Prebreakdown instability development in strong electric field

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Abstract – In terms of instabilities development in open systems existing conceptions of discharge channels initiation and development in liquid and solid dielectrics are analyzed. The stochastic-deterministic approach to quantitative description of discharge structure development on a basis of laws of electrodynamics and dielectric-plasma phase transition is suggested. The self-consistent mathematical model of the discharge development, which employs stochastic rules to describe the growth of discharge channels, and deterministic laws to describe the electric field, the charge, and energy dynamics within the discharge channels and the dielectric, is presented. Examples of the model usage for electric discharge investigation are given.

1. Introduction

Electric breakdown of condensed insulators is accompanied by growth of stochastic discharge structure (DS) of conducting plasma channels. The structure growth starts in the region of the maximal intensity of the electric field (as a rule, near to the electrode with the greatest curvature). Formation of the channels is caused by phase transition of dielectric material from non-conducting to conducting state (melt, dense plasma) owing to interaction of charge carriers with atoms and molecules of material in strong electric field. DS development is affected by various factors: dielectrics properties, voltage parameters, geometry of the electrodes, etc. Despite of long-term and multidimensional investigations of electric breakdown in condensed dielectrics the quantitative theory of DS growth till now is not created. It is caused by many reasons among which it is possible to note: a plenty of the interconnected pre-breakdown processes which occur simultaneously; multiplicity of spatial and temporal scales leading to necessity of consideration of processes both at micro-, and macroscopic levels; unstable stochastic character of dielectric material phase transition to conducting state.

In the work results of stochastic-deterministic approach development are presented. In the framework of this approach it is possible to create dielectric breakdown models, quantitatively describing growth of discharge channels, dynamics of the electric field, movement of charges and channel conductivity change as the self consistent and interconnected processes.

2. Prebreakdown instabilities

The basic process, which is responsible for formation of the conducting phase, is generation and interaction of charges carriers with atoms and molecules of dielectric material in strong electric field E. Generation of the electrons, holes and ions occurs from electrodes and conducting phase as a result auto-(cold) and thermal electron emission. Besides charge carriers can be generated within the dielectric due to molecules dissociation, shock or electrostatic ionization own and especially impurity states of atoms. Formation of the conducting phase is promoted also by ionization of gas cavities (inclusions, micro cracks, bubbles) existing and formed in dielectric in strong field. Detailed analysis of various mechanisms of generation and carry of charges in dielectrics can be found in monographs [1–9].

Formation of discharge channels in condensed dielectrics is caused by current crowding owing to *S*-shaped voltage-current characteristic [10, 11]. On a part of the negative differential conductivity homogeneous distribution of the current density is unstable, and the steady state corresponds to the distribution of electric current in the form of discharge channels. Microscopic processes of charge carriers interaction with atoms, atomic and structural defects, macroscopic heterogeneities, and also the polarizing phenomena, which are responsible for formation *S*-shaped voltage-current characteristic and instability development, depend on dielectric type and breakdown conditions. Main types of instabilities, which development leads to breakdown, are thermal, electromechanical, ionization and superheating.

The most universal type of instability is thermal which is characteristic for materials with strong dependence of conductivity on temperature $\sigma(T)$ and a positive feedback between σ and T. Conductivity growth leads to increase in joule thermal power release σE^2 and in case of the limited heat dissipation causes increase of the temperature. That leads to the local boiling of liquid dielectrics, melting and/or evaporation of solid dielectrics with the subsequent ionization and formation of discharge channels. The existing theories of the thermal breakdown of solid dielectrics generalized in [2, 3] are as a matter of fact stationary criteria of the melting temperature reaching, i.e. describe only part of consequences of the thermal instability development. Examples of thermal instability modeling are given in [12, 13].

Electromechanical instability develops under the action of electromechanical (ponderomotive) forces resulting due to interaction of free and bound charges with electric field. The electromechanical instability develops, if ponderomotive electromechanical forces lead to changes in insulator, which strengthen their action. For example, in solid insulator mechanical pressure can lead to occurrence of microcracks. In strong electric field there will be ionization of the gas being in them and injection of the charge in microcracks. Liquid dielectrics under action of this force come to electro-hydrodynamical movement (EHD-flow). Coulomb pushing away of the same polarity charges creates the lowered pressure in a liquid and, together with EHD-flow and electrostriction, can lead to the formation of cavitation bubbles. Ionization of gas in microbubbles will result in the further strengthening of the electric field. The theories of breakdown based on electromechanical instability, are considered in [9, 14, 15–17].

