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A generalized physical principle of development of plasma channel of a high-voltage pulse spark discharge in a dielectric

Goal. *Development of the generalized physical principle of development of plasma channel of a high-voltage electrical pulse spark discharge in the homogeneous dielectric of the different aggregate state.* ***Methodology.*** *Basis of physical optics, theoretical electrical engineering, electrophysics bases of technique of high-voltage and large pulse currents, bases of high-voltage pulse technique and measuring technique.* ***Results.*** *Development of physical principle of development of plasma channel of an electric pulse spark discharge is executed in a homogeneous gas dielectric on the applied example of the use in calculations and experiments of the double-electrode discharge system (DEDS) with a long air interval, testing action of standard interconnect aperiodic pulse of high-voltage of temporal shape of T_m/T_d≈200 μs/1990 μs of positive polarity. The generalized formula is got for the calculation of total length of l_c of the real way of development of an pulse spark discharge in an air dielectric, which allowed to formulate the offered physical principle in the following kind: «The plasma channel of an pulse spark discharge in a gas dielectric spreads from one of its points to other after a way length of l_c, providing the least falling on it of electric voltage of U_c». It is shown that this principle in the first approaching can be applied and to the homogeneous liquid and hard dielectrics. Comparison of the developed physical principle of distribution of plasma channel of an electrical spark discharge is executed in a dielectrical environment with fundamental Fermat physical principle (a law) for distribution of light in an optically transparent environment, which specifies on mathematical likeness and closeness on destiny of these physical principles. Calculation estimations of falling of electric voltage of U_c on total length of l_c of the real zigzag way of development in the air dielectric of DEDS a «edge-plane» with the least length of its discharge interval of $l_{\min}$=1,5 m is presented, that a value U_c does not exceed 9 % from the experimental level of aggressive voltage of U_{md}≈611,6 кV in this DEDS for the aperiodic pulse of voltage of T_m/T_d≈200 μs/1990 μs. It is set that the estimated time of t_d advancement of leader channel of electric pulse discharge in air DEDS ($l_{\min}$=1,5 m) on its real way total length of l_c≈1,53 m makes t_d≈15,3 μs, and experimental duration of cut of T_{dc} of the indicated aperiodic impulse of voltage utilized in experiments, characterizing time of short circuit by the plasma channel of discharge of air interval in DEDS, appears equal T_{dc}≈t_d≈17 μs.* ***Originality.*** *The generalized physical principle of development of plasma channel of a high-voltage electrical pulse spark discharge is first developed in the homogeneous dielectric of the different aggregate state.* ***Practical value.*** *Application in electrical engineering practice and high-voltage pulse technique of the offered principle of distribution in the dielectrics of plasma channel of an pulse spark discharge will allow to develop both new and to perfect the existent methods of computer design of electro-discharge processes in the gas, liquid and hard insulation of different high-voltage electrical power engineering and electrophysics devices, directed on the increase of reliability of their operation.* References 25, figures 5.

Key words: **plasma channel, spark discharge, dielectric environment, physical principle of development of plasma channel, calculation, experiment.**

Надані результати розробки узагальненого фізичного принципу розвитку в гомогенному діелектричному середовищі плазмового каналу високовольтного електричного імпульсного іскрового розряду. Показано, що канал даного виду електричного розряду в газовому діелектрику розповсюджується по зигзагоподібному шляху завдовжки l_c, який забезпечує найменше падіння на ньому електричної напруги U_c. Для обґрунтування прийнятих початкових фізичних положень і верифікації отриманих розрахункових електрофізичних даних представлені результати високовольтних сильнострумових експериментів по електричному пробою довгого повітряного проміжку в двоелектродній розрядній системі «вістря-площина» ($l_{\min}$=1,5 м) із застосуванням стандартного комутаційного аперіодичного імпульсу високої напруги часової форми T_m/T_d≈200 мкс/1990 мкс позитивної полярності. Виконано порівняння розробленого фізичного принципу розповсюдження плазмового каналу високовольтного електричного імпульсного іскрового розряду в діелектричному середовищі з фундаментальним фізичним принципом (законом) Ферма для розповсюдження світла в оптично прозорому середовищі, яке вказує на схожість за формою математичного запису і близькість за змістовним призначенням даних фізичних принципів. Бібл. 25, рис. 5.

Ключові слова: **плазмовий канал, іскровий розряд, діелектричне середовище, фізичний принцип розвитку плазмового каналу**, **розрахунок, експеримент.**

State-of-the-art and relevance of the problem. Electric pulse spark discharge in vacuum, gas, liquid and solid dielectric media, which is carried out with the help of high-voltage low- and high-current electrical equipment, has found quite wide practical application for both scientific and technological purposes [1-5]. Let us point out that this type of high-voltage electric discharge belongs to one of the known and well-studied classical types of self-discharge in a dielectric today in electrophysics [6-8]. Electric discharge technologies based on the transformation of electrical energy stored, as a rule, in powerful high-voltage capacitor batteries into the energy of phase transitions, chemical reactions, explosion of solid substances, shock waves, into mechanical work, heat and other types of energy [3, 9-11], have one fundamental difference from other technologies: they are capable of providing a large energy density in the pulse mode of its action to the substance under investigation or the processed product (object). At the same time, the time of this action can vary in a wide range: from hundreds of milliseconds to units of nanoseconds. Taking into account the prospects of electrical discharge technologies based on pulse spark discharge, in recent decades the following important scientific results were obtained by domestic and foreign electrical engineering scientists and electrophysicists in this area of high-voltage pulsed technology (HPT) [1, 3-12]: data on the dependence of the electrical strength of many dielectrics from the length of the interelectrode gaps, the geometry of the electrodes used in these gaps of different metals and conductive compositions, the amplitude-time parameters (ATPs) of the electric voltage (current) acting on the dielectric, and the electrophysical parameters of the surrounding dielectric insulating medium; volt-second characteristics of electrical breakdown of many types of dielectrics; found distributions of the strength of high pulse electric field in linear and heterogeneous dielectrics placed in interelectrode spaces with electrodes of different configurations; determined main types of electric discharge structures and the parameters of discharge plasma channels in the main types of dielectrics at different ATPs of voltage (current); obtained the first adequate calculation data for computer modeling of complex electrophysical processes of the development of the plasma channel of an electrical pulse spark discharge in some types of dielectrics.

