Simulation of Apparent and True Charges of Partial Discharges

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ABSTRACT

Here it is considered partial discharges in the bubbles inserted in the fluid volume in the case of electrode systems "plane-plane" and "point-plane". The calculated "true" and "apparent" charges show that the apparent charge is many times smaller than the true charge. Smaller bubble size leads to greater ratio of the true charge to the apparent charge. There are two cases when the values of these charges are close. First case: the size of the bubble is large enough, namely close to the value of the gap in the case of flat electrodes. Second case: the void is in contact with the electrode. The latter case is realized in the case of the electrode system "point-plane". The experimental and calculated data are compared for this case.

Index Terms — **True charge, Apparent charge, Partial discharge, Transformer oil, Bubbles, Simulation, Measurement.**

1 INTRODUCTION

PARTIAL discharge (PD) registration is one of the most effective methods of diagnosis, which can detect defects in electrical insulation, such as gas inclusions, bubbles, layer separation, cracks. Since the PD is responsible for the deterioration of the insulation, its energy characteristics are most important. The main energy characteristic is the PD charge. This conclusion is logically correct: greater PD charge, leads to greater energy, which in turn leads to greater destructive effect on the insulation. But it is not possible to measure the true PD charge. Only the PD current pulse in the external circuit can be measured. The charge carried by this current PD is apparent charge. For this reason, the most frequently used for the diagnosis of PD characteristics are the voltage inception and the occurrence of so-called "apparent charge" [1]. Last term followed from simplistic capacitive PD model. It was introduced by A. Gemant and Philippoff in [2]. Later Kreuger [3] introduced an additional parallel capacitance of bulk dielectrics in model. As a result the classical capacitive model became the base of IEC standard [1] and was included in reference book on HV engineering [4]. An apparent charge became the main characteristic of PD intensity in acceptance tests of different HV equipment.

The success of capacitive equivalent circuit can be explained by simple description of charge transfer from the PD origin to external electrodes

$$\frac{q}{Q} = \frac{C_b}{C_b + C_c} \approx \frac{C_b}{C_c} \tag{1}$$

where q and Q are the apparent and the true charges of PD; C_c is the cavity capacitance and C_b is the stray capacitance of the bulk dielectric between the cavity and electrodes.

However, the requirements of regulatory documents concerning of "the intensity of the PD" have proved their

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viability, at least, with respect to acceptance tests of new equipment. Moreover, PD detection became the best method of technology checking in manufacturing conditions. This means that the apparent charge of PD, one way or another, is linked with any defect.

On the other hand, the physical processes of PD in electrical insulation should depend on the true charge, i.e., the actual physical charge, which was formed as a result of ionization processes. Its value and PD energy have to be measured, for estimation of gassing of insulating fluids, particularly for transformer oils. Thus, it is necessary to know the true PD charge, but a researcher has only one possibility: to measure the apparent i.e. the induced PD charge.

The Pedersen and his followers [7-12] offered the field theoretical approach based on the dipole concept. This approach starts from the moment of the extinction of individual partial discharge. During the partial discharge development in void the complex dynamic changes of the electric field, gas density and surface charges take place [13-15]. The field approach passes the mentioned physic processes and all simulations begin at the PD extinction moment when the charges of both polarities generated by ionization processes precipitate on opposite walls of void and form the dipole with the size equal to the void size *d*. The induced or apparent charge, q, is given [11, 14] by

$$q = -K\varepsilon\,\varepsilon_0\Omega(\boldsymbol{E}_i - \boldsymbol{E}_t)\cdot\boldsymbol{\nabla}\,\lambda_0, \tag{2}$$

Where Ω - void volume, K –dimensionless coefficient, depending on void form and dielectric permittivity of media ε, $\boldsymbol{E}_i - \boldsymbol{E}_t$ **-** change of the uniform electric field inside the void at PD, λ_0, - is the solution of Laplace's equation.

