# Simulation of the Pulse Electric Breakdown Conclusion of Condensed Dielectric

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**Abstract – The physical-mathematical model of the discharge structure development which consistently describes electro dynamical processes within the discharge gap and variation of the voltages and currents in the high-voltage pulse generator is presented. Based on numerical realization of the model program application is used for quantitative description of the field and current characteristics of the propagating discharge channels. Simulation results of the condensed dielectric breakdown in the needle-plain electrode geometry are presented.**

## 1. Introduction

Investigation of the electrical discharge development in the condensed dielectrics is interested both theoretically and experimentally due to active development of the high-voltage pulse power equipment and electrical discharge technology [1,2]. Using of the mathematical modeling is expedient for quantitative description and prediction of the discharge development. Simulation of the discharge structure growth is considered in papers [3,4], however simulation was carried out only until the bridging of the electrode gap by the discharge structure. The model which consistently describes discharge channels development and pulse-voltage generator operation both at the growth stage and at the stage of energy injection in the plasma channel is presented.

## 2. Model

Discharge structure development in the dielectric and operation of the pulse-voltage generator are simulated on the base of equivalent oscillatory circuit. The equivalent circuit of the high voltage generator consists of capacitance $C$, resistance $R$, inductions $L$, $L_1$ and key K (Fig. 1). Choice of the given scheme is conditioned by the type of generators which is used in high voltage laboratories and pulse electrical discharge technology. Electric load consists of discharge gap which parallel connected with the stray capacitance $C_s$ of the supply conduction path. Precharge capacitance $C$ is the energy collector, and the circuit inductions $L$, $L_1$ consists of the inductions of switches K, generator capacitors and discharge gap.

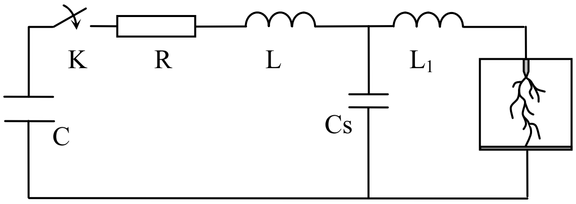



Fig. 1. The equivalent circuit of the high-voltage generator and the discharge gap: $C$ is the generator capacitance, $K$ is the key, $L$ and $L_1$ are the circuit inductions, $R$ is the variable resistance of the circuit, $C_S$ is the stray capacitance

The variable circuit resistance $R$ takes into account the resistance of the generator conductors and spark switches of the generator $K$. It is supposed that after circuit commutation (point of time $t$=0) the resistance $R$ exponentially decreases:

$$R = R_1 + (R_0 - R_1)e^{-t/\theta_R}, \quad (1)$$

where $R_0$ is the initial resistance at the instant time $t$=0, $R_1$ is the limit minimal value of the resistance, Value of the $R_1$ for the usually used 6–10 stepped Arkadiev-Marks multiplying circuit generators with the air switches is equal to 1–3 Ohm; $\theta_R$ is the resistance decrease characteristic time. Stray capacitance $C_s$ is the sum of the stray capacitances of the elements of construction. After bridging $K$, the sum of the voltage drops across the circuit elements is equal to zero:

$$U_c + U_R + U_L + U_{L_1} + U_D = 0 \quad (2)$$

where $U_C$ is the generator capacitance $C$ voltage; $U_R=IR$ is the voltage drop across the resistance $R$; $U_L = -L\frac{dI}{dt}$ is the voltage drop across the induction $L$; $U_{L_1} = -L_1\frac{dI_D}{dt}$ is the voltage drop across the induction $L_1$; $U_D$ is the voltage drop across the discharge gap; $I = C\frac{dU_c}{dt}$ is the current via generating capacitor $C$. The current $I$ is the sum of current of the stray capacitance $I_S = C_S\frac{d(U_D + U_{L_1})}{dt}$ and discharge gap current $I_D$.

$$I = I_S + I_D \quad (3)$$

The voltage drop $U_D(t)$ and the discharge gap current $I_D(t)$ calculated with the help of the equations (1)–(3) consistently with discharge development simulation within the dielectric.

The model employed describes growth of the discharge channels, movement of charges along the channels, dynamics of the electric field and time variation of the channels conductivity. The discharge development is considered in the needle-plain electrode geometry. The step probability function of the local field is used to describe the channel growth. The probability density $\omega_n$ of the conductive channel growth in direction $\vec{n}$ is assumed to be proportional to the square of the local field projection $E_n$ on this direction, if the projection value exceed the critical strength:

$$\omega_n = \alpha\, \theta(E_n - E_c) E_n{}^2 , \qquad (4)$$

where α is the growth rate coefficient, $E_c$ is the critical field for discharge channel growth, θ($x$) is the step function (θ($x$) = 1, for $x$>0 and θ($x$) = 0 for $x$≤0). Quadratic dependence of the growth probability of the discharge channel is caused by that the electric field energy is spent on the conductive phase formation.

