Journal of Electrostatics 94 (2018) 8–13

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

"Relay-race" mechanism of partial discharges in a long chain of cavities for stochastic nature of process

A.L. Kupershtokh*, D.I. Karpov

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

ARTICLE INFO

Keywords:
Electrostatics
Solid dielectrics
Partial discharges
Wave of partial discharges
Computer simulation

ABSTRACT

A stochastic model of partial discharges (PDs) inside a linear chain of gas cavities in condensed dielectrics is developed. The equations for electric field potential and electric charge transfer are solved together for dielectric with these inclusions. Computer simulations show the possibility of a "relay-race" mechanism of propagation of partial discharges in this chain of gas cavities even if the stochastic nature of partial discharge is taken into account. This mechanism can be realized if the distances between cavities are small enough and the dependence of probability function of partial discharges $r(E)$ on electric field strength is rather sharp. In this case, the wave of partial discharges can propagate along the chain of cavities. The PD waves can be initiated in the first cavity as well as in the last cavity in the chain. Occasionally, two PD waves can arise from the both edges of the chain. The sequence of partial discharges in the inclusions has a completely stochastic character for a weak mutual influence of cavities on each other.

1. Introduction

When a high voltage is applied to an interelectrode gap with a condensed dielectrics, the pulses of the electric current can be registered in the external circuit (partial discharges). The partial discharges (PDs) do not lead to the loss of the insulating properties of the dielectric as a whole. The frequency and magnitudes of PDs can be used to predict the possibility of a breakdown of the interelectrode gap. One type of partial discharges in condensed dielectrics is the electrical discharges inside small gas inclusions (voids in solid or bubbles in liquid dielectrics) [1,2].

The breakdown strength of gas inside the small cavities in solid dielectrics or inside the microbubbles in a liquid is much lower than that of the condensed matter. To start an ionization avalanche inside a cavity, it is necessary the sufficient value of electric field strength inside a cavity. This determines the threshold character of the partial discharge. The threshold character of electrical breakdown of dielectrics is well known and was observed in numerous studies [3–7]. Hence, to simulate the partial discharges, their threshold features should be taken into account. Moreover, the stochastic behavior of electrical breakdowns and partial discharges that is caused by appearance of initial electrons must be also taken into account.

To describe the main features of partial discharges, the method of equivalent electric circuit for a cavity was proposed in Ref. [8]. One of the first attempts to introduce the stochastic nature of PDs into this method was realized in Ref. [9]. Later, this approach was developed in Refs. [3,10,11]. However, all these studies did not take into account the spatio-temporal evolution of the electric field strength in the gap. Moreover, the classical capacitance model is practically insensitive to the position of a cavity inside the gap. The works [12–15] were devoted to the computer simulations of partial discharges in liquid and solid dielectrics where the electric field distribution was calculated at every time step. The partial discharges in coupled cavities (with close distance between them along an electric field line) were simulated in Refs. [13,14]. After the discharge in one cavity, the electric field strength inside the neighbor cavity sharply increased. Therefore, the increase of the probability of PD in the neighbor cavity was demonstrated.

In the present paper, the possibility of the propagation of a PD wave along a chain of gas inclusions is studied. Such chains of bubbles may occur at the boundaries of layers in a multilayer paper insulation. The chains of bubbles also arose during the decay of cylindrical channels of an incomplete electrical discharge after the termination of the previous voltage pulse [16].

A stochastic model of partial discharges (PDs) inside a linear chain of gas cavities in condensed dielectrics is developed. The partial discharges are studied in condensed dielectrics that fills the space between two flat electrodes. Two-dimensional computer simulations of partial discharges in a linear chain of such gas inclusions located in a condensed dielectric are carried out. The inclusions are placed along the electric field line at equally close distances from each other.

* Corresponding author.
E-mail address: skn@hydro.nsc.ru (A.L. Kupershtokh).

https://doi.org/10.1016/j.elstat.2018.05.002
Received 31 October 2017; Received in revised form 8 May 2018; Accepted 16 May 2018

