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Stochastic Modeling of Discharge in Long Gaps Under Positive Impulse Voltage

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ABSTRACT

In the present paper a stochastic model is used for the simulation of positive discharges in long gaps, under the application of impulse voltage. The model is taking into account the existence of two phases of different conductivity during the propagation of the discharge, namely streamer and leader. Qualitative results concerning the time of inception of first corona t_I and the time to breakdown t_B, together with patterns of the discharge propagation along the gap were obtained.

KEY WORDS: Breakdown, modeling and simulation, long gaps, impulse voltage

1. INTRODUCTION

Dielectric breakdown in gases is of great importance for power energy systems, because it defines the limitation of insulation of many electrical apparatus. Discharges in gases occur in a variety of different forms. The physical mechanism that governs the discharge depends mainly on kind of gas, gap distance, atmospheric pressure and on applied voltage.

Stochastic growth models have been developed for simulation of breakdown process in gaseous, liquid and solid dielectrics [1-11]. Inception and growth of streamers and leaders are closely related to a function of local electric field i.e. $r(E)$ [1-3, 6, 9]. Pietronero and Wiesmann have shown how the stochastic growth models are related to the microscopic mechanism of dielectric breakdown [12]. By using these models one can simulate a very complex physical phenomenon such as dielectric breakdown in a rather simple way. The conductive patterns obtained in several of the pre-mentioned works are in good agreement with the shape of discharge patterns observed in experiments. However in most of the pre-mentioned works, the authors have not investigate if it is possible to obtain, using their models, data like breakdown voltage, times to breakdown, velocity of propagation etc.

The stochastic model used in this paper has been developed specially for the case of long gaps. It is interesting, particularly, to investigate if this class of models can be applied in order to describe the random distributions of breakdown voltage, statistical time lag, velocity of propagation etc. In the present paper some qualitative results concerning distribution of the time of inception of first corona and distribution of the time to breakdown have been obtained, under the impulse voltage with short rise time (1.2/50). Qualitative results can also be obtained using any kind of voltage, like DC, AC etc.

2. BREAKDOWN IN GASES

Spark discharge occurs at voltages above the breakdown level and at pressures equal to or greater than atmospheric in gaps of 1 cm or longer, that is, if $pd > 10^3$ Torr· cm. When the distance between electrodes is greater than 5 cm, the breakdown occurs via the growth and propagation of streamers. Streamers are thin and weakly ionized channels that propagate through the gap, following the positively charged trail left by the primary avalanche.

Loeb, Raether and Meek et al developed the theory of streamer in [13-15]. Above a critical voltage the streamers start to propagate along the gap. When they reach the opposite electrode breakdown occurs. However, streamers themselves cannot reach the opposite electrode in long gaps. As the streamers propagate along the gap, the electric field ahead the streamer tips reduces and streamer propagation eventually stops. In this case, the breakdown occurs via the growth of a leader from one electrode to another. Leader is a thin ionized channel with magnitude of conductivity higher than those for streamer channels by several orders. The leader channel 'extends' the tip of the electrode by shifting a point of high potential towards to the opposite electrode. Thus, the occurrence of breakdown is possible in long gaps with relatively low mean electric field between the electrodes. Breakdown occurs when the streamers reach the opposite electrode

3. STOCHASTIC MODEL OF BREAKDOWN IN LONG GAPS

The existence of two types of channels of different conductivity during the propagation of the discharge requires the development of a model with two criteria, the first for the streamer growth and the second for the streamer-to-leader transition. For the simplification of the model, some assumptions were made. First, it was assumed that the streamer does not influence the distribution of the electric field because of its low conductivity. Second, the leader is considered to be equipotential due to its high conductivity [9, 10]. Thus, the electric field is calculated by solving the Laplace equation with boundary conditions on the electrodes and leader structure.

