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The main characteristics of the leader channel during breakdown of a long air gap by high pulse voltage

Goal. *Calculation-experimental determination of basic descriptions of plasma channel of leader at an electrical breakdown of long air gap in the double-electrode discharge system (DEDS) «edge-plane» by artificial electricity of high pulse voltage of positive polarity.* ***Methodology.*** *Bases of the theoretical electrical engineering and electrophysics, electrophysics bases of technique of high and extra-high voltage, large pulse currents and high electromagnetic fields, basis of high-voltage pulse and measuring technique.* ***Results.*** *The simplified electrophysics model of origin and development of positive leader is offered in the long air gap of probed DEDS, which the followings descriptions of plasma channel of this positive leader were found on the basis of: a closeness of n_{eL} charge and electric potential U_{eL} in the head of leader; linear charge q_{Ll} of leader of plasma channel; closeness δ_{eL} of electron current i_{eL} and this current i_{eL} in the channel of leader; strength of high electric field outside E_{Le} and inwardly E_{Li} of the channel of leader; length l_s of streamer area before the head of leader; maximal electron temperature T_{mL} in plasma of channel of leader; linear active resistance R_{Ll} and active resistance R_{Lc} of channel of leader. Executed on a domestic powerful over-high voltage electrical equipment outdoors in the conditions of electrophysics laboratory high-voltage experiments with the use of standard interconnect aperiodic pulse of voltage $U_e(t)$ of temporal shape of T_m/T_p≈200 μs/1990 μs of positive polarity for probed DEDS at a change in it of minimum length l_{min} of its discharge in air gap in the range of 1 m≤l_{min}≤4 m confirmed power and authenticity of row of the got calculation correlations for the indicated descriptions of plasma channel of positive leader which is formed and develops in this DEDS.* ***Originality.*** *In a complex kind calculation-experimental way the indicated basic descriptions of plasma channel of positive leader are certain in probed DEDS. By calculation way it is first rotined that on the stage of development of positive leader in atmospheric air of indicated DEDS high electric potential U_{eL} of his spherical head with the charge of q_{eL}≈58,7 nC has a less value (for example, U_{eL}≈605 kV for length of his channel of l_L=0,395 m at l_{min}=1,5 m) the radius of R_{eL}≈0,5 mm, what high potential $U_e(t)$≈$U_e(T_d)$≈611,6 kV its active metallic electrode-edge. Obtained result for the maximal electron temperature T_{mL}≈1,639·10^4 K in plasma of the probed leader testifies that this plasma is thermo-ionized.* ***Practical value.*** *Practical application in area of industrial electrical power engineering, high-voltage pulse technique, techniques of high and extra-high voltage of the obtained new results in area of physics of gas discharge allows not only to deepen our electrophysics knowledges about a leader discharge in atmospheric air but also more grounded to choose the air insulation of power high and over-high voltage electrical power engineering and electrical engineering equipment, and also to develop different new electrical power engineering and electrophysics devices in area of industrial electrical power engineering and powerful pulse energy with enhanceable reliability and safety of their operation in the normal and emergency modes.* References 49, figures 7.

Key words: **long air gap, leader discharge, electrical breakdown of gap, plasma channel of positive leader, characteristics of positive leader.**

Надані результати розрахунково-експериментального визначення основних характеристик плазмового каналу позитивного лідера при електричному пробої довгого повітряного проміжку двоелектродної розрядної системи (ДЕРС) «вістря-площина» стандартним комутаційним аперіодичним імпульсом високої напруги часової форми T_m/T_d≈200 мкс/1990 мкс позитивної полярності. Запропоновано спрощену електрофізичну модель виникнення і розвитку позитивного лідера в довгому розрядному повітряному проміжку досліджуваної ДЕРС, на основі якої у комплексному вигляді були знайдені наступні основні характеристики плазмового каналу даного позитивного лідера: густина n_{eL} електронів і електричний потенціал U_{eL} в головці лідера; погонний заряд q_{Ll} лідерного плазмового каналу; густина δ_{eL} електронного струму i_{eL} і цей струм i_{eL} в каналі лідера; напруженості сильного електричного поля всередині E_{Li} і зовні E_{Le} каналу лідера; довжина l_s стримерної зони перед головкою лідера; максимальна електронна температура T_{mL} в плазмі каналу лідера; погонний активний опір R_{Ll} і повний активний опір R_{Lc} каналу лідера. Виконані на вітчизняному потужному надвисоковольтному електрообладнанні на відкритому повітрі в умовах електрофізичної лабораторії високовольтні експерименти підтвердили працездатність і достовірність низки отриманих розрахункових співвідношень для вказаних характеристик плазмового каналу позитивного лідера електричного розряду, який формується і розвивається в цій високовольтній повітряній ДЕРС. Бібл. 49, рис. 7.

Ключові слова: **довгий повітряний проміжок, лідерний розряд, електричний пробій проміжку, плазмовий канал позитивного лідера, характеристики позитивного лідера.**

State and relevance of the problem. According to the provisions of modern gas discharge physics, the electrical breakdown of both long (length l_d of the order of 1–10^2 m, which corresponds to the gas insulation of extra- and high-voltage electrical equipment), and ultra-long (length l_d of the order of (1–3)·10^3 m, which is characteristic of extra-high-voltage lightning discharges in the Earth's troposphere) air gaps occurs according to the leading electrophysical mechanism and ends with spark form of the discharge and their short-circuiting mode [1–4]. As a result of this breakdown, the gas medium of these gaps passes from a dielectric state in the zone of propagation of this discharge to an electrically conductive one by transforming it into plasma. At the same time, the leader discharge in atmospheric air has one characteristic property [1–3]: from a source of artificial (charged with high electric potential of the order of φ_e≈±1 MV metal electrode of an electrical device [1, 3]) or natural (charged in the Earth's troposphere thundercloud with extra-high electric potential of the order of φ_R≈±(100–500) MV [2, 5]) electricity, a thin (radius of about R_L≈0,5·10^{-3} m [1, 3]) plasma thermionic channel with main spherical part (head with radius R_{eL}≈R_L with excess charge q_{eL} of the corresponding polarity) that glows brightly, which in the electrophysics of high (extra-high) voltages is called a «leader». From the head of this leader towards the grounded metal electrode of the discharge electrical system or the surface of the earth with objects on it, when considering linear lightning, numerous streamers develop, which are capable of branching. After the head of the developed leader, which has an electric potential $\pm U_{eL}$, meets the grounded metal electrode (surface of the earth or ground technical object) to which it developed, the charge ±qeL of the leader head is neutralized and a stage of powerful reverse discharge occurs in the leader channel [1–3]. Further, with speed of about 10^7 m/s [1, 3] in the direction of the potential electrode of the specified systems, first a wave of potential removal in the leader channel with the disappearance of its charge $\pm q_L$ propagates, and then a wave of a large discharge pulse current, and finally, in place of a thin zigzag leader plasma channel with absolute temperature of the order of $T_{mL}\approx(5–10)\cdot 10^3$ K [3] of its plasma, a strongly ionized spark plasma channel with absolute temperature of the order of $(20–40)\cdot 10^3$ K and a maximum radius $r_{mk}>>R_L$, which is determined by the Braginsky formula [6, 7], with volumetric electron density n_{ei} in it of the order of $n_{ei}\approx(10^{21}–10^{23})$ m^{-3} [1, 3].

To date, from the published results of research on the leader and spark stages of electrical breakdown of long (ultra-long) air gaps in various discharge electrode systems (mainly in two-electrode extra- and high-voltage systems «tip-plane» and «thundercloud-ground»), high-current pulse discharges in gas and condensed media in the field of high-voltage technology (HVT), high-voltage pulse technology (HVPT) and atmospheric electricity with its huge reserves of electrical energy and powerful thunderstorm discharges according to [1–33], the questions that remain poorly studied are those related to the computational and experimental determination of the quantitative values of such basic characteristics of the leader plasma channel in atmospheric air as:

- electron density n_{eL} and electric potential U_{eL} in the leader head;
- linear electric charge q_{Ll} of the leader channel;
- density δ_{eL} of electron current i_{eL} and this current i_{eL} in the leader channel;
- high electric field strengths inside E_{Li} and outside E_{Le} of the leader channel;
- length l_s of the streamer zone in front of the leader head;
- maximum electron temperature T_{mL} in the plasma of the leader channel;
- linear active resistance R_{Ll} and total active resistance R_{Lc} of the leader channel.

Knowledge of the quantitative values of these characteristics of the zigzag plasma channel of the leader will contribute to the deepening of scientific knowledge about such a complex electrophysical phenomenon in nature as the electrical breakdown of long and ultra-long air gaps, which we need in practice for the well-founded design and engineering selection of high-voltage gas insulation of power electrical and electrical equipment for various ground and air technical facilities and their reliable protection against the striking action of linear lightning.

The **purpose** of the article is the computational and experimental determination of the main characteristics of the plasma channel of the leader during the electrical breakdown of a long air gap in a double-electrode discharge system (DEDS) «tip-plane» by artificial electricity of high pulse voltage of positive polarity.

