Numerical simulation of partial discharges in deformed bubbles in transformer oil

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Abstract—The accurate systematic calculations of the true and apparent charges of partial discharge a spherical bubble between plane electrodes in dependence on the position of the cavity were performed. The influence of the partial discharge in one bubble on the discharge in another bubble is studied in dependence on the distance between the bubbles. The effect of bubble elongation because of hydrodynamic flow on the value of the apparent charge and the true charge is studied too for the approximation of the bubble with the ellipsoid of revolution. The linear dependence of the apparent charge value on the bubble volume is obtained for both spherical and elliptic bubble even for the case of the large bubbles. The true charge is found to be proportional to the surface area for the spherical bubbles as well as for the ellipsoidal bubbles. The dependence of the apparent charge reduced to the bubble volume on the bubble deformation coefficient is obtained. The inception of streamers from the apex of the deformed bubble was experimentally registered after partial discharge in bubble. The numerical estimations of the maximal electric field near the bubble after partial discharge are made that showed insufficient magnitude of the field necessary for the streamer inception. The possible mechanism of this phenomenon is proposed.

Keywords—Partial discharges, computations, apparent and true charge, bubble deformation, streamer inception from the bubble

I. Introduction

The phenomenon of partial discharge (PD) in dielectrics is studied experimentally for decades. The partial discharges (PDs) in dielectric liquids occurs in two forms. First, these are incomplete streamers that develop from metallic parts of the high voltage equipment to insulation [1]. Second, these are the discharges inside the bubbles that appear in a liquid inevitably. We focus on the PD in the bubbles in the presented work.

Registering of PD activity is the powerful method of detecting of the current state of the insulation. Nevertheless, some questions remain unclear. Two of them are what is the “intensity” of PD and how the PD “intensity” depends on the experimental conditions. The so-called “apparent” charge flowing through the electric circuit during PD can be used to characterize the intensity of a PD in a single void as well as the PD frequency is used to describe the PD activity. We carried out systematic theoretical studied of the PD intensity from the point of view of the value of an “apparent” charge and the corresponding “true” charge deposited on the walls of a bubble after PD. The regulatory documents used for the assessment of PD through the apparent charge are based on the simple equivalent circuits. These circuits allow obtaining only rough estimations of the electrical characteristic of PDs [2] that do not take into account the real distribution of electric fields, charges and currents during PD. Our work is devoted to the exact calculations of electric fields and charges related to PD in bubbles. In the development of the work [3] we calculated the values of the true and apparent charges for PD in spherical and deformed bubbles of different sizes and studied the mutual influence of two bubbles one to another.

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II. Experiments

For the first time, we carried out the systematic experiments with the chains of floating up bubbles in dielectric liquid. The experimental setup was described in [4] in details. The experimental cell is shown in Fig. 1. The bubbles were supplied from the syringe 6 to the electrode gap filled with transformer oil. The sizes of the bubbles varies from 1 to 2 mm. The bubbles floated up one by one in the central part of the gap along the electrode surfaces with the average velocity of 0.25 m/s at the distance of about 5 mm. The alternating voltage of the frequency of 50 Hz was applied to the gap. The video registration of bubbles was made together with the current signal in the circuit. The so called apparent charge of PD was measured as well as the deformation of the bubbles in the electric field before and after PD.

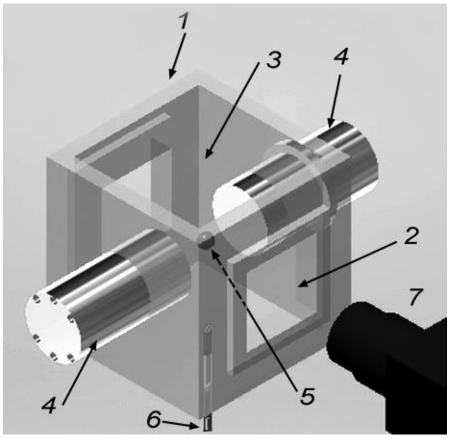

Fig. 1. Experimental cell. 1 – PMMA walls; 2- glass optical window; 3 – transformer oil; 4 – flat electrodes; 5 – floating up bubble; 6 – syringe for bubble generation.