A two-dimensional square lattice is introduced in the space between the two electrodes (fig. 1). A new streamer bond is added to the structure in accordance with a certain stochastic rule, for example, if the condition

$$E_i > E_* - \delta \tag{1}$$

is fulfilled. Here E_i is the mean value of projection of electric field onto the corresponding lattice bond. The parameter E_* depends on the properties of a particular dielectric. The random variable ä is assumed to take into account the uncertainty in the value of E_* due to several reasons, for example, inhomogeneities of the dielectrics, thermal and other fluctuations, including the influence of external conditions (such as air density, humidity, atmospheric ionization, etc).

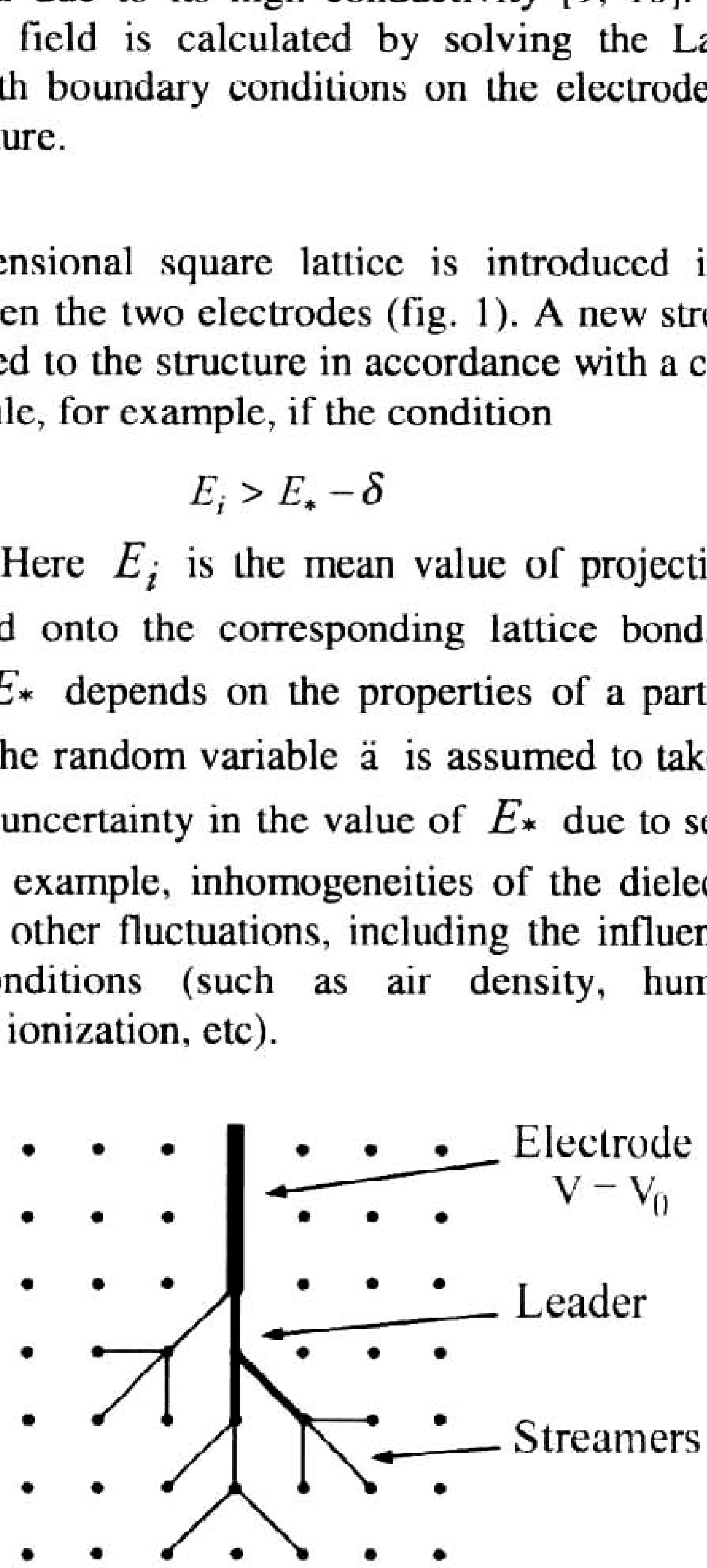

Figure 1. Growth of the conductive structure on the lattice. Thin lines illustrate streamers while thick lines illustrate leaders.

