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Simulation of Partial Discharge Activity in Solid Dielectrics under AC Voltage

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Abstract—A model describing the main stochastic properties of partial discharges (PDs) under alternating-current (ac) voltage is proposed. PDs corresponding to microdischarges in small voids randomly distributed in a solid insulator are considered. The PD initiation is simulated using a stochastic criterion. The decay of plasma in a void and the resulting drop in the conductivity until complete vanishing are described using a simple threshold criterion. Computer simulations show that, upon the application of ac voltage to the electrodes, short current pulses are observed in the external circuit, with each peak corresponding to a microdischarge (PD) in the void.

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As is known [1–3], there are three main types of partial discharges (PDs): (i) microdischarges in small voids, which always exist both at the surface of electrodes and in the volume of insulators; (ii) breakdowns along the boundaries between two insulators (typically, along the solid insulator–gas interface); and (iii) PDs in the channels of branched structures (streamers) propagating in the volume of a dielectric medium. The second and third PD types can be considered as incomplete breakdown, since the insulating properties of a dielectric are violated. The most complete information is provided by the so-called "phase resolved data," which have been determined for PDs of all types in numerous experimental investigations. Several works were devoted to the simulation of PDs of the third type [4–7].

This Letter considers only PDs of the first type, which take place at relatively low voltages. Small gas-filled voids present in solid dielectrics strongly influence the electrical strength of such materials and, hence, the lifetime of equipment, since the electric strength of a gas filling the voids is usually much lower than that of the solid dielectric. In addition, the electric field strength inside a void is higher than that outside. The probability of microbreakdown in a void depends on the local internal field. Shortly after the microbreakdown, the discharge in the void exhibits quenching because of charge accumulation on the void surface.

The behavior of voids occurring in depth of a solid dielectric is frequently studied using the method of an equivalent circuit (Whitehead method), which is based on the consideration of discrete capacitors [8–10].

The simplest criterion of microdischarge initiation in a void is offered by the well-known field threshold criterion (FTC) formulated as $E > E_*$, where E is the local electric field strength and E_* is the threshold value. This criterion has a deterministic character. However, PDs have a substantially stochastic nature, which is manifested by the random distribution of the moments of PD onset and by strong variation of the amplitudes of narrow current peaks observed in the external circuit. Obviously, such processes have to be modeled using adequate methods.

One of the first attempts at Monte Carlo modeling of PDs using an equivalent circuit of a void was undertaken by Hikita et al. [9]. The probability of PD initiation was assumed to be proportional to the overvoltage. Subsequently, several other attempts were made to model PDs with allowance for their stochastic nature [11–15]. However, these investigations did not take into account the spatio-temporal evolution of the electric field. Thus, all these models did not consider intermediate positions of the void and ignored the possible influence of a microdischarge in one void on the processes in other voids.

Recently, Wu et al. [16] took into account the electric field distribution by solving the Poisson equation for a single disk-shaped void. It was assumed that a microdischarge inside a rather large void is inhomogeneous and consists of branching streamer channels. Indeed, experiments [17] showed that the discharge pattern in a flat void with a height on the order of 1 mm and a diameter of 40 mm represented hundreds of bright spots with a characteristic size on the order of 1 mm, which were uniformly distributed over the void cross section.

In this Letter, we describe a new approach, which makes possible modeling of the main stochastic properties of alternating-current (ac) PDs taking place in voids of compact shape with a characteristic size below 1 mm. The proposed model involves direct calculation of the electric field distribution between electrodes in a dielectric containing voids. In addition, the stochastic character of the process of PD initiation in voids is described in terms of the modern multielement stochastic time lag (MESTL) criterion [18, 19]. According to this, a stochastic time of microbreakdown delay for all voids occurring in a nonconducting state is calculated using a probability density distribution function $F(t_i) = r(E)\exp(-r(E)t_i)$, which is equivalent to the random quantity $t_i = -\ln(\xi_i)/r(E)$ (here and below, ξ is a random value uniformly distributed on the interval from 0 to 1). During a time step Δt, microdischarges occur in all voids for which the stochastic time lag is smaller than the time step ($t_i < \Delta t$). The breakdown probability function $r(E)$ depends on the local electric field strength in a void and it must rather sharply increase to provide an adequate qualitative description of the quasi-threshold character of microdischarges. In this study, we adopted the law $r(E) = BE^4$. In the general case, this function can also depend on the void size and the gas pressure inside the void. It was assumed that, immediately upon microbreakdown in a void, the gas filling this void converts into a conducting plasma with constant conductivity σ_0.

