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CORONA DISCHARGE FROM LIGHTNING RODS IN CONDITIONS OF ACTION OF STRONG ELECTRIC FIELD

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INTRODUCTION

The necessity to increase reliability of lightning protection gave rise to the idea of creation of lightning rods of new types that realize the mechanism of Early Streamer Emission (ESE), called “ESE terminals” or “active” lightning rods. They are to provide the faster creation of a counter leader for lightning, compared to a usual lightning rod. The present market of devices of protection of buildings and structures against lightning strike is quickly filled with such specimens of lightning rods. Among manufacturers of ESE terminals there are world-famous companies in the lightning protection area. Advertising prospectuses placed at sites of such companies announce very attractive technical characteristics of these devices that provide protection zones many times larger than the usual lightning rods. According to information from the site of The International Lightning Protection Association (http://www.intlpa.org/about-us/) as at 2018, more than 680 thousand of such devices had been installed in the world.

To use the modern devices in the practice of lightning protection, it is necessary to have confidence that properties announced by a manufacturer correspond to the facts. Quality control is proposed to perform by the procedure regulated by France standard NF 17-102:2011[1]. However, this standard is recognized, besides France, in Spain, Argentina, Lithuania and some other countries. World scientific community including such distinguished scientists in the area of lightning physics as M.A. Uman[2], V.A. Rakov, V. Cooray, M. Becerra[3], E. Bazelyan and others consider the points of this standard to be insufficiently substantiated because the trustworthiness of the proposed method has not been proved by

[1] Lightning protection. Protection of structures and open areas against lightning using early streamer emission air terminals. NF C 17-102. AFNOR, 2011. 91 p.

[2] Uman M.A., Rakov V.A. A Critical Review of Nonconventional Approaches to Lightning Protection. *BAMS. American Meteorological Society*. December 2002. P. 1809–1820. DOI: 10.1175/BAMS-83-12-1809.

[3] Becerra M., Cooray V. Laboratory experiments cannot be utilized to justify the action of early streamer emission terminals. Journal of Physics D: Applied Physics. 2008. Vol. 41. No. 8. 8 p. DOI: 10.1088/0022-3727/41/8/085204.

corresponding scientific researches. Among the main drawbacks of the method the following were pointed:

- absence of substantiation of the specified value of velocity of the counter leader;
- absence of substantiation of parameters of the lightning rod which was taken as the reference one to compare results obtained in different testing laboratories;
- influence of corona discharge on the process of formation of a counter leader is not determined;
- absence of evidence base for extrapolation of results of laboratory tests to real conditions.

Presence of such drawbacks made it necessary to determine expediency of introduction of standard NF 17-102:2011 in Ukraine. From the name of ESE terminals it follows that the physical basis of their functioning is a streamer-leader process from the rod elements. The initial stage of this process is corona discharge that arises from sharp edges in strong electric field, or with application of high potential. Therefore, investigation of these processes is necessary to analyze the mentioned drawbacks in relation to determination of properties of ESE terminals.

Besides, considerable human casualties in the world that occurred as a result of lightning strike, for example, in Germany during the rock festival in June 2016, caused relevance of creation of systems of warning about lightning hazard. One of the aspects of this trend is development of elements of the system that react to increase of electric field strength in environment to critical values, which is a precondition of development of lightning discharge. Therefore, the two trends are united by investigation of corona discharge in strong electric field, which made this work relevant.

1. Theoretical studies of the electric field at the top of the rod

Let’s look at the theoretical justification of the hypothesis about the benefits of a flat-top rod by examining the effect of the parameters of the system’s air terminal — a conducting plane modeling a cloud on pre-discharge conditions. The mathematical model of the initial stage of the process of formation of stationary corona around the top of the rod air terminal was selected to be maximally approximate to the parameters of the physical model regulated in performing tests by France standard NF C 102-17. The model has such geometrical parameters: electrostatic field is created by two round conducting plates 2R = 10 m in diameter each. One of the plates has potential $U = 10^4$ V, the other is grounded (U=0). The distance (H) between the plates is varied in the range from 3 m to 10 m. The length of the rod air terminal (h) is selected to be 2 m in the cases when otherwise is not specified.

The mathematical model of electrostatic problem for calculation of electric field strength distribution over the surface of the metal rod placed into electric field of specified strength, and in the air space near the rod was considered. By introducing the scalar potential by equation $\boldsymbol{E} = -\,\mathrm{grad}\,\varphi$, a classic statement of the inner Dirichlet problem for potential φ, with the corresponding boundary conditions is obtained:

$$\Delta\,\varphi = 0, \tag{1}$$

$\varphi\,/_{s1} = U$, where s1 – the surface of the potential electrode (the upper);

$\varphi\,/_{s2} = 0$, where s2 – the surface of the grounded electrode;

$\varphi\,/_{s3} = 0$, where s3 – the surface of the rod;

$\varphi\,(r) \to 0$ at $r \to \infty$, where r – the distance from the center of Cartesian coordinates, which is located at the geometric center of the surface of the lower electrode.

The main assumptions are the following:

– relative permittivity of air environment is 1;

– the selected dimensions of the plates allow us to not take into account influence of the edge effect on distribution of charges at the rod.

