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"Relay-race" mechanism of propagation of partial discharges in condensed dielectrics at linearly increasing voltage

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Abstract. A stochastic model of partial discharges (PDs) inside gas cavities in condensed dielectrics is 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" mechanism of propagation of partial discharges in a linear chain of gas cavities. This mechanism can be realized if the spacing between cavities is relatively small and the dependence of probability function of partial discharges on electric field strength $r(E)$ is relatively sharp. In this case, the wave of partial discharges propagates along the chain of cavities. The PD waves can be initiated in the first cavity or in the last cavity in the chain. Occasionally, two PD waves can be observed together from the both ends of the chain. The sequence of partial discharges in the inclusions has a completely stochastic character at a relatively weak dependence $r(E)$ or if the mutual influence of cavities on each other is weak.

1. Introduction

When the high voltage is applied to an interelectrode gap filled with a dielectrics, the partial discharges (PDs) may occur that do not lead to the loss of the insulating properties of the dielectric as a whole. At this time, the pulses of the electric current are registered in the external circuit, the number and intensity of which can predict the probability of a breakdown of the gap. One type of partial discharges in condensed dielectrics is the electrical discharges inside the small gas inclusions (voids or bubbles) in solid or liquid dielectrics. One of the first attempts to simulate the stochastic nature of PDs using an equivalent electric circuit of a void was carried out in [1]. Later, this approach was developed in [2-4]. However, these studies did not take into account the spatio-temporal evolution of the electric field in the gap. The works [5-8] are devoted to the computer simulations of partial discharges in liquid and solid dielectrics with calculations of electric field distribution at every time step.

In present paper, the partial discharges in condensed dielectrics between two flat electrodes are studied. Gas inside the small cavities in solid dielectrics or inside the microbubbles in a liquid has an electric strength which is much lower than that of the condensed matter. Two-dimensional computer simulations of partial discharges in a chain of such gas inclusions located in condensed dielectric are carried out. The inclusions are located along the electric field line at the same close distance from each other.

The possibility of the wave of partial discharges in the chain of gas inclusions is demonstrated. In this case, the partial discharges occur sequentially one by one along the chain of insulation defects.

This interesting phenomenon can be named as a "relay-race" mechanism of propagation of partial discharges in the chain. This mechanism differs from "hopping spread streamers" in the medium with bubbles simulated in [9]. For "relay-race" mechanism, the streamers do not occur in the condensed phase but occur only inside the gas filled cavities. Moreover, it is most important that the "relay-race" mechanism of propagation can be realized even if the stochastic nature of the phenomenon is taken into account.

2. Partial discharges in a chain of gas inclusions spaced in condensed dielectric

At the same dimensions of these cavities in the bulk of the dielectric and at the same gas pressure inside them, the probability of micro-breakdowns inside the inclusions depends on the local electric field within them E_i.

The stochastic criterion MESTL (multi-element stochastic time lag) [10, 11] is used to describe the occurrence of micro-discharges in cavities. For all nonconducting cavities, the stochastic lag times t_i are calculated in accordance with the density distribution function for the probability of rare events

$$F(t_i) = r(E_i)\exp(-r(E_i)t_i). \tag{1}$$

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-breakdown in a cavity is approximately equal to $f \approx r(E)\Delta t$. It is assumed that the micro-breakdown in a cavity occurs during the current time step if the condition $t_i < \Delta t$ is satisfied.

The function $r(E)$ on the local electric field inside the gas inclusion that describes the threshold character of partial discharges has the form [5]

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

Here, E_* is the threshold electric field above which partial discharges in the gas inclusions are possible. The breakdown voltage of air in a void of size $d \sim 10$ microns is approximately equal to 350 V [12], which corresponds to the threshold field $E_* \approx 350$ kV/cm. The functions $r(E)$ for different values of α are shown in figure 1*b*.

A chain of several identical gas inclusions spaced along the electric field lines in condensed dielectric between two flat electrodes is studied (figure 1*a*). The spaces between all neighbor inclusions are equal to Δy.

