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INFLUENCE OF CORONARY DISCHARGE PARAMETERS ON THE EFFICIENCY OF LIGHTNING PROTECTION SYSTEM ELEMENTS

Purpose. ***Investigation of the formation of space charge in the region of the apex of lighting rod, under the action of the electric field of a thunderstorm cloud, to evaluate the efficiency of elements of lighting protection systems. Methodology. We have applied the mathematical simulation of electromagnetic field distribution on the top of metal rod by different forms. As a mathematical apparatus, we use the finite element method. We considered two forms of the rod section: round and square. The round (cylindrical) rod has a sharp apex. The square rod has a flat top. The experimental study investigates the features of corona discharge formation. A high-voltage test equipment is created an electric field. Experiments carried out using a configuration consisting a potential plate and vertical rod electrode on grounded plate. The electric field strength varied from 1 kVm^{-1} to 100 kVm^{-1}. This range corresponds to the thunderstorm condition. Results. We have obtained a correlation between the corona current and the strength of the electric field for various shapes of the rod top. The results of experimental studies confirmed the correctness of the conclusions of theoretical estimates. We show that the time parameters of streamer current pulses vary by no more than 30%, but a streamer charge increase to three time with increasing electric field strength. We proposed and applied a method for measuring the velocity of motion of a streamer in the discharge gap. As a result, it is established that the streamer speed is nonlinear in time. For a discharge gap of 1.2 m, the speed varies from 1.8·10^4 m/s to 1.1·10^6 m/s. Originality. For the first time, we have carried out a complex of studies of corona discharge parameters from lightning protector rod to apply for the certification procedure of ESE terminals. Practical value. Based on the set of obtained results, it is obviously that the standard NF C 17-102:2011 will not be introduced as a national standard of Ukraine before full introduction of scientifically justified data will be include into the requirements of the standard.*** References 10, tables 4, figures 9.

Key words: **rod lightning terminal, pulse corona, electric field intensity of thunderstorm cloud, corona current, streamer speed.**

Приведены результаты теоретических и экспериментальных исследований процессов формирования объемного заряда в области вершины стержневого молниеприемника. Рассмотрены особенности формирования стримерной короны на стержневых молниеприемниках с различными конфигурациями вершины в электрическом поле грозового облака. Установлены зависимости силы тока короны от напряженности электрического поля и высоты для каждого варианта стержня. Показано, что при этом временные параметры импульсов тока стримера меняются не более чем на 30%, а заряд стримера, и как следствие, сила тока короны увеличиваются по мере роста напряженности электрического поля. Предложено метод измерения скорости продвижения стримера. Метод основан на одновременном измерении напряжения и тока на разрядном промежутке. Результаты предлагается учесть при сертификации молниеприемников. Библ. 10, табл. 4, рис. 9.

Ключевые слова: **стержневой молниеприемник, импульсная корона, напряженность электрического поля грозового облака, ток короны, скорость стримера.**

Introduction. The basis of lightning protection systems for buildings and structures from direct lightning strikes are metal structures in the form of rod, cable and grid lightning receivers. The requirements for the device of such systems are regulated by the Standards IEC 62305-1: 2010 and IEC 62305-3: 2010. In contrast to the systems mentioned above, which can be conditionally called «passive», attempts have been made in the world over the last decade to create active devices that provide a significant increase in the size of the protection zone, compared to the protection zone of the classical Franklin lightning detector (hereinafter referred to as the passive rod lightning detector – PRL). Such devices include the so-called «Early streamer emission terminals (ESE)», which, according to the developers, provide a faster, compared with the PRL, the creation of a counter streamer that facilitates the interception of lightning. The declared radius of protection ESE of lightning receivers is directly proportional to the lead time [1]. The basis of such an approach is the fact of experimenting repeatedly formed by the formation of counter leaders from metal objects, both grounded and not having contact with the ground. However, not all the features and conditions for the formation of the counter leader have been sufficiently studied. In particular, the probability of meetings of the channel of the descending lightning with the ascending leaders is of a probabilistic nature. In addition, the speed of advancement of the oncoming ascending leader depends on the potential of the head of the lightning channel, which also has a random value.

The market also offers various options for devices called dissipaters, which reduce the likelihood of lightning striking the object by creating a volume of air around the top of the object, saturated with charged particles. This effect provides a reduction in the electric field strength above the top of the object, as a result of which the counter leader appears at high values of the electric field strength formed by the lightning channel, which leads to a decrease in the probability of the object being struck by lightning.

At the Scientific-&-Research Planning-&-Design Institute Molniya» of the National Technical University «Kharkiv Polytechnic Institute» (NIPKI «Molniya» NTU

«KhPI») over the past 10 years, more than 20 types of different ESE lightning detector and dissipater samples of almost all companies presented on the world market. In 2007, comparative tests of the ESE terminal of ERICO Company (USA) were conducted at the laboratories of the Technical University of Valencia (Spain) and NTU «KhPI» (Ukraine). The results of the tests showed that the provisions of the first edition (1995) of the Standard of France [1] are not sufficient for a reliable estimate of the size of the protective zone of ESE lightning detectors. During the discussion of the results it was proved [2] that it is necessary to introduce additional requirements for the variance of lead time and to establish the parameters of the reference PRL. In the new edition (2011) of the Standard [1], these recommendations are taken into account.

A significant part of the scientific community, united in the framework of the International Conference of the International Conference Lightning Protection (ICLP), categorically denies the scientific validity of the provisions of the standard [1]. The main aspects that do not have the proper experimental confirmation are:

– estimation of the radius of the ESE lightning protection zone is carried out by multiplying the advance time (defined as the arithmetic mean value of 100 digits) by the speed of advancement of the oncoming leader from the lightning detector, which is set equal to 10^6 m·s^{-1}. The experimental velocities obtained with the help of high-speed video cameras lie in the range (10^4 – 10^6) m·s^{-1};

– the lack of a documented experimentally confirmed larger protection radius compared to the PRL. Repeated joint tests on simulations did not confirm this fact.