Despite the above-mentioned scientific results, in the field of modern HPT, in the study of pulse spark discharge in dielectrics, those related to the development of mechanisms and the description of analytical models of the development of the plasma channel of this discharge in them remain poorly studied issues. The presence of similar mechanisms and analytical models will contribute to the further improvement of computer modeling methods of the development of the plasma channel of electric spark discharge in dielectrics of various natures [13-18], which have important applied value in the field of high-voltage electrical engineering, industrial electric power engineering, HPT, high-current electronics, nuclear engineering and protection of aircraft and ground infrastructure objects from the impact of atmospheric electricity (lightning).

The goal of the article is to obtain a generalized physical principle of the development of a plasma channel of a high-voltage pulse spark discharge in a homogeneous dielectric of a different aggregate state.

1. Problem definition. For the certainty of solving this applied electrophysical problem, consider a high-voltage double-electrode discharge system (DEDS), which contains a potential electrode in the form of a metal rod 1 of finite geometric dimensions pointed at the edge and a grounded electrode in the form of a metal plane 2 of unlimited geometric dimensions (Fig. 1). Let the electric potentials of these electrodes 1 and 2 be equal to φ_1 and $\varphi_2=0$, respectively, and between them in the interelectrode air gap of minimum length $l_{\min}$, equal to the length of the straight line drawn from the tip of the potential electrode 1 along the normal to the flat surface of the grounded electrode 2, a homogeneous gas is placed by the following atmospheric conditions [19]: gas pressure $P_a \approx (1.013 \pm 0.003) \cdot 10^5$ Pa; absolute gas temperature $T_a \approx (293.15 \pm 5)$ K; relative humidity of gas (45±15) %. Let us assume that the electrical strength of the interelectrode air gap in the DEDS in relation to the average level of its breakdown voltage of high pulse electric field for the electric voltage pulse applied to the DEDS is equal to E_d. Here, the potential φ_1 acquires a value equal to φ_{1d}.

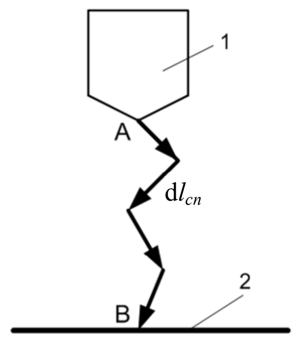

Fig. 1. Schematic representation of the aerial DEDS, on the example of which the process of the development of a plasma channel of a high-voltage electric pulse spark discharge in a gas dielectric is considered (1, 2 – respectively, the metal rod with potential φ_1 and the metal plane with potential φ_2; A, B – the starting and ending points of the path of the spatial development of the pulse plasma channel spark discharge in a gas dielectric)

We will limit ourselves to the consideration of the applied case, when the ATPs of high electrical pulse voltage $U_{12}(t)=(\varphi_1-\varphi_2)$ in the interelectrode air gap of the DEDS changes in time t according to the law of the standard switching aperiodic voltage pulse of the time shape $T_m/T_d \approx (250 \pm 50)$ μs/(2500±750) μs of positive polarity with appropriate tolerances on its parameters [20, 21]. It is this type of high pulse voltage that is most often used in industrial electric power and HPT when determining the electrical strength of the internal and external insulation of various high-voltage electrical equipment and powerful high-voltage electrophysical test equipment. Taking into account the leading stage of the development of the plasma channel of an electric discharge in a gas dielectric, when the discharge channel can branch out and have a zigzag character [8], we will limit ourselves to considering the processes at the stage of the formation of a conductive pulse spark channel in an air DEDS after passing through the leader channel of the return wave of the pulse current, which causes its bright glow [5]. Based on the analysis of calculated and experimental data relating to the flow of the main electrophysical processes in the studied discharge air gap of the DEDS (see Fig. 1), it is necessary to develop the physical principle of the development of the plasma channel of a high-voltage pulse spark discharge in the gas dielectric adopted for the study and further generalize it to homogeneous dielectrics of a different aggregate state, the physical properties of which change in space continuously without jumps.

2. Basic physical conditions and calculation relationships. Taking into account the electromagnetic nature of light and the plasma channel of a brightly glowing high-voltage electrical pulse spark discharge in the studied gas dielectric [8, 19], for a better understanding of the complex electrophysical processes in the air DEDS under consideration, let us first dwell on the well-known Fermat physical principle from the field of geometric optics, which for the optical length L_0 of a real light beam in an optically transparent medium is written in the following classical analytical form [22]:

$$L_0 = \int_A^B n_0 \mathrm{d}s, \quad (1)$$

where n_0 is the dimensionless index of refraction of the light beam, which is minimal for a real beam in an optically transparent medium; ds is the length of the elementary section of the propagation of a light beam in an optically transparent medium from the starting point A to the ending point B of the real path of propagation of light in it.

In the case when the index of refraction n_0 of the medium spatially changes continuously in it, then according to (1) the optical length L_0 of the path traveled in it by a real light ray from point A to point B will be less than the optical length of any other path or the length of any other geometric curve connecting these extreme points of the light ray propagation path. Therefore, the time t_0 of passing through this or that medium with the index of refraction n_0 of the light beam of this path with the optical length L_0 will be the smallest. At the same time, it should be noted that the indicated time t_0 of the beam passage will have the following calculated analytical form: $t_0=L_0/c$, where $c \approx 3 \cdot 10^8$ m/s is the speed of light propagation in a vacuum [19]. Note that according to Maxwell law, there is a valid formula for the value of the index of refraction n_0 of the medium [22]:

$$n_0 = \sqrt{\varepsilon_r \mu_r}, \quad (2)$$

where ε_r, μ_r are, respectively, the relative dielectric and magnetic permeability of the medium in which the light beam propagates.