An examination of (2) leads to the following conclusions.

a) The induced charge is proportional to the relative permittivity ε of the dielectric surrounding the void which makes perfect sense.

b) The induced charge depends on the volume of the void, but rather by a complex way. If the field strength drop corresponding to the ignition and the extinction of the partial discharge would be constant, the induced charge would be proportional to the volume of void, and, hence, to the cube of the void size. But a field drop in the void after the partial discharge cannot be permanent. With increase of a void size, both field strengths are falling but the difference between them must be considered for each void dimension separately.

c) If the diameter of a spherical void, *d*, is much less than total inter-electrode gap *b*, one can consider $\boldsymbol{\nabla}\,\lambda_0 = \nabla\,\lambda_0 \approx {}^1/_b$ [13].

d) For the large-size cavities the induced charge is likely to grow faster than in direct proportion due to both factors: the increase of the true charge and the increase of the field member ∇λ.

Unfortunately, knowledge of these parameters can only be available for measurements made under controlled laboratory conditions. Analysis of measurements made on actual electrical equipment will almost certainly lack such input data. Besides the ∇λ determination requires computer simulation of electric field.

E. Lemke [16] proved that the field analysis can be substantially simplified if the establishment of a dipole moment in a uniform field between solid dielectric layers is considered instead of spherical or ellipsoidal shape of void. But this model in fact presents void as one dimension formation that doesn't correspond to real voids.

A new capacitive model has been proposed in [17]. This model used the induced charge concept and demonstrated that "the induced charge concept and the change in capacitance are actually the same thing – a coin with two different faces".

Authors of [18] used the finite element method for calculation of voltage in a void embedded in a solid dielectric. As a result they showed that diameter of void and its distance from electrodes have a big influence on void voltage in solid dielectric. Some improvements of the capacitive model were achieved in [19, 20]. The second edition of textbook on HV engineering repeats the PD capacitive equivalent circuit with some field pictures and comments concerning them [21].

From the practical point of view most interesting thing is to know how the permissible levels of apparent charge correspond to the size of defects like the air void in solid dielectrics or gas and vapor bubbles in liquid dielectrics. For this reason we try to find the answers on the next questions:

– What relation exists between true and apparent charges?

– How this relation depends on relative sizes of void (bubble) and dielectrics?

– How this relation depends on void position between external electrodes and on uniformity of the electric field created by them?

In the papers devoted to PD in voids [22-26] or PD in bubbles [27-31] it is possible to find many interesting details concerning these questions but the simple and clear answers are absent. So, the goal of this work is the numerical simulation of both true and apparent charges in cases of PD inception in gas bubble both in uniform and sharp non-uniform fields. The transformer oil was chosen as dielectric media for the following comparison with the experimental data obtained by authors of [32] and with own test results [33]. Besides the peculiarities of experimental data [34] are explained in this paper.

2 OBJECTS FOR MODELING

2.1 PD IN CASE OF PLANE-PLANE ELECTRODES

The main difference from the PD and usual discharge between the electrodes is their "self termination", which is explained by the influence of the electric field generated by the surface charges deposited on the dielectric walls of the cavity at the time of PD process. In our simulation model the next process is considered. PD occurs in the gas void that has the shape of a sphere of radius R_b. A uniform field is produced by plane electrodes of radius R_e, a thickness of 2 mm with interelectrode gap b=10 mm between them. The gas bubble is located on the central power line of the electric field at different distances from the electrodes (Figure 1). The volume between the electrodes is filled with an insulating medium having a relative permittivity of 2.2 (transformer oil). A medium with a relative permittivity of 1 (air) is situated outside of electrode system at distances more than $50 \cdot R_e$. In computation model the one electrode has a potential of 1 V, and the other has zero potential. The model for the computation is shown in Figure 1.

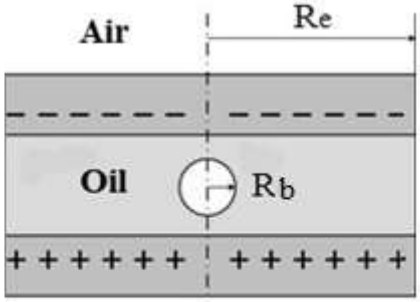

Figure 1. The void inside of plane capacitor. Here it is shown charges distribution before partial discharge.