The electric potential distribution φ within the dielectric is calculated from the Gauss theorem for dielectric:

$$\nabla(-\varepsilon \cdot \nabla\varphi) = \rho / \varepsilon_0 , \qquad (5)$$

where $\varepsilon_0$ and ε are absolute and relative dielectric permittivities, ρ is the total volume density of free charges in the dielectric and discharge channels.

The change of the volume charge density in the insulator is calculated from the charge conservation law:

$$\frac{\partial \rho_V}{\partial t} = \nabla(\sigma \nabla \varphi) , \qquad (6)$$

where $\rho_V$ is the volume charge density in the insulator, σ is the specific conductivity of the dielectric.

The change of the linear charge density $\rho_\ell$ along the discharge channel is determined by the continuity equation and Ohm law:

$$\frac{\partial \rho_l}{\partial t} = -\frac{\partial}{\partial \ell}\left(\gamma \cdot E_l\right), \qquad (7)$$

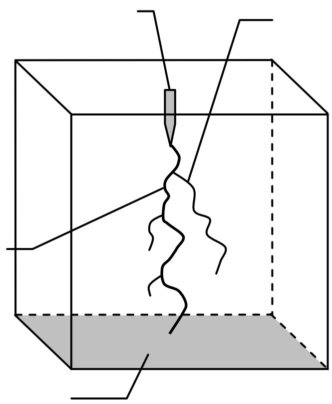
where γ is the conduction of the channel length unit, which is determined as the product of the channel cross-section square and specific conductivity of the plasma within the channel, $\ell$ is the coordinate along the channel, $E_l$ is the electric field projection onto the channel direction.

The change of the linear channel conduction during the discharge development is determined by the modified Rompe-Wiezel equation [5]:

$$\frac{\partial \gamma}{\partial t} = \chi \gamma E_l^2 - \xi \gamma , \qquad (8)$$

where χ and ξ are parameters of the rate of increase and decrease of the conduction respectively. The first term in the right part of equation (8) is related to increasing of the conduction due to Joule energy release within the discharge channels. The second term describes the conduction decay due to energy dissipation into the surrounding space.

The matching of the high-voltage generator operation and discharge development is realized with the help of the boundary condition. The potential value of the positive electrode $S_P$ (upper side of the simulation region and needle) is equal to discharge gap voltage $\varphi|_{S_P} = U_D$, the potential value of the ground electrode $S_0$ (bottom side of the simulation region) is equal to zero $\varphi|_{S_0} = 0$ (Fig. 2).



Besides, the equality of the total current across the potential electrode and the discharge gap current takes place:

$$\int_{S_P} \left( -\varepsilon\varepsilon_0 \frac{d}{dt}\left(\vec{\nabla}\varphi\right) - \sigma\vec{\nabla}\varphi \right) d\vec{s} + \sum \gamma E_l = I_D . \qquad (9)$$

The first term under the integral in the equation (9) is related to displacement current across the potential electrode surface, the second term is related to bulk conductivity current. The sum in equation (9) corresponds to the total conductivity current along the discharge channels, connected with the electrode. On the lateral sides of the simulation region the cycle boundary conditions are specified.

## 3. Simulation results

Simulation of the discharge development has been carried out in the case of the needle-plain electrode geometry. Computer experiments are made at the following parameters of the discharge circuit $C$ = 10 nF, $L$ = 23 μH, $L_1$ = 0,1 μH, $C_S$ = 0,2 nF $R_0$ = 10 MOhm, $R_1$ = 2 Ohm, $\theta_R$ = 10 ns. The discharge gap equals $2{\cdot}10^{-2}$ m, relative dielectric permittivity of the insulator ε = 81, initial voltage of the generator capacitor $U_C^0 = 300$ kV. The model parameters have been selected so as to provide a good match to measured spatial temporal and current characteristics of the discharge development in deionized water. The following values for the parameter set have been used to simulation $E_C$=15 MV/mv, $\alpha$=7,5·10$^{-9}$ m$^2$·V$^2$/s, $\gamma_0$ =1,5·10$^{-9}$ S·m, $\chi$ = 1·10$^{-5}$ S·m$^2$/J, $\xi$ = 1,5·10$^7$ s$^{-1}$.