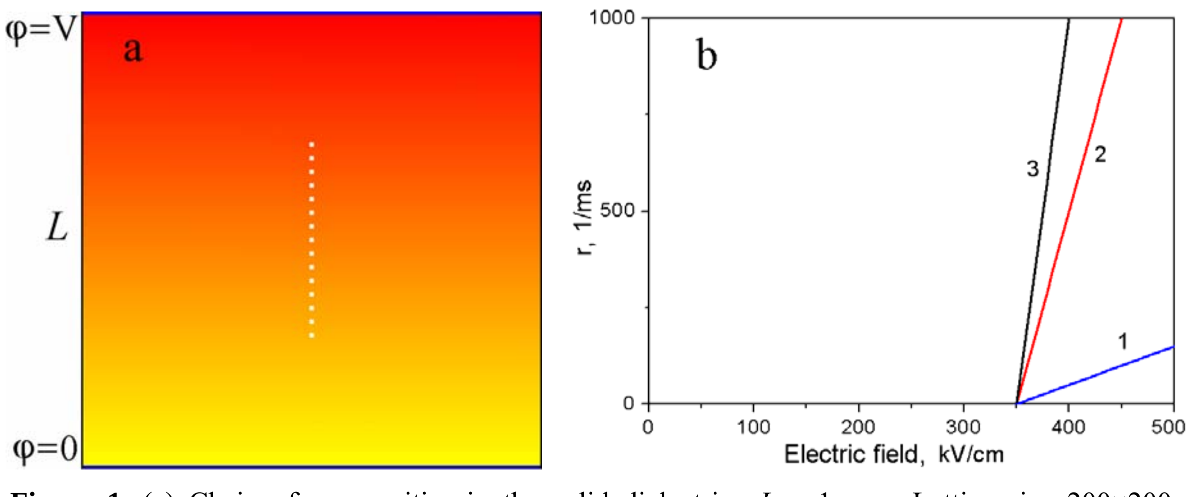

Figure 1. (a) Chain of gas cavities in the solid dielectric. $L =$ 1 mm. Lattice size 200×200. $\Delta y = 6h$. (b) Probability function $r(E)$ for PD in a cavity. Curves 1, 2 and 3 correspond to $\alpha =$ 1, 10 and 20 cm/(kV·ms).

The distribution of the electric field potential in the whole region between the flat electrodes (figure 1*a*) is calculated numerically at each time step by solving the Poisson's equation together for the electric field potential with the equations of the electric charge transfer inside inclusions during the partial discharges [6, 7]

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

$$\frac{\partial q}{\partial t} = -\mathrm{div}\,\mathbf{j}\,, \tag{4}$$

Here, ε is the permittivity of fluid, q is the electric charge density. The distribution of electric field strength is defined by the equation $\mathbf{E} = -\nabla\varphi$. It is assumed that the conductivity σ and the current density $\mathbf{j} = \sigma \cdot \mathbf{E}$ are nonzero only within gas inclusions during the partial discharges. The time-implicit finite-difference scheme is used to solve this system of equations [7, 10]. The computational lattice spacing is h. The periodic boundary conditions are used in x direction. The permittivity of the condensed dielectrics is assumed to be equal to $\varepsilon = 2$.

The values of electric field strength inside gas inclusions are greater than the electric field strength in condensed dielectric but are lower than the one inside a single isolated spherical cavity $E_0 = 3E\varepsilon/(2\varepsilon+1)$.

For linearly increasing voltage $V = \gamma t$ applied to the electrodes, the values of the electric field inside the first and the last gas inclusions in the chain become somewhat greater than the threshold value E_* at a certain moment of time (figure 2). Then, the probabilities of micro-discharge f during time step Δt inside these gas inclusions become noticeable. The rate of voltage rise is assumed to be equal to $\gamma = 10$ kV/ms.