Ionization instability is related with charge carriers generation as a result of electrostatic and shock ionization. Generation of intrinsic charge carrier due to electrostatic ionization is improbable even at breakdown field intensity of solid insulators $E_b=10^8$ V/m, but it is possible for impurity states. Shock ionization can occur, when electrons under action of an electric field get kinetic energy sufficient for ionization of the valence band or impurity levels. Ionization instability develops, when the energy has gotten by electron from an electric field, more than power losses of interaction with environment. The various theories of shock and electrostatic ionization, founded on the basis of classical and quantum conceptions, are presented in [1–4, 6–8, 18].

Superheating electric instability is related with the charge carriers heating in dielectric. In a strong electric field even if heating is insignificant, dielectrics possess the significant conductivity caused, as a rule, by movement cold electrons in a conduction band or holes in a valence band. In the case when the charge carriers heating leads to substantial growth of conductivity, occurrence of the negative differential conductivity is possible. The theory superheating electric instability is applied to the description of semiconductors and dielectrics breakdown in [10, 11].

All existing dielectric breakdown models have criterial character and are based on consequences of development of any one instability. Though in strong fields all above described instabilities (and may be also others) can develop simultaneously and synergistically strengthening each other. Furthermore development of various types of the instabilities is stochastic in time and space, and also depends on local intensity of an electric field. Stochasticity of the instability initiation is associated with fluctuations of material state parameters, dielectric structure and electrode heterogeneity. For all types of the instabilities presence of the threshold field intensity is characteristic. Instability development is possible only when the electric field intensity exceeds some critical value E_c. The value E_c depends on a kind of instability and dielectric properties. In real dielectrics one of instabilities can transform to another (for example, ionization occurs in cavitation bubbles, superheating electric instability develops on the background of the thermal instability, etc.). In this case the value of the threshold intensity E_c will decrease. The decrease of E_c can take place also owing to presence of "weak places" in real dielectrics and on electrodes, facilitating instabilities initiations. "Weak places" are cracks, bubbles, inclusion of impurity phases and other similar defects.

3. Self-consistent model of discharge development

In the frame work of stochastic deterministic approach the model of discharge development has been created. The model describes growth of conducting channels, movement of electric charges, change of channel conductivity and dynamics of electric field, as the interconnected and self consistent processes. Growth of discharge channels is consequence of dielectric-plasma phase transition in local area of dielectric as a result of one or several instability development in strong electric field. The probability density $\omega(\vec{n})$ for the formation of new channel segment at any location from an existing structure in a direction $\vec{n}$ is proportional to the square of the local field projection E_n on this direction, if E_n exceeds the critical value E_c, i.e. $E_n > E_c$, and zero if $E_n < E_c$:

$$\omega_n = \alpha \cdot \theta(E_n - E_c) \cdot E_n^2, \quad (1)$$

where α is the growth rate coefficient. The use of a random selection for the growth direction reflects the impact of inhomogeneity of dielectric material and instability of the discharge channel formation process.

Movement of electric charges and redistribution of an electric field are described deterministically. The electric field is created by the charges located along the discharge channels, on the electrode surfaces and within dielectric volume. The electric field distribution within the dielectrics is calculated by the Gauss theorem in the differential form:

$$\nabla(\varepsilon\varepsilon_0\vec{E}) = \rho, \quad (2)$$

where ε and ε_0 are the relative and absolute dielectric permittivities, respectively, ρ is the free charge density. The boundary conditions are determined by the potentials and geometry of the electrodes.

Movement of charges along the discharge channels and within dielectric is determined by Ohm law and charge preservation law. Change of volumetric charge density ρ_V in dielectric with specific conductivity y is described by the continuity equation:

$$\frac{d\rho_V}{dt} = -\nabla\left(\sigma \cdot \vec{E}\right). \quad (3)$$

Dynamics of linear charge density ρ_L along the channels is obtained from the equation:

$$\frac{d\rho_L}{dt} = -\frac{d}{dl}\left(\gamma \cdot E_l\right), \quad (4)$$

where γ is conduction of the channel per length unit, l is coordinate along the channel. In branching points the condition of equality to zero of the algebraic sum of currents (Kirchhgoff equation) is satisfied.

In the present paper the conductivity y of the dielectric material does not change in time. The conductivity γ of the discharge channels changes during the breakdown. The Rompe-Weizel [19] formula is here modified by introducing the channel conduction decay and used to describe change of the channel conductivity:

$$\frac{d\gamma}{dt} = \chi \cdot \gamma \cdot E_l^2 - \xi \cdot \gamma, \quad (5)$$

where χ and ξ are parameters for the rate of increase and decrease of conduction, respectively. The conductivity of a newly formed channel is equal to the initial conductivity γ_0.

4. Discharge channel formation

On the basis of the presented model application programs permitting computer simulation of discharge development under different conditions have been created and used for discharge investigation [20–24].

The modeling result of anode DS growth in liquid is shown in Fig. 1. Voltage increase leads to growth of the DS fractal dimension D, speed of channel propagation and the discharge current.