The following parameters of the rods are varied:

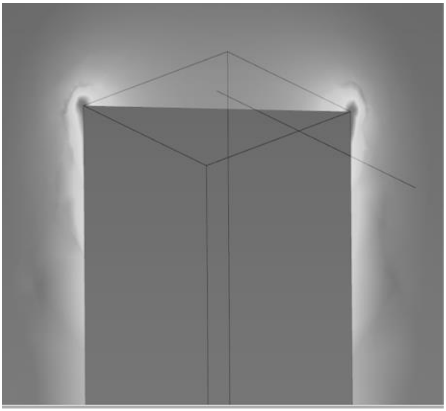
– form of rod cross-section (circle, square, hexagon, octagon);

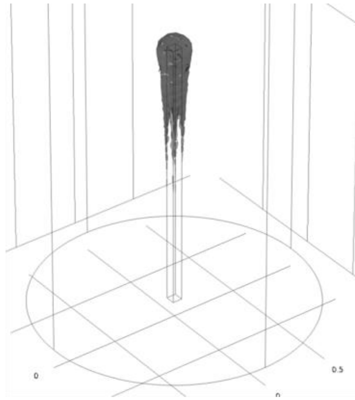
– characteristic dimension of cross-section from 10 mm to 60 mm;

– form of the top (section at right angle, tapered – only for rods of round cross-section).

The simulation is performed with the use of module AC/DC COMSOL Multiphysics: 2D / 3D axisymmetric →AC/DC →Electrostatics, Boundary Elements (*esbe*). For round rods, the calculations were performed in two modes: 2D and 3D, which made it possible to assess a possible error of realization of 3D mode, associated with the considerable number of nodes of the calculation grid, which allowed determining grid parameters of the 3D model for other variants of rods. The total number of grid nodes did not exceed 10^6. The calculations were performed with the use of computer on the basis of quad-core processor Intel Core i5 with RAM 8GB. The purpose of the simulation is determination of such variant of combination of parameters of the rod air terminal at which the maximal value of “stressed volume” is achieved all other things being equal. As an illustration, in Fig. 1 presented are distribution of E-field strength (Fig.1a) and “stressed volume” (Fig. 1b) in the space near the rod of square cross-section.

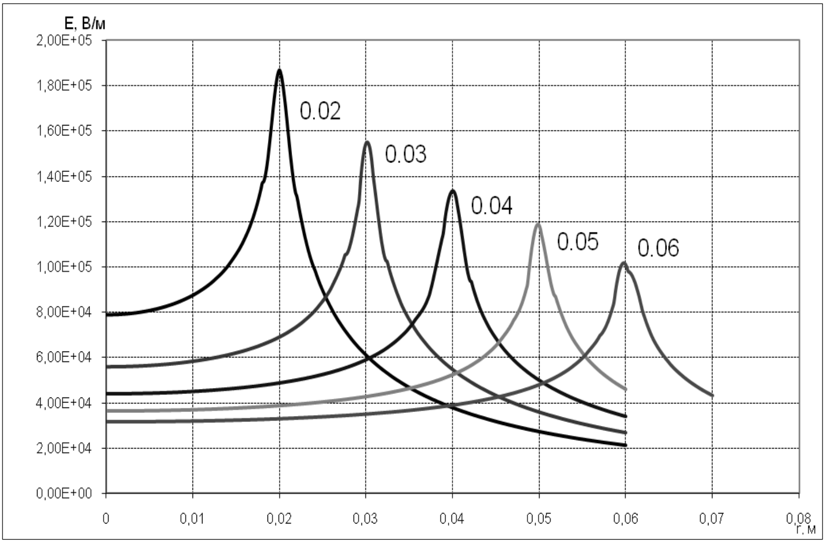
It is found that when radius of the rod of round cross-section decreases (i.e. the area of the butt), electric field strength at its surface increases as shown in Fig. 2. According to requirements to lightning rods, the minimal value of the area of cross-section should be no less than 144 mm^2. Therefore, in the subsequent experimental investigations, the rod of square cross-section 12 x 12 mm was selected.





а)   б)

Fig. 1. Distribution of E-field strength in the space near the rod of square cross-section



Distance, m

Fig. 2. Plots of E-field strength at the surface of butt of round rod depending on the value of rod radius (h=2 m; h/H= 0.4; E_0=2 kV/m)

It was found that as a result of increasing the height of the rod (cylinder with radius 0.05 m) in the range from 1 m to 4 m, the maximal value of electric field strength increases linearly. Functional dependence which is well (with error less than 5%) described by empirical formula (2) was generalized.

$$E_m(h, r)/E_0 = 45.0\ h\ g\ [1 - 0.11(r-2)], \quad (2)$$

where: $E_m(h,r)$ – maximal value of E-field strength at rod rib, V/m;

E_0·– strength of acting electric field, V/m; h – rod height, m (from 1 m to 4 m); r – rod radius, m (from 1 cm to 6 cm), g – coefficient of influence of cross-section form (g = 1 for circle; 1.3 for hexagon; 1.5 for square).

