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# Partial Discharges Registration in Transformer Oil at the 'Point-Plane' Electrode System

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**Abstract.** The results of the experimental studies of partial discharges in GK transformer oil with electrode system "point-plane" that provide sharp inhomogeneous electric field are presented. It was found out that two types of partial discharge pulses which differ in form and time duration appeared at the negative point polarity of the needle. The study of different types of pulses was conducted by electric and electro-optical methods of partial discharge registration.

## Introduction

It is well known that partial discharges (PD) are dangerous; they lead to gradual insulation degradation and electrical breakdown. Otherwise, the partial discharges measurements allow power companies to detect electrical equipment with progressive defects in advance. The mechanisms of partial discharges appearance and development in the voids of the solid insulation are well known and have been studied earlier [1], while the formation mechanisms of PD in the transformer oil are based on assumptions up to now. For this reason, the purpose of the work is to study the PD characteristics in the transformer oil.

Research on discharges in transformer oil aimed to define gas-producing factors was formerly carried out by [2]. In such a case, the authors' construction of an experimental cell leads to a creeping discharge occurrence. Thus, several questions are bound to arise. Was there electric field strength when PD took place? How accurate the values of an apparent charge and consumed energy were determined?

The purpose of the work is to detect characteristics of the partial discharge in the 'point-plane' electrode system.

## An Experimental Setup

An experimental HV cell (1) and registration circuit were placed in a grounded metal box (Fig.1). An oil-filled bushing with a high-pass filter resistor (2) was mounted to the box wall. The registration of the processes was carried out both with a coupling capacitor (3) (such was a suspension insulator PS-70 E, with the capacity of 40 pF) and with an electron-multiplier phototube (5). A signal was recorded by a digital oscilloscope (4) with the pass band of 70MHz and sampling frequency of 2 GHz. In these experiments, transformer oil GK without degassing (but after filtration) was used.

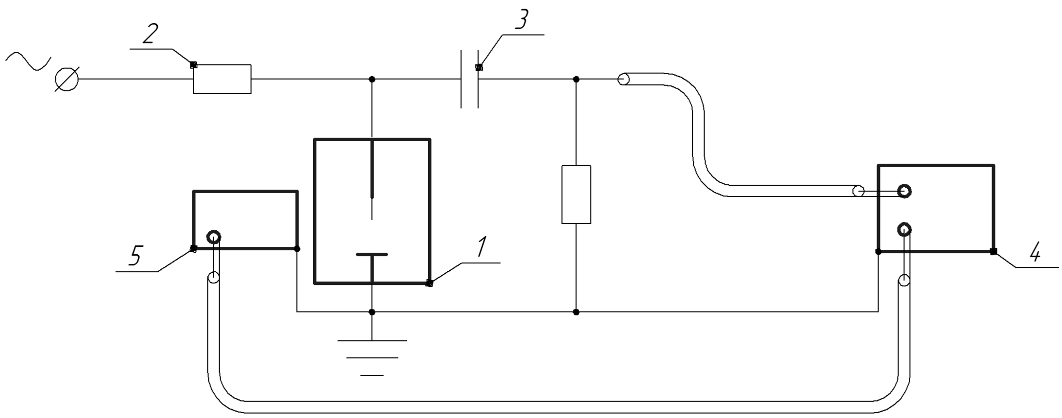



Fig. 1. Experimental setup.
1- HV cell; 2-resistor; 3-coupling capacitor; 4-digital oscilloscope; 5- photomultiplier

The experiments [3] in the 'point-plane' electrode system when point radius was less than 5 μm show that, when point polarity was negative, the current pulses were registered after reaching the field intensity of 4÷11 MV/cm (depending on the type of liquid). In our opinion, these were the PD pulses. Therefore, in the work we try to carry out the experiments with the field intensity being higher than the field intensity given above. To exclude the appearance of PD in the high voltage elements of the metering circuit, the RMS voltage was limited to 20÷25 kV [4]. Based on the data given at [5], the distance between electrodes was chosen as 30mm. For these parameters, the plot of electric field against point radius was built according to the next expression:

$$E = \frac{2U}{r \ln\left(\frac{4d}{r}\right)}, MV / cm. \quad (1)$$

where r is spherical radius of the needle point; d is the distance between the end of the point and the opposite electrode (plane).