Another part of the community, which is mainly composed of manufacturers and distributors of the devices under consideration, is integrated within the International Lightning Protection Association (ILPA), which conducts its own scientific symposia.

The arising contradiction has not only a scientific aspect, but it causes important problems of practical application of new devices. The erroneous determination of the size of the protection zone causes a decrease in the probability of interception of lightning by the lightning protection system, which can have negative consequences. Nevertheless, to date, the Standard [1] has been implemented in a number of countries, including France, Spain, Kazakhstan, Latvia, which have actually legalized the use of ESE lightning detectors in view of the design protection zone. Persistent attempts are being made to introduce the Standard [3] in Ukraine. The current circumstances prompted NIPKI «Molniya» NTU «KhPI» and the Technical Committee of Ukraine on standardization in the field of electromagnetic compatibility (TC 22) to initiate research in order to understand the physics of the accompanying phenomena.

The basis of the principle of operation of both types of new devices is the processes of corona discharge from metal rods and needles. Therefore, the scientific justification of the real protective properties of such devices requires a detailed study of the physics of corona discharge in conditions of finding products in the electric field of a thunderstorm cloud.

Analysis of recent investigations and publications. Studies of corona discharge processes have been carried out for many decades. However, they continue to this day. The reason is that the processes are of a probabilistic nature, and the completeness and reliability of the results of the research depends to a large extent on the means used to measure the electrophysical quantities and the speed of the video recording. Naturally, the information received in recent years, more accurately due to a qualitatively new level of the technology mentioned above.

The operating principle of the ESE terminal is based on the assumption that the occurrence of a streamer passing to the leader of a downstream zipper from the terminal takes place earlier than from a conventional rod lightning detector [1]. Therefore, the lead time value is the main technical characteristic of the ESE terminal. At the same time, the upstream streamer appears against the background of the corona discharge, which is an integral part of the process. Therefore, the solution of the problem in our institute is begun with the study of the regularities of the development of the streamer corona and its transition to the counter leader [2].

To a certain extent, the appearance of the crown adversely affects the protective properties of the lightning receiver its presence hinders the development of a counter leader. Many studies have been devoted to the study of the corona discharge process, including [3-6]. To ignite the corona, the magnitude of the electric field at the tip of the corona electrode should exceed a certain critical value (E_c). This value was first obtained empirically by the Peak for a cylindrical electrode:

$$E_c = 29.8\delta\left[1+\frac{0.3}{(\delta R)^{1/2}}\right], \qquad (1)$$

where E_c is the critical value of the field strength, kV/cm; $\delta = N/N_0$; N, N_0 is the gas density under existing and normal conditions, respectively, R is the electrode radius, cm.

The paper [5] presents the formula (2) for an electrode of spherical geometry with radius R

$$E_c = 27.8\left[1+\frac{0.54}{(R)^{1/2}}\right]. \qquad (2)$$

A comparison of the results of the estimation with these formulas for electrodes of radius $R\leq 1$ cm, for which the formulas are valid, is presented in Table 1.

Table 1
The values of the critical electric field strength, calculated by Peak and Baselian formula [5]

R, cm	0.1	0.5	1.0
E_c, kV/cm	58.5	42.6	39.0
E_c [5], kV/cm	75.1	48.9	42.8

Obviously, the discrepancy between the values of the critical strength increases with decreasing radius of the electrode.

In the intervals with a high degree of inhomogeneity of the electric field, the plasma region arising from the corona discharge can penetrate into the zone with a low intensity only in the form of a thin channel – a streamer. When the streamer enters the weak field, its speed slows down, it can stop. Such an incomplete process is called an impulse or streamer crown. The propagation continues as long as the electric field strength is greater than the minimum allowable. The average value of the electric field strength E_s along the streamer channel with positive polarity is in the range 450 $kV{\cdot}m^{-1}$ – 500 $kV{\cdot}m^{-1}$ [3]. Waters (1987) and Gallimberti (1979) show that increasing the length of the streamer L is directly proportional to the growth of the voltage U_i, as long as L is small compared to the length of the discharge gap. The coefficient of proportionality is equal, respectively, to the mentioned authors: 0.145 $cm{\cdot}kV^{-1}$ и 0.152 $cm{\cdot}kV^{-1}$.

According to the authors of [5], blunt lightning rods are more effective in intercepting lightning than sharp ones. On the contrary, it is stated in [7] that, by varying the radius of the lightning-conductor within rather wide limits (practically significant), it is impossible to influence the magnitude and distribution of the space charge of the corona in its vicinity. This contradiction also requires experimental verification.

The boundary velocity of the rise of the pulse front for a quasi-stationary regime, when the voltage variation during the development of streamers can be neglected, is 50 $kV{\cdot}\mu s^{-1}$. According to formula (2) from [7], it follows that for a linear increase in the electric field strength, the corona current increases linearly, and when E_0 is stabilized, the current decreases with time. The data of experimental studies [6] do not confirm this fact. If the steepness of the front is above the boundary, the streamer moves forward during the entire time of voltage growth at the gap, while its velocity increases.

A strong streamer flash injects so much charge into the gap that the field on the entire anode falls far below the ionization threshold, as a result of which there is a pause in the development of the discharge [7]. If the voltage across the gap does not change or changes slowly, the pause time can be long – about the time of ion drift by a distance comparable to the anode radius (for $r_a \sim 10$ cm and average electric field strength of 5 $kV{\cdot}cm^{-1}$ $\Delta t \sim 10^{-3}$ s). This phenomenon is characteristic of a rod with an acute conical vertex, because the element that injects the charge has a point size. Consequently, a flat top of the rod should have advantages in creating a stable streamer sequence.

