Theory and Application of Pulsed X-ray Induced Partial Discharge Measurements for HV-Equipment

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Abstract* – The statistical time lag of partial discharge (PD) inception was eliminated by using short X-ray pulses (duration 50 ns) for triggering. It was shown that the X-ray pulses provide the necessary start electrons to start an avalanche by gas ionisation. Phase resolved PD (PRPD) measurements were performed at low electric field levels with self-produced spherical voids in epoxy samples. Even very small voids were detected without statistical time lag and no significant difference between the PRPD patterns after X-ray pulse triggering and naturally incepted PDs was observed. A minimum X-ray dose which is needed to provide at least one start electron in the void for successful PD inception was experimentally determined. Further, in order to study the effect of the X-ray pulse on the triggering and on the discharge mechanism, time-resolved PD measurements with an ultra-wideband detection circuit were made. Particular emphasis was placed on the effect of the X-ray dose on the PD mechanism and its differences to a naturally incepted PD without X-ray application.

I. INTRODUCTION

Partial discharge (PD) diagnostic is an important quality check for the insulation of high voltage equipment. The sources of PD are mostly imperfections and cavities in the insulation material resulting from the manufacturing process or due to mechanical or electrical stresses during operation. PDs are gas discharge events in a cavity which may lead to material degradation and total breakdown of the insulator. Their initiation occurs only if two conditions are met, namely if the electric field in the cavity exceeds a minimum inception value E_{inc} and a start electron is available. The start electron availability is a statistical process and is mostly provided by natural irradiation. Its production rate is low and causes a statistical time lag which can be in the order of hours or days, depending on the void size [1-3]. This is especially problematic for factory outgoing or commissioning tests, where measurement time is limited to typically a few minutes.

To eliminate the inception time delay a start electron has to be created artificially by other means.
First reports on X-ray application to PD detection are from the 60`s [4] and more recent works can be found in [5-8]. 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. It was concluded that the X-ray beam ionized the gas in the void to the point of conductivity, thus shielding the electric field.

The pulsed X-ray induced partial discharge (PXIPD) measurement method, by using ultra short X-ray pulses, offers the possibility of ionizing the gas in a void as a first step and detecting the PD activity immediately after the decay of the X-ray pulse, so that the unwanted interaction of a continuous X-ray beam with the PD is avoided.

First PXIPD experiments have been successfully used to detect PD both on laboratory samples and real GIS insulators [9-11]. However, a more comprehensive study of the interactions of the X-ray pulse with the gas void and its influence on the partial discharge mechanism and its development is needed.

This paper shows PRXPD (phase resoled X-ray induced PD) and TRXPD (time-resolved X-ray induced PD) measurements on self-produced epoxy samples containing single spherical voids of defined size. The main aim of the experiments is to show how reliable PRXPD is on detecting all relevant voids in insulation. Further, the effect of the X-ray dose on the PD characteristics through comparing it to a natural PD inception is investigated. The minimum X-ray dose for PD inception is determined experimentally and general guidelines are given how to implement a PRXPD setup on any HV - equipment.

II. THEORETICAL BACKGROUND

A. *PD Inception*

A PD in a spherical void with a diameter d causes a voltage breakdown in the void and deploys the charge $\pm q$ on the walls of the void. This charge displacement can be measured as an apparent charge on the electrodes of the sample. More than one type of discharge has been identified to occur in voids [12-13]. Streamer discharges are considered to be the dominant PD mechanism as they have higher charge pulses and are easier to detect with conventional measurement systems.
For a PD to develop the electric field $f{\cdot}E_0$ in the void (cf. Figure 1) must exceed a certain minimum inception field strength and a starting electron must be available. This critical electric field is given as a threshold criterion and usually called the streamer criterion [11]:

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

where E_0 is the applied background field. 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 depends on the void shape and the permittivity of the surrounding bulk material [2, 15]. For spherical voids in epoxy (ε_r=4) f~1.33. p is the pressure in the void and is typically assumed to be in the range of p = 50 - 100 kPa [14].

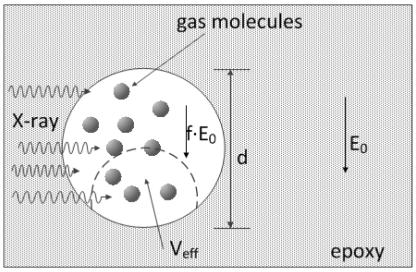

Figure 1. X-ray application to a void in a solid insulator

The start electron is mainly provided by gas ionization, i.e. natural irradiation or by other processes like field emission from conductive electrode surfaces or the insulation surface [2, 3].