This formula allows us to determine the necessary rod height for occurrence of corona discharge in electric field of specified strength, which was used in analysis of results of experimental investigations presented in Section 2.

To check reliability of results obtained by numerical methods, comparison with results of calculation by analytical equations, obtained in work[4] for the grounded half of spheroid in external electric field, was performed. For this purpose, E-field strength at the top of round rod with radius 0.05 m with the top in the form of half-sphere was determined. Input parameters of the model were: H=5m, h=2m, U = 10 kV. According to result of the calculation, the maximal value of E-field strength is $7.225\ 10^4$ V/m, i.e., 36 times as much as $E_0=2\ 10^3$ V/m. With the use of plot 10 from work for spheroid with the ratio of height to radius equal to 20, amplification coefficient is 30. Taking into account the difference between the geometrical figures and not-too-accurate scale in the plot in the mentioned work, there is reason to consider results obtained by numerical method to be reliable.

2. The results of experimental studies

High-voltage testing stand (BBC-1.2) was developed and created to realize experimental investigations. BBC-1.2 includes power distribution cabinet; control pulpit; autotransformer; step-up rectifying device; pulsed voltage generator (GIN) 1.2 MV; pulsed current generator 100 kV/ 70 kA; universal ignition unit; formation device; field-formation system; measuring complex. General view of the part of the complex is presented in Fig. 3, where 1 – step-up rectifying device PVU-1; 2 – pulsed voltage generator; 3 – pulsed current generator; 4 – formation device; 5 – field-formation system in the form of strip line (SL); 6 – universal ignition unit. During designing GIN 1.2, the maximal value of output voltage (1.2 MV) limited by the distance to surrounding elements of the hall was taken into account. GIN 1.2 is designed to generate lightning and switching voltage pulses. Appearance of GIN-1.2 is presented in Fig. 4, where 1 – insulating

[4] Moore C.B., Rison W., Mathis J., Aulich G. Lightning rod improvement studies. *J. Appl. Met*. 2000. № 39. P. 593–609.

construction; 2 – capacitor IK-100-0.4; 3 – charging-discharging resistor; 4 – damping resistor; 5 – multi-gap switch MZK-100.

The discharge circuit of GIN-1.2 includes 13 stages, each created by capacitor of IK 100-0.4 type, multi-gap air switch MZK-100, two charging-discharging resistors (each 60 kΩ), assembled of resistors of TVO type, and two damping resistors. The damping resistors are made of Ni-Cr alloy tape laid zigzag with insulating gaskets and encapsulated in epoxy compound. The value of resistance of each resistor is 2.5 Ω. Start of GIN is performed by application of trigger pulse to the middle electrode of the first switch.

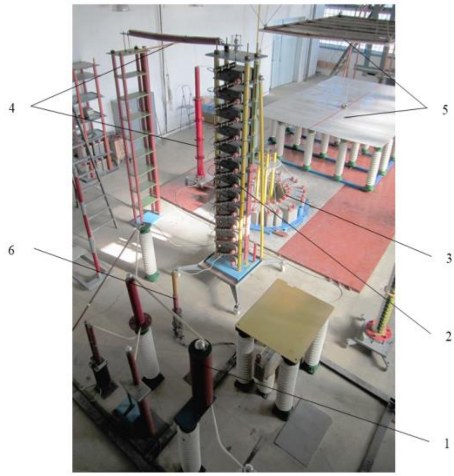


Fig. 3. Testing stand BBC-1.2

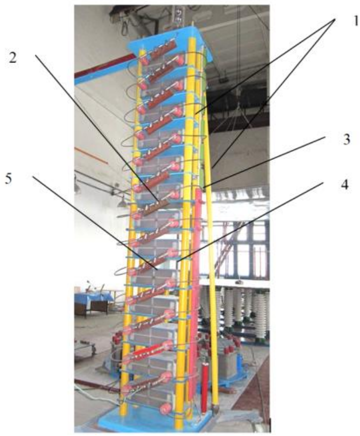
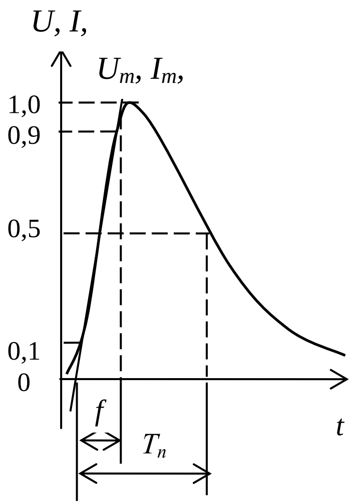


Fig. 4. Pulsed voltage generator GIN-1.2

Selection of parameters of the discharge circuit was performed by way of simulation with the use of program Micro-Cap. Main output parameters of BBC-1.2 concerning formation of pulsed voltage are presented in Table 1. Overall dimensions and electric characteristics of BBC-1.2 in full measure satisfy requirements of standard NF C 102-17 concerning certification of ESE terminals, which was confirmed by external audit of foreign customers. The standard requires application of constant electric field which strength is from 20 kV/m to 25 kV/m. This requirement simulates the environment that is characteristic for conditions of lightning development. The considerably wider range from 1 kV/m to 100 kV/m was investigated in the experimental studies, which allowed us to obtain additional results about parameters of corona discharge, the use of those is described in Section.

