PULSED X-RAY INDUCED PARTIAL DISCHARGE MEASUREMENTS (PXIPD)

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ABSTRACT

It is difficult to detect small voids in solid insulators due to the large statistical time lag. The use of pulsed x-ray irradiation is a practical method to detect small defects at lower electrical stress so that potentially harmful effects of high voltage testing can be minimized. It is a method to artificially trigger partial discharges in an insulation void that is similar to the natural triggering.

The statistical time lag disappears when pulsed x-rays are used and even voids as small as a few 100 µm can be detected. The PD inception levels and PRPD pattern of samples after conventional and PXIPD measurement are compared. It is shown that not all of the samples that had voids could be detected after the conventional PD measurement, and the detection of the voids with a diameter less than 0.5 mm was successful only with the PXIPD measurements.

Further, attenuation measurements were done to find the minimum required x-ray dose for PXIPD.

1. INTRODUCTION

The absence of partial discharges (PD) in the insulating material of high voltage equipment is one key criterion for its dielectric quality.

With the conventional method of PD measurement it is difficult to detect small voids of few tens of µm up to some mm even if the testing voltage is high enough because of the absence of a start electron, which would initiate PD and make the void detectable. This start electron is usually provided by natural radiation and the rate of its occurrence is directly proportional to the size of the void, i.e. the larger the void the higher the probability of its occurrence in a certain period of time. The absence of the start electron consequently leads to a time delay between the application of the voltage and the occurrence of a PD. This delay can be in the order of hours for very small voids.

Another way of creating free electrons is by field emission from the electrodes or other sharp shapes on the void walls by applying a high local electric field. However, imposing an overrated high electric field to an insulator for a long time could initiate electrical trees at other stressed parts of the component and cause irreversible damage.

In order to avoid the inception delay and applying an overvoltage to the test equipment, in the last decades experts tried to artificially provide a start electron in a void during a PD measurement, e.g. by using the ionizing radiation of continuous x-rays [1, 3]. However in [1] it was observed that that continuous high radiation doses can even inhibit PD completely, so that no detection is possible.

A new method of PD measurement which uses pulsed x-rays on the other side offers a possibility of ionizing a void and measuring the PD in the absence of ionizing radiation, so that the interaction of a continuous x-ray beam with the PD can be avoided [2].

In this paper PD measurements with pulsed x-rays are compared to conventional PD measurements without x-rays.
2. EXPERIMENTAL

2.1 PXIPD SETUP AND EQUIPMENT

Figure 1 shows schematically the experimental setup of the PXIPD measurements. The setup includes lead plates for radiation safety, as ionizing radiation with energies up to 150 kV is used.

![Experimental setup of x-ray source with test object.](image)

We tested a total of 36 samples of rod-rod geometry typical for laboratory samples. Two rod shaped electrodes were casted in filled epoxy resin, with an electrode distance of 2 mm. The other dimensions are given in Fig. 2.

![Sample design of the tested samples. Left: sample of filled epoxy, 60% SiO2, with shield electrodes and the spheroidal void shape shown with minor radius a and major radius b; right: dimensions of the sample in mm (in axial symmetry, axis is left), with shield electrodes.](image)

After the PXIPD measurements, two x-ray images of each sample were made. It could be easily seen that the voids had an ellipsoidal shape and the major and minor radii of the voids were measured optically. Some of the samples had voids of major radius up to 0.7 mm because of insufficient degassing during curing. The analysis of the x-ray images showed that all of the voids are attached to one of the electrodes or have a thin layer of epoxy between the electrode and the upper wall of the void.

The pulsed x-ray source used was the XR200 x-ray source from Golden Engineering which emits short pulses of 50 ns duration. The maximum photon energy is 150 kV and the repetition rate of the pulses is 15 Hz. This x-ray source cannot be triggered at the ms scale, but still it has to be ensured that an x-ray pulse is given close to the voltage maximum. As the voltage frequency (50 Hz) and the x-ray pulse repetition rate (15 Hz) differ, one can estimate that with 5 repetitive X-ray pulses the maximum distance to the voltage maximum is 1.66 ms, which is only 13% below the voltage peak value.

For the PD measurements, an LDS-6 System by Lemke Diagnostics was used, having a bandwidth of 100 – 400 kHz. The capacitance of the coupling capacitor was 1000 pF. With this setup, PD amplitudes down to 0.3 pC can be measured.

2.2 MEASUREMENTS AND COMPARISON TO THEORY

The 36 samples of filled epoxy had already been tested conventionally without x-rays one month before the PXIPD measurements. The PD magnitude and PD inception field for each sample that had shown PD had been recorded and the inception field classified as "apparent PD inception field".

During PXIPD measurements each of the 36 samples was tested according to the following procedure: Starting at 2 kV (rms) the voltage was increased in steps of 1 kV (rms). At each voltage level first a PD measurement was carried out for 60 s without irradiation. If no PD was detected, the sample was irradiated with 5 x-ray pulses and a new measurement was started immediately. If PD was incepted the pattern was then recorded for 60 s and the sample was classified as "simultaneous X-ray triggered PD inception". If no PD inception occurred even after irradiation the voltage was increased to the next level and the procedure continued until an inception occurred or the voltage of 22 kV (rms) was reached. In case of PD inception without irradiation at a certain voltage level, but after having irradiated at the previous voltage level without any detectable PD activity, the sample
was classified as “delayed x-ray induced PD inception”.

The radiation dose at the centre of the sample was calculated to be 35 µSv for 1 pulse.

