ISSN 1063-780X, Plasma Physics Reports, 2021, Vol. 47, No. 3, pp. 279–288. © Pleiades Publishing, Ltd., 2021.
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PLASMA DIAGNOSTICS

The Problem of Control Actions on the Lightning Discharge

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Received September 30, 2020; revised November 2, 2020; accepted November 3, 2020

Abstract—The specificity of the development of a counter discharge from a grounded electrode in the field of a negative stepped lightning leader has been established. It is shown that high-voltage control pulses are effective only when acting directly on a counter leader. Analytical expressions are derived for estimating the conditions for the start of the counter discharge directly in the streamer form, which bypasses the stage of nonstationary ultra corona, and also for determining the amplitude of the control pulse capable of exciting an upward lightning from an electrode of a given height in the atmosphere free from the ultra corona charge. The parameters of the control voltage pulse for the excitation of a trigger lightning in a real thunderstorm situation are determined by numerical simulation. A sharp decrease in the effectiveness of control actions with the duration of a few microseconds is established. It is experimentally proven that the consequences of the impact of such pulses is a delay in the formation of a counter leader, but not in any way its stimulation. The origin of the decrease in the efficiency of lightning rods of early streamer initiation in comparison with traditional ones of the same height is established.

Keywords: lightning, electric field, counter discharge, control voltage, computer simulation, ultra corona, streamer, leader, active lightning rod

DOI: 10.1134/S1063780X2103003X

1. INTRODUCTION

It is doubtless that an answer to the question about the possibility of controlling a lightning discharge is positive. The basis for this is the long-term experience of artificial reproduction of the so-called trigger lightnings, which, in a thunderstorm, start from the top of a small-sized rocket, which brings a grounded wire to a height of about 200 m [1]. No less convincing is the fact that lightning is generated by large-sized airliners flying in the immediate vicinity of charged clouds [2]. An analysis of the efficiency of control actions on lightning by high-power laser radiation is given in a review [3]. The problem is not in establishing the fact of lightning control but in estimating the level of effective control actions. It has become the subject of increased attention in recent years due to the saturation of the lightning protection market with the so-called active lightning rods, which, according to their developers, provide the high reliability of protection against direct lightning strikes over a large area.

Attention to the artificial change in the conditions for the formation of a long spark discharge was manifested at the beginning of the twentieth century, when the unsuccessful attempts to lower the dielectric strength of air by its radioactive irradiation were made at the M. Curie's laboratory. Nevertheless, this failure did not prevent the mass production of radioactive lightning rods in the middle of the twentieth century with advertising guarantees of extremely high reliability of intercepting downward lightning. Today, nobody remembers them since long, when advertising new designs of active lightning rods. All of them are united by a unique principle of advertising construction. It is based on a description of a really existing physical phenomenon, which is fundamentally capable of changing the conditions for the nucleation or the trajectory of a long spark. At the same time, the required level of the control action, its field and energy characteristics are hushed up. The developers of such systems are not much confused by the results of the analysis of the operation of active lightning rods in real conditions, which demonstrate a sufficiently high probability of lightning breakthrough into their protection zone [4]. The counter-argument here is the fact that the reliability of the operation of any protective device is obviously less than unity, and the specific time of the lightning breakthrough to the protected object cannot be predicted. A skeptical attitude towards the results of the comparative tests of active lightning rods and traditional ones of the same height under the field [5] and laboratory conditions [6] seems natural. Regardless of the effect of an additional voltage pulse in these experiments, which stimulate an earlier start of the counter discharge from the top of the active lightning rod, the predominant interception of the spark channel was observed in the experiments not by it but by a traditional lightning rod devoid of any control actions.

The purposeful criticism of active lightning rods, primarily ESE (early streamer emission) systems, has been going on without much success for at least two decades. As a rule, the basis of critical works is a comparison on the basis of the computer simulation of the conditions for changing the electric field in the atmosphere due to the formation of a downward lightning leader and a counter leader starting from the top of the lightning rod [7–9]. Unfortunately, the results of such works are limited to qualitative conclusions of a particular nature. They cannot give an unambiguous quantitative estimate of the actual efficiency of the considered lightning protection system. As an example, the main conclusion [7] may be cited: "However, this ESE effect does not apply for lightning rods under the electric fields produced by downward lightning leaders. Due to the fact that the rate of increase in the lightning electric fields changes from slow to fast, while the switching electric field rate of change varies from fast to slow, the development of positive leaders from lightning rods under natural conditions and in the laboratory is different." Based on the foregoing, it is hardly possible to explain the unexpected results of experiments [5, 6], moreover, to convince to abandon the production and sale of ESE lightning rods.