The free charges on the bubble surface are absent until PD. There are only "polarization charges": a negative charge on the cathode side of the bubble and the positive charge on the anode side of the bubble. At the moment of PD cavity is filled with plasma, which is separated under the influence of an electric field. The positive charges move towards the cathode and adhere to the cathode side of the bubble, the negative of ionization processes. As a result of PD the anode charges move toward the anode and adhere to the anode side of the bubble. The electric field inside the bubble is reduced up to the field for discharge extinction and to the termination side of the bubble gets a free negative charge and the cathode side of the bubble gets free positive charge. The charges are equal in magnitude (Figure 2). Here it is look like a dipole. The value of the surface charge is true or physical charge Q of PD.

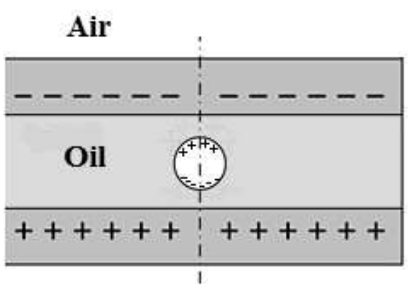

Figure 2. Over-simplified charge distribution after PD.

From the standpoint of an engineer the electric charge transferred at the PD is increase of capacitance ΔC. If the electrodes are connected to a voltage source, the electrodes should obtain an additional charge.

If the test cell is connected to a voltage source in series with a high impedance resistor (as in the case of actual measurements of PD), the test cell immediately after PD should be considered as disconnected from the source. It is understood that the charge on the electrode surfaces must have the same value as before the PD. The sharp increase in capacity would lead to a jump in voltage. In turn, this leads to a jump in the current pulse register circuit; and so-called "apparent charge" of PD can be obtained after the integration of the current: $q = U \cdot \Delta C$.

In modeling the apparent charge was determined by integration of surface charges on the electrode surface, including all sides of the electrode. For comparison, integration was performed on both electrodes. Calculations were performed for three cases: no bubble; a gas bubble in before the PD; with bubble after PD. In the latter case, it was assumed that the bubble has equipotential surface. The apparent charge Q is determined as the difference between the charges of electrodes in the second and third cases.

True physical charge Q was calculated by integrating the surface charge density on the bubble after process of PD: $Q = \int \sigma dS$. The outer surface of the bubble was used for integration. The surface charge on the upper hemisphere (Figure 2) is regarded as a true charge Q. If one take into account that $\sigma = \varepsilon\varepsilon_0 E$, then $Q = \varepsilon\varepsilon_0 \int E dS$.

2.2 PD IN CASE OF POINT-PLANE ELECTRODE SYSTEM

In the case of PD in non-uniform field pattern is quite different from that considered in Section 2.1. The main difference is that PD occurs close to the electrode and thus the PD occurrence region may be regarded as electrically connected with the electrode (Figure 3 a, b).

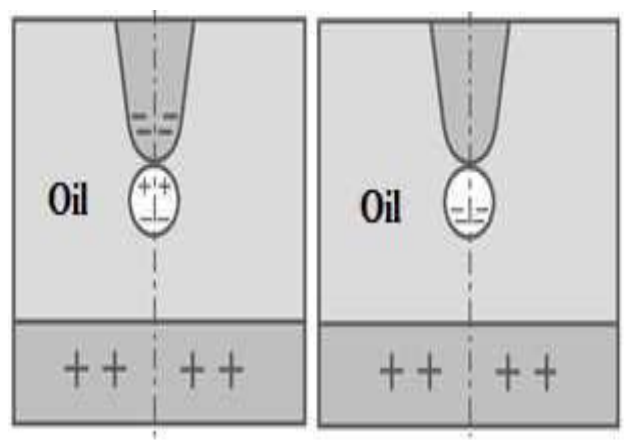

Figure 3. The bubble close to a needle in "point-plane" capacitor. a - before PD, b – after PD.

