UDC 621.3.022: 621.396.6: 533.93 https://doi.org/10.20998/2074-272X.2024.2.07

M.I. Baranov

Calculation and experimental determination of the speed of advancement of the plasma leader channel of a pulse spark discharge in atmospheric air

Goal. *Calculation and experimental determination of middle speed v_L of advancement of plasma leader channel of a pulse spark discharge in the long air interval of the double-electrode discharge system (DEDS) «tip-plane».* ***Methodology.*** *Bases of the theoretical electrical engineering and electrophysics, electrophysics bases of technique of ultra- and high-voltage and high pulse currents, bases of high-voltage pulse technique and measuring technique.* ***Results.*** *The close calculation and experimental method of determination of middle speed v_L of advancement of plasma leader channel of an electric pulse spark discharge is offered in the long air interval of DEDS «tip-plane». This method is based on the offered calculation empiric formula for finding of the indicated speed v_L and results of decoding of oscillograms of process of cut of in-use standard interconnect aperiodic pulse of over- and high-voltage of temporal shape of $T_m/T_d \approx 200$ μs/1990 μs of positive polarity at an electric hasp in indicated DEDS of long air intervals with their minimum length of $l_{\min}$, numeral making 1,5 m (first case) and 3 m (second case). It is shown that middle speed v_L of advancement in atmospheric air of front of plasma channel of positive leader of an electric pulse spark discharge in probed DEDS «tip-plane» for two considered applied cases at $l_{\min}$=1,5 m of $l_{\min}$=3 m numeral makes approximately $v_L \approx (1 \pm 0{,}03) \cdot 10^5$ m/s. The found numeral value of this speed v_L well coincides with the known experimental information for speed of advancement of $v_L \approx 10^5$ m/s in atmospheric air of plasma channel of negative leader for a long storm spark discharge in DEDS «charged cloud-earth». It is set that for the standard interconnect aperiodic pulse of high- and ultra- voltage of temporal shape of $T_m/T_d \approx 200$ μs/1990 μs of positive polarity middle value of aggressive strength E_d of high pulse electric field in the air interval of probed DEDS «tip-plane» numeral makes minimum length of l_{min}=1,5 m near $E_{d1} \approx 360{,}8$ kV/m, and for his minimum length of $l_{\min}$=3 m of − $E_{d2} \approx 313{,}4$ kV/m.* ***Originality.*** *The comfortable is developed in the use and reliable in practical realization technicians-and-engineers calculation and experimental method of research in the conditions of high-voltage electrophysics laboratory of difficult electro-discharge processes of development of leader hasp of long air intervals and determination of minimum electric durability of air insulation of electrical power engineering and electrophysics equipment on working voltage of classes of 330-1150 kV.* ***Practical value.*** *Application in area of industrial electrical power engineering and high-voltage pulse technique of the got numeral electrophysics results and offered calculation and experimental method of determination of middle speed v_L of advancement in atmospheric air of plasma channel of leader of a long spark discharge will allow, from one side, to deepen our scientific knowledges about a long electric pulse spark discharge in an air dielectric, and, from other side, to develop high-voltage electrical power engineering and electrophysics devices with enhanceable reliability of their work both in normal operation and malfunctions.* References 20, figures 5.

Key words: **plasma leader channel, electric pulse spark discharge, air dielectric, advance speed of a spark discharge front, calculation, experiment.**

Надані результати розрахунково-експериментального визначення усередненої швидкості v_L просування плазмового лідерного каналу електричного імпульсного іскрового розряду в довгому повітряному проміжку двоелектродної розрядної системи «вістря-площина» (для двох прикладних випадків при $l_{\min}$=1,5 м і $l_{\min}$=3 м), яка випробовує дію стандартного комутаційного аперіодичного імпульсу високої і надвисокої напруги часової форми $T_m/T_d \approx 200$ мкс/1990 мкс позитивної полярності. Запропонований метод чисельної оцінки величини v_L в даній розрядній системі базується на використанні отриманої емпіричної формули та отриманні осцилограм процесу зрізу застосованих імпульсів над- і високої напруги при електричному пробої в ній довгих повітряних проміжків вказаної мінімальної довжини $l_{\min}$. На основі запропонованої наближеної розрахункової формули і виконаних за допомогою потужного надвисоковольтного випробувального обладнання сильнострумових експериментів показано, що вказана швидкість v_L розповсюдження в атмосферному повітрі переднього фронту позитивного лідера імпульсного іскрового розряду чисельно складає $v_L \approx (1 \pm 0{,}03) \cdot 10^5$ м/с. Отримані розрахунково-експериментальні дані для усередненої швидкості v_L просування в повітрі лідерного каналу імпульсного іскрового розряду добре узгоджуються з її прийнятими для грозових іскрових розрядів в атмосферному повітрі чисельними показниками. Бібл. 20, рис. 5.

