Plasma Physics Reports, Vol. 31, No. 1, 2005, pp. 75–91. Translated from Fizika Plazmy, Vol. 31, No. 1, 2005, pp. 84–101.

The Effect of a Corona Discharge on a Lightning Attachment

N. L. Aleksandrov*, E. M. Bazelyan, and Yu. P. Raizer*****

**Moscow Institute of Physics and Technology, Institutskiĭ pr. 9, Dolgoprudnyĭ, Moscow oblast, 141700 Russia*

***Krzhizhanovskiĭ Rower Engineering Institute, Leninskiĭ pr. 19, Moscow, 117927 Russia*

****Institute for Problems of Mechanics, Russian Academy of Sciences, pr. Vernadskogo 101, Moscow, 117526 Russia*

Received June 30, 2004

Abstract—The interaction between the lightning leader and the space charge accumulated near the top of a ground object in the atmospheric electric field is considered using analytical and numerical models developed earlier to describe spark discharges in long laboratory gaps. The specific features of a nonstationary corona discharge that develops in the electric field of a thundercloud and a downward lightning leader are analyzed. Conditions for the development of an upward lightning discharge from a ground object and for the propagation of an upward-connecting leader from the object toward a downward lightning leader (the process determining the point of strike to the ground) are investigated. Possible mechanisms for the interaction of the corona space charge with an upward leader and prospects of using it to control downward lightning discharges are analyzed.

1. INTRODUCTION

Lightning discharges are the most frequent and most dangerous effect of atmospheric electricity on ground objects. During the lightning season, each square kilometer of the Earth's surface suffers one to ten lightning strikes (two to four strikes in moderate-climate regions of Russia). Intracloud lightning discharges occur three to four times more frequently. The frequency of lightning strikes increases with the height of a ground object. On the flat ground near Moscow, narrow objects ~30 m in height (like radio masts or towers) suffer, on average, one lightning strike every ten years; a 100-m high building undergoes a strike nearly every year; and such an extremely high structure as the Ostankino TV tower suffers 25–30 lightning strikes every year.

Unlike Benjamin Franklin, modern experts on lightning protection are acquainted with mechanisms for the development of lightning; however, the means that are at their disposal differ little from Franklin's lightning rods. Being above an object to be protected, the lightning rods intercept the approaching lightning channel. However, conventional methods of lightning protection often do not meet the needs of modern practice. Lightning rods are capable of efficiently protecting a certain point of the object, e.g., its easily flammable or explosive element. It is this purpose for which they were proposed by Franklin two and a half centuries ago. Modern buildings, however, contain almost no flammable elements. Precast or monolithic concrete does not burn, whereas its metal armature efficiently conducts the lightning current to the ground. In this respect, modern buildings need no lightning protection. The most dangerous effect for them is the electromagnetic field excited by the lightning current, rather than its thermal effect. The lightning current increases at a rate of more than 10^{11} A/s and gives rise to dangerous overvoltages in the electric circuits of the object under protection. Among the elements that are in most danger are low-voltage control and automation circuits and microelectronic devices, as well as channels for information transfer and processing.

It makes little sense to set lightning rods on the roof to protect a building from electromagnetic strays. After intercepting the lightning discharge, the rod will anyway direct the current into the building armature; as a result, the overvoltage level will be almost the same as in the case of an unprotected roof. To significantly reduce electromagnetic strays, it is necessary to eliminate lightning strikes in the close proximity of the protected object. For this purpose, lightning discharges must be either intercepted (or redirected) far away from the object. In principle, distant lightning interception is feasible. This requires the creation of long-range lightning protectors covering a sufficiently large area. General considerations naturally lead to the idea of using very tall lightning rods. However, mounting such rods is rather expensive. Moreover, the radius of the protected region increases rather slowly with the height of the lightning conductor. For example, lightning strikes to the ground were observed at distances as short as 200 m from the 540-m-high Ostankino TV tower, which can be regarded as an extremely tall lightning rod. For ordinary lightning rods, the radius of the protected region (at the ground level) is close to the rod height, whereas in the case of the Ostankino TV tower, it is nearly three times smaller. Obviously, substantially increasing the height of conventional lightning rods would have no significant effect. This is why methods for actively influencing lightning discharges have been searched over the last few decades.

1063-780X/05/3101-0075$26.00 © 2005 Pleiades Publishing, Inc.

Two approaches that yield diametrically opposite effects have been developed concurrently. The aim of the first approach is to increase the attraction of lightning to the lightning rod as much as possible, whereas the aim of the second approach is to hinder the propagation of lightning toward the protected object. Both approaches are based on Golde's hypothesis about the lightning attachment (the place of the lightning strike) [1, 2]. According to this hypothesis, lightning propagates toward a ground object because of the development of a highly conducting plasma channel (the so-called upward-connecting leader) from its top. The upward leader channel is produced in a strong electric field of a thundercloud enhanced by the approaching leader of downward lightning. The mutual attraction between these leaders of opposite polarities results in their merging, thereby determining the point of strike.

All methods for controlling lightning discharges with the aim of lightning protection can be ultimately reduced to either exciting (as early as possible) an upward-connecting leader from the lightning rod or, alternatively, hampering its development from the protected object. However, the development of these seemingly clear ways of affecting lightning discharges encounters great difficulties and is thus far from being complete. The point is that Golde's hypothesis has not yet been confirmed theoretically. For a number of principal issues, the process of mutual attraction between the leaders and the problem of the lightning attachment are still poorly understood even at a qualitative level. Laboratory experiments fail to shed light on these phenomena because of the significant difference in the spatial scales and the absence of justified scaling laws. Until recently, theory was not able to estimate the efficiency of nonconventional approaches to lightning protection. It is only in recent years that certain progress has been made owing to the parallel use of experimental data on laboratory spark discharges, theoretical models (often semi-empirical) of such discharges, and results from natural lightning observations and computer simulations of different stages of the lightning formation. However, this problem is still the subject of vigorous debate among practical engineers and also "pure" geophysicists (see, e.g., [3–6]). The fact that the authors of the present review are involved in this dispute might to a certain extent deprive the text of the paper of its chronicle neutrality.

The focus of our review is one aspect of the problem of the lightning attachment: the interaction of the lightning leader with the corona space charge that is accumulated near the top of the protected object in the atmospheric electric field. Based on the results of analytical considerations and numerical simulations, we analyze different ways of affecting the lightning trajectory and demonstrate the feasibility of their practical implementation with the help of specially designed corona systems.

The problem can be divided into several more or less independent physical tasks. First, it is necessary to understand to what extent the attachment of the leader channel of downward lightning is related to the origin and stable development of an upward leader from the top of the protected object. Second, there is a need for a quantitative description of a nonstationary corona that is first formed in the thundercloud electric field and then in the field of a downward leader with quite a large channel charge. Third, one must find out to what extent the redistribution of the electric field in the vicinity of the corona electrode is able to affect the origin and stable development of the upward leader that gives rise to an upward lightning discharge. As is well known, skyscraper objects with a height of 200 m and more are mainly subject to upward lightning flashes. Finally, it is necessary to reveal a possible mechanism for the influence of the corona space charge on the downward lightning leader. Here, the point is either the delayed origin (or termination) of an upward-connecting leader or such a change in its trajectory that eliminates the strike to the protected object. At present, the above issues are at different stages of their development and require further investigation. The general picture, however, is clear enough to predict prospects of new lightning protection technologies.

2. ATTACHMENT OF LIGHTNING TO A GROUNDED OBJECT IN THE CASE OF A CONVENTIONAL LIGHTNING ROD

2.1. Development of a Leader from a Grounded Object in the Atmospheric Electric Field

The development of a leader from a grounded object due to the enhancement of the atmospheric electric field by the charge of the approaching channel of a downward leader is a real phenomenon. It can easily be modeled under laboratory conditions [7, 8]. The leader starts after the initial flash of a pulsed corona—a bunch of streamers with a common stem. It is the streamer flash from which the leader channel begins to develop. The streamer-flash current flowing through the stem delivers an energy sufficient for the heating of the cold streamer plasma to the temperature of ~5000 K. Electrons are then produced mainly due to the processes whose rate depends slightly on the electric field, and a longitudinal electric field of $\sim 10^2$ V/cm is quite sufficient to maintain the channel in the conducting state over a fairly long time [9–11]. Theoretical predictions and experimental data show that, under normal atmospheric conditions, the necessary gas heating in the stem can be achieved if the voltage drop over the streamer branch is no lower than $\Delta U_{cr} \approx 400$ kV [8, 12]. Such a voltage drop is sufficient to form a branch of cathode-directed streamers with a length l_{st} of about 1 m.

The formal criterion for initiating a leader in the stem of the streamer flash can be written as

$$\Delta U(l_{st}) > \Delta U_{cr} \approx 400 \text{ kV}. \quad (1)$$

This criterion can easily be satisfied under real conditions even for relatively low grounded objects without assistance of the electric field of the downward leader. For example, when the thundercloud electric field near the ground is E_{0cl} = 20 kV/m (which is quite realistic), a grounded rod of height h = 20 m enables a voltage drop of $\Delta U = E_{0cl}h \sim 400$ kV near the top of the rod. Nevertheless, no one has ever observed leader development from such a low grounded object located on flat ground in the absence of a close cloud-to-ground lightning discharge. The reason is that the leader development must be preceded by a streamer flash starting from the rod top. There is no problem in exciting a streamer flash under laboratory conditions when the rise time of a pulsed voltage is from a few microseconds to a few milliseconds. However, the actual thundercloud electric field increases very slowly between the lightning discharges (over tens to hundreds of seconds). In such a field, a quiet streamerless corona occurs over a long period of time. This kind of corona has also been observed under laboratory conditions. Such a corona consists of a thin (less than a few millimeters) ionization zone and the outer region occupied by the drifting ions [13]. The length of the outer zone can be very large—up to tens or even hundreds of meters.