Table 1

Output parameters of BBC-1.2 (concerning voltage pulses)

Name of parameter or characteristic	Measurement unit	Value	Form of Voltage pulses
Amplitude of lightning voltage pulse	kV	250 – 1000	
Duration of lightning voltage pulse front	μs	1.2 ± 0.36	
Half-decay duration of lightning voltage pulse	μs	50 ± 10.0	
Amplitude of aperiodic switching voltage pulse,	kV	250 – 1000	
Duration of front of aperiodic switching voltage pulse	μs	250±50	
Half-decay duration of switching voltage pulse	μs	2500±750	

The investigation was performed with ten rod specimens that were different in form of cross-section, dimensions, and top form. Modified characteristics of rod air terminals are presented in Table 2. The rods are positioned between two parallel metal planes with dimensions: the lower – 4.02 x 6.56 m, the upper – 3.63 x 5.22 m. The lower plane was grounded in this variant. The upper plane is potential, high voltage (HV) of both polarities up to 150 kV was applied to it. The distance between the planes (H) was set 2.20 m. The rods had the same length – 0.75 m and were placed at the insulated support. The length of the air gap between the rod top and the upper plane was 1.3 m (error < ±1 mm).

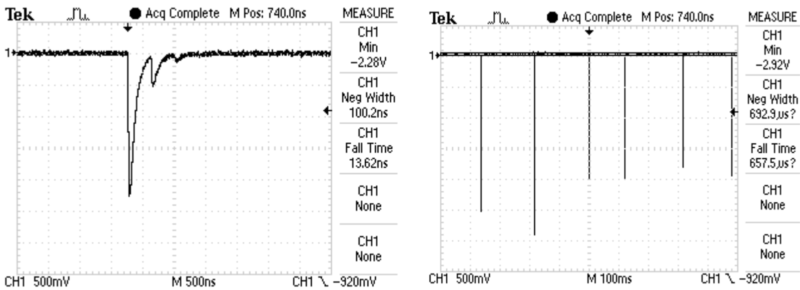
Table 2

Characteristics of rod specimens

Rod #	Name	Material	Cross-section dimensions, mm	Rod top
1	square	steel	12	flat
2	square	steel	16	flat
3	hexahedron	steel	12	flat
4	hexahedron	steel	19	flat
5	circle	steel	Ø12	flat
6	circle	steel	Ø22	flat
7	circle	Д16	Ø10	flat
8	circle	Д16	Ø20	flat
9	circle	Д16	Ø10	cone
10	circle	Д16	Ø20	cone

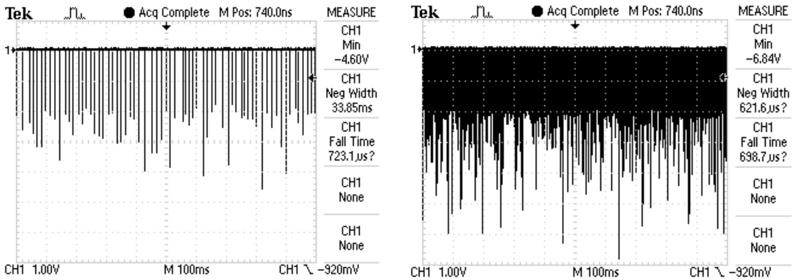
Parameters of corona current were registered with help of coaxial shunt CSh-50 (R_s=50 Ω) and digital oscilloscope Tektronix TDS 1012 connected by coaxial radio-frequency cable of РК-50 type 30 m in length. Time of transient response of CSh-50 does not exceed 2 ns.

With voltage at the potential plane being increased continuously, the moment of occurrence of pulse of streamer flash was recorded at the oscilloscope screen. Sensitivity of the measuring system allowed us to register a signal which level exceeded 5 mV, which corresponds to the current value more than 0.1 mA. Therefore, currents of “silent corona” did not influence results of the investigations. As an example, oscillograms of characteristic bursts of corona current (streamer flashes) for air terminal #5 of round cross-section 12 mm in diameter with flat top are presented in Fig. 5 and 6. Corona occurred at voltage 92 kV (electric field strength in this case is 41.8 kV/m), amplitude of single burst was 46.5 mA.