The maximum criticism of ESE lightning rods is to equate their protective action with the efficiency of traditional lightning rods [8], which is far from obvious if the already mentioned experimental results [5, 6] are taken into account.

To estimate the possibilities of lightning control in the interests of lightning protection, it seems appropriate to consider quantitatively the consequences of the effect of the control voltage on the conditions of start and subsequent development of a counter discharge from the top of the lightning rod, focusing on estimating the effect of the amplitude of the control pulse and its time parameters in the range characteristic of the formation of a downward lightning.

2. COUNTER DISCHARGE FROM GROUND STRUCTURES

This type of discharge is of the greatest interest from the considered positions, since it is most accessible for control actions, and its development predetermines the point of impact of the downward lightning [10] or the conditions for the start of the upward one [11]. Detailed studies of the counter discharge showed that it begins in a slowly growing electric field of a thunderstorm cloud in the form of a nonstationary streamerless ultra corona, which is characterized by a weak corona current of a microampere level [11]. The corona is formed not only from tall structures. In a thunderstorm, a wide variety of objects with a small radius of the top, e.g., tree branches, shrubs and even grass, form a corona. All together, this creates a space charge cloud above the Earth's surface, which reduces the electric field of the thundercloud below it.

The computer model of a nonstationary streamerless corona, which is developed in [12], uses the experimentally confirmed assumption of the stabilization of the electric field strength on the corona surface [13]. The model makes it possible to estimate the dynamics of filling the near-electrode space near the corona source with a space charge and to trace the screening action of this charge in the electric field of a thundercloud that increases with time, e.g., by the relaxation law

$$E_0(t) = E_{0\,\max}(1 - e^{t/T}) \tag{1}$$

and the field of the charge of the leader of the downward lightning superimposed on it [14].

The transition of the counter discharge to an energetically more powerful streamer form requires an increase in the corona current up to a certain critical value depending on the radius of the corona vertex r_0. In [15], the transition condition was identified with the separation from the corona surface and the displacement of the region with the maximum electric field strength into the gap depth, which was perceived as the creation of an ionization wave. For electrodes of spherical geometry, the critical current according to this condition can be estimated as

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

where $E_{\rm cor}$ is the corona ignition threshold, ε_0 is the dielectric permittivity of vacuum, μ_i is the mobility of the main type of corona ions. For electrodes of the typical radius r_0 = 1–2 cm, a critical current of 5–10 mA in a slowly growing field of a thundercloud is not achievable even for extremely high constructions with a height of ~500 m.

The conditions for the formation of a nonstationary ultra corona are affected to a much larger degree not by the magnitude of the electric field of the atmosphere but by the rate of its growth. At the initial time, the corona current is identically equal to the rate of charge growth at the corona-forming surface of the electrode. For the corona-forming hemisphere

$$i_{\rm cor} = 2\pi\varepsilon_0 r_0^2 \frac{dE}{dt}. \tag{3}$$

Substitution of $i_{\rm cor} = i_{\rm cr}$ into (3) taking into account (2) gives an estimate of the rate of growth of the field that guarantees the start of the counter discharge directly in the streamer form, which bypasses the ultra corona,

$$\frac{dE_0}{dt} = A_{E\,\rm cr} = \frac{4\mu_i}{r_0 K_E} E_{\rm cor}^2, \tag{4}$$

where $K_E = E/E_0$ is the multiplicity of the amplification of the atmospheric field near the electrode tip.

For a rod electrode with a tip radius of ~1 cm, regardless of its height at $K_E = 10^4$, the critical rate of increase of the electric field is close to 10^8 V/(m s). The condition is easily achievable in a modern high-voltage laboratory. To this end, the control voltage pulse of about 40 kV should be applied to the electrode (self-discharge ignition threshold at $r_0 = 1$ cm) with a front of ~4 μs.

Under real conditions, the critical rate of growth of the acting voltage can be also noticeably lower than the estimated one due to the statistical delay time of the discharge at the electrode with a small apex area. For an electron that appears in the high-field zone with a delay Δt with respect to the start of the voltage growth, the situation is perceived as the effect of a rectangular voltage pulse with an amplitude of $U = \Delta t(dU/dt)$.