Ключові слова: **плазмовий лідерний канал, електричний імпульсний іскровий розряд, повітряний діелектрик, швидкість просування фронту іскрового розряду, розрахунок, експеримент.**

State-of-the-art and relevance of the problem. In the technique of high (ultra-high) electrical voltages, the real danger for the used electrical equipment is an electrical breakdown of its vacuum, gas, liquid or solid insulation, which is accompanied by the occurrence of a short circuit in the electrical circuit, the formation of a highly conductive spark (arc) channel at the breakdown site and discharge through it of a high pulse current. Air insulation has found a sufficiently wide practical application both in industrial electricity and in the field of high-voltage pulse technology (HPT) intended for scientific and technological purposes [1-6].

It is known that in long air gaps (with lengths of 1 m or more), their electrical breakdown is carried out by the growth from one electrode (for example, from the potential anode) of a high-voltage device to another (for example, to the grounded cathode) of the leader of the electric gas discharge – a thin plasma conductive channel, the degree of ionization of gas molecules (atoms) in which is much higher than in the initial discharge streamer channel [3, 7]. After the head of the leader of the electric discharge, which glows brightly, reaches the opposite electrode-cathode and propagates along the leader channel towards the anode with speed of about $v_E \approx 10^7$ m/s, first the return wave of a high electric field (electric potential wave) and then the return wave of the conduction current on site of the leading channel, a strongly ionized discharge spark channel is formed, which glows brightly [3, 7]. Due to the flow of a large pulse current through this highly conductive channel and intense energy release on its ohmic resistance, the temperature and pressure in it increase sharply, which leads to the expansion of the spark discharge channel with the rapid radial spread of its low-temperature plasma and the formation of a powerful shock wave in the surrounding air environment. Despite the presence of well-known theories of streamer and leader breakdown of air insulation, which have been tested many times in scientific laboratories around the world [1, 3, 7], those related to taking into account the peculiarities of the physics of pulse spark discharge in atmospheric air remain poorly studied issues today regarding its flow in the conditions of action of sharply heterogeneous high pulse electric fields, characteristic for electrotechnical practice, and determination of the speed v_L of the advancement of its plasma leader channel, which is the first to short out the air gaps of electrical discharge systems that are part of various high-voltage devices at breakdown.

The results of mathematical and computer modelling of complex electric discharge processes in various types of dielectrics [1, 3, 8-14], which are aimed at increasing the electrical strength of gas, liquid and solid insulation of high-voltage electrical equipment used in the electric power industry and HPT, do not allow to give answers to the specified above are relevant issues in the field of gas spark discharge electrophysics. The deepening of our scientific knowledge about electric pulse spark discharge in gas insulation (in particular, in long air gaps), which is a complex and complicated electrophysical phenomenon of nature, allows to more rationally develop the designs of many high-voltage electrical engineering and electric power devices with increased reliability of their operation in normal and emergency modes, as well as means of lightning protection both for various aircraft and strategic industrial and technical facilities of ground infrastructure.

The goal of the article is to calculate and experimentally determine the average speed v_L of the advancement of the plasma leader channel of an electrical pulse spark discharge in the long air gap of a two-electrode discharge system «tip-plane».

1. Problem definition. A typical example in the field of HPT of the electric discharge systems with a sharply inhomogeneous high pulsed electric field is a double-electrode discharge system (DEDS) «tip-plane», containing a vertically placed potential electrode in the form of a metal rod 1 with radius r_0 with a pointed lower edge with radius of its curvature $r_c<<r_0$ and the grounded electrode in the form of a horizontally located metal plane 2 of unlimited dimensions (Fig. 1). Let the electric potentials of these electrodes 1 and 2 be equal to φ_1 and $\varphi_2=0$, respectively, and homogeneous atmospheric air is placed between them in the interelectrode insulating 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 under the following physical conditions [15]: gas pressure $P_a\approx(1.013\pm0.005)\cdot10^5$ Pa; absolute gas temperature $T_a\approx(293.15\pm5)$ K; relative humidity of gas $\gamma_a\approx(45\pm15)$ %.

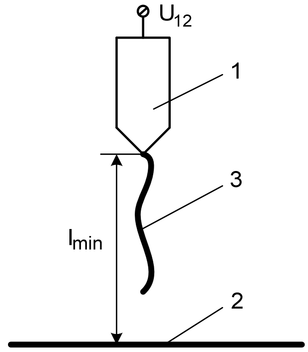

Fig. 1. Schematic representation of the investigated air DEDS, on the example of which the electrophysical process of propagation of the plasma leader channel of a puls spark discharge in atmospheric air is considered (1, 2 − potential and grounded metal electrodes, respectively; 3 − zigzag-shaped leader channel of the spark discharge in the DEDS)