a) single streamer (U=92 kV, I=46.5 mA) b) sequence of streamers at U=92 kV

Fig. 5. Characteristic oscillograms of streamer flashes



a) Streamer corona at U=100 kV b) Streamer corona at U=140 kV

Fig. 6. Oscillograms of developed corona depending on voltage level

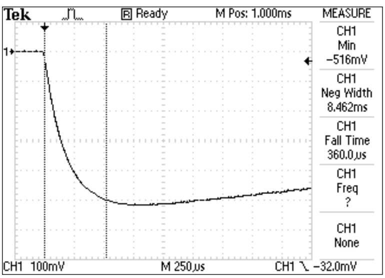
A single streamer is presented in Fig. 5a, and oscillogram of sequence of streamers with duration 1 s at critical voltage value – in Fig 5b. Oscillogram of scanning during 1 s at voltage 100 kV is presented in Fig. 6a, and oscillogram of scanning during 1 s at voltage 140 kV – in Fig. 6b. Similar oscillograms were obtained for all specimens of air terminals mentioned in Table 2. Statistics of sixteen measurements was collected for each specimen. Frequency of occurrence of current pulses was determined by oscilloscope with the use of the special option. Results of statistical processing for the variant of negative polarity of the potential electrode are presented in Table 3. Analysis of the results shows that for rods with cone top (#9 and #10), occurrence of streamer flashes is observed at electric field strength about 10 kV/m. In this case the current value is units of milliamperes. It is important to note that for rods #9 and #10 with pointed top, when voltage is being increased, the moment comes when the process of formation of pulsed corona ends. In the performed experiments it took place at voltage 100 kV (45.5 kV/m).

Table 3

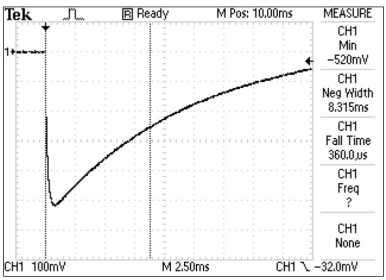
The value of single streamer current with occurrence of streamer corona

Rod#	Voltage at potential electrode *U*cr, kV	Current amplitude of single burst, mA	Voltage drop at shunt, V	*E*cr, kV/m
1	78	26.8	1.34	35.45
2	84	27.2	1.36	38.18
3	80	28	1.4	36.36
4	96	30.4	1.52	43.64
5	92	45.6	2.28	41.82
6	122	52.8	2.64	55.45
7	80	38.4	1.92	36.36
8	112	48.4	2.42	50.91
9	20	1.72	0.086	9.09
10	24	3.12	0.156	10.91

In Section 2 above, the proposition to use the rod of square section 12 mm on side with flat top as an alternative reference specimen of air terminal instead of the recommended by standard NF C 17-102:2011 (diameter 28 mm with tapered top) was made. To compare parameters of the two variants of rod specimens, experimental investigations by the procedure of the mentioned standard were performed. During testing each specimen, 100 discharges of pulsed voltage of negative polarity with amplitude about 600 kV and form 360/8460 μs were applied. The distance between the planes in the tests was 2.20 m, the rod top was at the distance of 1.0 m from the lower plane. Measurements of parameters of testing voltage pulse and lead time were performed simultaneously with help of high-voltage capacitive divider and electric field sensor. Forms of the signals registered by the two measuring paths were in good agreement (within 3%). Type oscillogram of form of voltage pulse that acts on air terminal specimens is shown in Fig. 7.



a) front

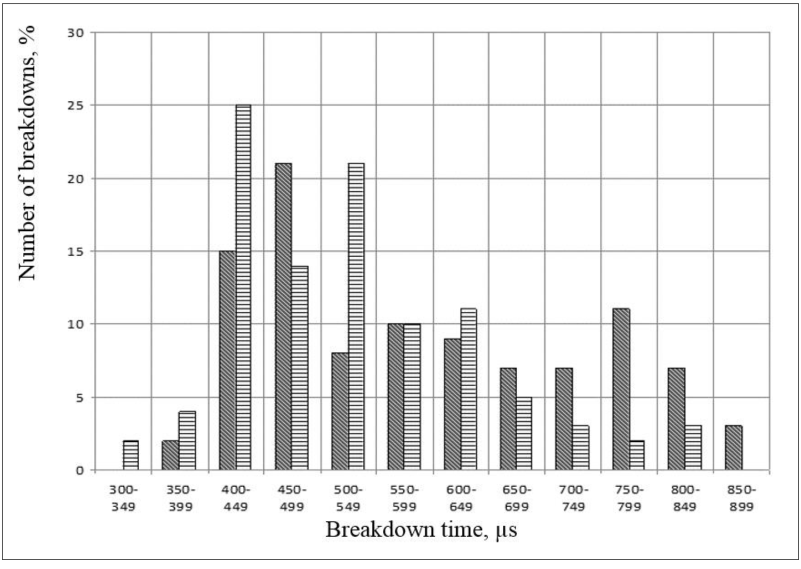


b) decay

Fig. 7. Oscillograms of voltage pulse

Generalization of the results is presented in the form of histogram of distribution of time of air gap breakdown, depicted in Fig. 8. In histograms, the number of breakdowns for those breakdown time falls into the corresponding time interval (in this case this number coincides with probability expressed in percent) is laid off as ordinate. Duration of each time interval is 50 μs.

Analysis of the histograms shows that distribution of probability of breakdown time of both specimens has a similar character. However, the difference in the average breakdown voltage is only 1.2 kV, which corresponds to 0.2% of the applied voltage. It is known, that variation of breakdown voltage of long gaps can achieve 10%. Therefore, the difference of 0.2% is considered to be insignificant, caused by change of environment conditions (temperature, humidity, and pressure) during the tests. To eliminate this influence, both specimens were installed in the test volume at the distance between the rods more than 1.5 m to determine the correlation of probability of air gap breakdown with parameters of lead time.



