

# Experimental study and numerical simulation of partial discharges in deformed bubbles in transformer oil

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**Abstract**— The experiments on partial discharges (PDs) in gas bubbles floating up in transformer oil and calculations of the characteristics of partial discharge (PD) in the bubbles were made. For floating up bubbles, it was shown that the PD did not occur even if the electric field was higher than that obtained from Pashen's law. The experiments on inception of PD in bubbles with X-rays were performed. They confirmed our hypothesis that the absence of PDs can be explained by the lack of initial electrons in floating up bubbles at the conditions of low radiation background. The calculations of the "apparent" and "true" charges of PD in elliptic cavities in a condensed dielectric were performed. A good agreement of the simulations with our experiments was revealed. For the elliptic bubbles, the "apparent" charge is proportional to the bubble volume while the "true" charge is proportional to the surface of the bubble.

**Keywords**— partial discharges, transformer oil, floating up bubbles, X-ray inception, "true" and "apparent" charges, computer simulations

## I. INTRODUCTION

Partial discharges (PDs) in liquid dielectrics are the subject of numerous experimental and theoretical investigations for decades [1-2]. Being the reason of the deterioration of the insulation in high-voltage apparatus, PDs are also an informative method of estimation of the current state of the insulation. PD is registered usually as a current pulse in the external circuit. The rate of PD can also be measured. Thus, the main electrical characteristic of PD is the electric charge transferred in an external circuit. This charge is called "apparent" charge. In this study we focused mainly on the PDs in bubbles that can appear inside the insulation during operation. The registered value of the "apparent" charge is influenced by many factors such as the location of the bubble inside insulating system, the current size and shape of the bubble, the number of bubbles in insulation. These factors make it difficult to give a clear definition of the PD intensity in dielectrics that is required in regulatory documents for high-voltage equipment testing. Strongly speaking, the intensity of the partial discharge is the intensity of the ionization and conduction processes in the gas inside bubble. The detailed description of these processes is still in developing [3]. The charge deposited on the walls of the bubble (so called "true" charge) is used as the integral

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final result of these processes. So, the relation between the "true" and "apparent" charge is of great importance for the answering the question how intensive is the PD in some bubble. The works [4-6] focused on the role of mainly the size and position of spherical bubble in the interelectrode gap. In the present work we made the calculations for a deformed bubble of different size. The experimental investigations of the PD in transformer oil were made for floating up bubbles. The video registration was used to fix the shapes of bubbles before and after PDs. Unexpectedly, we found the deviation of the inception voltage of the PD from the Pashen's law. This gave us an idea to perform the experiments on the PD inception in floating up bubbles stimulated with the X-ray source. The results of these experiments are reported too.

## II. THE EXPERIMENTS ON PD MEASUREMENTS

### A. Experimental Setup

The experimental cell for measuring the PD in floating up bubbles was developed. The cell with the high-voltage input and measuring equipment was put into the room with the metallic walls. The room itself is in a basement of multi-storey building with the concrete floors.

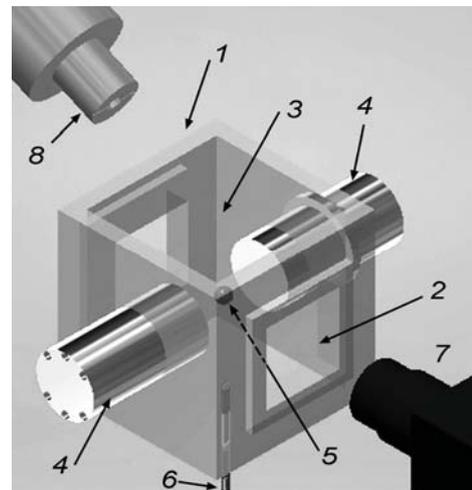


Fig. 1. Experimental cell for the registering the PDs in floating up bubbles. 1) PMMA walls of the cubic cells, 2) the glass window for optical registration, 3) the space of the cell filled with the transformer oil, 4) the plane cylindrical electrodes, 5) a bubble, 6) the syringe for the generation of the chain of bubbles, 7) video camera, 8) X-rays source. The size of the cell is 10x10x10 cm.