This leads to the obvious conclusion that the true charge Q is "apparent charge" q exactly! In our experiments [33], non-uniform field was produced by the electrode system of "point-plane". The radius of curvature of the needle electrode is 3 µm and the electrode gap length was 30 mm. All dimensions in modeling cell correspond to the real size of the electrode system. Form and size of electrode system including needle was introduced into simulation, point by point by using of electrode system photo image.

3 SIMULATION MODEL [35,36]

The electrode system capacitance and electric field with bubbles and no bubbles within the dielectrics is determined by calculating the distribution of potential *E=- grad u.* In simple case when bubble axis coincides with the axis of the electrode system, the potential distribution ***u*** can be obtained by solving a two-dimensional problem in a cylindrical coordinate system,

$$-div\{\varepsilon(r,z)grad[u(r,z)]\} = 0 \qquad (3)$$

where ε - relative permittivity.

The boundary conditions are

$$u\big|_{S_1} = 0,\ u\big|_{S_2} = 1,\ \frac{\partial u}{\partial n}\bigg|_{S_3} = 0, \quad (4)$$

where S_1 and S_2 mean the surfaces of first and second electrode, S_3 – outer remote boundary of computation area (here S_3 was remote on 1 m from the center of electrode system). A numerical solution of equation (3) with boundary conditions (4) was performed using the subsystem of the own TELMA software package [36]. Field simulations with the help of own program performs us to understand all limits of model in comparison with original.

Taking into account that the surface of the ionization zone has the same potential, the permittivity of this area in equation (3) should be supposed as $\varepsilon = \infty$. In the process of simulation ε inside ionized bubble was chosen as 10^6, which provided the equipotentiality with inaccuracy less than $2 \cdot 10^{-4}$%.

Another inaccuracy was associated with the discrete computational domain. To minimize this error all problems were solved using the same finite element mesh. The deviation values were obtained and verified by mesh refinement and they do not exceed 2%.

4 RESULTS

4.1 AN UNIFORM FIELD

The computation results of q, Q, ΔC for electrodes of different sizes R_e and different bubbles radius R_b are presented on Table 1.

Table 1. Results for Large Bubbles Located in the Gap Center.

R_e, mm	R_b, mm	ΔC, fF	Q, fC	q/Q
10	1	2.96	16.90	0.175
	2	24.50	69.90	0.350
	4	299	376.0	0.795
20	1	2.987	16.90	0.177
	2	24.64	70.16	0.350
	4	261.6	378.3	0.690
30	1	2,986	16.90	0.177
	2	24.64	70.17·	0.350
	4	261.5	378.4	0.690
40	1	2.982	16.90	0.177
	2	24.64	70.17	0.350
	4	261.5	378.4	0.690
50	1	2.991	16.90	0.177
	2	24.64	70.17	0.350
	4	261.5	378.4	0.690

For small bubbles situation is the same. The smaller bubble leads to a smaller q/Q. The dependence of q/Q upon the radius of the bubble is shown in Figure 4 in a double-logarithmic scale for an electrode diameter of 50 mm.

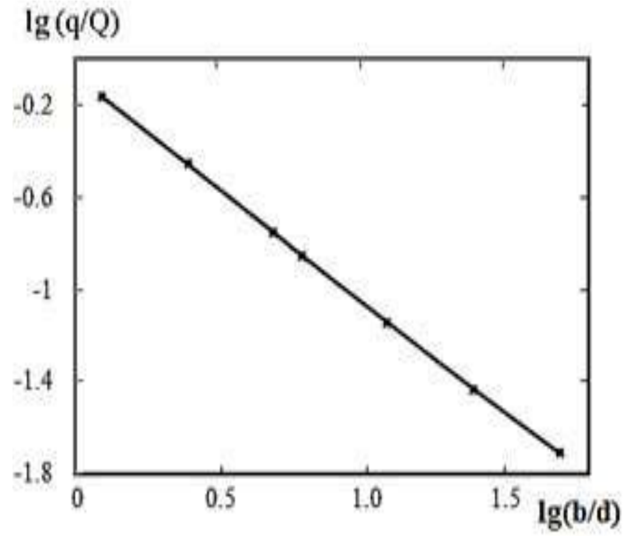

Figure 4. "Apparent" charge to true charge ratio for different bubble radius. Here d = $2R_b$.