Discharge starts with the formation of one or several channels at the initiating needle, when the electric field strength exceeds the critical field ($t$ = 137 ns). Channels propagation speed increases with discharge voltage grows and discharge structure approaches to the ground electrode (Fig. 3a-c). Average speed of the discharge structure development equals $v$ = 3,9·10$^4$ m/s. This value is in a good agreement with measurements of the discharge speed propagation in the nanosecond time interval [6,7]. As a result of discharge structure growth electrode gap bridging by main discharge channel occurs (the main discharge channel is shown in Fig. 3c by thick line). Due to the fact that the most part of the current flows through the main discharge channel, the conduction of the remaining channels quickly decrease and they decay. As a result only the main discharge channel remains (Fig. 3d).

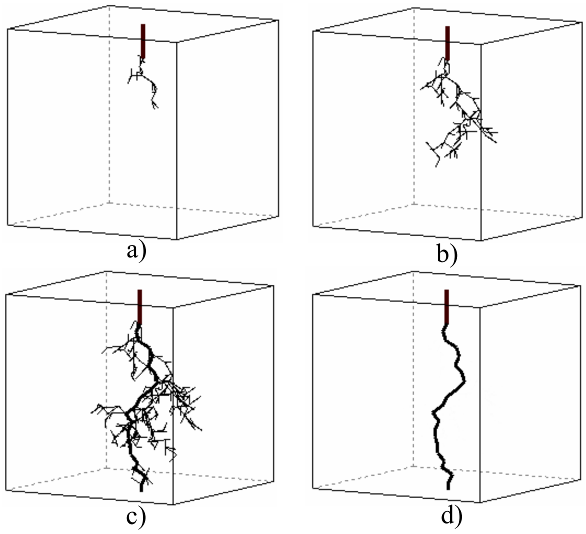



Fig. 3. Discharge channels structure at the various points of time t: a) t = 161 ns, b) t = 175 ns, c) t = 188 ns, d) t = 288 ns

After bridging of the electrodes gap by the discharge channel the sharp increase of the discharge current and reduction of the discharge voltage occur whereas inductive voltage increase (Fig. 4). The short oscillations which occur after reduction of the discharge voltage are caused by the stray capacitance $C_s$ discharging. These oscillations come to stop in a 250 nanosecond.

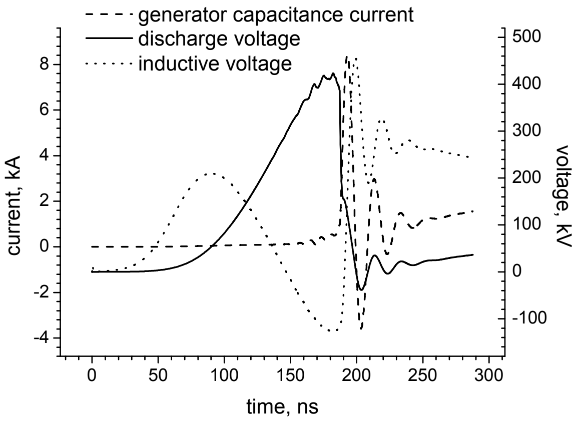



Fig. 4. Time dependencies of the discharge voltage, discharge current and inductive voltage at the growth stage and bridging point of time

After dielectric breakdown damped oscillations begin in the generator circuit (Fig. 5). During this process the main discharge channel acts as the variable nonlinear resistance. At each point of time the sum of the voltage drops across the discharge circuit elements is equal to zero.

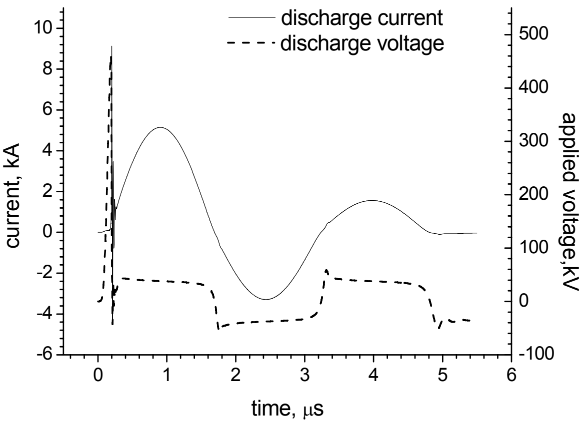



Fig. 5. Time dependencies of the discharge voltage and discharge current

Period of the oscillation is determined by the induction $L$ and capacitance $C$ of the generator. At the chosen simulation parameters oscillations stop occurs in a five microsecond. The oscillation of the discharge voltage has trapezoidal form. It is caused by the variation of the main channel conduction during the discharge process.