After the voltage is applied to the gap, new streamer bonds can be added to the structure at each time step (fig. 1) and, hence, the discharge propagates in the space. After formation of the streamers, other physical phenomena take place, leading to the formation of highly conductive channels called leaders. The streamers normally arise from a common root called the stem. Because of the electric current flow inside the streamers, the temperature of plasma inside stem is increasing that leads to the liberation of electrons from negative ions appeared earlier [16-18]. The increase of the conductivity results in the increase of the current flow and, hence, the transition of plasma from lowly conductive phase (streamer) to highly conductive phase (leader) occurs.

For the calculation of the energy released, a somewhat simplified approach was used. If we consider a small segment of the streamer as a cylinder with length h, cross section S and conductivity ó, then the total energy released by time t is

$$W = h \cdot S \cdot \sigma \cdot \int_{t_i}^{t} E^2(t)\, dt \tag{2}$$

where t_i is the time when this bond arose. Thus, if the released energy is greater than a certain critical value, a new leader segment is formed.

4. CALCULATIONS

The potential of electric field φ is calculated at every time step by solving the Laplace equation

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} = 0 \tag{3}$$

with boundary conditions on the electrodes and the leader structure. A standard iterative method is used for calculation of potential for all lattice nodes of two-dimensional square lattice. The simulation was carried out in a rectangular area on lattices up to 100 × 100. A positive impulse voltage with short rise time is applied to a rod–plane electrode system (fig. 2). The mean value of electric field projection between two neighbor nodes of the lattice (for example i, j and i, j–1) is calculated as follows

$$E_{i+1/2,j} = \frac{\varphi_{i,j} - \varphi_{i,j-1}}{h} \tag{4}$$

where h is the distance between these nodes. At every time step, new streamer bonds can be added to the structure, and some of the existent streamer bonds can transform to new leader segments.