Let's assume that the electrical strength of the interelectrode air gap in the DEDS in relation to the average level of its breakdown voltage E_d of a high pulse electric field for an ultra- and high-voltage pulse supplied to the DEDS is E_{d1} for $l_{\min}$=1.5 m and E_{d2} for $l_{\min}$=3 m. In these two practical cases, the electric potential φ_1 at the edge of the rod with a DEDS tip will acquire critical values equal to φ_{1d1} and φ_{1d2}, respectively. We will limit ourselves to considering the case when the amplitude-time parameters (ATPs) of the electric pulse voltage $U_{12}(t)=(\varphi_1-\varphi_2)$ in the interelectrode air gap of the DEDS change 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 [16-18]. Let us point out that it is this temporal shape of high (ultra-high) pulse voltage that is usually used in industrial power engineering and HPT when determining the electrical strength of the internal and external insulation of various high-voltage electrical equipment. On the basis of calculation and experimental data, which relate to the flow of electrophysical processes in the discharge long air gap of the DEDS (see Fig. 1), it is necessary to numerically determine the average speed v_L of the advancement of the positive leader in the plasma channel of the electric pulse spark discharge in the air gap of the investigated DEDS «tip-plane» with the specified two numerical values of its minimum length ($l_{\min}$=1.5 m and $l_{\min}$=3 m).

2. Calculation and experimental estimation of the speed v_L of the advancement of the plasma leader channel of a pulse spark discharge in atmospheric air. The research results of research in the field of electrical breakdown of long air gaps in DEDS «tip-plane» using a standard switching pulse voltage of the time shape $T_m/T_d\approx$200 μs/1990 μs of positive polarity indicate that the development in them of the plasma leader channel of high-voltage pulse of a spark discharge occurs along a zigzag path, the length of which l_c always exceeds their minimum length $l_{\min}$ with the obligatory fulfillment of the inequality of the form $l_c\geq1.1l_{\min}$ [1, 3, 17-19]. When the minimum length $l_{\min}$ of their discharge intervals is changed in the indicated air DEDS in the range

$l_{\min}$ ≈(1−4) m, the given difference between the lengths l_c and $l_{\min}$ is from 10 to 15 % [17-19]. For the certainty of further calculation estimations of the averaged value of the sought parameter v_L, let's focus on the case in which this difference between the lengths l_c and $l_{\min}$ turns out to be approximately 13 % on average, and the ratio $l_c/l_{\min}$ is numerically close to $l_c/l_{\min}$≈1.13. Taking into account this research result, the formula for an approximate estimation of the average speed v_L of the advancement of the plasma leader channel of a high-voltage electrical pulse spark discharge in the atmospheric air of the adopted DEDS «tip-plane» at $l_{\min}$≈(1−4) m takes the following empirical form:

$$v_L \approx 1{,}13 l_{\min} / T_{dc}, \qquad (1)$$

where T_{dc} is the duration of the cut of the voltage pulse, which causes an electrical breakdown of a long air gap in the DEDS «tip-plane» under study, the minimum length of which is numerically $l_{\min}$≥1 m.

In (1), the numerical value of the parameter $l_{\min}$≥1 m for the «tip-plane» aerial DEDS is selected by the personnel of the test team and fixed by the appropriate measuring instrument (a long metric ruler) experimentally, and the numerical value of the duration of the cut T_{dc} of the voltage pulse is determined by deciphering its oscillograms in the process of electrical breakdown of the air gap in the DEDS with length $l_{\min}$ using a digital storage oscilloscope and an ultra-high-voltage ohmic voltage divider (OVD). The use of this type of ultra-high voltage divider in the case under consideration by us is due to the relative simplicity of its manufacture and the relatively low cost of the electrical components included in its composition [18, 20].

The use of the T_{dc} value in (1) is explained by the physical condition that this duration of the cut T_{dc} of the pulse of high (ultra-high) pulse voltage applied to the air DEDS characterizes the time of shortening along the air path of the real length l_c by the conducting plasma leader channel of the selected electric pulse spark discharge air gap in this DEDS with its minimum length $l_{\min}$ and, accordingly, the time of equalization of electric potentials (φ_1≈φ_2≈0) on the electrodes of the DEDS we are investigating.

Figure 2 shows the general view of the investigated DEDS «tip-plane» with a long discharge air gap of length $l_{\min}$=3 m, which was galvanically connected to a high-current discharge electric circuit of an ultra-high-voltage generator of standard switching aperiodic voltage pulses of the time shape T_m/T_d≈200 μs/1990 μs of positive (negative) polarity, developed and created at the Research and Design Institute «Molniya» of National Technical University «Kharkiv Polytechnic Institute» [17, 18].

Figure 3 shows an experimental oscillogram of a complete standard switching aperiodic 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 specified ultra-high-voltage test generator [17, 18] on the air DEDS «tip-plane» we are investigating without an electrical breakdown of its long air space of length $l_{\min}$=3 m.