Continuous filling – square rod / intermittent – round rod

Fig. 8. Histograms of breakdown time for rod specimens

The tests were performed at two values of discharge voltage of GIN: 650 kV and 910 kV with form 360/8460 μs. After application of 50 voltage pulses with level 650 kV, it was found that 25 discharges occurred in each specimen. After application of 50 voltage pulses with level 910 kV, the discharges were distributed as follows: 27 – into the square rod, and 23 – into the round. Therefore, by the main objective parameter – probability of discharge, both specimens are practically the same when voltage pulse 650 kV is applied. However, when voltage with the quicker rise was applied (910 kV), the rod of square section has some advantages (stability of breakdown voltage, which confirms the choice of such rod to measure high voltage in standard IEC 60052). This fact gives birth to the question about the measure of correlation between the average value of breakdown time and probability of interception of lightning. Therefore, first, it is necessary to determine efficiency of ESE terminal by way of comparative simultaneous tests with reference specimen.

Determination of the value of streamer velocity that is used in the standard to determine a protection zone of ESE terminal is fundamental. The author believes that the quickness of development of the positive counter leader, which forms the basis for the announced advantage of such air terminals, was exaggerated approximately by an order of magnitude – from 10^5 m/s to 10^6 m/c. Such contradiction requires that streamer velocity be measured during certification of ESE terminals. The proposed method is as follows. During tests, recording of the form of the voltage applied to discharge gap and the value of current of the streamer which intersects the gap and causes breakdown is performed simultaneously. The type oscillogram obtained for the specimen with square section is shown in Fig. 9.

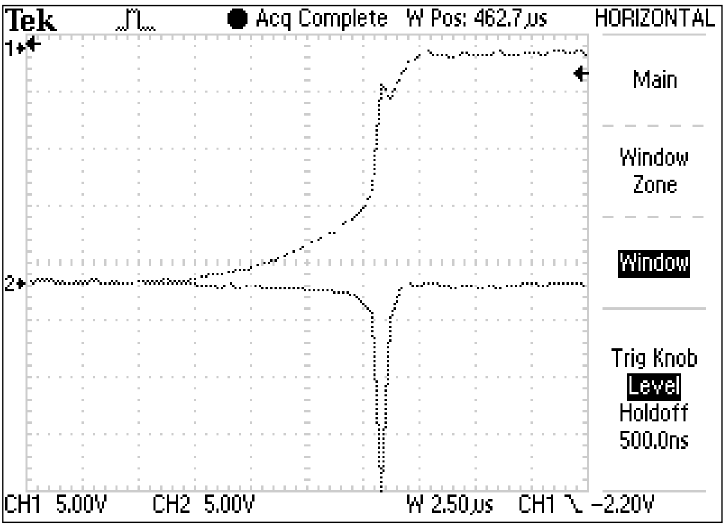


Fig. 9. Type oscillograms of voltage and current of breakdown of air gap

The distance from the top of air terminal to the upper potential electrode was 1.2 m. The time of development of the process of sprouting of the streamer determined from this oscillogram, from the beginning of increase of current (the higher curve) till the moment of breakdown according to the voltage oscillogram (the lower curve) is 9 μs. Visual investigations indicate that the streamer in such conditions has one channel. Let us make the assumption based on this fact: the amount of charge is directly proportional to the length of the streamer channel. Therefore, oscillogram of current gives information on the length of streamer channel, taking into account the value of distance between the rod top and the potential electrode. The time interval was divided into 10 equal parts 0.9 μs each. The distance covered by the streamer for each time interval was determined. Results of calculation of the average streamer velocity over each interval are presented in Table 4.

Table 4

Streamer velocity

Interval#	Duration, μs	Distance covered, m	Average velocity over interval, 10^4 m/s
1	0.9	0.036	4.0
2	0.9	0.042	4.7
3	0.9	0.039	4.3
4	0.9	0.036	4.0
5	0.9	0.037	4.1
6	0.9	0.039	4.3
7	0.9	0.049	5.4
8	0.9	0.078	8.7
9	0.9	0.21	23.3
10	0.9	0.634	70.4

According to the presented results streamer velocity varies from $4 \cdot 10^4$ m/s to $7 \cdot 10^5$ m/s. Average velocity in this case is $1.3 \cdot 10^5$ m/s. It is evident that when determining dimensions of protection of air terminal, it is necessary to take into account the average velocity of streamer over the time of its propagation. It should be noted that the obtained results well correlate with the corresponding results of measurement of streamer velocity by other methods, for example, with the use of ultra-fast video recorder (10^6 frames per second). Additional information can be found in the work[5].

[5] Chernukhin O.Yu. Influence of Coronary Discharge Parameters on the Efficiency of Lightning Protection System Elements. *Electrical Engineering & Electromechanics*. 2017. No. 3. P. 47–56. DOI: 10.20998/2074-272X.2017.3.07.

The results obtained determined concrete additional conditions that were proposed to include into the version of the corresponding Standard GOST which is at the stage of approval of the second revision. The history of development of requirements and changes to France standard NF 17-102 is presented in Table 5.

