“Apparent” And True Charges of Partial Discharges

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***Abstract*— The partial discharges in transformer oil are simulated. Here are considered partial discharges in bubbles, inserted in bulk of liquid in cases of electrode systems “plane-plane” and “point-plane”. Computed “true” and apparent charges show that apparent charge is much time less than true charge. More bubble radius – more ratio of apparent charge to true charge. Both charges are close one to other in two cases. First case: bubble size is large enough, namely close to the gap size in case of plane electrodes; second case: the bubble contacts to the electrode. Last case is in “point-plane” electrode system. Experimental and computed data are compared for the point-plane electrode system.**

Keywords—bubbles; partial discharge; transformer oil; apparent charge; computation; measurements

I. Introduction

The registration of partial discharges (PD) is the one of effective diagnostics methods that performs to detect some defects of electrical insulations such as gas inclusions, bubbles, layer separations, cracks, etc. Since PDs are responsible for the insulation deterioration, so their energy characteristics are in the most of interest. The basic characteristic of energy is a PD charge. This conclusion is logically correct: the more PD charge, the greater its energy, the more their destroying effect on the insulation. But it is not possible to measure PD true charge. Only the PD current pulse in the external circuit may be measured. The charge transferred by this current is PD apparent charge. For this reason the most used basic characteristics of PD for diagnostics are voltage inception and so called “apparent charge”.

According to IEC 60270 “apparent charge is that charge which, if injected within a very short time between terminals of test object in a specified test circuit, would give the same reading on measuring instrument as the PD current itself”. Then the note follows “the apparent charge is not equal to the amount of charge locally involved at the site of this discharge, which can not be measured directly”.

After such explanations the question arises what is the necessity to measure the apparent charge, if it is unclear how it is linked with real PD phenomenon? However, the requirements of regulatory documents concerning of "the intensity of the PD" have proved their viability, at least with respect to factory testing of new equipment. Moreover, PD method became the best method of technology checking in manufacturing condition. This means that the apparent charge PD, one way or another, linked with any defect.

On the other hand, the physical processes of PD in electrical insulation should depend on true charge, i.e., the actual 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, in particular, transformer oils. Thus, it is necessary to know the true PD charge, but a researcher has only one possibility: to measure the PD apparent charge.

The goal of the work is simulation of both true and apparent charges in transformer oil in cases of PD inception in gas bubble both in uniform and sharp nonuniform fields. Besides in last case computer simulation is compared with experimental data.

II. Model

A. PD in uniform field

The model is based on PD physical mechanism studied E.G. in [1-4]. The main difference of PD from discharges between conductive electrodes is their "self damping" explained by the action of electric field created by surface charges on the dielectric walls of the bubble or cavity during PD.

In our model simulation is performed by the next way. PD “occurs” in gas inclusion which form is sphere of radius Rs. Uniform field is produced by plane electrodes of radius Re, thickness of 2 mm, and interelectrode gap b = 10 mm between them. The gas inclusion is situated in central power line at different distances from electrodes (Fig.1). Interelectrode volume is filled by insulating media with relative dielectric permittivity 2.2 (transformer oil). Outside of electrode system at distances more than 50◌Re there is media with relative dielectric permittivity 1. In computation one electrode has potential 1 V and other – 0. The model for computation is shown on the Fig.1.

The free surface charges on bubble surface are absent before partial discharge. Here are the so called “polarization charge” only: negative charge at the cathode side of the bubble and positive charge at the anode side of the bubble. At the moment of PD bubble cavity is filling by plasma then electric field action leads to plasma splitting. Positive charges move to

978-1-5090-2804-7/16/$31.00©2016 IEEE

cathode and stick to cathode side of bubble bound, negative charges move to anode and stick to anode side of bubble. The field intensity inside bubble is decreased, sometimes to field disappearance. This process leads to partial discharge termination. As a result of PD the cathode side of bubble obtains free negative charge and anode side of bubble obtains free positive charge of the same absolute value (Fig.2). The magnitude of surface charges is true charge Q of partial discharge.

