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Study of partial discharges in bubbles and microsphere in transformer oil

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Abstract. Partial discharges in free bubbles floating in transformer oil and in a glass sphere are studied both experimentally and theoretically. Optical, electrical and optoelectronic registration was performed to obtain partial discharge pattern. The time duration of electrical and optoelectronic signals were practically the same and equaled to 50 ns. PDs in bubbles were rare events even at the electric field two times higher than required by Pashen's law. In the case of rigid sphere the voltage of PD inception was practically the same as the value given by Pashen's law. Simulations of PD gave the values of "true" and the "apparent" charges close to those measured at the experiments. Simultaneous PDs in bubble and closely situated sphere were not recorded.

1. Introduction

It is well known that partial discharges in paper-oil insulation are most hazardous events that lead to failures of high voltage equipment. The most dangerous defects in the electrical insulation give rise to the lowest values of the voltage necessary for PDs inception and to the largest values of the so-called "apparent" PD charge. This can be easily shown for gas cavities in a solid insulation, because the Paschen's law holds in this case $E/p = f(pd)$. Here, E is the electric field strength necessary for a self-sustaining discharge, p is the pressure, and d is the cavity size. Since the pressure is usually constant and equal to the atmospheric one, and the electric field magnitude is proportional to the voltage, the voltage necessary for the PDs inception increases with the length of a cavity along the rising branch of the Paschen's curve. Defects with rigid walls usually exist in solid dielectrics, bubble defects are in main insulation of oil filled power transformer. PDs in floating bubbles were registered previously [1]. The aim of this paper is the study of PD both in free bubbles and in a glass sphere, including a case where bubble is situated close to the sphere.

2. Experimental setup

Experimental setup (Figure 1) was practically the same as described in [1]. Some differences were in microsphere (5) that was supported in the bulk (2) of transformer oil by means of nylon filament (3). Sphere was glued to filament. The position of the microsphere was selected in such a way that during floating the helium bubble touched its wall. Electrodes (1) were installed at a distance of 6.8 mm. The



PD signal was registered using the registration scheme described in [1], and the FEU-97 (8). The video camera (9) was installed coaxially with the photomultiplier (8) for optical detection of the PD in the bubbles (4). The glass sphere was made of molybdenum glass, having the outer diameter of about 2-2.5 mm, and the internal diameter - of 1 mm.