The existence of a streamer discharge does not mean that a counter leader will form from the electrode. As is known [16], a positive long spark at a slow rate of the voltage growth has a pronounced phase of the stepwise development. The computer analysis performed in [17] gives grounds to believe that the channel formed during the development of steps and clearly recorded in continuous photographic sweeps in the visible optical range is only a trace left by a sufficiently fast streamer, the formation rate of which reaches 10^9 cm/s. The gas temperature of such a channel does not exceed 400–500 K, and the conductivity is not preserved even for 1 μs. A powerful streamer flash with a branch length of about 1 m is required for the start of a leader with a high-temperature conducting channel. The voltage drop across it should be at least 400 kV. At such a voltage, the total current of the streamer branches provides heating of the gas in the volume of their common stem, which stimulates the start of the leader channel there [18].

In a slowly increasing atmospheric field, condition (2) is not satisfied not only at the start of the counter discharge but even during the long-term corona formation, when its current is many times higher than the initial value (3). The transition of the discharge to the streamer form and the subsequent start of the counter leader are possible only due to the rapid amplification of the electric field by the charge of the leader of the downward lightning. In the simplest model with a uniform distribution of the linear charge τ_L along the length of the channel, the rate of growth of the electric field near the Earth's surface is defined as

$$\frac{dE_0}{dt} \approx \frac{\tau_L v_L}{2\pi\varepsilon_0 h^2}. \quad (5)$$

Here, v_L is the average rate of increase of the leader of the downward lightning, which, in the performed estimate, was assumed to grow strictly vertically along the axis of the grounded electrode, and h is the height of its head above the Earth's surface. For fairly typical values of $\tau_L = 0.5$ mC/m and average velocity $v_L = 2 \times 10^5$ m/s the rate of increase of the electric field of the atmosphere at the Earth's surface will exceed

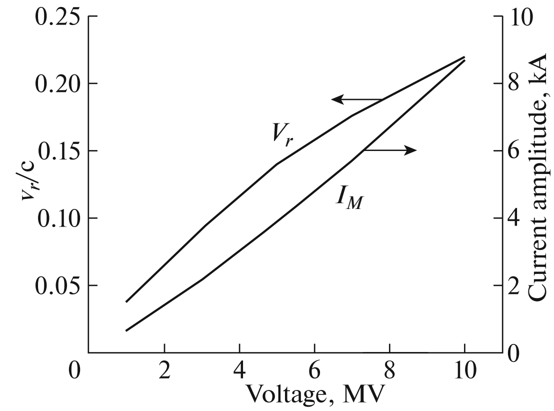

Fig. 1. Estimate of the propagation velocity of the recharge wave in the negative leader stage.

10^8 V/(m s) when the lightning channel drops to 135 m with respect to the Earth's surface.

As a rule, the leader of the negative downward lightning moves stepwise. The step mechanism is determined by the development of a volume leader, which starts from the boundary of the branches of the negative streamer zone and grows mainly towards the negative downward leader [19]. Upon their contact, the volume leader is recharged and acquires the potential of the combined leader channel. Qualitatively, the wave process of recharging is similar to the main stage of the lightning (return stroke). The velocity of the recharge wave depends on the voltage jump, which is implemented in this case. When the lightning strikes the ground, the potential change is up to 100–200 MV, when the wave velocity can reach 1/2–2/3 of the speed of light. As the potential and, accordingly, the current decrease, the wave velocity becomes noticeably lower. This mode should be characteristic for the steps of the negative lightning leader. The calculated data in Fig. 1 give an idea of the possible velocity of the recharge wave of a step, the length of which on average is close to 30 m, and the longest ones reach 100–200 m [20]. Their current and potential are not measurable. Therefore, the computer estimates were carried out with a variation of the recharge voltage within the range of 1–10 MV, which corresponds to the current amplitude during recharge of 0.5–9 kA. All parameters of the calculated computer model exactly corresponded to those presented in [21].

The calculated data showed that even at the minimum voltage and current values, the speed of the wave recharging the stage channel does not fall below 10^7 m/s, which is almost two orders of magnitude higher than the average velocity of the downward negative lightning leader.