Fig. 2. General view of the ultra-high-voltage air DEDS «tip-plane» ($l_{\min}$=3 m), in which to the potential upper steel rod electrode pointed at the lower edge with radius r_0≈15 mm, placed in the center of its grounded lower flat electrode made of galvanized steel with overall dimensions of 5×5 m, OPN-2,5 for nominal electrical pulse voltage of 2.5 MV with the division coefficient K_d≈53650 is connected [18]

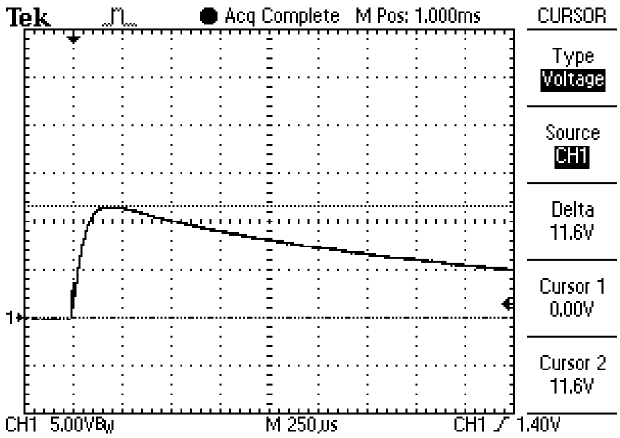

Fig. 3. Oscillogram of a complete switching aperiodic high-voltage pulse of the time shape T_m/T_d ≈200 μs/1990 μs of positive polarity without electrical breakdown of a long air gap of length $l_{\min}$=3 m in the DEDS «tip-plane» (U_{mc}≈11.6 V × 53650≈622.3 kV – high voltage pulse amplitude; T_m≈200 μs – time of rise of the voltage pulse to U_{mc} amplitude; T_d≈1990 μs – duration of the voltage pulse at the level of 0.5 U_{mc}; vertical scale – 268.2 kV/div; horizontal scale – 250 μs/div)

Figure 4 shows the experimental oscillogram of the standard switching aperiodic high-voltage pulse T_m/T_d≈200 μs/1990 μs used in the experiments cut off on the rising part with an electrical breakdown of a long air discharge gap in the DEDS «tip-plane» with minimum length $l_{\min}$=1.5 m, ATPs of which was determined according to the requirements of the current Standard [16].

Using obtained according to Fig. 4 research numerical data for the cut-off duration T_{dc}≈17 μs of the corresponding high-voltage pulse (for the case where U_{mcd}≈611.6 kV) in the considered air DEDS ($l_{\min}$=1.5 m) from (1) for the averaged speed v_L of the advancement of the plasma leader channel of a pulse spark discharge in the atmospheric air of its specified long discharge interval results that v_L≈0.997·10^5 m/s. At a given speed v_L of propagation in the atmospheric air of the positive leader of a pulse spark discharge, the actual path length l_c through it in the interelectrode air gap of the DEDS (l_{min}=1.5 m) at its electrical breakdown (T_{dc}≈17 μs) by the applied high-voltage pulse is numerically l_c≈$v_L T_{dc}$≈1.695 m. We can see that in this case, the real length l_c of the development path of the leader channel of the spark discharge in the studied DEDS exceeds the minimum length l_{min}=1.5 m of its discharge air gap by approximately 13 %.

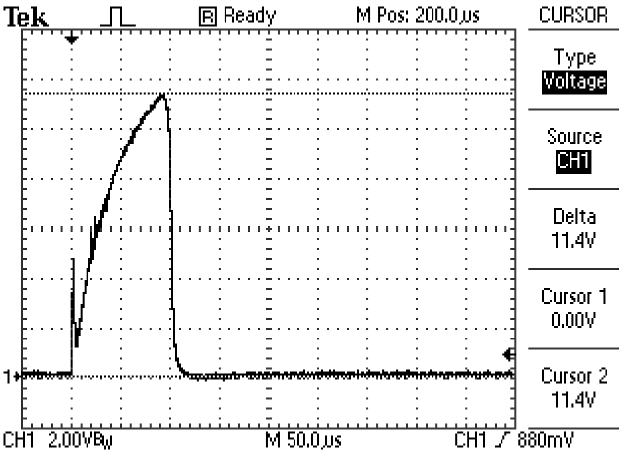

Fig. 4. Oscillogram of a truncated standard high-voltage switching aperiodic pulse of the time shape T_m/T_d ≈200 μs/1990 μs of positive polarity at electrical breakdown of a long air gap of length l_{min} =1.5 m in the DEDS «tip-plane» (U_{mcd}≈11.4 V × 53650≈611.6 kV – pulse cut-off voltage level; T_c ≈95 μs – cut-off time of the voltage pulse; T_{dc}≈17 μs – duration of the cut (commutation) of the voltage pulse; vertical scale – 107.3 kV/div; horizontal scale – 50 μs/div)

Note that at the rate of increase of the pulse voltage $U_{12}(t)$, which is applied to the discharge gap of the air DEDS, equal to d$U_{12}(t)$/dt≥5 kV/μs (as in our electrophysical cases), the development of the positive leader in atmospheric air occurs continuously (without stepwise formation of separate plasma leader channels in DEDS) [3]. With this process of advancement of the positive discharge leader in the air, the length l_c of its plasma channel in this DEDS will monotonically increase (see Fig. 1).

