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Mechanism of Orientation and Parameters of Lightning in Context of Lightning Protection

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Abstract—Details of the process of lightning formation and orientation of the downward leader required to solve applied problems in the field of lightning protection are considered. It is shown that it is necessary to take into account the mechanism of the bipolar leader formation in the thundercloud electric field, according to which the thunderstorm cell cannot be regarded as a conducting charged electrode, the potential carried by the downward leader channel is determined by the start point and path of the lightning, and the effect of the thunderstorm cell charge reveals itself to a much less degree. An algorithm is proposed for calculating the orientation height, charge per unit channel length, and attraction radius of lightning from the value of the return stroke current. It is stated that lightning current measurements currently used at tall structures cannot serve as a basis to estimate the frequency of dangerous lightning strikes to structures of ordinary height. A scheme of the field research of lightning is proposed that allows the required statistics of lightning currents to be accumulated for a foreseeable time period at admissible material costs. The need to study the mechanism of the competing development of counter discharges from ground-based electrodes is proven, and the relevant technique is offered.

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1. INTRODUCTION

In gas-discharge physics, there are not so much problems that have not been solved reliably for almost one century of research. Estimation of the reliability of protection against lightning strokes is one of them. The beginning was optimistic. When lightning was found to be nothing else as a very long spark, it seemed natural to organize model laboratory experiments by decreasing the scale of lightning rods and protected objects in accordance with dimensions of the used laboratory discharge gap. Something similar has been done up to date [1, 2], although the fundamental violation of similarity laws in several-meter-long spark discharges has long been established [3]. Results of experiments turned out to depend on the gap length, the polarity of the voltage pulse, and its time parameters. In the best case, it could be hoped to determine qualitative regularities of the lightning orientation process, but in no way to quantitatively estimate the reliability of lightning rod operation, which is needed in practice.

Experience in using different lightning protection systems also has delivered not so much. A few reliable data were obtained only for air high-voltage power transmission lines; however, regretfully, the range of their heights is rather limited and organization of systematic observations of lumped structures of different height has failed for the present. Thus, a favorable atmosphere was created for developing theoretical calculation models pretending to the engineering estimation of the number of lightning strokes to different objects and the reliability of their protection by lightning rods. Some models became so commonly used that were included into national and international normative documents on lightning protection (see, e.g., the IEC 62305 standard). They still continue to be used in design calculations in spite of the absence of reliable physical argumentations and clear violation of the established regularities and experience of operation.

Such a situation has served as a basis for one more attempt made in this work to analyze modern concepts of the process of lightning orientation in order to assess existing methodical developments and gain some idea of the possibility to develop a reliable calculation model of the lightning orientation process on the basis of the actual data on the lightning parameters that are in disposal of specialists today.

2. BASICS OF THE PHYSICAL MECHANISM

To initiate a discharge in the thundercloud electric field, its strength in some region should, at least, exceed the threshold for air ionization. However, during surveys of clouds, such a strong field has not been detected. The maximum measured field values were found to be smaller by an order of magnitude than those required for air ionization [4]. This means that lightning starts from a region where the field is locally enhanced for a short time either as a result of some mechanically organized charged particle density or due to the polarization of a conducting medium. There are no rigorously justified concepts as of yet in this respect. Fortunately, the mechanism of initiation of the lightning leader is not of particular significance for the formulation of ideas on the process of lightning orientation near the ground surface.

It is of fundamental importance that the charged thunderstorm cell cannot be regarded as a conducting electrode that gives up its electric charge to the leader channel of the forming lightning. Most probably, the cell is an aggregate of separate electrically charged hydrometeors having no significant galvanic coupling between them. Such coupling is not required at all to form a lightning. Moreover, lightning can start from a certain initiating element (of yet unknown nature) beyond the thunderstorm cell. In this case, its should develop in the form of two interconnected leaders of opposite polarity. A hypothesis of this kind was first developed at the qualitative level in [5] and formulated quantitatively in [6]. The convincing proof of the hypothesis is numerous excitations of lightnings by airliners during their flights in the vicinity of the thunderstorm front without penetration beyond its outer boundary.

In this case, it is incorrect to say that the lightning leader transports the potential from its starting point (minus the voltage drop across its channel) to the ground. The actual situation is different. The potential of the tip of a downward leader is specified by the distribution of the electric field along the entire length of the developed bipolar leader structure. It can differ substantially from the potential at the start point even if the leader plasma is perfectly conducting. This follows from the well-known Grinberg theorem, according to which the potential of a solitary conductor of length l (not connected to other electrodes) in the potential field $U(x)$ under the assumption that the capacitance of the conductor per unit length is constant along its length is described by the curvilinear integral

$$U_0 = \frac{1}{l}\int_l U(x)dx.$$

Numerical integration in this formula makes it possible to calculate the potential of a conductor of any length and configuration in the field produced by arbitrarily located charges. In this case, the dependence of the rate of extension of each channel of a bipolar leader on the difference between the potentials $\Delta U_1 = U_0 - U(x_1)$ and $\Delta U_2 = U_0 - U(x_2)$ at the locations of its tips with coordinates x_1 and x_2 can be introduced into the calculation model, which allows one to evaluate how the potential transported to the ground by a downward leader depends on the thundercloud charge, the point of lightning initiation, and the leader path. A typical result of such evaluation is presented in Fig. 1. Here, the dipole model of a thundercloud with a charge of 15 C, uniformly distributed over the charged spherical cells of radius 500 m, was used. The center of the negative cell is located at an altitude of 3000 m, while the center of the positive cell, at an altitude of 6000 m. The perfecting conducting leaders of different polarity were assumed to propagate vertically along the dipole axis or with a 500-m horizontal shift from it.

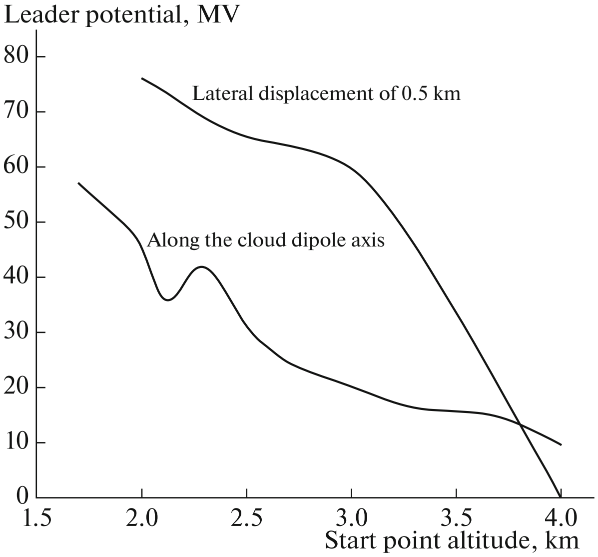

Fig. 1. Potential delivered to the ground by a downward leader vs. altitude of the lightning start point.