1. Problem definition. Let us consider a high-voltage DEDS placed in the atmospheric air in the form of a «tip-plane» discharge system [3, 27]) with air gap of length l_d from the range 1 m$\leq l_d \leq$100 m, in which in the vertical direction from the potential metal electrode-rod of this DEDS with radius r_0 with pointed lower edge with the radius of its curvature $r_c<<r_0$ to its grounded metal electrode-plane, the development of the plasma channel of the positive leader with radius R_L is observed in time t (Fig. 1).

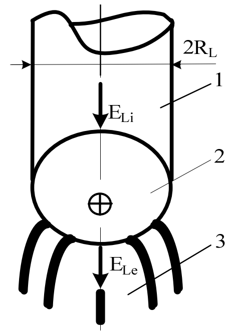

Fig. 1. Schematic representation of a positive leader during its development and movement in a long air gap of the tip-plane DEDS (1 − leader channel with radius R_L; 2 − leader head with radius $R_{eL}\approx R_L$; 3 − leader streamer zone)

Let the electric potentials of the specified electrodes of this DEDS, varying in time t, be equal to $\varphi_e(t)$ and $\varphi_0(t)\approx 0$, respectively, and the air placed between them corresponds to the following normal atmospheric conditions [34]: the pressure of its gas molecules is $P_a\approx(1,013\pm 0,03)\cdot 10^5$ Pa; their absolute temperature is $T_a\approx(273,15\pm 10)$ K; the relative humidity of these gases is $\gamma_a\approx(45\pm 30)$ %. We assume that the density $\rho(h)$ of air in the DEDS under consideration, in the first approximation, can be, depending on the height $h\approx l_d$ of its upper electrode location relative to the Earth's surface with potential φ_e of the order of 1 MV, described by the relation of the form [4]: $\rho(h)\approx\rho(0)exp(-h/H)$, where $\rho(0)\approx 1,293$ kg/m^3 is the air density at the Earth's surface [34], and $H\approx 7,5\cdot 10^3$ m is the height of the Earth's homogeneous troposphere [35]. Therefore, at $h\approx l_d\approx 100$ m, the ratio $\rho(h)/\rho(0)$ takes a numerical value of about 0,98. In connection with this, the influence of the density $\rho(h)$ of the atmospheric air in the DEDS under study on the value of the radius R_L of the plasma channel of the positive leader in it can be neglected in the case under consideration [3, 7].

We assume that the radius R_L of the leader channel in the DEDS is quantitatively determined in the first approximation by the level $R_L\approx 0,5$ mm [1]. This value for R_L corresponds to the known ratio for the maximum radius R_a of the electron avalanche head in air, which has the following form: $R_a\approx 0,5\ \alpha_i^{-1}$, where $\alpha_i\approx 10^3$ m^{-1} is the impact ionization coefficient of atmospheric air in the DEDS [1, 3]. It is known that the positive leader in the DEDS under study arises on the basis of a positive (cathode-directed) streamer developed in its air with significant heating of its channel by the current. This initial streamer with density of n_{es0} electrons in it originates in a spherical zone with radius of $r_i \approx x_i$ of active impact ionization by air electrons near the active electrode-tip of the DEDS, when the maximum electron temperature T_{ms} in its channel reaches a level near $T_{ms} \approx (5–10)\cdot 10^3$ K [3]. Therefore, this absolute temperature T_{ms} is also characteristic of the maximum electron temperature T_{mL} of the equilibrium plasma of the channel of the positive leader at the beginning of its emergence [3]. Let us consider the case of a multi-streamer-leader electric discharge in the air of a DEDS [1, 3], when near the electrode-tip of this DEDS, N_s of individual positive streamers with excess positive charge q_{es} in their heads simultaneously start from the spherical head with radius R_{eL} of the positive leader towards its grounded electrode-plane, the radius R_s of the plasma channel of which is much smaller than the radius R_L of the channel of the positive leader with excess positive charge q_{eL} of its head, which corresponds to the modulus of the electron density n_{eL} in it. We assume that at $q_{eL} \approx N_s q_{es}$ this density n_{eL} of electrons in the head with radius $R_{eL} \approx R_L \approx 0{,}5$ mm [1, 3] of the positive leader, which is formed in the spherical zone with radius $r_i \approx x_i$ of active impact ionization by air electrons near the electrode-tip of this DEDS, corresponds to the density n_{es} of electrons in the head of a separate positive streamer with radius $R_{es} << R_{eL}$ with the inequality $n_{es} << n_{eL}$ being fulfilled. According to [1, 3] the density n_{es0} of electrons in the initial developed positive streamer of the DEDS should be of the order $n_{es0} \approx 10^{19}$ m^{-3} and more. Under these physical conditions and the above-mentioned levels of temperature T_{ms} and electron density n_{es0} in the initial developed positive streamer in the spherical zone with radius $r_i \approx x_i$ near the potential electrode of the tip-plane DEDS, a positive leader can be formed, which will grow from this zone with velocity v_L into the long air gap of this DEDS with the help of individual positive streamers in their number N_s (see Fig. 1) and photoionization of atmospheric air molecules [1, 3, 15].

Let us limit ourselves to considering the electrophysical case when the rate of change in time t of the high voltage $U_e(t) \approx \varphi_e(t) - \varphi_0(t)) \approx \varphi_e(t)$ in the DEDS under study, during the electrical breakdown of its long air gap with length of 1 m $\leq l_d \leq$ 100 m, satisfies the inequalities of the form $\mathrm{d}U_e(t)/\mathrm{d}t \geq 5$ kV/μs [3] and the development of the positive leader in it occurs continuously, i.e. without the stepwise formation of the «tip-plane» of individual leader channels in the long discharge gap of this DEDS. This position regarding the specified electrophysical influence of the derivative $\mathrm{d}U_e(t)/\mathrm{d}t$ on the nature of the development of the positive leader in the atmospheric air of this DEDS for a separate case when the length l_d of this gap in the DEDS corresponded to the range 1 m $\leq l_d \leq$ 4 m, was confirmed by us experimentally using domestic ultrahigh-voltage equipment [4, 27].

It is necessary, taking into account the calculated and experimental data, to determine in an approximate form the main characteristics of the plasma channel of the positive leader in the DEDS under study, which include the values of the following physical indicators: electron density n_{eL} and electric potential U_{eL} in the head of the positive leader; linear charge q_{Ll} of the leader plasma channel; density δ_{eL} of electron current i_{eL} and this current i_{eL} in the leader channel; strong electric field strengths inside E_{Li} and outside E_{Le} of the leader channel with specific electrical conductivity E_{Le} of its plasma; length l_s of the streamer zone in front of the leader head; maximum electron temperature T_{mL} in the plasma of the leader channel; active resistance R_{Lc} of the leader channel.

2. Determination of the parameters of the zone of active impact ionization of air in the DEDS. As is known, diatomic oxygen molecules O_2 in the composition of the atmospheric air gases of the DEDS under study occupy up to 21 % of the working volume of its long discharge gap [34]. At the same time, according to the data of Table 1.6 from [3], the ionization energy $W_i \approx W_{i0}$ of oxygen molecules O_2 by electron impact is one of the smallest for the main atoms (molecules) of gases that make up the air of this DEDS, and is numerically about $W_{i0} \approx 12{,}5$ eV. For comparison, we note that for diatomic nitrogen molecules N_2, which occupy up to 78 % of the volume of the air gap of the DEDS «tip-plane» [34], the ionization energy of them by electron impact is about $W_i \approx W_{iN} \approx 15{,}6$ eV [3]. Therefore, the shortest duration of the process of ionization of air insulation gases in this DEDS by electron impacts will be determined by the ionization energy $W_i \approx W_{i0}$ of its diatomic oxygen molecules O_2. Taking this into account, in further calculations of the process of active impact ionization by electrons of atmospheric air in the studied DEDS, we will limit ourselves to using the ionization energy W_{i0}, which is characteristic of its oxygen molecules O_2.

Let us consider the case when the process of avalanche-like electron propagation in the atmospheric air of the DEDS under study is carried out due to the impact ionization of this air under the influence of one initial electron (N_0=1) for gas-discharge plasma formations, which are caused by the action of an ultra-strong electric field in a spherical zone with radius of $x_i \approx r_i$ of active air ionization by electron impacts near the DEDS electrode-tip. In this electrophysical process at the edge of this zone with radius of $x_i \approx r_i$ of active ionization by electrons of atmospheric air, located near the potential metal electrode of the DEDS, the number of electrons N_x in the head of the developed positive streamer, which is formed in this zone due to the specified process of their multiplication, in the first approximation will be described by the dependence [1, 3]: $N_x \approx N_0 exp(\alpha_i^* x_i)$, where $\alpha_i^* = (\alpha_i - \eta)$ is the effective coefficient of impact ionization of air in the DEDS, and η is the coefficient of electron adhesion in the air of this DEDS.

