Partial discharges in free helium bubbles in transformer oil

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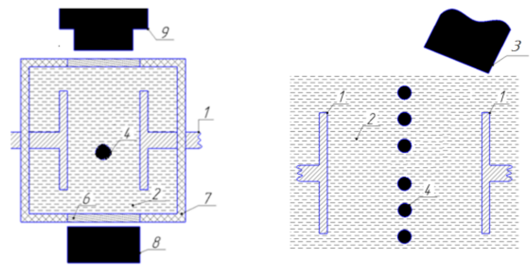
Abstract: **Partial discharges (PD) in a floating bubble in transformer oil were studied experimentally and theoretically. In test cell, the PD inception was very rare event. Sometimes PD occurred after an exposition of more than 10 hours at the voltage that corresponds to the value three times larger than that required in accordance with the Paschen's law. The problem is in initiating electrons. Analysis showed that, at the conditions of PD occurrence in helium bubbles, the mechanism of breakdown corresponds to the streamer one. Registrations of electrical and optical signals of PD were performed to estimate both apparent charge and the number of radiated photons. As a result of estimation, number of electrons is approximately equal to the number of photons.**

I. INTRODUCTION

Bubbles in oil filled high voltage equipment are frequently discussed problems. Among oil-filled apparatuses, the power transformer is one of the important and expensive units in power system. The main element in it is oil-barrier insulation with oil channel. Oil stream flowing in the channel has two functions: insulating and cooling of windings. The appearance of free bubbles in the oil channel and the PD activity in them may become the cause of the transformer outage. Some PD characteristics (PD inception voltage as a function of the bubble size, phase-resolved patterns etc.) were investigated in air and vapor bubbles [1]. The aim of this work is to analyze the physical picture of PD in a free helium bubble.

II. EXPERIMENTAL RESULTS

Experimental setup (Figure 1) was practically the same as described early [2]. The difference was in the use of the photomultiplier for the optical registration of the PD glow. Electrodes (1) were installed in the plexiglass cell (7) at an interelectrode gap of 6.8 mm with optical glass windows. The cell was filled by mineral transformer oil GK (2). The video camera (9) was installed coaxially with the photomultiplier (8) for the optical detection of the PD in the bubble (4). Electrical signal of PD was obtained with the help of the usual circuit with a coupling capacitor and registered by the digital oscilloscope Rigol. Bubbles supply with diameters of 1.5±0.1 mm generates approximately one bubble per second. Calculated inception voltage for helium bubbles according to Paschen's curve was 6 kV. In our experiments, the voltage of PD inception was 15 kV. Moreover, the waiting period of PD appearance sometimes exceeded 10 hours. It is many times more than estimations [2].



a) view from above b) side view

Figure 1. Experimental setup. Here, 6 is the optical window, 7 is the cell body, 3 is the light source with a wavelength of 635 nm.

Simultaneous oscillograms of electrical and optical signals of PD are presented in Figure 2. One could see that the pulses have the same shape, the leading edges of pulses are the same, and the trailing edges of pulses are slightly different. Rise time was approximately 20 ns.

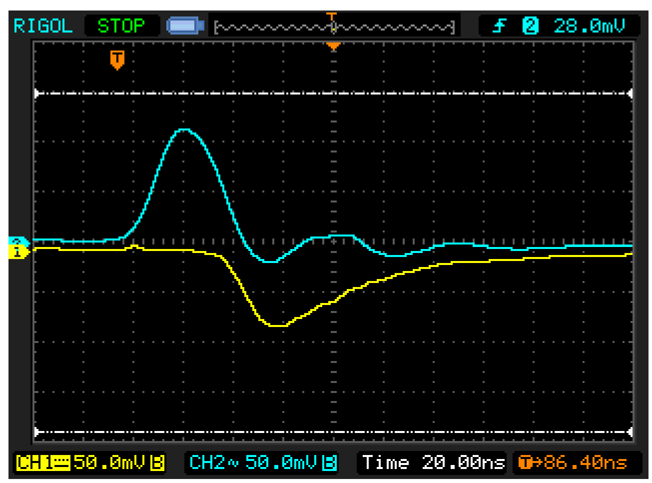


Figure 2. Electrical (upper blue curve) and optical (yellow lower curve) signals of PD.

III. DISCUSSION

A. Estimation of Charges and Photon Number

The analysis of the number of photons taking into account their absorption in oil and taking into account the space angle of the

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photo detector as well as its sensitivity allows us to estimate this number. When the experimental work was planned, we assumed as one of the tasks of the work to determine the coefficient of "radiation", equal to the ratio of the number of photons to the number of ionization events

$$n = N_p/N_i \quad (1)$$

Assuming that the number of ionization events is equal to the number of ions deposited on the surface after PD, then the value of N_i can be determined from the value of the true charge

$$N_i = Q/e \quad (2)$$

The true charge, in turn, can be determined from the apparent charge by our method [3].