The most important feature of the streamerless corona (it is sometimes called an ultra corona [14]) is the stabilization of the electric field at the surface of the corona electrode at the level of corona ignition, E_{cor}. For the simplest electrode configurations, this field can be calculated by the empiric Peek formula [15]. This circumstance and the fact that the ionization zone is narrow allowed one to develop a simple and widely used numerical model of a corona in a long air gap (see [13, 16]). The model assumes that the ions are emitted directly from the surface of the corona electrode of radius r_0 and the boundary condition $E(r_0) = E_{cor}$ = const is satisfied on the electrode surface. This allows one to ignore the processes occurring in the ionization zone and to restrict oneself with an analysis of the ion drift in the outer region. For this purpose, the continuity equation for the density of the ions, which drift with a given mobility,

$$\frac{\partial n_j}{\partial t} + \nabla \cdot (n_j \mu_j \mathbf{E}) = S,$$

is solved together with Poisson's equation for electric field $\mathbf{E}$,

$$\nabla \cdot \mathbf{E}(\mathbf{r}) = \rho/\varepsilon_0.$$

Here, $\rho = e\Sigma n_j$ is the space charge density, n_j and μ_j are the density and mobility of the jth ion species, and S is the term describing the production and loss of ions in ion–molecular reactions.

Analytic solutions to these equations were earlier obtained for the simplest electrode systems with a spherically symmetric or an axisymmetric electric field (concentric spheres or coaxial cylinders of unlimited length) and one ion species. The solutions were obtained for a steady-state operating mode, assuming that the discharge voltage was constant and the drifting ions had time to cross the discharge gap.

Steady-state solutions cannot be used to analyze the corona in an atmospheric electric field because the field itself varies significantly over time, whereas the ions have time to cover only a minor fraction of the gap between the grounded electrode and the cloud over the characteristic time of the electric field variations. As the electric field increases, the space charge front propagates away from the top of the corona electrode; this clearly indicates that the discharge is nonstationary.

An approximate analytical description of a nonstationary corona performed in [17, 18] is in good agreement with the results of numerical simulations carried out for conditions typical of a streamerless corona in a thundercloud field [18]. The details of analytical studies and numerical simulations are beyond the scope of the present study. Below, we will consider only those features of a nonstationary corona that are important for analyzing the conditions for the origin and stable development of the leader from a grounded object.

2.2. Features of a Nonstationary Corona

A nonstationary corona can be observed in gaps of any length. The discharge remains nonstationary until the space charge front reaches the opposite electrode and the applied voltage ceases to change. All other factors being the same, the duration of the transient regime is a function of the gap length. In the ground–cloud gap, steady-state regime may not be established at all. The main difference between nonstationary and stationary coronas is that, in the former, the current is determined not only by the instantaneous value of the applied voltage but also its growth rate [17, 18]. As a result, the current in a nonstationary corona can be many times higher than that in a stationary corona. This is illustrated in Fig. 1, which shows the results of the numerical solution of the above equations for a 5-m-long laboratory gap. The unsteady current exceeds its steady-state value when the voltage rise time is much shorter than the propagation time of the space charge front across the gap. The approximate analytical theory gives similar results [17, 18]. It will be shown below that the dependence of the current on the field growth rate is of crucial importance for the initiation of a leader from the grounded electrode.

A nonstationary corona is also characterized by a much weaker dependence of the current on the ion mobility μ. Instead of the direct proportionality between the steady-state corona current i_{cor} and μ, the functional dependence of the current on the ion mobility in a nonstationary corona is determined by the gap geometry: $i_{cor} \sim \mu^{1/2}$ for spherical geometry and $i_{cor} \sim \ln(\mu^{1/2})$ for cylindrical geometry. For the limiting case of plane geometry, the current does not depend on the

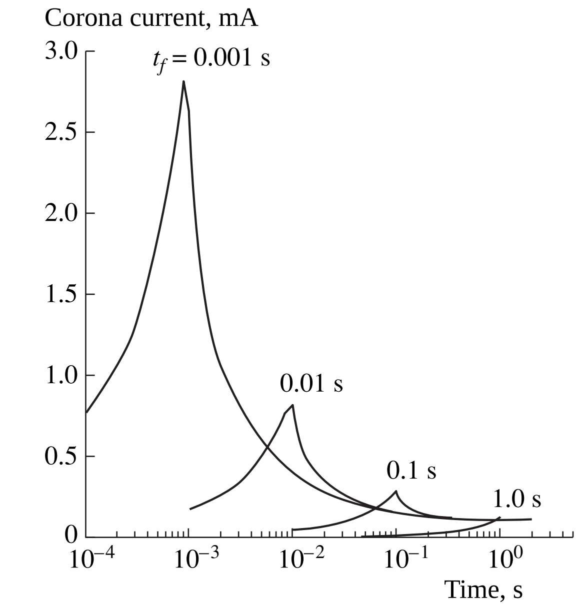

Fig. 1. Numerical simulations of the current of a transient corona in a gap between concentric spheres with radii of 1 cm and 5 m. The voltage increases linearly to 300 kV over a time t_f and is kept constant at $t > t_f$.

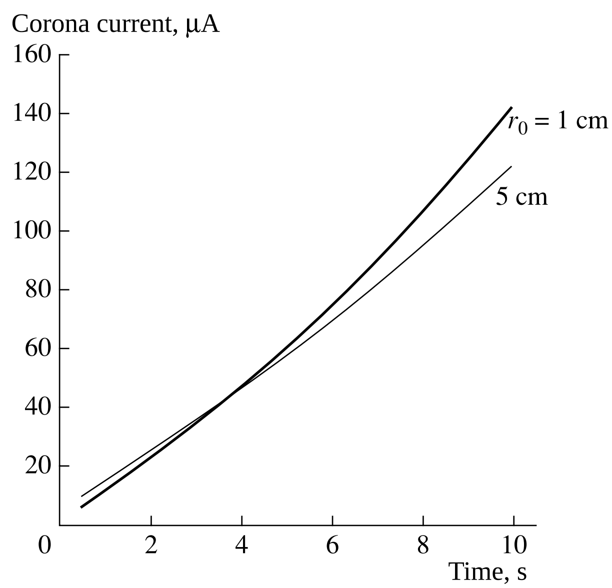

Fig. 2. Time evolution of the corona current from a 50-m-high rod electrode in a thundercloud field linearly increasing to 20 kV/m over 10 s.

mobility at all [19]. The weak dependence on the mobility allows one to simplify the calculation model of a corona in a thundercloud field; in this case, the lightning protection can almost always be calculated with allowance for only one ion species.

To sustain the current of a nonstationary corona at a fixed level, one has to continuously increase the gap voltage (the thundercloud electric field). The law according to which the field should increase over time is again determined by the geometry of the corona system. For a spherical electrode, the corona current will remain constant if the electric field increases as $E_0(t) \sim t^{1/3}$, and in the limiting case of a plane system, it should vary as $E_0(t) \sim t$. A long conductor of small radius occupies an intermediate place between these cases [19]. In a constant electric field E_0, the more uniform the field of the corona electrode, the faster the decrease in the corona current. In the limiting case of a plane electrode whose own electric field is uniform, the current almost instantaneously drops to zero. The decay of the corona current at $E_0(t)$ = const impedes the accumulation of a significant space charge near the top of the corona electrode.

Analytical studies and numerical simulations show that, if the thundercloud electric field significantly exceeds the external field E_{0cor} required for corona onset, then the corona current i_{cor} depends weakly on the electrode radius. According to the calculated time dependences $i_{cor}(t)$ presented in Fig. 2, the fivefold increase in the radius of the rod electrode leads to the 15% decrease in the current amplitude. The main cause for the decrease in the current is an increase in the threshold field E_{0cor} for corona onset. Even if one increases the electrode radius to a few meters, provided that the condition $E_{0cor} \ll E_{0max}$ is satisfied (e.g., by placing short needles over the electrode top), then the corona current changes by no more than a few tens of percent. According to analytical estimates and numerical simulations performed for grounded electrodes a few tens of meters high (such as conventional lightning conductors and protected objects), the maximum corona current in a thundercloud field is about 10^{-4} A. Therefore, over a corona lifetime of ~10 s, a charge of ~10^{-3} C is injected into the atmosphere. Although the front of the charged ion cloud can propagate from the corona surface over a distance of up to 10^2 m, the ion density exceeds the natural background of ~10^3 cm^{-3} only at distances of shorter than ~10 m from the top of the grounded electrode [18].

The approaching downward leader intensifies the corona due to a significant increase in the field growth rate dE_0/dt, rather than to the amplification of the atmospheric electric field by the leader charge. This is illustrated by the results of numerical simulations presented in Fig. 3. The calculations were performed for a 5-cm-radius rod with a height of h = 50 m. The downward leader started from the height of 3000 m, when a linearly increasing thundercloud field had already reached a value of 20 kV/m over 10 s. The radial deviation of the downward leader with respect to the grounded rod was r = 150 m. The electric charge per unit length of the downward leader was assumed to be constant and equal to 0.5 mC/m, which corresponded to an ordinary lightning. It can be seen that, even for a significant radial

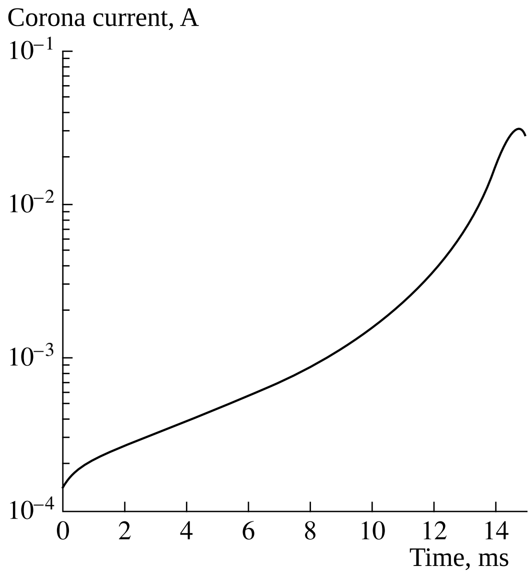

Fig. 3. Time evolution of the corona current during the propagation of the downward leader with a linear charge of 0.5 mC/m. The time is reckoned from the instant of the leader start.

