Partial discharges in liquids

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Abstract— Experimental results concerning partial discharges in liquids are considered. For partial discharge initiating, there has to be initiating electron, the electric field strength sufficient for impact ionization and the conditions for secondary electrons appearance. Interruption could be at the change of conditions, decrease of electric field. Partial discharge in free bubble is a rare event due to lack of initiating electrons. PD in microsphere has usual properties like PD in gas inclusion inside solid dielectrics. In the case of PD with simultaneous movement of two bubbles, each PD in one bubble leads to PD in the second one usually. PD in point-plane electrode system occurs at the condition of extreme electric field when impact ionization in the oil takes place.

Keywords—Partial discharges, transformer oil, x-rays, streamers.

I. Introduction

Usually gas inclusions in solid electrical insulation are considered as the main source of partial discharges [1, 2]. Bubbles in oil filled high voltage equipment are one of the most dangerous inclusions, because they can lead to power failure due to breakdown. It is considered that the origin of insulation breakdown is frequently a partial discharge (PD) in gas bubbles with low electrical strength. The aim of this work is to analyze physical picture of PD in bubble.

The questions considered in this paper are as follows partial discharges in free bubbles, PD in microsphere, interaction of PD in bubbles and microsphere and in pair of bubbles, streamer breakdown due to PD in bubble. The new is simultaneous registration of bubble geometry (shadow picture), electrical and electrooptical PD signals. Other new data are X-rays effect on PD process and inception voltage.

The next question is experimental study of PD and gassing due to PD in point-plane electrode system in mineral oil and rapeseed oil.

Additional useful information concerning PD could be in case of electrooptical study of prebreakdown processes in nitrobenzene. The simulation and experimental data were compared. It allowed us to determine the electric field in the region with or without partial discharges in bubbles inside this region. Another result of this part of work is an estimation of electrohydrodynamic (EHD) flow velocity and space charge density at the injection from electrode into liquid.

The correlation between the breakdown voltage and the concentration of water in transformer oil is of great importance and it will be discussed in this work. Besides the role of water in breakdown due to appearance of water-oil emulsion, the water molecules could be the source of initiating electrons in the bubble.

II. Methodology

Mainly the experimental results concerning partial discharges in liquids are presented here. First, experiments were performed with PD in specially prepared helium bubbles at AC voltage. Experimental setup is presented in Fig.1.

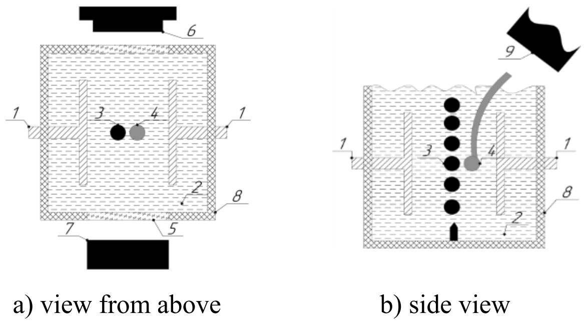

Fig. 1. Experimental setup.

Several different types of experimental setup were used (Figure 1). The main part of experimental setup was practically the same as described early [3, 4].

In the case of free-floating bubbles, a high-speed video camera (6) and a photomultiplier (7) were used for registration. They were located coaxially. Illumination of the interelectrode gap was carried out from the upper part of the cell. Illumination has red color and photomultiplier was equipped by filter with blue band sensitivity

In experiments with X-ray apparatus, the photomultiplier was absent. In this case, the experimental setup included a high-speed video camera (6) installed coaxially with illumination (7) for the optical detection of the PD in the bubble (3).

III. Results

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A. *Partial discharges in free bubbles*

Bubble generation system creates several bubbles per second automatically. The diameter of bubbles was 1.5 mm usually. First experiments were performed with air bubbles. Estimation of PD inception voltage according to Pashen's law gives 25 kV approximately. Nevertheless, up to 42 kV no one PD was detected.