Electrons with their charge modulus $e_0 = 1{,}602\cdot 10^{-19}$ C and rest mass $m_e = 9{,}109\cdot 10^{-31}$ kg [34] between their two successive collisions with effective frequency v_m with atoms or molecules of air (for example, oxygen O_2) in the DEDS under study, gain near the potential electrode-tip of this DEDS in its superstrong electric field with averaged strength E_x a drift velocity of approximately $v_{ed} \approx e_0 E_x/(m_e v_m)$ and, accordingly, an energy $W_e \approx e_0 E_x v_{ed}/v_m$ [1], which for the condition of the beginning of the process of active ionization of this air must be at least equal to the ionization energy $W_i \approx W_{i0}$ of its oxygen molecules O_2. Therefore, from the equality $W_e \approx W_{i0} \approx e_0^2 E_{xk}^2/(m_e \nu_m^2)$ one can obtain a calculated expression for the averaged value of the critical strength E_{xk} of the electric field at the edge of the ionization zone of the atmospheric air under consideration. This value turns out to be equal to $E_{xk} \approx e_0^{-1} \nu_m (m_e W_{i0})^{1/2}$. At $\nu_m \approx 2{,}96 \cdot 10^{12}$ s^{-1} [1] and $W_{i0} \approx 12{,}5$ eV [3] the critical electric field strength E_{xk} in the DEDS under study takes a quantitative value of about $E_{xk} \approx 24{,}9 \cdot 10^6$ V/m. In this case, the drift velocity $v_{ed} \approx e_0 E_{xk}/(m_e \nu_m)$ of electrons at this edge of the spherical zone with radius $x_i \approx r_i$ of active impact ionization of air near the potential electrode of the DEDS is equal to $v_{ed} \approx 1{,}48 \cdot 10^6$ m/s.

According to [1], the coefficient η of electron adhesion to molecules for the atmospheric air we have adopted in the DEDS under study, with the frequency of their adhesions $\nu_\eta \approx 10^8$ s^{-1} and the electron drift velocity $v_{ed} \approx 1{,}48 \cdot 10^6$ m/s in the plasma of the positive streamer discharge channel in the DEDS, takes a numerical value of about $\eta \approx \nu_\eta / v_{ed} \approx 67$ m^{-1}. Therefore, with $\alpha_i \approx 10^3$ m^{-1} [1, 3], the influence of electron adhesion on their propagation in the air of this DEDS can be neglected, and the parameter α_i^* depending on the number of electrons N_x in the head of the developed positive streamer in the specified zone of its ionization is taken equal to α_i.

Let us indicate that the radius $x_i \approx r_i$ of the zone of active impact ionization of atmospheric air molecules by electron impacts near the potential electrode-tip of the DEDS is determined by the following calculated expression: $x_i \approx r_i \approx U_{ed}/E_{xk} \approx U_{ed} e_0 \nu_m^{-1} (m_e W_{i0})^{-1/2}$, where U_{ed} is the voltage of the appearance of a continuous positive leader in the air DEDS [3]. According to formula (5.35) from [3], the voltage U_{ed} in the studied DEDS is determined by the approximate expression: $U_{ed} \approx E_{e0} l_{\min}/k_c$, where $E_{e0} \approx 23[1+1{,}22(r_{ec})^{-0{,}37}]$ with the dimension (kV/cm) is the initial electric field strength in the DEDS at the edge of its metal electrode-tip with the equivalent radius of its curvature $r_{ec} \approx r_c$, and $k_c \approx (14+1{,}5 l_{\min})$ with the dimension of the minimum length $l_{\min}$ of the DEDS air gap in (m) is the critical value of the dimensionless coefficient of electric field heterogeneity in the DEDS. We see that the electric voltage U_{ed} in the DEDS «tip-plane» depends both on the length of the air gap $l_d \approx l_{\min} \geq 1$ m in the DEDS, and on the geometry (curvature) of the edge of its potential electrode-tip. With the increase in the length $l_{\min}$ of the gap in the DEDS, its influence on the voltage U_{ed} decreases. We note that the reliability of this calculation expression for $x_i \approx r_i$ in the DEDS under consideration, at 1 m $\leq l_d \leq$ 4 m, was confirmed by us experimentally [4, 27].

For the electrophysical case, when in the high-voltage DEDS the «tip-plane» is investigated, at $r_{ec} \approx r_c \approx 3$ mm ($r_0 \approx 15$ mm) and the electrical breakdown of its air gap with minimum length $l_d = l_{\min} = 1{,}5$ m, which corresponds to the length of the straight line drawn from the tip of the potential electrode of the DEDS along the normal to the flat surface of its grounded plane, the calculation voltage U_{ed} according to the above-mentioned relations from [3] is numerically equal to about $U_{ed} \approx 616{,}6$ kV. Note that in this case, the experimental breakdown (discharge) voltage U_d for a switching aperiodic voltage pulse of the time shape $T_m/T_p \approx 200$ μs/1990 μs of positive polarity (T_m, T_p are, respectively, the time corresponding to the amplitude U_{em} and the duration of the voltage pulse $U_e(t)$ in the DEDS at the level of $0{,}5U_{em}$) took the quantitative value $U_d \approx 611{,}6$ kV [4, 27], which differs from the calculated value $U_{ed} \approx 616{,}6$ kV within 1 %. Therefore, at $\nu_m \approx 2{,}96 \cdot 10^{12}$ s^{-1} [1], $U_{ed} \approx 616{,}6$ kV and $W_{i0} \approx 12{,}5$ eV [3], which is characteristic of electron impact ionization of oxygen molecules O_2 in the atmospheric air of the studied DEDS ($\alpha_i \approx 10^3$ m^{-1} [1, 3]), the radius of the spherical zone of active ionization by electron impacts of air near its potential metal electrode-tip takes the numerical value $x_i \approx r_i \approx 24{,}7$ mm.

According to [1, 3], taking into account the above calculated relations, the density n_{es0} of electrons in the head of a developed positive streamer with radius $R_{es} \approx 0{,}5\alpha_i^{-1} \approx 0{,}5$ mm, which is formed in a spherical zone with radius $x_i \approx r_i \approx 24{,}7$ mm ($U_{ed} \approx 616{,}6$ kV) of active impact ionization of air by electrons near the electrode-tip of the DEDS, $N_0 = 1$ and $\alpha_i \approx 10^3$ m^{-1} is approximately equal to the numerical value $n_{es0} \approx 10{,}2 \cdot 10^{19}$ m^{-3}. We see that the obtained estimated quantitative value nes0 corresponds to the required level of electron concentration (of the order of $n_{es0} \approx 10^{19}$ m^{-3} [1, 3]) in the head of the initial developed positive streamer, on the basis of which a positive leader with radius of about $R_L \approx 0{,}5$ mm of its plasma channel can be formed in a spherical zone with radius of $r_i \approx x_i \approx 24{,}7$ mm near the potential electrode-tip of the studied DEDS «tip-plane».

3. Determination of the electron density n_{eL} in the head of the positive leader in the air DEDS. At the level of high electric voltage $U_e(t) \geq 1$ MV in the studied DEDS and the duration $t_L \approx T_d \approx 100$ μs of the main phase of electric discharge processes in its long air gap [3, 15, 24], where the parameter T_d corresponds to the time of its electrical breakdown (the time of cut-off T_c of high voltage $U_e(t)$ at this insulating gap), the positive leader in the considered high-voltage DEDS will correspond to the mode of its continuous development in its air with the fulfillment of the specified condition $\mathrm{d}U_e(t)/\mathrm{d}t \geq 5$ kV/μs. For an approximate calculation of the electron density neL in the head of the positive leader in a high-voltage air DEDS «tip-plane», we use the well-known generalized Saha formula for the electron density n_{eL} in the equilibrium plasma of this DEDS as a function of their temperature T_{mL} and the ionization energy W_i of neutral atoms (molecules) of atmospheric air gases in this plasma [1, 36]:

$$n_{eL} \approx (Ag_+ / g_a)^{1/2} n_{nL}^{1/2} T_{mL}^{3/4} \exp(-0{,}5W_i / T_{mL}), \quad (1)$$

where $A = 6{,}06 \cdot 10^{21}$ cm$^{-3} \cdot$eV$^{-3/2}$; g_+, g_a are, respectively, the statistical weights of ions and neutral atoms (molecules) of air gases in the leader plasma; nnL is the density of neutral atoms (molecules) of atmospheric air in the leader plasma (cm^{-3}); T_{mL} is the maximum electron temperature in the leader plasma (eV); W_i is the ionization energy of neutral atoms (molecules) of air in the leader plasma (eV).

According to [1], the Saha equation (1) was obtained using statistical physics methods regardless of the mechanisms of electron generation in the equilibrium plasma under consideration. In the case of atmospheric air in the DEDS, which is a mixture of different gases, this Saha equation can be used for atoms (molecules) of each type that are part of it [1]. Therefore, during a single impact ionization by electrons of oxygen molecules O_2 (g_+=4, and g_a=3 [1]), which are present in the electroneutral air plasma of the long discharge gap of the studied DEDS, the specified Saha formula (1) takes the following simplified form:

$$n_{eL} \approx 0{,}9 \cdot 10^{11} n_{nL0}^{1/2} T_{mL}^{3/4} \exp(-0{,}5W_{i0} / T_{mL}) , \quad (2)$$

where n_{nL0} is the density of neutral oxygen molecules O_2 of the atmospheric air DEDS in the leader plasma (cm^{-3}); W_{i0} is the impact ionization energy of neutral oxygen molecules O_2 of the atmospheric air DEDS in the leader plasma (eV).