So the experimental setup was isolated from the external ionizing radiation thoroughly. The scheme of the cell is shown in Fig. 1. The cubic cell (1) was made of PMMA with two glass windows (2). It was filled with the transformer oil Nitro (3). Two flat round electrodes (4) of the diameters of 50 mm were mounted along a horizontal axis in such a way that the floating up bubbles go by the electrodes at the same distance from each of them. Thus, the bubble velocity was perpendicular to the electric field stress in the middle part of the cell. The alternating voltage with the frequency of 50 Hz was applied to the cell.

The method of gas supply with the syringe (6) was developed that allowed us to produce the chain of floating up equidistant bubbles. The diameters of the bubbles were approximately the same in each series but we could vary the diameters from about one millimeter to several millimeters from series to series. The bubbles of sizes from 1.5 mm to 1.78 mm moved up with the velocity from about 0.23 to 0.27 m/s. The distance between the neighbor bubbles was about 5 mm so there were 7 or 8 bubbles that moved in the interelectrode space at the same moment of time.

The electric circuit included high-voltage transformer 190 V/140 kV, the coupling capacitor SMAIV-110/3-7.33 nF, the current transformer, the PD registering circuit, the oscilloscope, and the cell itself. The electrical signal of PD in the bubbles was measured with two methods. First, we used the current transformer connected to the ground circuit and, second, we used the usual PD registering circuit.

The resistor R1 was placed at the high-voltage side of the transformer for two reasons (Fig. 2):

- 1) for restricting the current after the breakdown of the interelectrode gap,
- 2) for filtering the noise from partial discharges which enters the registration system making difficult the revealing of the signal from the noise.

Low-inductance resistors TVO-60 W were used. The value of this resistor was chosen experimentally. It was found, that the value of 28 kOhm provides the efficient noise filtering.

We used the video camera (Fig. 1, (7)) with the rate of 1200 frames per second for the video registration of the deformation of the bubbles after PDs. Synchronous registration of the photomultiplier signal was also made.

The oil was degassed thoroughly before each experimental series. We produced helium filled bubbles since helium has very low breakdown voltage, from one hand, and it is a monatomic simple gas with well-known characteristics, from another hand. Several series of the experiments were made with the air bubbles.

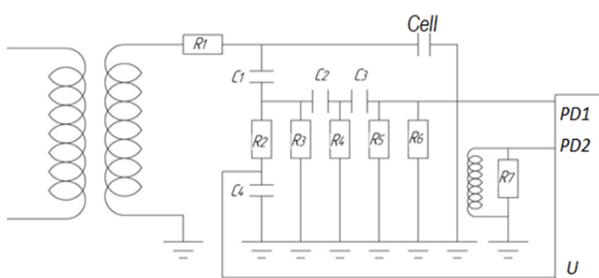


Fig. 2. High-voltage electric circuit.

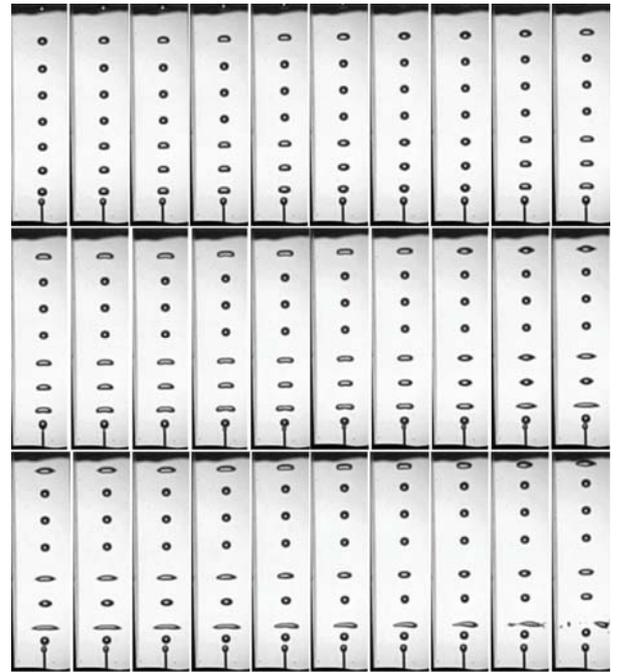


Fig. 3. Sequential frames of the gap between the electrodes just after the action of X-ray pulse. Time between the frames is 0.83 ms. The effective applied voltage is 7.8 kV. Gap distance is 10 mm. The lead barrier of 4 mm thickness was used. The vertical size of the frames is equal to 50 mm.