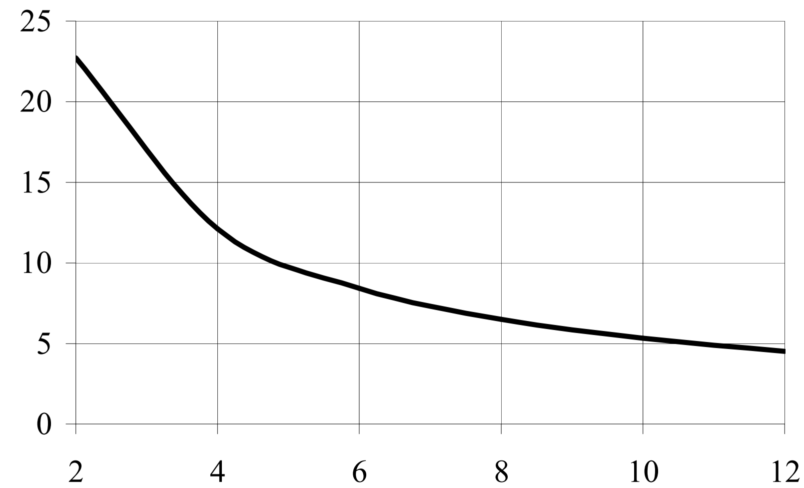
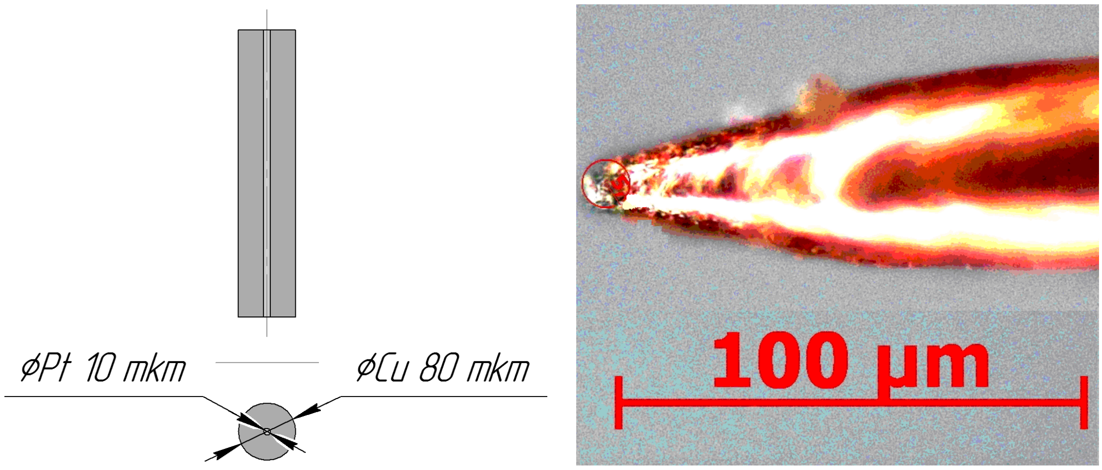



Fig. 2. Dependence of electric field intensity in the point vicinity. RMS voltage is 25 kV

In Fig. 2, one can see that an optimal spherical radius should be 4÷6 μm, to provide the necessary electric field intensity at the tip of the point. It is known that in order to provide inhomogeneous electric field sewing needles are usually used, but they cannot provide such a small spherical radius of the point. For that reason, the needles with a small point radius were made by the etching method. The Cu-Pt wire was used as a blank (Fig. 3a).




a) b)

Fig. 3. Cu-Pt wire before and after etching

The etching was carried out in a concentrated nitric acid. The best result is presented in Fig. 3b (the spherical radius is about 3 µm).

In our experiments, filtered and dry transformer oil GK was used.

**Registration of the processes**

It was registered that the PD inception voltage (RMS) was 16 kV and 18 kV, in case of negative and positive points, respectively. The partial discharges were recorded near the cathode and the anode when the value of phase angle was $50^o \div 60^o$ (Fig. 4).

