ø ≤ 0.5 mm discharge activity observed only during pulsing, (iii) a previous PD inception favors a later CONV. PD inception but E_{inc} are still very high, (iv) no pattern difference between PXIPD and CONV: PD was observed; x-ray pulse supplies only initial electrons.

Improvement of the TRPD measurement circuit and simulation of partial discharges in spherical voids are the next scopes of this work.

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