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# Simulation of Prebreakdown Phenomena in Air Gaps of Rod Plane Configuration of Electrodes

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*Abstract:* - In the present paper the simulation of the streamer propagation along a gap of a rod plane configuration of electrodes is taking place. The gap length varies between 5 to 20cm and a DC voltage of positive polarity is applied to the gap. For the simulation of the streamer propagation a stochastic model based on Biller's criterion for the creation of a new bond to the conductive structure is used. The simulation is realized with the usage of a square lattice of points that represent the electrodes and the area between them, that is the dielectric. Streamers propagate from the anode towards the cathode in a stepwise manner, by adding a new point to the conductive structure in every iteration of the computer program. Numerical results concerning the minimum breakdown voltage of the gap for different distances between the electrodes were obtained. The results were compared with experimental data obtained from the international literature.

*Key-Words:* - Air, Breakdown, Simulation, Stochastic Model, DC Voltage

## 1 Introduction

Breakdown in solid, gaseous and liquid dielectrics are of great importance for Electrical Engineers, which are involved in designing of power systems and electrical apparatus, because it determines the limitations of insulation of cables, transformers, electrical rotating machinery etc. The mechanism of electrical breakdown depends on the nature of the dielectric but in any case is a physical phenomenon with complex evolution.

Especially for the gaseous dielectrics two different mechanisms of breakdown exist. In very short gaps at low pressures, approximately at $pd < 200 Torr \cdot cm$, the breakdown is based on the multiplication of avalanches via secondary cathode emission (Townsend Mechanism of Breakdown). In gaps greater than 1cm long and in pressures above atmospheric, that is $pd > 10^3 Torr \cdot cm$, the mechanism of breakdown is based on the development of thin, weakly ionized channels of plasma called streamers (Streamer Mechanism of Breakdown) [1-3]. In air gaps of many meters and in lightning discharges the breakdown occurs via the growth of the so-called leader, which is also an ionized channel but with a conductivity orders of magnitude higher than the conductivity of streamer channel.

The boundary values of the $pd$ at which the above mentioned breakdown mechanisms replace each other are not yet precisely estimated. According to [1] the transition from the Townsend mechanism to the streamer mechanism in air occurs at $d \approx 5cm$. On the other hand in long air gaps, greater than 50 cm approximately, breakdown occurs via the formation of leader channels in the gap. In this case streamers also exist, starting from the head of the leader channel, which acts like a metallic tip.

In the present paper the simulation of prebreakdown phenomena in air gaps is taking place, in distances between anode and cathode from 5cm up to 20cm, where the Streamer Mechanism of breakdown is predominant. A stochastic model is used for the simulation of the streamer propagation along the gap.

Stochastic models are widely used to simulate the propagation of streamers and leaders before breakdown in solid, liquid and gaseous dielectrics. Niemeyer, Pietronero and Wiesmann introduced the first stochastic model in 1984 [4], (the so-called NPW model). In this model for the first time the probability of streamer growth $p$ was related to the local electric field as $p \propto r(E)$. The growth probability function was of power – law form $r(E) \propto (E/E_*)^n$. In a later work [5] Pietronero and Wiesmann tried to establish the relation between the physical mechanisms of breakdown in dielectrics with the NPW model. Since then, several other authors proposed either completely new models or modifications to the basic NPW model [6-12].

The main disadvantage of the pre-mentioned models is that their parameters took arbitrary values and thus most of them are incapable of giving any results concerning actually measurable magnitudes like breakdown voltage, velocity of streamer propagation etc. In order to purchase numerical results of practical interest, stochastic models with better-defined parameters should be developed. Towards this direction, special efforts were taken in order to ensure that the proposed model in this paper was in correspondence to physical dielectric breakdown, taken of course into account the restrictions, which are imposed by the nature of a stochastic model.