Computer simulations have revealed that the potential of a downward leader depends strongly on its path and start altitude. For a potential of about 220 MV at the bottom of a negatively charged cloud cell, no more than 80 MV were delivered to the ground, while the minimum value of the downward leader potential turned out to be close to zero. This result is of fundamental importance, because the leader potential determines both the orientation height of lightning and the amplitude of the return stroke current. There are reasons to assume that the statistics of lightning currents, spanning for two orders of magnitude, is predetermined not by the equally wide variations in the charge of thunderstorm cells, but by a random spread in the initiation points, paths, and branches of the lightning channel.

An important circumstance is the rather fast change in the potential of the downward leader as it approaches the ground to a distance closer than several hundred meters. Under the simulation conditions corresponding to Fig. 2 (the lightning starts at an altitude of 3500 m at a point shifted from the dipole axis by 500 m), the potential of the downward leader

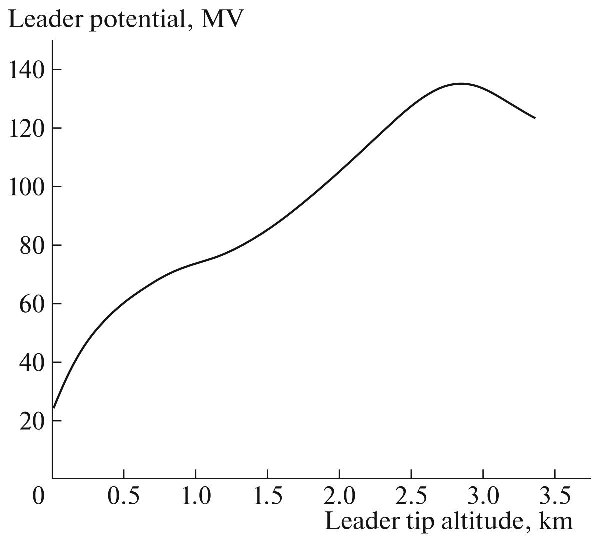

Fig. 2. Variation in the potential of a downward leader as it propagates to the ground.

changes more than 2.5-fold as the leader tip propagates from an altitude of 500 m to the ground. This is just the altitude range at which lightning orientation takes place for typical objects.

Almost all calculation models relate the process of downward leader orientation to the electric field near the top of a ground-based structure. In this case, it is often disregarded that the distribution of the electrostatic field in the thunderstorm situation is distorted substantially by the space charge introduced by the counter discharges developing from the ground-based structures, including the lightning rod and the protected structure itself. For a typical time of electric field relaxation between lightning strikes of no shorter than several tens of seconds [7], the counter discharge develops as a streamerless corona with a microampere current. Its characteristics were thoroughly studied in [8, 9]. It was shown that the introduced charge, as a rule, exceeds by one order of magnitude and more the charge that could be induced on the surface of the grounded structure by the same electric field in the absence of a corona. As an example, Fig. 3 shows the calculated dynamics of the growth of the space charge of a corona developing from a 50-m-high lightning rod with a radius of 2 cm in the atmospheric electric field growing linearly up to 20 kV/m for 20 s. In the absence of a corona, the charge induced on the rod would be ≈0.1 mC, whereas the charge actually introduced in the atmosphere is 15 times larger. Moreover, this charge is removed far enough from the top of the corona electrode. It can be seen from Fig. 3 that, by the time of 20 s, the space charge front has moved toward the thundercloud by 75 m.

It should be noted that corona characteristics are low-sensitive to the radius of the coronating top if the atmospheric electric field is much higher than the threshold field for corona ignition [10].

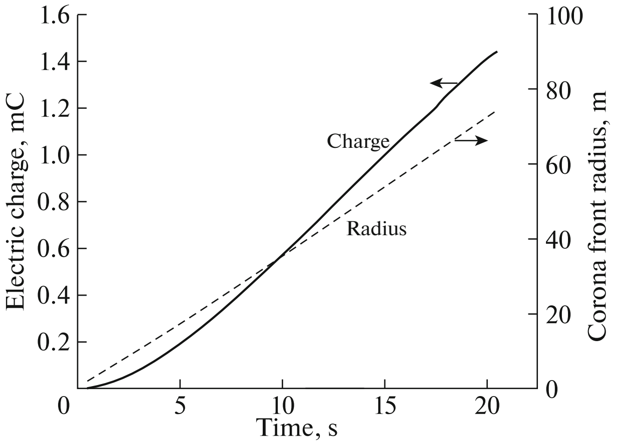

Fig. 3. Formation of a corona on the top of a 50-m-high rod electrode with a radius of 2 cm in the thundercloud electric field, which grows to 20 kV/m for 20 s.

Streak images of tens-meter-long laboratory sparks always demonstrate the presence of a streamer zone in front of the leader head with a length of several meters. There are no similar images of downward leaders as of yet. Nevertheless, the calculation models have been developed that relate the process of lightning orientation to the deterministic propagation of its channel inside the streamer zone having reached the surface of a ground-based structure. The streamer zone length can be estimated on the basis of a sufficiently reliable information on the electric field E_{st} required to maintain the development of long streamers. For the anode-directed streamer, inherent in the negative downward leader, we have $E_{st} \approx 1000$ kV/m [11]. The potential of the leader tip, U_{tip}, needed for such an estimate is provided by the hypothesis of the leader charge neutralization at its contact with the grounded surface. According to this hypothesis, the lightning current forms during the wave process of charge neutralization, in the same way as it was described, e.g., in [6]. Depending on the relation between the wave impedance of the lightning channel and the resistance of the circuit connecting it to the ground, the equivalent resistance in the circuit of the lightning current I_L, defined as $Z_{eq} = U_{tip}/I_L$, amounts to 500–1000 Ω [12]. This means that, for a moderate-power lightning with a current of 30 kA, the potential of the downward leader tip is in the range of 15–30 MV, while the length of the streamer zone is about 15–30 m (note that this distance is too short for the observational data on lightning attraction to ground-based structures of different height could be explained on its basis).