For the case of using in the calculations of the electron density neL in the head of the positive leader the process of impact ionization of neutral oxygen molecules O_2 of atmospheric air in a high-voltage DEDS (n_{nL0}≈2,52·10^{11} cm^{-3} according to the data of Table 8.3 from [1]) at W_i≈W_{i0}≈12,5 eV [3] and T_{mL}≈1,639·10^4 K (see Section 8), which corresponds to T_{mL}≈1,413 eV [34, 37], by (2) the electron density n_{eL} in the head of the positive leader in the air DEDS under study is quantitatively equal to approximately n_{eL}≈0,7·10^{21} m^{-3}. Therefore, for this case, the degree of ionization χ≈n_{eL}/N_L, where N_L=2,687·10^{25} m^{-3} is the Loschmidt number [34, 38], the air in the tip-plane DEDS will be about χ≈0,26·10^{-4}. The numerical value of neL obtained by (2) differs from the density n_{eL}≈0,9·10^{21} m^{-3} adopted in Section 8 when determining the specified plasma temperature T_{mL} by (12) within 22 %. Let us point out that these quantitative values of the electron density neL in the positive leader are in good agreement with the known data for the concentration of free electrons in air plasma at its temperatures of the order of T_{ms}≈T_{mL}≈(5–10)·10^3 K [1, 3, 39, 40]. In addition, the result obtained for (2) for the density neL of electrons in the positive leader corresponds to the condition of the Loeb electrical breakdown for gas insulation, according to which the density n_e of electrons in their avalanche when a streamer appears on its base in short gas gaps (air of the DEDS) must be at least $n_e \geq 0{,}7 \cdot 10^{18}$ m^{-3} [1, 3].

4. Determination of the linear charge q_{Ll} of the positive leader channel in the air DEDS. When calculating the linear charge q_{Ll} of the leader plasma channel in the high-voltage DEDS under study, we will proceed from the physical position that this charge is formed by positively charged heads of positive electric streamers with charges q_{es}≈q_{eL}/N_s, which are formed by the positive leader growing in the air of this DEDS. During this leader germination in the air, the positive charge q_{eL} of its head and the electron density modulus n_{eL} in it according to (2) remain for this DEDS of artificial origin little changed until the moment of the through discharge phase in its long air gap. With similar approximate mechanism of the electrophysical development of this leader in a short time Δt_L≈R_L/v_L of its advancement in the air gap of the DEDS, the total positive charges q_{ess}≈$q_{es}N_s$≈q_{eL} of the heads of individual electric streamers starting from the leader head into the air will determine the charge q_{Ll} of the leader channel. Therefore, for the linear positive charge q_{Ll} of the leader plasma channel in an air high-voltage DEDS, in which the electron current i_{eL} and its density δ_{eL} are determined by the negatively charged sections of positive streamers with radius R_{es}≈0,1α_i^{-1}≈0,1·10^{-3} m [1, 3] moving towards the grounded electrode-plane of the DEDS in a total quantity of about N_s≈2(R_{eL}/R_{es})^2≈50 with density of electrons n_{es} in them, and the ion current i_{iL} and its density δ_{iL} are determined by the heads of these cathodically directed positive streamers with module of the density of electrons n_{es} in them (see Fig. 1), we have the following approximate calculation relationship:

$$q_{Ll} \approx 0{,}5 q_{es} N_s R_L^{-1} \approx 0{,}5 q_{eL} / R_L \approx 2\pi e_0 n_{eL} R_L^2 / 3 . \quad (3)$$

According to (3), the greater the value of the charge q_{eL} of the head of the positive leader, the greater the linear positive charge q_{Ll} of its plasma channel will be.

With n_{eL}≈0,7·10^{21} m^{-3} and R_L≈0,5α_i^{-1}≈0,5·10^{-3} m [1] according to (3), the linear charge q_{Ll} of the plasma channel of the positive leader in the air of the studied DEDS ($l_{\min}$≈1,5 m) has a value of about q_{Ll}≈58,7·10^{-6} C/m. To compare this result for q_{Ll} with known data, we indicate that with leader high-current extra-high-voltage discharge in this DEDS ($l_{\min}$≈100 m) with switching aperiodic pulse of extra-high electric voltage $U_e(t)$ with amplitude U_{em}≈3,2 MV of time shape T_m/T_p≈1,5 μs/3000 μs of positive polarity, the linear charge q_{Ll} of this leader was q_{Ll}≈100 μC/m [3].

With the germination of the DEDS channel of this leader with speed v_L in the air, its all new cylindrical sections will receive the indicated positive charges from the heads of positive streamers emerging from its spherical head. Taking into account such monotonic charging of the leader channel, its positive charge q_L will increase until it covers the air gap of this DEDS (within the limit of q_L≈q_{Ll}·$l_{\min}$). In this case, the total current $i_{L\Sigma}$ of the plasma channel of the positive leader in this DEDS is determined by the sum of its ionic current i_{iL}≈q_{Ll}·v_L and electron current i_{eL}, which is determined by the negatively charged areas of the specified positive streamers, caused by this positive leader, and directed towards the grounded electrode of the DEDS. According to (3), at q_{Ll}≈58,7·10^{-6} C/m and v_L≈10^5 m/s [1, 27], the ionic current i_{iL} in the channel of this leader takes the approximate value i_{iL}≈5,87 A, and its density δ_{iL}≈i_{iL}/(πR_L^2) is approximately δ_{iL}≈7,47·10^6 A/m^2.

5. Determination of the density δ_{eL} of the electron current i_{eL} and the current i_{eL} in the channel of the positive leader in the air DEDS. According to the proposed approximate model of the electrophysical development of the positive discharge leader with the actual use of charges from its streamer zone from the atmospheric air of the DEDS and the further advancement of this leader towards the grounded electrode of the DEDS «tip-plane» (see Fig. 1), for the velocity ved of the directed motion (drift) of electrons in the plasma channel of the leader towards the potential electrode-tip of this DEDS, caused, among other things, by positive streamers with density nes of electrons in their individual channels, one can use the well-known formula [38]: v_{ed}≈δ_{eL}/($e_0 n_{eL}$). On the other hand, for this electron velocity ved we have the following expression [1]: v_{ed}≈$e_0 E_{xk}$/($m_e \nu_m$), where

$E_{xk} \approx e_0^{-1} v_m (m_e W_i)^{1/2}$ is the critical strength of the extra-high electric field in the long air gap of the studied DEDS. As a result, for the density δ_{eL} of the electron current i_{eL} in the plasma channel with radius $R_L \approx 0{,}5\alpha_i^{-1} \approx 0{,}5$ mm [1, 3] of the studied positive leader in this DEDS, we can obtain an analytical relation of the form:

$$\delta_{eL} \approx e_0 n_{eL} m_e^{-1/2} W_i^{1/2} . \qquad (4)$$

From (4) it follows that the density δ_{eL} of the electron current i_{eL} in the channel of the positive leader is determined by the density n_{eL} of electrons in its spherical head with radius $R_{eL} \approx R_L \approx 0{,}5\alpha_i^{-1} \approx 0{,}5 \cdot 10^{-3}$ m [1, 3]. The greater the value of this density n_{eL} of electrons in its head, the greater the density δ_{eL} of the electron current i_{eL} in the leader channel.

At $n_{eL} \approx 0{,}7 \cdot 10^{21}$ m^{-3} and $W_i \approx W_{i0} \approx 12{,}5$ eV [3] (in the case of impact ionization by electrons of oxygen molecules O_2 in the atmospheric air of the DEDS), the density δ_{eL} of the electron current i_{eL} in the plasma channel of the positive leader in this air DEDS «tip-plane» by (4) takes a quantitative value of about $\delta_{eL} \approx 1{,}66 \cdot 10^8$ A/m^2. This value of δ_{eL} corresponds numerically to the current density in the positive leader, which is given in [1, 3, 40].