## 2 Principles of the model

Stochastic models are capable of reproducing the course of the streamer propagation by using some special rules, which are based on the probabilistic nature of the streamer advancement through the gap. For the development of the model presented in this paper the rules, which govern the growth of the discharge pattern (i.e. the streamer), were the following:

1) The simulation is taking place in a two dimensional square lattice of points. Some of the points represent the electrodes, while the others represent the dielectric.
2) The discharge pattern grows in a stepwise manner. The pattern consists of points, which are connected with thick lines called bonds.
3) At each step only one bond is added to the discharge pattern, linking a point of the pattern with a new point. From this moment the new point is considered to be a point of the pattern.
4) The electric potential of all points of the lattice that belong to the dielectric, is calculated by solving the Laplace equation with the boundary conditions on the electrodes and the discharge pattern.

The selection of the new point, which will be added to the discharge pattern, is a crucial part of the computational process because it determines the direction of propagation of the pattern. The procedure we used includes three steps.

The first step was to determine all the possible directions for the propagation of the discharge pattern. The directions were chosen on the basis of local electric field, i.e. the electric field between a point that belongs to the discharge pattern and the adjacent points that belong to the dielectric. If the local electric field $E_{loc}$ was greater than a threshold value $E_{th}$:

$$E_{loc} > E_{th} \quad (1)$$

the direction was chosen as a possible one for the propagation of the pattern at the current iteration of the computer program.

The second step was to apply to each possible direction a characteristic time for the growth of a new bond, which is equivalent to the necessary time for the propagation of the discharge pattern from one point of the lattice to another. This time was firstly introduced by Biller [13], and it was named ‘physical time’. Biller considered the process of the bond growth as a stochastic process, namely a Poisson random event. A stochastic bond growth time τ can then be calculated from this probability distribution with the help of a random number δ uniformly distributed in the unit interval:

$$\tau = -\ln(\delta) / r(E) \quad (2)$$

where r(E) is a field depended growth rate function. This function is equivalent to the mean value of the distribution and Biller was assumed arbitrary power-law dependence:

$$r(E) = A \cdot [E_{loc} / (U/d)]^n \quad (3)$$

In equation (3), the parameter A is a constant with dimension 1/sec, $n$ is a number that controls the variation of the growth rate with the electric field, U is the applied potential at the anode and d is the gap distance. Parameter A can be calculated theoretically and during the simulations took the value $3.7 \times 10^5$ $sec^{-1}$. After the calculation of the growth time for each candidate bond, the computer program identifies the ‘winning’ bond defined by τ = minimum. The winning bond is added to the discharge structure.

With the creation of the new bond the procedure already mentioned, is repeated again, starting a new cycle of calculations, taking into account the evolution of the discharge pattern. The simulation terminates when the pattern reaches the cathode or when the local electric fields at the streamer tip drops below the threshold value $E_{th}$.

The introduction of the stochastic features in the calculation of the growth time of the new streamer segment can be justified as follows. If we considered that photoionization [14-15] is the main mechanism of the generation of seed electrons for the creation of secondary avalanches, we may assume that they are emitted and absorbed in a random manner; hence situations are possible in which a new predominant

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direction for the streamer propagation appears even in areas of a relative low electric field. The random appearance of seed electrons is a likely mechanism of the generation of experimentally observed zigzag streamers and spark channels.

## 3 Results

The simulation was carried out in a two dimensional rectangular area, with a point to plane electrode configuration. The cathode (plane) was at an electric potential of $\varphi = 0$ while the anode (rod) was at an electric potential of $\varphi = V_0$. The lattice, which was used, varied from 150x150 (5cm gap space) up to 300x300 (20cm gap space). The dimension of the lattice varied in order to maintain constant (equal to 0.1cm) the distance between two adjacent points of the lattice in x and y direction. The length of the rod was also constant during the simulations and equal to 10cm.

The stochastic model was used for the determination of the minimum breakdown voltage of the gap but it is also capable for the determination of the mean velocity of streamer propagation. As it was expected the results of the simulation were greatly affected by the values of the parameters $E_{th}$ (threshold value of electric field), $E_S$ (voltage drop along the channels), A and n (parameters of equation 3). In Fig. 1 and 2 different streamer patterns, which the model created for different values of the parameters, are illustrated.