III. EQUATIONS AND COMPUTATIONS

The Poisson theorem of electrodynamics was used to calculate the electric field potential in the dielectric filling the space between the electrodes and in gas bubbles (non-conducting and conducting). The dielectric permittivity of the dielectric was $\varepsilon = 2.2$ that corresponds to the transformer oil used in our experiments. The dielectric permittivity of the bubble was equal to 1. The continuity equation was used for the calculation of the electric charge transfer inside the bubble during PD. We did not simulate the process of the avalanche development in the bubble during PD since our interest was focused on the integral characteristics such as the total true charge, the apparent charge, the electric fields around the bubble. Thus, the simple model of constant conductivity of the substance inside the bubble during PD was applied. The value of the conductivity $\sigma = 0.018$ S/cm was derived from the maxwellian relaxation time that was estimated from our experiments. The three-dimensional calculations were performed on the lattice of size 256×256×256 nodes. The exact calculations of apparent charges took the relative accuracy for the field computation not worse than 10^{-11} that was achieved with the use of the graphic processing units (GPU) as the computing devices.

IV. PD CHARACTERISTICS OF SPHERICAL CAVITY

In the experiments, the shape of the bubble changes with the voltage magnitude [4]. At relatively low voltages (if the Pashen's limit of discharge is low as in case of helium bubbles) the deformation of bubble is small and the bubble shape can be approximated with a sphere. At the higher voltages bubble deforms because of the hydrodynamic flows that we observed in our experiments [4].

The calculations of the apparent and true charge of PD for spherical bubbles were performed in a wide range of the size of the bubble. The applied voltage, the gap distance and the maxwellian relaxation time were used as the units of measurements in simulations. In each simulations, we found the initial field distribution in the gap between flat electrodes filled with a dielectric with the spherical bubble in center. We considered that the voltage on the bubble is equal to or higher than that necessary for the discharge development. Thus, after the calculation of the initial field, we "switch on" the constant conductivity in the bubble simulating PD. The case of total charge relaxation was studied. To find the electric characteristics of the PD we scaled the reduced calculated values to the real experimental conditions. The gap length was taken equal to 10 mm as in our experiments. The voltage of bubble breakdown was calculated using Pashen's law for the given value of the product pl where l is the bubble size and p is the atmospheric pressure. Then, we found the applied voltage and calculated the apparent Q_{app} and true Q_{true} charges. The results of the calculations of the charges are shown in Fig. 2.

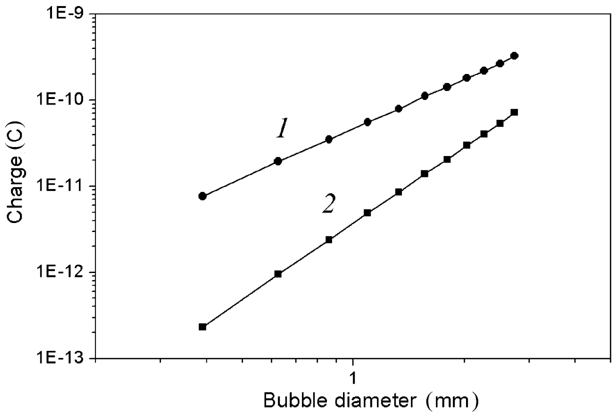

Fig. 2. Dependence of the true charge (curve 1) and the apparent charge (curve 2) on the diameter of a spherical bubble.

The curves for $Q_{\mathrm{true}}(l)$ and $Q_{\mathrm{app}}(l)$ are linear in bilogarithmically scale. Power dependences $Q \sim l^m$ best fit these curves if the exponents are $m = 1.94 \pm 0.04$ for the true charge and $m = 2.97 \pm 0.03$ for the apparent one. We obtained the values of the exponents equal to 2.058 and 3.059 correspondingly if we assume the same applied voltage for different sizes of bubble. Thus, the apparent charge most likely proportional to the bubble volume as the true charge is proportional to the area of the bubble surface up to the large bubble having the sizes of the same order as gap distance.

If there is some source of bubbles inside the insulation it can produce several bubbles. For example, the decay of the streamer channels of incomplete discharge in liquid leads to the formation of the chain of bubbles located close one to another. The wave of unloading behind the shock front can produce a cluster of bubbles. The question arises if the PD in one bubble is able to stimulate the PD in neighbor bubbles. To clear up the question we placed two bubbles of the same radiuses along the electric field line symmetrically to the electrodes at different distances from them. Then, we considered that PDs arise simultaneously inside both these bubbles and calculated true charge on the walls of the bubbles. The results of the simulations for two symmetric bubbles are shown in Fig. 3. Here the radiuses of the bubbles were equal to $0.08d$.