The elementary estimate for the step length $\Delta l \gg h$ shows that the rate of increase in the electric field near

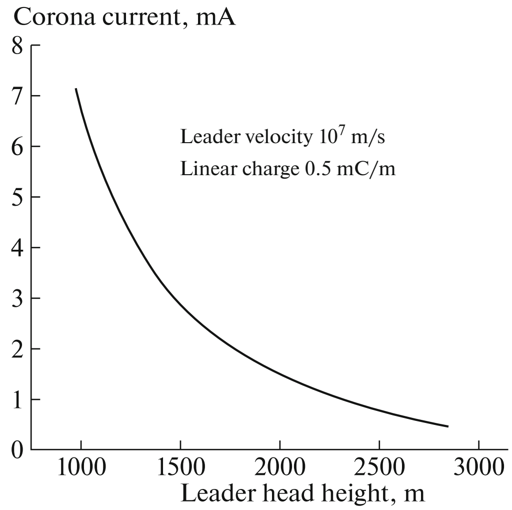

Fig. 2. Growth dynamics of the ultra corona current from the 30-m-high rod electrode during the development of an arrow-shaped leader with the linear charge of 0.5 mC/m at the velocity of 10^7 m/s.

the Earth's surface, which is excited by the formation of a step at a height h, is determined as

$$\frac{dE_0}{dt} = A_E \approx \frac{\tau_L v_r}{2\pi\varepsilon_0 h^2}. \quad (6)$$

It follows that the critical rate of field growth $A_E \sim 10^8$ V/(m s) can be provided by an average lightning with a linear charge of $\tau_L = 0.5$ mC/ m at a step height above the ground level of $h \sim 1000$ m even in the case of a very low speed propagation of the recharge wave of about 10^7 m/s. The appearance of such a step ensures the transition of the counter discharge to the streamer form. However, under such conditions, the streamer flash that has arisen does not lead to the start of the counter leader, since (as noted above) for heating its stem, the required energy input into its volume can be provided only when the voltage drop across the streamer branches exceeds 400 kV [18]. The computer estimates according to the calculation program [12, 14] showed that for this purpose the leader of the downward lightning with a linear charge of 0.5 mC should approach the ground at a distance of no more than 650 m.

It should be noted that the rate on the order of 10^7 m/s is also characteristic for the continuous growth of the arrow-shaped leader of the subsequent lightning components. Therefore, the estimate made here fully applies to the counter discharge excited by them. The calculated data according to the computer program [12, 14] in Fig. 2 demonstrate the dynamics of the growth of the ultra corona current during the development of the arrow-shaped leader, which started at the altitude of 3000 m and moved to the ground vertically with a radial displacement of 90 m relative to the 30-m-high rod electrode with the radius of 1 cm. The linear charge of the arrow-shaped leader in the calculation was left equal to 0.5 mC/m. The corona current reached the critical value when the head of the arrow-shaped leader descended to the altitude of 1100 m, which is not too different from the previously obtained result for the stepped negative leader. As already shown above, a streamer flash under such conditions is not able to initiate the start of a counter leader.

Thus, it is difficult to determine the time of the start of the counter leader unambiguously. It largely depends on such random parameters as the linear charge of the lightning leader, the average rate of its development, the number of steps, the length of each of them and the height of their occurrence. This means that the electric field of the atmosphere in which the oncoming leader has to advance also varies in a random manner.

3. ESTIMATE OF THE EFFECTIVENESS OF CONTROL ACTIONS

Neither the ultra corona with its space charge nor the streamer flash, which retains conductivity only for tenths of a microsecond, can affect the orientation of the leader of the downward lightning. Only a counter leader is capable of this, the length of which for a practically significant effect, at least, should be comparable to the height of the object from which it started. Consequently, the effectiveness of control actions should be estimated by the ability not only to stimulate the start of the counter leader but also to maintain its sustainable development for a sufficiently long time. The results of this section were obtained using a simplified computer model of the leader process from a grounded rod electrode of a specific height and radius [18]. The model uses the results of calculating the nonstationary ultra corona from the top of the electrode in the electric field of the atmosphere, which grows according to a given law for a given time, as the initial data. Based on the results of these calculations, the initial distribution of the electric field in the ultra corona space charge layer above the electrode tip is introduced into the program for calculating the counter leader. The electric field of the thundercloud is assumed unchanged during the calculation of the counter leader. The conditions for the emergence of a counter leader are not considered. It is assumed that its start is a priori provided by a streamer flash of the required power.