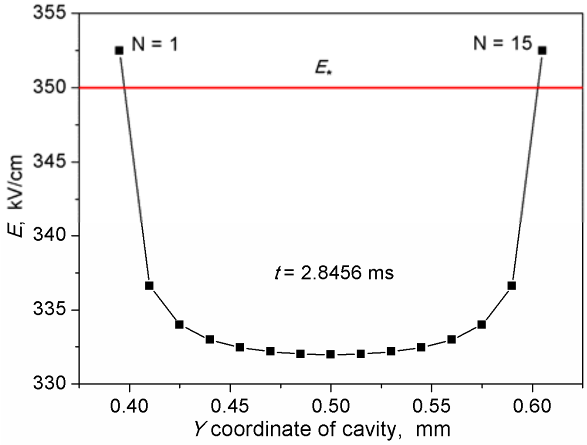

Figure 2. The values of electric field inside all gas inclusions in the chain just before the first partial discharge ($t = 2.8456$ ms). $L = 1$ mm. $E_* = 350$ kV/cm. $\Delta y = 3h$. $h = 5$ µm. $\alpha = 20$ cm/(kV·ms). Lattice size 200×200.

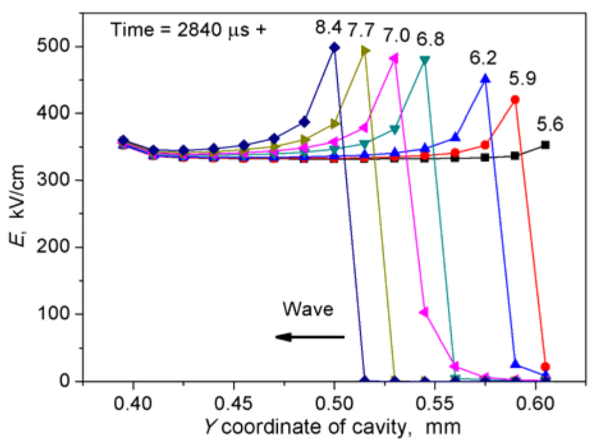

Figure 3. The electric field values inside the cavities as the wave of PDs propagates along the chain. $L = 1$ mm. $E_* = 350$ kV/cm. $\Delta y = 3h$. $h = 5$ µm. $\alpha = 20$ cm/(kV·ms). Lattice size 200×200.

One example of simulations is shown in figure 3. After the micro-discharge in the last gas inclusion (N = 15), this gas cavity becomes conductive, and the value of electric field in the neighbor gas cavity (N = 14) becomes considerably greater than the threshold value E_*. Hence, the probability of electrical breakdown in this gas inclusion increases significantly, and after short time, the micro-discharge occurs inside this gas cavity. Then, the process repeats for the next neighbor gas cavity (N = 13) and so on. As a result, the wave of partial discharges propagates along the chain of inclusions (figures 3 and 4). This interesting phenomenon can be named as a "relay-race" mechanism of propagation of partial discharges in the chain of insulation defects.

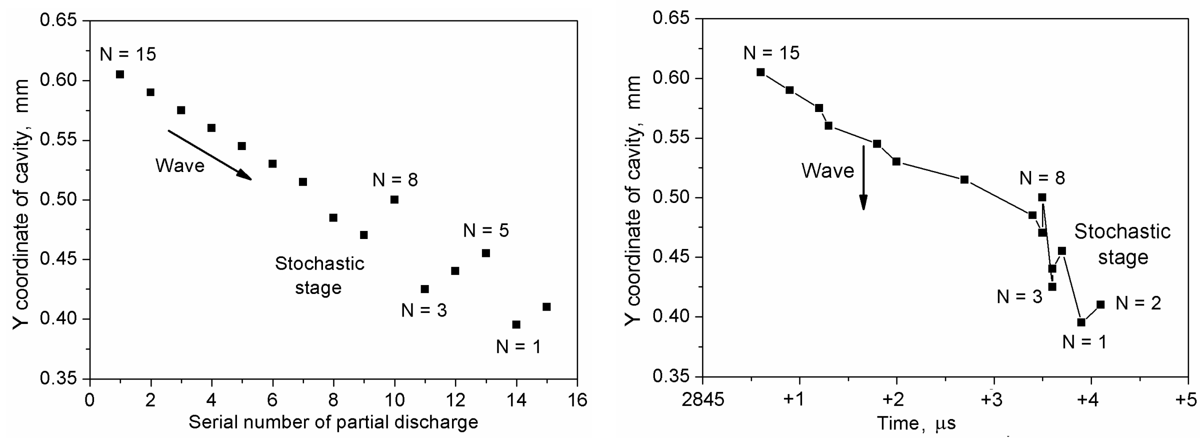

Figure 4. (a) The sequence of partial discharges in cavities. Wave of PDs and stochastic stage. (b) The sequence of partial discharges in time. $L = 1$ mm. $E_* = 350$ kV/cm. $\Delta y = 3h$. $h = 5$ µm. $\alpha = 20$ cm/(kV·ms). Lattice size 200×200.