The Golde hypothesis [13] on the initiation of orientation by the development of channels of counter leaders propagating from grounded structures is well known and seems to be attractive. Such channels are clearly observed in streak images of tens-meter-long laboratory sparks and lightnings. Unfortunately, the number of the latter is clearly insufficient for statistical processing. However, results of model laboratory experiments failed to provide the unambiguous conclusion, because, in tens-meter-long gaps, the moments of the contact of the streamer zone with the grounded surface and the emergence of the counter leader from it are difficult to separate. Nevertheless, conditions required for the initiation of a counter leader still continue to draw considerable attention and have been subjected to detailed numerical simulations [14].

It is established that the counter discharge begins from the formation of the above-mentioned streamerless corona on the tops of grounded structures of different height, including branches of trees, bushes, and even grass, i.e., at any extended conducting elements with a small curvature radius r_0, which locally enhance the atmospheric electric field E_0 by approximately $h/(2r_0)$ times, where h is the element height. To excite a counter leader, a transition of the corona into the streamer is needed, for which the corona current should exceed a certain critical value. For spherical electrodes of radius r_0, the critical current is evaluated as [15]

$$i_{\text{cr}} = 8\pi\varepsilon_0\mu_i r_0 E_{\text{cor}}^2, \tag{1}$$

where E_{cor} is the threshold for corona ignition and μ_i is the mobility of the main corona ions. Formula (1) also allows one to estimate conditions for the excitation of a streamer flash in the gap that is still free of the corona space charge, if we take into account that the initial corona current from a solitary spherical grounded electrode located at a height h in the atmospheric field E_0 is defined as

$$i_{\text{cor}} = 4\pi\varepsilon_0 r_0 \frac{dE_0}{dt}. \tag{2}$$

It follows from Eqs. (1) and (2) that, for this purpose, the following inequality should be satisfied:

$$h\left(\frac{dE_0}{dt}\right)_{\text{cr}} > 2\mu_i E_{\text{cor}}^2, \tag{3}$$

the right-hand side of which is close to 5×10^9 V/s. Since the thundercloud field grows over a time on the order of 10 s and more, while its strength near the ground surface in the thunderstorm situation is a priori lower than 100 kV/m, the initial excitation of a counter discharge in the streamer form is excluded for objects of any practically significant height. A streamer flash can arise only in the electric field of the lightning downward leader approaching the ground at the velocity v_L, the strength of which in the case of vertical coaxial development increases at the rate

$$\frac{dE_L}{dt} \approx \frac{\tau_L v_L}{2\pi\varepsilon_0 h_{\text{tip}}^2}. \tag{4}$$

Here, h_{tip} is the height of the tip of the downward leader which is assumed to be uniformly charged. It is characteristic that the growth rate of the field strength defined by Eq. (3) is independent of the radius of the top of the grounded electrode, which casts a very serious doubt on the hypothesis that the result of lightning orientation is related to the value of the electric charge induced in this electrode [16, 17].

The method of computer simulation of a corona discharge in the atmospheric electric field developed in [9] can also be applied to electrodes of not only spherical but also other geometry. This makes it possible to find conditions at which the counter discharge transforms into a streamer under the action of the total field of the thundercloud and downward leader with allowance for the influence of the space charge of the preceding streamerless corona formed on an electrode of arbitrary height.

Figure 4 presents, as an example, results of such calculations for 2-cm-radius lightning rods of different height h displaced in the radial direction by the distance $r = 3h$. It is assumed that, before the start of a downward lightning, a corona discharge forms for 20 s near the rod top during a monotonic linear growth of the thundercloud field to 30 kV/m. The values of the initial leader charge per unit length of the downward lightning are indicated near the calculated curves. It can be seen that the ratio H_{st}/h is not constant but strongly depends on both the downward leader charge per unit length and the height of the grounded electrode.

The initiation of the counter leader requires the heating of the streamer flash base (the so-called stem). It is the streamer stem where the current contracts into a narrow channel due to overheating instability, thereby becoming a starting element of the incipient leader. Laboratory experiments and numerical estimates have shown that the energy deposited in the stem of the streamer flash proves to be sufficient if the voltage in front of the top of the grounded electrode exceeds 400 kV across a length of about 1 m [6]. As a rule, this condition is satisfied automatically at the moment of transformation of the counter discharge into the streamer due to the substantial amplification of the atmospheric electric field by the charge of the approaching downward leader. For the same reason, the ambient atmospheric electric field exceeds the average longitudinal field in the channel of the starting counter leader, thereby ensuring its development in the space charge layer of the corona and predetermining the point of the lightning stroke.

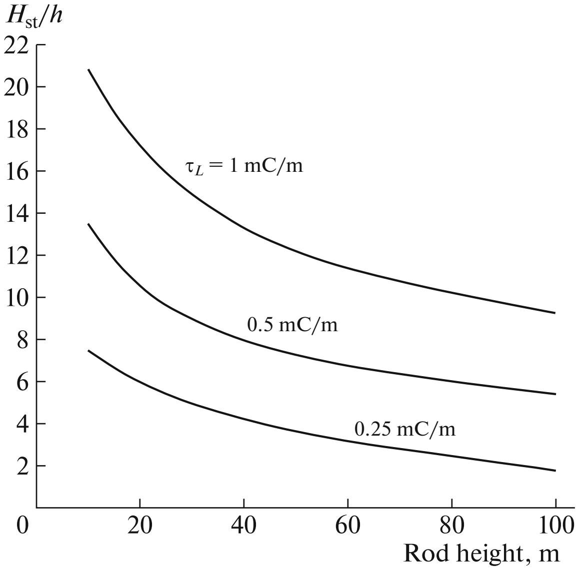

Fig. 4. Calculated altitude of the downward leader tip at the start of the streamer flash from a rod electrodes as a function of the rod height.

3. LIGHTNING PARAMETERS REQUIRED TO SOLVE APPLIED PROBLEMS

The available experimental data cannot be considered quite sufficient. Their generalization performed in the 2013 CIGRE report (WorkingGroup C4.407 Rep. no. 549) shows that the most reliable data concern the return stroke current measured under lightning strokes to ground-based structures. All together, the statistics is restricted to several hundred direct oscilloscope measurements from which the amplitude distributions of lightning currents were constructed (Fig. 5). That is all that can be expected.