To compare the numerical result obtained above for the average speed v_L of the positive leader, which is characteristic of the electric discharge processes that occur under laboratory conditions in the air DEDS «tip-plane» with its long discharge gap (l_{min}=1.5 m), we note that according to [7], the smallest average speed v_L of the advance in the atmospheric air of the front of the negative leader of a long spark discharge between the thundercloud and the surface of the earth (lightning) is quantitatively about v_L≈10^5 m/s. As we can see, the experimental result obtained in laboratory conditions using this DEDS at l_{min} = 1.5 m and a standard switching aperiodic ultra-high voltage pulse of the time shape T_m/T_d ≈200 μs/1990 μs of positive polarity approximated taking into account (1) the calculated and experimental result for the averaged the speed v_L ≈0.997·10^5 m/s of advancement in atmospheric air of the plasma leader channel of a pulse spark discharge is practically equal to its quantitative value accepted in the field of physics of atmospheric electricity (lightning) and electrophysics of ultra-high voltages (v_L≈10^5 m/s [7]).

It should be noted that when performing ultra- and high-voltage experiments using the «tip-plane» air DEDS under investigation (see Fig. 2) and the results obtained by us for long discharge air gaps (l_{min}=1.5 m and l_{min}=3 m) experimental results according to Fig. 4, 5, both an ohmic voltage divider of the OPN-2,5 type (K_d ≈53650) [18] and a Tektronix TDS 1012B digital oscilloscope certified by the State Metrological Service, which stores useful electrical signals (calibration certificate UA01 No. 1312 dated 29.06. 2023) were used.

Figure 5 shows an oscillogram of an ultra-high-voltage standard switching aperiodic voltage pulse T_m/T_d ≈200 μs/1990 μs cut off on the frontal part used in the laboratory high-current experiments performed by us with an electrical breakdown of a long air discharge gap in the studied DEDS «tip-plane» with minimum length l_{min}=3 m.

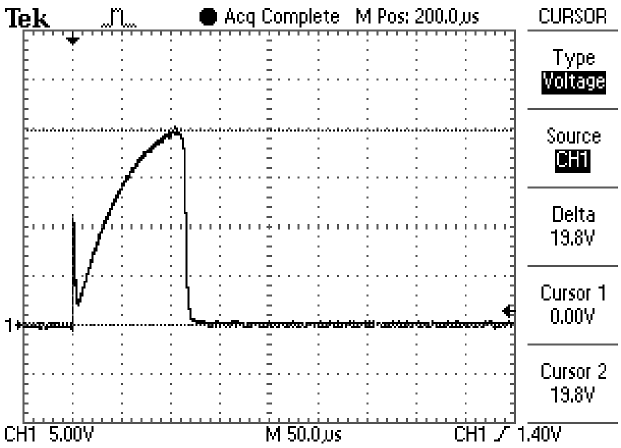

Fig. 5. Oscillogram of a truncated standard switching aperiodic ultra-high voltage pulse of the time shape T_m/T_d ≈200 μs/1990 μs of positive polarity during an electrical breakdown of a long air gap of length l_{min}=3 m in a «tip-plane» DEDS (U_{mcd}≈19.8 V × 53650 ≈1062.3 kV – voltage pulse cut-off level; T_c≈104 μs – voltage pulse cut-off time; T_{dc}≈33 μs – voltage pulse cut-off (commutation) duration; vertical scale – 268.2 kV/div; horizontal scale – 50 μs/div)

Let us point out that the presence of peak-like bursts shown in presented in Fig. 4, 5 oscillograms of truncated voltage pulses (at first their frontal parts) are related to the structural features of the construction of the ultra-high-voltage generator of the GIN-4 type [17, 18] used in the circuit for the formation of aperiodic voltage pulses used by us, which has a massive steel screen-roof with an area of about 60 m^2. The rapid charge and discharge of the electric capacity of this screen-roof GIN-4 causes the appearance of the indicated voltage peaks. These peak-like voltage surges cannot affect the development of electric discharge processes in our DEDS.