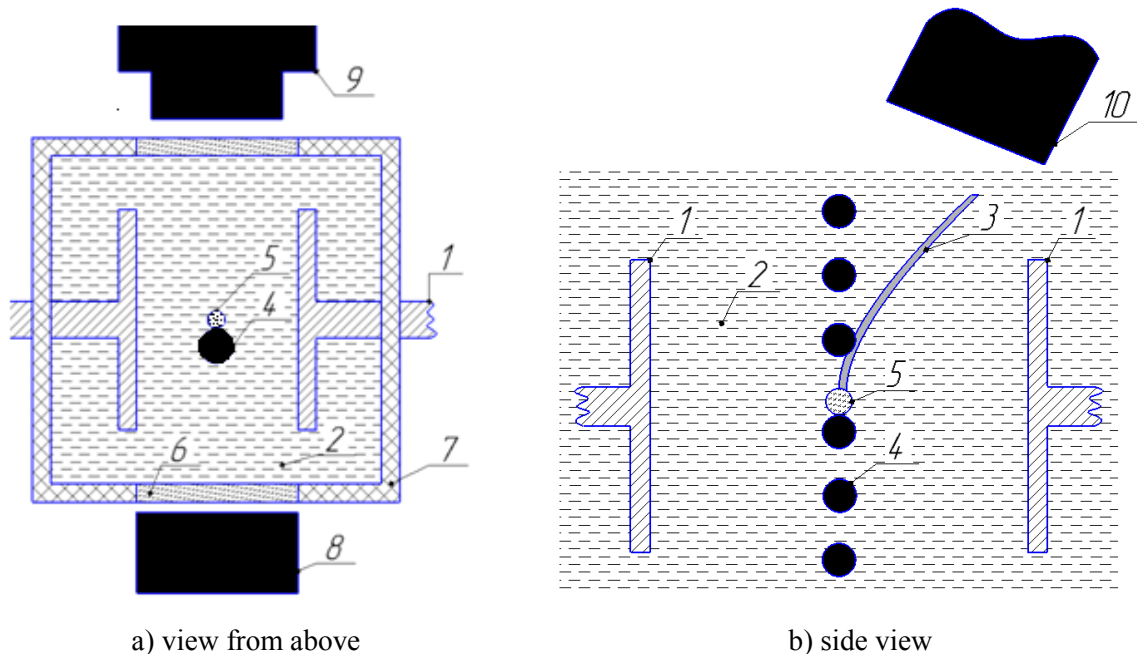


Figure 1. Experimental setup. 6 – optical window, 7 – cell body, 10 – source of light with the wavelength of 635 nm.

3. Experiments

3.1. PD signals in microsphere and bubble

Before the study, the inception voltage of the PD was determined that was approximately in accordance with the curve by Paschen for air gap, and was equal to 27 kV. The experimental value of 24 kV was found. Partial discharges developed in the sphere much more often than in a bubble, more than once per second when the voltage corresponding to the inception potential was reached. One can conclude that Paschen's law holds in this case. Figure 2 shows the electrical signals of partial discharges in helium bubbles with a diameter of 1.6 mm at the amplitude voltage of 35 kV, as well as in the sphere at different voltages.

3.2. Registration of the effect of the PD in the microsphere on the PD appearance in the pop-up helium bubble

Since the PD in the microsphere appears regularly, an attempt was made to ignite the PD in the bubble that ran to the sphere. Unfortunately, we were unable to achieve the location of helium bubble and microsphere along the electric field. During the experiment, the effect of the PD in the microsphere on the development of the PD in the bubble was not detected. At the voltage of 24 kV across interelectrode gap, PDs in microsphere appeared, but the emerging helium bubbles were subjected only to deformation, both in the course of emergence and immediately upon contacting with the wall of the microsphere. The contact time with the microsphere was approximately equal to 2 periods of voltage action (determined by the deformation of the bubble). We emphasize that, both in approaching the sphere and in moving along its surface, the bubble and microsphere were in a plane perpendicular to the electric field strength. The PD in the bubble (Fig. 3) was recorded after a rather long time, at a distance approximately equal to 4 bubble diameters.

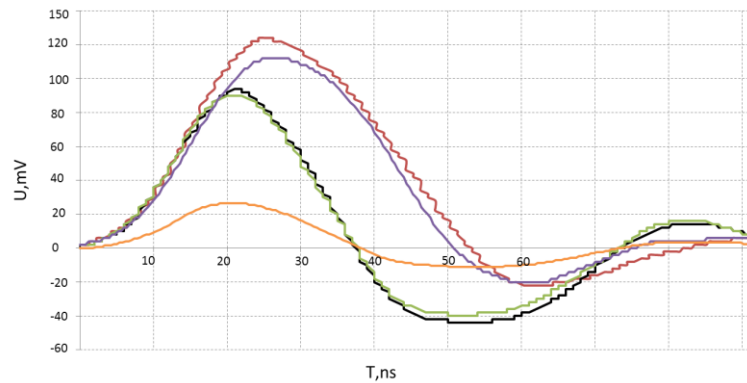


Figure 2. Electrical signals of partial discharges. Red and blue upper curves correspond to the helium bubble ; middle two curves (green and black) correspond to microsphere at 35 kV; lower yellow curve is for microsphere at 24 kV.