In the second group of modeling the bubble is shifted by the distance ΔX from the center in the vertical direction. The calculation results are presented in Figure 5. As can be seen from Figure 5 the ratio of q/Q is dependent on the bubble size, but almost independent of the location of the bubbles.

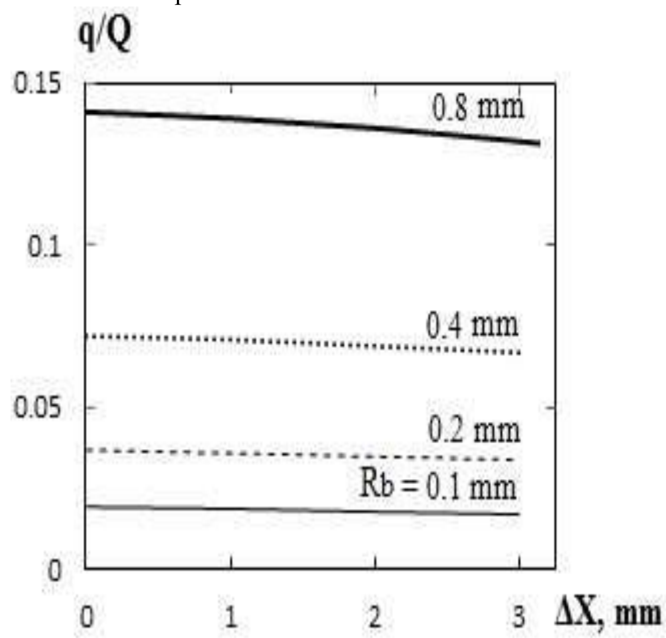

Figure 5. "The apparent" charge to the true charge ratio for bubbles with different radius on the shift distance ΔX

Computations of apparent charge in case of PD in liquid q_1 and PD inside bubble q_2 show that its values are practically the same (accuracy 15%) if size of resulting bubble after PD is the same in both cases.

4.2 A NON-UNIFORM FIELD

The calculated PD charge q = Q, ΔC for needle electrode with the bubbles of different radius R_b at the point (Figure 3) are shown in Table 2.

Table 2. Computation Results for Bubbles Located on the Tip of Needle.

R_b, μm	5	10	20	50	100	200	400
ΔC, fF; Q = q, fC	5	16	50	197	518	1310	3220

If the ionization zone is not in contact with the electrode calculations show that the "apparent" charge Q is much smaller than that in the case of this region is connected to the electrode. For example PD in the bubble with R_b = 5 microns, which is at a distance of 10 microns from the tip of the needle makes apparent charge q ≈ 0.002 fC, which is three orders of magnitude less than for the same size bubble which is in contact with the electrode.

5 DISCUSSION

Bubble size has the strongest impact on the ratio of true to apparent charge. The apparent charge in case of submillimeter bubbles (10-100 μm) is two or three orders of magnitude less than the true charge. For a rough estimate it could be considered as

$$q/Q \approx d/b \quad (5)$$

The apparent charge of PD is close to the true charge, when the bubble size becomes comparable to the size of the gap (the thickness "b" of the oil gap).

Influence of deviation of the bubble from the center of the gap to electrodes on the ratio q/Q does not exceed 15% (in the investigated range of deviation). The transverse size of the electrode R_e has weak effect on the ratio of PD charges too. For example, if the radius of the electrode is increased from 10 to 50 mm, the ratio of the charges does not vary more than 2% for the bubble with a radius of 1 mm.

