A "Relay-race" Wave Propagation of Partial Discharges in a Chain of Gas Inclusions in Condensed Dielectrics

A. L. Kupershtokh, D. I. Karpov
Lavrentyev Institute of Hydrodynamics of SB RAS
Novosibirsk, Russia
skn@hydro.nsc.ru, karpov@hydro.nsc.ru

***Abstract*— The level of the partial discharges (PDs) activity in solid or liquid dielectrics indicates to a reliability of electrotechnical equipment. A stochastic model of partial discharges inside gas inclusions (voids or bubbles) in solid or liquid dielectrics was developed. The equations for electric field potential and electric charge transfer are solved together for dielectric with gas voids. Computer simulations show the possibility of a "relay-race" propagation mechanism of a wave of partial discharges in a linear chain of gas inclusions. This mechanism can be realized if the distances between voids are relatively small and the dependence of probability function is relatively sharp. In other cases, the partial discharges in the chain of gas voids is completely stochastic.**

Keywords—breakdown of dielectric liquids; partial discharge; stochastic model; electric field; computer simulation

I. Introduction

When the high voltage is applied to an electrode gap filled with a solid or liquid dielectric, partial discharges may occur that do not lead to the loss of the insulating properties of the dielectric as a whole. The pulses of current are registered in the electric circuit at this time. The number and intensity of these pulses can predict the probability of a future breakdown of the gap.

One type of partial discharges in condensed dielectrics is the electrical discharges inside the cavities or bubbles. One of the first attempts to model the stochastic nature of PDs using an equivalent electric circuit of a void was carried out in [1]. The probability of PD initiation was assumed to be proportional to the over voltage in a void. Later, several other attempts were made to model PDs with allowance for their stochastic nature [2-5]. However, these studies did not take into account the spatio-temporal evolution of the electric field in the gap. Thus, all these models did not consider relative positions of the voids and ignored the possible influence of a micro-discharge in one void on the processes in other voids. The works [6-7] were devoted to computer simulations of the partial discharges in liquid and solid dielectrics and took into account the electric field distribution in the gap. The partial discharges in closely spaced voids were simulated. After the discharge in a void, the internal electric field in the neighbor void increased. The increase of the probability of PD in the neighbor void was demonstrated.

In the present paper, the partial discharges in a chain of several identical gas inclusions placed along the electric field line in condensed dielectric between two flat electrodes are studied. The possibility of a "relay-race" propagation of the wave of partial discharges in the chain of voids is demonstrated. This mechanism differs from deterministic mechanism of hopping spread streamers in the medium with bubbles [8, 9], since the stochastic nature of PDs plays important role at the "relay-race" mechanism of propagation.

II. Partial Discharges in a Single Void

Gas inside a small cavity in solid dielectrics or inside a micro-bubble in a liquid has the dielectric strength which is much lower than that of the condensed matter. The probability of a micro-discharge in an inclusion during time step Δt depends on the local electric field E inside an inclusion. The stochastic criterion MESTL (multi-element stochastic time lag) [10] was used to describe the probability of occurrence of a micro-discharge in a cavity. The stochastic lag time t_S of a micro-discharge is calculated in accordance with the density distribution function for the probability of rare events

$$F(t_S) = r(E)\exp(-r(E)t_S)\,. \tag{1}$$

Here, $r(E)$ is the sharply increasing function of the electric field. For small time step $\Delta t << 1/r(E)$, the probability of a micro-discharge in a cavity is equal to $f \approx r(E)\Delta t$. It was assumed that the micro-discharge in a cavity occurs at the current time step if the condition $t_S < \Delta t$ is satisfied.

The dependences of the function $r(E)$ for the occurrence of partial discharges in the cavity are shown in Fig. 1 that take into account the threshold character of partial discharges [11]

$$r(E) = \begin{cases} 0 & \text{for} \quad E \le E_*\,, \\ \alpha(E - E_*) & \text{for} \quad E > E_*\,. \end{cases} \tag{2}$$

Here, E_* is the value of the electric field above which the partial discharges in the cavity become possible. For inclusions of $d \sim 10$ microns, the breakdown voltage of air in a cavity is ≈ 350 V [12], which value corresponds to the threshold field

The study was supported by the Russian Science Foundation (Grant No. 16-19-10229).