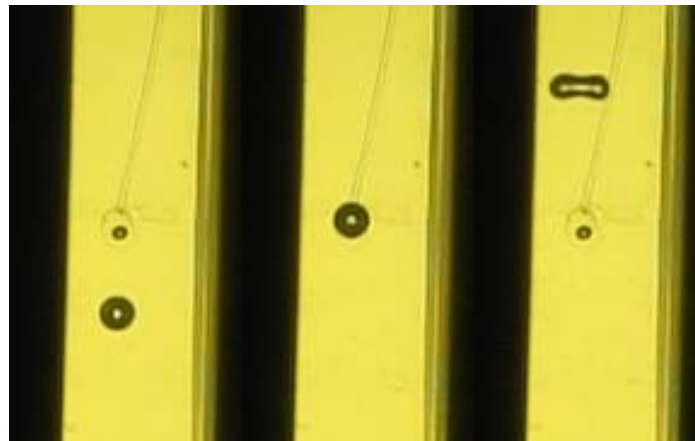


Figure 3. Bubble movement close to the sphere. First frame was made before contact with the sphere, second frame was at the contact, and the third frame was made after the bubble moved away to the long distance from the sphere and PD in the bubble occurred.

4. Simulation of electric field and apparent charge at PD

Simulations of partial discharge in spherical cavities placed into dielectric filling a gap between plane electrodes were carried out. Three-dimensional lattices of sizes up to $256 \times 256 \times 256$ nodes were used. The potential of the electric field was set to 1 at the right electrode (see Figure 4) and to 0 at the left electrode. The dielectric permittivity of the dielectric was equal to $\varepsilon = 2.3$ while the permittivity of the gas inside the cavity was $\varepsilon = 1$. We assumed that the inner space of the cavity was plasma with some constant conductivity. The value of the conductivity was $\sigma = \varepsilon_0 \varepsilon / \tau$, where τ is the Maxwellian relaxation time that corresponds to the characteristic time of PD decay of the order of 50 ns.

We calculated the apparent and true charges for PD in a glass cavity with the external radius of 0.88 mm and the internal radius of 0.48 mm. The dielectric permittivity of glass was chosen to be equal to 7.

The initial distribution of the horizontal component of the electric field in the central cross section of the gap is shown in Figure 4. The regions of high values of E are shown in blue colors. The green curve shows the values of the electric field along the symmetry axis of the electrode gap. The true charge inside the glass cavity was found to be 420 pC. The value of the apparent charge was 33.7 pC

provided that the electrode distance was 6.8 mm and the voltage of 22 kV was applied to the gap. Thus, the calculations are in a qualitative agreement with the measurements. The difference of the apparent charge obtained in experiment from the calculated one can be explained by the fact that when we integrate the measured signal of PD current we cannot exclude accurately the oscillations at the tail of the signal. Also, if the discharge is the incomplete one, the measurement gives lower values for the Q_{app} in comparison with simulation where we obtained the value of Q_{app} for fully completed discharge. It should be noted that both our simulations and computations by other method [2] and measurements give practically the same values of apparent charge for free bubbles.

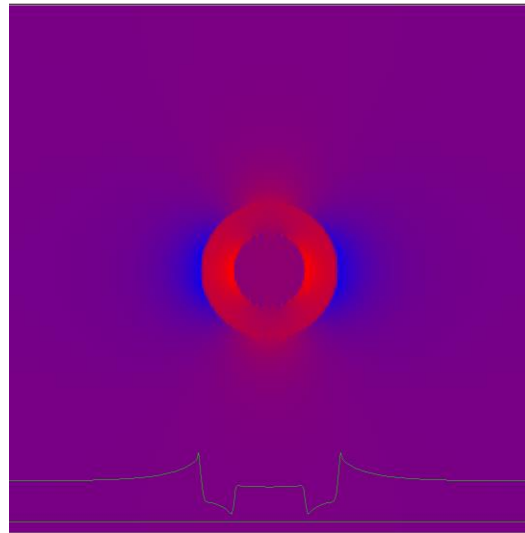


Figure 4. The horizontal component of the electric field in the central cross section of the electrode gap (anode is the right electrode, cathode is the left one). Red color shows weaker field.