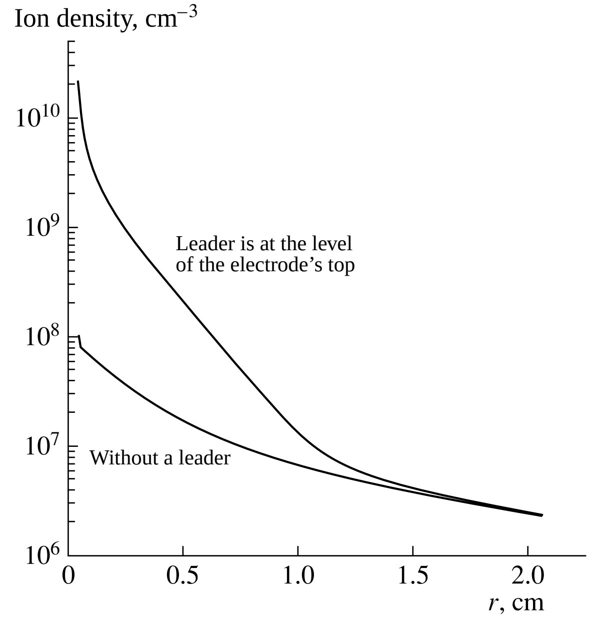

Fig. 4. Ion density near the top of a corona electrode for the conditions of Fig. 3 as a function of the distance from the top.

deviation of the leader (r/h = 3), the corona current increases by nearly three orders of magnitude. However, this does not result in a significant increase in the corona charge because of the short development time of the downward leader, which propagates with an average velocity of 2×10^5 m/s and reaches the ground over 15 ms. In the case under consideration, the total corona charge increases by only 10%. Nevertheless, this additional charge plays an important role. Since this charge has no time to propagate far from the electrode, it is concentrated near the surface of the corona electrode, thereby greatly increasing the local ion density (Fig. 4). As a result, the point at which the electric field is maximal leaves the corona surface and begins to propagate into the gap. This effect can be regarded as the propagation of an ionization wave. From this instant, the corona discharge cannot be treated as streamerless and the model used fails to be adequate.

The condition for the termination of a streamerless corona can be derived from the relation $(dE/dr)_{r = r_0} \geq 0$ using the approximate solution for the electric field in a spherical corona system [17, 18]

$$E = E_{\mathrm{cor}}\sqrt{\frac{r_0^4}{r^4} + \frac{i(r^3 - r_0^3)}{6\pi\varepsilon_0\mu r^4 E_{\mathrm{cor}}^2}}. \quad (2)$$

The critical current is [17]

$$i_{\mathrm{cr}} \approx 8\pi\varepsilon_0\mu r_0 E_{\mathrm{cor}}^2. \quad (3)$$

For the above case of an electrode with a top radius of r_0 = 5 cm and for a typical ion mobility of μ = 1.5 cm^2/V s, we have $i_{\mathrm{cr}} \approx 15$ mA, which is comparable to the critical current of 10 mA obtained in numerical simulations for a rod electrode with the same radius.

Inequality (1), which determines the conditions for the development of an upward leader, can be applied only after the termination of the streamerless corona and the onset of a streamer flash.

2.3. Viability of an Upward Leader

We are interested here in viable upward leaders that are capable of growing in the external electric field after emitting from the top of a grounded electrode. For a leader to grow, it is necessary that the field in the leader channel be weaker than the undisturbed external electric field [20, 21]. Only in this case will the increase in the length l_L of a vertically growing leader be accompanied by an increase in the difference $\Delta U_{\mathrm{tip}} = U_{\mathrm{tip}} - U_0$ between the potential of the leader tip $U_{\mathrm{tip}} = -E_L l_L$ and the potential of the undisturbed external electric field $U_0 = -E_0(h + l_L)$ at the position of the leader tip. It is ΔU_{tip} that determines the growth rate of the charge of the propagating leader and, consequently, its current i_L and velocity v_L.

If we ignore the disturbance of the external electric field by the corona space charge, then the viability condition for the nascent leader can be found from the charge conservation law

$$i_L = \tau_L v_L = C_1\Delta U_{\mathrm{tip}} v_L, \quad (4)$$

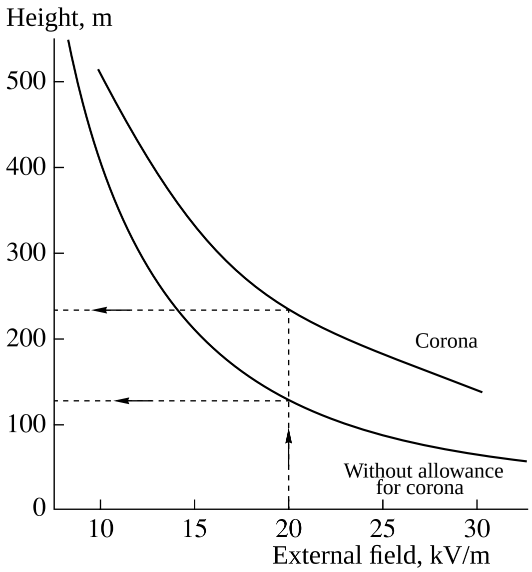

Fig. 5. The height of a ground object at which a viable leader can develop from the top of the object vs. external electric field.

and following semi-empiric formulas [8]:

$$E_L = \frac{b}{i_L}; \quad b = 300 \text{ V/(cm A)}, \tag{5}$$

$$v_L = a(\Delta U_{\text{tip}})^{1/2}; \quad a = 1500 \text{ cm/(s V}^{1/2}), \tag{6}$$

where τ_L and C_1 are the charge and capacitance per unit length of the leader channel, respectively. These formulas were shown to adequately describe leaders in long laboratory gaps with lengths of up to 100 m [8, 20, 22]. Substituting expressions (4)–(6) into the inequality $E_0 > E_L$, we obtain an estimate for the external electric field that is necessary to sustain a leader propagating from a grounded electrode of height h [23]:

$$E_{0\text{cr}} \geq \frac{3.7 \times 10^5}{h^{3/5}} \text{ V/m}. \tag{7}$$

Under the thundercloud, near the ground, the electric field undisturbed by the corona space charge of grounded objects can be as high as 20 kV/m. According to criterion (7), this field is able to sustain a nascent upward leader propagating from an object whose height is no less than h = 130 m. For ordinary objects with a height of h = 20–30 m, the required external field must be much higher, $E_{0\text{cr}}$ = 50–60 kV/m. Such a strong field cannot be produced by a thundercloud.

The actual critical field is significantly higher than that predicted by criterion (7) because of the influence of the corona space charge (Fig. 5). Thus, computer simulations [23] show that, for a leader to grow from a corona electrode in an external field of 20 kV/m, the electrode must be higher than 225 m. In the absence of a corona, a height of 135 m is quite enough.

These estimates allow us to conclude that the main cause for the propagation of an upward leader from the top of a moderately high grounded object is the field of the approaching channel of a downward lightning leader, whereas an upward leader starting from a skyscraper object can develop even in a weaker thundercloud field. The effect of a corona on the emission of a viable leader under the action of the thundercloud field has been confirmed by experiments with lightning triggered by rockets drawing a grounded wire [24].

2.4. Phenomenology of the Downward Lightning Attachment

Observations of lightning and experiments with long laboratory sparks have shown that the discharge channel undergoes many accidental deflections. Nevertheless, on the average, it propagates along the external electric field. Hence, in order to deflect the leader of downward lightning from the vertical direction, the disturbing field must be comparable to the thundercloud field E_0. This is also true for an upward leader propagating from a grounded object. Therefore, if the field generating the upward leader is mainly produced by the downward leader (rather than the thundercloud charge), then the attachment of downward lightning, which ends in the lightning strike to the object, indeed begins with the emission of a viable upward leader. In this case, the nascent upward channel will propagate toward the downward leader and, sooner or later, will direct it to the object top. According to the above estimates, this takes place for moderately high grounded objects near which the thundercloud field is a few times lower than $E_{0\text{cr}}$ and the necessary field is mainly produced by the charge of the approaching downward leader.

It should be noted that the direct influence of the charge of a grounded object on downward lightning is significantly weaker than that required for the deflection of the channel trajectory toward this object. Indeed, a linear charge $\tau_{\text{el}}(z)$ that is induced on the surface of a grounded electrode with a height h and radius $r_0 \ll h$ in a uniform external field E_0 linearly increases from the base of the electrode to its top:

$$\tau_{\text{el}}(z) = \frac{4\pi\varepsilon_0 z E_0}{\ln\frac{2h}{r_0} - 2}.$$

Even if all the charge of the grounded electrode

$$q_{\text{el}} = \frac{2\pi\varepsilon_0 h^2 E_0}{\ln\frac{2h}{r_0} - 2}$$

were concentrated at its top, the horizontal component of the field induced by this charge at the position of the downward leader tip (with a height H and radial deviation r) would not exceed

$$\Delta E_{\text{hor}} = \frac{q_{\text{el}} r}{4\pi\varepsilon_0}\left\{\frac{1}{[(H-h)^2+r^2]^{3/2}} - \frac{1}{[(H+h)^2+r^2]^{3/2}}\right\}.$$

For example, if $H = r = 3h$ and $h/r_0 = 10^3$, we then have $\Delta E_{\text{hor}} \approx 0.01E_0$, which is much lower than the thundercloud field. Such a disturbance is too weak to deflect the downward leader toward the grounded electrode. Hence, the lightning attachment is indeed provoked by the emission of an upward leader directed towards the downward leader tip. As the leaders approach one another, the disturbing effect of the upward leader on the downward one increases in an avalanche manner; as a result, the latter gets redirected toward the grounded object.

For skyscraper-type objects, the situation is different. Here, the thundercloud field can be quite enough to maintain a viable upward leader that has started from the top of a grounded object. It follows from criterion (7) that, for $E_0 \approx 20$ kV/m, this becomes possible for grounded objects higher than $h \approx 130$ m. The nascent leader will not necessarily develop toward the downward leader, whose influence is yet weak. There is no reason to call it an upward-connecting leader since, being controlled by the thundercloud field, the leader channel will propagate mainly upward, thereby forming a ground-to-cloud lightning discharge, rather than toward the downward leader.

Note that, in this case, the downward lightning discharge also is not affected by the upward leader. The disturbance of the external electric field near the tip of the downward leader is much smaller than the thundercloud field and is not able to deflect the leader channel toward the grounded object. On the average, the downward leader keeps propagating downward.

Thus, Golde's hypothesis is not applicable to skyscraper-type grounded objects, because, in this case, the downward leader does not control the propagation of the nascent upward leader. According to the results of numerical simulations presented in Fig. 5, this is the case for objects higher than 200 m. Observations show that it is these objects that most often undergo upward lightning strikes [25].