Formula (2) clearly indicates the electromagnetic nature of light. It follows from (2) for an air medium ($\varepsilon_r=1$; $\mu_r=1$) that the physical parameter n_0 in this case is numerically close to $n_0=1$ [19].

In this regard, Fermat physical principle, which is a general law of geometric optics, according to (1) and the accepted principle in the field of modern optics, is formulated as follows [22]: «*Light propagates from one point of the medium to another along a path for which the least amount of time is spent*». From Fermat principle the physical statement follows that light in an optically transparent medium propagates in a straight line [22]. Taking into account the above-mentioned electromagnetic nature of light and the plasma channel of the electric discharge, it is quite reasonable to accept the physical provision that the development of the plasma leader channel of the electric discharge and then the plasma spark channel of this pulse discharge in the air discharge gap (n_0=1) of the investigated DEDS on its short elementary sections of length dl_{cn}<<$l_{\min}$ occurs along rectilinear directions of one or another spatial orientation. Moreover, given rectilinear directions on elementary sections of length dl_{cn}, both at the stage of development of the plasma leader channel of the discharge in air, and at the stage of development of its spark channel in it, will satisfy the condition of the maximum value of the specific electrical conductivity γ_{cn} of the conductive path in the gas dielectric at the specified elementary sections of length dl_{cn} of the plasma leader (spark) discharge channel.

We believe that this conductive path is initiated by its main part (the head of the discharge leader) growing in space, which glows brightly and moves quickly in this dielectric (at the average velocity v_L of the forward front of the discharge leader in the air $v_L \approx 10^5$ m/s [8]) from the potential to the grounded electrodes of the DEDS. Spatial distributions in the discharge interval of the investigated DEDS of values of γ_{cn} on the elementary sections with the length dl_{cn} of the germinating leading channel of the pulse discharge are, as a rule, probabilistic in nature. These spatial probability distributions of γ_{cn} values in one or another dielectric are determined both by the technology of their manufacture (this applies more to solid and liquid insulation), and by the physical state and composition of the gas dielectric, as well as the properties of the gas or liquid insulating medium surrounding the solid dielectric [1 , 5]. Therefore, in the case of an electrical breakdown of the air discharge gap in the investigated DEDS with a conducting plasma channel of a pulse discharge with a total length $l_c=\sum_{n=1}^{m} \mathrm{d}l_{cn} = \int_A^B \mathrm{d}l_{cn}$ the indicated rectilinear elementary sections of the length dl_{cn} of the plasma leader channel of a pulse electrical discharge, which quickly grows in the air, will form a broken zigzag curve of the real path (l_c>$l_{\min}$) of the studied pulse spark discharge in the DEDS between the starting point A and the ending point B of the development of the plasma channel of this type of electric discharge (see Fig. 1).

Based on Ohm law in the differential form [22], for a rectilinear elementary section with a length dl_{cn} (see Fig. 1) of a conducting plasma channel of a high-voltage electric pulse spark discharge in the studied air DEDS, which corresponds to the specific electrical conductivity γ_{cn} of the gas dielectric, the following relation can be written:

$$\mathrm{d}l_{cn} = \gamma_{cn} \delta_{cn}^{-1} \mathrm{d}U_{cn}, \quad (3)$$

where δ_{cn} is the density of the discharge current in the channel of the high-voltage air electric spark discharge in its elementary section of the length dl_{cn}; dU_{cn} is the electric voltage drop in the elementary section with the length dl_{cn} of the plasma channel of the high-voltage pulse spark discharge in the air DEDS.

Then, from (3), for the total length l_c of the plasma channel of the high-voltage electrical pulse spark discharge in the studied air DEDS, in general form, we obtain:

$$l_c = \int_A^B \mathrm{d}l_{cn} = \int_A^B \gamma_{cn} \delta_{cn}^{-1} \mathrm{d}U_{cn}. \quad (4)$$

In the case of a continuous change in the plasma channel of an air pulse spark discharge, the value of the specific electrical conductivity γ_{cn} of its rectilinear elementary sections with length dl_{cn} and the invariance of the density $\delta_{cn} \approx \delta_c$ of the discharge current along the plasma spark channel, expression (4) has the following form:

$$l_c = \delta_c^{-1} \int_A^B \gamma_{cn} \mathrm{d}U_{cn}. \quad (5)$$

The maximum values of the specific electrical conductivity γ_{cn} of the low-temperature plasma, both from the beginning of the leader channel and further of the spark channel of the air discharge in the DEDS on its rectilinear elementary sections with length of $\mathrm{d}l_{cn}$, will correspond to their minimum electrical resistances. In this regard, the plasma leader (spark) channel of the pulse discharge in the air DEDS will spatially germinate (develop) to the place where it and the dielectric, which is under the action of the external high electric field of the discharge leader, will ensure the minimum value of the electric voltage drop $U_c=\int_A^B \mathrm{d}U_{cn}$. As an approximation of the fulfillment of the equality $\gamma_{cn}\approx\gamma_c$, which satisfies the largest current value of γ_{cn} on the path of propagation in the gas of the leader (spark) channel of the discharge, formula (5) for the real path of development of a high-voltage electrical pulse spark discharge in an air dielectric takes the form:

$$l_c = \gamma_c \delta_c^{-1} \int_A^B \mathrm{d}U_{cn} \ . \tag{6}$$

In the well-known formula (1), the integral $\int_A^B n_0 \mathrm{d}s$ determines the minimum value of the optical length L_0 of a real light beam in an optically transparent medium. In the obtained formula (6), the minimum value of the integral $\int_A^B \mathrm{d}U_{cn} = l_c\delta_c/\gamma_c$, which corresponds to the maximum value of γ_c, determines the minimum value of the total length $l_c=\int_A^B \mathrm{d}l_{cn}$ of the real plasma channel of the spark discharge in its specific conditions of spatial development in the gas dielectric. Therefore, when considering an electric discharge in a gas, we can say that for the electrophysical process of the development of a high-voltage electric pulse spark discharge in a gas dielectric, the physical laws of minimizing its main characteristics are also fulfilled, which lead to the minimization of energy consumption to support the flow of such a process in it.