According to the research data (Fig. 5), in the case of an electrical breakdown of a long air gap in the investigated DEDS «tip-plane» (l_{min}=3 m), the duration of the cut-off T_{dc} at the front of the ultra-high-voltage (U_{mcd}≈1062.3 kV) standard switching aperiodic voltage pulse T_m/T_d ≈200 μs/1990 μs of positive polarity takes a numerical value equal to approximately T_{dc}≈33 μs. We see that with a doubling (from 1.5 m to 3 m) of the minimum length $l_{\min}$ of the air discharge gap in the «tip-plane» DEDS, the duration of the cut-off T_{dc} on the rising part of the used test voltage pulse $U_{12}(t)$ almost doubles (approximately from 17 μs to 33 μs according to the data of experimental oscillograms in Fig. 4, 5). These experimental results indicate that the average speed v_L of the advancement of the plasma leader channel of a pulsed spark discharge in the atmospheric air of the studied DEDS «tip-plane» with a sharply inhomogeneous high pulse electric field when the minimum length $l_{\min}$ in it changes in the range of $l_{\min}$=(1.5–3) m practically does not depend on the length of the long air gap electrically broken in this DEDS by a high or ultra-high pulse voltage $U_{12}(t)=(\varphi_1-\varphi_2)$, which at $l_{\min}$=1.5 m takes a numerical value of about U_{mcd} ≈611.6 kV (see Fig. 4), and at $l_{\min}$=3 m – approximately U_{mcd}≈1062.3 kV (see Fig. 5). Concrete confirmation of this is the fact that in the used air DEDS «tip-plane» ($l_{\min}$=3 m), which tests the effect of a standard switching aperiodic voltage pulse of the time shape T_m/T_d≈200 μs/1990 μs, the average speed v_L of advancement in atmospheric air of the plasma channel of the positive leader of a pulsed spark discharge taking into account the empirical formula (1) at $l_{\min}$=3 m and T_{dc}≈33 μs is numerically about $v_L \approx 1.03\cdot10^5$ m/s. This quantitative value for v_L (at $l_{\min}$=3 m in air DEDS) differs by no more than 3 % from the one previously obtained by us on the basis of the calculation and experimental method proposed here for the quantitative determination of the average speed v_L of the advancement in air of the positive leader of a long spark discharge during electrical breakdown in the same DEDS of the discharge air gap with a minimum length $l_{\min}$=1.5 m of the numerical value for v_L, which is approximately $v_L \approx 0.997\cdot10^5$ m/s. The actual path length l_c of advancement in the interelectrode gap of the air DEDS of the positive leader of the spark discharge in this case ($l_{\min}$=3 m; T_{dc}≈33 μs; $v_L \approx 1.03\cdot10^5$ m/s) will be numerically equal to about $l_c \approx v_L T_{dc} \approx 3.399$ m, which is approximately 13 % higher than the specified minimum length $l_{\min}$=3 m of the discharge air gap in the «tip-plane» DEDS under study. At a significantly lower speed v_L of the advancement of the positive leader of the discharge in the air, the «tip-plane» DEDS (for example, at $v_L \approx 1.5\cdot10^4$ m/s, see Fig. 5.36 in [3]), in which the electrical breakdown of its discharge gaps ($l_{\min}$=1.5 m and $l_{\min}$=3 m) is also determined by the supply to its corresponding electrodes of a standard high (U_{mcd}≈611.6 kV) or ultra-high (U_{mcd}≈1062.3 kV) switching aperiodic pulse voltages of the time shape T_m/T_d ≈200 μs/1990 μs of positive polarity, for the actual numerical values of the duration of their cut-off T_{dc} recorded by us (respectively equal to ~17 μs and ~33 μs according to the data of Fig. 4, 5) passing through it (a similar positive leader of the charge) of the indicated real paths of length $l_c \approx v_L T_{dc}$ (in the first case for l_c≈1.695 m, and in the second one l_c≈3.399 m) becomes fundamentally impossible. At the specified speed $v_L \approx 1.5\cdot10^4$ m/s [3], for the passage by such a discharge leader of the used lengths $l_c > l_{\min}$, T_{dc} values will be required, which should numerically be at least (110-220) μs, which will contradict the conditions and realities of our ultra-high-voltage experiments. In this regard, the known experimental data given in [7] (see Table 17.2) for the lowest average speed $v_L \approx 10^5$ m/s of the advancement of the negative lightning leader in the atmospheric air are more reliable. The physics of the development of leader breakdown of long air gaps in both natural and laboratory conditions, despite the significant difference in the levels of ultra-high voltage $U_{12}(t)$, at $dU_{12}(t)/dt \geq 5$ kV/μs should remain the same. The data obtained with the help of the proposed calculationl and experimental method for the average speed v_L of advancement in the atmospheric air of the positive leader of the pulse spark discharge in the DEDS «tip-plane» at $l_{\min}$=(1.5–3) m complement and clarify the little-studied electrophysical features of the mechanisms of manifestation in the world of leader breakdown of long air gaps in the used DEDS «tip-plane» with a sharply inhomogeneous high pulse electric field.

Taking into account the approximate numerical data for v_L presented in this work and the minimum measurement error of the ATPs used in the conducted experiments with the air DEDS «tip-plane» of standard switching aperiodic pulses of ultra- and high-voltage of the time shape T_m/T_d≈200 μs/1990 μs of positive polarity, which is at least 3 % [16, 17, 20], it can be assumed that the average speed v_L of the advancement in the atmospheric air of this DEDS of the leading front of the positive leader in the plasma channel of the pulse spark discharge is numerically about $v_L \approx (1\pm0.03)\cdot10^5$ m/s.