Nevertheless, the emission of an upward leader is hardly possible without a downward lightning discharge because the slowly varying thundercloud field is not able to increase the corona current from the top of a grounded object to the threshold value i_{cr} corresponding to the excitation of a streamer flash. To show this, it suffices to consider an approximate analytical solution for an isolated sphere of radius r_0 [17, 18]. According to this solution, the current of a nonsteady corona with a linearly increasing voltage $U(t) = A_U t$ is

$$i(t) \approx 2\pi\varepsilon_0 t\sqrt{\frac{\mu A_U^3}{3}}. \quad (8)$$

This formula holds for the quite high effective voltage $U(t) \gg r_0 E_{\text{cor}}$ that is usually observed during a thunderstorm. In this case, the corona current is almost independent of the sphere radius. The critical current, determined by formula (3), is reached at a voltage amplitude of $U_{\max} = U(t_f) = A_U t_f$, which is equal to

$$U_{\max} \approx \sqrt[3]{\frac{3 i_{\text{cr}}^2 t_f}{4\pi^2\varepsilon_0^2\mu}}. \quad (9)$$

For a typical critical current of $i_{\text{cr}} = 10$ mA, we have $U_{\max} \approx 18.5$ MV. Even for such an extremely high object as the Ostankino TV tower ($h = 540$ m) and for the maximum possible regeneration rate of the thundercloud charge ($t_f \approx 10$ s), the required voltage drop can be reached in an external field as high as $E_{0\max} = U_{\max}/h \approx 34.5$ kV/m. Such a high field is hardly expected to frequently occur during a thunderstorm without involving downward lightning discharges.

2.5. The Frequency of Lightning Strikes to a Grounded Object

Here, we consider lightning strikes to an isolated grounded object whose height is much larger than its transverse dimensions, e.g., a conventional lightning rod. The frequency of lightning strikes can be most easily determined for relatively low objects that do not excite upward lightning discharges and suffer only downward lightning strikes. As was shown above, the attachment of downward lightning proceeds via the development of an upward-connecting leader. Hence, the main problem is to find the instant at which the upward leader starts and to test its viability taking into account the design features of the grounded object and the space charge injected from its top into the atmosphere under the action of a corona discharge. As soon as the start instant of a viable upward leader has been found, the height H_0 of the tip of the downward lightning channel at the beginning of the attachment process can be determined by solving a purely electrostatic problem. The radius of the attraction zone can then be found using the equidistance principle [20]. As a result, we obtain an estimate for the frequency of lightning strikes to an object of a given height and configuration.

Note that, in spite of its primitivity, the equidistance principle is widely used for estimates in lightning protection. According to this principle, a downward lightning leader does not feel the ground until its tip comes down to a certain height H_0 called the attractive height. The lightning channel then propagates along the shorter of the two paths: along the path of length H_0 toward the ground or along the path of length $\sqrt{(H_0 - h)^2 + r^2}$ (where r is the radial deviation of the downward leader tip with respect to the top of the object of height h) toward the grounded object. The equality of these

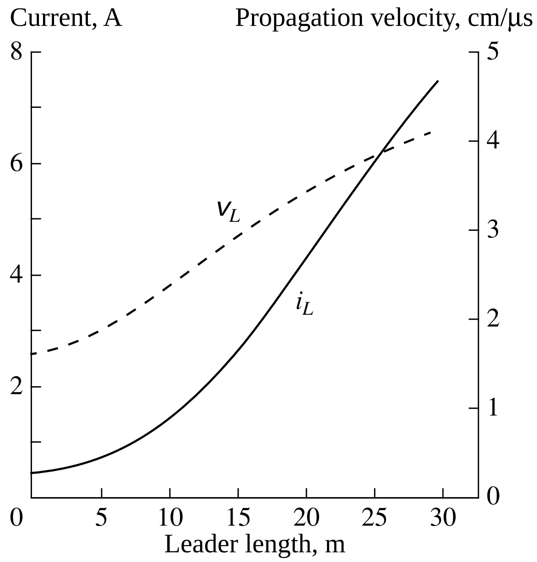

Fig. 6. Current and propagation velocity of an upward leader starting from a 30-m-high electrode as functions of the leader length.

lengths determines the attractive radius of a downward lightning,

$$R_{at} = \sqrt{2H_0h - h^2}. \quad (10)$$

The calculation algorithm is as follows:

(i) Determining the characteristics of a nonstationary corona at the top of a grounded rod electrode first in a thundercloud field that varies in a specified way and then in the field of a downward leader approaching the ground.

(ii) Calculating the position of the downward leader tip at the instant when the corona current becomes equal to the critical value that is necessary for a streamer flash to occur.

(iii) Checking whether condition (1) for the origin of an upward leader in the stem of the initial streamer branch is satisfied.

(iv) Calculating the parameters of the upward leader propagating in the space charge layer of the corona and checking its viability.

The computer code developed [18] allowed us to calculate the corona current from a rod electrode in an arbitrarily varying thundercloud electric field. When simulating a corona in the sum of the thundercloud field and the field produced by a downward leader, the leader was represented by an infinitely thin vertical charged channel. The propagation velocity of the leader was assumed to be constant. In the simplest version of the code, the distribution of the linear charge density along the leader channel was also assumed to be constant, $\tau_L(z)$ = const. However, the code also allowed us to perform calculations with an arbitrary distribution $\tau_L(z)$, e.g., with a charge density linearly increasing from the base to the tip of the leader channel (such a distribution corresponds to the polarization of an ideal conductor in a uniform electric field). To check the viability of the nascent upward leader, we used the above simplified semi-empiric theory, which relates the leader current, the leader propagation velocity, and the longitudinal electric field in the channel to the difference ΔU_{tip} between the leader tip potential and the potential of the undisturbed external field at the position of the leader tip. In calculations, the nascent upward leader was represented by a straight charged channel. At every time step, the charge distribution along the channel was determined by solving a set of integral equations with potential coefficients. The equations related the potential of each channel segment with its charge, the charges of all the other channel segments, the space charge in the gap, and the external field created by the thundercloud and the downward leader. The images of the charges in the ground were taken into account. The obtained charge distribution was used to find the potential of the upward leader tip. Using this potential, the running values of the leader current, the leader propagation velocity, and the field in the leader channel were then determined.

Figure 6 presents the result of simulations (similar to those described in [26]) of the development of an upward leader from a 30-m-high grounded electrode with a hemispherical 2-cm-radius top. The downward leader started at a height of 3000-m at the instant when the linearly increasing (over 10 s) thundercloud field reached 20 kV/m near the ground. The downward leader propagated toward the ground with a velocity of 2×10^5 m/s. The radial deviation of the downward leader with respect to the grounded electrode was 90 m. The density of a uniformly distributed linear charge was 0.5 mC/m. The corona current exceeded its critical value 13.7 ms after the start of the downward leader, when its tip had already propagated down to a height of 225 m and the voltage drop across the streamer zone was nearly three times higher than $\Delta U_{cr} \approx 400$ kV, which was required for the emission of an upward leader. The leader was stable since the very beginning of its propagation. The propagation velocity of the upward leader and its current increased relatively slowly only over the first several meters of its path, where the corona space charge was maximum. Over 1 ms, the leader passed about 30 m, went beyond the space charge layer, and then propagated freely.

Figure 7 shows the calculated height H_{tip} of the downward leader tip at the start instant of a viable upward leader as a function of the radial deviation r. The calculations were performed for a grounded electrode with a height h = 30 m for the same conditions as in Fig. 6. The solution to the equidistance equation $H_{tip} = [r^2 + (H_{tip} - h)^2]^{1/2}$ determines the limiting radial deviation $r = R_{at}$ at which downward lightning is yet attached towards the object and the height $H_{tip}(r = R_{at}) = H_0$ from which it starts to be attached. In Fig. 7, $H_0 = 8h$

and $R_{at} \approx 3.8h$, which corresponds to an attraction area of $S_{at} = \pi R_{at}^2 \approx 0.04$ km^2 (one lightning strike per twelve years of operation for a lightning strike frequency of about two strikes per year per kilometer squared, which is characteristic of central Russia). Similar calculations for a 100-m-high object with a 2-cm-radius top give $H_0 = 5h$ and $R_{at} \approx 3h$. The ratio R_{at}/h decreases with increasing h over the entire range of the practically important heights and for different densities of the linear charge of the downward lightning leader used in the model.

The above method for determining the start instant of an upward leader is applicable to objects with heights from a few tens of to a few hundred meters. Numerical simulations allow one unambiguously determine the conditions for the origin of a viable upward leader. Quite another matter is the role it plays in the lightning attachment. Our results show that the development of an upward leader from a sky-scraper object does not necessarily affects the downward lightning discharge. There may be a situation in which the upward and downward leaders will not sense one another, i.e., there will be no attraction between them. The leader of the downward lightning discharge will propagate towards the ground or some another grounded object. The evolution of the excited upward leader is not known in advance. It can decay or convert into an upward lightning flash. Since upward lightning is almost as dangerous as downward lightning, it is important to find the conditions under which it can develop from different objects.

As was shown above, an upward leader can arise from objects as low as 10–20 m owing to the amplification of the electric field by a nearby downward leader. There may be a situation in which downward lightning does not strike a grounded object but, nevertheless, stimulates the development of an upward leader from it. For low objects, such a leader will develop as long as the strong electric field of the downward leader exists. This field disappears when the downward leader touches the ground and the current wave of the return stroke is excited. This wave propagates upward from the ground at a velocity of about 30% of the speed of light. It recharges the lightning channel and substantially reduces its electric field [20]. As a result, the upward leader ceases to propagate. In Fig. 8, the leader starting from a 30-m-high object stops developing as early as 3 μs after the downward lightning leader has reached the ground.

For sky-scraper objects, the situation is quite different. We simulated the development of an upward leader from a 200-m-high grounded rod electrode with a top radius of 2 cm [27]. The process was induced by a downward leader with a linear charge density of 0.5 mC/m. The radial deviation of the downward leader was 750 m. The upward leader started when the tip of the downward leader came down to a height of 520 m and was at a distance of 860 m from the electrode top.