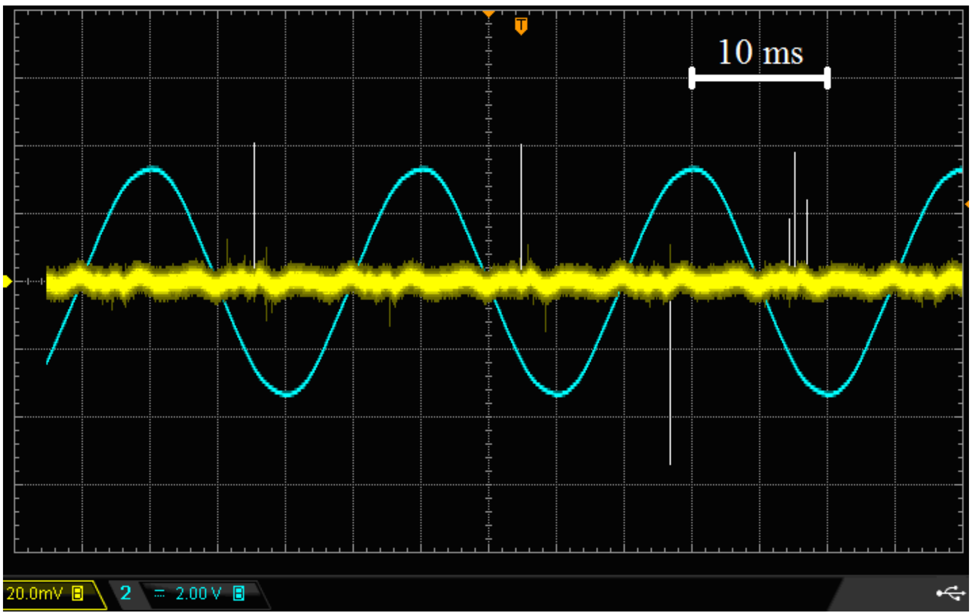
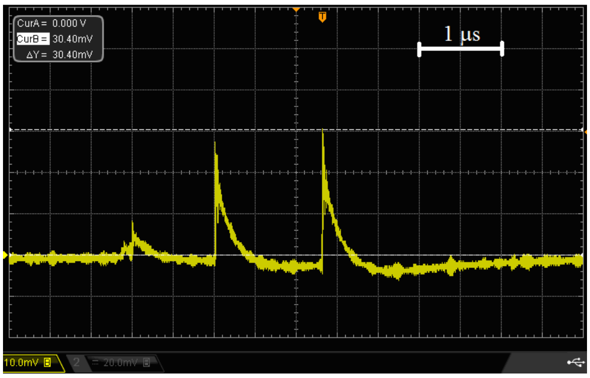
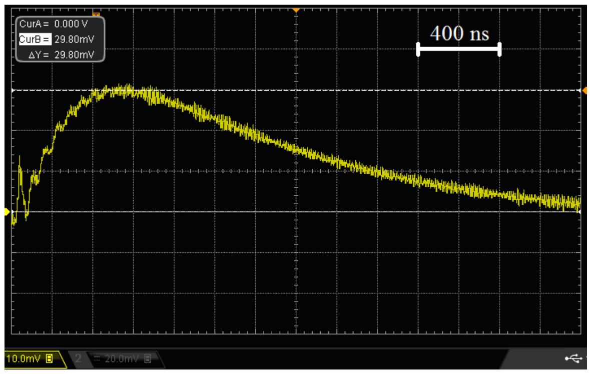



Fig. 4 The phase distribution of PD

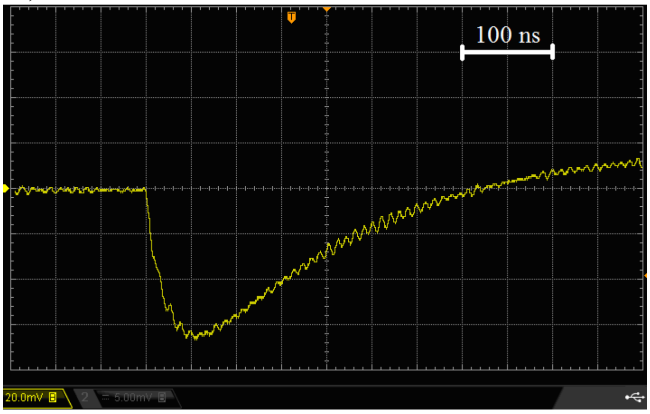
Typical forms of the negative and positive PD pulses are presented in Fig. 5 a-c.




a)




b)




c)

Fig. 5. PD near the cathode and the anode (voltage is the PD inception voltage plus 3 kV) a, b – point cathode; c –point anode.