978-1-5090-4877-9/17/$31.00 ©2017 IEEE

$E_* \approx 350$ kV/cm.

In the simulations, we used the pattern of the conductive structure arising inside a cavity during the partial discharge shown in Fig. 2.

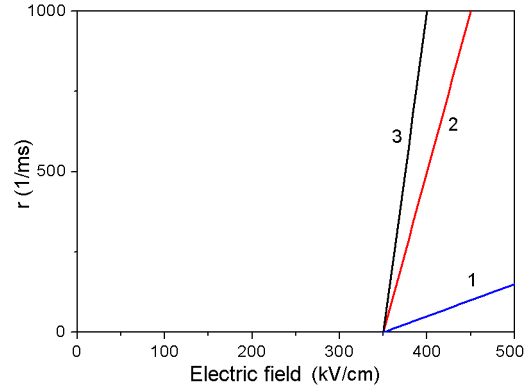

Fig. 1. Probability function $r(E)$ for PD in a cavity. Curves 1,2,3 correspond to $\alpha =$ 1, 10, 20 cm/(ms·kV).

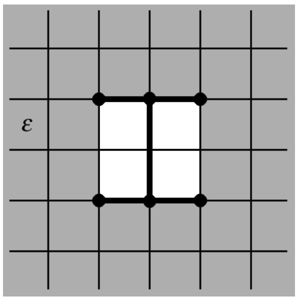

Fig. 2. Pattern of a conductive structure arising in a cavity during PD [7].

The Poisson's equation was used for numerical calculations of the distribution of the electric field potential φ between the electrodes at each time step. The electric charge transfer inside the conductive cavities was used together with Ohm's law

$$\mathrm{div}(\varepsilon\varepsilon_0\nabla\varphi) = -q\,, \qquad \mathbf{E} = -\nabla\varphi\,, \tag{3}$$

$$\frac{\partial q}{\partial t} = -\mathrm{div}\,\mathbf{j}\,, \qquad \mathbf{j} = \sigma\cdot\mathbf{E}\,. \tag{4}$$

Here, ε is the permittivity of fluid, q is the electric charge density. The periodic boundary conditions are used in x direction. It was assumed that the current density $\mathbf{j}$ and the conductivity σ are nonzero only within gas inclusions after their breakdown. The permittivity of the condensed dielectric is taken as $\varepsilon = 2$. The time-implicit finite-difference schemes were used for charge transfer and Poisson's equations [13].

III. Partial Discharges in a Chain of Gas Cavities

A chain of several identical gas inclusions placed along the electric field line is studied (Fig. 3). The distance between the inclusions is constant and equal to Δy. The computational lattice spacing is h. The constant voltage V sufficient for the occurrence of partial discharges is applied to the electrodes.

At the same dimensions of the cavities and at the same gas pressure inside them, the probability of micro-discharges in the inclusions depends on the local electric field within them E_i. The stochastic criterion MESTL [10] was used to describe the occurrence of micro-discharges in the cavities. For all nonconducting cavities, the stochastic lag times t_i of all possible micro-discharges were calculated in accordance with (1). It was assumed that the micro-discharge in the void occurs at the current time step if the condition $t_i < \Delta t$ is satisfied.

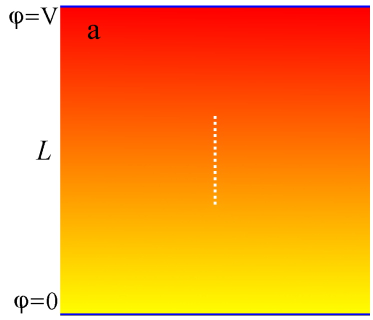

Fig. 3. Chain of gas cavities in the solid dielectric. $L =$ 1 mm. Lattice is 200×200. $\Delta y = 4h$. $h =$ 5 µm.

The initial values of the electric field in the voids after voltage application are shown in Fig. 4. The electric fields inside first and last voids exceed the threshold value E_*.