As for the electron current ieL in the channel of the positive leader under study, it is calculated by the approximate formula of the form: $i_{eL} \approx \pi R_L^2 \delta_{eL}$. At $\delta_{eL} \approx 1{,}66 \cdot 10^8$ A/m^2 and $R_L \approx R_{eL} \approx 0{,}5\alpha_i^{-1} \approx 0{,}5$ mm [1, 3] this electron current i_{eL} in the cylindrical plasma channel of the positive leader for the specified applied electrophysical case during the electrical breakdown of a long air gap in the studied high-voltage air-based DEDS «tip-plane» ($l_{\min}$=1,5 m; $U_d \approx 611{,}6$ kV [4, 27]; $\alpha_i \approx 10^3$ m^{-1} [1, 3]; $v_m \approx 2{,}96 \cdot 10^{12}$ s^{-1} [1]; $N_s \approx 50$; $W_i \approx W_{i0} \approx 12{,}5$ eV [3]; $x_i \approx 24{,}6 \cdot 10^{-3}$ m) is quantitatively approximately $i_{eL} \approx 130{,}5$ A. The obtained calculated numerical result for the electron current ieL in the positive leader channel corresponds to the empirical data that were previously provided in a number of literature sources in the field of HVT and HVPT [1, 3, 40]. We note that in the plasma channel of the positive leader in this DEDS, the obtained electron current $i_{eL} \approx 130{,}5$ A significantly exceeds the above-mentioned ion current $i_{iL} \approx 5{,}87$ A, which is provided by the motion with speed of about $v_L \approx 10^5$ m/s [1, 27] of this channel. Physically, this difference can be explained by the corresponding speeds of directed motion of these electricity carriers (these drift speeds in the leader channel are about 10^6 m/s for electrons, and 10^3 m/s for ions [1, 3, 15]).

6. Determination of the electric field strengths inside E_{Li} and outside E_{Le} of the positive leader channel in the air DEDS. For an approximate calculation of the longitudinal electric field strength E_{Li} inside a thin zigzag cylindrical channel ($R_L \approx 0{,}5 \cdot 10^{-3}$ m [1]) of the positive leader in the air DEDS under study, we will use the classical electrodynamic relation of the form: $E_{Li} \approx \delta_{eL}/\gamma_{Le}$ [41–43]. Then, for the length-averaged longitudinal electric field strength E_{Li} inside the plasma channel of the positive leader in this DEDS, taking into account (4), we use the expression:

$$E_{Li} \approx i_{eL} / (\pi \gamma_{Le} R_L^2) \approx e_0 n_{eL} \gamma_{Le}^{-1} m_e^{-1/2} W_i^{1/2} , \qquad (5)$$

where $\gamma_{Le} \approx 10^4$ $(\Omega \cdot \text{m})^{-1}$ is the specific electrical conductivity of the plasma of the positive leader channel in the DEDS [1], which takes into account the change in the degree of ionization $\chi \approx n_{eL}/N_L$ of its air with increase in the maximum electron temperature T_{mL} of the plasma of the positive leader channel in this DEDS.

According to (5), the length-averaged longitudinal electric field strength E_{Li} inside the plasma cylindrical channel of the positive leader in the air DEDS «tip-plane» is determined both by the value of the electron density n_{eL} in its head with radius $R_{eL} \approx R_L \approx 0{,}5\alpha_i^{-1} \approx 0{,}5$ mm [1, 3], and by the specific electrical conductivity γ_{Le} of the discharge leader plasma. At $n_{eL} \approx 0{,}7 \cdot 10^{21}$ m^{-3}, $W_i \approx W_{i0} \approx 12{,}5$ eV [3], $R_L \approx 0{,}5$ mm [1, 3] and $\gamma_{Le} \approx 10^4$ $(\Omega \cdot \text{m})^{-1}$ [1] according to (5) the calculated length-averaged electric field strength E_{Li} in the case of using the specified standard switching aperiodic voltage pulse $U_e(t)$ during electrical breakdown of a long air gap ($l_{\min}$=1,5 m) takes a quantitative value of about $E_{Li} \approx 16{,}6$ kV/m. This value of E_{Li} corresponds to the accepted in HVT and HVPT levels of length-averaged longitudinal strong electric field strength inside the channel of the positive leader, which develops in the microsecond time range in the high-voltage air DEDS «tip-plane» for its gaps from the range 1 m $\le l_{\min} \le$ 5 m [3, 39, 40]. According to [40], at values of the minimum length $l_{\min}$ in this DEDS of the order of $l_{\min} \approx 100$ m, the level of electric field strength E_{Li} in the channel of the positive leader approaches its minimum numerical value of the order of $E_{Li} \approx 10$ kV/m [1], which is observed in the channel of an open stationary electric arc at currents of the order of 1 A.

When determining the length-averaged values of the electric field strengths outside (in the streamer zone of the leader according to Fig. 1) E_{Le} and inside E_{Li} of the plasma channel of the positive leader in the air DEDS «tip-plane», as well as the averaged length ls of the streamer zone in this DEDS when the condition $\mathrm{d}U_e(t)/\mathrm{d}t < 10^3$ kV/μs is met, we will use the balance equation for the electric voltage on the discharge long air gap of this DEDS, which corresponds to the moment of the onset of the through phase of the discharge in this air gap of the high-voltage DEDS [3, 40]:

$$U_e(t) \approx U_d \approx E_{Li}(l_d - l_s) + E_{Le} l_s , \qquad (6)$$

where $l_d \approx 1{,}13 l_{\min}$ is the length of the zigzag path of the leader-streamer discharge in the air of the DEDS [4, 27].

We note that when the through phase of the leader-streamer discharge occurs in the DEDS under study, the following geometric equality is satisfied: $(l_L + l_s) = l_d$, where l_L is the length of the positive leader channel in the DEDS.

According to [40], under normal atmospheric conditions in the DEDS, which correspond to the conditions we have adopted for its air, the value of the length-averaged electric field strength E_{Le} in the streamer zone of the positive leader is quantitatively equal to about $E_{Le} \approx 465$ kV/m. We see that this numerical level of the averaged longitudinal electric field strength E_{Le} outside the cylindrical plasma channel of the positive leader in its air streamer zone corresponds to the range of strong pulsed electric fields [37]. The reliability of this value given above for the level of averaged electric field strength E_{Le}≈465 kV/m outside the plasma channel of the positive leader (in its air streamer zone) in the DEDS under study may be indicated by the experimental data obtained by us when determining the maximum breakdown strength $E_{d\max}$≈U_{em}/$l_{\min}$≈462,6 kV/m of the electric field for this high-voltage air DEDS «tip-plane» ($l_{\min}$=1,5 m), which, during its electric spark breakdown, experienced the direct action of a standard switching aperiodic voltage pulse $U_e(t)$ with amplitude U_{em} of the time shape T_m/T_p ≈ 200 μs/1990 μs of positive polarity [4, 27].

From (6) for the averaged length l_s of the streamer zone in the DEDS «tip-plane» we have the following expression:

$$l_s \approx (U_d - E_{Li} l_d)/(E_{Le} - E_{Li}) . \quad (7)$$

For the electrophysical case of the action in the air DEDS «tip-plane» ($l_{\min}$=1,5 m; l_d≈1,13$l_{\min}$≈1,695 m) of the above-mentioned aperiodic voltage pulse $U_e(t)$ of positive polarity with breakdown voltage U_d≈611,6 kV [4, 27], using (7) at E_{Li}≈16,6 kV/m and E_{Le}≈465 kV/m, we obtain a quantitative value for the average length l_s of the streamer zone in the DEDS, which will be about l_s≈1,3 m. Let us indicate that according to [1] in this air DEDS at 1,5 m ≤ $l_{\min}$ ≤ 10 m the streamer zone extends in front of the head of the positive leader to a distance of the order of l_s≈1 m. The numerical result obtained by calculation and experimental methods for the averaged length l_s≈1,3 m of the streamer zone in the «tip-plane» DEDS may indicate the validity of the data we used for the averaged length-wise electric field strengths inside E_{Li}≈16,6 kV/m and outside E_{Le} ≈ 465 kV/m of the positive leader channel in this DEDS.

For a rough numerical estimate of the maximum value E_{Lem} of the electric field strength in the air streamer zone with the radial coordinate x_s>>R_{eL} of the positive leader of the studied DEDS with sharply inhomogeneous electromagnetic field, the following approximate relationship can be written using the theory of the electrostatic field [41]:

$$E_{Lem} \approx q_{eL} /(4\pi\varepsilon_0 x_s^2) \approx e_0 n_{eL} R_{eL}^3 (3\varepsilon_0 x_s^2)^{-1} , \quad (8)$$

where x_s is the distance along the radius from the center of the spherical head of the leader in the air towards the grounded electrode-plane of the DEDS; q_{eL}≈4π$e_0$$n_{eL}$$R_{eL}^3$/3 is the electric charge of the head of the positive leader in the air gap of the DEDS, which at n_{eL}≈0,7·10^{21} m^{-3} and R_{eL}≈R_L≈0,5α_i^{-1}≈0,5 mm [1, 3] is approximately q_{eL}≈58,7 nC; ε_0=8,854·10^{-12} F/m is the electric constant [34].