The estimation of the number of photons is more difficult. The technique is as follows. According to the data on the photomultiplier (PM), we determined what current of the photomultiplier I corresponds to the light flux F (with the wavelengths in the visible region)

$$S=I/F. \quad (3)$$

Here it is necessary to consider the combined spectrum of the filter mounted in front of the photocathode using transmittance characteristics of colored UV (300–400 nm) and blue (400–500 nm) glasses. This is the blue and near-ultraviolet part of the spectrum. For estimation, let us take the wavelength at the violet edge of visible light of λ=400 nm. Recalculating the energy to photons N_{pc}^{λ}, we have got on the PM photocathode in the spectral band reception, given by the average photon energy in this spectrum.

A photon with this wavelength has the energy of $Q=5\ 10^{-19}$ J, its reciprocal value corresponds to the number of photons per second in 1 W radiation at λ = 400 nm:

$$Nph\ [1W]\ (\lambda_1) = 1 / Q\ (\lambda_1) = 2\cdot 10^{18}\ [photons/sec] \quad (4)$$

For light with a wavelength of 555 nm, there is a connection between the number N and the light flux

$$Nph\ [1W]\ (1) = 683\ lm \quad (5)$$

For a different wavelength, the light efficiency is lowerby a factor of k_1, which means that the same number of photons will result in fewer lumens.

$$N_{ph\ [1lm]}\ (\lambda_1) = N_{ph\ [1W]}\ (\lambda_1) / 683/k_1 =$$
$$= 0.3\cdot 10^{16}\ [photons/sec]/k_1 \quad (6)$$

Next, we use the spectral sensitivity S of the PM to determine the light flux incident on the photomultiplier F = I / S

$$N_{ph\ [F]}\ (\lambda_1) = N_{ph\ [1W]}\ (\lambda_1) / 683/k_1/S*I \quad (7)$$

The light flux emitted by PD will be larger, due to the geometric factor k_2 (the ratio of the area of the photocathode to the area of the sphere with a radius equal to the distance from the photocathode to the PD). In addition, it should be taken into account that the filters weaken the light flux. This coefficient k_3 was estimated through a decrease in the photomultiplier current when the filter was installed. Determine the number of photons emitted by the PD

$$N_p = {N_{ph}[F](\lambda)}\big/{k_1 k_2 k_3} \quad (8)$$

For the conditions, when the recorded PD, U = 30 kV voltage, the estimated true charge is about 2900 pC, and the number of ions deposited on the surface of the bubble was $1.8\ 10^{10}$ particles. Estimates for the expression (8) for the number of emitted photons give approximately $0.7\ 10^{10}$ photons. We determine from (1) the desired value n ~ 0.3 ÷ 0.4.

Surprisingly, this value turns out to be close to the one previously determined in the classical work of Raether [4], n=0.4, despite of another gas and its pressure. The foregoing estimates are not of high accuracy, and it can apparently be asserted that for a PD, the number of ions formed is approximately equal to the number of excited molecules or, more accurately, the number of emitted photons.

It is shown that if we take the registered apparent charge of PD, determine the true charge, and divide it by the electron charge, then this obtained value is approximately equal to the number of photons. It means, for a given kind of discharge, that the number of excited molecules is approximately equal to the number of ions.

B. Nature of Breakdown in a Helium Bubble

It is assumed that the breakdown nature in small gaps like bubbles is a multi-avalanche process [5,6]. Each avalanche produces next avalanche by the photoionisation or the ion impact on the surface. Nevertheless, the excess of experimental values of the PD inception voltage in comparison with estimations according to Paschen’s curves brings us to check the possibility of the realization of the streamer mechanism [7]. One has managed to find experimental data concerning impact ionization coefficient in helium [8,9]. Approximated curves are presented in Figure 3.

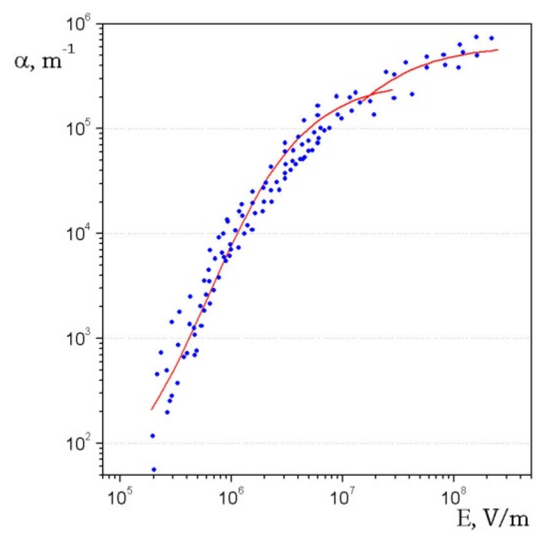

Figure 3. Approximation of the first Townsend coefficient α in helium. Blue points – experiments, curve – approximation.