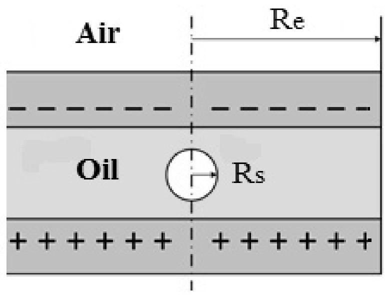


Fig. 1. The bubble inside of plane capacitor. Here it is surface charges distribution before partial discharge.

From electrical engineer point of view the charge transferred due to PD is equivalent to capacitance increase ΔC. If electrodes are connected to voltage source, additional charge appears on electrodes.

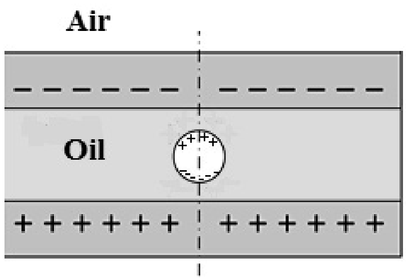


Fig. 2. Over-simplified charge distribution after PD.

If test unit is connected to voltage source in series with high resistance resistor (as it takes place in case of real measurements of PD), then in computations one should consider it as disconnected unit. It is clear that the charge on electrode surface should have the same value as it had before PD. The abrupt capacitance increase should lead to voltage jump. In turn this jump leads to pulse current in registration circuit; and the so called "apparent charge" q of PD could be obtained after current integration: q = U·ΔC.

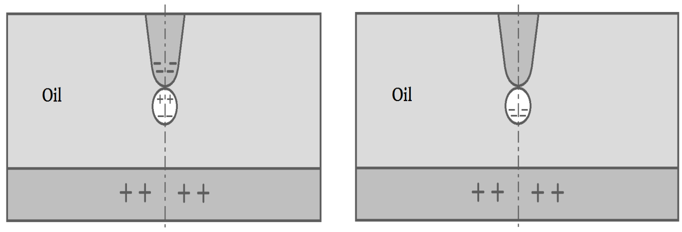
In simulation the apparent charge was determined by using ΔC by forth integration of surface charges on electrode surface including faceplate and outer surface of one of electrodes. For comparison the forth integration was performed both on one and other electrodes. The computations were fulfilled for three cases: without bubble; with gas bubble before PD; with bubble after PD. In last case it was supposed that bubble has equipotential surface. The apparent charge q was determined as difference between electrode charges in the second and the third cases.

True charge Q was computing by integration of surface charge density just after PD occurrence: Q = ∫σdS. The outer surface of bubble was used for integration. For distinctness surface charge on upper hemisphere (Fig.2) is considered as true charge Q. If take into account that σ = εε0E, then Q = εε0 ∫EdS.

B. PD in nonuniform field

In case of PD in nonuniform field the picture has significant differences from the one considered in section 2.1. The main difference is that PD occurs close to electrode that is why past PD occurrence this defect could be considered as electrically connected with electrode (Fig. 3 a, b). This leads to obvious conclusion that true charge Q equals to "apparent charge" q!

In our experiments [5] nonuniform field is produced by electrode system "point-plane". Radius of needle electrode curvature is 3 μm, interelectrode gap is 30 mm. The sizes in simulation well correspond to real dimensions of electrode system [5].



a) b)

Fig. 3. The bubble inside of "point-plane" capacitor. a - before partial discharge, b – after PD.

III. SIMULATION MODEL

The capacitance of electrode system with and without bubble inside electrical insulation body was performed by computation of potential distribution E=-grad(u). If bubble axis coincides with electrode system axis, the potential distribution u could be obtained by solving of two-dimensional problem in cylindrical coordinate system

$$-div\left\{\varepsilon_0\varepsilon(r,z)\,grad\left[u(r,z)\right]\right\}=0 \qquad (1)$$

where ε – is relative dielectric permittivity. The boundary conditions are:

$$u\big|_{S_1}=0\,,\;\; u\big|_{S_2}=1\,,\;\; \left.\frac{\partial u}{\partial n}\right|_{S_3}=0\,, \qquad (2)$$

where S1 and S2 mean the surfaces of first and second electrode, S3– outer remote boundary of computation area (here S3 was remote on 1 m from the center of electrode system).