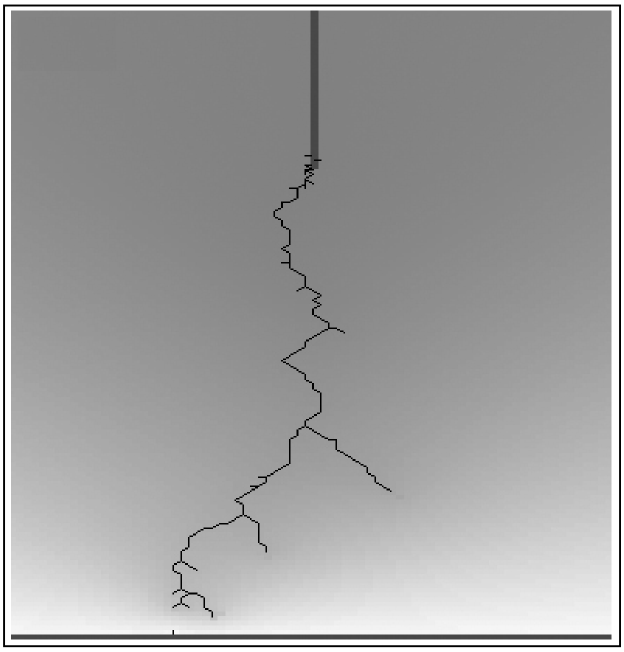

Fig.1 Streamer pattern obtained from the simulations - $E_{th}$=26kV/cm, $E_S$=5kV/cm, n=3, 90kV applied voltage. Gap Length: 10cm.

Fig.2 Streamer pattern obtained from the simulations - $E_{th}$=26kV/cm, $E_S$=5kV/cm, n=2, 79kV applied voltage. Gap Length: 10cm.

The procedure we used for this estimation of the minimum breakdown voltage versus the gap length was the following. For each value of the gap length, several different values of applied voltage were tested. For simplicity it was assumed that the breakdown of the gap occurs when the first streamer branch touches the cathode. The discharge was assumed to be incomplete if during time step the electric field in the vicinity of streamer structure was everywhere less than $E_{th}$. Applied voltage was varied with the step of 1kV and the lowest value of voltage for which the streamer pattern bridges the gap was assumed to be the minimum breakdown voltage.

The results of the simulations were compared with experimental data concerning the voltage $U_{50}$, taken by two different sources from the literature [16, 17]. For numerical representation of experimental values, the approximation:

$$U_{50} = 12 + 5 \cdot d \qquad (4)$$

was proposed in [16] (where $d$ is the gap distance in cm, $U_{50}$ is the voltage in kV) while in [17] it was proposed the following formula:

$$U_{50} = 14 + 4.55 \cdot d \qquad (5)$$

In Tables 1, 2, 3 and 4 the results of the simulation with $E_{th}$=31kV/cm and $E_{th}$=26kV/cm are shown, for three different values of the voltage drop along the channels. At the same tables the results that are derived from the empirical formulas (4) and (5) are also shown.

Table 1. Results of simulations and experimental values – $E_{th}$=26kV/cm.

| | Experiments | Simulations | | |
|---|---|---|---|---|
| **Gap size, (cm)** | $U_{50}=12+5\cdot d$ **(kV)** | $E_{th}$=26kV/cm $E_S$=5kV/cm **U (kV)** | $E_{th}$=26kV/cm $E_S$=4.5kV/cm **U (kV)** | $E_{th}$=26kV/cm $E_S$=4kV/cm **U (kV)** |
| 5 | 37 | 38 | 37 | 37 |
| 7 | 47 | 50 | 47 | 45 |
| 10 | 62 | 67 | 63 | 59 |
| 15 | 87 | 96 | 89 | 82 |
| 20 | 112 | 126 | 116 | 106 |

Table 2. Results of simulations and experimental values – $E_{th}$=31kV/cm.