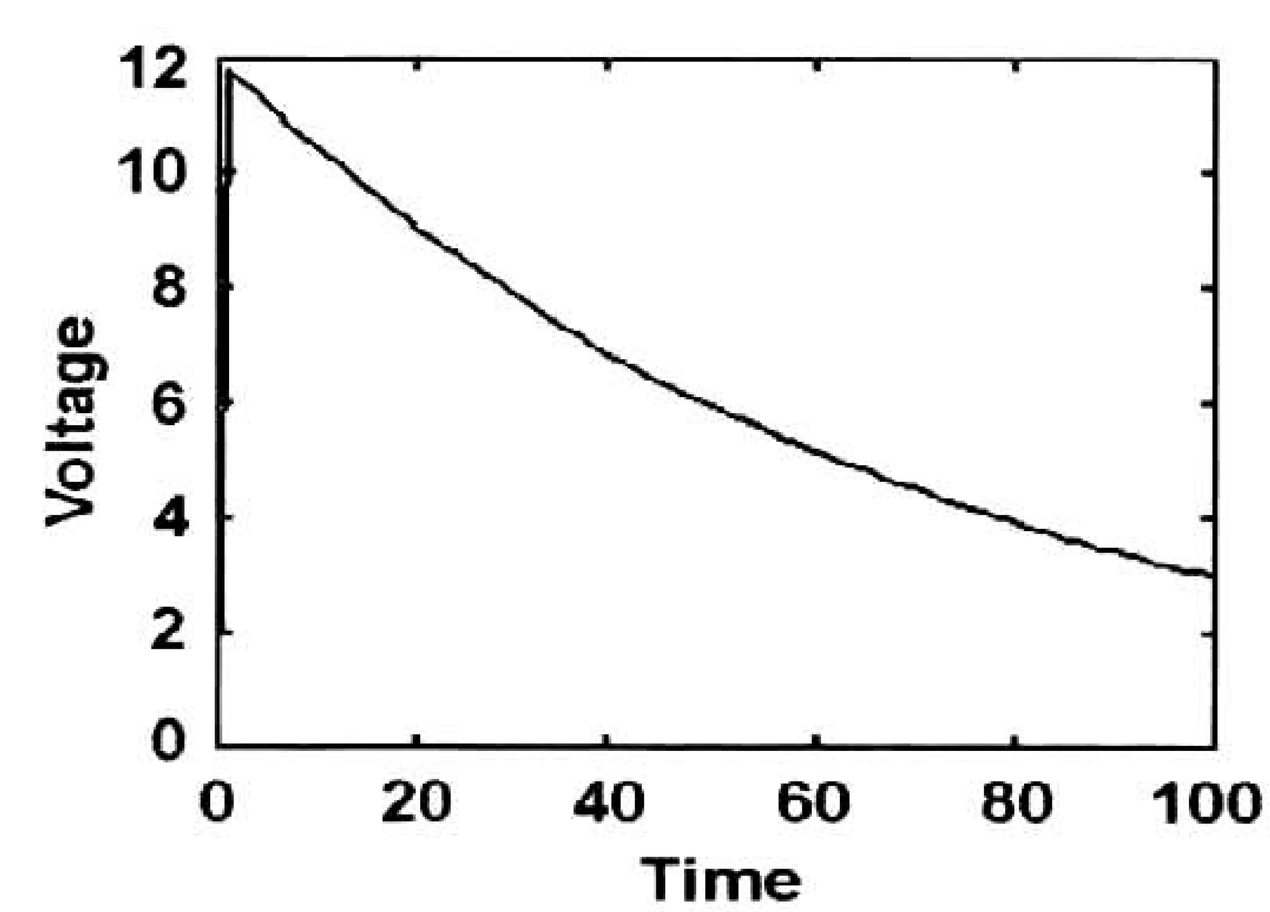

Figure 2. Impulse voltage with short rise time.

In all simulations arbitrary units were used. To introduce physical units it is necessary to choose a reciprocally complementary set of scales for space, voltage and time. These three scales can be determined from reliable experimental data for each particular case that is to be simulated.

5. RESULTS

One of the conductive patterns of discharges obtained for a rod–plane configuration by using the stochastic model is shown in figure 3. Thick lines show leader structure, while thin lines show streamers. It is convenient to use the value $E_0 = V/d$ where V is the applied voltage and d is the gap distance. In fact, E_0 is the mean value of electric field along the gap.