If take into consideration that surface of ionization area is equipotential then in equation (1) the permittivity of ionization area should be supposed as ε=∞ In process of simulation ε was chosen as 106, that provided the equipotentiality with inaccuracy less than $2 \cdot 10^{-4}$ %.

Another inaccuracy was connected with discretization of computation area. For its minimization all problems were solved on the same finite-element mesh. Deviation of obtained values Q and ΔC was checked by mesh refinement and it not exceed 2 %.

IV. RESULTS

A. Uniform field

The results of computations of q, Q, ΔC for electrodes of different sizes Rel and bubbles of different radius Rs are presented on Table 1.

TABLE I. COMPUTATION FOR LARGE BUBBLES SITUATED IN THE GAP CENTER

R_e, mm	R_s, 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 smaller bubbles the situation is the same. The less bubble – the less q/Q. The dependence of q/Q versus bubble radius is shown in Fig. 4 in double logarithmic scales for electrodes with diameter of 50 mm.

In second group of simulations the bubble is shifted on distance ΔX from center in vertical direction. The results of computations are shown in Fig. 5. One can see from Fig. 5 that q/Q ration depends on bubble size but practically doesn't depend on bubble location.

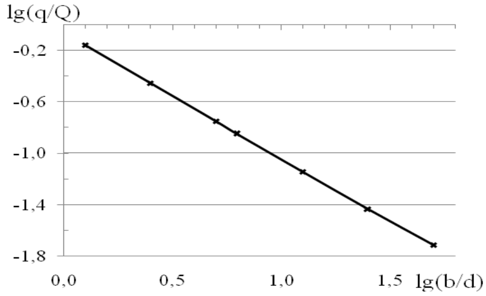


Fig. 4. "Apparent" charge to true charge ratio for different bubble radius. Here d=2Rs.

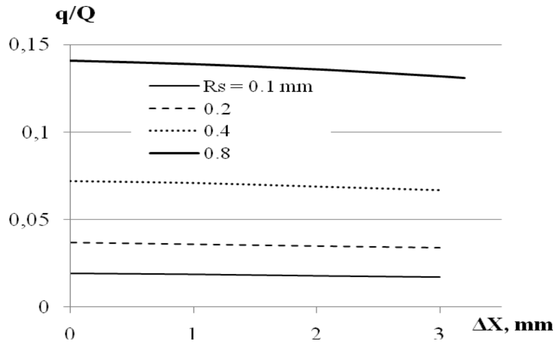


Fig. 5. "Apparent" charge to true charge ratio for bubbles with different radius versus shift distance.

B. Nonuniform field

The results of computations of q = Q, ΔC for needle electrode with bubbles of different radius Rs on the tip are presented on Table 2.

TABLE II. COMPUTATION FOR BUBBLES SITUATED ON THE TIP OF NEEDLE

R_b, µm	ΔC, fF; Q=q, fC
5	5.2
10	16.3
20	50.3
40	144.5
50	197.3
100	518
200	1310
400	3220

If ionization area has no contact with electrode the computations show that "apparent" charge q is much less that this one in case of area connected with electrode. E.G. for bubble Rs =5 µm situated at distance 10 µm from the tip of needle apparent charge is q≈2 10-3 fCl, that is three orders of magnitude less than for connected bubble.

V. Discussion

The size of bubble has the strongest impact on the ratio of apparent to true charge. Apparent charge in case of submillimeter bubbles (10-100 µm) is two or three orders of magnitudes less that true charge. For rough estimation one could consider as $q/Q \approx 2Rs/b$. The PD apparent charge is close to true charge when the bubble size becomes comparable with the size of gap (thickness “b” of oil gap).

The influence of bubble deviation from the center gap to the electrodes on the ratio q/Q does not exceed 15%. The transverse dimension of the electrode has a weak effect on the ratio of PD charges too.

Indirectly, the dependence of relationship q/Q explains correctness of PD permissible intensity in standards, e.g. in standards on power transformers. Indeed, in some features the cell model imitates the first oil channel between the winding and the pressboard barrier because the thickness of channel is about 10-15 mm.