Table 5

Changes in requirements of standard NF 17-102

Parameter normalized	Standard NF 17-102:1995	Propositions of RDI "Molniya" 2004–2010 years	Standard NF 17-102:2011	Propositions of RDI "Molniya" 2011-2019 years
Reference rod	-	Necessary to introduce	Section – circle, diameter 28 mm	Section – square 12x12 mm
Dispersion	-	Necessary to introduce	$\sigma_{ESE} < \sigma_F$	Conditions by formula[1)] $\sigma_{ESE} < 0{,}5\ \Delta T - \sigma_F$
Velocity, m/s	10^6	Requirements of substantiation	10^6	Must be defined in the range 10^5–10^6

Note: 1. The processes of breakdown of air gaps are described by the log normal distribution. According to Chebyshev condition, the probability that the value of random quantity is at the distance more than k standard deviations from the mathematical expectation is k^{-2}. Thus, probability that this value is in the range 2σ is no less than 95%. It makes sense to determine a condition that connects values of standard deviation (σ) and lead time (ΔT).

3. Principle of operation of the lightning hazard indicator

This part includes results of investigation of effects of corona discharge from the rod to determine possibility to create an indicator of thunderstorm activity on the new principle. On the basis of results of the experimental investigations presented in Section 2, the hypothesis for possibility of creating the device to warn about occurrence of lightning was formulated. The hypothesis is based on such facts: it is established that the value of current of each streamer for the range of field strength from 5 kV/m to 40 kV/m and rod length from 1 m to 4 m varies no more than by 50%, and time parameters – less than by 30%, in this case the exponential dependence of the number of streamers per unit of time is observed. It is established that occurrence of streamers begins when electric field strength achieves a concrete value that depends on the form of rod cross-section, form of its top and length. However, for a concrete rod all parameters are sufficiently stable. Besides, installation of sensors of lightning current taking into account probability of lightning strike into an object, which fundamentally widens the information base for prediction, is proposed. The proposed approach gives the possibility to create a national net of prediction of lightning activity by integration of thousands or maybe tens thousands of local systems through Internet and cellular communication. In designing a local system for concrete application, a previous calculation assessment of probability of strike into object elements by statistical method was used. This will allow us to optimize the places of installation of sensors to obtain the most reliable information on the lightning processes.

Taking into account data of Table 3, the rod of round cross-section 10 mm in diameter was selected as a sensitive element of the warning system. To generalize results of investigation of dependence of frequency of occurrence of pulses of corona discharges on the main parameters of the process, method of planning of multi-factor experiment was used. Structure of orthogonal central compositional plan (OCCP) of three-factor experiment was selected:

Target function: Frequency of streamer occurrence (the number per second).

Input variables were the following: h – rod height (range from 2 m to 5 m); E_0 – electric field strength (from 5 kV/m to 20 kB/m), taking into account that at $E \leq 3$ kV/m pulses do not occur; k – a dimensionless quantity, the ratio of the point height to radius of the round rod (range from 3 to 5).

Planning and processing results of fulfillment of full factor experiment of FFE 2^3 type for 8 points of the plan were carried out. Linear model (1) was formulated.

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + +b_{23}x_2x_3 + b_{123}x_1x_2x_3, \quad (3)$$

To check uniformity of assessments of test results, Cochran's criterion was used, for the case of the same number of parallel tests (two) at all points of the plan. Design value of the criterion $G_p = 0.369$. The table critical value G_p from Cochran distribution for significance level $\alpha = 0.05$; the number of degrees of freedom $f_\Sigma = 8$; runs 2 ($f_u = 1$), is $G_{\text{табл}} = 0,68$. According to the result $G_p = 0,369 < G_{\text{табл}} = 0,68$, which indicates that dispersions are uniform. Therefore, results of measurement of response at all points of the plan are equally accurate (all order dispersions belong to the same general population).

Fulfillment of the requirement of uniformity of order dispersions S_u^2 allows us to determine dispersion of reproducibility (of assessment of general dispersion) as the arithmetical mean of the order dispersions. Results of calculation of coefficients of linear model (3) are presented in Table 6.

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Table 6

Results of calculation of b – coefficients of the model

b_0	b_1	b_2	b_3	b_{12}	b_{13}	b_{23}	b_{123}
2331.563	367.6875	1755.313	213.0625	-8.3125	21.4375	102.5625	11.6875

Check of significance of b – coefficients is performed with the use of t-distribution. Calculated was $b_{кр} = t_{tab}\ S_{bi}$, where t_{tab} – parameter for t –distribution with the corresponding degrees of freedom (f_Σ =8), significance level (α = 0.05): t_{tab} = 2.306; S_{bi} = standard deviation of b – coefficients:

$$S_{bi}^2 = \frac{S_y^2}{nN} = \frac{2438}{2 \cdot 8} = 152\,, \tag{4}$$

$$\sqrt{S_{bi}^2} = \sqrt{152} = 12{,}3\,, \tag{5}$$

where n – the number of parallel inquiries; N – the number of combinations (inquiries).