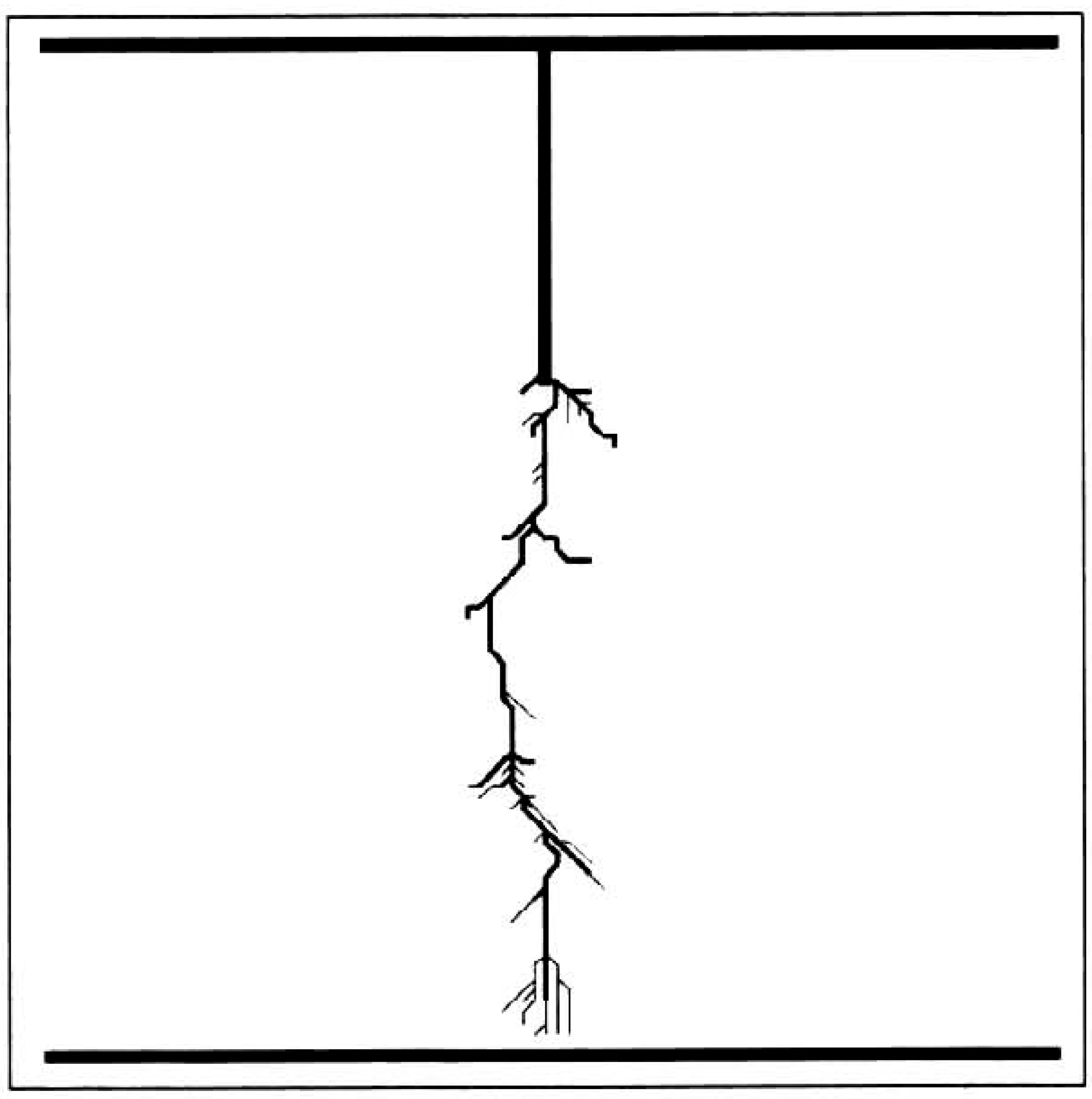

Figure 3. Typical pattern of discharge obtained using stochastic model. $E_0 = 0.2$, $E_* = 1$ and $g = 0.08$.

The histogram of the times to breakdown t_B is shown in figure 4. The results were obtained at the time step τ = 0.05. The number of trials was $N_0 = 40$.