The sequence of partial discharges becomes stochastic (figure 4) after the moment when the values of electric field strength inside the interior cavities become greater than the critical value (figure 5). As the wave of partial discharges propagates along the chain of cavities, the electric field increases inside the remaining cavities.

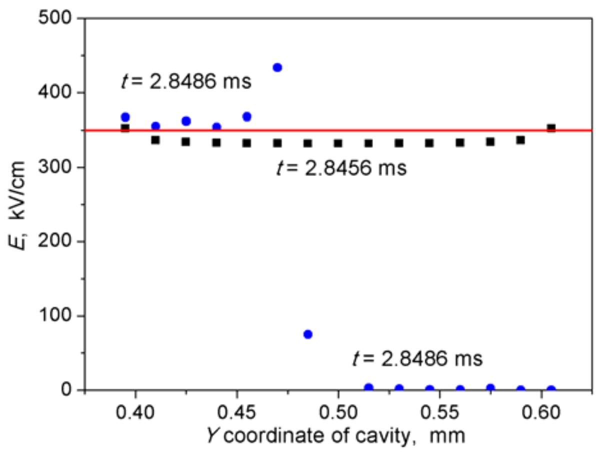

Figure 5. The values of electric field inside gas inclusions before the first PD (▪) and during the stochastic stage (●). $L = 1$ mm. $E_* = 350$ kV/cm. $\Delta y = 3h$. $h = 5$ µm. $\alpha = 20$ cm/(kV·ms). Lattice size 200×200.

The "relay-race" mechanism of propagation of partial discharges can be realized if the dependence $r(E)$ is sharp enough and the spaces between the cavities Δy are relatively small. For relatively small spacing Δy, the difference in values of electric field inside the cavities at the ends of the chain and in the central region of the chain is greater than for large distances (figure 6). After the micro-discharge inside a cavity, the electric field in the neighbor cavity increases significantly and becomes considerably greater than the threshold value E_*. The maximal values of electric field ahead of the

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front of the waves of PDs at different spacing between cavities Δy are shown in figure 7. For relatively small spacing Δy, the enhancing of electric field in the neighbor cavity is more pronounced.

The PD waves can be initiated as at first cavity and at last cavity in the chain (figures 6 and 7). Occasionally, two PD waves can be observed together from the both ends of the chain (figure 7).

The sequence of partial discharges in the chain of cavities has a stochastic character at a relatively weak dependence $r(E)$ or if the spacing Δy is relatively large and the mutual influence of cavities on each other is weak. The stochastic regime of partial discharges in the chain of cavities at $\Delta y = 7h$ is shown in figure 8a. In this case, the mutual influence of cavities on each other is weak, and the values of electric field inside cavities have approximately the same values (figure 8b).

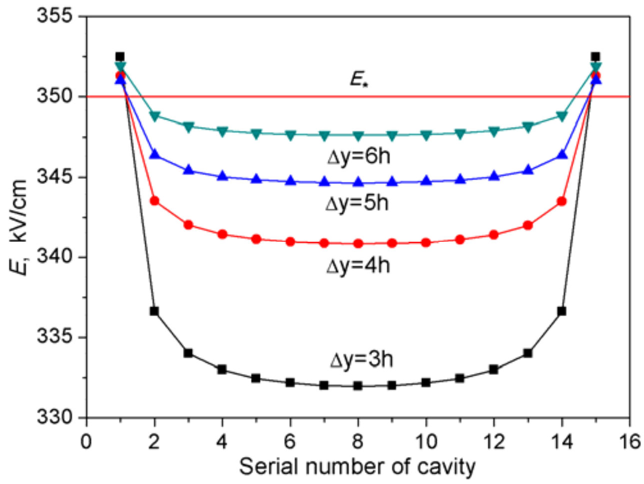

Figure 6. The values of electric field inside gas inclusions before the first PD in the chain at different spacing between cavities Δy. $L = 1$ mm. $E_* = 350$ kV/cm. $h = 5$ µm. $\alpha = 20$ cm/(kV·ms). Lattice size 200×200.