We see that the proposed formula (6) for the development of a plasma channel of a high-voltage electric pulse spark discharge in a gas dielectric is close to the classical formula (1) for the propagation of light in an optically transparent medium in terms of its mathematical form and purpose. From the comparison of the obtained formula (6) for the total length l_c of the real path of the development of the plasma channel of a high-voltage electrical pulse spark discharge in the air DEDS during an electrical breakdown of its gap and formula (1), which corresponds to the Fermat physical principle, which determines the minimum optical length L_0 during the propagation of a real light beam in an optically transparent medium, it can be concluded that the total length l_c of a real plasma channel of a high-voltage electrical pulse spark discharge in an air dielectric between the points of its beginning A and ending B corresponds to the minimum drop of electric voltage on it $U_c=\int_A^B \mathrm{d}U_{cn}$.

Taking into account the above, the proposed physical principle of the development of the plasma channel of a high-voltage electric pulse spark discharge in relation to the studied air DEDS can be formulated as follows: «*The plasma channel of a pulse spark discharge in a gas dielectric spreads from one point to another along the path of length l_c, which provides the smallest drop in it of electric voltage U_c*». For the calculated quantitative assessment, taking into account the proposed formula (6), the drop in electric voltage $U_c=\int_A^B \mathrm{d}U_{cn}$ on the total length l_c of the real path of development in the homogeneous gas dielectric of the studied DEDS of a plasma channel of a high-voltage pulse spark discharge, we use the following approximate relationship from the field of HPT [5]:

$$l_c \approx (\varphi_{1d} - \varphi_2) / E_d \ . \tag{7}$$

When φ_2=0, from (6) and (7), for the drop in electric voltage U_c over the total length l_c of the real path of development in the gas dielectric of the plasma channel of a high-voltage electrical pulse spark discharge, in the accepted approximation, we obtain the expression:

$$U_c \approx \int_A^B \mathrm{d}U_{cn} \approx \delta_c \varphi_{1d} / (\gamma_c E_d) \ . \tag{8}$$

By substituting into formula (8) calculated and experimental numerical data for a high-current plasma channel of a pulse spark discharge in atmospheric air ($\delta_c\approx5.8\cdot10^7$ A/m^2; $\gamma_c\approx1625$ $(\Omega\cdot\text{m})^{-1}$; $\varphi_{1d}\approx611.6$ kV; $E_d\approx400$ kV/m), obtained by the author in the electric circuit of a powerful high-voltage test electrical equipment [23-25] containing the investigated DEDS ($l_{\min}$ =1.5 m), we find that the desired value of the electric voltage drop U_c on the total length $l_c>l_{\min}$ of the real path of development in the accepted air environment of the plasma channel of the high-voltage pulse spark discharge is numerically approximately $U_c\approx54.6$ kV. As we can see, $U_c=\int_A^B \mathrm{d}U_{cn} \ll (\varphi_{1d} - \varphi_2)$. The calculated numerical value of the electric voltage drop $U_c\approx54.6$ kV obtained from (8) on the high-current plasma channel of an air pulse spark discharge does not exceed 9 % of the level of the breakdown electric voltage $U_{12d}(t)\approx\varphi_{1d}\approx611.6$ kV (φ_2=0) in this DEDS. This calculated value of $U_c\approx54.6$ kV correlates well with the experimental result for $U_c\approx I_{mc}R_{c0}l_{\min}\approx53.6$ kV given by the author in [24] regarding a high-voltage, high-current pulse spark discharge in a tip-plane DEDS with a long air gap ($l_{\min}$= 1.5 m; the amplitude of the pulse discharge current $I_{mc}\approx213.9$ kA, which corresponds to the time $t_{mc}\approx38$ µs, during the electrical breakdown of the air gap in this DEDS; the running active resistance $R_{c0}\approx0.167$ Ω/m of the plasma channel of the air spark discharge in the DEDS). The reliability of these experimental results is indicated by the author's calculated estimates of some parameters for this applied electrophysical case (for example, the maximum radius r_{mc}≈34.27 mm of the plasma channel of the spark discharge in atmospheric air; the amplitude of the current density δ_{mc} in the discharge channel $\delta_{mc}≈I_{mc}/(\pi r_{mc}^2)≈5.79·10^7$ A/m^2; the value of the specific electrical conductivity γ_c of its low-temperature plasma $\gamma_c≈(\pi r_{mc}^2 R_{c0})^{-1}≈1624$ $(\Omega·m)^{-1}$) of electric discharge processes in the studied high-current plasma channel of pulse spark discharge in air DEDS using the Brahinsky formula for the radius r_{mc} of the plasma channel [6, 8].

The results of mathematical modeling of electric discharge processes in homogeneous liquid and solid dielectrics using the investigated DEDS and the existing mechanisms of their electrical breakdown [5, 7] will fundamentally not differ in anything (except for the numerical values of the parameters l_c, γ_c, δ_c, φ_{1d}, E_d and U_c) from those given above calculation results for the development of a plasma channel of a pulse spark discharge in a homogeneous air dielectric DEDS (see Fig. 1). Therefore, in the first approximation, the calculated relation (6) and the physical principle of the development of the plasma channel of a high-voltage electrical pulse spark discharge in a gas, based on it, proposed by the author, can be applied also for homogeneous liquid and solid dielectrics.