We see that according to (8) this maximum strength E_{Lem} in the streamer zone of the positive leader with the radius R_L of its thin plasma channel is directly proportional to the value of the electron density n_{eL} in the spherical head with the radius R_{eL}≈R_L of this leader. At n_{eL}≈0,7·10^{21} m^{-3}, R_{eL}≈R_L≈0,5α_i^{-1}≈0,5·10^{-3} m [1, 3] and x_s≈10R_{eL}≈5 mm according to (8) the maximum strength E_{Lem} of the electric field in the vicinity of the head of the positive leader in the studied DEDS takes the quantitative value E_{Lem}≈21,1 MV/m. This level of the electric field strength E_{Lem} outside the head of the positive leader corresponds to the range of ultra-strong pulsed electric fields [40]. It was shown above that the critical electric field strength E_{xk} near the metal electrode-tip of the studied DEDS, which causes active impact ionization by electrons of its atmospheric air, should have a value of the order of E_{xk}≈24,9 MV/m. Therefore, in the atmospheric air of this DEDS near the spherical head with radius R_{eL} ≈ R_L ≈ 0,5 mm [1, 3] of the positive leader (x_s ≈ 10R_{eL} ≈ 5 mm) at the level of the maximum electric field strength near E_{Lem}≈21,1 MV/m, physical conditions will be created for the active development in its given local air zone (see Fig. 1) of electron avalanches and, accordingly, positive streamers, which will supply to this spherical head of the positive leader the electric charges necessary for its development and advancement in the atmospheric air of this DEDS.

7. Determination of the electric potential U_{eL} of the head of the positive leader in the air DEDS. According to (6), when the «tip-plane» through-phase of the leader-streamer discharge occurs in a high-voltage DEDS, when the equality (l_L+l_s)=l_d is satisfied, for the electric potential U_{eL} of the spherical head with radius R_{eL}≈R_L≈0,5 mm [1, 3] of the positive leader in the air DEDS studied by us, the following approximate calculation relation can be obtained:

$$U_{eL} \approx U_d - E_{Li}(1{,}13 l_{\min} - l_s) . \quad (9)$$

Taking into account the results of our quantitative determination of the average length l_s≈1,3 m of the streamer zone in this DEDS ($l_{\min}$=1,5 m; U_d≈611,6 kV [4, 27]) according to (9) at E_{Li}≈16,6 kV/m for the potential U_{eL} of the head of the positive leader (l_L≈1,13$l_{\min}$–l_s≈0,395 m) we obtain a value that is numerically about U_{eL}≈605 kV. We see that in this case the voltage drop U_L on the channel of the positive leader takes a numerical value that is approximately equal to U_L≈$E_{Li}l_L$≈6,6 kV. Thus, the main part of the voltage during the leader-streamer through-phase discharge (U_d≈611,6 kV [4, 27]) by an aperiodic voltage pulse $U_e(t)$ of the time shape T_m/T_p≈200 μs/1990 μs of positive polarity of a long air gap with minimum length $l_{\min}$=1,5 m falls on the positive streamers (voltage about U_s≈605 kV), which develop from the leader head towards the grounded electrode-plane of the DEDS. When the head of the positive leader touches the grounded electrode-plane of the DEDS, its electric potential takes on a zero value (U_{eL}≈0), and the entire breakdown voltage U_d is added to the leader channel.

8. Determination of the maximum electron temperature T_{mL} in the plasma of the positive leader channel in the air DEDS. When determining the temperature level in the plasma of the positive leader, which propagates in the long air gap of the high-voltage DEDS under study, we will proceed from the position that in the adiabatic regime, due to the rapid in time t flow of thermal processes in the plasma channel of this leader (with its change of the order of 10^6 K/s [4, 9, 15]), it corresponds to the maximum temperature T_{mL} of its electrons, which have a speed of movement (drift) in it of the order of 10^6 m/s [3]. We will indicate that in this case the maximum temperature T_{mi} of ions for the equilibrium plasma of the leader at their drift speed in it of the order of 10^3 m/s [3] is equal to the specified temperature T_{mL} of electrons. To find the maximum electron temperature T_{mL} in the plasma of the positive leader channel in the DEDS, we will use the relation known from thermal physics for the maximum heat flux density q_{mL} in the leader channel [38]:

$$q_{mL} \approx \pi^{-1}\sigma_c T_{mL}^4 , \quad (10)$$

where σ_c=5,67·10^{-8} W(m^{2}K^4)$^{-1}$ is the fundamental Stefan-Boltzmann constant [34].

Due to the fact that the primary source of energy input into the leader plasma channel is the electrical energy stored in the studied DEDS, the following approximate electrophysical expression can be used for the heat flux density q_{mL} [44]:

$$q_{mL} \approx \delta_{eL} U_{e0} , \quad (11)$$

where δ_{eL} is the electron current density in the plasma channel of the leader; U_{e0} is the electrode voltage drop in the plasma channel of the positive leader at the moment of its genesis near the potential metal electrode-tip of the DEDS (this constant electric voltage U_{e0} varies in the numerical range U_{e0}≈(5–10) V for various metal electrodes of this DEDS, which are used in the field of HVT and HVPT [3, 4, 45]).

Then, taking into account (4), (10) and (11), to calculate the maximum electron temperature T_{mL} in the plasma channel of the positive leader, which is formed in the zone with radius r_i≈x_i of impact ionization by air electrons near the potential metal electrode-tip of the studied DEDS, we have the relation:

$$T_{mL} \approx \sqrt[4]{\pi e_0 n_{eL} U_{e0} m_e^{-1/2} W_i^{1/2} \sigma_c^{-1}} . \quad (12)$$

We see that according to (12) the electron temperature T_{mL} in the equilibrium plasma of a positive leader, which is born and develops in a long air gap of the DEDS «tip-plane», is mainly determined by the level of electron density n_{eL} in the head with radius R_{eL}≈R_L≈0,5α_i^{-1}≈0,5 mm [1, 3] of this leader. For example, at n_{eL}≈0,9·10^{21} m^{-3} [4], W_i≈W_{i0}≈12,5 eV [3] and U_{e0}≈6,1 V (for a DEDS steel electrode-tip) [44] according to (12) the maximum electron temperature T_{mL} in the plasma of the positive leader takes a numerical value of approximately T_{mL}≈1,639·10^4 K. At n_{eL}≈0,7·10^{21} m^{-3} according to (12) this maximum temperature T_{mL} is equal to about T_{mL}≈1,539·10^4 K. These approximate temperature levels T_{mL} obtained by (12), which differ within 6 %, correspond both to the characteristic range of its change in the positive leader channel at the beginning of its occurrence in atmospheric air of the «tip-plane» DEDS during the electrical breakdown of its long gap, indicated in [3], and to the value of this temperature given in [1] of the order T_{mL}≈(2–4)·10^4 K in the air equilibrium plasma of the positive leader. In addition, these quantitative values of the temperature T_{mL} in the plasma channel of the positive leader obtained by (12) correspond to the threshold temperature level T_{mL}≈(1–2)10^4 K [1, 39], upon transition of which the value of the degree of ionization χ≈n_{eL}/N_L of its plasma increases significantly. Let us point out that, for example, the temperature value T_{mL}≈1,639·10^4 K corresponds to the beginning of active thermal ionization of atmospheric air in the studied DEDS, for which the temperature in this channel is not less than 8·10^3 K [1]. By the way, the generalized Saha formula according to (1) takes into account the influence of the plasma temperature T_{mL} in the positive leader channel on the process of thermal ionization of atmospheric air gases in the DEDS. Now the physical reasons for the bright glow of the positive leader head in this DEDS, which is a harbinger of an electrical breakdown of a long air gap in the DEDS, become clearer to us.

9. Determination of the active resistance R_{Lc} of the positive leader channel in the air DEDS. For the linear active resistance R_{Ll} of the positive leader channel in the high-voltage air DEDS «tip-plane», we have the classical approximate relationship [38, 43]:

$$R_{Ll} \approx (\pi \gamma_{Le} R_L^2)^{-1} . \quad (13)$$

At R_L≈0,5α_i^{-1}≈0,5 mm [1, 3] and γ_{Le}≈10^4 (Ω·m)$^{-1}$ [1] by (13) we find that the linear active resistance R_{Ll} of the plasma channel of the positive leader in the air DEDS under consideration, the emergence and development of which in its long discharge interval is due to the action of the standard switching aperiodic high voltage pulse $U_e(t)$ of the above-mentioned time shape [4, 27] used in it, has a quantitative value of about R_{Ll}≈127,3 Ω/m. Then, for an air gap of length $l_{\min}$=1,5 m in this DEDS, the total active resistance R_{Lc} of the plasma channel of the positive leader will take at l_d≈1,13$l_{\min}$≈1,695 m [4, 27] a value that will be numerically equal to about R_{Lc}≈R_{Ll}·l_d≈215,8 Ω. At this value of the resistance R_{Lc}, taking into account the influence of the resistance R_{Lc}≈4,59 kΩ of the current-limiting resistor, the discharge in the electric circuit of the powerful ultrahigh-voltage generator of test switching aperiodic high-voltage pulses $U_e(t)$ used by us [46–48], the electrical circuit and general view of which are shown in Fig. 2, 3 with the studied DEDS «tip-plane»according to Fig. 4, at the stage of development in its long air gap of the leader channel, which at time t≈T_d≈T_c≈95 μs together with positive streamers covers (galvanically short-circuits) this gap, will be aperiodic in nature.