There are dissipative processes (radiation, erosion of the void wall, etc.) that lead to the decay of plasma. At present, it is rather difficult to provide a strict description of these phenomena. For this reason, we used the following simple model. When the electric field in a void decreases below a certain critical level (E_{cr}), the microdischarge ceases to operate and the conductivity vanishes (becomes equal to zero). It was assumed that plasma exhibits complete decay, since the deposited energy is lower than the lost one. Thus, the proposed model qualitatively describes the pulse character of the conductivity.

In order to calculate the distribution of the electric field potential φ and the field strength $\mathbf{E}$ in the region between electrodes at each time step, we jointly solved the Poisson equation and the charge transfer equations:

$$\begin{gathered}\operatorname{div}(\varepsilon\nabla\varphi) = -4\pi q, \quad \frac{\partial q}{\partial t} = -\operatorname{div}\mathbf{j}, \\ \mathbf{j} = \sigma\cdot\mathbf{E}, \quad \mathbf{E} = -\nabla\varphi.\end{gathered} \tag{1}$$

Here, ε is the permittivity, q is the charge density, σ is the conductivity, and $\mathbf{j}$ is the current density (σ and $\mathbf{j}$ were assumed to be nonzero only inside voids). The problem was solved in a two-dimensional rectangular region, for which the boundary conditions were set as follows. The potential φ was set zero on the bottom electrode and had a constant value (applied voltage V) on the top electrode; along the x axis, the boundary conditions were periodic.

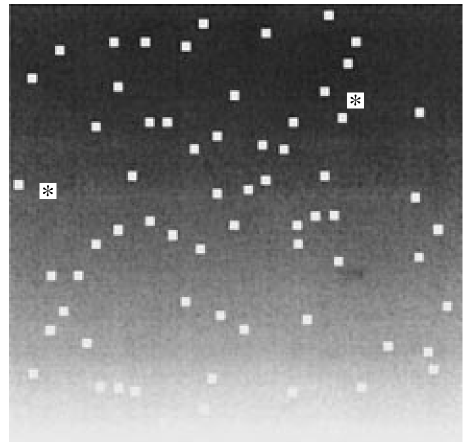

Fig. 1. The arrangement of voids in a typical variant of simulations. The potential varies from $\varphi = 0$ at the bottom electrode to $\varphi = V_0$ at the top electrode, as indicated by gray levels ($N = 68$; 100×100 grid).

The time-implicit finite-difference equation of charge transfer is as follows (in short notation):

$$q^{n+1} = q^n + \operatorname{div}(\sigma\nabla\varphi^{n+1})\Delta t, \tag{2}$$

where Δt is the time step. This equation was substituted (as proposed in [18]) into a finite-difference approximation of the Poisson equation for the upper temporal layer. The resulting equations

$$\operatorname{div}(\varepsilon\nabla\varphi^{n+1}) = -4\pi(q^n + \Delta t\operatorname{div}(\sigma\nabla\varphi^{n+1})) \tag{3}$$

were solved by iterations with respect to $\varphi_{i,j}^{n+1}$ for the next temporal layer. Then, the new values of the charge density $q_{i,j}^{n+1}$ were calculated using Eqs. (2). This scheme ensures charge conservation and is more stable than the scheme explicit in time.

We have considered a system of voids randomly distributed in the volume of a solid dielectric between two (top and bottom) plane electrodes (Fig. 1). The alternating voltage $V = V_0\sin(2\pi ft)$ applied to the electrodes had an amplitude V_0 that was sufficient to induce PDs. The calculations were performed on a 100×100 grid; accordingly, the distance L between electrodes is equal to one hundred grid mesh size. Numerical calculations were performed for the following values of parameters: $f = 50$ Hz; $\varepsilon = 2$; $B = 10^5$; $E_{cr} = 0.1$ (here and below, we use a system of arbitrary units for the voltage and current).

In the course of calculations, we recorded the temporal evolution of all PDs in the voids, their positions in the interelectrode gap, and the current in the external

