Journal of Physics: Conference Series **1675** (2020) 012105 doi:10.1088/1742-6596/1675/1/012105

Simulations of partial discharges in a chain of gas cavities at AC voltage

A L Kupershtokh and D B Lazebnyi

Lavrentyev Institute of Hydrodynamics SB RAS, 15 Lavrentyev Prosp., Novosibirsk, 630090, Russia

E-mail: skn@hydro.nsc.ru

Abstract. The stochastic model of partial discharges (PDs) in chains of gas caverns in condensed dielectrics is improved. The equations for electric field potential are solved in a region filled by dielectric containing gas caverns. The opportunity of a "relay-race" propagation of PDs in a linear chain of gas caverns under constant and ramp voltage was shown in previous studies. This mechanism is possible if the interval between caverns is relatively small. In this case, the wave of PDs can travel along the chain. This paper is devoted to modelling "relay-race" waves in a zigzag chain of gas-filled caverns under AC voltage.

1. Introduction

The specific kind of partial discharges (PDs) is the phenomenon of electrical discharges in small gas-filled caverns in liquid or solid dielectrics that do not result in the electrical breakdown of the dielectric as a whole. Earlier, in many works [1-3], PDs in separated small gas caverns in condensed dielectrics were simulated. Every PD in cavern is accompanied by the short pulse of the current in the external circuit. An increase in PD activity in time may indicate the high possibility of a subsequent breakdown of the gap. The propagation of PDs in the form of waves along the linear chains of such caverns at a constant and ramp voltage is possible [4,5]. It is well known that gas inside caverns has lower electric strength as compared to condensed material. Moreover, the electric field strength inside an individual spherical gas cavern before PDs is $E = 3E_0\varepsilon/(2\varepsilon+1)$ and it is greater than the averaged electric field in the bulk of condensed dielectric $E_0(t)$. However, for cavities located in the chain, the values of electric field strength inside them are somewhat lower than for a single cavity. After PD in one of the caverns, the electric field in neighboring caverns increases. This leads to subsequent PDs inside them. Then, the PDs proceed sequentially one by one along the series of gas caverns. Accordingly, a wave of PDs propagates in the chain. This unusual mode was called “relay-race” mechanism [4-6]. This scenario can work if the intervals between gas caverns are comparatively small. The conditions for the transition from the ordered regime of PDs propagation to entirely stochastic one were revealed. For the "relay-race" mechanism, streamers do not arise in the condensed phase, but only PDs proceed inside the caverns filled with gas. Hence, it is different from “hopping spread streamers” mechanism demonstrated in [3] for the cluster of bubbles in liquid dielectrics.

In practice, most power equipment operates on alternating voltage (AC voltage). Therefore, in this paper, we investigated the possibility of the appearance of several PDs waves in a chain of caverns under AC voltage. A condensed dielectric containing a zigzag chain of seven caverns is placed between parallel electrodes. Gas cavities are randomly located in a certain neighborhood of the selected electric field line. This study takes into account the spatio-temporal changes in the electric field in the area between electrodes.

It is very remarkable that the "relay-race" mechanism of PDs propagation can exist, despite the stochastic nature of electrical discharges inside cavities. Moreover, the "relay-race" waves in the chain of gas-filled caverns can be repeated for AC voltage in the following half-periods.

2. Distribution of electric field in the interelectrode gap

The equation (1) for the electric field potential φ is solved numerically at every time step Δt in the area between electrodes. The electric currents of PDs inside the caverns are also calculated

$$\mathrm{div}(\varepsilon\varepsilon_0 \nabla\varphi) = -q\,,\ \frac{\partial q}{\partial t} = -\mathrm{div}\,\mathbf{j}\,. \quad (1)$$

Here, $\varepsilon = 2$ is the dielectric constant of the fluid, q is the density of electric charge. It is obvious that the conductivity σ and, consequently, current density $\mathbf{j} = \sigma \cdot \mathbf{E}$ in the gas-filled cavern exist only for a short time of PD.