3. Results of an experimental study of the development of a plasma channel of a pulse spark discharge in an air DEDS. In order to verify some obtained approximate calculation results for electric discharge processes in air DEDS, appropriate experiments were performed using powerful high-voltage high-current test equipment of the Research and Design Institute «Molniya» of NTU «KhPI» [25]. Figure 2 shows the general view of the studied tip-plane DEDS with a discharge air gap of length l_{min}=1.5 m.

Fig. 2. The general view of the tip-plane air DEDS with a discharge gap of length l_{min}=1.5 m (the tip on a vertically placed steel electrode-rod with a diameter of 30 mm has a radius of rounding of its edge ~1 mm; the horizontal plane of the electrode is 5 m × 5 m made of thin galvanized steel sheets)

Figure 3 shows an experimental oscillogram of a complete standard switching aperiodic high-voltage pulse of the time shape T_m/T_d≈200 µs/1990 µs of positive polarity, which acts in the discharge circuit of the high-voltage, high-current test electrical equipment based on the GIN-4 generator [25] on the investigated tip-plane DEDS without electrical breakdown of its air gap of length l_{min}=2 m, and Figure 4 shows an oscillogram of a truncated similar high-voltage voltage pulse with an electrical breakdown of the air discharge gap in the tip-plane DEDS of length l_{min}=1,5 m.

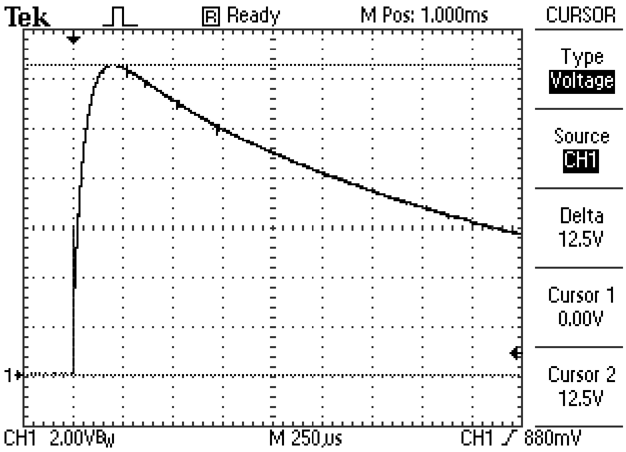

Fig. 3. Oscillogram of a complete standard switching aperiodic voltage pulse of the time shape T_m/T_d≈200 µs/1990 µs of positive polarity without electrical breakdown of the air gap of length l_{min}=2 m in the tip-plane DEDS ($U_m≈\varphi_{1m}$≈12.5 V × 53650≈670.6 kV – amplitude of the voltage pulse; T_m≈200 µs – time of rise of the pulse to the voltage amplitude U_m; T_d≈1990 µs – voltage pulse duration at the level of 0.5 U_m; vertical scale – 107.3 kV/div; horizontal scale – 250 µs/div)

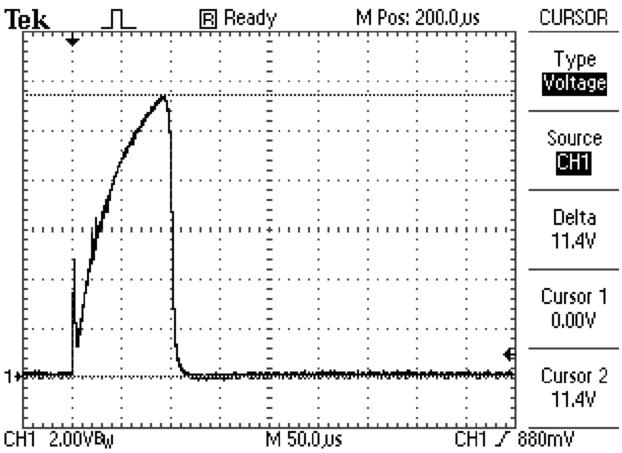

Fig. 4. Oscillogram of a truncated standard switching aperiodic voltage pulse of the time shape T_m/T_d≈200 µs/1990 µs of positive polarity during electrical breakdown of an air gap of length l_{min}=1.5 m in a tip-plane DEDS ($U_{md}≈\varphi_{1d}$≈11.4 V × 53650≈611.6 kV – voltage pulse cut-off level; T_c ≈95 µs – voltage pulse cut-off time; T_{dc}≈17 µs – duration of the cut-off of the voltage pulse, which corresponds to the time t_d of the propagation of the conductive channel of the leader of the electric pulse discharge in the air gap of the DEDS of length l_c between its potential and grounded metal electrodes; vertical scale − 107.3 kV/div; horizontal scale – 50 µs/div)

Let us point out that when measuring the ATPs shown in Fig. 3, 4 of high-voltage test switching aperiodic voltage pulses, which are intended for the experimental study of the development of the plasma channel of the electric pulse spark discharge in the air tip-plane DEDS (see Fig. 2), an ohmic voltage divider of the OPN-2.5 type was used (for a maximum voltage of up to 2.5 MV with a division factor of K_d≈53650 [25]) and a Tektronix TDS 1012 digital oscilloscope.

Figure 5 shows the general view of a high-current plasma channel of a high-voltage electric pulse spark discharge, which glows brightly in the atmospheric air, in the investigated tip-plane DEDS with the length of the air discharge gap $l_{\min}$=1.5 m, obtained in the summer of 2023 during the experimental determination of electrical strength of air insulation more than 1 m long with the use of ultra-high-voltage equipment of the experimental range of the Research and Design Institute «Molniya» of NTU «KhPI» [25].