At PXIPD a very short X-ray pulse is used, which ionizes some molecules of the void gas and provides at least one start electron to start the avalanche. After a first-PD has started, no further X-ray pulse is needed to ensure continuous PD development. The subsequent PDs run without any further X-ray pulse. The start electrons for the subsequent PDs are the charges deployed and trapped on the void surface from a previous discharge [2, 15].

B. Required Minimum X-ray Dose for PD Inception

A portable X-ray source from Golden Engineering, Inc. XRS-3T is used. It generates a short pulse of 30 - 50 ns duration with maximum photon energy of 300 keV. The source can be triggered with a time delay of 2.5 µs upon receiving the trigger signal. The X-ray beam irradiates the sample while simultaneously the ac voltage is applied.

After having determined the E_{inc} for the particular void size to be detected (using equation 1) the key question is: which X-ray dose is necessary to create at least one electron in the void volume to successfully trigger a PD.

As an avalanche needs a certain minimum length to reach the critical number of electrons to develop into a streamer, not all electrons produced in the gas volume V contribute to the streamer development. It is necessary to create at least one electron in the critical volume V_{eff} of the void (cf. Figure 1). The effective void volume V_{eff} is a function of the applied field and for a spherical void can be calculated by [2]:

$$V_{eff} \approx \frac{4}{3}\pi\left({}^{d}/_{2}\right)^{3}\left(1-\nu^{-\beta}\right), \quad (2)$$

where d is the void diameter and $\nu = U_0/U_{inc}$ the overvoltage factor i.e. the ratio between the applied voltage and the minimum inception voltage. The exponent β is a relevant parameter in the streamer criterion and for the case of gas epoxy interface is taken to be ~*2* [2].

For an effective void volume V_{eff} which is irradiated by a dose D (in Röntgen), the number of electrons N_e produced in the gas of density ρ can be calculated by using the following relation [17]:

$$N_e = K_R \cdot D \cdot \rho \cdot V_{eff}. \quad (3)$$

The proportionality constant is derived from the definition of *Röntgen* and is $K_R = 1.61 \cdot 10^{15} \frac{1}{kg\ R}$. It is assumed that the void gas, in respect to the ionization characteristics, is not much different than dry air [16].

III. EXPERIMENTAL SETUP

Samples of rod-rod geometry that contain a single spherical void were made from transparent epoxy (cf. Figure 2). The void size range was 0.1 mm – 2 mm and the gap distance between the rod electrodes was 3 mm and 4 mm depending on the void size. They were produced in the same way as they occur during insulator production in a factory, i.e. by gelation of gas bubbles in curing epoxy. This way voids of different sizes and with the almost same surface conditions as in technical reality are achieved. In [17-18] the sample production method is described in more detail.

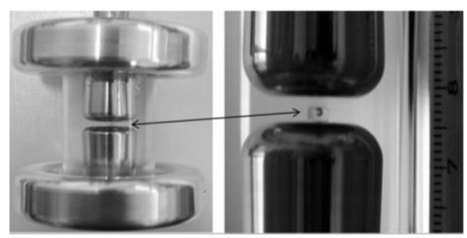
Figure 2. Left: sample with shield electrodes (as used in PRXPD); Right: design of the transparent epoxy samples with rod-rod geometry electrodes and the single spherical void (1 mm diameter) between.

The PXIPD measurement is based on the conventional PD detection setup according to IEC 60270. Additionally, a pulsed X-ray source is integrated in the setup (cf. Figure 3). The X-ray beam irradiates only the sample containing a single void while simultaneously the AC voltage is applied.

The measurement series were done independently in two main sessions at 50 Hz ac voltage, after defining an adequate measurement procedure for each session.

In the first session PRXPD measurements were performed with the conventional PD diagnostics system and the setup shown in Figure 3. R_m is shortened and Z_m is used as the PD measuring impedance. This PD detection system makes use of a relatively small bandwidth and records the apparent discharge magnitude and its phase position. 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 at sufficient X-ray dose such as to produce some tens of starts electrons. If there was a PD inception at the current voltage level the PRPD pattern and the inception voltage were registered.