The goal of the paper is investigation of the formation of space charge in the region of the apex of a rod lightning detector under the action of the electric field of a thunderstorm cloud to evaluate the efficiency of elements of lightning protection systems.

Results of theoretical investigations. Obviously, the lightning receiver, the conductor connected to the ground, has a zero potential. As the thundercloud approaches, an electric charge is induced on it, the surface density of which is determined by the strength of the electric field at the top in the region of greatest inhomogeneity. Under certain conditions described above, there is a corona discharge and streamers, which subsequently grow into a leader facing the lightning.

The speed of the lightning detector depends on the degree of ionization of the surrounding airspace. If ionization is active, a cloud of charged particles is formed, complicating the germination of the oncoming leader. This effect is based on the designs of dissipaters, which are combinations of thin conductors. If the ionization is weak, there are no charges necessary for the formation of avalanches. Hence, we can assume that there is a design of the top of the lightning detector, which will provide the corona current optimal for minimizing the formation time of the oncoming leader. This fact is important for the selection of a standard sample of the lightning detector, the need to determine which was initiated in [2] and confirmed by the standard [1].

In order to study the initial phase of the formation of a stationary corona at the apex of a rod lightning detector, the mathematical model is maximally approximated to the real conditions when testing in accordance with the standard [1]. The electrostatic field is formed by two circular disk-like conductive plates, 10 m in diameter each. One of the plates (upper) is assigned a potential of 10 kV, the other is grounded (U = 0). The distance between the plates of the model varies in the range from 3 m to 10 m. The value of the potential is chosen in this way for reasons of the electric field strength $E_0 \geq 1$ $kV{\cdot}m^{-1}$, characterizing the pre-threat situation. The height of the lightning rod is assumed to be 2 m. The mathematical model of the problem is as follows. In airspace, the electric field is potential, and the potential satisfies the Laplace equation. The boundary conditions of the problem are given by the vanishing of the potential on the lower plate and rod; positive potential of 10 kV on the upper plate; the remaining boundaries correspond to the condition of continuity of the potential.

The aim of the simulation is to determine the ratio of the parameters of the rod lightning receiver, in which an optimum ratio of the maximum field strength near the vertex and the volume of this region (the stressed volume) is obtained, which is favorable for the streamer process.

Calculation of the electric field strength on the surface of the pointed rod is carried out along the generatrix of the cone of its vertex. The degree of sharpness of the vertex of the rod is characterized by the sharpness coefficient (k), which is equal to the ratio of the height of the tip to the radius of the rod. Variants are considered when the coefficient takes the values 1; 2; 3 and 4 for a rod with a radius of 0.05 m. The results of calculating the electric field strength at the tip of a point of a pointed rod 2 m high, found in an electric field of intensity 2 $kV{\cdot}m^{-1}$, are shown in Table 2. The calculated values of the field strength factor K at the point under consideration are also given there.

Table 2
The electric field strength at the tip of the point of a pointed rod of 2 m high

k	1	2	3	4
E, kV·m^{-1}	220	600	1020	1250
K	110	300	510	625

The results of the solution of the problem for various variants of the height of the rod (in the range from 1 m to 8 m), the cross section (circle, square, polygons), its size (from 10 mm to 30 mm) and the shape of the vertex (plane, point[8]). The simulation results showed that the maximum value of the electric field strength on the rod surface increases in direct proportion to the rod height. In particular, for a rod of square cross-section, this dependence is described by formula (3) with an error ≤ 5%.

$$E_m(h) = 26.7 \cdot E_0 \cdot h \,, \qquad (3)$$

where $E_m(h)$ is the maximum value of the strength of the E-field on the edge of a vertex of a square rod with a flat vertex, V·m^{-1}; E_0 is the intensity of the electric field in which the rod is placed, V·m^{-1}; h is the rod height, m.

In order to verify the results, a comparison is made with the results of calculations obtained by other researchers: using the formulas given in [4] for the grounded half of a spheroid in an external electric field and the numerical method of work [9]. The intensity of the E-field at the tip of the rod with a radius of 0.05 m with a vertex in the form of a hemisphere is calculated. The input parameters of the model are: H = 5 m, h = 2 m, U = 104 V. According to our estimates, the maximum value of the electric field strength at the top of the rod is 77.2·10^4 V·m^{-1}, that is 36 times greater than E_0 = 2·10^3 V·m^{-1}. When using graph 10 from [4] for a spheroid with a height-to-radius ratio of 40, the gain is determined close to 30. As a result of the numerical solution in [9], the result is close to 35. Taking into account some difference between the geometric figures used in the calculations, And a not too exact scale on the graph in [4], there are grounds to believe that the results of the numerical method used by us are reliable. An illustration of the stressed volume around a rod of square cross section is shown in Fig. 1.