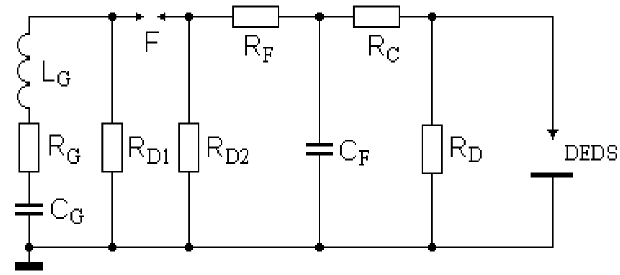

Fig. 2. Electrical substitution circuit of the discharge circuit of the generator of standard switching voltage pulses of the time shape T_m/T_p≈200 μs/1990 μs of positive (negative) polarity with amplitude of up to U_{em}≈±2 MV (R_G≈4,5 Ω, L_G≈80 μH, C_G≈0,125 μF – the intrinsic electrical parameters of the pulse voltage generator of the GIN-4 type; R_{D1}≈440 kΩ – the discharge resistance of the GIN-4 generator with switch F; R_{D2}≈32,7 kΩ – the additional discharge resistance; R_F≈4,28 kΩ – the resistance of the shaping resistor; C_F≈13,3 nF – the shaping capacitance for voltage of ±2,5 MV; R_C≈4,59 kΩ – the resistance of the current-limiting resistor; R_D≈107,3 kΩ – the resistance of the high-voltage ohmic arm voltage divider type OPN-2,5 for nominal impulse voltage of ±2,5 MV with division factor K_d≈53650) [46]

Fig. 3. General view of a powerful extra-high-voltage generator of standard switching aperiodic voltage pulses of the time shape T_m/T_p≈200 μs/1990 μs of positive (negative) polarity with amplitude of up to U_{em}≈±2 MV (on the left, on an insulating support 12 m high, a forming capacitance C_F≈13,3 nF is installed, to the upper potential electrode of which forming R_F≈4,28 kΩ and current-limiting R_C≈4,59 kΩ high-voltage resistors are connected) [46]

Fig. 4. General view of the high-voltage aerial DEDS «tip-plane» ($l_{\min}$=1,5 m), in which an ohmic voltage divider of the OPN-2.5 type for a nominal pulse voltage of ±2,5 MV with division factor equal to K_d≈53650 is connected to the potential upper steel rod electrode pointed at the lower edge (r_c≈3 mm) with radius r_0≈15 mm, located in the center of its grounded lower flat electrode made of galvanized steel with dimensions of 5 m × 5 m

This discharge mode in the generator circuit is confirmed by the data of the oscillograms in Fig. 5, 6. Therefore, with this discharge mode, the amplitude I_{me} of the current $i_e(t)$ in its electrical circuit can be calculated by the following expression [43]: $I_{me}≈U_e(T_d)/(R_{Lc}+R_C)$. As a result, this amplitude I_{me} of the discharge current at $U_e(T_d)≈U_d≈611{,}6$ kV, $R_{Lc}≈215{,}8$ Ω and $R_C≈4{,}59$ kΩ can take the numerical value $I_{me}≈127{,}3$ A. We see that this value of the discharge electric current I_{me} ≈ 127,3 A practically corresponds (within an error of 3 %) to the previously obtained electron current i_{eL}≈130,5 A in the positive leader channel.

10. Results of some experimental studies of breakdown of long air gaps in DEDS.

Figure 4 shows a general view of a high-voltage air DEDS «tip-plane», which tested the direct action of a standard switching aperiodic voltage pulse $U_e(t)$ of the time shape T_m/T_p≈200 μs/1990 μs of positive polarity from a powerful ultra-high-voltage generator of the corresponding voltage pulses $U_e(t)$, the general view, electrical diagram and parameters of the discharge circuit of which were given in [46–48] and additionally presented in Fig. 2, 3.

Figure 5 shows the oscillogram of the full standard switching aperiodic high-voltage pulse $U_e(t)$ with amplitude of U_{em}≈622,3 kV of the time shape T_m/T_d≈200 μs/1990 μs of positive polarity, which acts in the discharge circuit of the powerful ultra-high-voltage test generator of the corresponding voltage pulses [46] used by us on the tip-plane DEDS without electrical breakdown of its long air gap of length $l_{\min}$=3 m.

Figure 6 shows an oscillogram of a standard switching aperiodic high-voltage pulse T_m/T_d≈200 μs/1990 μs cut off on the rising part with electrical breakdown of a long air discharge gap in a test DEDS «tip-plane» with minimum length $l_{\min}$=1,5 m.

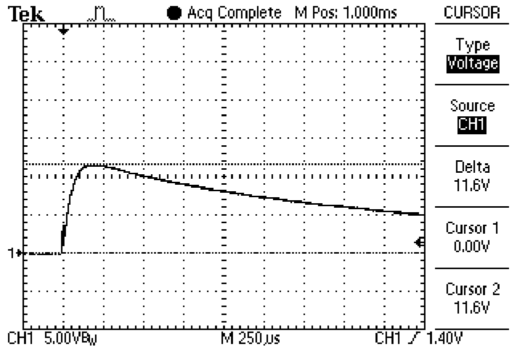

Fig. 5. Oscillogram of a full switching aperiodic high-voltage pulse $U_e(t)$ of the time shape T_m/T_p≈200 μs/1990 μs of positive polarity without electrical breakdown of a long air gap in the «tip-plane» DEDS ($l_{\min}$=3 m; U_{em}≈11,6 V × 53650≈622,3 kV – amplitude of the high-voltage test pulse; T_m≈200 μs – rise time (rise) of the high-voltage pulse to its amplitude U_{em}; T_p≈1990 μs – duration of the voltage pulse at the level of 0,5 U_{em}; vertical scale – 268,2 kV/div; horizontal scale – 250 μs/div) [27]

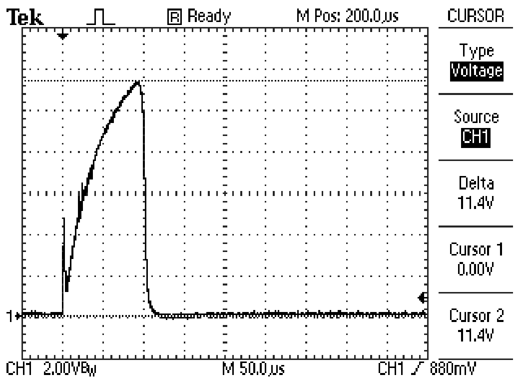

Fig. 6. Oscillogram of a truncated standard switching aperiodic high-voltage pulse $U_e(t)$ of the time shape T_m/T_p≈200 μs/1990 μs of positive polarity during an electrical breakdown of a long air gap in the «tip-plane» DEDS ($l_{\min}$=1,5 m; U_d≈11,4 V × 53650≈611,6 kV – voltage pulse cut-off level; T_c≈T_d≈95 μs − voltage pulse cut-off time (breakdown); T_{dc}≈17 μs – voltage pulse cut-off (switching) duration; vertical scale – 107,3 kV/div; horizontal scale – 50 μs/div) [27]

We would like to point out that when obtaining the experimental data according to Fig. 5, 6, the following were used: a domestic powerful generator of standard switching aperiodic pulses of ultra-high voltage $U_e(t)$ of the time shape T_m/T_p≈200 μs/1990 μs of positive (negative) polarity for a nominal electrical voltage of ±2 MV [46, 48]; an ohmic voltage divider of the OPN-2.5 type (K_d≈53650) for a nominal pulse voltage of ±2,5 MV [47]; a digital oscilloscope Tektronix TDS 1012B certified by the State Metrological Service, which stores measured electrical signals (calibration certificate UA01№1312 dated 29.06.2023). We would like to note that the amplitude-time parameters of high-voltage pulses $U_e(t)$ according to the data in Fig. 5, 6 were determined according to the requirements of the Standard [49].

Figure 7 shows a general view of the spark discharge channel and the spherical zone of active impact ionization of air near the potential electrode in the tip-plane DEDS ($l_{\min}$=1,5 m; U_d≈611,6 kV).

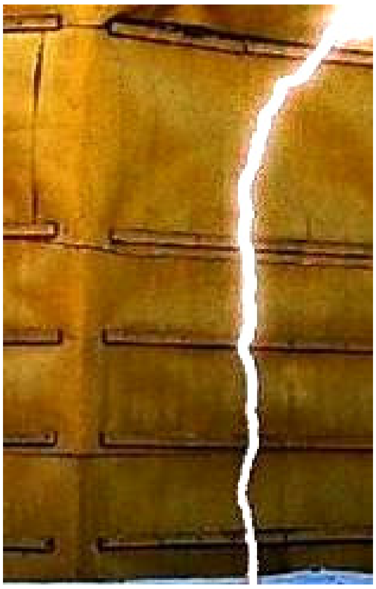

Fig. 7. General view of a zigzag cylindrical plasma channel of a spark discharge with almost spherical zone of radius r_i≈x_i of active impact ionization of air, which glows brightly at the top near the potential electrode of the DEDS «tip-plane», during the electrical breakdown of its air gap by a switching aperiodic high-voltage pulse of the time shape T_m/T_p≈200 μs/1990 μs of positive polarity ($l_{\min}$=1,5 m; $U_e(T_d)$≈U_d≈611,6 kV [27])

Let us point out that according to the approximate experimental data obtained by us, the diameter $2x_i$ of the spherical zone of active impact ionization of atmospheric air near the edge of a potential steel rod-tip with diameter of $2r_0$≈30 mm in the DEDS, in terms of its bright luminosity, was approximately twice as large as the diameter $2r_0$ of the electrode-tip and four times as large as the diameter $2r_{mk}$ of the plasma channel of the spark discharge (see Fig. 7) [4, 27].