Two-dimensional modelling is performed in the square calculation area between parallel electrodes (Figure 1) on a lattice of 1024×1024. The interelectrode gap is L = 0.256 mm, the diameter d of caverns is equal to 10 μm. The lattice spacing is h = 0.25 μm. In x direction, the boundary conditions for potential are periodic. An alternating voltage $V = V_0 \sin(2\pi f t)$ is applied to the electrodes, where V_0 = 10.7 kV, f = 50 Hz. The time-implicit finite-difference scheme proposed in [7,8] is used for solving the system of equations (1). The distribution of electric field strength is then found using the relation $\mathbf{E} = -\nabla\varphi$. Subsequently, the maximum field strength in each cavity is calculated.

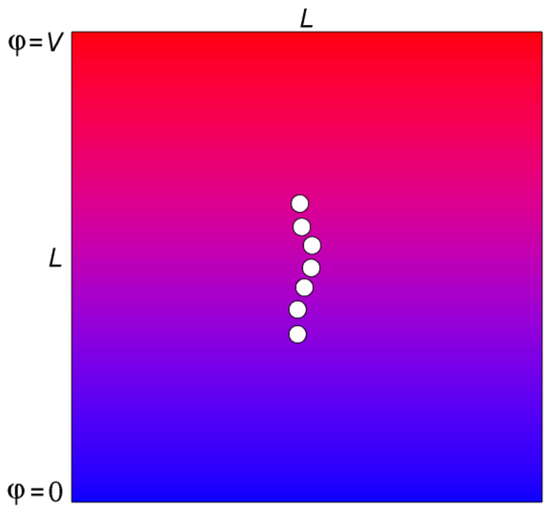

Figure 1. Zigzag chain of gas-filled caverns in the condensed dielectric. L = 0.256 mm. Lattice size is 1024×1024. $r = 20h$. d = 10 μm.

3. Stochastic model of partial discharge in a gas-filled cavity

We simulate a chain of air-filled caverns of the same size and with the same air pressure inside them (1 atm). Hence, the probability of micro-discharges inside them can depend only on the inner electric field E_i.

To simulate the stochastic features of the appearance of micro-discharges in caverns, we use the stochastic criterion MESTL (multi-element stochastic time lag) proposed in [7,9]. In the limit of small probabilities, the probability density for the distribution function of rare events can be written as

$$F(t_i) = r(E_i)\exp(-r(E_i)t_i), \tag{2}$$

where, $r(E)$ is the abruptly increasing function. Hence, the stochastic lag time t_i is calculated for each non-conducting cavity as a random value $t_i = -\ln(\xi_i)/r(E_i)$, where a random number ξ is in interval from 0 to 1. During a time step of modeling Δt, partial discharges occur according to the MESTL criterion [7,9] in all cavities for which $t_i < \Delta t$.

To represent the threshold behavior of PDs inside the gas cavern, the function $r(E)$ can be approximated as $r(E) = \alpha(E - E_*)$ for $E > E_*$ [1]. The PD in the gas cavity is possible if the electric field inside it exceeds the value E_*. For a cavity of size $d \sim 10$ µm, the threshold voltage of PD in air at pressure 1 atm was measured at the level of 350 V [10]. Hence, the threshold value for such a cavern corresponds to 350 kV/cm. The typical plots of function $r(E)$ are shown in Figure 2.

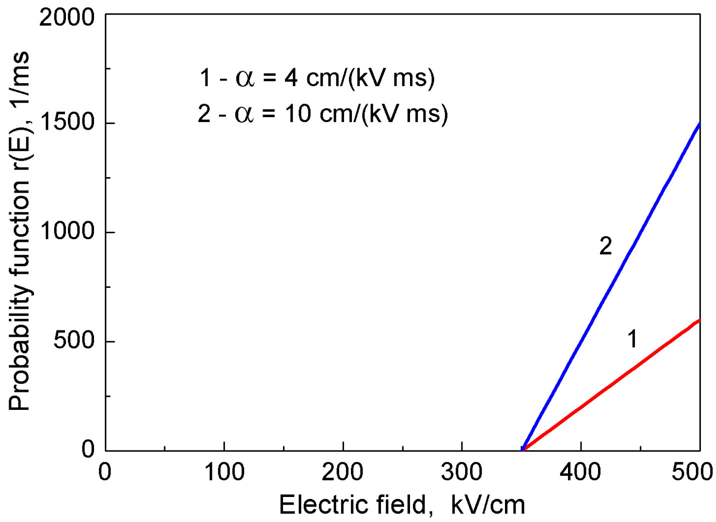

Figure 2. Probability function $r(E)$ for PD in a cavity ($d = 10$ µm). $\alpha =$ 4 (curve 1) and 10 (curve 2) cm/(kV·ms).