The oscillations of the current and voltage result in periodical variations of energy released within the discharge channel (Fig. 6).

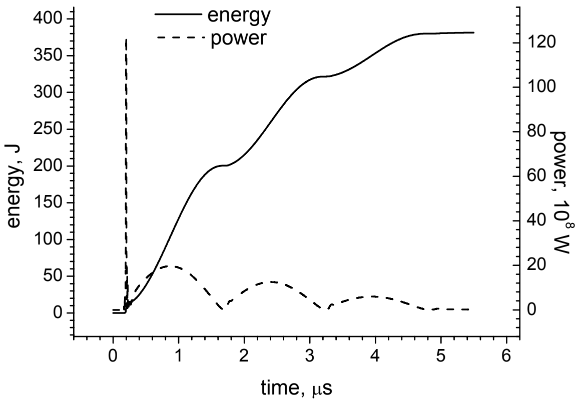



Fig. 6. Time dependencies of the total energy and Joule power release within the breakdown channel

At the instant time the energy stored in the generator capacitor is equal to 450 J. The total energy which released within the main discharge channel amounts to 85 % of the energy accumulated in the generator capacitance. Almost half of the released energy has released during the first half-period of the discharge oscillation. Other part of the energy released within the active resistance *R* of the generator.

Oscillation of the power leads to the oscillation of the breakdown channel conduction (Fig. 7). Minimums of the conduction are related to the time points when the current takes on a zero value.

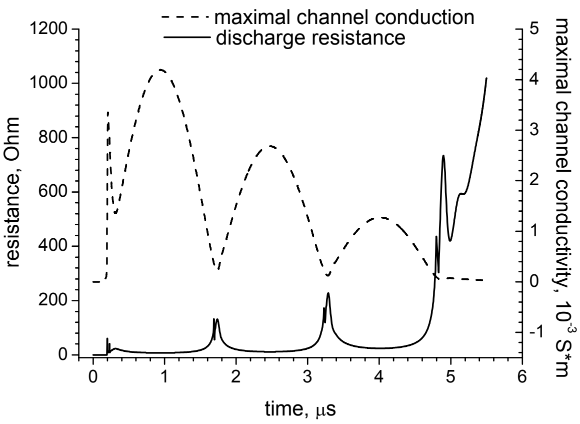



Fig. 7. Time dependencies of the maximal conduction of the discharge channels and electrode gap resistance

Time dependencies of the electrical characteristics of the main discharge channel are in qualitative agreement with the experimental data [8,9]. Quantitative differences are related with other type of the generator and discharge conditions.

## 4. Conclusion

The presented mathematical model takes into account main processes determining the dielectric breakdown consistently with the high-voltage pulse generator operation. On the basis of the numerical realization of the developed model program application has been created permitting computer simulation of electric discharge development in the dielectric for the needle-plain electrode geometry. Obtained discharge characteristics in the liquid are in agreement with the experimental data. It improves the model adequacy and workability. The created model may be used for the investigation of the discharge phenomena in the dielectric and improvement of the electrical discharge technology.

This work was supported by grants of RFBR № 05–08–50203, and CRDF №RUE 1–1360(2)–T0–04.

## References

[1] B.V. Semkin, A.F. Usov, V.I. Kurets *The principles of the electric impulse destruction of material*, RAS, 1995, 278p. (in Russian).

[2] G.A. Mesyats. *Pulsed power and electronics*. Moscov: Nauka, 2004, 704p.

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

[4] M.D. Noskov, A.S. Malinovsky, *in Proc. VI International conference "Recent problems of the electrophysics and electrohydrodynamic of the liquid",* 2000, pp. 159–162. (in Russian)

[5] R. Rompe and W. Weizel, Zs. Physik **B.122**, 9 (1944).

[6] V.V. Lopatin, V.Y. Ushakov, V.P.Chernen-ko, Izv. Vuzov "Physics". 1975. №3, (in Russian)

[7] V.F. Klimkin, JTP Letters, **16**, 14 (1990).

[8] E.V.Krivitsky, V.V.Shamko, *Transient processes at the high voltage discharge in water*, Kiev, Naukova dumka, 1979, 208 p. (in Russian)

[9] K.A. Naugolnyh, N.A. Roy, *Electrical discharges in water*, Moskow, Nauka, 1971, 155 p. (in Russian)