Experimental studies of the electrical breakdown in the tip-plane DEDS (see Fig. 4) of long air gaps with length of 1 m ≤ $l_{\min}$ ≤ 4 m, carried out in the conditions of the high-voltage electrophysical laboratory of the Research and Design Institute «Molniya» of NTU «KhPI» using the above-mentioned test equipment, allowed us to confirm [4, 27] the following for the case of using in the experiments a standard switching aperiodic high-voltage pulse $U_e(t)$ of the time shape T_m/T_p≈200 μs/1990 μs of positive polarity: first, the emergence near the potential metal electrode-tip of the DEDS under study of an almost spherical zone with radius of about x_i≈r_i≈(25–30) mm of active impact ionization by electrons of atmospheric air; secondly, the emergence and further development in the long air gap of the DEDS under study of the positive leader channel always occurs from this local zone with radius of x_i≈r_i of active air ionization; thirdly, the level of the breakdown pulse voltage U_d in this DEDS, which at $l_{\min}$=1,5 m was about U_d≈611,6 kV (T_d≈95 μs), and at $l_{\min}$ =3 m – U_d ≈1062,3 kV (T_d ≈104 μs); fourthly, the fulfillment of the approximate relationship l_d≈1,13$l_{\min}$ for the length of the zigzag path of channel development in the long air gap of the DEDS; fifthly, the physical position that the electrical breakdown of air gaps with the specified length lmin in the studied DEDS always occurs on the increasing frontal part of the high-voltage switching pulse $U_e(t)$ used in the experiments.

Conclusions.

1. A simplified electrophysical model of the emergence and development of a positive leader in a long discharge air gap of a tip-plane DEDS is proposed, which tests the action of a standard switching aperiodic high-voltage pulse $U_e(t)$ of the time shape T_m/T_p≈200 μs/1990 μs of positive polarity. This approximate electrophysical model allows us to find in a complex form a number of basic characteristics of the plasma channel of this discharge leader during electrical breakdown of a long air gap in the DEDS under study by a high pulse voltage of positive polarity.

2. Approximate calculated relations are obtained for determining the following basic characteristics of the plasma channel of a positive leader in a tip-plane DEDS with atmospheric air: electron density n_{eL} and electric potential U_{eL} in the head of this leader; linear charge q_{Ll} of the leader plasma channel; density δ_{eL} of the electron current i_{eL} and this current i_{eL} in the leader channel; ion current i_{iL} and its density δ_{iL} in the leader channel; strong electric field strengths inside E_{Li} and outside E_{Le} of the leader channel; length ls of the streamer zone in front of the leader head; maximum electron temperature T_{mL} in the plasma of the leader channel; linear active resistance R_{Ll} and total active resistance R_{Lc} of the leader channel. Data are provided that confirm the reliability of a number of these approximate calculated relations for the plasma channel of a positive leader in air DEDS.

3. It is shown by calculation that the maximum electron temperature T_{mL} in the equilibrium plasma of the positive leader in the air DEDS «tip-plane» at a density n_{eL}≈0,7·10^{21} m^{-3} of electrons in the plasma of the leader of this DEDS takes the numerical value T_{mL}≈1,539·10^4 K, which corresponds to the characteristic range of its change in a similar leader adopted in the field of HVT and HVPT for a long discharge gap of DEDS with atmospheric air and approaches the level T_{mL}≈(2–4)·10^4 K, characteristic of a developed positive leader and obtained using known spectroscopic measurements. This obtained temperature level T_{mL} indicates that the plasma in the channel of the positive leader in this DEDS becomes thermoionized.

4. Based on the Saha equation known in plasma physics, in the case of ionization by electron impacts of neutral oxygen molecules O_2 of atmospheric air of the high-voltage «tip-plane» DEDS studied by us, it is shown that the density neL of electrons in the air equilibrium plasma of the positive leader channel of this DEDS at T_{mL}≈1,639·10^4 K takes a quantitative value of about n_{eL}≈0,7·10^{21} m^{-3}, which corresponds to its known numerical values in the field of physics and technology of high-voltage gas discharges of atmospheric pressure.

5. It is shown by calculation and experimental methods that for the electrophysical case considered in the air DEDS «tip-plane» ($l_{\min}$=1,5 m), at the stage of emergence, development and advancement of a positive leader in the atmospheric air of the studied DEDS at the electron density neL in the spherical head of this leader with radius R_{eL}≈0,5·10^{-3} m near n_{eL}≈0,7·10^{21} m^{-3} its electric potential U_{eL} changes from the level $U_e(T_d)$≈U_d≈611,6 kV (the beginning of the leader development) to approximately zero (the completion of the leader development and the onset of the through-discharge phase at the length of its plasma channel l_L≈1,13$l_{\min}$ in the air gap of the DEDS). For the intermediate state of development in the long air gap of this DEDS of the leader channel (l_L≈0,395 m), the electric potential U_{eL} of the head of the positive leader in its atmospheric air will be quantitatively U_{eL}≈605 kV with voltage drop on the leader channel U_L≈6,6 kV.

6. It has been established that in the streamer zone of the air gap near the head of the positive leader (at a distance x_s≈10R_{eL}≈5 mm from it) of the studied DEDS ($l_{\min}$=1,5 m) an extremely strong electric field is formed with maximum strength E_{Lem}≈21,1 MV/m (with averaged over the length of this gap strength E_{Le}≈465 kV/m, which is characteristic of the streamer zone in front of the leader), which is comparable to the critical strength E_{xk}≈24,9 MV/m of the electric field, which causes active impact ionization by electrons of its atmospheric air. In this regard, outside the head of this leader, physical conditions will be created for the active development of electron avalanches and positive streamers in the amount of N_s, which start from the head of the leader with its excess positive charge q_{eL}≈58,7 nC towards the grounded electrode-plane of this DEDS.

7. It is shown that the strength E_{Li} of the longitudinal electric field inside its plasma channel with radius of about R_L≈0,5·10^{-3} m in a high-voltage air DEDS «tip-plane» for the case when $l_{\min}$=1,5 m and $U_e(T_d)$≈U_d≈611,6 kV, with specific electrical conductivity γ_{Le}≈10^4 (Ω·m)$^{-1}$ of the equilibrium plasma of the channel of this leader, numerically amounts to approximately E_{Li}≈16,6 kV/m.

8. The value of the average length ls of the streamer zone in front of the head of the positive leader was obtained by calculation and experiment, which for the case of using in the air DEDS «tip-plane» ($l_{\min}$=1,5 m) a standard switching aperiodic high-voltage pulse $U_e(t)$ of the time shape T_m/T_p≈200 µs/1990 µs of positive polarity with breakdown voltage U_d≈611,6 kV is l_s≈1,3 m.

9. It was established that the density δ_{eL} of the electron current i_{eL} in the plasma channel of the positive leader for a high-voltage air-based DEDS «tip-plane» ($l_{\min}$=1,5 m) takes the quantitative value δ_{eL}≈1,66·10^8 A/m^2, and the electron current i_{eL} towards its grounded metal electrode-plane is i_{eL}≈130,5 A.

10. It is shown that the linear charge q_{Ll} of the thin plasma channel of the positive leader, which moves in the atmospheric air of the tip-plane DEDS, has a quantitative value of q_{Ll}≈58,7·10^{-6} C/m. This electric charge determines the ion current iiL in the plasma channel of this leader, which is numerically approximately equal to i_{iL}≈5,87 A at its density of about δ_{iL}≈7,47·10^6 A/m^2.

11. It is established that with the specific electrical conductivity γ_{Le}≈10^4 (Ω·m)$^{-1}$ of the thermoionized plasma of the positive leader channel in the high-voltage air tip-plane DEDS, the linear active resistance R_{Ll} of the plasma channel of this leader is quantitatively about R_{Ll}≈127,3 Ω/m. In this case, the total active resistance R_{Lc} of the zigzag plasma channel of the positive leader in this DEDS ($l_{\min}$=1,5 m) will take a value that will be numerically equal to R_{Lc}≈1,13R_{Ll}·$l_{\min}$≈215,8 Ω.

12. The corresponding experimental studies of electric discharge processes in the DEDS «tip-plane» with lengths of 1 m ≤ $l_{\min}$ ≤ 4 m of its long air gap, carried out on domestic powerful ultrahigh-voltage equipment in the open air under the conditions of an electrophysical laboratory, indicate the validity of the simplified model proposed by us of the formation near the potential electrode-tip of this DEDS and the further development in its atmospheric air of a thin plasma channel of the positive leader with its main characteristics indicated above.

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Conflict of interest. The author declares no conflict of interest.

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