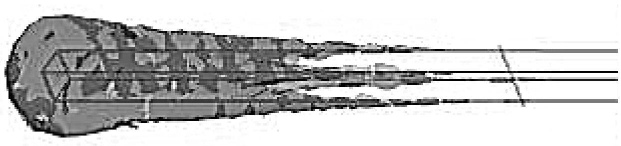

Fig. 1. The intense volume of the E-field around the rod square section (model rotated 90° to the left)

In order to generalize the results of the investigation of the process of corona discharge formation from rod lightning receivers, computer simulation was carried out on the basis of a multifactor experimental design. As a response function, the value of the intensive volume of space around the vertex of the rod is chosen. The intensive volume is the volume of pace, in which the strength of the external electric field exceeds 30 kV·m^{-1}. Based on the analysis of the results of experimental studies, quantitative and qualitative factors are selected that fully determine the value of the response function. These factors are: the strength of the electric field, the length of the rod, the shape of the cross section, the dimensions of the section, the shape of the vertex. A priori, it is assumed that the significance levels of these factors are comparable. From experience it is known that the response function has several maxima, depending on the shape of the cross-section of the rod. Therefore, the choice of the model zero point is related to the cross-sectional shape of the rod. The functional relationships constructed earlier from the experimental data show that they are analytical and allow one to specify a specific type of dependence of the objective function on each of their chosen factors. This allowed us to confine ourselves to a two-level factorial plan of type 2^k (k is the number of factors). To ensure the possibility of checking the adequacy of the chosen mathematical model and the correctness of the determination of constants, an unsaturated plan was used (the number of experiments exceeds the number of unknown constants in the model). A full factorial experiment is performed on the basis of which the target response function is constructed.

The value of the intensive volume, determined from the established functional dependence, is compared with the value of the number of streamer pulses obtained experimentally. Comparison made it possible to determine the required minimum stressed volume at which the corona discharge process begins. In addition, the value of the length of the initial steamers is determined, depending on the values of the experimental factors.

The main results of theoretical studies are as follows:

– since the zone of increased tension is localized near the ribs of the rod, the «intensive volume» increases with the perimeter of the rod;

– the maximum value of the electric field strength and the magnitude of the stressed volume on the surface of the lightning receptacle, at other things being equal, is achieved when using a rod of square cross-section with a flat top. Such a rod is proposed as a new standard for the document [1].

Results of experimental investigations. At a certain value of the electric field strength into which the lightning detector is placed, streamer flashes with a current of tens of mA occur against the background of a «quiet» corona whose current is not more than hundreds of microamperes. Only a streamer flash can transform into a leader under certain conditions. Therefore, the determination of the critical value of the electric field strength at which streamer flares occur and the nature of their behavior when the level of electric field strength varies is an important task. Modeling was carried out on the high-voltage test bench BBC-1.2 at the NIPKI «Molniya» NTU «KhPI». To estimate the performance of a particular lightning detector, it is proposed to use the values of streamer parameters that arise when placed in an electric field.

To reveal the relationship between the parameters of streamers and the protective properties of the lightning detector, a set of studies was carried out, including the determination of the characteristics of streamers at a constant and pulsed voltage. Investigations at constant voltage make it possible to evaluate the behavior of the lightning detector when a thunderstorm cloud approaches, while the other part of the study is related to the study of the process of the appearance of streamers when exposed to a pulsed electric field accompanying a growing lightning channel.

The investigations were carried out on rod lightning receivers placed between two parallel metal planes. Dimensions of the planes: lower – 4×6.5 m, upper – 3.6×5.2 m. The scheme of the test setup for studying the characteristics of the current of the corona at a constant and varying voltage and its external view are shown in Fig. 2 and 3 respectively.

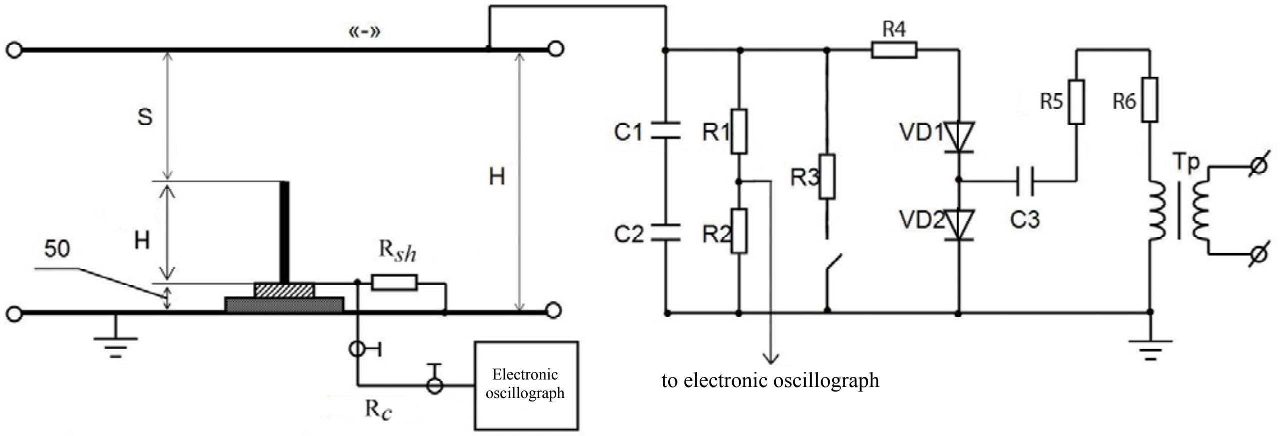

Fig. 2. Circuit of the test bench BBC-1.2
(C1 = 0.381 μF; C2 = 0.385 μF; C3 = 0.4 μF; R1 = 300 MΩ; R2 = 30 kΩ; R3 = 60 kΩ; R4 = 510 kΩ; R5, R6 = 60 kΩ; R_{sh} = 75 Ω; R_c = 75 Ω; Tp – transformer ИОМ 100/25)