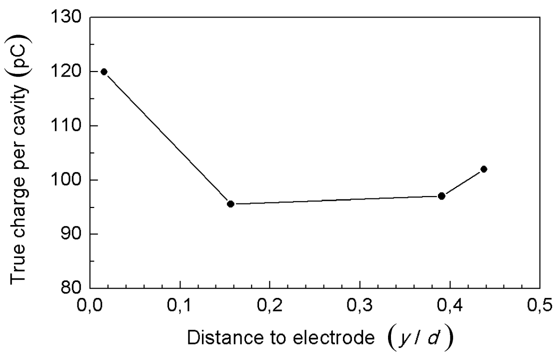

Fig. 3. Dependence of the true charge on the position of the center of bubble for the case of the two spherical symmetrically placed bubbles.

The true charge has maximal value and it is equal to the apparent one when the bubbles are in contact with the electrode surfaces. The true charge becomes about 1.5 time smaller if there is a layer of dielectric between the bubble and electrode. The true charge per a bubble has approximately the same value until the minimal distance between the bubble edges becomes smaller than the bubble diameter. Since the affect of the electric field on one bubble to another bubbles was not revealed at the distances larger than the bubble size even for the conducting bubble then it is negligible for dielectric bubbles for the same distances.

V. Dependence of True and Apparent Charge on the Bubble Deformation

The electric forces at the gas-liquid interface deform the bubble in a high enough field [4]. The deformation affects the electric characteristics of PD. We simulated the true and apparent charge of PD in dependence on the bubble elongation and volume of the deformed bubble. Since the hydrodynamic processes accompanying discharges have characteristic time of the order of milliseconds we considered that the bubble shape is constant during PD event that lasts for tens of nanoseconds. The shape of the bubble was approximated with the ellipsoid of revolution with the large half-axis b and the small half-axis a. The elliptic cavity was placed to the center of the interelectrode gap. The results of simulations of the apparent charge and the true charge are presented in Table I. The area of the surface of the ellipsoidal bubble S and its volume V are also shown in the table.

The true charge increases with the area of the bubble surface for the deformed bubble (fig. 4) as it was observed for the bubble of a spherical shape. Fig. 5 shows that the apparent charge value increases linearly with the cavity volume. Thus, the dependence of Q_{app} on the bubble volume is of general type and do not depends if the bubble is deformed or it is not deformed. Nevertheless, the apparent charge reduced to the bubble volume Q_{app}/V can depend on the deformation of the bubble. We plotted the relation between Q_{app}/V and the coefficient of the deformation b/a. This dependence is linear when the deformation coefficient is higher then 1.2 as it is represented in Fig. 6.

TABLE I
TRUE AND APPARENT CHARGES FOR ELLIPSOIDAL BUBBLES

a, mm	b, mm	S, cm^2	V, cm^3	Q_{true}, pC	Q_{app}, pC
0.35	0.69	0.0081	$2.654\ 10^{-4}$	68.96	8.30
0.40	0.80	0.0106	$4.063\ 10^{-4}$	92.44	12.83
0.45	0.90	0.0138	$5.90\ 10^{-4}$	118.8	18.73
0.64	1.28	0.0266	0.00167	245.24	55.0
0.69	1.38	0.0311	0.00212	288.36	69.86
0.74	1.49	0.0360	0.00265	335.59	87.49
0.80	1.59	0.0412	0.00325	386.74	107.92

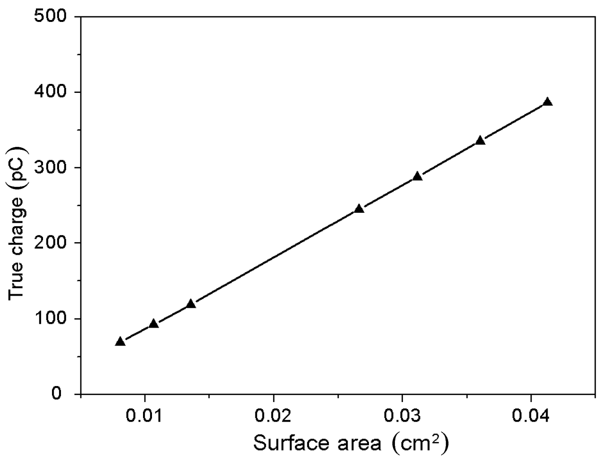

Fig. 4. Dependence of the true charge of PD in a gas-filled elliptic cavity on the surface area of the cavity.