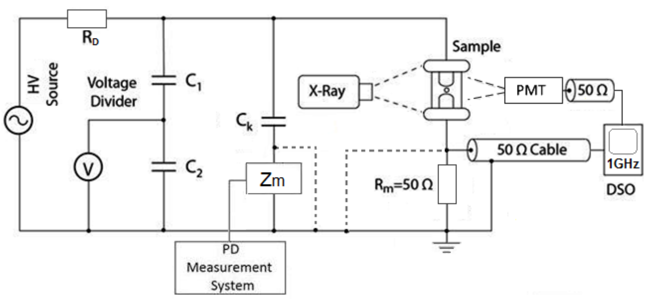

Figure 3. Principle diagram of the PXIPD circuit. By shortening of either Z_m or R_m it can be used as PRXPD or TRXPD setup. For TRXPD measurements the C_K is replaced by the self-built C_K shown in Figure 4.

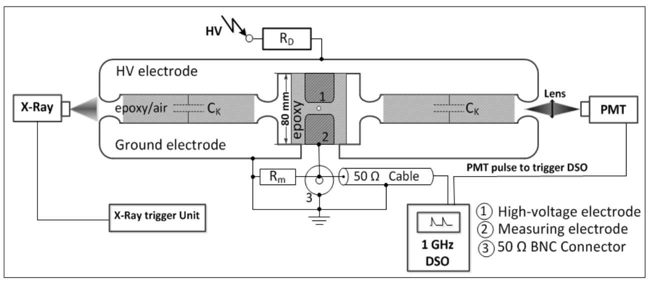

Figure 4. Diagram of the TRXPD measurement circuit and the PMT: Cross section of the “short discharge path ring coupling capacitor” C_K with the sample in the middle. The epoxy ring with the high voltage electrode and ground electrode builds the coupling capacitor.

In the second session TRXPD measurements were performed to study the discharge mechanism of PDs by recording their apparent current pulse shape. The measurement procedure was improved by applying the X-ray pulse at different phase angles of the voltage (see section IV). In this way the minimum level of inception field was determined even more precisely.

Considering the time constant of a few ns for a typical PD (streamer-like), the time constant of the measuring circuit has to be small, i.e. a high bandwidth is needed for the TRXPD session [19-20]. In the basic setup in Figure 3 this is achieved by shortening Z_m and using R_m as the measuring impedance. Additionally, because of the large geometric dimensions of the conventional coupling capacitor C_K which causes stray capacitances and inductances (factors influencing the time constant), a new compact ring C_K was built. This is depicted in Figure 4.

A LeCroy digitizing oscilloscope with a bandwidth of 1 GHz with 10 GS/s was used. The PD current through the 50 Ω resistor R_m is transmitted as a voltage signal by the 50 Ω transmission cable. The terminal connection to the oscilloscope is done over 50 Ω, so that reflections are avoided. Using the equivalent circuit, as in [13], a time constant of about 230 ps was calculated. This is well acceptable, since the PD pulses measured show a time constant of several hundreds of picoseconds, mostly around 1 ns. For a more detailed description of the setup see [21].

The TRXPD measurements detect the individual PDs as an electrical pulse and at the same time the light emitted by the PDs was detected by a photomultiplier tube (PMT, Hamamatsu). The PMT signal was used as the trigger signal for the oscilloscope which then acquired both the electrical signal and the PMT signal. The PMT pulses are not used as PD pulse qualification data and will not be analysed further in this work; they are used to trigger the DSO.

IV. RESULTS

A. PD Inception Field

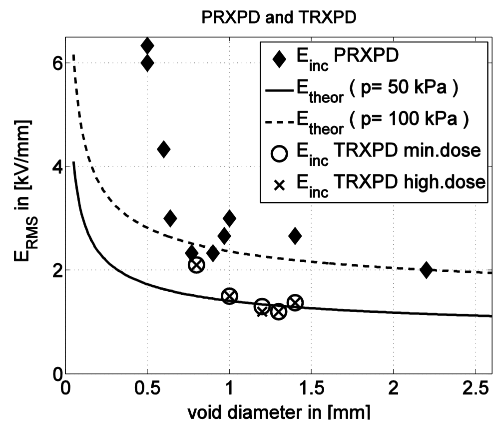

Figure 5. Inception field (background rms) vs. void diameter.

Figure 5 shows the E_{inc} vs. void size for both measurement sessions. It shows 15 tested samples which showed PD at X-ray application. It can be clearly seen that PD are detected at electric field strengths close to the theoretical streamer inception field calculated with equation (1). E_{inc} tends to increase with decreasing void diameter. The black diamond points show the results of the first session (PRXPD measurements). In the diameter range ~ 0.5 mm the X-ray inception fields are much higher than the theoretically expected ones. Voids < 0.5 mm showed no PD activity even at electric fields of 11 kV/mm.