### B. Experiments on PD measurements

First, the experiments with air floating up bubbles were carried out. Alternating voltage of different amplitudes was applied. The electrode gap was  $h = 6.8$  mm and the diameter of the floating up bubbles was about 1.5 mm. It was revealed that PD did not occur even at the voltage 2 times higher than the voltage followed from Pashen's law. We waited for hours until the PD in a bubble occurred. Similar experiments with the helium bubbles showed that it took more than ten hours to observe first PD at the applied voltage of the magnitude of 15 kV that is 2.5 times larger than the Pashen's voltage. We measured the "apparent" charge of PD using our circuit of current registration. For the effective amplitude of the applied voltage of 15 kV, we found the value that equals approximately 80 pC.

It was suggested that the reason of the fail of the Pashen's law was the lack of initial electrons in bubbles that crossed the space between the electrodes very rapidly. This lack can be the result of the effective isolation of the experimental setup from natural radiation. To test this idea, we carried out the experiments with an artificial source of ionization.

## III. THE EXPERIMENTS ON PD INCEPTION WITH THE X-RAYS

### A. PD registration

The X-ray source (8) was added to the experimental setup (Fig. 1). The source gives the pulses of X-rays of the duration about 10 ns with approximately rectangular shape. The spectrum of the source includes photons of the energy in the range from 20 keV to 100 keV with the maximum of the intensity equal to about 50 keV. The pulse frequency was 6 Hz. We could change also the duration of X-ray action.

The first experiments with X-rays showed that the X-ray pulse induced PDs immediately in all the floating up bubbles that were in the space between the electrodes. This result was the same for the air and helium bubbles. Thus, X-ray beam

produced efficiently the electrons that initiate the partial discharges in floating up bubbles.

Then, we studied the PDs in helium bubbles more carefully. We started from the voltage of the magnitude of 15 kV and decreased it gradually from one experiment to another. The partial discharges stopped to appear when the voltage amplitude decreased down to about 6.5 kV that corresponds to the Paschen's limit (the voltage on the gap strongly corresponded to the Paschen's voltage in a bubble was 6.45 kV). When the voltage fell down below the Paschen limit we did not observe the PDs at all.

It is well-known that the discharge inception is a stochastic process. So, it is interesting how the probability of the PD inception in gas bubble in liquid varies with the intensity and the spectrum of X-ray radiation. The number of the PD events is significantly less than the number of period of the voltage because of the smaller frequency of the X-ray pulses. We had 6 short pulses per each 100 half-periods of the voltage. The bubbles undergone the action of radiation had enough time to leave the region of the high-electric field until the next X-ray pulse. Thus, we can consider that each subsequent X-ray pulse affected a new portion of the bubbles and the previous discharges during previous X-ray pulse did not influence the discharge inception by the subsequent pulses. Theoretically, this gives us a possibility to find the probability of PD initiation at the known level of the radiation.

We placed the blinds of lead of different thickness in the central part of the X-ray beam thus decreasing the intensity and the bandwidth of X-rays. First, the 2 mm blind was used to shade the region between the electrodes from the radiation. The operating time of the X-ray machine was 12 seconds and the applied voltage  $V = 6.45$  kV corresponded to the Paschen's voltage on the helium bubble.

The lead blind of thickness of 2 mm screens the space behind it very effectively in the used range of the photon energies from 20 to 100 keV. The minimal attenuation was for the range from 80 to 88 keV. The intensity of the X-ray beam in this range decreases by about 100 times [7].

The results of measurements of the number of the PD events are shown in table I. The bubbles that are deformed significantly are the bubbles where PD occurred. It is seen that the screening of the radiation results in the diminishing of the number of discharged bubbles. We explain this fact by the diminishing of the photons that produced the initiating electrons.

Fig. 3 shows the sequential frames of the video record of the chain of floating up bubbles at the moments just after the action of X-ray pulse. The voltage of effective amplitude of  $V = 7.8$  kV was applied and the lead screen of thickness of 4 mm was placed to the center of X-ray beam. The record captured about three half-periods of the voltage.