To calculate the electric field, it is necessary to know the path of a particular lightning leader and the charge distribution over its channel, which is inaccessible to modern measurement techniques. Therefore, we have to orient ourselves to numerical model estimates based on the statistics of the lightning current—a unique parameter measured sufficiently reliably. The relation between the lightning current and the potential of the tip of the downward leader channel is provided by the return stroke model, in which the channel of the leader touching the grounded surface is regarded as a long line with averaged distributed values of the capacitance per unit length, inductance per unit length, and highly nonlinear resistance per unit length. This resistance decreases as the plasma channel is heated by the current wave propagating from the ground to cloud [6]. Numerical calculations by this model allow one to find the relation between the amplitude of the measured current and the potential of the downward leader tip for different values of the grounding resistance. For practically significant values of the latter, the amplitude value of the current varies weakly (Fig. 6), which makes it possible to use its averaged value.

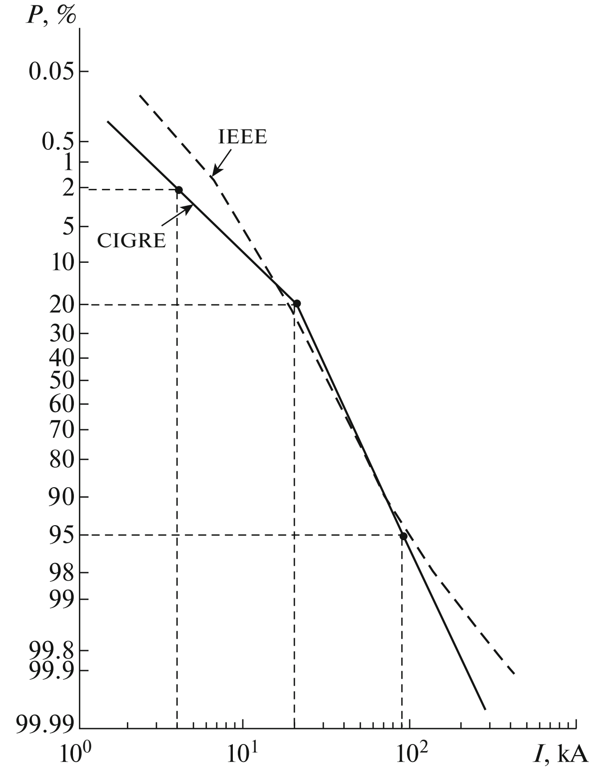

Fig. 5. Statistics of lightning currents.

The relation between the lightning current and the potential of the lightning channel tip (Fig. 7) calculated using the above model is satisfactorily approximated by the second-degree polynomial

$$U_L = 3.6858 + 0.7282 I_L - 0.000818 I_L^2 \text{ [MV]}, \quad (5)$$

where the lightning current is in kiloamperes.

Using relationship (5) between the lightning current and the potential of its channel tip, it is possible to calculate the main parameters characterizing the process of lightning orientation: the orientation height H_o and the radius of lightning attraction to an object of height h. When roughly specifying the orientation height H_o, it can be assumed that it depends linearly on the lightning leader potential U_L,

$$H_o = h(1 + AU_L). \quad (6)$$

This expression implies that the orientation height for the channel of a downward leader carrying the minimum possible potential cannot be smaller than the object height h. As to the lightning attraction radius R_{att}, it can be assumed in the first approximation that the distance from the tip of the lightning channel having reached the orientation height to the ground sur-

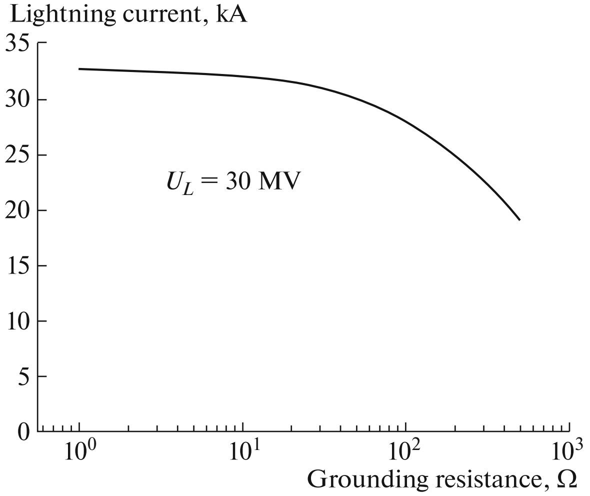

Fig. 6. Calculated dependence of the lightning current amplitude on the grounding resistance of the affected object at a downward leader potential of 30 MV (medium-power lightning).

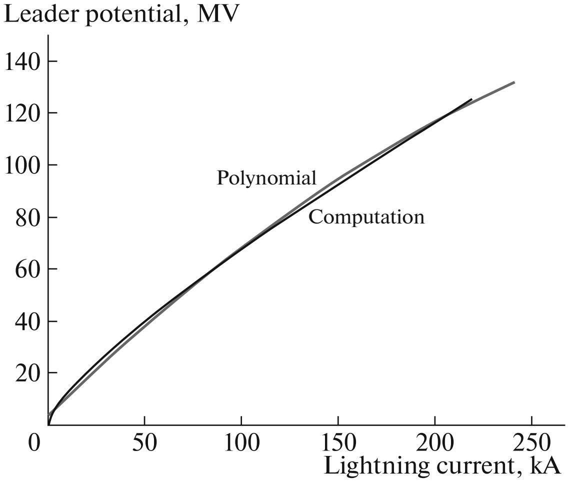

Fig. 7. Calculated dependence of the lightning current amplitude on the downward leader potential.

face is equal to its distance to the grounded object of height h (equidistance principle),

$$\frac{R_{\text{att}}}{h} = \sqrt{\frac{2H_{\text{o}}}{h} - 1}. \tag{7}$$

To use Eqs. (5)–(7) in practice, it is necessary to estimate the unknown constant A. For this purpose, one more parameter known from experience of operation can be involved: the so-called effective radius of lightning attraction to objects of height h. In most practical guides, this parameter is derived from the annual total number of lightning strokes N_{L} as

$$R_{\Sigma} = \sqrt{\frac{N_{\text{L}}}{\pi n_{\text{L}}}} \approx 3h, \tag{8}$$

where n_{L} is the annual density of lightning strikes per unit undisturbed ground surface for the site of the object location. The formal calculation of R_{Σ} from expressions (6) and (7) requires integration over the entire range of lightning currents with allowance for their statistical weights,

$$R_{\Sigma}/h = \int_{I_{\min}}^{I_{\max}} R_{\text{att}}(I)F(I)dI. \tag{9}$$

Here, $I_{\min}$ and $I_{\max}$ are the minimum and maximum values of the lightning current and $F(I)$ is the probability density of the current with the amplitude I. To calculate integral in Eq. (9), the only available statistics of lightning strokes presented in Fig. 5 was used.