During this session another group of samples with the same void size range as in Figure 5 were tested without X-ray. Only 2 of 8 voids showed natural inception at very high electric fields. Most of the voids remained undetected despite of background electric field up to 11 kV/mm and waiting times more than 30 minutes.

The open circles in Figure 5 show the results of the second session (TRXPD measurements) with minimum X-ray dose. The crosses inside the circles show the inception field of the same samples when a high X-ray dose was used. There is no difference in the inception field. At this session the smallest void to show PD at any X-ray dose and even at high overvoltage was 0.8 mm. Voids < 0.8 mm showed no PD activity at any time and overvoltage factor.

The inception fields for the TRXPD voids are closer to the theoretical inception curve for 50 kPa whereas for the PRXPD voids the inception fields are closer to the 100 kPa line and show a higher scatter. This may be due to the pressure differences in individual voids or the improved measurement procedure for the TRXPD tests.

Figure 6 shows the experimental determination of the minimum inception voltage for a void of 1.3 mm diameter by applying the X-ray pulse at different phase angles of the ac voltage. The full circles are the points where PD incepted and the open circles show the points where the X-ray pulse was applied but no PD inception occurred. A minimum inception level is clearly visible irrespective of the applied voltage level. This is 5 kV_{rms} at 90 ° angle or 9 kV_{rms} at 33 °.

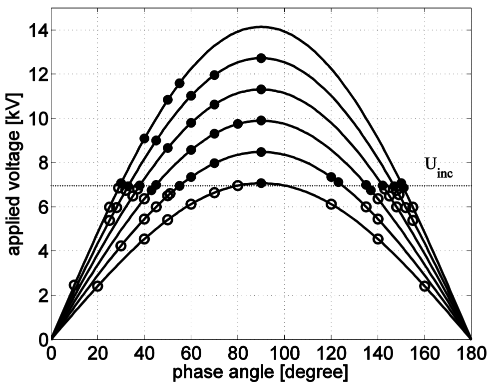

Figure 6. Voltage on sample vs. phase angle instant of single X-ray pulse application. Each point in the graph represents a new TRXPD measurement. The full circles refer to a successful PD inception and the open ones give the voltage levels where no PD inception occurs.

B. Effect of X-ray dose on PD pulse characteristics

The results shown in this section are for a spherical void of 1.2 mm diameter. Four other void sizes were tested with the TRXPD setup and showed very similar behaviour with respect to PD pulse mechanism, the used X-ray dose and test voltage [21].

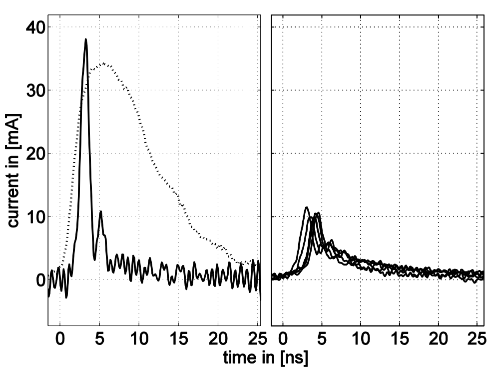

Figure 7. Left: First-PD with minimum X-ray dose at E=1.3 kV/mm. Electrical pulse and PMT pulse (dotted line). The electrical pulse has a rise-time of 1.3 ns pulse and pulse-width 1.4 ns. The PMT pulse has a rise-time 2.9 ns and pulse-width of 10.6 ns. Right: 5 subsequent-PDs (PD number 2 to number 6) with minimum X-ray dose. Average rise-time of subsequent pulses is 2.3 ns and pulse-width 2.3 ns.

The experimental inception voltage for this sample was always 4 kVrms (1.3 kV/mm background field). Using equation 1 we get a void pressure of about 50 kPa which at applied minimum X-ray dose of 2 μSv gives Ne ≈ 3 start electrons and the with maximum X-ray dose of 70 μSv provides Ne ≈ 130 (see section II.B).

Figure 7 (left) shows the first-PD pulse that incepted with a minimum dose of X-ray at a background inception field of 1.3 kV/mm. It has a peak value of about 40 mA and rise-time of 1.3 ns, the pulse-width is 1.4 ns. The corresponding PMT pulse is shown as a dotted line and is always broadened, this one having a rise-time of 2.9 ns and pulse-width of 10.8 ns. The general observation of longer PMT signals was made throughout all measurements.