At the same time, light emission with the help of photomultiplier was used. It should be noted that the positive and negative light pulses had practically the same form as current pulses. As one can see from Fig. 5, the positive and negative PD pulses had different width of both rise time and falling time duration. Two types of pulses were recorded on the cathode: 'short' – with the rise time 2÷3 ns and falling time 350÷380 ns, and 'long' – with the rise time 200÷250 ns and falling time 2÷2,5 µc. The long pulse has a more complex form, e. g., it consists of preliminary short pulse (Fig.5 b). The pulses with the rise time 45÷55 ns and falling time 350 ns were recorded in the case of point anode. 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.

**Discussion**

While analyzing the data, we used the results of papers [6, 7]. In [6] it was shown that short current pulses (~20÷30 ns) appeared at the interval of 0,1÷1,5 µs in the n-hexane, when the point radius was 1 µm and the voltage was more than 20 kV. The simultaneous photorecording showed the following:

After the first current pulse appearance, the optical picture didn't change, but after the subsequent pulses one could see the growth and detachment from the dark tree electrode - type formation. The total time duration of the photorecording was about 6 µs, the duration of the one frame was about 100 ns, and the pause between frames was 500 ns. The growth of the formation to the moment of detachment from the point lasted 3÷4 µs. The final radius of the formation was 25÷30 µm, which corresponded to the average growth rate of ~10 m/s. The values of apparent charge and average pulse current were 2÷3 pC and 5÷20 µA, respectively.

The mechanism of propagation of such subsonic streamer formations was examined in the paper [7]. It is considered that streamer formation near the cathode represents low-density gas-vapor phase in which the discharge is formed according to the Paschen's law.

$U_{\text{through the streamer}} = f(p\cdot d);$ (1)
where p is an internal pressure; d is the length of the streamer zone.

In addition, the discharge inside the cavity should charge the cavity walls, which lead to surface charge appearance and, as a result of Coulomb forces acting on these charges, to the wall movement. In fact, it is the model of streamer propagation. It should be pointed out that surface charges result in decrease of voltage drop on the streamer, this situation sometimes leading to discharge termination. Thus, the current pulse is formed. When the streamer grows, the voltage across the cavity increases again, and partial discharge may be repeated. In such a way, a series of current pulses are formed during the streamer propagation. It should be mentioned that practically the same bubble model of breakdown initiation in liquids was proposed earlier [8].

As for the analysis of PD in transformer oil, the following may be done. As a rule, short pulses of PD appear serially (Fig. 5a). In our view, short pulses of PD have the same character as the pulses described in the papers given above; the pulses are the result of appearance and propagation of streamers in liquid that developed in vapor and gas cavity. It seems that the long pulses behavior can be explained in the following way. The first short pulse may have the same nature as the usual short pulses described above, but the next phase should be considered in detail.

For this reason, let us consider the difference of the conditions in which short and long pulses appeared. According to the chromatographic data, the amount of dissolved air in the experiments where long pulses were registered was up to 30% from the equilibrium concentration. In case of more careful degassing, long pulses were not recorded. In our opinion the discharge in streamer zone occurs according to the left branch of Pashen's curve. That is why in degassed oil elongation of streamer cavity should lead to more desirable termination of discharge in comparison with the streamer propagation in air saturated oil. The reason is air diffusion from oil into cavity and increase of product *pd.*

It was established earlier [7] that supersonic positive streamers had currents of 0.1 - 0.5 A. In our case, the current of positive streamers did not exceed 30 μA. Therefore, a positive PD cannot be a supersonic streamer. According to the model [7], both positive and negative subsonic streamers propagate due to Paschen's discharge multiple avalanche in the streamer cavity. In such a case, the processes of the appearance of the so-called 'initiating' electron and processes of avalanche reproduction play the main role. In case of negative streamer, an initiating electron appears on the metal cathode because of cold emission and adsorbed negative ion decay [9]. The avalanche reproduction does not meet any difficulties, as it can be realized both by photoemission of the electrons from the cathode and by impact of positive ions upon the cathode surface. Therefore, one can understand why the PD appears at the negative point polarity at lower voltage in comparison with the positive point. As is mentioned above, the voltage of PD inception is 18 kV. According to expression (1), the field intensity at PD inception is about 20 MV/cm if we take into account that the point radius is 3 μm. If we take into account that the real radius could be 3÷4 μm and instantaneous voltage is 16÷18 kV, the electric field intensity close to the point is 15÷20 MV/cm. In our opinion, it means that the impact ionization threshold in transformer oil is about 15÷20 MV/cm. Reliable experimental data concerning collision ionization in transformer oil has not been obtained earlier. Nevertheless, these data for some other dielectric liquid (7 MV/cm for pentane, decane and cyclohexane, 11 MV/cm for liquid nitrogen) [3] agree well with our experimental data if take into account the presence of electron acceptors in transformer oil.