If millimeter-sized bubbles occur in the oil channel, so PDs in them are deadly threat to the surface of the solid insulation: barrier and turn-to-turn insulation. But in these cases the sensitivity of PD detection increases due to convergence of apparent and true charges. For this reason the dangerous bubbles are easily revealed. On the contrary, small bubbles are harmless because they can quickly dissolve in oil. The fact that they are not registered (due to very small values of apparent charge) protects test personal against false estimation of danger.

Let’s compare the calculated apparent charge and its limits in standards for power transformers. We remind that the charges values given in table 1 applied when the voltage between the electrodes was equal of 1 V. For real power transformer with rated voltage of 110 kV, for example, the amplitude of the phase voltage is approximately 100 kV and, accordingly, the calculated data of true PD charge have to be multiplied a hundred thousand times. Knowing that it is easy to determine that the limiting values of the apparent charge about 300 pC correspond to PD events in bubbles with a radius of about 1 mm.

Besides, the calculated data are not contrary with the experimental data for PD in bubbles pop-up in oil channel [4]. In these experiments the range of apparent charges for PD encountered in bubbles with a diameter of 2 mm was (200-2000) pC. As you can see, the lower bound of this range is completely coincides with our calculation. Evaluation (300 pC) as its upper bound value of the range can be caused by the deformation of bubbles in an electric field, the fluctuation of their moving trajectory between the electrodes and the overlay of signals from PD a few bubbles.

Another comparison of calculated data can be held, involving experimental results of authors [6]. In experiments with cavities in the epoxy compound they found that if the cavity diameter increased from 0.3 to 0.9 (.three times), the magnitude of the apparent charge increased 13 times. The disproportionate growth of apparent charge PD can be explained by two factors.

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

b) By increased relationship of apparent charge to true charge. According to our calculations it should be approximately triple.

The computations could help to estimate size and form of discharges that was registered earlier [5]. The typical values of an apparent charge of the long cathode pulses were $15 \div 40$ pC, short cathode pulses were $1{,}5 \div 5$ pC, and anode pulses were $1{,}5 \div 5$ pC. If suppose that cathode PD has the form of sphere its diameter should be $2 \div 3$ µm. As for as «short» cathode and anode pulses small values of PD apparent charge show, in our opinion, on filament type of partial discharge channel.

VI. Conclusion

For single partial discharge in gas bubble the ratio of apparent to true charge is mainly defined by relative size of bubble. The smaller the bubble diameter, the greater the ratio of true charge to apparent charge reaching several orders of magnitude for small cavities. For the diameter of bubbles, comparable to the thickness of bulk dielectric the apparent and true charges of PD are close to each other.

The transverse dimension of the electrodes and the offset of the bubble in the interelectrode gap would not significantly affect the ratio of the apparent charge to the true charge.

Acknowledgment

One of the authors (S.M.K) grateful to RNF (grant 16-19-10229) for support in part concerning bubble modeling.

References

[1] A. Pedersen. Current Pulses Generated by Discharges in Voids in Solid Dielectrics. A Field Theoretical Approach IEEE Publication 86CH2196-4-DEI (1986) pp.112 – 114.

[2] R. J. Van Brunt. Physics and chemistry of partial discharge and corona: recent advances and future challenges, IEEE Trans. Diel. Elec. Insul, 1 (5) (1994) pp. 761–784.

[3] I.V. McCalister. Electric Fields and Electric Insulation IEEE Trans. on DEIS, Vol.9 (2002), No5 pp.672 – 694.

[4] M. G. Niasar, H. Edin, X. Wang and R. Clemence. Partial discharge characteristics due to air and water vapor bubbles in oil Proc. of XVII International Symposium on High Voltage Engineering, Hannover, Germany, August 22-26, 2011. – Paper D-067.

[5] Bychkov A.L., Ovsyannikov A.G., Korobeynikov S.M. Partial Discharges Registration in Transformer Oil at the ‘Point-Plane’Electrode System Applied Mechanics and Materials Vol. 698 (2015) pp 615-620.

[6] V. Swinka, F. R. Robert. Imaging of voids in dielectric materials by x-ray induced partial discharge Review of scientific instruments, Vol. 73 (No 3) (2002) pp. 1288 – 1292.