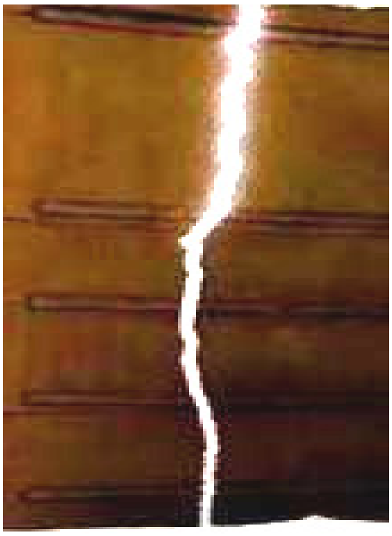

Fig. 5. General view of a high-current plasma channel of a high-voltage electric pulse spark discharge in a tip-plane DEDS with atmospheric air during electrical breakdown of its air gap of length l $l_{\min}$=1.5 m by a standard switching aperiodic voltage pulse of the time shape T_m/T_d≈200 μs/1990 μs of positive polarity (U_{md}≈φ_{1d}≈611.6 kV; T_c≈95 μs – voltage pulse cut-off time; T_{dc}≈17 μs – duration of voltage pulse cut-off, which characterizes the time of rapid shortening by the conductive plasma leader channel of a pulsed discharge of a long air gap in the DEDS)

From the experimental data (Fig. 5), we can see that in the used tip-plane DEDS ($l_{\min}$=1.5 m; φ_2=0) a real high-current plasma channel of a high-voltage pulse spark discharge in air under normal atmospheric conditions [19] is characterized by a zigzag geometric shape (l_c>$l_{\min}$). This is indicated also by the calculated numerical estimates according to (6) taking into account (8) at φ_{1d}≈611.6 kV and E_d≈400 kV/m of the total length l_c of the spark discharge channel in the studied air DEDS ($l_{\min}$=1.5 m): l_c≈φ_{1d}/E_d≈1.53 m. This unequivocally indicates that during the electrical breakdown of the gas (air) dielectric, the main part of the plasma leader channel of the pulse discharge, which glows brightly, spatially grows into those areas of the specified dielectric located between the potential 1 and grounded 2 electrodes (Fig. 1) of the investigated DEDS, which have the highest specific electrical conductivity γ_{cn} and, accordingly, the lowest electrical resistance in the specific conditions of such an electrical breakdown of this insulation. In this regard, this experimental result from the field of HPT indicates the reliability of the basic physical provision associated with the orientation of the main part of the leader channel of the discharge during its germination, adopted by the author in the development of the proposed physical principle of the development of the high-voltage plasma channel of a pulse spark discharge in the studied gas dielectric to those sections of it that are characterized by the highest specific electrical conductivity γ_{cn} at the given moment of time.

And if this is so, then the physical principle of the development of a plasma channel of a pulse spark discharge in it, formulated in this work in relation to a gas dielectric, which indicates the spread in this type of dielectric first of the leader and then of the spark channels of the discharge along the path with the smallest drop in the electric voltage U_c, is also confirmed the results of these high-voltage, high-current experiments performed with the author's participation. In addition, the experimental data obtained according to Fig. 4 at U_{md}≈(φ_{1d}–φ_2)≈611.6 kV testify to the fact that when using in the investigated air tip-plane DEDS ($l_{\min}$=1,5 m; φ_2=0) of a standard switching aperiodic pulse of high voltage of the time shape T_m/T_d ≈200 μs/1990 μs of positive polarity, the average breakdown voltage of the high electric field E_d≈φ_{1d}/l_c for atmospheric air in this DEDS at U_{md}≈φ_{1d}≈611.6 kV and l_c≈1.53 m is numerically approximately E_d≈400 kV/m with a tolerance of ±3 %, which is mainly determined by the minimum measurement error of the test high pulse voltage from powerful ultra-high-voltage electrical equipment using an ohmic voltage divider of the OPN-2.5 type (K_d≈53650 [25]) and the applied digital Tektronix TDS 1012 oscilloscope.

Experimental data according to Fig. 4 also indicate that the plasma leader channel of the electric discharge in the studied air DEDS ($l_{\min}$=1.5 m) has a total path length of l_{cm}≥l_c≥1.53 m, where l_{cm} is the maximum length of the actual path of the gas discharge in the DEDS, from the potential electrode to the grounded electrode of this DEDS passes through the air during the time t_d, which is numerically equal to about t_d≈T_{dc}≈17 μs. It is during the time T_{dc}≈17 μs that the conductive plasma leader channel of the pulse discharge shortens the air gap in the investigated DEDS ($l_{\min}$=1.5 m) and equalizes the electric potentials (φ_1≈φ_2≈0) on its metal electrodes (see Fig. 4). According to the developed physical principle of the development of the plasma channel of an electric pulse spark discharge in a gas dielectric at the average speed v_L of the advance in the air of the leading edge of the leader in the channel of this electric discharge, quantitatively equal to v_L≈10^5 m/s [8], the calculated numerical value for the specified time t_d relative to of atmospheric air in this DEDS is found at l_c≈1.53 m equal to t_d≈l_c/v_L≈15.3 μs. As we can see, the calculated numerical value obtained for the time parameter t_d≈15.3 μs differs from its corresponding experimental value t_d≈T_{dc}≈17 μs according to the oscillogram in Fig. 4 for a truncated standard switching aperiodic high-voltage pulse of the time shape T_m/T_d ≈ 200 μs/1990 μs of positive polarity during electrical breakdown of the air gap of length l_c in the tip-plane DEDS (l_{min} =1.5 m) within 11 %. Note that at T_{dc}≈17 μs, the maximum length l_{cm} of the real path of the plasma channel of the gas discharge in the studied DERS will be approximately equal to l_{cm}≈$v_L T_{dc}$≈1.7 m. The calculated numerical value of l_c≈1.53 m obtained above differs from this experimental value of l_{cm} by more than 11 %. These computational and experimental data also indicate the reliability of the basic initial physical assumptions adopted in the work and the calculated results obtained on their basis, which relate to the physics of the development of electric discharge processes in a homogeneous gas dielectric of the investigated DEDS and the quantitative selection according to formulas (6), (7) of the total the length l_c of the real path of the development of the plasma channel of the high-voltage electric pulse spark discharge in the atmospheric air of this DEDS.