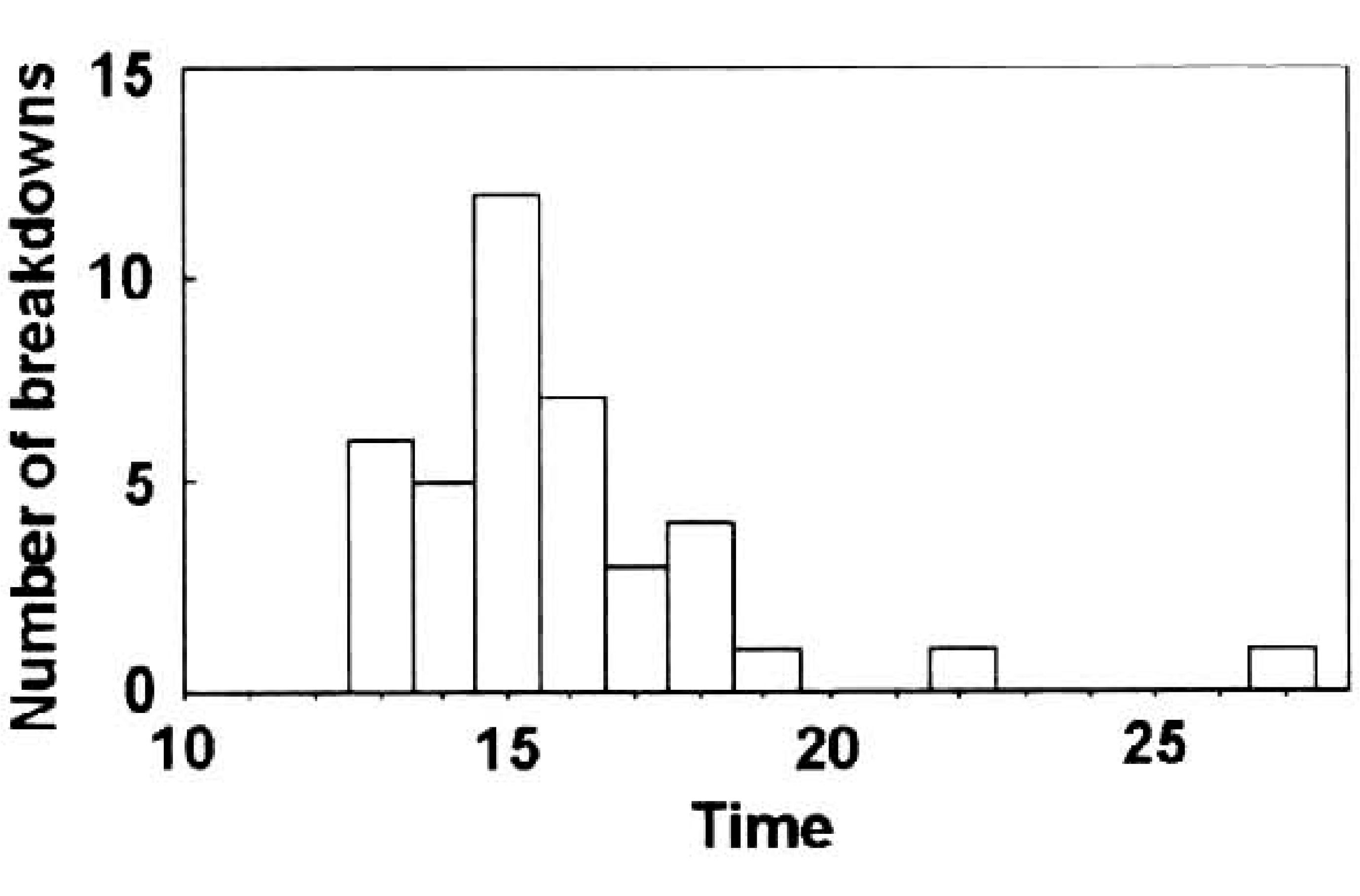

Figure 4. Distribution of times to breakdown. $E_0 = 0.2$, $E_* = 1$ and $g = 0.09$.

The distributions of times of first corona inception t_I for different values of the parameter g are shown in figure 5. The number of trials was $N_0 = 74$ (a) and 70 (b). The time step was $\tau = 0.005$.