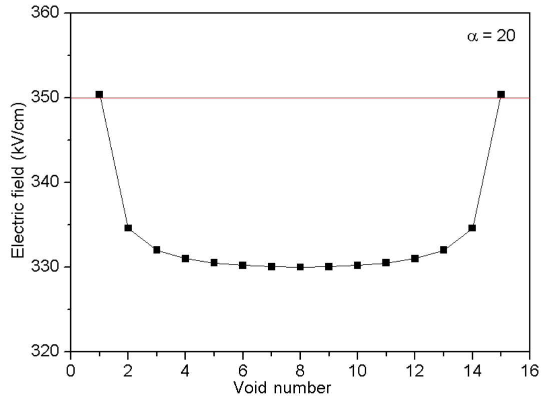

Fig. 4. Initial values of electric field inside cavities. $E_* \approx$ 350 kV/cm. $\Delta y = 3h$. $h =$ 5 µm. $V =$ 28.39 kV. $\alpha =$ 20 cm/(ms·kV).

IV. Computer Simulations of Partial Discharges

The sequence of partial discharges in the inclusions has a stochastic character at a relatively weak dependence of micro-discharge probability on a local electric field $r(E)$ or at the weak mutual influence of cavities on each other (Fig. 5).

If the dependence $r(E)$ is sharper, then under certain conditions, there is an interesting phenomenon that is a "relay-race" mechanism of propagation of the partial discharges along the chain of insulation defects (Figs. 6 and 7).

After the micro-discharge in the last void ($N =$ 15, see Fig. 6), this void become conductive, and the value of electric field in neighbor void ($N =$ 14) become larger than the

978-1-5090-4877-9/17/$31.00

threshold value E_*. Then, the probability of a micro-discharge in this void ($N = 14$) become noticeable, and after short time the micro-discharge occurs inside this void (Fig. 7). Then, the process repeats for the next void ($N = 13$) and so on. Thus, a wave of breakdowns occurs in the chain of inclusions.

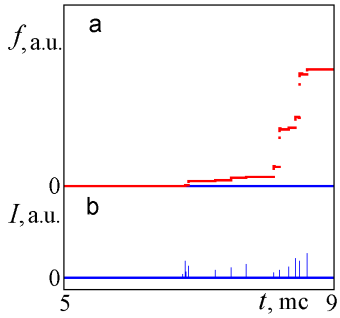

Fig. 5. (a) – Increase of the probability $f = r(E)\Delta t$ of a microdischarge during time step in one of the cavities after each discharge in other cavities [14]. (b) – The current I in the external electric circuit induced by partial discharges in voids.

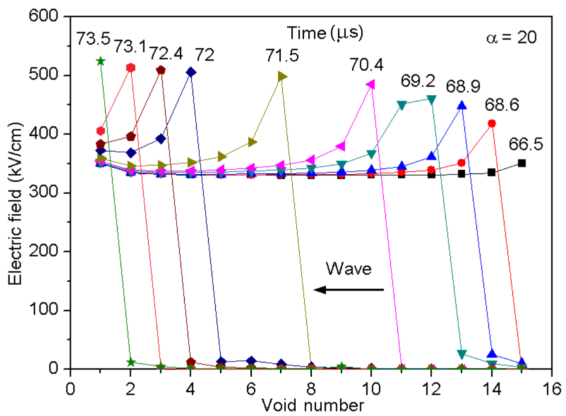

Fig. 6. Wave of partial discharges in the chain of voids. $L = 1$ mm. $\Delta y = 3h$. $h = 5$ μm. $\Delta t = 0.1$ μs. $V = 28.39$ kV. $\alpha = 20$ cm/(ms·kV).

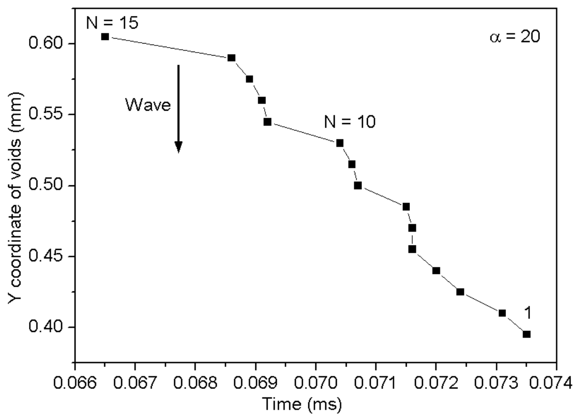

Fig. 7. Wave of partial discharges in the chain of voids. $\Delta y = 3h$. $h = 5$ μm. $\Delta t = 0.1$ μs. $V = 28.39$ kV. $\alpha = 20$ cm/(ms·kV).