| | Experiments | Simulations | | |
|---|---|---|---|---|
| **Gap size, (cm)** | $U_{50}=12+5\cdot d$ **(kV)** | $E_{th}$=31kV/cm $E_S$=5kV/cm **U (kV)** | $E_{th}$=31kV/cm $E_S$=4.5kV/cm **U (kV)** | $E_{th}$=31kV/cm $E_S$=4kV/cm **U (kV)** |
| 5 | 37 | 44 | 44 | 44 |
| 7 | 47 | 54 | 53 | 53 |
| 10 | 62 | 72 | 69 | 65 |
| 15 | 87 | 102 | 95 | 88 |
| 20 | 112 | 130 | 121 | 112 |

Table 3. Results of simulations and experimental values – $E_{th}$=26kV/cm.

| | Experiments | Simulations | | |
|---|---|---|---|---|
| **Gap size, (cm)** | $U_{50}=14+4.55\cdot d$ **(kV)** | $E_{th}$=26kV/cm $E_S$=5kV/cm **U (kV)** | $E_{th}$=26kV/cm $E_S$=4.5kV/cm **U (kV)** | $E_{th}$=26kV/cm $E_S$=4kV/cm **U (kV)** |
| 5 | 36.75 | 38 | 37 | 37 |
| 7 | 45.85 | 50 | 47 | 45 |
| 10 | 59.5 | 67 | 63 | 59 |
| 15 | 82.25 | 96 | 89 | 82 |
| 20 | 105 | 126 | 116 | 106 |

Table 4. Results of simulations and experimental values – $E_{th}$=31kV/cm.

| | Experiments | Simulations | | |
|---|---|---|---|---|
| **Gap size, (cm)** | $U_{50}=14+4.55\cdot d$ **(kV)** | $E_{th}$=26kV/cm $E_S$=5kV/cm **U (kV)** | $E_{th}$=26kV/cm $E_S$=4.5kV/cm **U (kV)** | $E_{th}$=26kV/cm $E_S$=4kV/cm **U (kV)** |
| 5 | 36.75 | 44 | 44 | 44 |
| 7 | 45.85 | 54 | 53 | 53 |
| 10 | 59.5 | 72 | 69 | 65 |
| 15 | 82.25 | 102 | 95 | 88 |
| 20 | 105 | 130 | 121 | 112 |

A very good quantitative agreement exist in the case of $E_{th}$=26kV/cm and $E_S$=4.5kV/cm. It should be noted that the results are strongly affected on the parameters $E_{th}$ and $E_S$ but they are uninfluenced on the parameters A and n of the equation (3). The increase of the values of the parameters $E_{th}$ and $E_S$ results to the increase of the breakdown voltage of the gap. The parameters A and n may influence the values of breakdown voltage only in the case of time limited voltage application like an impulse voltage.

## 4 Conclusions

The stochastic model proposed in the present paper is a next valuable step in modeling of breakdown phenomenon. It expands the favorable possibilities to develop new models with greater quantitative accuracy. The stochastic model describes qualitatively the main stochastic features of breakdown in air (for example, statistical time lag, asymmetry and non-reproducibility of detailed conducting structure, etc).

The results concerning the breakdown voltage are very hopeful and lead us to better comprehension of interrelation physical phenomena mentioned above. For example, it was obtained that the parameter $E_{\text{th}}$ exerts most strong influence on the value of the minimum breakdown voltage than other parameters. It should be noted that in most cases during the simulations, the transition from the situation of withstand to breakdown of the gap occurred in a stepwise manner. There were no observations of any values of applied voltage for which the breakdown occurred with a probability, like in reality (i.e. the standard deviation $\sigma = 0$). This is most likely a result of the condition for breakdown. It was assumed that breakdown occurs when the streamer reaches the cathode. However in reality the streamers may reach the cathode without the occurrence of breakdown, which should be taken into account in a future work. Another subject for future work should be the use of Poisson's and charge transfers equations for the calculation of potential distribution in the area between the electrodes.

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