Such processing with allowance for the equality $R_{\Sigma} = 3h$ yields the value $A \approx 0.128$ m/MV, which was used to construct the dependence of the orientation height on the lightning current presented in Fig. 8. Knowing the orientation height, we can find the effective attraction radius R_{att} of lightnings with a given value of the current. For rodlike objects, Eq. (7) can be used. Substituting the values of H_{o}/h borrowed from the calculated data in Fig. 8 into Eq. (7), we obtain the dependence $R_{\text{att}}/h = f(I_L)$, presented in Fig. 9.

It is of fundamental importance that the dependence $R_{\text{att}}/h = f(I_L)$ was obtained using formal relations without involving any physical mechanisms of development of the counter discharge. The estimates relied only on the lightning current statistics and the experimentally evaluated value of the effective radius of attraction to lumped ground-based structures. However, there is a fundamentally different approach to determining this functional relation. The calculation model involving this approach is entirely based on the physical pattern of the counter discharge. Comparison of these two approaches deserves special consideration.

The main parameter of the physical model is the charge per unit length of the downward leader channel, because it is this charge that rapidly enhances the electric field near the ground surface, thereby changing the shape of the counter discharge near the top of the ground-based construction, which eventually results in the generation of the counter leader. Knowing the path of the downward leader channel, the radius of its charge sheath, the number and sizes of branches, and the thundercloud electric field, there is no problem to numerically calculate the charge per unit length of the leader channel. Unfortunately, all these parameters vary from discharge to discharge and cannot be taken into account statistically. Therefore, using the estimate for the averaged radius of lighting attraction, it is reasonable to abandon the parameters of a certain particular lightning and consider the elementary calculation model with a vertical channel without branches by introducing the average capaci-

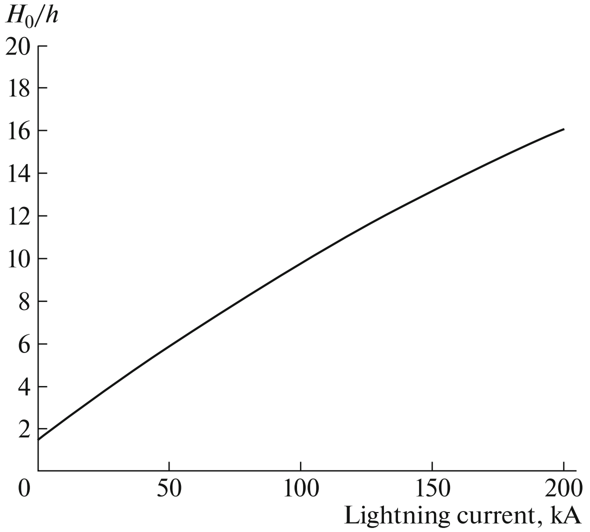

Fig. 8. Orientation height as a function of the amplitude of the first component of a negative lightning.

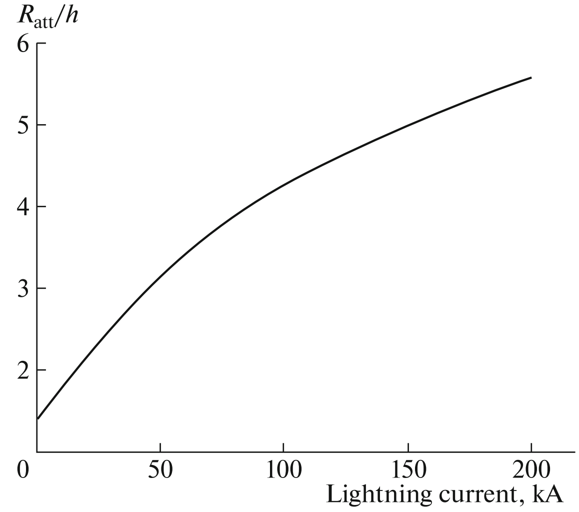

Fig. 9. Normalized effective attraction radius of lightnings as a function of the lightning current amplitude.

tance per unit length of the downward leader. As is known, the charge per unit length of a solitary extended electrode is related to its geometric dimensions through a logarithmic function, defining the capacitance per unit length,

$$C_0 = \frac{2\pi\varepsilon_0}{\ln(l/r_e)}, \tag{10}$$

where l and r_e are the length and radius of the extended electrode. Here, by the radius we mean the radius of the plasma sheath covering the leader channel filled with the space charge. Quantitative estimates can be obtained on the basis of the following considerations.

(i) To find the relation between the return stroke current and the charge per unit length of the downward leader, the channel length of no more than $l \approx 1000$ m, within which the front of the return stroke current wave is located, is of importance.

(ii) The radius of the charge sheath is determined by the distance at which the electric field remains at the level of the threshold field E_i for air ionization; therefore,

$$r_e \approx \frac{\tau_L}{2\pi\varepsilon_0 E_i}. \tag{11}$$

On the other hand,

$$\tau_L = C_0 U_L = \frac{2\pi\varepsilon_0 U_L}{\ln(l/r_e)}, \tag{12}$$

where U_L is the potential of the downward leader. It follows from Eqs. (11) and (12) that

$$C_0 = \frac{2\pi\varepsilon_0}{\ln\left(\dfrac{lE_i \ln(l/r_e)}{U_L}\right)}. \tag{13}$$

It is well known that the lightning current depends on the potential transported to the ground by the downward leader. This dependence, however, plays a minor role when estimating the capacitance per unit length, because the potential U_L enters into this dependence under the logarithm sign. Therefore, in the first approximation, the dependence on r_e can be neglected by setting $\ln(l/r_e) \approx 7$ ($l/r_e \sim 1000$). Then, for $E_i \approx 3$ MV/m and $l \sim 1000$ m, we obtain

$$C_0 \approx \frac{2\pi\varepsilon_0}{\ln\left(\dfrac{2\times 10^{10}}{U_L}\right)}, \tag{14}$$

where U_L is in volts.