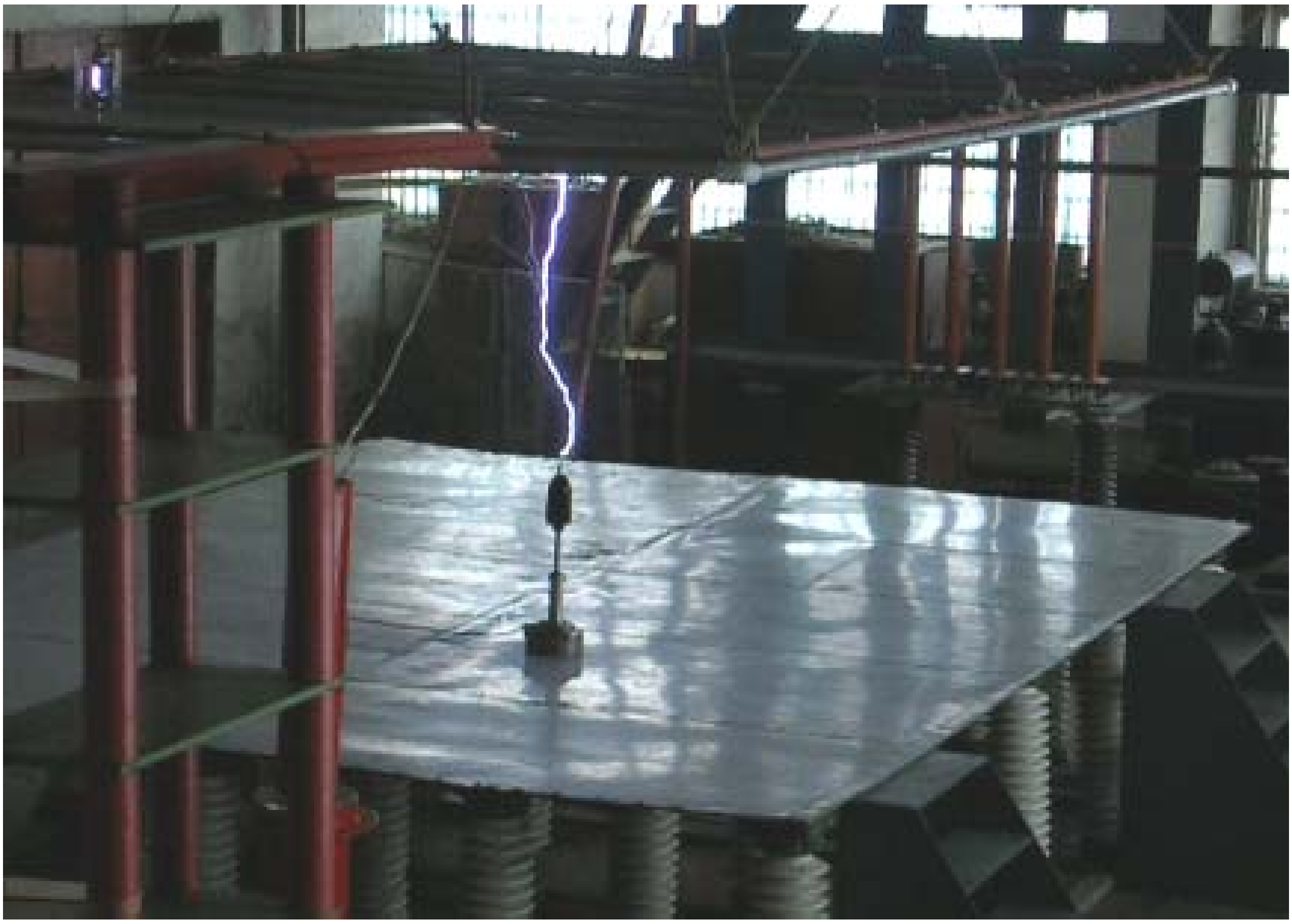

Fig. 3. External view of the test bench BBC-1.2

In this variant, the lower plane is grounded. The upper potential plane – it is supplied with a high voltage of negative polarity. The distance (S) between the vertex of the rod and the potential upper electrode varied in the range from 2.5 m to 0.5 m.

Here, the initial value of the electric field strength in the gap did not change. The results of experimental investigations are presented in detail in [6-8]. A generalization of these results allows us to draw the following conclusions. A typical oscillogram of the current strength of a single streamer is shown in Fig. 4. The charge contained in the streamer is approximately $5.85 \cdot 10^{-9}$ C. For comparison, in [5], measuring the charge of the streamer by an alternative method yielded an average value of $5 \cdot 10^{-10}$ C. Taking into account the difference in the configurations of the vertices of the rods and the heights of the rods, the coincidence of the results is satisfactory.

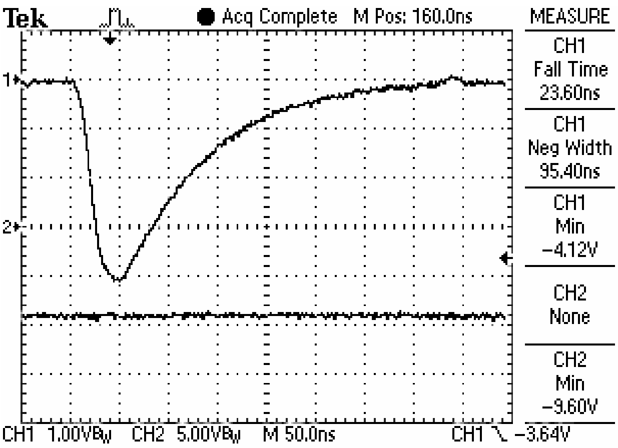

Fig. 4. Oscillogram of a single streamer from a rod of square cross section 12×12 mm^2 with a rod height of 1.7 m, which is in the electric field of intensity 30 kV·m^{-1} (the signal is received from the 75 Ω resistor, charge in the pulse 58.5 10^{-10} C)

The dependences of the average arithmetic number of streamer flares on the electric field strength for the pointed and square rods are shown in Fig. 5.