In the next series of experiments helium bubbles behavior was studied. Theoretical estimations of PD inception voltage give 6.6 kV. In reality it requires at least 15 kV. Moreover, this PD in bubble is very rare event. One PD was observed for several hours. The discharge inside bubble in all registered cases leads to elongation of the bubble and its division into two charged parts (Figure 2). At the action of alternating electric fields these parts move and oscillate in opposite directions. Sometimes when one of the secondary bubbles brings nearer to an electrode a secondary powerful PD takes place. Any dependence on voltage phase of PD inception wasn't registered even at the electric field two times higher than required by Pashen's law.

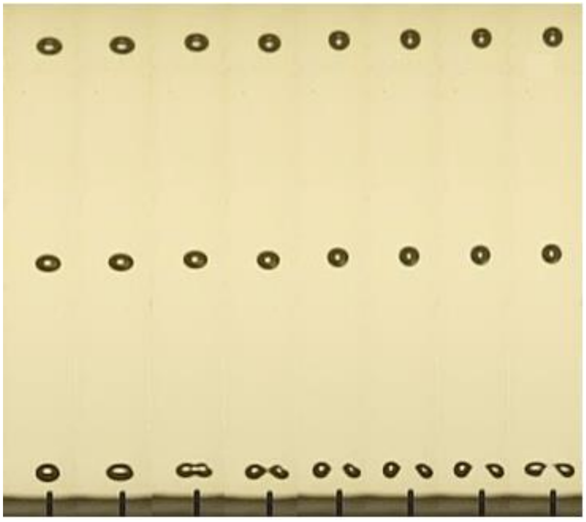

Fig. 2. Partial discharge in lower bubble in transformer oil at U=16 kV.

The traces of electrical and optical PD signals in bubble are shown in Fig. 3. One can see that the pulses have the same shape, the leading edges of the pulses are the same, and the falling edges of the pulses are slightly different. The delay of optical signal followed due different lengths of measuring cables and transit time of electrons inside the photomultiplier. Rise time of both signals was about 20 ns (at own rise time of scope 15 ns).

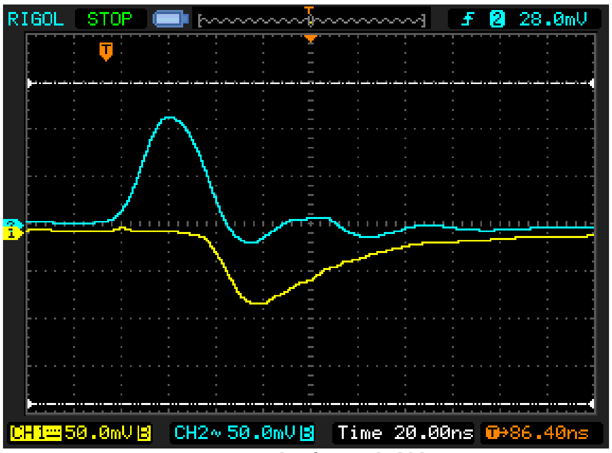

Fig. 3. Signals of PD in bubble:
Upper - electrical, lower – optical.

Several experiments were performed with PD appearance in glass hollow microsphere. The aim of these tests was to reveal a possible influence of PD in microsphere on PD appearance inside bubble close to microsphere (up to contact one to other). It was established that PD in the microsphere has usual properties like conventional PD in gas inclusion inside solid dielectrics. The PD patterns and the voltage inception were the same. But the influence of frequent PD in microsphere on rare occurrence of PD in free bubble wasn't registered.

Interesting result was obtained in case of simultaneous floating of two bubbles. The distance between them was less than bubble radius (Fig.4.) Several PD were registered. Every PD in one bubble led to PD in the second one.

Fig. 4. Generation and floating of bubble's pairs.