According to model calculations presented in Fig. 7, the potential U_L within the practically significant range of lightning currents with amplitudes of up to 200 kA varies approximately from 10 to 120 MV, which leads to a change in the capacitance per unit length of the downward leader channel in the range of 7.3–10.8 pF/m. Therefore, the main factor governing the charge per unit length of the lightning downward leader is the potential of its channel, which varies within one order of magnitude, depending on the lightning power. As to the range of variation in the charge of the lightning downward leader, it varies, according to Eq. (12), from ~50 μC to ~1 mC (Fig. 10). It is worth mentioning that the lower boundary is close to values directly measured in superlong laboratory gaps, while the upper boundary was earlier mentioned in some theoretical works (see, e.g., [18]).

Results of calculations presented below were obtained for lumped structures (lightning rod, overhead line support) with a height of 30 m, which is typical of civil constructions and high-voltage transmis-

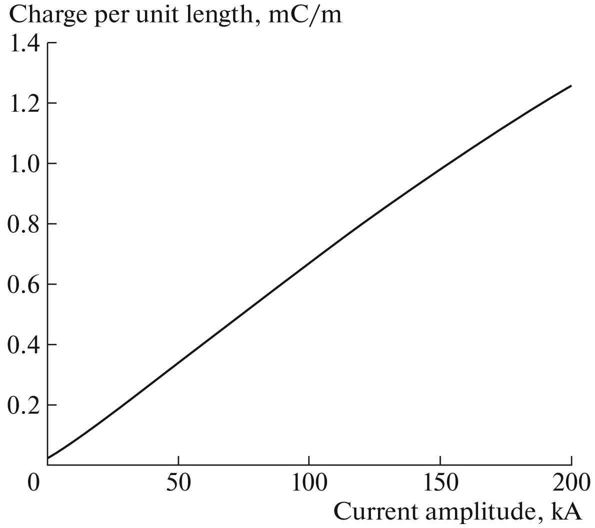

Fig. 10. Calculated charge per unit length of a downward leader as a function of the amplitude value of the return stroke current.

sion lines. It was assumed that lightning starts at an altitude of 3000 m and propagates vertically to the ground with an average velocity of 2 × 10^5 m/s. The thundercloud electric field near the undisturbed ground surface is assumed to grow linearly up to 20 kV/m during 10 s (in accordance with the relaxation rate of the thundercloud field from [7]). It should be noted that the value and growth rate of the thundercloud field, as well as the height of the start point of the downward leader, insignificantly affect the estimated value of the orientation height.

Figure 11 shows, as an example, the calculated time dependence of the corona current from a 2-cm-radius rod in the thundercloud electric field. As was expected, the maximum value of the corona current here is two orders of magnitude smaller than the critical value at which, according to Eq. (1), the corona transforms into the streamer giving rise to the counter leader. The critical current is reached only if the electric field is amplified by the charge of the downward leader approaching the ground (Fig. 12). Test calculations have shown that, by the moment of the corona transformation into the streamer, the electric field is always sufficient to satisfy the condition $\Delta U_{\text{cr}} = 400$ kV, at which the counter leader arises in the streamer stem, which, as is assumed, corresponds the beginning of the orientation process.

Figure 13 shows a typical calculated dependence of the orientation height of a downward lightning on its radial displacement relative to the ground-based structure. Here, a manipulation required to find the attraction radius R_{att} according to the equidistance principle is performed. Similar calculations were also carried out for other values of the charge per unit length of a downward lightning. The values thus

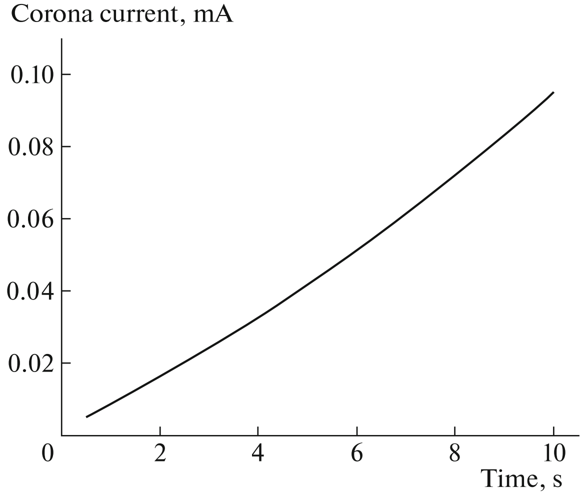

Fig. 11. Time evolution of the corona current in the thunderstorm electric field.

obtained were plotted on the previously derived dependence $R_{\text{att}}/h = f(I_L)$ (Fig. 14). Good agreement between the obtained values indicates the validity of the physical assumptions used in the model for determining the orientation height and effective attraction radius of downward lightnings.

Thus, it can be stated that the commonly used procedure of calculation of the number of lightning strokes from a constant value of R_{att}/h makes it impossible to find true values of the frequency at which lightnings with different currents strike an object, because, within the current range of 10–200 kA, the values of this frequency should differ nearly threefold,

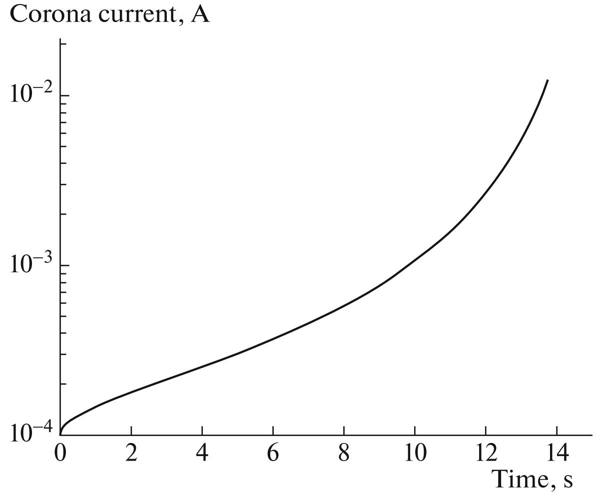

Fig. 12. Time evolution of the corona current in the field of a downward leader with a charge per unit length of 0.5 mC/m. The time is counted from the start of the downward leader.