In case of positive streamer, the explanation of discharge propagation is more difficult. Initiating electrons have to appear due to the field ionization of the molecules of liquid or due to the presence of the gas bubbles in the bubble volume. It is clear that it is difficult for the initiating electrons to appear in comparison with the case of negative streamer. The avalanche reproduction in the developing streamer is more difficult too. Besides, there is one more factor that should determine the streamer nature. When the positive subsonic streamer is developed, the positive charge moves through the cavity to the point of the propagating streamer. As the mobility of positive charges is much lower (several times) than the mobility of the electron in the gas phase, electrical conductivity of positive streamer must be less than that of the negative streamer. This can lead to slower development of the streamer. In our opinion, the increase in time rise of positive PD, as compared to the negative one, can be explained by this model.

## Conclusion

1. It has been found experimentally that the partial discharges in the ‘point-plane’ electrode system with positive and negative polarity of the point have different time duration. Two types of pulses were recorded at the point cathode: ‘short’ – with the rise time of about 2÷3 ns, and with the falling time of 350÷380 ns, and ‘long’ – with the time rise of about 200÷250 ns, and with the falling time of 2÷2.5 μs. The pulses recorded at the point anode had rise time of 45÷55 ns, and falling time of 350 ns.

2. The threshold intensity of the impact ionization in the transformer oil estimated from experimental data is 15÷20 MV/cm.

3. The most plausible explanation of the PD appearance in oil is the formation of subsonic streamers, the propagation of which is kept by multi avalanche discharge inside the streamer cavity.

## References

[1] R. J. Van Brunt “Physics and chemistry of partial discharge and corona – recent advances and future challenges”, IEEE Conference on Electrical Insulation and Dielectric Phenomena, 1994, pp. 29-70 (IEEE Catalog Number 94 CH 3456-1).

[2] Darian L.A. and Arakelyan V.G. “Gassing resistance of insulating liquids” Electrotehnika, 1997, No. 2, pp. 45-49 (in Russian).

[3] Kattan, A. Denat and K. Bonifaci “Formation of vapor bubbles in non polar liquids initiated by current pulses”, CNRS. Laboratoire d'Electrostatique et de Materiaux Dielectrique BP 166X-38042 GRENOBLE Cedex (France) ICDL 1990, Conference Record, P.340-345;

[4] G. S. Kuchinsky The partial discharges in the high voltage constructions. – L.: Energy. Leningradskoe department, 1979. – Vol. 224, il (in Russian).

[5] M. Pompili, C. Mazzetti “Partial Discharge Pulse Sequence Patterns and Cavity Development Times in Transformer Oils under ac Condition”. IEEE Transaction on Transformers and Electrical Insulation, 2005, Vol. 12, No. 2.

[6] K.L. Stricklett, Observations of partial dischrges in heksane under high magnification / K.L. Stricklett, E.F. Kelley, H. Yamashita et all. // Conference Record of Tenth International Conference on Conduction and Breakdown in Transformer Liquids. – 1990 pp. 381-386.

[7] A. Denat, High Field Conduction and Prebreakdown Phenomena in Transformer Liquids / A. Denat // IEEE Transactions on Transformers and Electrical Insulation , 2006, Vol. 13, No. 3; pp. 518-525.

[8] Optical Study of Prebreakdown Cathode Processes in Deionized Water / A.V. Melekhov, V.G. Posukh, A.G. Ponomarenko, S.M. Korobeynikov, V.M. Antonov, E.L. Boyarintsev // IEEE Transactions on Dielectrics and Electrical Insulation, 2009, vol.16, Issue 2, pp. 504-508.

[9] S.M. Korobeynikov “Bubble model of ignition of the pulse electric discharge in liquids, Author’s Abstract of Doct. Phys.-Math. Sci. Dissert., Tomsk, 1998 (in Russian).