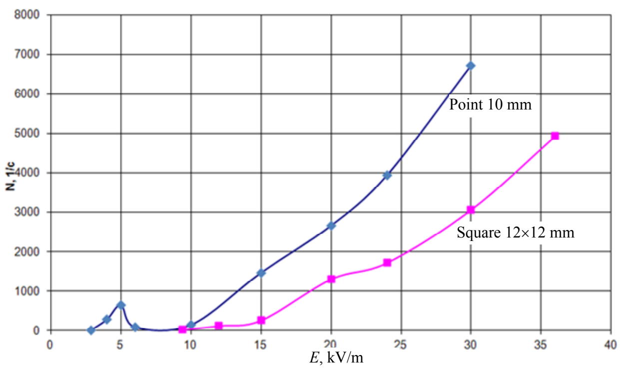

Fig. 5. Dependence of the streamer frequency on the sharpened (diameter 10 mm, sharpness coefficient $k = 3$) and square (12×12 mm^2) rods on the electric field strength. The length of each rod is 3.4 m

The results of statistical processing of the experimental data are presented in Table 3, 4 for the pointed and square rods, respectively. It should be noted that the time parameters (shape) of the current of a single streamer for all considered cases vary within ± 30 % of the arithmetic mean. Significant changes are observed only for the peak value of the pulse, hence, the value of the charge of the streamer. At each voltage, at least 50 measurements were made. The values of root-mean-square (RMS) deviation presented in the tables unambiguously show a much smaller spread of values for a rod of a square cross-section as compared to a rod with a pointed vertex. This property is characteristic of a rod of any length within the limits considered. It is no accident that the bars of the square section are defined as the elements of the discharge gap for the standard of high voltage value (standard IEC 60062).

Table 3

The results of measurement of the streamer frequency for a pointed rod of circular cross section (diameter 10 mm, sharpness coefficient $k = 3$, height 3.4 m)

U_0, kV	E_0, kV·m^{-1}	Streamer numbers per second, N	RMS
14.5	2.9	9.16	1.31
20	4	276	7.02
25	5	636	12.58
30	6	78	15.97
50	10	136.6	59.53
75	15	1460	145.60
100	20	2656	322.20
120	24	3940	523.70

From the presented results, it is evident that a «dead» zone (in the range from 6 kV·m^{-1} to 10 kV·m^{-1}) is located near the pointed top. The effect is determined by the point character of the corona element. The presence of such an effect explains the opinion of the authors of [5] mentioned above that blunt lightning rods are more effective at intercepting lightning than sharp ones. It is important to note that this effect is not observed for a rod of square cross section.

Table 4

Results of frequency measurements of streamers for a square rod (12×12 mm^2, height 3.4 m)

U_0, kV	E_0, kV·m^{-1}	Streamer numbers per second, N	RMS
47	9.4	14.7	1.40
60	12	116	4.81
75	15	258	4.74
100	20	1302	20.54
120	24	1720	23.85
150	30	3064	32.77
180	36	4930	93.15

The dependence of the strength of the corona discharge current on the electric field strength, for the rods described above, is shown in Fig. 6. It follows from Fig. 6 that with an electric field strength greater than

15 kV·m^{-1}, the current from the square rod is greater than from the pointed rod, despite the fact that the number of streamers from the pointed rod is about 2 times larger (see Fig. 5). The reason for this is due to the large charge of each streamer from the rod of the square cross section.

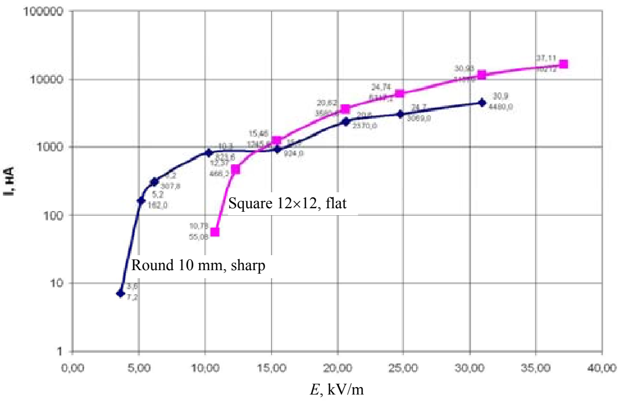

Fig. 6. Dependence of the current of the corona on the strength of the electric field for the pointed (diameter 10 mm, sharpness ratio k = 3) and square rods. The length of each rod is 3.4 m

From the presented experimental results, the following conclusions follow:

– the pointed rod (diameter 10 mm, k = 3, height 3.4 m) begins to react with an electric field strength of 3 kV·m^{-1}, and a square-section rod (12×12 mm^2) of the same height not earlier than from 9 kV·m^{-1};

– corona discharge from the pointed rod in the E-field intensity range from 6 kV·m^{-1} to 10 kV·m^{-1} stops, which fully corresponds to the results of [5] cited above in the introduction;

– at an E-field strength exceeding 10 kV·m^{-1} the number of streamers from the pointed rod is approximately twice as large as from the square rod;

– the average peak value of the current of an individual streamer is higher for a square rod, for example, at strength $E \approx 10$ kV·m^{-1}, this value is 5 mA for a pointed rod and 60 mA for a square rod;

– the value of the root-mean-square deviation, with other identical conditions for the case of a square rod, is less than for the case of a pointed rod.

Alternative method for measuring the streamer speed. The traditional method of measuring the speed of streamer-leaders is ultra-fast video recording. To implement this method requires the presence of a high-speed video camera, for example, the type FASTCAM SAS (with the option of up to 10^6 frames per second) and a special mode of illumination of the investigated discharge gap. The limitation of the realization of this method is not only the high cost of the camera, but also the fixed sector of the survey, which makes it difficult to use the method effectively when investigating long (more than 3 m) discharge gaps.