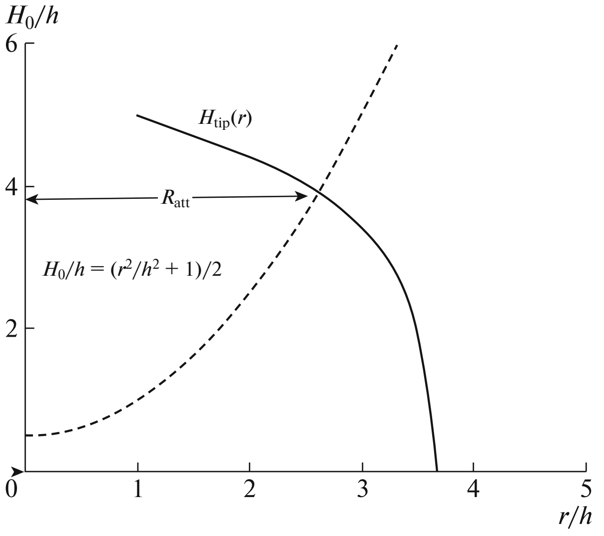

Fig. 13. Orientation height of a downward leader with a charge per unit length of 0.2 mC/m as a function of its radial displacement relative to the 30-m-high rod electrode.

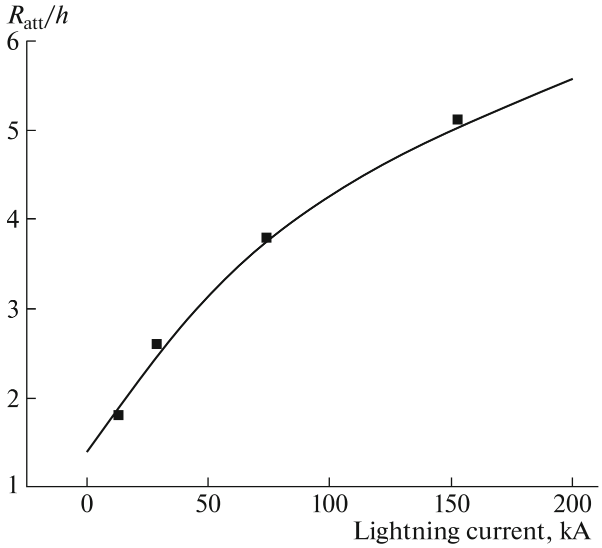

Fig. 14. Comparison of the dependences of the effective attraction radius on the lightning current, calculated by different methods.

while the areas of lightning attraction for an object of fixed height should differ by one order of magnitude.

Similar calculations can also be performed for structures with other heights *h* in order to find out whether it is possible to calculate the protective effect of lightning rods for given values of the parameters H_o/h and R_{att}/h, as is frequently done in practice. The results presented in Fig. 15 demonstrate that, for lightnings with a downward leader charge per unit length of 0.5 mC (a lightning current of ~75 kA), a change in the object height from 15 to 60 m leads to a decrease in the parameter H_o/h approximately from 10 to 6, while R_{att}/h decreases from 4.5 to 3.5 (Fig. 15).

4. DESIRABLE AND ACTUALLY POSSIBLE WAYS TO REFINE THE CALCULATED PROTECTING EFFICIENCY OF LIGHTNING RODS

In practical lightning protection, two parameters are of greatest interest: the expected number of lightning strokes to the object and the protecting efficiency of lightning rods. At present, the method for calculating the first parameter is rather well substantiated and a calculation algorithm is developed that allows one to quantitatively estimate not only the total number of lightning strokes for a given time period, but also to determine the expected number of lightning strokes with currents at a given level. For this purpose, the dependences of both the orientation height and the attraction radius of a downward leader on the lightning current are derived theoretically. Taking into account these dependences and the statistics of lightning currents, it is possible, in principle, to estimate the frequency of lightning strikes with given value of the current to a solitary object of given height. Here, a unique (but exclusively important) problem is the reliability of the above statistics. As is known, it is based on direct measurements of lightning current to objects of very great height. For example, the tower used in the well-known lightning measurements [19] rises over the surface of Lake Lugano by more than 600 m. In this case, about 90% of lightnings affecting it were upward ones. Taking into account the performed estimates of the attraction radius, it is hardly possible to find weighty

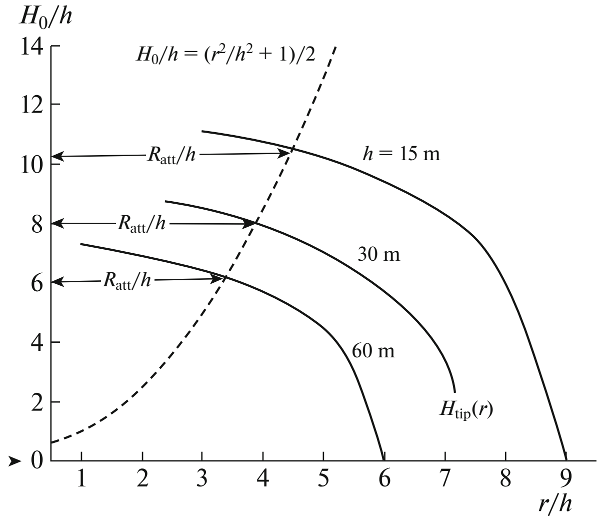

Fig. 15. Estimation of the influence of the object height on the effective attraction radius for a leader charge per unit of 0.5 mC/m.

arguments for transferring the statistics of currents compiled there to objects of ordinary height, first of all, lying in the range of 10–100 m. Only the complete absence of alternative approaches forces one to do this.

The following question naturally arises: how serious and costly is to solve the problem of gathering the current statistics on lightnings strikes to objects of ordinary height? Orienting to an average object height of 50 m and assuming the attraction radius to be $R_\Sigma = 3h$, for Russia regions with typical thunderstorm activity, nearly 0.2–0.3 lightning strokes per year can be expected for such an object, which will allow 2000–3000 records to be accumulated for 10 years of observations over 1000 objects. In this case, an important circumstance is the possibility to combine measurement data accumulated at objects of different height into a single statistical sample. To verify this possibility, we calculated the attraction radius R_{att} for lumped objects with heights of 20 and 100 m by the method illustrated in Fig. 13 as applied to downward lightnings with a charge per unit length of 0.2 and 1.0 mC/m. For a 20-m-high object, the ratio of the squared attraction radii (i.e., the attraction areas) for weak and strong lightnings was 4.0, while for a 100-m-high object, it was 3.36. The difference within 20% seems to be small enough to form a combined statistics.

At present, the relatively low cost of modern instruments for recording the lightning current becomes a fundamental point. Instruments similar to those described in [20] are suitable for mass records of the amplitude and time parameters of the lightning current. They have undergone hard operational checkout under field conditions, are equipped with a self-contained power supply, and have no need of technical service during the entire thunderstorm season. Certainly, the program of such measurements is difficult to be considered low-cost; however, its implementation has incomparably greater reasons than recording of lightning currents at tall structures.