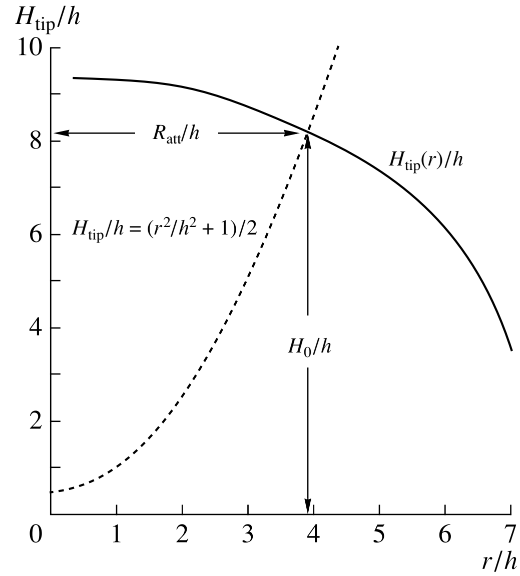

Fig. 7. Height of the downward leader tip at the instant of the excitation of an upward leader from a grounded electrode of height 30 m and radius 2 cm as a function of the radial deviation of the downward leader with respect to the electrode. The downward leader charge is uniformly distributed along the leader channel with a linear density of τ_L = 0.5 mC/m. The dashed curve shows the locus of points corresponding to the equal distances from the downward leader tip to the ground and to the object top.

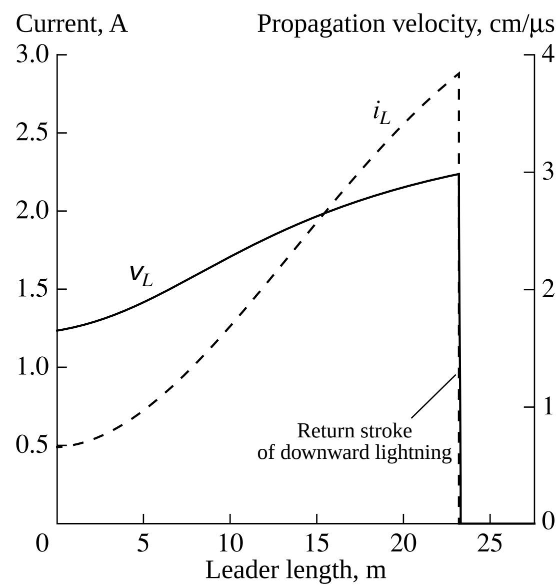

Fig. 8. Current and propagation velocity of an upward leader vs. leader length. The height of the grounded electrode is 30 m, and the radial deviation of the downward leader with a linear charge of τ_L = 0.5 mC/m is 150 m.

Such a distant lightning discharge was not able to strike the electrode; however, it efficiently sustained the development of the upward leader. By the instant when the return stroke of the downward lightning discharge

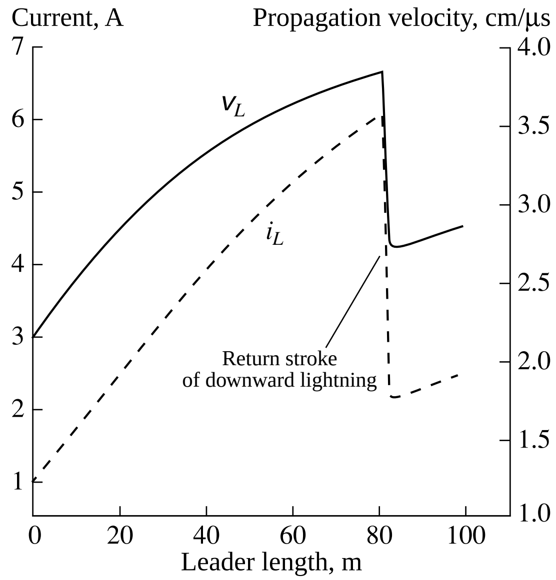

Fig. 9. Current and propagation velocity of an upward leader vs. leader length. The radial deviation of the downward leader with a linear charge of τ_L = 0.5 mC/m is 750 m, and the height of the grounded object is 200 m.

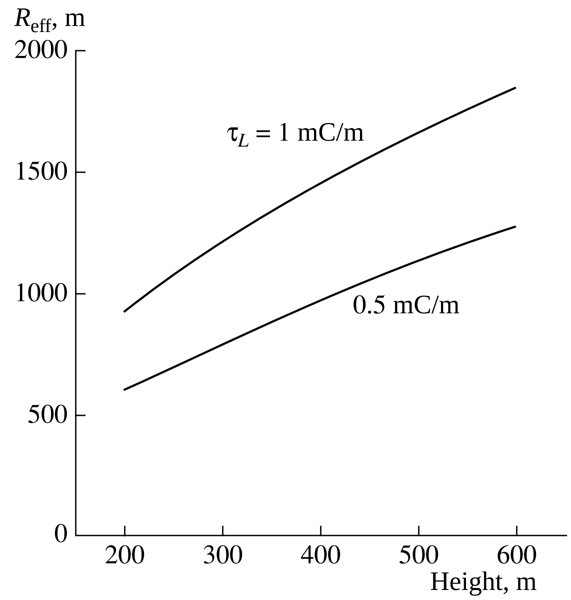

Fig. 10. Effective interaction radius R_{eff} of a grounded object as a function of its height.

began, the upward leader had grown to approximately 80 m, i.e., it had gone beyond the cloud of the corona space charge. For a freely propagating leader, the presence of the corona charge leads to the amplification (rather than the attenuation) of the external field. No longer restrained, the upward leader continues to develop even after the neutralization of the charge of the downward leader during the return stroke of lightning. The only effect is that the propagation velocity and current of the upward leader decrease for a short time, after which these again begin to increase (Fig. 9). This process finally results in the origin of upward lightning, which strikes the ground object.

Because of the lack of data on the attachment mechanism, it is impossible to predict with certainty the further evolution of an upward leader starting from a high grounded object. It can either be attracted to the downward leader (in this case, the development of a downward lightning leader completes with a strike to the object) or, as was shown above, continue to propagate toward the cloud, thus converting into an upward lightning discharge. If one does not distinguish between downward and upward lightning strikes, the total frequency of strikes can be found using computer simulations. As long as one searches for the maximum possible radial deviation of the downward leader at which a viable leader can develop from the top of a grounded object of a given height, the algorithm for solving this problem is identical to that discussed above. This deviation determines the effective interaction radius R_{eff}—the radius of the area within which any downward lightning either strikes the grounded object or induces an upward lightning discharge from its top. Figure 10 shows the calculated values of R_{eff} [27] for two different linear charges of the leader of downward lightning.

The number of lightning strikes estimated from the effective interaction radius ($N_{lightn} = n_0 \pi R_{eff}^2$, where n_0 is the number of lightning strikes per unit area of the ground surface) can be verified experimentally. In particular, one can use the representative data from observations over the Ostankino TV tower [25]. For the average yearly number of lightning strikes to the ground near Moscow of n_0 = 2.5–3.0 km^{-2}, the tower suffers about 30 lightning strikes over the lightning season. Our calculations provide a similar result for the R_{eff} value corresponding to that shown in Fig. 10 for a linear charge of a downward leader of ~1 mC/m.

3. PROSPECTS FOR CONTROLLING THE FREQUENCY OF LIGHTNING STRIKES TO A GROUNDED OBJECT

As was mentioned in the Introduction, there are two approaches to the problem of lightning protection that yield diametrically opposite effects: the reduction of the number of lightning strikes to the protected object and, alternatively, the increase in the attraction of lightning to the lightning rod. The implementation of these approaches should not be related to the use of such exotic, expensive, and not quite reliable means as a high-power laser that lengthens the grounded electrode with a long plasma channel or chemical reagents destroying the thundercloud. It seems that the only acceptable means may be a counter discharge that is formed in a relatively weak electric field, is characterized by a moderate voltage drop, and can operate in a controllable regime, e.g., a streamer or streamerless corona discharge.

Attempts to excite an early counter discharge with the aim of emitting an upward-connecting leader that should intercept downward lightning are described in [5, 28, 29]. On the other hand, the grounded corona systems have been considered that should delay or almost completely prevent the emission of an upward-connecting leader [30]. Such systems are supposed to guarantee that downward lightning will not notice the object under protection.

Below, both these approaches are analyzed using the results of numerical simulations.

3.1. Lightning Protection Systems Based on the Early Streamer Emission

The concept of lightning protection on the basis of early streamer emission (ESE) is very simple. The top of the lightning rod is shaped in such a way as to enable the earliest excitation of a streamer flash; i.e., the radius of curvature of the electrode top is made as small as possible. It is assumed that the early initiation of a streamer flash stimulates the early development of an upward-connecting leader. As it propagates toward the downward lightning leader, it intercepts the channel of the latter. To boost this effect, extra voltage (usually, a few tens of kilovolts) is applied to the top of the corona electrode. To obtain this extra voltage without employing an external power supply, the current flowing through the electrode top in the early stage of the counter discharge can be used. For example, this current may charge a storage capacitance, which then discharges through the forming *LC* circuit. The extra voltage thus obtained is applied to the top of the corona electrode (for this purpose, the top is insulated from the ground). The efficiency of ESE lightning rods is claimed to be many times higher than that of conventional lightning rods.

Unfortunately, there are no reliable statistical data on the efficiency of ESE lightning rods in the literature. Moreover, there are no works on laboratory studies that could clarify (at least at a qualitative level) the relation between the conditions for the excitation of a counter discharge from a grounded electrode and the probability of striking this electrode by a long downward spark. Nevertheless, as early as in the mid 1970s, a series of experimental studies aimed at determining the so-called critical radius of a high-voltage electrode in long air gaps were carried out in [31, 32]. It was shown that, when a positive pulsed voltage with a rise time of several hundred microseconds was applied to a rod–plane or sphere–plane gap, the electrical strength varied only slightly with increasing anode radius r_0 until the radius exceeded a certain critical value r_{cr}. The critical radius was found to be fairly large and to be a function of the interelectrode distance. For example, in a gap of length

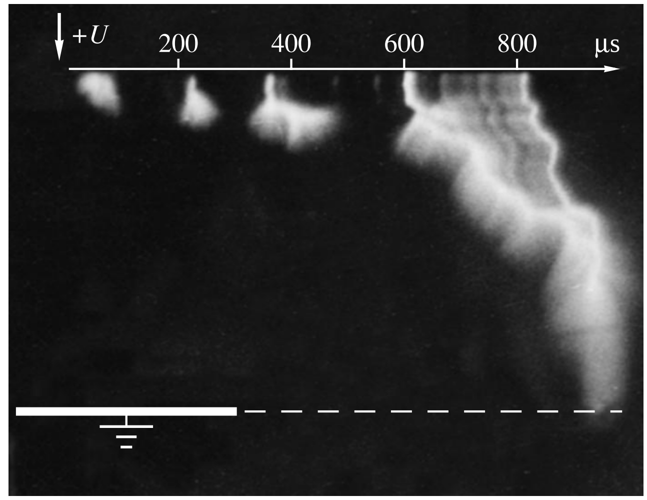

Fig. 11. Streak image of a leader in a 8-m-long rod–plane gap after a positive voltage pulse with a rise time of about 3 ms is applied to the rod.