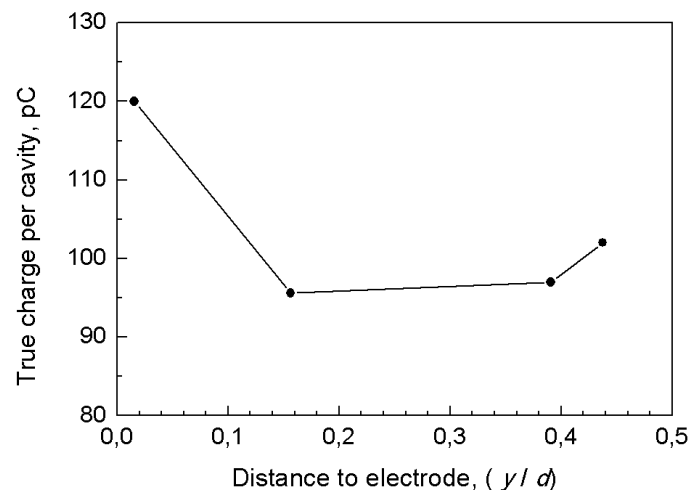


Figure 5. True charge per cavity for two identical cavities placed symmetrically at the equal distances from the electrodes. The radiuses of the cavities were 0.43 mm. $V = 22$ kV, $d = 6.8$ mm.

The mutual influence of two identical cavities during PD was studied. We assumed that the cavities were placed symmetrically along the field at the same distances from the electrodes, and PD occurred simultaneously in them. The values of the true charges in cavities at different distances of the cavities

from the electrodes are presented in Figure 5. It is seen that the PD in cavities started influencing each another if the distance between cavities was compared or smaller than the cavity diameter.

It is found that the true charge in each of these two cavities was approximately the same as in the case of one cavity. Nevertheless, the PD current magnitude and the apparent charge for two cavities differ from these values for one cavity by just about 30% (not twice).

Thus, we conclude that the influence of the PD process in one cavity on the process in another cavity manifests itself only if the cavities are close to one another and it is obvious that their centers were placed along the electric force line. At different conditions, one can neglect this influence.

5. Discussion

Several interesting points are worth discussing. First one is the difference in PD appearance in microsphere and bubble. The problem is in initiating electrons [3]. Usually, these electrons appear due to cosmic radiation and the gamma-background from the Earth's interior. It can be expected that in our conditions (basement, shielded metal room) the PD inception voltage in free bubbles was several times higher than predicted by Pashen's law. As for sphere it was observed that at first voltage action the delay time was several hours, that well corresponds to the data of [2]. But next PD occurs immediately at the voltage switch. What does it mean? For PDs in air cavities in solid dielectrics, the mechanism consists in the generation of initiating electrons by the decay of negative ions. Negative ions can be generated inside the cavity under the action of previous PD in pre-history of the PD process. These ions could drift in the cavity and settle at the surface where they were held by the electrostatic image forces.

Unfortunately, the data on the equilibrium ion density at the surface of a dielectric do not exist. We can suppose that there is also a certain amount of oxygen ions at the surface of a cavity in dielectric. These ions can initiate electrons.

The decay energy of a negative ion is determined by the electron affinity that is equal to 0.4–1 eV for the oxygen, according to different sources. The decay of negative ions in air was observed at $E/p \geq 90$ V/(cm·mm Hg) (for atmospheric pressure, $E/N \geq 270$ Td) [3]. At PDs in cavities smaller than 1 mm, this criterion is satisfied, and this mechanism for the generation of initial electrons is realistic.

This mechanism could be realized in the case of a sphere, but in the case of a free bubble it is impossible. The reason is in unfeasibility of the presence of the negative ion at the surface of the bubble. Ions that were generated as a result of previous PD firstly attach to the surface and then should leave the surface under the action of image forces. The distance for the ion drift could be estimated through the diffusion length $l_D = \sqrt{Dt}$ that is of the order of several tens of micrometers. That is why every PD in a free bubble has no ions for more preferable generation of initiating electrons. We suppose that PD appears easier in bubbles attached to electrodes. Here there is no problem for initiating electrons to appear.