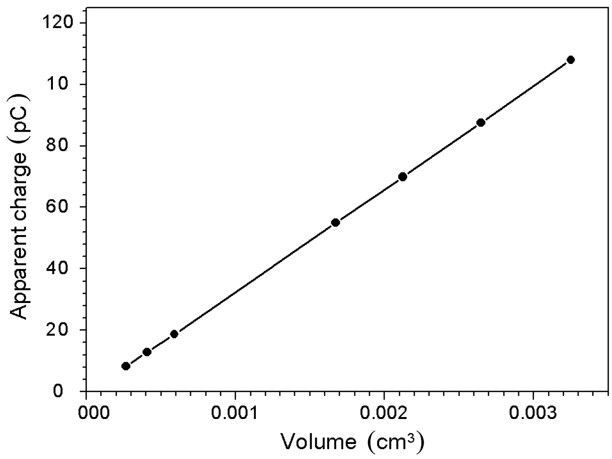

Fig. 5. Dependence of the apparent charge of PD in a gas-filled elliptic cavity on the volume of the cavity.

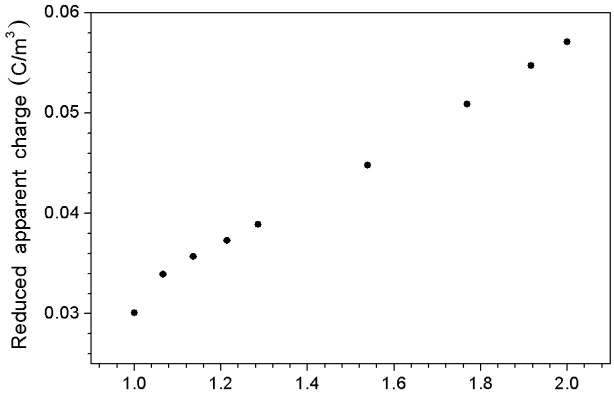

Fig. 6. Dependence of the value of the apparent charge per bubble volume on the coefficient of bubble deformation.

VI. The Streamer Initiation from the Top of the Bubble

In some experiments, we observed the generation of filamentary streamers in liquid phase in transformer oil just after PD in a bubble (fig. 7). The bubbles were deformed significantly after PD having got a larger size along the electric field. The streamers started from the tops of the bubble. The free electric charge (true charge) at the apexes of the bubble amplifies the electric field at the tops (Fig. 8). We supposed that this amplified field is sufficient for the initiation of the streamers in liquid phase. Thus, these experiments can be used to define the electric field strength for the breakdown initiation in liquid dielectric. To define this field, we made the calculations of the electric field distribution around elongated bubble of the shape of ellipsoid of revolution with the different coefficients of deformation. Three-dimensional calculations were performed on the lattice having the shape of parallelepiped with the sizes of 448x256x256 nodes. The plane electrodes were placed at the ends of this parallelepiped. Thus the gap distance was equal to the largest size of this parallelepiped. The cavity was simulated with the elliptic region with the electric permittivity $\varepsilon = 1$ placed to the very center of the electrode gap. The gap distance was $d = 1$ cm in our experiments so we scaled the calculation to this size. This means that spatial resolution for the field calculation was about 22 μm. Periodic boundary conditions were used at the sides of the lattice.

Fig. 7 shows the component of the electric field stress along the symmetry axis of the gap before and after PD for an elliptic bubble with large axis $b = 3.43$ mm and small axes $a = 0.62$ mm. We considered the case of the complete charge relaxation in the bubble.

The maximal electric field stress at the apex of the bubble depends on the bubble deformation. The electrohydrodynamic simulation of the bubbles showed [4] that the deformation of a dielectric gas bubble at equilibrium is about $b/a = 1.5$. This deformation increases after a partial discharge. We could not register the deformation at the moment of the streamer inception because of the insufficient temporal resolution. Therefore, we calculated the electric filed at the apex of the ellipsoidal bubble for different bubble deformations to find the possible limits for the field. The results of calculations are shown in Table II.

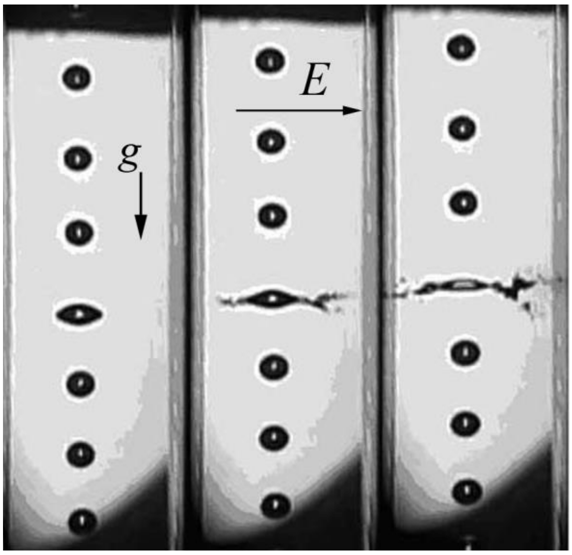

Fig. 7. The inception of a streamer in transformer oil from the apex of the deformed helium bubble after PD in the bubble.