Thus, the obtained value $b_{кр}$ = 28.5. If $|b_i| \le b_{кр}$, then the corresponding coefficient is not significant, and it can be ignored. Regression equation in coded variables has the form:

$$y = 2331 + 367x_1 + 1755x_2 + 213x_3 + 102x_2x_3\,, \tag{6}$$

Check of adequacy of the model was performed by Fisher's test. The check showed that $F_р = 1{,}45 < F_{кр} = 4{,}07$, then the model should be recognized to be adequate to experimental data with reliability $p = 1 - \alpha =$ 0.95. Transition to physical variables was made by way of substitution of coded values (7) into (6):

$$x_1 = \frac{H-3}{0{,}41}\,,\ x_2 = \frac{E_0 - 13}{5{,}8}\,,\ x_3 = \frac{k-4}{1}\,, \tag{7}$$

Finally, the empirical formula that determines dependence of streamer frequency on parameters of the problem has the following form (8):

$$F_s = -4225 + 896\,h + 231.9\,E_0 - 16.8\,k + 17.6\,k\,E_0, \tag{8}$$

Scope of the formula (8) is limited by ranges of input variable parameters: h – rod height (range from 2 m to 5 m); E_0 – electric field strength (from 5 kV/m to 20 kV/m), k – dimensionless quantity, the ratio of point height to radius of the round rod (range from 3 to 5).

The obtained results were used in creation of specimens of devices of warning against lightning hazard (X1, ML-FCSH, TWS-KS) that function without any moving element, which is qualitatively different from known devices with electric "mill", and micro electro-mechanical sensors. Determination of the hazard level is performed by recommendations of standard IEC 62793:2016 for devices of FSM type (Field Strength Meter): the level of giving a hazard signal when electric field strength achieves (7–10) kV/m, recommended range of measurement ±20 kV/m.

CONCLUSIONS

The results obtained are relevant to the problem connected with increasing efficiency of lightning protection by way of investigation of physical processes of corona discharges from rod air terminals in conditions of action of strong electric field of thundercloud. The investigation was performed by experimental methods with the use of created specialized high-voltage complex BBC-1.2 and the corresponding mathematical models. According to the results of the performed investigations, a number of important conclusions concerning the possibility of introduction of France standard NF C 102-17: 2011 in Ukraine, also concerning creation of the new type of lightning hazard indicators, were made.

1. It is proved that breakdown of air gap rod-plane with the use of rod of square section (dimensions 12×12 mm^2) has the most stable characteristics among the considered variants, including the traditional pointed rod. This fact indicates appropriateness of the use of rod with square section in lightning protection practice.
2. The requirement, that deals with assessment of results of certification of lightning rods by the procedure of France standard NF C 102-17: 2011, to the value of dispersion of function of distribution of lead time was improved, which provides increase of reliability of advantages in relation to interception of lightning with predicted probability.
3. Method of measurement of velocity of propagation of streamer-leader in interelectrode space, based on comparative analysis of oscillograms of voltage between the electrodes and current from the electrode that forms discharge was developed. It was shown that leader velocity increases by square law as its head propagates. With the use of ultra-fast video recording, satisfactory agreement with results of measurements was obtained (within 15%). It is proved that velocity of streamer propagation in the interelectrode space 1.2 in length does not exceed 7.0 10^5 m/s, and the mean value over the time of propagation is 1.3 10^5 m/s.

4. Relationship between the value of constant electric field strength, at which corona discharge begins, and height of rods of different form of cross-section (square, circle, hexahedron) with flat top was determined.

5. It is experimentally proved that for air gaps more than 1 m, in the range of electric field strength from 4 kV/m to 120 kV/m, corona discharge is formed by pulses of individual electron avalanches that have front duration of units of nanoseconds and half-decay duration of tens of nanoseconds. Besides, the time parameters practically do not depend on the value of electric field strength. It is found that frequency of occurrence of current pulses uniquely depends on the level of electric field strength. This aspect supplements results obtained by Trichel and Kipp (1938) for short gaps (up to 10 cm).

6. The obtained functional dependence of streamer frequency on electric field strength was used as the basis for creation of a number of indicators to use as the device of warning against lightning hazard.

SUMMARY

Subject of the research is related to the decision with solution of the topical scientific-practical problem of granting permission to use new types of lightning rods that realize mechanism of Early Streamer Emission (ESE). To use the newest devices in practice of lightning protection, it is necessary to have confidence that properties announced by a manufacturer correspond to the facts. Quality control is proposed to be carried out according to the procedure regulated by France standard NF17-102: 2011. However, this standard is recognized only in some countries besides France. It is proved that it is necessary to change the requirement of the standard to the value of dispersion of function of distribution of lead time which ensures lightning interception with predicted probability taking into account the time at which the distribution has the maximal value. Method of measuring the velocity of propagation of streamer-leader in interelectrode space, which is based on comparative analysis of oscillograms of voltage between the electrodes and current from the electrode that forms discharge has been developed. It is shown that leader velocity increases by square law as his head propagates. It is proved that velocity of streamer propagation in the interelectrode space with length 1.2 m is no more than $7.0\ 10^5$ m/s, and the average value over the time of propagation is equal to $1.3\ 10^5$ m/s. The relationship between the value of constant electric field strength at which corona discharge begins, and height of rods of different forms of cross-section (square, circle, hexahedron) with flat top, and round cross-section with pointed top, was determined.

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