~10 m, the critical radius is as large as $r_{cr} \approx 30$ cm. The explanation of this effect was given in [33]. In brief, the essence of the effect is that the too early excitation fails to provide the required viability of the leader. It first forms in the so-called flash mode (with long pauses between the flashes) [34], and its stable continuous propagation begins only after increasing the applied voltage (Fig. 11).

The fact that the critical radius r_{cr} is rather large casts some doubt on the concept of ESE lightning protection. In [26], numerical simulations were performed of the excitation of a counter discharge from a grounded electrode of given height, starting with the generation of a nonstationary corona in a slowly increasing thundercloud field up to the initiation of a streamer flash due to the field amplification by the charge of an approaching downward leader. The probability of emitting an upward leader and the viability of the nascent leader while it propagates in the cloud of the corona space charge were estimated. The calculations were performed for different top radii of the grounded electrode. The results presented in Fig. 12 show that varying the electrode top radius within the range r_0 = 0.1–1 cm (which is typical of the lightning protection practice) affects the conditions for the excitation of a streamer flash but does not influence the viability of the upward leader.

The above effect of the electrode top radius r_0 on the excitation of a streamer flash is quite expectable because, according to formula (3), the critical current nearly linearly depends on r_0 for spherical electrodes as long as the corona threshold field E_{cor} can be considered constant. However, for small electrode top radii, just after the excitation of a streamer flash, either condition (1) for the origin of an upward leader is not met or the

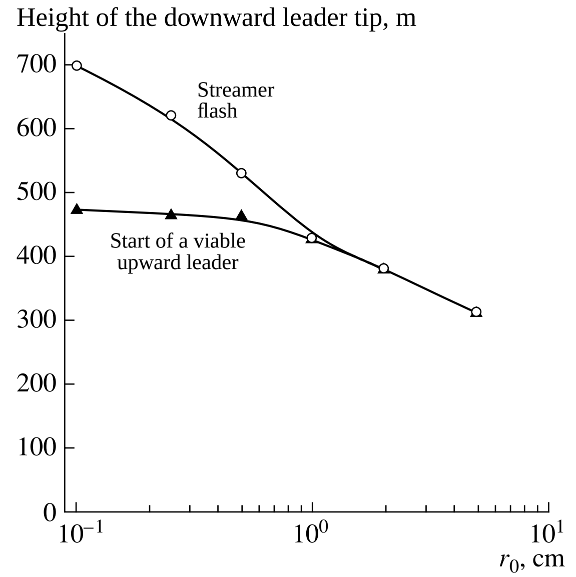

Fig. 12. Height of the downward leader tip at the instant of a streamer flash and at the start instant of a viable upward leader propagating from the top of a 50-m-high lightning rod vs. top radius. The downward leader with a linear charge of 0.5 mC/m starts from a height of 3000 m at the instant when a thundercloud field linearly increasing over 10 s has reached a value of 20 kV/m. The radial deviation of the downward leader is 50 m.

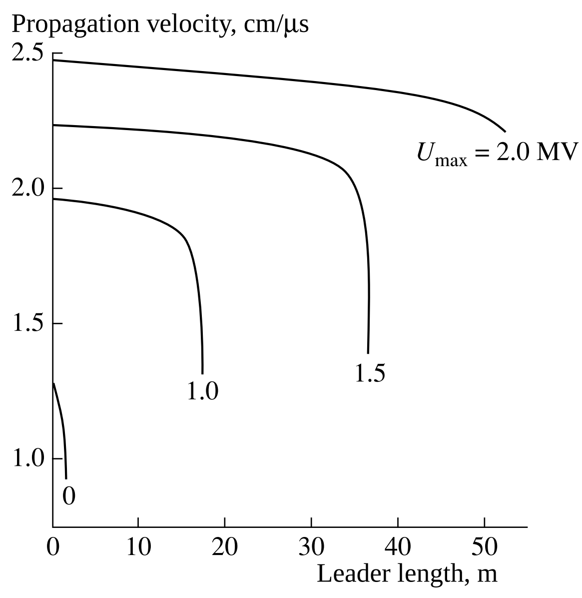

Fig. 13. Propagation velocity of an upward leader emitted from the top of a 150-m-high grounded rod under the action of a 1-ms controlling voltage pulse vs. leader length. The leader starts at the instant when a thundercloud field linearly increasing over 10 s has reached a value of 20 kV/m.

nascent leader is not able to penetrate through the layer of the corona space charge in a still relatively weak external field. Hence, the sharpening of the electrode does not increase the efficiency of the lightning rod. In this respect, it worth noting the results of field experiments [35, 36], which did not reveal any advantage of lightning rods with a pointed top against those with a blunt top (on a number of principal issues, those experiments need a more thorough analysis, which is beyond the scope of this study).

Besides a decrease in the top radius, ESE from the top of a grounded electrode can also be provoked by applying an additional voltage between the top of the electrode and its grounded base. There is no doubt in the efficiency of this method. The only problem is to determine the required value of this controlling voltage. Attempts to resolve this problem experimentally were made several decades ago. In recent years, numerical simulations have been used for this purpose.

The results of numerical simulations presented in Fig. 13 demonstrate how an upward leader developed from a 150-m-high grounded electrode grows under the combined action of a thundercloud field that increases to 20 kV/m over 10 s near the ground surface and the field produced by applying an additional (controlling) voltage U_{max} to the electrode top. The full width at half-maximum of the additional voltage pulse is 1 ms. It was shown that, for the leader to propagate without bound, the amplitude U_{max} of the additional voltage pulse should exceed 2 MV, which is much higher than the 20–30 kV voltage that can be obtained by accumulating energy from the atmospheric electric field due to the corona current (as is assumed to happen in ESE lightning rods).

To qualitatively estimate the effect of the increase in the potential of the lightning electrode top by this quite a moderate value provided by the internal scheme of an ESE lightning rod, it is necessary to consider the following circumstances. First, this value is less than 10% of the threshold voltage drop $\Delta U_{cr} \approx 400$ kV required to enable the leader emission from a grounded electrode. Second, it is quite easy to increase the voltage drop by 20–30 kV in a natural way. For this purpose, it is enough to increase the height of the lightning rod by only 1.0–1.5 m in a thundercloud field of ~20 kV/m. Finally, to produce an electric field comparable to the above controlling field due to the effect of an approaching downward leader, it is quite sufficient that the leader pass a relatively short additional distance toward the ground. Indeed, in the first approximation, the leader field near the ground, just under the leader tip, can be estimated as follows:

$$E_L \approx \frac{\tau_L}{2\pi\varepsilon_0 H_{tip}},$$

where H_{tip} is the height to which the leader came down. The drop between the zero potential of the top of a grounded lightning rod of height h and the potential induced at the position of the top by the charge of the downward leader is

$$\Delta U_L \approx \frac{\tau_L h}{2\pi\varepsilon_0 H_{\text{tip}}}.$$

For example, if $H_{\text{tip}}/h = 5$, which is typical for the initial stage of lightning attachment, and $\tau_L = 0.5$ mC/m, then we have $\Delta U_L \approx 1.8$ MV. The controlling voltage provided by the internal scheme of an ESE lightning rod is less than 2% of this value. To increase ΔU_L by 2%, it is sufficient that the length of the downward leader increase by approximately the same amount, which is too small to lead to any significant consequences.

Finally, let us consider the experience acquired in the use of electric-power transmission lines. The energized wires of these lines are at a certain potential with respect to the shield wires, the wires of dc power transmission lines having potentials of opposite polarities. Nevertheless, no difference in using lightning wires to protect ground objects and high-voltage power transmission lines (at least, up to voltages of 500 kV) has been observed. Moreover, no difference has been observed in the number of lightning strikes to the positive and negative wires of a dc power transmission line, although about 90% of all downward lightning discharges carry a negative charge.

According to the above, the increase in the potential of the lightning rod by a few tens of kilovolts cannot significantly affect its protecting ability. Thus, to date, there are no experimental data or theoretical predictions indicating the increased efficiency of ESE lightning rods against conventional ones.

3.2. Lightning Protection Systems Based on Suppressing the Upward-Connecting Leader

Systems of this kind are being actively discussed now [5, 6]. These are multipoint corona systems with a total radius of up to 10 m. The corona needles with a height of about 10 cm and radius $r_{\text{ndl}} \sim 1$ mm (or less) uniformly fill a surface that has the shape of an umbrella. The total number of the needles can be as high as several thousands. The corona space charge is assumed to suppress the emission of an upward leader and thus to prevent lightning strikes to the object above which the system is placed.