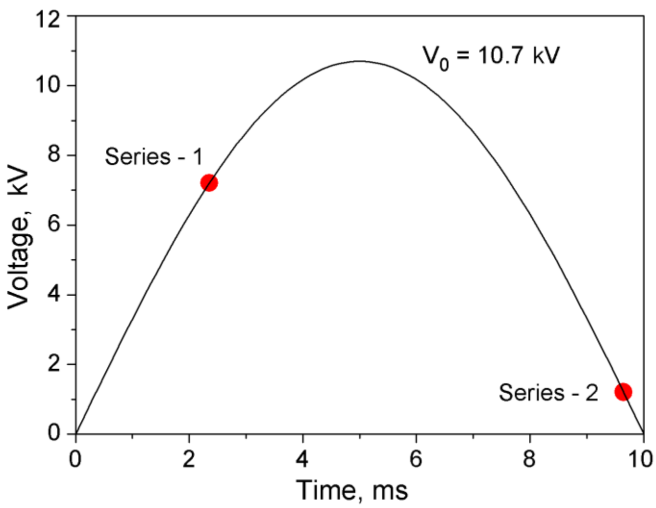

Figure 3. The value of applied AC voltage vs. time. Two series of partial discharges in the chain.

4. Results of simulations

The chain consists of the gas-filled caverns that are randomly distributed in a certain neighborhood of the electric field line in the central area between the electrodes (Figure 1).

At a certain moment for the AC voltage (Figure 3), the electric fields inside the first and last caverns in the chain become slightly greater than the threshold value E_* [5,6]. Then, the probabilities of PDs inside these caverns become noticeable. Therefore, the wave of PDs usually begins to propagate at one of the ends of the chain. Nevertheless, there is a possibility that two PD waves start simultaneously from both edges of the chain [5,6].

Figure 4 shows the example of "relay-race" mode of PDs propagation. Before the PDs occur in a chain, the maximum of electric field strength is in the first gas-filled cavity ($N = 1$) and it is higher than 350 kV/cm. During the micro-discharge in this cavern, the substance inside it becomes conductive (plasma state), and the magnitude of electric field in the next gas-filled cavity ($N = 2$) getting significantly greater than E_* ($t = 2350$+4.21 μs). Consequently, the probability of electrical discharge in this gas cavern enhances considerably. Since a short period, the micro-discharge happens inside this cavern ($t = 2350$+4.53 μs). After that, the process is repeated for the next gas cavern ($N = 3$) and so on. Thus, the PDs wave propagates very quickly along the chain (Figure 4).

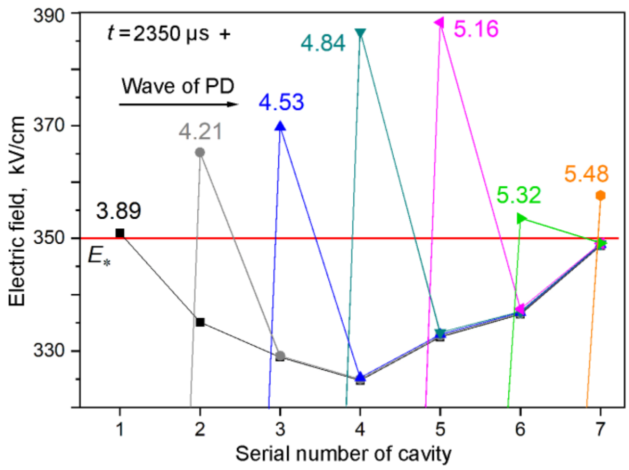

Figure 4. The magnitudes of electric field inside the caverns as the first wave of PDs propagates from left to right along the chain (series 1 in Figure 3). $L =$ 0.256 mm. $E_* = 350$ kV/cm. Lattice size is 1024×1024.