Two waves are also possible that propagate from both ends of a chain (Figs. 8 and 9). As the wave of partial discharges propagates along the chain of the cavities, the electric field increases inside the cavities remaining nonconductive ahead of the waves (Figs. 6 and 8).

This "relay-race" mechanism of wave propagation of partial discharges in the chain of inclusions differs from the hopping spread streamers in the medium with bubbles [8,9], since the "relay-race" mechanism simulated in the present work takes into account the stochastic nature of the phenomenon.

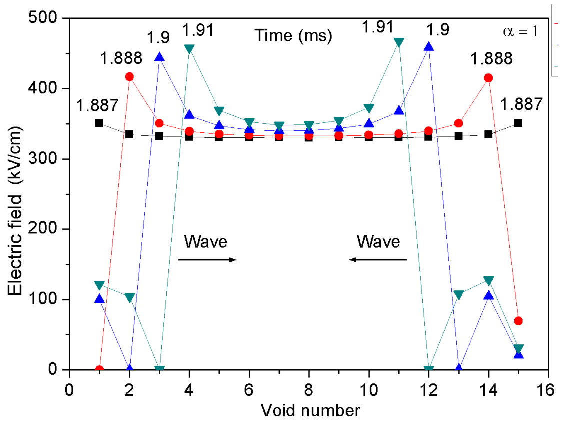

Fig. 8. Two waves of partial discharges propagate from the first and from the last voids in the chain. $L = 1$ mm. $\Delta y = 3h$. $h = 5$ μm. $\Delta t = 0.1$ μs. $V = 28.4$ kV. $\alpha = 1$ cm/(ms·kV).

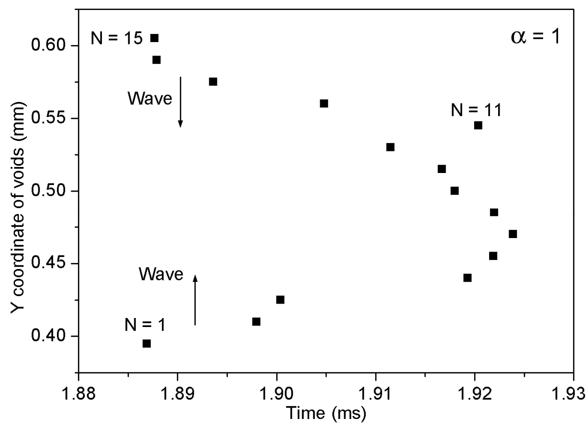

Fig. 9. Two waves of partial discharges propagate from the first and from the last voids in the chain. $\Delta y = 3h$. $h = 5$ μm. $\Delta t = 0.1$ μs. $V = 28.4$ kV. $\alpha = 1$ cm/(ms·kV).

If the distances between voids are not small and the dependence of the probability function is not relatively sharp and the initial values of electric field exceed critical value in all voids, the behavior of partial discharge become completely stochastic (Fig. 10).

V. Conclusion

The stochastic model of partial discharges inside gas inclusions in solid or liquid dielectrics was developed. The computer simulations show the possibility of the "relay-race" mechanism of wave propagation of partial discharges in the linear chain of gas inclusions.

978-1-5090-4877-9/17/$31.00 ©2017 IEEE

This mechanism can be realized if the distances between voids are relatively small and the dependence of probability function is relatively sharp. The applied voltage should be near the critical value so that the values of electric field in the voids at the ends of the chain exceed the critical electric field E_*, but the values of electric field in the inner voids are less than critical one. In other case, the behavior of partial discharges in the chain of the voids is completely stochastic.

The experimental study of this phenomenon can give the important information about the dependence of the probability function $r(E)$.

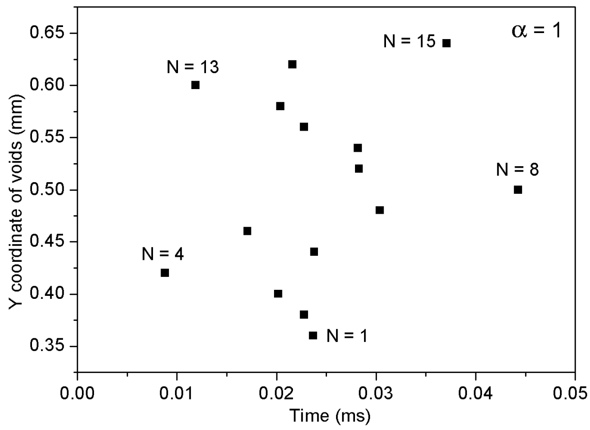

Fig. 10. Completely stochastic behavior of partial discharges in the chain of voids. $\Delta y = 4h$. $h = 5$ µm. $\Delta t = 0.1$ µs. $V = 30$ kV. $\alpha = 1$ cm/(ms·kV).