Several processes are observed at these frames. First, the highly deformed bubbles are the bubbles after the PD. There are four discharged bubbles and three dielectric bubbles in the several first frames. Then, the polarity of the voltage changes and one of the bubbles (the third from the bottom) restores its shape. It means that the electric charges on its walls disappear by some reason. It can be a reverse discharge or some mechanism of leakage of charges out of the bubble. Sometimes, we registered after PD in a bubble the formation of filamentary streamers developing from the bubble tops to the transformer oil at the moment of maximal deformation.

TABLE I. PD RATES IN HELIUM BUBBLES.

Effective voltage amplitude, kV	Lead barrier thickness, mm	Number of PDs	Number of "active" periods	Total number of bubbles
6.6	2	58	72	504
7.8	2	61	72	504
9.4	2	79	72	504
6.6	4	13	72	504

All other bubbles oscillated synchronously with the electric field. We registered the repeated PD in some of the bubbles. The next discharges can cause breaking of a large bubble into smaller bubbles (last frames in Fig. 3, the second bubble from the bottom). The secondary bubbles are attracted to the electrodes since they carry a free charge.

### B. Probabilities of PD inception

For the applied voltage 6.6 kV, we observed 5 half-periods when 4 bubbles discharged simultaneously after the X-ray pulse, 2 half-periods with 3 bubbles and 10 half-periods with 2 bubbles of total amount of 7 bubbles in a gap per a period. For the applied voltage 9.4 kV, we observed the PDs in 4 bubbles for 4 times, in 3 bubbles for 7 cases, and in 2 bubbles in 17 cases (half-periods). Thus, the increase of the voltage amplitude leads to the increase of the number of half-periods where the multiple PDs observed.

There is no synchronization of the X-ray signal and the applied voltage so we can consider that the probability density of X-ray action is uniformly distributed in time. If we suppose that primary ionization by X-rays decay very quickly than the probability of the discharge inception in a bubble is proportional to the time interval where the current voltage exceeds the Paschen's voltage level. These intervals for 3 values of the applied voltage amplitude are shown in the Fig. 4 as  $T_1$ ,  $T_2$ , and  $T_3$ . Thus, from theoretical point of view, the probability of the PD in a floating up bubble should be 1.36 times higher for  $V = 9.4$  kV in comparison with  $V = 7.8$  kV and 3.7 times higher than for  $V = 6.6$  kV in our experiments. The table I does not confirm these relations. We consider that this discrepancy can be the result of the effect of reflected and scattered X-ray radiation since we shaded the central part of the beam only.

Nevertheless, the effect of the X-rays on the probability of the PD inception in the floating up bubbles is beyond doubt that is demonstrated clearly by the data in table I.

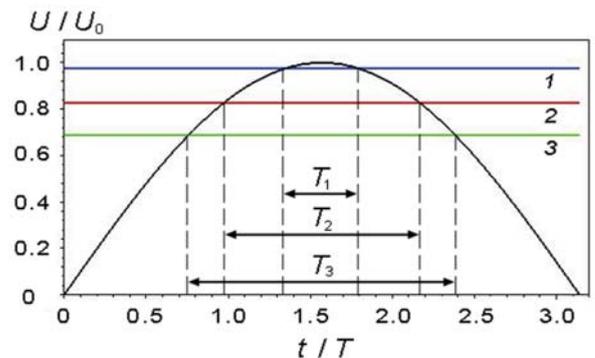


Fig. 4. The limits for PD inception in a bubble at different amplitudes of the applied voltage. 1 – 6.6 kV, 2 – 7.8 kV, 3 – 9.4 kV.

The probability of the discharge initiation is proportional to the number of photons falling on a bubble. For the bubble of size of 1.5 mm, we estimated this number as  $\sim 2 \cdot 10^4$  per one pulse for the photons of the energy about 80 keV. Here we have taken into account the 40 percent X-ray attenuation in the layer of the transformer oil of the thickness of 4 cm (the distance from the oil surface to the center of the gap between the electrodes) [7]. This estimation takes into account only direct beam and does not include reflected beams, scattering in the bulk of the oil that can produce additional ionization in gas, and processes of reemission.