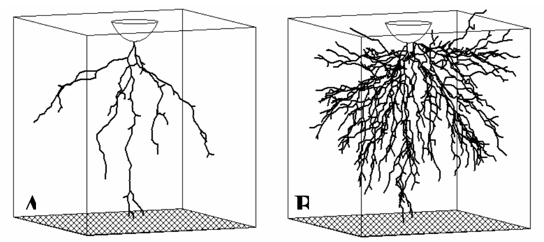


Fig. 1. Simulated discharge structure (a) U=10 kV, D=1.38, t=4.6 μs; (b) U=20 kV, D=2.43, t=1.6 μs

Heterogeneity of spatial distribution of dielectric permeability and conductivity within the insulator, and presence of the charged areas (volumetric charges) effects on the discharge development. The spherical inclusion of the high permeability located between electrodes attracts the growing structure, and with the lowered permeability pushes it away. Barriers of the increased permeability lead to a curvature and retention of the DS within the barrier layer.

The effect of inclusions with the conductivity different from that of the matrix depends on the relation between the characteristic times of the DS propagation τ_p and the charge relaxation τ_r. The field redistribution does not occur and the discharge trajectory does not deviate, when τ_p is much shorter τ_r. In opposite case ($\tau_p > \tau_r$) the space charges generation and the electric field redistribution occur. A spherical inclusion with conductivity $\sigma*$ smaller the

a

b

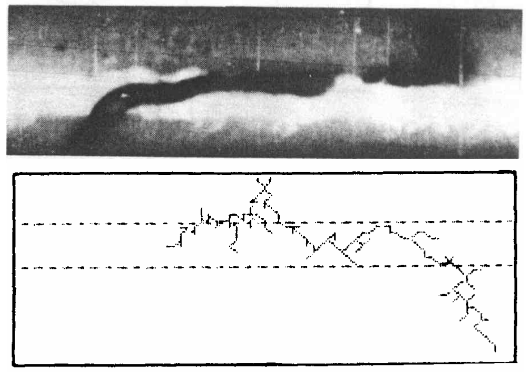
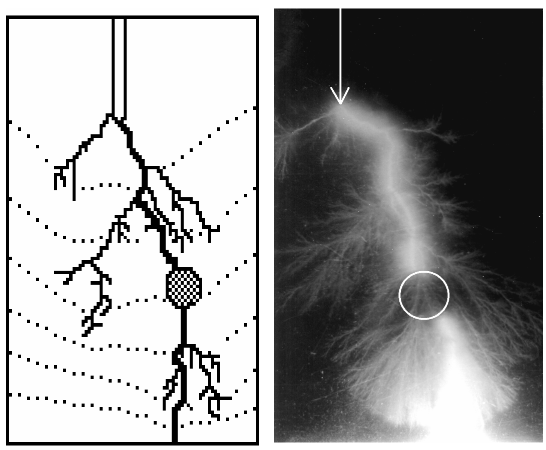


Fig. 2. Retention of the discharge structures within barrier layer: (a) experiment (breakdown trace) $\varepsilon_b/\varepsilon_s$=4.3, (b) simulation $\varepsilon_b/\varepsilon$=15. Insulator thickness 1.1·mm

conductivity σ of the matrix results in the discharge trajectory repulsion from the inclusion. Inclusions with high conductivity ($\sigma*>\sigma$) are more typical for the electric impulse treatment of materials. In this case the inclusion attracts the discharge trajectory. Figure 2 shows results of the simulation of the trajectory attraction and the shadow photograph of the electric discharge in glycerin with a metallic inclusion.



a) b)

Fig. 2. Spark track in dielectric with a conducting inclusion (sphere), (a) simulation, (b) experiment

In space charged dielectric of high charge density and the small sizes of the charged area, discharge channels completely occupy the area with the introduced charge (Fig. 3). Decrease of the charge density leads to linear reduction of the DS sizes (Fig. 4). Rate of channels growth, their conductivity and discharge current increase with increase of the charge density.

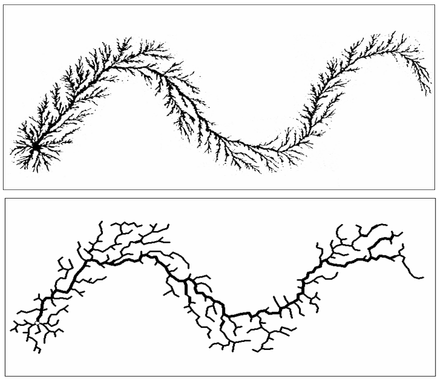


Fig. 3. Growth of discharge structure along a sinusoidal strip of charge (sample size 80 mm×160 mm, charge density 0.8 μC/cm^2) (a) experiment, (b) simulation