B. *Experiments with X-rays*

The main hypothesis explaining the rarity of partial discharges even under the action of increased voltage is the lack of initiating (starting) electrons. For testing, we decided to affect the gap (with pop-up bubbles) by X-rays (Figure 5).

Fig. 5. Partial discharges in helium bubbles when exposed to x-rays. Voltage U=16 kV.

Under this condition partial discharges appeared in all bubbles simultaneously. When voltage decreases, PDs stop at U=6.6 kV when Paschen's law ceases.

C. PD in point-plane electrode system

Another type of PD occurs in a liquid in the presence of local strong electric fields. In our experiments [5] two liquids: mineral transformer oil and rapeseed oil were used. "Point-plane" electrode system was used to generate strong electric field. The curvature radius of point electrode was less than 2 μm. Estimated electric field strength in liquids close to needle tip exceeded 15 MV/cm.

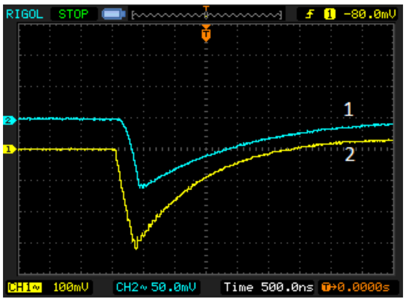

Fig. 6. PD in transformer oil (1) - photomultiplier; (2) – electric signal.

Comparative characteristics of PD pulses in oils are given in Table I.

TABLE I
CHARACTERISTICS OF PD PULSES

№	Oil type		
	Regular	Transformer	Rapeseed
1	Pulse width, ns	500	500
2	Duration of the leading edge, ns	200-400	200-500
3	The maximum current of the PD, μA	39-69	27-57
4	Apparent charge, pC	36-62	19-53

D. Electrooptical study of prebreakdown processes in nitrobenzene: the simulation

Our old experimental data concerning electrooptical registration of prebreakdown processes (see e.g [6]) were reconsidered from the PD point of view. The electrooptical Kerr effect is a powerful tool for study prebreakdown processes in liquids with huge induced birefringence like nitrobenzene [6]. The obtained experimental material was not fully analyzed either because of the high laboriousness of the processing, and because of the lack of an adequate mathematical model of the processes under study at that time. The analyzed picture with PD is presented in Fig. 7. Here it is scan of the polarized light passed through optical slit and analyzer (kerrogram).

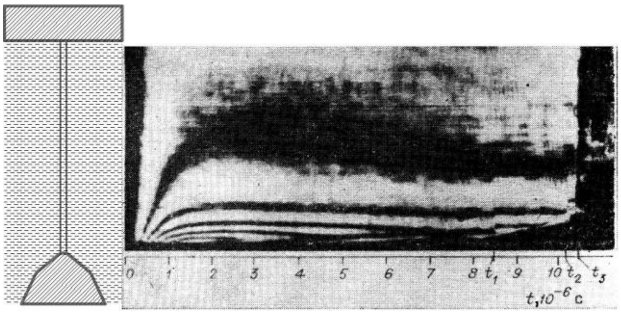

Fig. 7. Rotating-prism scan of prebreakdown events near cathode. t1, t2 – moments of PD inside bubble zone, t3-breakdown initiation.

Kerr fringes are lines of equal:

$$\int_{\varepsilon_1}^{\varepsilon_2} E_{\perp}^2(x,z,t)\,dz$$

That is why redistribution of electric field after PD will lead to redistribution of intensity and the position of each Kerr fringes. Local increase of electric field in front of ionized local zone should shift closest fringe away from electrode and don't shift other fringes far from this zone.