Using an estimate of the field strength in the bubble, it can be determined that the impact ionization coefficient α was approximately in the range $(4÷6)\ 10^4$ 1 / m, and for a bubble

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diameter d = 1.5 mm, the product is αd > 20, which indicates the streamer mechanism of PD inside these bubbles.

We have performed preliminary simulations of the initial stage of the discharge development in an elliptic helium bubble placed to the center of the electrode gap filled with the dielectric with electrical permittivity 2.5. The electrodes were planes. The diffusion-drift model was used in simulations. The equations of the model are similar to that of the work [10]. For the coefficients of ionization and recombination of the electrons as well as for the electron mobility we used the experimental data from [10]. The data were fitted with non-linear functions. As an example, the approximation of the first Townsend coefficient is shown in figure 3. The mobility and the diffusion coefficients for ions were constant and were taken from [11]. For small concentrations and small electron temperatures, the recombination coefficient is approximately constant [12]. In our calculation, for the initial stage of the development of the gas ionization by electron impact, the recombination did not influence the rate of ionization and can be neglected.

The electrically neutral origin that was the mixture of electrons and helium ions with the Gaussian profiles was placed at one of the ends of the bubble. The calculations were performed for the constant voltage of the magnitude of 12 kV applied to the gap, with the maximal size of the bubble equal to 1.3 mm.

The propagation of the avalanche increases the field ahead ofthe ionization front as shown in Figure 4. The corresponding concentration curves for the electrons on the axis of the electrode gap are shown in Figure 5. It is seen that when the avalanche crosses approximately half of the bubble (along its large axis) the electric field at the head of the avalanche becomes comparable to the “external” electric field that was in the bubble before the ionization. It means that a streamer process starts at this distance. The role of the recombination is still small at this stage.

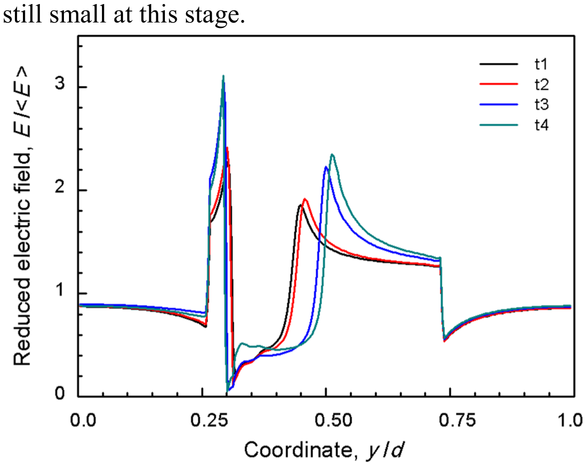

Figure 4. Electric field stress on the symmetry axis of the electrode gap. $t_1 = \tau_0$, $t_2 = 1.04\tau_0$, $t_3 = 1.44\tau_0$, $t_4 = 1.6\tau_0$. Here $\tau_0 = 1.5 \cdot 10^{-5} d^2 / D_+$. Here, d is the gap length, D_+ is the diffusion coefficient of helium ions in pure helium.

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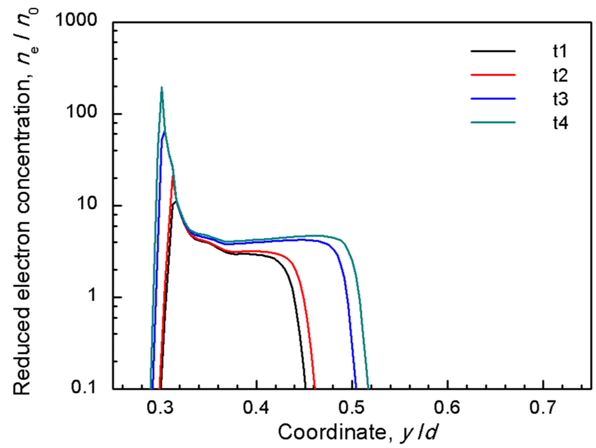

Figure 5. Electron densities on the axis of electrode gap. The parameters are the same as in figure 4.

IV. Conclusion

Analysis of the experimental data and preliminary simulations allow us to conclude that the PD inside a helium bubble develops in the form of a streamer. The number of excited atoms is approximately equal to the number of ions in PD.

Acknowledgements

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