An important parameter of the pre-discharge processes is the speed of the oncoming streamer, which is formed from the grounded object. With higher the averaged speed, the probability of lightning entering the object is higher. It is known [10] that the streamer speed depends on the electric field strength in the discharge gap. Thus, in a region where the field strength E exceeds $3\cdot10^6$ V·m^{-1}, the streamer speed can reach 10^7 m/s. However, such tension, and, consequently, speed, is possible only in the streamer zone of the head of the lightning leader. It is indicated in [10] that the measured average leader speed is $3.36\cdot10^5$ m/s, the minimum is $8\cdot10^4$ m/s, and the maximum speed is $2.6\cdot10^6$ m s. It is proved that there is a minimum streamer speed, which is 10^3 m/s in air under normal conditions. At lower values, the tape drive stops. Consequently, the range of change of the parameter under study (the streamer-leader speed) is more than four orders of magnitude.

It is known [10] that the ionization wave is formed from the top of the rod and propagates in the interelectrode gap towards the opposite electrode. As a rule, in air gaps up to 5 m long (typical for most laboratory conditions), the streamer-leader has a single-channel structure without significant branching. A weakly conducting cover forms around the channel of the streamer. The streamer model adopted is based on the following assumptions:

– the channel of the critical streamer is single (not branching);

– the diameter of the channel, taking into account the cover, is constant;

– the density of charges in the channel is uniform.

Under these assumptions, the length of the streamer is directly proportional to the charge in the channel (taking into account the cover). The integral value of the charge in the channel is proportional to the streamer current and time by formula (4). In fact, this is the area under the curve $I(t)$, represented on the oscillogram (Fig. 7)

$$Q = \int_0^T I(t)dt\,, \tag{4}$$

there Q is the charge value in the channel; T is the duration of the process, $I(t)$ is the dependence of current on time since the beginning of the process.

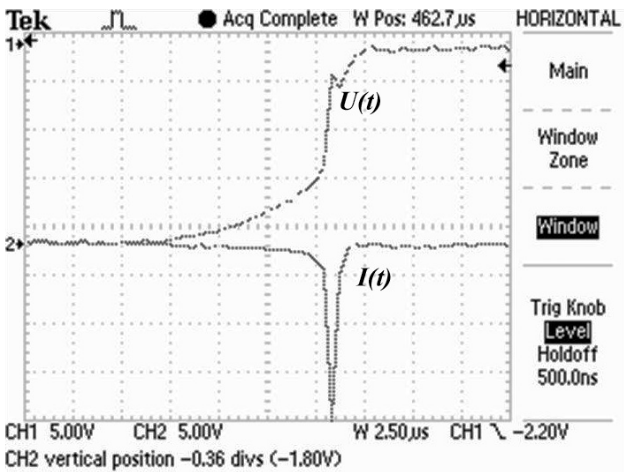

Fig. 7. Oscillogram of the dissemination process of the critical streamer

Denote the channel length of the streamer L_k. It is obvious that at the moment of contact of the opposite electrode L_k is equal to the length of the air gap L, and the streamer charge has the value of Q. This moment is fixed by the abrupt failure of the voltage $U(t)$ applied to the air gap.

It should be noted that the moment of closure of the gap by the streamer cannot be determined from the maximum streamer current, since the maximum value of the current strength is reached after closing the gap and is determined by the magnitude of the discharge voltage in the discharge loop.

Consequently, the result of the experiment gives such initial data:

– total channel charge (Q);

– time interval (T), during which the streamer crosses the air gap;

– the length of the air gap (L).

From these data, it is easy to determine the mean of the streamer speed at an interval by the obvious formula (5).

$$V_A = LT^{-1}. \quad (5)$$

To estimate the instantaneous values of the streamer velocity at various points in the air gap space, we use the above assumptions about the nature of the streamer propagation. The streamer channel, in the form of a cylinder of length L, of a certain radius (whose value for the problem under consideration is not essential) is divided into N equal parts. At each n-th section, the value of the charge (Q_n) is estimated by the formula (6).

$$Q_n = Q/N. \quad (6)$$

Further actions are illustrated in Fig. 8, which shows a typical curve $I(t)$ on an enlarged scale. The area under the curve $I(t)$, giving the value of the charge Q, is determined. This area is divided into N equal parts. The partitioning algorithm for some particular cases will be presented later. The corresponding values of t_k are found. The streamer speed (V_n) at any arbitrarily small segment is determined by the formula (7).

$$V_n = L(N \cdot \Delta t_n)^{-1}, \quad (7)$$

where Δt_n is the value of the n-th time interval.

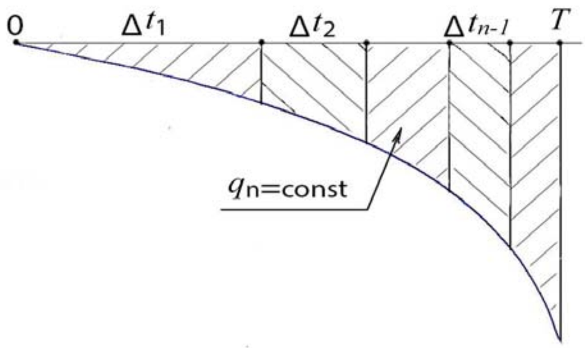

Fig. 8. The principle of subdividing the area under the curve

Results of the calculation estimation. Let us consider particular cases of the functional dependence of the streamer current on the propagation time. If the current does not depend on time, the streamer is distributed with a constant speed. Such an option is hypothetical, since in experiments is not visible.