3. Calculation and experimental estimation of the short-term electrical strength of long air gaps. Here it is important to emphasize that the electrical strength of air insulation in the power industry and HPT is determined and selected based on the effect on it of the following two forms of ultra- and high-voltage pulses [1, 3, 16]: first, a standard switching aperiodic pulse; secondly, a standard oscillating decaying sinusoidal pulse. Obtaining similar data for long air gaps (for $l_{\min}$=(1–10) m) at pulse voltage level $U_{12}(t)$=(1–5) MV is associated with great technical difficulties and material costs. In this case, it is necessary to reliably protect both the main electrical devices of the ultra-high-voltage test electrical equipment itself and the external power supply devices connected to it from electrical surges [1, 2]. In addition, at the same time, it is necessary to provide for special measures both for safety and to prevent possible electrical breakdowns in the insulation of used electrical devices [1, 3, 17]. In this regard, the calculation and experimental results, which are presented above for the ultra-high-voltage air DEDS «tip-plane», which belongs to one of the main basic discharge systems [1, 3], may have a certain applied value when choosing in the field of industrial electric power and HPT of the minimum levels of discharge electric voltages and breakdown field strengths E_d of a strong pulse electric field for long air gaps.

Taking into account the empirical formula (1), for the averaged value of the breakdown field strengths E_d of a high electric field in the long air gaps of the investigated «tip-plane» DEDS, the following calculation relationship can be written:

$$E_d \approx \varphi_{1d} /(1{,}13 l_{\min}) , \qquad (2)$$

where φ_{1d} is the electric potential at the edge of the upper electrode in the studied DEDS in case of electrical breakdown of its discharge air gap, which is characterized by its minimum length l_{min}.

In the applied case 1, when l_{min}=1.5 m, from (2) at $\varphi_{1d}\approx\varphi_{1d1}\approx U_{mcd}\approx$611.6 kV (see Fig. 4) for the average breakdown field strength level $E_d=E_{d1}$ of a high pulse electric field in the indicated long air gap of the DEDS «tip-plane» we get a numerical value approximately equal to $E_{d1}\approx$360.8 kV/m. For the applied case 2 with l_{min}=3 m and $\varphi_{1d}\approx\varphi_{1d2}\approx U_{mcd}\approx$1062.3 kV (see Fig. 5) from (2), we find that the average value of the breakdown field strength $E_d=E_{d2}$ of a high pulse electric field in this long air gap of this DEDS is numerically close to $E_{d2}\approx$313.4 kV/m. As we can see, with an increase (by a factor of 2 from 1.5 m to 3 m) in the studied DEDS with a sharply inhomogeneous high pulse electric field of the minimum length l_{min} of its discharge air gap, the average value of the breakdown field strength E_d in it decreases (by approximately 13.1 % from 360.8 kV/m to 313.4 kV/m). These calculation and experimental results for the averaged breakdown field strength E_d of a high pulse electric field in the air DEDS «tip-plane» at l_{min}=(1.5–3) m are in good agreement with the data known in the field of electric power, which relate to the minimum electrical strength of air gaps of length l_{min}=(1–4) m [1-3].

Conclusions.

1. An approximate calculation and experimental method for determining the average speed v_L of the advancement of the plasma leader channel of an electrical pulse spark discharge in the long air gap of the «tip-plane» DEDS is proposed. This method is based on the proposed empirical formula and experimental data for the duration of the cut (commutation) T_{dc} of the breakdown voltage pulses, obtained from the results of deciphering the oscillograms of the process of the cut of the standard switching aperiodic ultra- and high-voltage pulse of the time shape $T_m/T_d\approx$200 μs/1990 μs of positive polarity in the event of an electrical breakdown in the specified DEDS of long air gaps with their minimum length l_{min}, which varies discretely in the range l_{min}=(1.5-3) m.
2. It is shown that the average speed v_L of the advancement in the atmospheric air of the front of the plasma channel of the positive leader of the electric pulse spark discharge in the investigated DEDS «tip-plane» for the two considered applied cases at l_{min}=1.5 m and l_{min}=3 m is numerically approximately equal to $v_L\approx(1\pm0.03)\cdot10^5$ m/s. Our numerical result for v_L is in good agreement with the known experimental data for the speed $v_L\approx10^5$ m/s in the atmospheric air of the plasma channel of the negative leader for a long thunderstorm spark discharge in the «charged cloud-to-ground» DEDS.
3. It was established by calculation and experiment that for a standard switching aperiodic pulse of high- and ultra-high voltage of the time shape $T_m/T_d\approx$200 μs/1990 μs of positive polarity, the average value of the breakdown field strength E_d of a high pulse electric field in the long air gap of the studied DEDS «tip-plane» with minimum length l_{min}=1.5 m is numerically about $E_{d1}\approx$360.8 kV/m, and for its minimum length l_{min}=3 m − $E_{d2}\approx$313.4 kV/m. The obtained results for E_d correlate well with the known data for the minimum electrical strength of air gaps of length l_{min}=(1–4) m in the studied air DEDS «tip-plane».