During the PXIPD measurements 17 of the 36 samples showed detectable PD activity (see figure 3). The rest of the samples were PD free after both measurements. These samples had no voids that are visible in the x-ray images. For 6 of the samples PD inception was possible only after irradiation. Even though they had voids with a minor radius (elec. Field parallel axis of a void, see fig. 2) up to 250 µm no PD inception had been achieved with the conventional PD measurement until 22 kV (rms).

Figure 3 shows that the PD magnitudes using PXIPD are lower than the PD magnitude of the conventional PD measurements and the PXIPD magnitude is higher for larger voids for all types of inception.

Figure 4 shows the PD inception field with and without pulsed x-ray application. One can observe that the PD inception level after using pulsed X-Rays is much lower than after the conventional PD measurements. This is in agreement to the findings in [1] and [2].

Figure 5 shows a comparison of the measured PD inception fields to the theoretically expected values using the streamer inception criterion (see Eq. (1)) presented in [4, 5]:

\[ fE_0 > E_{str} = \left(\frac{E}{p}\right)_{crit} p \left[ 1 + \frac{B}{(p/2a)^n} \right] \]  \hspace{1cm} (1)

Where \( E_0 \) is the applied field and the parameters \( (E/p)_{crit} \), B and n are characteristics of the ionization process in the gas [5]. For air the literature values are \( (E/p)_{crit} = 25 \text{ V/(Pa*m)} \), B is \( 8.6 \text{ m}^{1/2} \text{ Pa}^{1/2} \) and n is 0.5 [4, 5]. f is a factor that quantifies the field enhancement inside the void and depends on the ratio a/b and the relative permittivity of the dielectric.

According Eq. (1) for the majority of the voids the gas pressure is between 50 kPa and 80 kPa. This fits well with the expected values and the estimations made at [2, 4].

Additionally, attenuation measurements with the 7 samples of inception type “simultaneous x-ray triggered PD inception” were done to define the minimum dose of x-ray needed to successfully
initiate PD. Steel plates of different thickness 0.5, 1, 1.5 and 2 mm that were packed closely were inserted between the x-ray source and the sample, at the beginning making a 20 mm steel thickness (except sample 3, start at 35 mm steel, see table 1). The voltage was brought to the “Simultaneous X-Ray PD inception level” and 5 x-ray pulses were applied. If there was no PD inception at the highest steel thickness the plates were removed gradually until a PD inception occurred. The tested samples and the minimum x-ray dose that induced PD are shown in table 1.

Table 1. Results of attenuation tests and calculated number of electrons. From left to right: sample number, electron number before attenuation, minimum x-ray Dose (attenuation test), electron number after attenuation and max. steel thickness that allowed PD inception.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Ne (X-Ray in µSv)</th>
<th>Ne after Attenu (PXIPD)</th>
<th>PXIPD</th>
<th>Steel/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.55E+03</td>
<td>2.45E-02</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>3.41E+03</td>
<td>3.21E-01</td>
<td></td>
<td>10</td>
</tr>
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<td>3</td>
<td>2.82E+03</td>
<td>4.00E-05</td>
<td>3.19E-03</td>
<td>32.5</td>
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<td>4</td>
<td>3.52E+02</td>
<td>7.83E-01</td>
<td>7.81E+00</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>9.51E+01</td>
<td>5.67E-02</td>
<td>1.53E-01</td>
<td>14</td>
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<td>6</td>
<td>1.13E+03</td>
<td>1.08E-02</td>
<td>3.45E-01</td>
<td>18</td>
</tr>
<tr>
<td>7</td>
<td>9.51E+01</td>
<td>1.25E+01</td>
<td>3.73E+01</td>
<td>2</td>
</tr>
</tbody>
</table>

After calculating the minimum x-ray dose that initiated PD one can estimate the number of free electrons produced by ionization in the void volume by using the definition of the Röntgen:

$$N_e = R \cdot \rho_{gas} \cdot V \cdot \frac{1}{e^-}$$  \hspace{1cm} (2)

\(N_e\): Number of electrons, \(R\): old unit, 1 R = 2.58-10^{-4} \text{ C/kg of ionization in air at room temperature.} \(V\): volume of the void. \(\rho_{gas}\) is the density of air at room temperature, 1.184 kg/m³. \(e^-\): elementary charge 1.602-10^{-19} \text{ C.}

Calculations with Eq. (2) for the x-ray dose without attenuation give a number of electrons that is well above one, depending on the void volume (see Table 1, 2nd column). However, the number of electrons calculated for the minimum x-ray dose show that for 3 cases the number of electrons is less than one although PD was incepted only after irradiation (table 1, column 4). This makes us assume that there may be other effects that could produce initial electrons under the influence of x-rays. Since all the voids have a contact to the electrode we may assume that the irradiation of the aluminium electrodes provides initial electrons due to the photoelectric effect.

This phenomenon has to be studied further in the next measurements with new samples.

3. CONCLUSIONS

Using pulsed x-ray irradiation in a PD measurement makes the statistical time delay disappear and the PD inception field is considerably lower than in the conventional PD measurement. This makes it possible to detect PD and test electrical insulation under a much lower electrical stress.

The detection of the voids with a diameter less than 0.5 mm was successful only with the PXIPD measurements and all the voids that could be seen on x-ray images showed PD activity after x-ray irradiation.

The theoretical calculations of the electron number using the minimum x-ray show that relatively low x-ray doses are sufficient to ionize a void of small size but further measurements concerning the minimum x-ray dose need to be done.

REFERENCES