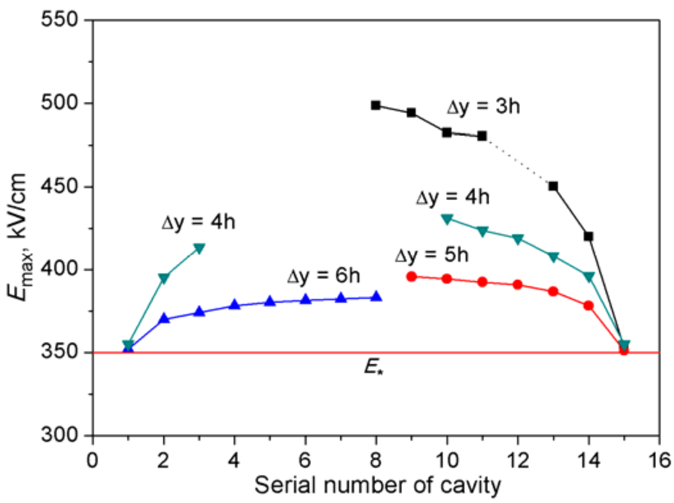

Figure 7. The maximal values of electric field ahead of the front of the waves of PD at different spacing between cavities Δy. $L = 1$ mm. $E_* = 350$ kV/cm. $h = 5$ µm. $\alpha = 20$ cm/(kV·ms). Lattice size 200×200.

3. Conclusion

The "relay-race" mechanism of propagation of partial discharges in a linear chain of gas inclusions at linearly increasing voltage is possible if the spacing between cavities Δy is relatively small. In this case, the wave of partial discharges propagates along the chain of cavities. The PD waves can be initiated as in the first cavity and in the last cavity in the chain. Occasionally, two PD waves can be observed together from the both ends of the chain. The sequence of partial discharges in the inclusions has a completely stochastic character at a relatively weak dependence $r(E)$ or if the mutual influence of cavities on each other is weak.

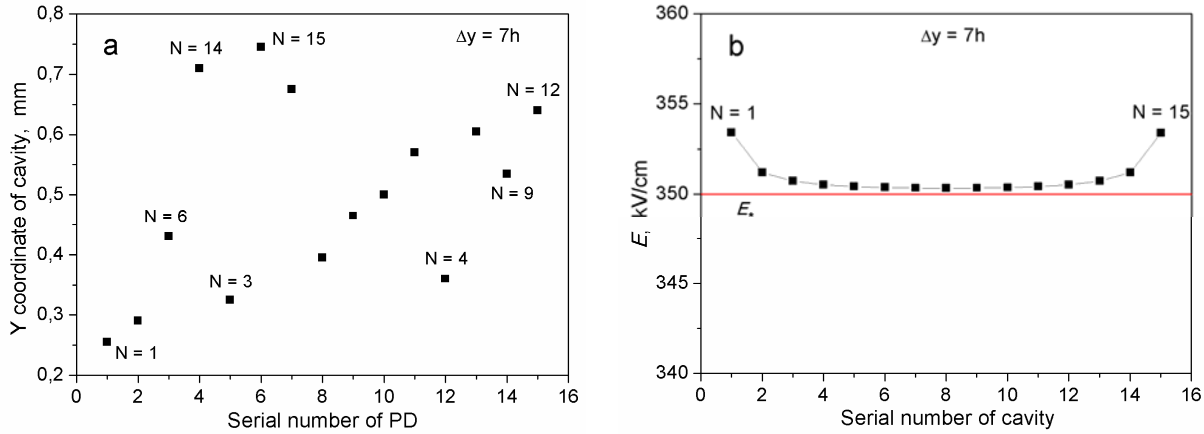

Figure 8. (a) The stochastic regime of partial discharges in the chain of cavities. (b) The values of electric field inside cavities before the first PD. $L=1$ mm. $E_*=350$ kV/cm. $\Delta y=7h$. $h=5$ μm. $\alpha=20$ cm/(kV·ms). Lattice size 200×200.

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