Indirectly, the relationship q/Q ratio explains suitability of PD permissible intensity standards, such as standards for power transformers. Indeed, some of the features of capacitance model simulate the first oil channel between the coil and the pressboard barrier as a channel thickness of about 10-15 mm. If millimeter-sized bubbles occur in the oil channel, PDs in them are a deadly threat to the surface of the solid insulation: the barrier and turn-by-turn insulation. But in these cases, the detection sensitivity is increased due to the convergence of the PD apparent and true charges. Dangerous bubbles are easily identified for this reason. In contrast, small bubbles are harmless because they are rapidly dissolved in the oil. The fact that they are not registered (due to the very low values q/Q) protects test personnel against false risk assessment.

Let's compare the calculated apparent charge and its value in the standards for power transformers. Remind that the charge values given in Table 1 were calculated for the case where the voltage between the electrodes was 1 V. For real power transformer with a nominal voltage of 110 kV for example, the phase voltage amplitude is of about 100 kV and, respectively, the estimated true PD charge must be multiplied a hundred thousand times. After this it is easy to determine that the limit values of apparent charge 300 pC indicates presence of the bubbles with a radius of about 1 mm.

Furthermore, the calculated data are consistent with the experimental data for PD in the floating bubbles in the oil channel [32]. In these experiments the range of apparent charges for PD occurring in bubbles with a diameter of 2 mm was (200-2000) pC. As you can see, the lower limit of this range is fully in line with our calculation. Data inaccuracy in [33] could be caused by a deformation of bubble in the electric field, fluctuation of their displacement path between the electrodes and the superimposed signals from PD few bubbles.

Another comparison of the computed data can be performed using experimental results [34]. In experiments with the cavities in the epoxy compound, they found that, if the cavity diameter increased from 0.3 to 0.9 mm (three times), the value of the apparent charge increased 13 times. Disproportionate growth of the apparent charge of PD can be explained by two factors:

a) Growth of true charge of PD. Assuming that cavities were filled with air at atmospheric pressure, then the growth of breakdown voltage according to Paschen law and reduction of the extinction voltage leads to an increase in the PD true charge approximately (4-4.5) times.

b) Increasing the ratio of the apparent charge to the true charge. According to our calculations it should be approximately triple.

The computations could help to estimate the size and form of the discharges that have been reported previously [33] in electrode system “point-plane”. The typical values of an apparent charge of the long cathode pulses were 15-40 pC, short cathode pulses were 1.5-5 pC, and anode pulses were 1.5-5 pC. Assuming that a long cathode PD has a spherical shape, its radius should be 2-3 μm. As well as ”short“ cathode and anode pulses, small values of PD apparent charge indicates, in our opinion, the type of filament channel partial discharge.

One could compare our method of PD consideration with most advanced Pedersen method. In our method PD could be considered in void of any form and size. Direct computation of electric field in real or model system before PD and past PD performed to obtain both true charge and apparent charge and define the energy release. In Pedersen model one should compute virtual field $\nabla\lambda_0$ (void free), estimate dipole moment, estimate coefficient K. These parameters could be estimated properly for ellipsoidal and spheroidal voids only. For other types of PD (see about PD types in [14]) approximate determination of PD required computation. Besides, true charge (physical charge) estimation has the same problems. It requires computations too.

7 CONCLUSION

For a partial discharge in the gas bubble the ratio of apparent to true charge is mainly defined by relation of bubble size to interelectrode gap. The smaller is the bubble diameter, the greater is the ratio of true charge to apparent charge. This ratio reaches several orders of magnitude for small cavities. For the diameter of bubbles, comparable to the thickness of dielectric layer the apparent and true charges of PD are close to each other.

The transverse size of the electrodes and the displacement of the bubble from central power line of interelectrode gap would not significantly affect on the ratio of the apparent charge to the true charge.

The proposed method of direct computation of the electric field in the insulation system before PD and past PD can be used to determine both the true and the apparent charge and determination of the energy released in the event of any type of PD.

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