#### IV. SIMULATIONS OF PD ELECTRICAL CHARACTERISTICS

In experiments, the time of one PD was about  $\tau_{PD} = 50$  ns. Thus, the duration of PD is significantly shorter than the characteristic time of the bubble deformation and the half-period of the voltage that allowed us to simulate electrical characteristics of the PD independently of other processes. The electric field and the charge distribution in the gap between electrodes were calculated with a finite-difference numerical method. At each time step the following system of equations was solved. In the region occupied by dielectric with a dielectric permittivity  $\varepsilon$

$$\operatorname{div}(\varepsilon \mathbf{E}) = 0, \text{ where } \mathbf{E} = -\nabla \varphi. \quad (1)$$

In the gas cavity where the electron avalanches can develop

$$\operatorname{div}(\varepsilon_0 \mathbf{E}) = \rho, \quad (2)$$

where  $\rho$  is the charge density.

We consider that the plasma in a cavity occurs instantly and then the conduction of a cavity is constant during PD. The charge is transferred in accordance with the continuity equation

$$\frac{\partial \rho}{\partial t} + \operatorname{div}(\mathbf{j}) = 0, \quad (3)$$

where the current density is  $\mathbf{j} = \sigma \mathbf{E}$ .

Here  $\sigma = 0$  in dielectric and  $\sigma = \text{const}$  in the cavity. We estimated the characteristic average value of the conductivity using the Maxwell relaxation time as  $\sigma = \varepsilon_0 / \tau_{PD} = 1.77 \cdot 10^{-4}$  S/m.

The simulations we made showed that the accurate calculations of the “apparent” charge  $Q_{ap}$  (the charge flowing in the external circuit during PD) is possible if the relative accuracy of the electric field potential calculations is not worse than  $10^{-11}$ . This required massive calculations and the parallel algorithms were realized for Graphic Processing Units (GPU) and used for the PD simulations. The GPU with 2880 computing cores was used for high performing parallel computations that shorten the simulation time 2 orders of magnitude.

The gap between two parallel plane electrodes was filled with a dielectric layer with the dielectric permittivity 2.2 that corresponds to the transformer oil in our experiments. The simulations were made on the lattice of sizes  $256 \times 256 \times 256$ .

The dielectric bubble is deformed in a high electric field [5] that influences strongly on the values of the “apparent” charge and “true” charge  $Q_{tr}$  (the charge deposited on the bubble-liquid interface) of PD.

TABLE II. RESULTS OF SIMULATIONS OF PD IN ELLIPTIC BUBBLE.

$a$ , mm	$b$ , mm	$Q_{tr}$ , pC	$Q_{ap}$ , pC	$Q_{tr}/S$ , $\mu\text{C}/\text{m}^2$	$Q_{ap}/V$ , $\text{mC}/\text{m}^3$
0.68	1.06	100,8	12,1	97,8	15,3
0.8	1.22	135,2	18,7	98,9	15,4
0.9	1.38	174,6	27,3	99,6	15,5
1.28	1.96	358,9	80,5	102,3	16,0
1.38	2.12	422,2	102,3	102,6	16,1
1.48	2.28	491,1	128,1	103,0	16,1
1.6	2.44	566,0	158,1	103,4	16,2

We placed a dielectric cavity to the center of the gap. The cavity had the shape of the ellipsoid of revolution that allowed us to take into account the elongation of the bubble in the electric field. Our previous calculations for spherical bubble [1-3] showed that the electrical characteristics of PD depend strongly on the volume of bubble.

The calculations for the elliptic bubble are represented in Table II. In the table,  $a$  is the transverse diameter of a bubble and  $b$  is its size along the large axis. The experimental measurements and computer simulation of the hydrodynamics of a gas bubble in a dielectric liquid [5] showed that the deformation of the gas (dielectric) bubble at high enough voltage (more than 9.4 kV for our experiments) can reach the values of  $b/a = 1.5$ . We kept this relation for all the calculations in the table II approximately.

All the results for the “apparent” and “true” charges were reduced to the applied voltage of  $V = 22$  kV in order to compare the calculations to the measurements in experiments. The gap distance was equal to 10 mm. The value of “apparent” charge obtained for the bubble of the size of 1.9 mm is very close to our value of 80 pC measured in experiments. It is interesting that the value of the “apparent” charge reduced to the bubble volume changes by only 6 percents when the volume change by 8.5 times. The same is valid for the relation of “true” charge to the surface of the elliptic bubble.

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