It is important to note that the minimum value of the voltage drop U_c along the length l_c of the real path of development in the air of the plasma channel of the pulse spark discharge will be conditioned by (6) and the minimum value of l_c. At a constant average speed v_L of propagation in the atmospheric air of the leading front of the leader in the plasma channel of the gas discharge (v_L≈10^5 m/s [8]), the minimization of the length l_c will also lead to the minimization of the time t_d of the advancement of both the plasma leader and the spark channel of the pulse discharge in the investigated air DEDS (l_{min}=1.5 m).

Conclusions.

1. A generalized physical principle of the development of a plasma channel of a high-voltage electrical pulse spark discharge in a homogeneous dielectric of a different aggregate state, mathematically written for the total length $l_c=\int_A^B dl_{cn}$ of the real path of the development of this type of electric discharge along rectilinear elementary sections of the plasma channel with a length of dl_{cn} of different spatial orientation in the gas dielectric of the accepted double-electrode discharge system (DEDS) with the smallest length l_{min} of its discharge gap is proposed. This principle (physical law) indicates that in DEDS the plasma channel of a high-voltage electric pulse spark discharge in gas, liquid and solid dielectrics spreads from its starting point A on the potential electrode of DERS to the ending point B on the grounded electrode of DEDS along a path that provides the smallest drop of electric voltage on it $U_c=\int_A^B dU_{cn}$, where dU_{cn} is the drop of electric voltage on the rectilinear elemental section of the plasma discharge channel of length dl_{cn}<<l_{min}.

2. It is shown that the proposed physical principle of the development of the plasma channel of an electric pulse spark discharge in the studied gas dielectric of the DEDS is by mathematical form and purpose close to the Fermat fundamental physical principle, which is a general law of geometric optics and which determines the minimum optical length $L_0=\int_A^B n_0 ds$ when propagating a real light beam in an optically transparent medium with the index of refraction of light n_0 between the starting point A and the ending point B of its propagation in this medium, where ds is the length of the elementary section of the propagation of the light beam in an optically transparent medium.

3. By calculation, it was established that the drop in electric voltage U_c on the total length l_c of the real zigzag path of development in the air dielectric of the investigated tip-plane DEDS (l_{min}=1.5 m) of the plasma channel of the high-voltage electric pulse spark discharge for a standard switching aperiodic pulse of high voltage of time shape T_m/T_d≈≈200 μs/1990 μs of positive polarity satisfies the inequality of the form U_c<<(φ_{1d}–φ_2) and at φ_{1d} ≈611.6 kV (φ_2 =0) it numerically amounts to U_c≈54.6 kV, which does not exceed 9 % of the experimental level of breakdown electric voltage $U_{12d}(t)$≈(φ_{1d}–φ_2)≈611.6 kV in this DEDS with atmospheric air. Here, the indicated calculated level of electric voltage drop U_c≈54.6 kV on this plasma channel of the spark discharge practically corresponds to the previously obtained experimental numerical level of electric voltage drop U_c≈53.6 kV on it in a similar air DEDS.

4. High-voltage, high-current experiments carried out on the powerful electrophysical equipment of the Research and Design Institute «Molniya» of NTU «KhPI» for the tip-plane aerial DEDS under investigation (l_{min}=1.5 m; φ_2=0), which tests the effect of a standard switching aperiodic high-voltage pulse of the time shape T_m/T_d≈200 μs/1990 μs of positive polarity, confirm the validity of the basic physical conditions underlying the developed generalized principle of the development of a plasma channel of a pulse spark discharge in a dielectric (on the example of atmospheric air in the DEDS), and some calculated results obtained for it (in particular, for the numerical values of the electric voltage drop U_c on the total length l_c of the real path of development in the atmospheric air of the plasma channel of the pulse spark discharge and the average breakdown voltage E_d for the atmospheric air of the high electric field E_d≈φ_{1d}/l_c≈400 kV/m under the conditions of action on the air DEDS of the specified a microsecond voltage pulse, as

well as for quantitative data of the total length l_c of the real path of the development of the plasma discharge channel $l_c \approx 1.53$ m, which confirm the fulfillment of the inequality of the form $l_c > l_{\min}$, which determines the zigzag shape of the development in atmospheric air of both the plasma leader discharge channel and further a similar shape of development of a high-voltage electric pulse spark discharge channel in this dielectric).

5. It is shown that the calculated time t_d of the advancement of the plasma leader channel of an electric pulse spark discharge in the investigated air DEDS ($l_{\min}$=1.5 m) along its real path in atmospheric air with a total length of $l_c \approx 1.53$ m at the average speed of propagation in this air of the front of the leader in the discharge plasma channel $v_L \approx 10^5$ m/s is numerically about $t_d \approx l_c / v_L \approx 15.3$ µs. This calculated result for the time t_d differs by no more than 11 % from the experimental duration of the cut-off $T_{dc} \approx t_d \approx 17$ µs, which characterizes the time of shortening by the electrically conductive plasma leader channel of the discharge of the air gap of length l_c in the DEDS, for a standard switching aperiodic pulse of high voltage of the time shape $T_m/T_d \approx 200$ µs/1990 µs of positive polarity ($\varphi_{1d} \approx 611.6$ kV) in the investigated DEDS with the minimum length of its discharge air gap equal to $l_{\min}$=1.5 m.