References

[1] M. Hikita, K. Yamada, A. Nakamura, T. Mizutani, A. Oohasi, and M. Ieda, “Measurements of partial discharges by computer and analysis of partial discharge distribution by the Monte Carlo Method,” IEEE Trans. Electr. Insul., vol. 25, pp. 453–468, 1990.

[2] B. Fruth and L. Niemeyer, “The importance of statistical characteristics of partial discharge data,” IEEE Trans. Electr. Insul., vol. 27, no. 1, pp. 60–69, 1992.

[3] F. Gutfleisch and L. Niemeyer, “Measurement and simulation of PD in epoxy voids,” IEEE Trans. Dielectr.Electr. Insul., vol. **2**, no. 5, pp. 729–743, 1995.

[4] A. Cavallini and G. C. Montanari, “Effect of supply voltage frequency on testing of insulation system,” IEEE Trans. Dielectr.Electr. Insul., vol. 13, no. 1, pp. 111–121, 2006.

[5] E. Lemke, “A critical review of partial-discharge models,” IEEE Electrical Insulation Magazine, vol. 28, no. 6, pp. 11–16, 2012.

[6] A.L. Kupershtokh, C.P. Stamatelatos, and D.P. Agoris, “Simulation of partial discharge activity in solid dielectrics under AC voltage,” Technical Phys. Lett., vol. 32, no. 8, pp. 680–683, 2006.

[7] A.L. Kupershtokh, D.I. Karpov, D.A. Medvedev, C.P. Stamatelatos, V.P. Charalambakos, E.C. Pyrgioti, and D.P. Agoris, “Stochastic models of partial discharge activity in solid and liquid dielectrics,” IET Sci. Meas. Technol., vol. 1, no. 6, pp. 303–311, 2007.

[8] N.Yu. Babaeva, D.V. Tereshonok, G.V. Naidis, and B.V. Smirnov, “Initiation of breakdown in strings of bubbles immersed in transformer oil and water: String orientation and proximity of bubbles,” J. Phys. D: Appl. Phys., vol. 49, no. 2, p. 025202, 2016.

[9] N.Y. Babaeva, R.S. Berry, G.V. Naidis, B.M. Smirnov, E.E. Son, and D.V. Tereshonok, “Kinetic and electrical phenomena in gas–liquid systems,” High Temperature, vol. 54, no. 5, pp. 745-766, 2016.

[10] A.L. Kupershtokh, V. Charalambakos, D. Agoris, and D.I. Karpov, “Simulation of breakdown in air using cellular automata with streamer to leader transition,” J. Phys. D: Appl. Phys., vol. 34, no. 6, pp. 936–946, 2001.

[11] K. Wu, Y. Suzuoki, and L.A. Dissado, "The contribution of discharge area variation to partial discharge patterns in disk-voids," J. Phys. D: Appl. Phys., vol. 37, no. 13, pp. 1815–1823, 2004.

[12] A. Peschot, C. Poulain, N. Bonifaci, and O. Lesaint, "Electrical breakdown voltage in micro- and submicrometer contact gaps (100 nm – 10 µm) in air and nitrogen," IEEE Holm Conference on Electrical Contacts, pp. 280–286, 2015.

[13] D.I. Karpov and A.L. Kupershtokh, “Models of streamers growth with "physical" time and fractal characteristics of streamer structures,” Conf. Record 1998 IEEE Int. Symp. on Electrical Insulation, IEEE No. 98CH36239, Arlington, USA, pp. 607–610, 1998.

[14] A.L. Kupershtokh and D.I. Karpov, “Simulation of waves of partial discharges in a chain of gas inclusions located in condensed dielectrics,” J. Phys.: Conf. Ser., vol. 754, no. 10, p. 102006, 2016.

978-1-5090-4877-9/17/$31.00 ©2017 IEEE