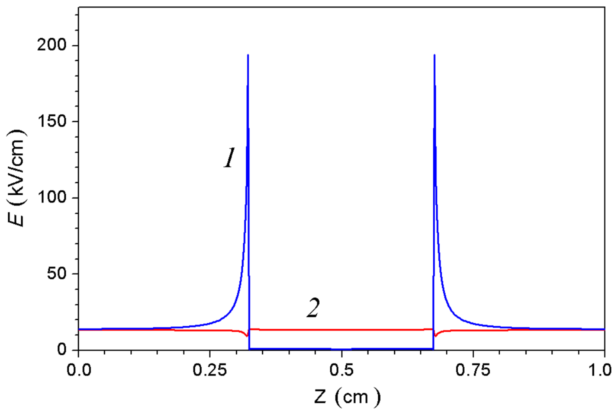

Fig. 8. Electric field stress along the symmetry axis of the electrode gap before and after PD. Elliptic bubble with the deformation coefficient 5.6 (see Table II).

The relation of the calculated values of the maximal electric field stress obtained in our calculation E_{calc} to the average electric stress in the gap $E_{av} = V_{app}/d$ is shown in the forth column of the table. It should be noted that the value of E_{calc} should be smaller than the real maximal value $E_{\max}$. Indeed, The value of the calculated field is $E_{calc} = \dfrac{\varphi_s - \varphi_l}{h}$, where φ_s and φ_l are the values of the electric potential in a lattice node on the bubble surface and in the nearest node in the dielectric liquid. Thus, E_{calc} is the average value over the lattice step $h = 22\mu\text{m}$. We can make the correction of the obtained value of maximal field if we increase this value by some factor β depending on the distance from the surface. This factor can be estimated as $\beta = 1 + h/R$, where R is the curvature radius of the apex of the ellipsoid. We considered that the discharge is of the Pashen type that is the voltage for PD inception is the function of the product of $p \cdot l$, where p is the atmospheric pressure and $d = 2l$ is the size of the bubble along the electric field line. This gave us the opportunity to calculate the applied voltage corresponding to the Pashen discharge in the bubble and then to estimate the electric field at the apex of the elliptical bubble after PD. The results of calculation of the value of $E_{\max}$ after PD are presented in the last column of Table II. It is seen that the maximal electric field $E_{\max}$ increases significantly with the deformation. Nevertheless, this field is significantly smaller then that is necessary for the filamentary streamer initiation in a liquid phase E_f. The numerous well-known estimations of E_f give the values not less than ~ 1-5 MV/cm. The question is how this field E_f can be reached at the bubble surface? In order to obtain the values of the maximal field $E_{\max} \sim E_f$ we should accept that the region of charge concentration is at least 5 times smaller then the lattice steps in our calculations.

That is we can suppose that the charge on the bubble surface is localized in a small spot at the apex of the bubble. Particularly, it is possible if the discharge inside the bubble has the shape of a thin enough streamer channel in a gas phase.

TABLE II
ELECTRIC FIELD STRESS AT THE APEX OF THE ELLIPSOIDAL BUBBLE FOR DIFFERENT BUBBLE DEFORMATIONS

a, mm	b, mm	b/a	E_{calc}/E_{av}	β	$E_{\max}$, kV/cm
0.62	0.79	1.29	3.18	1.092	39
0.62	0.92	1.5	3.52	1.107	43
0.62	1.23	2.0	4.35	1.143	52
0.62	1.54	2.5	5.18	1.179	62
0.62	1.85	3.0	9.50	1.214	114
0.62	3.43	5.57	14.95	1.40	194

V. CONCLUSION

In the presented work, we perform the systematic studies of electrical characteristics of PD in non-deformed and deformed bubbles. The wide range of the bubble sizes was studied. The relation between the apparent charge of PD and deformation of the bubble was obtained. The propagation of the streamers in transformer oil from the bubble was registered after PD. The estimations of the electric filed on the apex of the elongated bubble showed that this field is insufficient for the streamer inception. The mechanism of the streamer inception in liquid from the tip of the streamer in gas bubble was proposed.

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