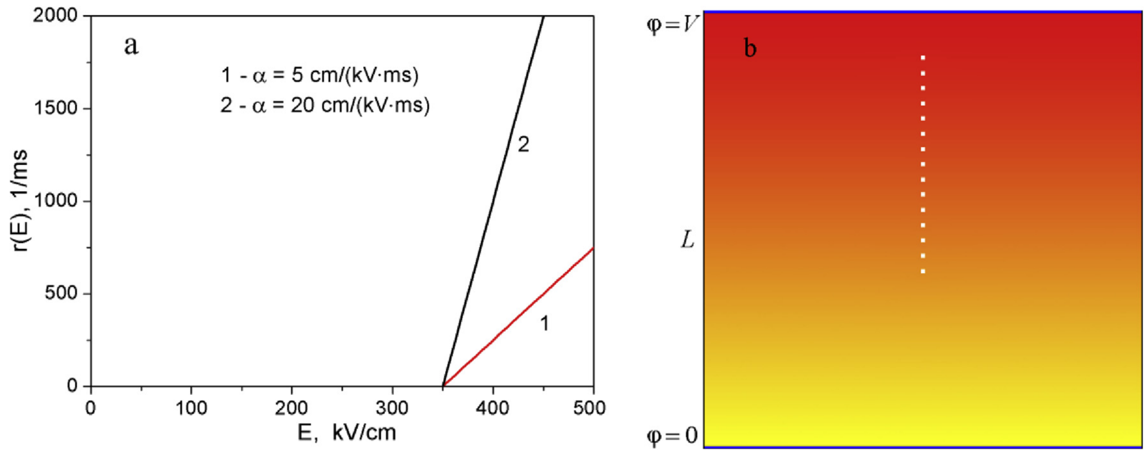

Fig. 1. (a) Probability function $r(E)$ for PD in a cavity. Curves 1 and 2 correspond to α= 5 and 20 cm/(kV·ms). (b) Chain of gas cavities in the solid dielectric. N = 15. L= 1 mm Δy = 6h.

The possibility of the wave of PDs that propagate along the chain of gas inclusions is demonstrated. In this case, the partial discharges occur sequentially in the inclusions one by one along the chain of these insulation defects. This interesting phenomenon can be named as a "relay-race" mechanism of propagation of partial discharges in the chain. For the "relay-race" mechanism, the streamers occur only inside the gas filled cavities but do not propagate in the condensed phase. There are several possible ways that can be used to observe this "relay-race" mechanism in experiments. The purpose of this article is to attract the attention of experimentalists to this phenomenon. 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. This mechanism differs from deterministic "hopping spread streamers" [17] that was simulated for three "bubbles" placed along electric field line in the condensed dielectrics.

2. Criterion of partial discharge in a gas cavity placed into condensed dielectrics

At the same size of gas 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.

In 1993 Biller [18] proposed a first stochastic criterion for streamer growth based on the idea of stochastic lag times t_i. The density distribution function was used 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 on the electric field strength. The random values of the stochastic lag times t_i can be calculated in accordance with the formula

$$t_i = -\ln(\xi_i)/r(E_i), \tag{2}$$

that is equivalent to the distribution function (1). Here ξ is a random number uniformly distributed in the interval from 0 to 1. The new segment of streamer structure was generated for which the stochastic lag time was minimal. This criterion was the first single-element criterion with physical time.

For streamer structures growth, the stochastic criterion MESTL (multi-element stochastic time lag) was proposed in Refs. [19,20]. Later we used this criterion to describe the occurrence of micro-discharges in gas cavities [13,14,21]. For all nonconducting cavities, the values of stochastic lag times (2) were calculated. The stochastic criterion MESTL assumes that the micro-discharges occur during the current time step Δt in all cavities for which the conditions $t_i < \Delta t$ are satisfied.

The function $r(E)$ depends on the local electric field inside a gas cavity. For small time step $\Delta t << 1/r(E)$, the probability of a micro-discharge in a cavity is approximately equal to $f \approx r(E)\Delta t$. The typical value of time step in simulations is chosen equal to $\Delta t = 10^{-4}$ms for which the probability is small $f << 1$.

When a linearly rising voltage is applied to a discharge gap, a scatter in discharge inception voltage due to the statistical time lag is observed. In works [7,22], it was obtained that the probability of the discharge initiation is proportional to overvoltage $\Delta V = (V - V_*)$, where V_* is the critical value of the breakdown voltage of a gap. Here, we also assume that the probability of partial discharge is proportional to overvoltage ΔV for cavities of equal size.

The function $r(E)$ that describes the threshold character of partial discharges has the form [7].

$$r(E) = \begin{cases} 0 & \text{for} \quad E \le E_*, \\ \alpha(E - E_*) & \text{for} \quad E > E_*. \end{cases} \tag{3}$$

Here, E_* is the threshold value of electric field above which PDs in the gas inclusions are possible. The coefficient α is the slope of the function $r(E)$. The probability of breakdown increases sharply in a narrow range of the electric field at $E > E_*$ [4]. The threshold breakdown voltage V_* of air in a void of size d~10 μm at pressure 1 atm is approximately equal to 350 V [6], which corresponds to the threshold field $E_* \approx$ 350 kV/cm. The functions $r(E)$ are shown in Fig. 1a for different values of α.

During the microdischarge inside a cavity, the electric field decreases there. If its value becomes less than some critical value E_{cr}, the energy release reduces and become small in comparison with the energy loss. Hence, a complete decay of plasma inside cavity occurs, and the microdischarge terminates. We assume that the conductivity after this moment becomes equal to zero.

3. Electric field values in gas cavities spaced in condensed dielectrics

The PDs in a chain of several identical gas inclusions equally spaced along the electric field line in condensed dielectric between two flat electrodes is studied (Fig. 1b). For 2D simulations, we use the lattice size 200 × 200 (40000 nodes). The distances between all adjacent inclusions are equal to Δy.

The form of cavity and conductive structure arising in a cavity that we used in simulations are shown in Fig. 2 [13]. Cavity size is $2h \times 2h$. Here, h is the computational lattice spacing. If the value of projection of electric field strength on a bond between nodes in gas phase become greater than critical value E_*, the all structure become conductive. As the first approximation, the conductivity of the elements of the conductive structure is assumed to be equal to a constant value σ during the short period of a partial discharge in a cavity.

The distribution of the electric field strength in the whole region