We simulated the intensities of light of Kerr fringes for the bubble near curved electrode. For this purpose, both electric field and passed light distribution were computed:

$$I(x,y) = I_0 \cdot \sin^2\left(\pi \cdot B \cdot \int E_{\perp}^2(x,y,z)\,dz\right)$$

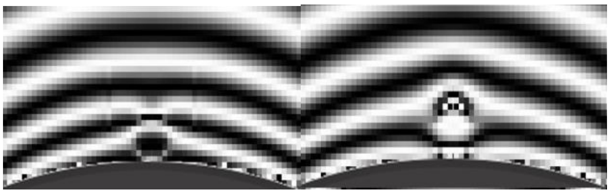

Fig. 8. Computed kerrogramms (a) — single bubble on electrode, (b) — the same bubble after ionization.

Fig. 8 b shows that computed closest fringe is shifted after ionization, and far fringe practically don't move.

E. The role of water in breakdown of transformer oil

In our opinion the water could play two roles in prebreakdown processes. First one is traditional. The water in form of little drop leads to field increase in the oil close to the poles of the bubble like the case with ionized bubble (Fig.8). In the case of a single drop in the bulk of liquid, the increase in the local field strength is about 3, for a drop on the electrode - up to 4. Under the action of an electric field, the drop is deformed and the electric field near its tips increases even more significantly. Another option, but also leading to a local field enhancement, is the emergence of instability of a charged drop surface, with the formation of, so-called "Taylor cone". These processes could explain the decrease of electric field strength in case of drop formation, detailed mechanism of PD generation and subsequent breakdown remains unclear. In our opinion water could play other role in PD inside bubbles. Water molecules have great electron affinity. Therefore, a number of molecules can attach an electron and be in oil in the form of negative ions. At the action of strong electric field these ions can lost electrons. It leads to forming free electrons capable of becoming so-called initiating electrons. The mentioned role of negative ions as supplier of initiating electrons is proved in [7, 8].

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IV. Discussion

There are a lot of types of partial discharges in liquids. What they have in common is that the discharge was initiated, but then interrupted. Two questions are most interesting. What were the reasons and conditions for discharge initiation? And what were the reasons and conditions for discharge interruption? For initiating here should be initiating electron, the electric field strength sufficient for impact ionization and the conditions for secondary electrons appearance. Interruption is because of the change of conditions such as decrease of electric field.

In the case of PD in free bubbles experiments with X-rays and without X-rays show that appearance of initiating electrons is the main problem of PD initiation [9]. PD stops due to decrease of electric field inside a bubble because of the screening of region inside the bubble by the charge deposited on the surface of the bubble after discharge. The Coulomb forces act on the charged surface of the bubble that leads to elongation and break up of the bubble into two charged parts. The action of the applied alternating voltage can initiate the next PD between a bubble and the closest electrode and, in some cases, the breakdown of the electrode gap at the subsequent half-periods. If we take into consideration the avalanche evolution then the streamer model of PD in bubble is preferable. In all our experiments criterion of avalanche-streamer transition is fulfilled.

PD in point-plane electrode system occurs at the condition of extreme electric field when impact ionization in the oil takes place [10, 11]. Then a tree of filament or bush-like streamers develops from the tip of needle. During streamers propagation the electric field near its tips decreases (the charge in tips decreases due to number of streamers and voltage drop on its length) impact ionization stops and PD stops.

As for as PD in nitrobenzene at pulse voltage action one could see that the dark zone (see Fig.7) close to electrode is appeared approximately 0.5 μsec before PD. This zone consists of bubbles. It isn't single bubble, but is a cluster of smaller bubbles. Kerr fringes don't change its position during development of bubble zone. Shifts of fringes at the moments t1, t2, show that PDs occur in the bubble zone. The development of this zone leads to breakdown initiation at the moment t3.

For the mixtures of water in transformer oil we can conclude that the colloidal form of water can initiate PD, and also water negative ions could give initiating electron.

V. Conclusion

Partial discharges in liquid could develop in several forms: gas discharge inside bubbles (streamer or multiavalanche discharge), impact ionization in liquid in case of extreme fields. Water plays significant role in PD inception. PD can initiate the subsequent breakdown.

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