The first five subsequent-PDs (number 2 to number 6) following the first-PD pulse are depicted on the right side of Figure 7. These subsequent-PD pulses are all similar but differ from the first-PD. They have a smaller amplitude, slower rise-time and longer pulse-width than the first pulse. Their peak values are nearly constant.

The same pulse shape was recorded also at inception with maximum x-ray dose and natural inception without X-ray. The subsequent PD pulses showed also the same behaviour as the ones in Figure 7.

V. DISCUSSION

These measurements clearly proved that pulsed X-ray application eliminates the statistical time delay and incept PD at low electric fields corresponding to the theoretical inception field. In this way overstressing of the electrical equipment could be avoided during testing. The minimum void size incepted showed that there is an area of void size where no PD development is possible. This 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.

The experimental determination of the minimum X-ray dose at minimum inception field 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.

This could be confirmed by the additional TRXPD measurements with different X-ray doses and at natural inception. It was shown that the number of start electrons has no significant impact on the discharge mechanism.

The first-PD pulse at natural inception has the same pulse characteristic as the pulses incepted with a minimum and maximum X-ray dose and the subsequent PD pulses have the same characteristic shape for all kind of inceptions.

VI. APPLICATION TO REAL HV-EQUIPMENT

The more general question to answer is how PXIPD detection can be used for more complex insulation systems such as power cables, bushings, instrument transformers, and the like. Here, the voids or other insulation defects (delamination, etc.) may be “shielded” by metallic or other parts that attenuate the X-ray beam (Figure 8).

An X-ray source is usually a point source radiating outward radially and forming a cone with an opening angle α. On the one hand, the intensity decreases with the inverse-square of the distance to the source. On the other hand, the intensity decreases by interaction with matter due to scattering and the photelectric effect, which is given by the mass atenuation coefficient μ of a material.

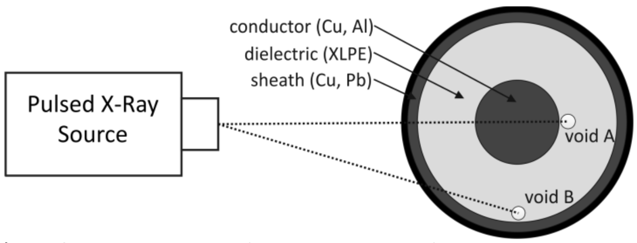

Figure 8. Schematic (simplified) representation of a solid insulated cable with two defects [17].

The mass attenuation coefficient for those metals/materials that stand between the X-ray beam and the point of interest (void A and void B in Figure 8) has to be considered and the energy spectrum of the used X-ray source should be known. For simplification only a few discrete bands (index k) of the energy spectrum of the X-ray source can be treated [17]. If I_0 is the initial X-ray intensity, then the intensity I after penetrating a certain number of different materials (index i) with thickness x_i is calculated by the Lambert-Beer law:

$$I = \sum_k I_{0k} \exp[-\sum_i(\mu_{ki} \cdot x_i)]. \quad (4)$$

Another important aspect to consider is that an X-ray source typically shows a strong angular emission characteristic which has to be taken into account. In the example of Figure 8, void B may see a lower dose than void A though there is less absorption along the line of sight.

In [17] it was shown how a pulsed X-ray source can be reliably integrated into a conventional PD measurement system. The minimum X-ray dose for PD inception in spherical voids was experimentally determined and verified theoretically. To do so, both the interaction of X-rays with gas molecules along with the attenuation phenomena of X-rays by matter was taken into consideration. As a result, guidelines and fundamental steps necessary for the design of a PXIPD setup with any insulation system were presented.

VII. CONCLUSION

The use of short X-ray pulses has proven to be very successful in eliminating the statistical time lag during PD measurements which results in detecting PD at low electrical fields.

The minimum dose measurements seem to justify the assumption that an X-ray beam mainly interacts with the void gas and even a small number of electrons produced can successfully lead to PD development. On this basis it was shown how any X-ray source can be used in a PXIPD setup.

The TRXPD measurements made it possible to detect the PD current and its light emission simultaneously. This confirmed that pulsed X-ray PD inception supplies only the start electrons and the further PD development shows no difference to a natural PD inception without X-ray application. Further, by applying start electrons (X-ray pulse) at different phase angles of the ac voltage, the minimum inception field strength for each tested void was determined very accurately.

ACKNOWLEDGEMENT

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