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REFERENCES

1. Dashuk P.N., Zayents S.L., Komel'kov V.S., Kuchinskiy G.S., Nikolayevskaya N.N., Shkuropat P.I., Shneerson G.A. *The technique of large pulsed currents and magnetic fields*. Moscow, Atomizdat Publ., 1970. 472 p. (Rus).
2. Knopfel' G. *Ultra strong pulsed magnetic fields*. Moscow, Mir Publ., 1972. 391 p. (Rus).
3. Gulyy G.A. *Scientific basis of the discharge-pulse technologies*. Kyiv, Naukova Dumka Publ., 1990. 208 p. (Rus).
4. Mesiats G.A. *Generation of power nanosecond pulses*. Moscow, Soviet Radio Publ., 1974. 256 p. (Rus).
5. Brzhezitsky V.O., Biliy I.V., Boiko M.I., Gul' V.I., Gurin A.G., Il'enko O.S., Isakova A.V., Kondra B.M., Kopshin V.O., Kravchenko V.I., Naboka B.G., Protsenko O.R., Rudakov V.V., Khymenko L.T., Khominich V.I., Shostak V.O., Yanishevsky V.I. *Technique and Electrophysics of High Voltages*. Kharkiv, NTU «KhPI», Tornado Publ., 2005. 930 p. (Ukr).
6. Lozanskyi E.D., Firsov O.B. *Theory of spark*. Moscow, Atomizdat Publ., 1975. 272 p. (Rus).
7. Ushakov V.Ja. *Pulse electrical breakdown of liquids*. Tomsk, TSU Publ., 1975. 255 p. (Rus).
8. Rayzer Yu.P. *Physics of gas discharge*. Moscow, Nauka Publ., 1987. 592 p. (Rus).
9. Vovchenko A.I., Bohuslavsky L.Z., Myroshnychenko L.N. Trends in development of high-powered high-voltage pulse current generators in the Institute of Pulse Processes and Technology of Ukraine (review). *Technical electrodynamics*, 2010, no. 5, pp. 69-74. (Rus).
10. Baranov M.I., Buriakovskyi S.G., Kniaziev V.V. A calculation of basic thermophysical, gasodynamic and electropower parameters of electric explosion is in the gas environment of metallic explorer. *Electrical Engineering & Electromechanics*, 2023, no. 1, pp. 40-50. doi: https://doi.org/10.20998/2074-272X.2023.1.06.
11. Boyko N.I., Evdoshenko L.S., Zarochentsev A.I., Ivanov V.M., Tour A.N. High-Voltage Spark Gaps for Technological Purposes. *Instruments and Experimental Techniques*, 2001, vol. 44, no. 2, pp. 204-212. doi: https://doi.org/10.1023/A:1017515003483.
12. Podoltsev A.D., Kucheryavaya I.N. *Multiphysics Modeling in Electrical Engineering*. Kyiv, Institute of Electrodynamics of the NASU of Ukraine, 2015. 305 p. (Rus).
13. Niemeyer L., Pietronero L., Wiesmann H.J. Fractal Dimension of Dielectric Breakdown. *Physical Review Letters*, 1984, vol. 52, no. 12, pp. 1033-1036. doi: https://doi.org/10.1103/PhysRevLett.52.1033.
14. Wiesmann H.J., Zeller H.R. A fractal model of dielectric breakdown and prebreakdown in solid dielectrics. *Journal of Applied Physics*, 1986, vol. 60, no. 5, pp. 1770-1773. doi: https://doi.org/10.1063/1.337219.
15. Kebbabi L., Beroual A. Fractal analysis of creeping discharge patterns propagating at solid/liquid interfaces: influence of the nature and geometry of solid insulators. *Journal of Physics D: Applied Physics*, 2006, vol. 39, no. 1, pp. 177-183. doi: https://doi.org/10.1088/0022-3727/39/1/026.
16. Hu H.M., Yang Y., Lu W., Zhao G.P. Electrical Tree Simulation Based on the Self-Organization Criticality. *Energy and Power Engineering*, 2013, vol. 5, no. 4, pp. 1273-1276. doi: https://doi.org/10.4236/epe.2013.54B241.
17. Pashchenko A.V., Maslov V.I., Naugolnij I.N. Fractal phenomenological theory of impulse breakdown of liquid and solid dielectrics. *Digest of Technical Papers. Tenth IEEE International Pulsed Power Conference*, 1995, vol. 2, pp. 863-868. doi: https://doi.org/10.1109/PPC.1995.599720.
18. Gladkov V.S., Maslov V.I., Naugolniy I.N., Pashchenko A.V. To the Problem of the Physical Model of the Fractal Discharge in Liquid and solid Dielectric. *Bulletin of National Technical University «Kharkiv Polytechnic Institute»*, 2002, vol. 1, no. 7, pp. 81-85.
19. Kuhling H. *Handbook of Physics*. Moscow, Mir Publ., 1982. 520 p. (Rus).
20. *Standard GOST 1516.2-97. Electrical equipment and installations for a.c. voltages 3 kV and higher. General methods of dielectric tests*. Minsk, Intergovernmental Council of Standardization, Measuring and Certification Publ., 1997. 31 p. (Rus).
21. Baranov M.I., Koliushko G.M., Kravchenko V.I. A switching aperiodic superhigh-voltage pulse generator for testing the electric strength of insulation of technical objects. *Instruments and Experimental Techniques*, 2013, vol. 56, no. 6, pp. 653-658. doi: https://doi.org/10.1134/S0020441213050126.
22. Kuz'michev V.E. *Laws and formulas of physics*. Kyiv, Naukova Dumka Publ., 1989. 864 p. (Rus).

23. Baranov M.I., Koliushko G.M., Lysenko V.O. Experimental determination of active resistance and conductivity of heavy-current plasma channel in the discharge chain of generator impulsive components of current of artificial lightning. *Electrical Engineering & Electromechanics*, 2011, no. 3, pp. 51-55. (Rus).
24. Baranov M.I. *Selected topics of Electrophysics. Monograph in 4 Vols. Vol. 3. Theory and practice of electrophysics tasks*. Kharkiv, Tochka Publ., 2014. 400 p. (Rus).
25. Baranov M.I., Buriakovskyi S.G., Kniaziev V.V., Rudenko S.S. Analysis of characteristics and possibilities of high-voltage electrical engineering complex Scientific-&-Research Planning-&-Design Institute «Molniya» of NTU «KhPI» for the tests of objects of energy, armament, aviation and space-rocket technique on electric safety and electromagnetic compatibility. *Electrical Engineering & Electromechanics*, 2020, no. 4, pp. 37-53. doi: https://doi.org/10.20998/2074-272X.2020.4.06.

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