The main objection to employing this method is that the increase in the number of the corona points slightly affects the space charge injected into the atmosphere by a well-developed corona. Indeed, if the atmospheric electric field greatly exceeds the threshold level $E_{0\text{cor}}$ corresponding to corona onset, then a continuous corona is formed over the surface of the system so that the corona space charge covers the entire system. As was noted above, under these conditions, the corona current depends slightly on the radius of the corona surface. This is also true if the surface of the system is divided into many separate corona sites. Figure 14

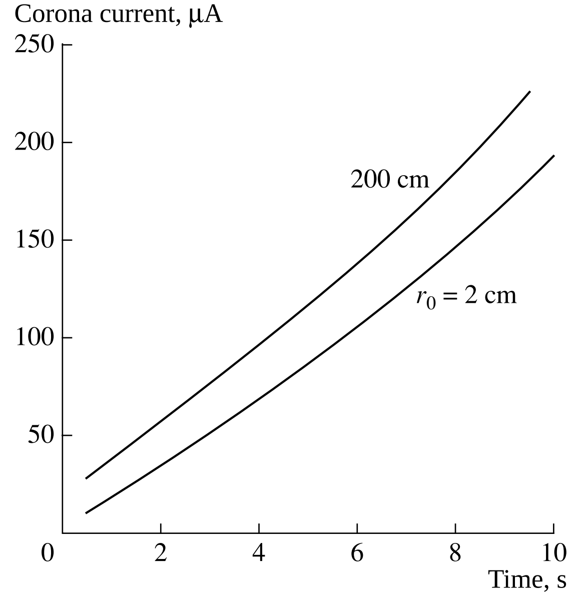

Fig. 14. Time evolution of the corona current through an isolated rod electrode and from a multipoint corona system of radius 2 m at the same corona threshold field $E_{0\text{cor}}$.

shows the calculated time evolution of the corona current from an isolated hemispherical 2-cm-radius electrode and from a multipoint corona system of radius 2 m in a thundercloud electric field. The needle dimensions are chosen such that the coronas from these needles are excited at the same value of the thundercloud electric field (about 1.4 kV/m), which increases linearly to 20 kV/m over 10 s. One can see that, in a well-developed corona, the corona current through the rod differs from that through the multipoint system by no more than 15%.

However, the increase in the injected charge is of minor importance for the protection ability of a multipoint corona system. The most important point is that the corona current is nearly uniformly distributed over the needles. Therefore, the current flowing through a needle decreases in proportion to the needle number N_{ndl}; as a result, it does nor reach the critical value i_{cr} corresponding to the excitation of a streamer flash. To illustrate, for a needle radius of $r_{\text{ndl}} = 0.1$ cm (which corresponds to $E_{\text{cor}} \approx 75$ kV/cm and $i_{\text{cr}} \approx 2$ mA) and for $N_{\text{ndl}} = 5000$ (which is quite realistic), the total corona current must exceed 10 A for a streamer flash to be excited at any needle tip. To compare, for a single electrode with a typical radius of 2 cm, this would occur at a corona current as low as 10 mA.

Figure 15 shows the total corona current from a multipoint corona system as a function of the height of the downward leader tip for a radial deviation of $r = 50$ m with respect to the grounded electrode. As before, the leader is represented by an infinitely thin vertical charged channel with a linear charge of $\tau_L = 0.5$ mC/m. The propagation velocity of the leader is assumed to be

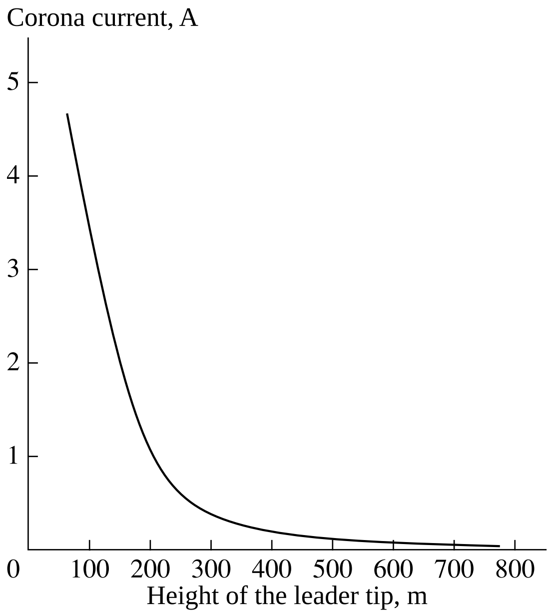

Fig. 15. Total current from a multipoint corona system of radius 2 m and height 50 m as a function of the height of the downward leader tip. The linear charge of the downward leader is 0.5 mC/m, and its radial deviation is 50 m.

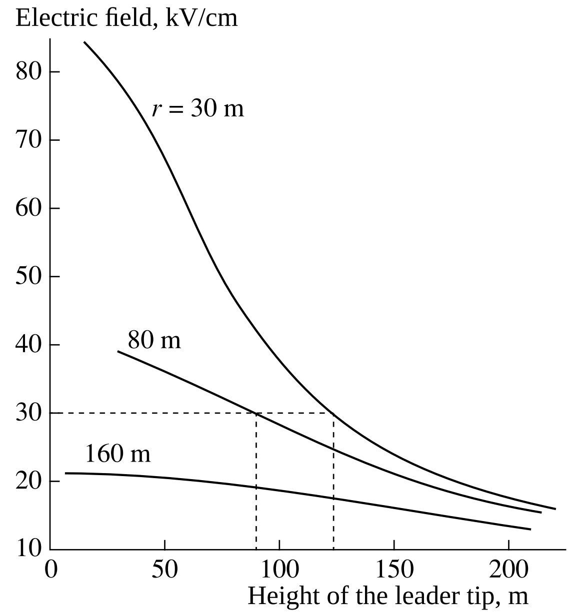

Fig. 16. Maximum electric field on the surface of a hemispherical multipoint corona system of radius 5 m as a function of the height of the downward leader tip.

2×10^5 m/s. Simulations show that, under these conditions, the current flowing through a single needle cannot exceed the critical value. For this to occur, the tip of the downward leader should more closely approach the corona electrode. By choosing the size of the corona system and the number of needles, it is always possible to keep the current flowing through the corona points below the critical level $i_{cr} = 8\pi\varepsilon_0\mu r_{ndl}E_c^2$ and thus to prevent streamer emission. The only exception is the case of the zero radial deviation of the downward leader, when its tip is just above the corona system.

The situation becomes critical when the ionization condition is satisfied not only at the needles but also at the surface of the system. In this case, the streamer flash may be excited at any point on the surface or even at a point near the surface where the electric field can be much higher than that on the surface. Such an anomalous disturbance of the electric field is caused by an intensely accumulated space charge. As was mentioned above, this charge does not have time to propagate by a significant distance during the development of a downward lightning leader and is thus accumulated near the grounded top. Figure 16 shows the electric field between the needles on the surface of a multipoint corona system as a function of the height of the downward leader tip. The simulations were performed for a hemispherical corona system of radius 2 m placed at a height of $h = 50$ m. By the start instant of the downward leader with a linear charge of 1 mC/m (a high-power lightning discharge), the thundercloud field has increased to 10 kV/m. For a radial deviation of $r = 160$ m of the downward leader with respect to the system axis, the electric field near the surface of the system does not exceed 22 kV/cm. This means that no streamer flash accompanied by a subsequent upward leader can occur in this case. For $r = 80$ m ($r/h = 1.6$), the field near the surface of the corona system increases to 30 kV/cm as the downward leader tip comes down to $H_0 = 90$ m ($H_0/h = 1.8$). Such a situation corresponds to the approximate equality of the distances from the downward leader tip to the ground (H_0) and to the corona system ($\sqrt{(H_0-h)^2+r^2}$). Recall that this equality determines the lightning attractive radius R_{at}. Finally, for $r = 30$ m, the condition for the emission of an upward leader is satisfied already at a height of $H_0 = 125$ m, when $H_0 > \sqrt{(H_0-h)^2+r^2}$; this definitely ensures a lightning strike to the corona system.

Thus, employing a large-radius multipoint corona system substantially (severalfold) decreases the attractive height of the leader of downward lightning and, consequently, the attractive radius R_{at} as compared to a conventional lightning rod of the same height. Note that the number of lightning strikes to a grounded object decreases in proportion to R_{at}^2.

All other factors being the same, the calculated attractive height H_0 depends strongly not only on the leader linear charge τ but also on its distribution along the channel. It is these lightning parameters that are still poorly investigated. To avoid the uncertainty related to

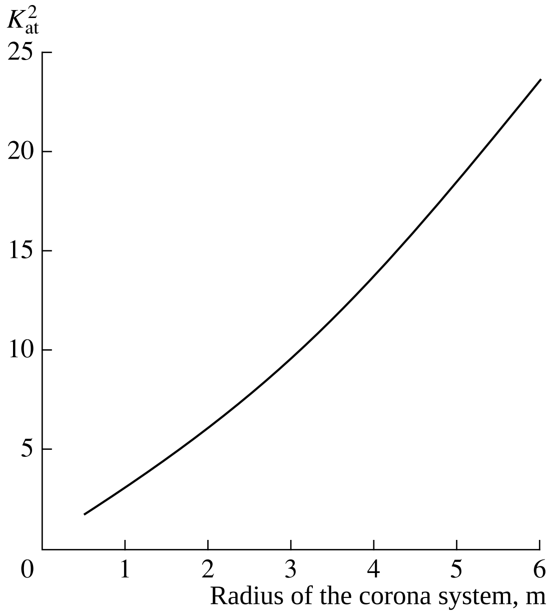

Fig. 17. Reduction factor of the lightning strike number for a 50-m-high object as a function of the radius of a multipoint corona system.

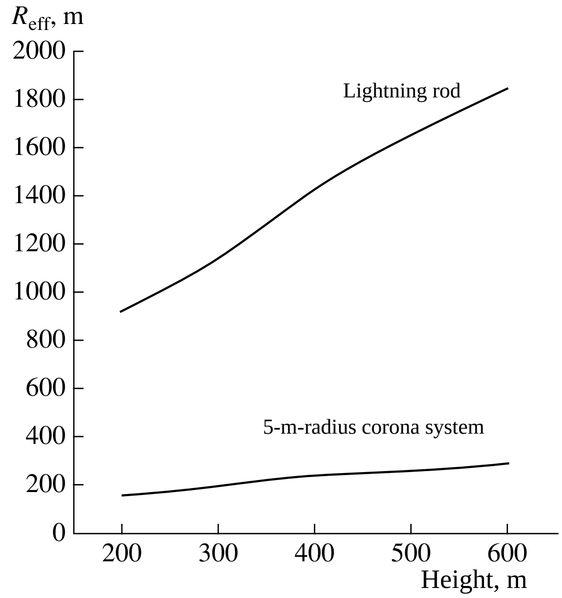

Fig. 18. Effective interaction radius R_{eff} as a function of the height of an object protected by a lightning rod and that protected by a multipoint corona system of radius 5 m.

this, it is reasonable to deal with the ratio between the attractive radius of a conventional lightning rod (R_{at0}) and that of a large-radius multipoint corona system (R_{at}) rather than with the absolute value of the lightning attractive radius. Obviously, both R_{at0} and R_{at} should be determined with allowance for the effect of the corona space charge as was described in Section 2. Computer simulations show that the uncertainty in determining the parameter $K_{at} = R_{at0}/R_{at}$ is much lower than in determining the attractive radius itself. This parameter is convenient for an analysis because the lightning attraction area is proportional to R_{at}^2; hence, the quantity K_{at}^2 is, in fact, the factor by which the number of lightning strikes to an object is reduced when the object is protected by a multipoint corona system instead of a conventional lightning rod. Figure 17 shows the protection efficiency of such a system installed at 50-m height as a function of the system radius. It can be seen that, for a system of radius 4–6 m, the number of strikes by downward lightning discharges can be reduced by one order of magnitude and more.