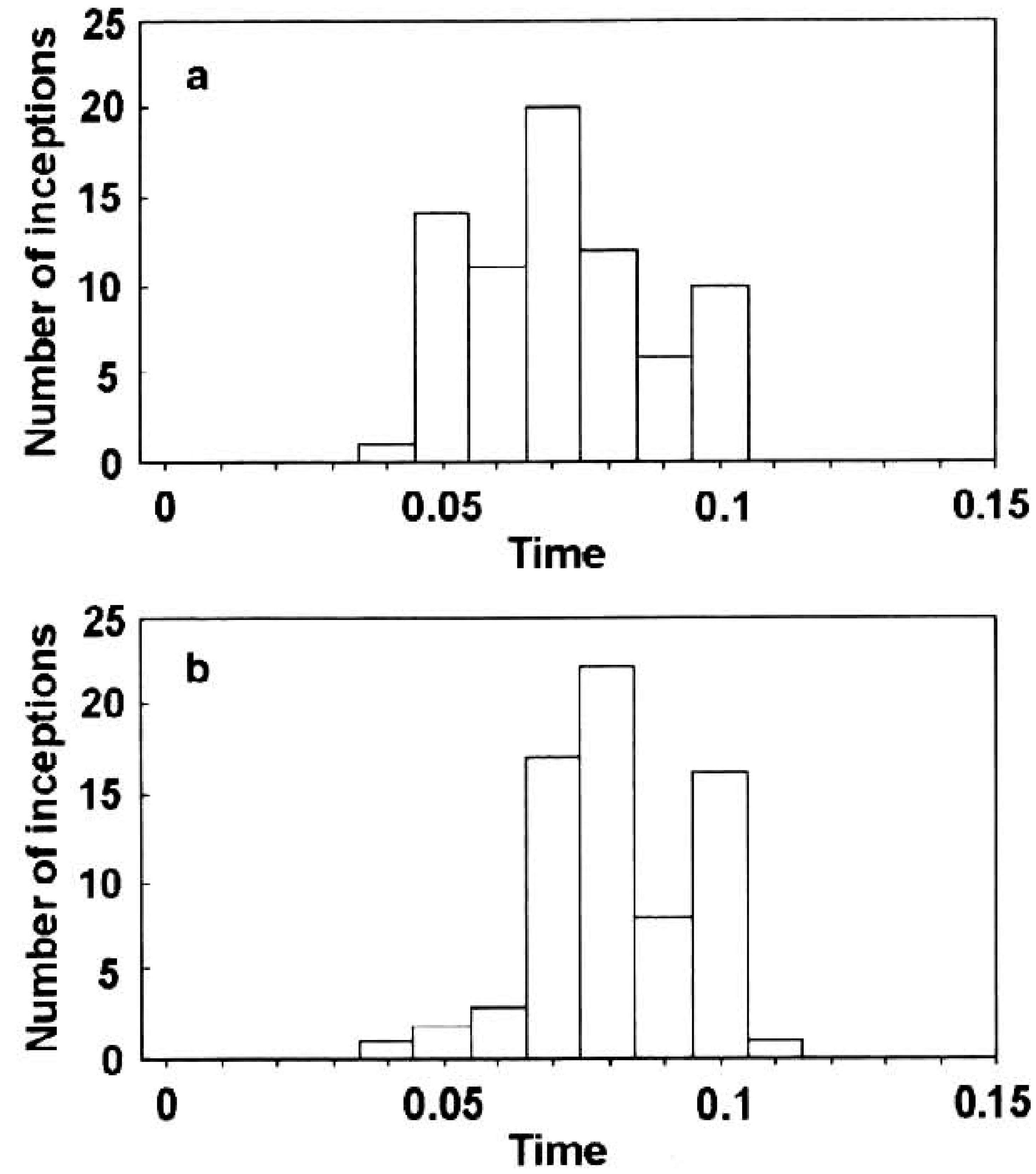

Figure 5. Distribution of the inception times of first corona. $E_0 = 0.2$, $E_* = 1$, $g = 0.09$ (a) and 0.07 (b).

6. CONCLUSIONS

The discrete stochastic model used in this paper for simulation of breakdown in long gaps under positive impulse voltage describes main features of breakdown such as statistical time lag, random place of origin, asymmetry and non-reproducibility of the conductive structure, etc. It can be used in principle for the determination of the V_{50} breakdown voltage for certain geometry of a gap.

This requires the calibration of the parameters of the model, together with the introduction of some improvements. The first way is to introduce a constant voltage drop along the streamer and leader channels [7, 8], because in reality leader channel have a finite conductivity, hence, it is not equipotential. The second way is to introduce a finite conductivity along streamer and leader channels and to calculate the electric field by solving Poisson's equation together with the equation of electric charge flow along the branches of conducting structure [3-6]. In this case streamers influence the distribution of the electric field as in reality, because of the positive space charge accumulated in their heads.

A next point that we have to pay attention to, is the criterion for streamer-to-leader transition. The necessary energy for Joule heating of the gas is transferred in a more complex way than it is supposed in equation (2). In any case the critical energy can be calculated, because it is known that the transition occurs when the gas heats up to temperature about 1500 K [16-19].

After the introduction of listed above improvements, it is possible to use proposed model for the determination of breakdown voltage distribution under applied voltage of any shape (DC, AC, impulse, etc).

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