Acknowledgment. The work was carried out with the support of the Ministry of Education and Science of Ukraine (project DB No. 0123U101704).

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

REFERENCES

1. 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).

2. Knopfel' G. *Ultra strong pulsed magnetic fields*. Moscow, Mir Publ., 1972. 391 p. (Rus).

3. Bortnik I.M., Beloglovskiy A.A., Vereshchagin I.P., Vershinin Yu.N., Kalinin A.V., Kuchinskiy G.S., Larionov V.P., Monastyrskiy A.E., Orlov A.V., Temnikov A.G., Pintal' Yu.S., Sergeev Yu.G., Sokolova M.V. *Electrophysics bases of HV technique*. Moscow, Publ. House of MEI, 2010. 704 p. (Rus).

4. Baranov M.I. A choice of sections of electric wires and cables in circuits of devices of high-voltage high-current impulse technique. *Electrical Engineering & Electromechanics*, 2018, no. 6, pp. 56-62. doi: https://doi.org/10.20998/2074-272X.2018.6.08.

5. Baranov M.I., Rudakov S.V. Electrothermal Action of the Pulse of the Current of a Short Artificial-Lightning Stroke on Test Specimens of Wires and Cables of Electric Power Objects. *Journal of Engineering Physics and Thermophysics*, 2018, vol. 91, no. 2, pp. 544-555. doi: https://doi.org/10.1007/s10891-018-1775-2.

6. 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).

7. Rayzer Yu.P. *Physics of gas discharge*. Moscow, Nauka Publ., 1987. 592 p. (Rus).

8. 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.

9. 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.

10. Hussein A.M., Janischewskyj W., Chang J.-S., Shostak V., Chisholm W.A., Dzurevych P., Kawasaki Z.-I. Simultaneous measurement of lightning parameters for strokes to the Toronto Canadian National Tower. *Journal of Geophysical Research: Atmospheres*, 1995, vol. 100, no. D5, pp. 8853-8861. doi: https://doi.org/10.1029/95JD00543.

11. Xia Y., Liu D., Wang W., Bi Z., Wang X., Niu J., Ji L., Song Y., Qi Z. Effects of previous ionization and excitation on the ionization wave propagation along the dielectric tube. *Journal of Physics D: Applied Physics*, 2016, vol. 49, no. 16, art. no. 165202. doi: https://doi.org/10.1088/0022-3727/49/16/165202.

12. 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.

13. 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.
14. Xiong Z., Robert E., Sarron V., Pouvesle J.-M., Kushner M. J. Dynamics of ionization wave splitting and merging of atmospheric-pressure plasmas in branched dielectric tubes and channels. *Journal of Physics D: Applied Physics*, 2012, vol. 45, no. 27, art. no. 275201. doi: https://doi.org/10.1088/0022-3727/45/27/275201.
15. Kuhling H. *Handbook of Physics*. Moscow, Mir Publ., 1982. 520 p. (Rus).
16. *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).
17. 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.
18. Baranov M.I., Koliushko G.M., Kravchenko V.I. Generation of standard switching aperiodic impulses of high and superhigh voltage for full-scale tests of electrical power objects. *Electrical Engineering & Electromechanics*, 2013, no. 2, pp. 52-56. (Rus). doi: https://doi.org/10.20998/2074-272X.2013.2.10.
19. Baranov M.I. *Selected topics of Electrophysics. Monograph in 4 Vols. Vol. 4. Effects of interaction of physical bodies with fields and currents*. Kharkiv, FOP Panov A.N. Publ., 2023. 552 p. (Ukr).
20. Baranov M.I., Buriakovskyi S.G., Rudakov S.V. The metrology support in Ukraine of tests of objects of energy, aviation and space-rocket engineering on resistibility to action of pulses of current (voltage) of artificial lightning and commutation pulses of voltage. *Electrical Engineering & Electromechanics*, 2018, no. 5, pp. 44-53. doi: https://doi.org/10.20998/2074-272X.2018.5.08.

Received 30.09.2023
Accepted 16.11.2023
Published 02.03.2024

M.I. Baranov[1], *Doctor of Technical Science*, *Chief Researcher,*
[1] Research and Design Institute «Molniya»
of National Technical University «Kharkiv Polytechnic Institute»,
47, Shevchenko Str., Kharkiv, 61013, Ukraine,
e-mail: baranovmi49@gmail.com (Corresponding Author)

How to cite this article:
Baranov M.I. Calculation and experimental determination of the speed of advancement of the plasma leader channel of a pulse spark discharge in atmospheric air. *Electrical Engineering & Electromechanics*, 2024, no. 2, pp. 48-54. doi: https://doi.org/10.20998/2074-272X.2024.2.07