The total duration of the propagation of this wave over all seven caverns is about 2 μs. It depends also on conductivity of plasma during partial discharge and its duration in gas-filled cavity. The electric field there decreases during the PD. The microdischarge inside the cavity terminates after the value of the electric field strength becomes less than some critical value $E_r \sim 10^{-3} E_*$ (residual electric field). The complete decay of plasma inside the cavity occurs because the release of energy decreases and becomes small as compared with the loss of energy. We assume that the conductivity after this moment tends to zero. The electric charges on the surface of a cavity remain unaltered because we assume that diffusion is practically absent during short time. As the wave of PDs propagates along the chain of caverns, the magnitudes of electric field in the remaining caverns increase.

The similar processes repeat for the second wave of PDs (Figures 3 and 5). In this case the PDs wave propagates from right to left. The total duration of the propagation is more than 6 μs.

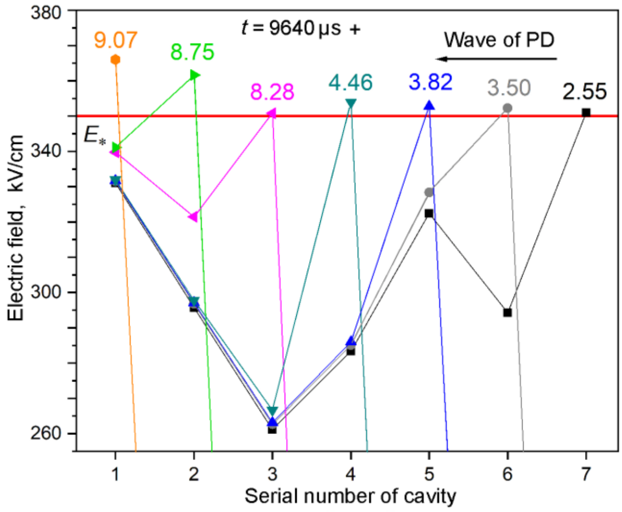

Figure 5. The magnitudes of electric field inside the cavities as the second wave of PDs propagates along the chain of caverns from right to left (series 2 in Figure 3). $L = 0.256$ mm. $E_* = 350$ kV/cm.

Conclusions

The stochastic model of PDs in a chain of gas-filled caverns in condensed dielectrics has been improved. The model is based on the stochastic nature of microdischarges in gas-filled caverns. Despite the stochastic nature of the processes, "relay-race" waves of PDs propagating along the chain are observed in computer simulations. The sequence of PDs in the chain is randomly determined in a case of comparatively weak dependence $r(E)$ or if the mutual influence of the caverns on each other is insignificant at a relatively large interval between them.

The "relay-race" waves start from the edges of the chain, where the electric fields inside cavities are maximal. Hence, the amplitude of applied AC voltage must be large enough so that the electric fields in the cavities at the edges of the chain exceed the critical magnitude E_*. Under AC voltage, the appearance of subsequent waves of PDs is possible.

Acknowledgments

The work was financially supported by Russian Scientific Foundation (grant No. 16-19-10229).

References

[1] Wu K, Suzuoki Y and Dissado L A 2004 *J. Phys. D: Appl. Phys.* **37**(13) 1815–23
[2] Kupershtokh A L, Stamatelatos C P and Agoris D P 2006 *Technical Phys. Lett.* **32**(8) 680–3
[3] Babaeva N Yu, Tereshonok D V, Naidis G V and Smirnov B V 2016 *J. Phys.* D: *Appl. Phys.* **49**(2) 025202
[4] Kupershtokh A L and Karpov D I 2016 *J. Phys.: Conf. Ser.* **754**(10) 102006
[5] Kupershtokh A L and Karpov D I 2018 *J. Electrostatics* **94** 8–13
[6] Kupershtokh A L and Karpov D I 2017 *Proc. 2017 IEEE International Conference on Dielectric Liquids* (Manchester, UK) Paper 1310, pp 1–4
[7] Karpov D I and Kupershtokh A L 1998 *Conf. Record 1998 IEEE Int. Symp. on Electrical Insulation, IEEE No. 98CH36239* vol 2 (Arlington, USA) pp 607–10
[8] Kupershtokh A L and Medvedev D A 2006 *J. Electrostatics* **64**(7/9) 581–5
[9] Kupershtokh A L, Charalambakos V, Agoris D and Karpov D I 2001 *J. Phys.* D: *Appl. Phys.* **34**(6) 936–46
[10] Peschot A, Poulain C, Bonifaci N and Lesaint O 2015 *IEEE Holm Conference on Electrical Contacts* (San Diego, USA) pp 280–6