As a first approximation, the curve of $I(t)$ dependence can be approximated by a straight line passing at a certain slope angle (k). In this case, the functional dependence of the current strength on time is described by formula (8)

$$I(t) = k \cdot t. \quad (8)$$

After substituting (8) into formula (4), for the total charge of the streamer we obtain (9)

$$Q = 0.5k \cdot T^2. \quad (9)$$

The instant of time (t_1) of the first segment passing by the streamer (coincides with the time interval) is found by formula (10)

$$t_1 = \frac{T}{\sqrt{N}}. \quad (10)$$

To calculate the subsequent values of t_n it is not difficult to obtain the recurrence formula (11)

$$t_n^2 = \left(\frac{T^2}{N}\right) + t_{n-1}^2. \quad (11)$$

The character of the curve on the oscillogram (Fig. 7, lower curve) can be described more accurately by an exponential dependence. In this case, it is more convenient to consider the dependence in the inverse time variant, without taking into account the sign, which allows us to introduce the function (12):

$$I(t) = \exp(-\alpha \cdot t), \quad (12)$$

where α is the coefficient determining the decay rate of the function.

The maximum value of the current is set equal to unity, since its absolute value does not affect the further results. The value of the parameter α is easily determined from the curve $I(t)$. For this it is sufficient to find the time moment (t_e) at which the current reaches a value of 0.368. The parameter $\alpha = t_e^{-1}$.

The recurrence relation for finding the values of time (t_n) from the previous value (t_{n-1}), is described by formula (13).

$$t_n = -\left(\frac{1}{\alpha}\right) \cdot \left[\exp(-\alpha t_{n-1}) - \left(\frac{1}{N}\left(1 - \exp(-\alpha T)\right)\right)\right]. \quad (13)$$

This relation makes it easy to find all the values of t_n with any given accuracy determined by the number of partitions N. It should again be pointed out that in this case the count of the time intervals is realized from the maximum of the current strength to the beginning.

In the example shown in Fig. 7, the distance from the top of the lightning collector to the upper potential electrode was 1.2 m. The time of development of the process of germination of the streamer, defined as the interval from the point of divergence of the curves to the instant of a sharp decrease in voltage, is 9 μs. The number of intervals is chosen equal to 10. The values of the corresponding time intervals are calculated using formula (13). On the basis of the obtained data, taking into account that each segment of the streamer length is equal to 0.12 m, a spatial dependence of the velocity, represented by the graph in Fig. 9.

In the example considered, the streamer speed varied from $1.8\cdot10^4$ m/s to $1.1\cdot10^6$ m/s. The average value of the streamer speed in the air gap is $1.3\cdot10^5$ m/s. The calculated values of the streamer velocity are in good agreement with the data obtained by other methods [10].

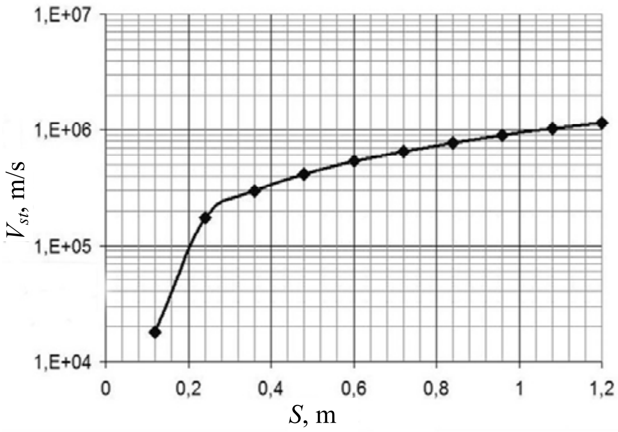

Fig. 9. Graph of the streamer speed change from the path

The proposed algorithm can be described as follows:

– the integral value of the charge Q (the area under the curve of the $I(t)$ curve) is determined;

– the number of partitions is chosen, for reasons of sufficient accuracy;

– the values of the time intervals for which the areas under the curve are equal are equal to and equal to the N-th part of Q;

– the speed at a specific spatial gap is defined as the quotient of the interval length divided by the time it intersects.

The method can supplement the procedure for attestation of lightning receivers according to the standard [1].

Conclusions.

The functional dependences of the streamer frequency with metal rods with a length of 3.4 m of circular cross section with a pointed vertex and a square section with a flat top have been determined experimentally.

It is established that the frequency of the streamer follow-up for the case of a rod of square cross section has a deterministic character: with increasing electric field strength, the repetition frequency increases monotonically with coefficient which is close to $0.25\ s^{-1}\cdot V^{-1}\cdot m$.

The value of RMS, under other identical conditions for the case of a square rod, is several times smaller than for the case of a pointed rod.

It has been established that corona discharge from a sharpened rod in the range of electric field strength from 6 kV/m to 10 kV/m ceases, and the repetition frequency with increasing intensity reaches 6 kHz.

On the basis of the obtained results of the investigation of the features of the formation of a streamer corona from the top of a rod lightning detector with a height of more than 1 m, it is proposed to take as a standard lightning detector for testing ESE terminals in accordance with the standard [1] a square bar ($12\times12\ mm^2$) with a flat top with height of 1 m.

Certification of ESE type lightning detectors is recommended to begin with comparative tests with a standard lightning detector, by placing them both in the working volume of the test bed and recording the discharge frequency in each of them when a voltage pulse with a front duration of more than 100 μs is applied to the gap.

A method for estimating the rate of advance of a critical streamer is proposed, based on the synchronous measurement of the voltage across the discharge gap and the streamer current from the lightning detector.

Based on the aggregate of the results obtained, the standard [1] is recommended not to be introduced as a national Standard of Ukraine until the introduction of scientifically justified data into the requirements of the standard.

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