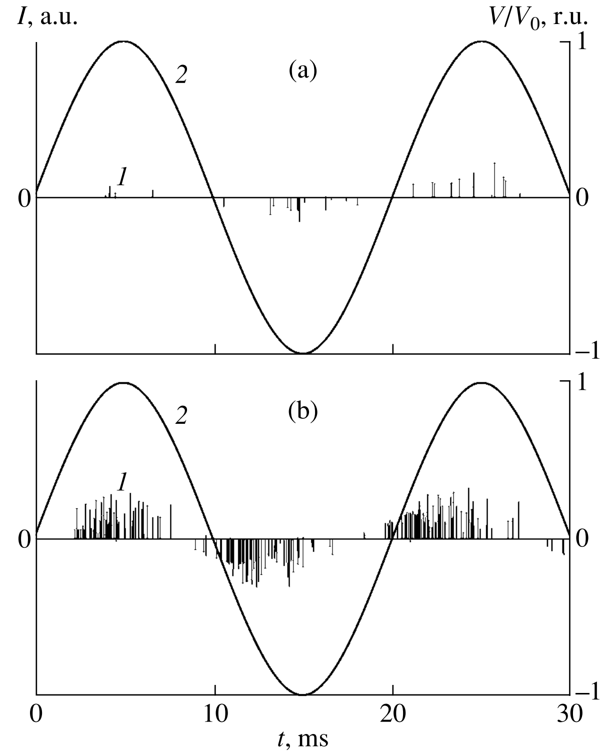

Fig. 2. The pattern of PDs during three voltage halfwaves (pulses *1*). Solid curves (*2*) show the applied voltage: (a) $V_0 = 10$ ($N = 70$); (b) $V_0 = 20$ ($N = 75$).

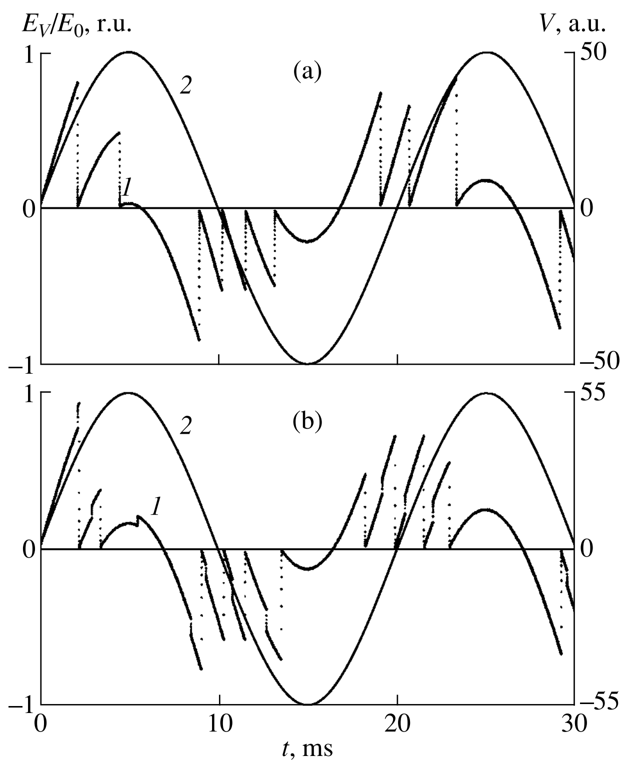

Fig. 3. Time variation of the applied voltage (curves *2*) and the relative electric field strength (curves *1*) (a) inside a single void occurring ($V_0 = 50$) and (b) inside one of the two voids closely spaced in the direction along the field ($V_0 = 55$) in a solid dielectric ($\varepsilon = 2$).

circuit. Figure 2 shows the typical pattern of narrow peaks (spikes) appearing with every microdischarge in voids of the solid dielectric. At some time after the microbreakdown, the discharge in the void exhibits quenching because of charge accumulation on the void surface, which leads to a decrease in the field strength inside the void. Such a current spike was observed at the onset of every microdischarge. An increase in the applied voltage amplitude led to a corresponding increase in the rate of PDs (Fig. 2b) and in the amplitude of current spikes. It should be noted that most of PDs during the first voltage halfwave took place in the voids containing no free surface charges. For this reason, the corresponding phase distributions of PDs differ from those observed in the subsequent halfwave. The onset times and amplitudes of the PDs in the pattern provided by the computer simulation actually exhibit a stochastic character. In Fig. 1, two voids (indicated by asterisks) occasionally occurred simultaneously in the conducting state. Evidently, the corresponding current spike amplitude was greater than average.

In order to study the process in more detail, we have also simulated the behavior of a single void in an applied electric field. Figure 3a shows the time variation of the electric field inside a void. Prior to the first microdischarge in the void, the electric field strength is somewhat greater than the current value of the unperturbed electric field between electrodes ($E = E_0\sin(2\pi ft)$, where $E_0 = V_0/L$ is the electric field amplitude in the solid dielectric) because $\varepsilon > 1$ and the void shape is close to compact. For example, the well-known result for the electric field inside a spherical uncharged cavity is $E_V = 3E\varepsilon/(2\varepsilon + 1)$. If the voltage was sufficiently high, but still below the characteristic breakdown voltage for the solid dielectric, microdischarges in the void were initiated several times per period (Fig. 3a). The values of electric field strength inside the void immediately before each discharge exhibited a certain random scatter; accordingly, the current peak amplitudes also changed in a stochastic manner. Figure 3b shows the pattern of electric field variation inside one of the two voids closely spaced in the direction along the field. Upon a PD in one of the voids, the electric field in the other void typically grows, which leads to an increase in the probability of breakdown in this void.

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