The results presented in Fig. 18 give an idea of to what extent the effective interaction radius R_{eff} decreases for sky-scraper objects protected by a multipoint corona system. For example, setting a multipoint corona system with a radius of 5 m at the top of the Ostankino TV tower would decrease R_{eff} by a factor of 6.4, which corresponds to a nearly fortyfold decrease in the total number of lightning strikes.

Such a high expected efficiency of a multipoint protection systems deserves further thorough investigation. The main attention should be paid to the experimental study of the conditions for the conversion of a streamerless corona into a streamer one that gives rise to an upward leader propagating from the top of a grounded electrode. The analytical estimates used in this paper have not yet been confirmed even under laboratory conditions.

It should be noted that above multipoint corona systems can in no way be regarded as a panacea that will resolve the problem of the lightning protection of skyscraper objects. Such systems provide only local lightning protection. They reduce the number of lightning strikes onto their own surface and the object components directly covered by it. Beyond the protecting "umbrella," the protecting effect of a corona charge decreases very rapidly. This does not allow one to use it to protect large-area objects. Note that, for extended corona conductors, the effect of a corona space charge has not yet been studied.

4. CONCLUSIONS

(i) The development of an upward leader from the top of a grounded object is determined by the amount and distribution of the space charge injected into the atmosphere by a corona discharge in the thundercloud electric field and the field of a downward lightning leader.

(ii) Theoretical analysis and computer simulations have shown that the corona discharge in the atmospheric electric field is nonstationary. In contrast to a steady corona, its current depends not only on the instantaneous value of the electric field but also on the rate of its time variations. This dependence, as well as the dependence of the corona current on the ion mobility, is strongly affected by the geometry of the discharge gap. The current of a well-developed nonstationary corona depends only weakly on the radius of the corona electrode.

(iii) The critical current of a nonstationary corona above which it cannot occur in a streamerless mode has been estimated. The formation of a streamer flash from a grounded electrode can result in the development of an upward leader if the voltage drop along the streamer branches exceeds a certain threshold value.

(iv) The corona space charge impedes the propagation of the nascent upward leader inside the ion cloud formed by the corona discharge. Consequently, any simulations of the leader propagation from stationary grounded objects without allowance for a corona discharge are invalid.

(v) Golde's hypothesis that the attachment of the leader of downward lightning is affected by an upward leader developing from a grounded object is valid only for moderately high objects that are incapable of exciting upward lightning. Generally, the development of an upward leader from a grounded sky-scraper object only slightly affects the attachment of downward lightning, although it is usually the lightning field that is the reason for the leader origin. The nascent upward leader propagates toward the thundercloud (in the form of a separate upward lightning discharge) rather than toward the leader of downward lightning.

(vi) A numerical model has been developed for estimating the frequency of the lightning strikes to grounded objects of various heights with allowance for the effect of the corona space charge. The estimates obtained agree with the results from observations of skyscraper-type objects.

(vii) Analytic results and computer simulations show that ESE lightning rods are unable to provide the expected manyfold increase in the protecting efficiency. This is because a substantial decrease in the top radius of the lightning rod, as well as an additional increase in the potential of the rod top by a few tens of kilovolts, does not provoke the early onset of a viable upward leader.

(viii) Setting a large-radius multipoint corona system on the object insignificantly increases both the corona current and the space charge formed near the corona top. Nevertheless, the use of such systems can reduce the frequency of lightning strikes by one order of magnitude or more. The reason is that the corona current is nearly uniformly distributed over numerous corona points; as a result, the current of any point does not exceed the critical value corresponding to the origin of a streamer flash followed by the initiation of an upward leader. In contrast to conventional lightning rods, the efficiency of multipoint corona systems does not decrease when placing them on sky-scraper objects.

(ix) Multipoint corona systems provide only local lightning protection. They reduce the number of lightning strikes onto their own surface and the object components directly covered by them. The question of extending the protection area of such systems still remains open.

REFERENCES

1. R. H. Golde, J. Franklin Inst. **286**, 451 (1967).
2. R. H. Golde, *Lightning Protection* (Edward Arnold, London, 1974).
3. R. H. Golde, *Lightning* (Academic, New York, 1977), Vols. 1, 2.
4. A. M. Mousa, IEEE Trans. Power Delivery **13**, 1120 (1998).
5. M. A. Uman and V. A. Rakov, Bull. Am. Meteorol. Soc., No. 12, 1809 (2002).
6. *Proceedings of the IEEE Power Engineering Society General Meeting, Toronto, 2003*, Panel "Nonconventional Lightning Mitigation: Fact or Fiction," IEEE Catalogue No. 03CH37491C (CD-ROM), Library of Congress, 2003106706.
7. Les Renardieres Group, Electra, No. 53, 31 (1977).
8. E. M. Bazelyan and Yu. P. Raizer, *Spark Discharge* (MFTI, Moscow, 1997; CRC, Boca Raton, 1998).
9. N. L. Aleksandrov, E. M. Bazelyan, I. V. Kochetov, and N. A. Dyatko, J. Phys. D **30**, 1616 (1997).
10. N. L. Aleksandrov and E. M. Bazelyan, Plasma Sources Sci. Technol. **8**, 285 (1999).
11. N. L. Aleksandrov, É. M. Bazelyan, and A. M. Konchakov, Fiz. Plazmy **27**, 928 (2001) [Plasma Phys. Rep. **27**, 875 (2001)].
12. É. M. Bazelyan, Élektrichestvo, No. 5, 20 (1987).
13. N. A. Kaptsov, *Electrical Phenomena in Gases and Vacuum* (Gostekhizdat, Moscow, 1950).
14. C. A. Uhlig, in *Proceedings of the High-Voltage Symposium of the National Research Council of Canada, Ottawa, 1956*, p. 15-1.
15. Yu. P. Raizer, *Gas Discharge Physics* (Nauka, Moscow, 1987; Springer-Verlag, Berlin, 1991).
16. L. B. Loeb, *Electrical Coronas* (Univ. California Press, Berkeley, 1965).
17. N. L. Aleksandrov, E. M. Bazelyan, R. B. Carpenter, Jr., *et al*., J. Phys. D **34**, 3256 (2001).
18. N. L. Aleksandrov, É. M. Bazelyan, M. M. Drabkin, *et al.*, Fiz. Plazmy **28**, 1032 (2002) [Plasma Phys. Rep. **28**, 953 (2002)].
19. N. L. Aleksandrov, E. M. Bazelyan, R. B. Carpenter, Jr., *et al.*, in *Proceedings of XXVI International Conference on Physics of Ionized Gases, Greifswald, 2003*, Vol. 4, p. 19.
20. E. M. Bazelyan and Yu. P. Raizer, *Lightning Physics and Lightning Protection* (Nauka, Moscow, 2001; IOP, Bristol, 2000).
21. P. Lalande, A. Bondiou-Clergerie, G. Bacchiega, and I. Gallimberti, C. R. Physique **3**, 1375 (2002).
22. N. L. Aleksandrov, E. M. Bazelyan, and Yu. P. Raizer, in *Proceedings of the 26th International Conference on Lightning Protection, Cracow, 2002*, Vol. 1, p. 279.

23. N. L. Aleksandrov, E. M. Bazelyan, and Yu. P. Raizer, in *Proceedings of the 12th International Conference on Atmospheric Electricity, Versailles, 2003*, Vol. 2, p. 451.
24. V. A. Rakov and M. A. Uman, *Lightning: Physics and Effects* (Cambridge Univ. Press, Cambridge, 2003).
25. É. M. Bazelyan, B. N. Gorin, and V. I. Levitov, *Physical and Engineering Principles of Lightning Protection* (Gidrometeoizdat, Leningrad, 1978).
26. N. L. Aleksandrov, E. M. Bazelyan, F. D'Alessandro, and Yu. P. Raizer, in *Proceedings of the 27th International Conference on Lightning Protection, Avignon, 2004*, Vol. 1, p. 427.
27. N. L. Aleksandrov, E. M. Bazelyan, R. B. Carpenter, Jr., *et al.*, in *Proceedings of the 27th International Conference on Lightning Protection, Avignon, 2004*, Vol. 1, p. 407.
28. D. Mackerras, M. Darveniza, and A. C. Liew, IEEE Proc. Sci. Meas. Technol. **144**, 1 (1997).
29. I. D. Chalmers, J. C. Evans, and W. H. Siew, IEEE Proc. Sci. Meas. Technol. **146**, 57 (1999).
30. N. L. Aleksandrov, E. M. Bazelyan, R. B. Carpenter, Jr., *et al.*, in *Proceedings of IX Symposium on Gaseous Dielectrics, Ellicott City, 2002*, Ed. by L. G. Christophorou and J. K. Olthoff (Plenum, New York, 2002), p. 149.
31. G. Carrara and L. Thione, in *Proceedings of the IEEE Summer Meeting, 1974*, Paper CH 0910-0-PWR.41.
32. G. Carrara and L. Thione, IEEE Trans. Power App. Syst. **95**, 512 (1976).
33. É. M. Bazelyan, Elektrichestvo, No. 7, 22 (1977).
34. B. N. Gorin and A. V. Shkilev, Elektrichestvo, No. 2, 29 (1974).
35. C. B. Moore, G. D. Aulich, and W. Rison, Geophys. Res. Lett. **27**, 1487 (2000).
36. C. B. Moore, W. Rison, J. Mathis, and G. Aulich, J. Appl. Meteorol. **39**, 593 (2000).

Translated by N.N. Ustinovskiĭ