The frequency of lightning breakthroughs to the protected structure is beyond the scope of practice of lightning protection and electromagnetic compatibility. Of interest are only breakthroughs that transport currents of a dangerous level. However, the problem on the differentiation of the protective effect of lightning rods in respect of downward lightnings carrying different electric charges has been developed only in the least. It follows from general considerations that, if the process of orientation is initiated by the starts of counter leaders from the tops of ground-based structures, then the choice of a particular point of the lightning strike should be determined by their competing development [22]. Data on this process are very scarce. They are retrieved only from laboratory experiments, rather than from records of actual lightnings, i.e., they are of purely qualitative in character [6]. The problem is reduced to the screening effect of the charge of the counter leader that was the first to start or progressed farther into the discharge gap on the subsequent leader channels. As a result, a positive feedback forms, due to which the consequences of any initial random change in the formation conditions of the counter discharge are enhanced. The closer the start points of the competing counter leaders, the larger the extent to which this effect manifests itself. However, even results of laboratory experiments are very hard to be described quantitatively, because it would require to take into account the following factors: statistical scatter in the start times of the initial streamer flashes, the configuration of the electrode top, the growth rate of the external electric field, the influence of the screening effect of the space charge introduced by streamer flashes under different start conditions, the propagation direction and velocity of the counter leader, and a number of other less significant factors. In the existing calculation models intended to determine the point of the lightning strike, the competing development of counter leaders is usually disregarded. Analysis is restricted to comparing the external field strengths near the tops of the lightning conductor and the protected object, although their quantitative estimate does not allow one to unambiguously judge on the further development of the counter leaders.

This work was not aimed at critical analysis of particular calculation models; most of them are well known to specialists. It is more important to indicate problems that attract attention of the authors of such methodical developments. It has to be stated that physical regularities of the competing development of opposite gas-discharge processes were beyond the scope of research there. The proposed computational algorithms were intended to describe the random character of the path of the downward leader (namely the downward one, because the related upward leader of opposite polarity was not taken into consideration for some reason). The charge distribution along the channel of the downward leader was refined with allowance for random bends of its path and the lengths of its steps; however, the influence of numerous extended branches, typical of most lightnings, was not taken into account. The electric field distribution near the tops of the lightning rods and protected objects was calculated in detail, but in the purely electrostatic approximation, without regard to a significant space charge introduced by the streamerless corona in pauses between lightning flashes. None of those models are able to shed light on the main issue of how the characteristics of counter discharges vary during their competing development under exposure to the atmospheric electric field growing at a variable rate due to the approach of the downward leader, which can propagate with different velocities and carry different electric charges.

There is no unambiguous answer to the elementary question of how the result of the competing development of counter leaders depends on the orientation height of the lightning downward leader. According to calculated data presented in Fig. 8, the growth of the lightning current from the minimum possible value to 200 kA can lead to an increase in the orientation height by one order of magnitude. This results in an increase in the gap lengths from the downward leader tip to the lightning rod and the protected object and, accordingly, in their breakdown voltages. Eventually, according to the probabilistic model [6, 12], the probability of lightning breakthroughs to the protected object should increase.

Nevertheless, in the field of lightning protection, there is also a diametrically opposed viewpoint, according to which only the weakest lightnings with a low charge per unit length and, accordingly, with a low orientation height penetrate to the protected object. For this could be possible, one has to assume that the mutual influence of counter leaders depends very strongly on the charge transported by the downward lightning leader. The question of whether this is the case remains open even for laboratory conditions and needs detailed studies, first of all, experimental ones. In this case, the methodical approach should differ fundamentally from model studies of the protective action of lightning rods, which have to be considered short-scale even when using discharge gaps with lengths of 20–30 m. The results of such studies cannot be unambiguously applied to the lightning discharge. When studying the competing development of counter leaders, it is unnecessary to reproduce the leader of the downward lightning. It is sufficient that the electric field in the gap be comparable with the field of a downward lightning near a grounded structure, which is quite accessible to the high-voltage sources used at the existing test benches. As for the height and configuration of the electrodes, the distance between them, and the length of the forming counter leaders, all this does not require scaling when tens-meter-long discharge gaps are used.

The method of experimental estimation of the mutual influence of counter leaders was developed sufficiently well in [6, 22]. The curves of the discharge voltage distribution can serve here as an indicator of the effect. As is known, under the simultaneous voltage supply from a common source to two uncoupled discharge gaps with the integral distribution curves $\Phi_1(U)$ and $\Phi_2(U)$, the voltage distribution for the system as a whole is described by the expression

$$\Phi_{\text{sys}}(U) = \int_0^U \{\varphi_1(U)[1-\Phi_2(U)] + \varphi_2(U)[1-\Phi_1(U)]\}\,dU, \tag{15}$$

where $\varphi_1(U)$ and $\varphi_2(U)$ are the probability densities of the above voltage distributions. As the mutual influence is enhanced, the distribution of the breakdown voltages of the system becomes more deterministic, asymptotically approaching the distribution for the gap where the leader process is more intense.

5. CONCLUSIONS

(i) Practical lightning protection needs reliable estimations of the frequency of lightning strokes with a given current value exceeding the dangerous level for the protected object. Such a problem has no reliable solution as of yet, because the existing statistics on lightning currents refers to tall structures and cannot be applied to objects of ordinary height.

(ii) The existing ideas about the lightning orientation mechanism give reasons for performing direct measurements of lightning currents at ground-based structures with heights of 20–100 m, while the developed pulsed measurement instruments make it possible, at admissible costs, to gather for 10 years statistical data sufficient to solve applied problems in the field of lightning protection of modern technological objects.

(iii) Having reliable statistics on lightning currents and using the developed physical models, it is possible to calculate the most important parameters governing the lightning orientation process as functions of the lightning current.

(iv) The recently developed calculation models intended to estimate the protective effect of lightning rods leave aside the mechanism of the competing development of counter leaders and, therefore, do not contribute to the development of physical ideas on the mechanism determining the position of the lightning strike point in the lightning rod–protected object system.

(v) The improvement of practical lightning protection needs the development of a theory and calculation model of the mechanism of interaction of counter discharges and their action on the lightning channel. Modern high-voltage sources allow one to perform experimental studies with the use of full-scale models, due to which their results can be directly applied to the lightning discharge.

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