Another question is in the absence of PD stimulation in bubbles by the discharges in a sphere. In our opinion, there are several reasons for it. Frequent PDs in sphere should promote the generation of initiating electrons in bubble by several ways. First one is the electric field increase after redistribution of electric field by settled surface charge after discharge. One could see from Figure 5 that influence in our case should be negligible. Especially if we take into account the thickness of microsphere wall (\sim inner diameter of the sphere d , see Fig. 6) and high dielectric permittivity (~ 7) of glass. Second reason is photons, generated during avalanches inside sphere. Perhaps photons that could lead to ionization could not reach bubble because of absorption of high energy photons by glass and transformer oil.

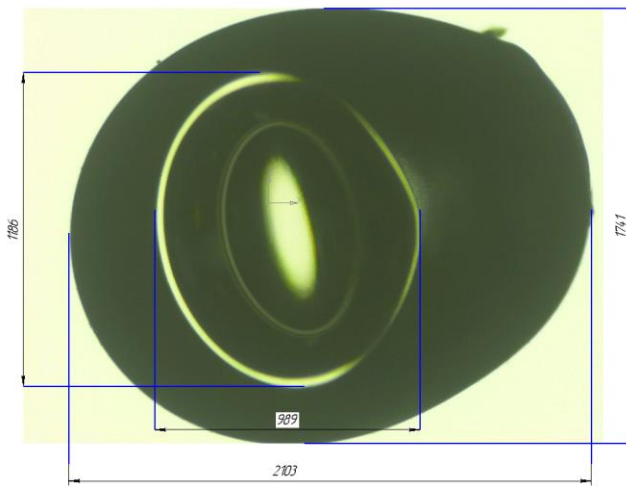


Figure 6. Photo of microsphere. The sizes are in micrometers.

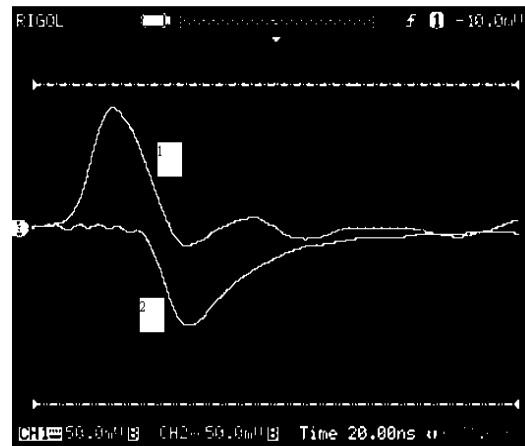


Figure 7. Electrical signal (upper line) and optical signal (from photomultiplier) (lower line) of PD.

The last but not the least point for discussion is the shape of electrical signal of PD. One could see from Figure 2 and 7 that the rise time of PD pulse in a bubble is 1.3 times greater than that of PD pulse in a sphere. Moreover, the rise time of PD in a sphere is the same at different voltages. In our opinion, the rise time is determined by transit time t of electrons inside gas cavity. Rough estimation gives $t \sim 10$ ns if we take the velocity $v \sim 10^7$ cm/s taking into account its saturation at high electric field. Several periods of transit time correspond well to the real value of the rise time both in case of bubble and sphere. The coincidence of the rise time of electrical signal of PD and its luminescence do not contradict this explanation.

6. Conclusion

As a result of optical and electrical investigations of partial discharges in free bubbles in transformer oil, the following conclusions can be made:

1. PDs in free bubbles are rare events even at the electric field two times higher than required by Pashen's law due to lack of initiating electrons.
2. The PD inception voltage in the case of rigid sphere well corresponds to Pashen's law.
3. The value of the measured "apparent" charge of PD is close to simulated one.
4. PDs in artificial sphere with thick wall don't generate PD in closely situated bubble.

Acknowledgements

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