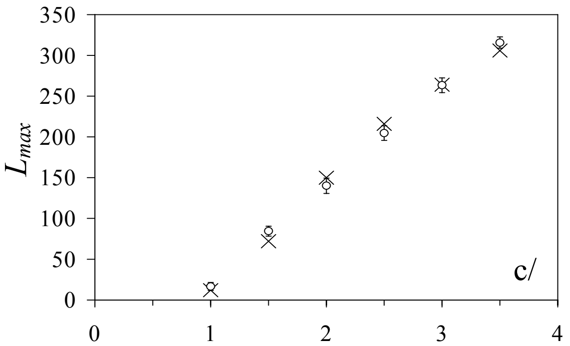


Fig. 4. Extension L_{max} of the discharge structure as function of space charge density (relative units), × – experiment, o – simulation

5. Conclusion

The phenomenological model describing formation of discharge channels in condensed dielectric is developed. Growth and contraction of channels results from the phase transition dielectric-plasma accompanied by the current instability. The probability of phase transition is determined by specific density of the electric field energy. Field and charge dynamics is described by the equations of electrodynamics. Such stochastic-deterministic approach has allowed formulating the physical and mathematical model connecting voltage parameters, dielectric properties, discharge gap geometry with spatial-temporal characteristics of the developing discharge channels, redistribution of electric field and charges within the dielectric and channels.

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References

[1] Vorobiev A.A., Zavadovskaya E.K. *Electric strength of solid dielectrics*, M:GITTL, 1956, 312 p. (in Russian)

[2] G.I. Skanavi, *Physics of dielectrics*, V.2, Strong electric fields, M, GIFML, 1961, 907 p. (in Russian)

[3] W. Franz, *Dielecktrischer durcschlag*, Handbuch der physic, Springer verlag, 1956.

[4] Vorobiev A.A., Vorobiev G.A., *Electric discharge and destruction of solid dielectrics*, M: Higher School, 1966, 224 p. (in Russian)

[5] Vershinin Y.N., *Electric breakdown of solid dielectrics*, Novosibirsk: Science, 1968, 210 p. (in Russian).

[6] Adamchevsky I., *Electric conductivity liquid dielectrics*, L.: Energy, 1972, 296 p. (in Russian).

[7] O'Dwyer I.I., *The theory of electrical conduction and breakdown in solid dielectrics*. – Oxford.: Clarendon Press, 1973. 384 p.

[8] Dissado L., Fothergill J. C., *Electrical degradation and breakdown in polymers*, London: Peregrinus, 1992, 601 p.

[9] Ushakov V.J., Klimkin V.F., Korobejnikov S.M., Lopatin V.V., *Breakdown of liquids at a pulse voltage*, Tomsk, STL, 2005, 488 p. (in Russian)

[10] Bonch-Bruevich V.L., Zvjagin I.P., Mironov A.G., *Dmain electrical instability in semiconductors*, M.: GIFML, 1972, 325 p. (in Russian).

[11] Vershinin Y.N., *Electric-thermal and detonation processes at electric breakdown of solid dielectrics*, Ekaterinburg: Ur.Br. RAN, 2000, 258 p. (in Russian).

[12] Zebouchi N., Malec D., J. Appl. Phys. **83**, 6190. (1998).

[13] Noskov M.D., Lopatin V.V., Cheglokov A.A, Shapovalov A.V., Izvestija vuzov. Fizika, **46**, 1, 87, (2003). (in Russian)

[14] Zeller H.R., Schneider W.R., J. Appl. Phys. **56**, 455 (1984).

[15] Watson P.K., Chadband W.G., Sadeghzadeh-Arighi M. IEEE Trans. EI., **26**, 543 (1991).

[16] Fothergill J.C., IEEE Trans. Elect. Insul. **26**, 1124 (1991)

[17] Lewis T.J., IEEE Trans. Diel. and Electr. Insul., **5**, 306 (1998).

[18] Ushakov V.J., *Pulse electric breakdown of liquids*, Tomsk, 1975, 256p. (in Russian).

[19] Rompe R., Weizel W., Zs. Physik B., **122**, 636 (1944).

[20] Karpov D.I., Lopatin V.V., Noskov M.D., Electricity, **7,** 59 (1995) (in Russian).

[21] Kuhta V.R., Lopatin V.V., Noskov M.D., Pleshkov O.I., Izvestija vuzov. Fizika, **4** (appendix) 63 (1996) (in Russian).

[22] Lopatin V.V., Noskov M.D., Badent R., Kist K., Schwab A.J., IEEE Trans. Diel. and EI, **5**, 250 (1998)

[23] Kurets V.I., Lopatin V.V., Noskov M.D., Physicotechnical problems of mining operations, **3,** 81 (2000). (in Russian)

[24] Noskov M.D., Malinovski A.S., Cooke C.M., Wright K.A., Schwab A.J., J. Appl. Phys., **92**, 4926 (2002).