At each calculation step, the distribution of the charge over the surface of the metal rod electrode and the already formed channel of the counter leader is determined, as well as the effective potential of its head, which serves as the initial parameter for calculating the length of the streamer zone of the leader, its current, longitudinal electric field strength in the channel, and the rate of increase of the channel. The effective voltage was understood as the potential difference between the leader head itself and the point of its location, where the field is produced by the space charge of the corona and the a priori given electric field of the atmosphere (its source is a thundercloud and the channel of the leader of the downward lightning). The sufficiently long time of the formation of the counter leader made it possible to assume that in most of its channel the state of the plasma does not differ from the state of the quasi-stationary arc, the field of which, according to [22], is taken inversely proportional to the leader current

$$E_L \approx \frac{a_E}{i_L} \text{ V/m}, \quad (7)$$

where $a_E = 3 \times 10^4$ VA/m. In this case, the rate of increase of the counter leader is set by the empirical ratio through the effective voltage on the head of its channel

$$v_L \approx b_v \sqrt{U_{ef}} \text{ ms}, \quad (8)$$

where $b_v = 15$ m/(V$^{1/2}$ s). The leader current was determined by the rate of the charge delivery to the forming channel with a linear capacity C_L

$$i_L = C_L U_{ef} v_L, \quad (9)$$

moreover, the linear capacity of the leader is determined mainly by the charge of its cover with the radius of R_{cov}

$$C_L = \frac{2\pi\varepsilon_0}{\ln(L/R_{cov})}. \quad (10)$$

The value $C_L = 24$ pF/m taken from experiments with a long laboratory spark [23] is used in the cited calculations. It is not fundamentally different from the meaning $C_L = \pi\varepsilon_0$, which is accepted in [21].

The qualitative nature of the computational model should be emphasized. It claims only to reveal general ideas about the control mechanism of the counter leader and therefore can put up with errors in the estimation of specific parameters at the level of tens of percent, primarily due to the uncertainty of the value of the running capacity of the counter leader and the dependence of its rate of growth from the energy input into the channel. Nevertheless, testing the model based on the results of laboratory studies of the leader process in long laboratory air gaps [22] showed the legitimacy of its application within the task.

4. NUMERICAL SIMULATION RESULTS

It is methodologically expedient to initially exclude taking into account the screening effect of the ultra corona space charge and estimate the level of the control voltage, ΔU, at the electrode with respect to the ground, which can support the stable formation of a counter leader in the electric field of the atmosphere free of the space charge. Using (7)–(9) for this purpose, it is possible to write down the elementary equation

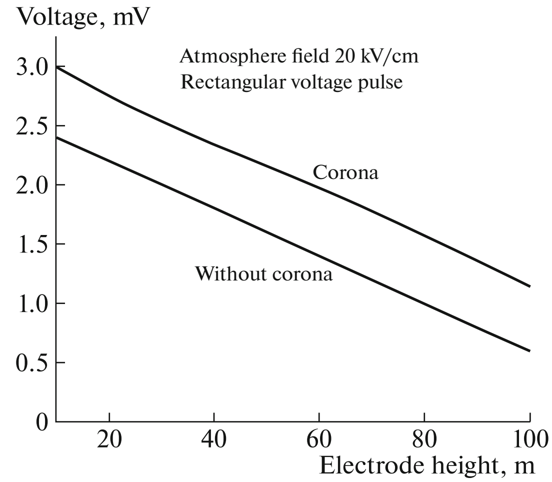

Fig. 3. Calculated amplitude of the control voltage pulse of unlimited duration for the excitation of an upward lightning.

$$\Delta U = \left(\frac{a_E}{b_v C_L E_0}\right)^{2/3} - E_0 h. \quad (11)$$

It demonstrates the fact that the leader continues its development without deceleration until the longitudinal electric field strength in its channel exceeds the field E_0 in the atmosphere. The level of the effective control voltage ΔU is determined by two main parameters, the electric field strength of the atmosphere E_0 and the height of the electrode h. The dependence $\Delta U(h)$ is plotted in Fig. 3 according to the expression (10) for $E_0 = 20$ kV/m. A stronger field of a thundercloud near the Earth's surface is unlikely due to the screening of the Earth's surface by the corona charge from numerous local field enhancement sources. As the height of the object increases from 10 to 100 m, the required control action decreases monotonically but even for an extremely high one, it does not drop below 500 kV (Fig. 3). If we focus on an ordinary height of the construction of about 30 m, the control voltage is about 2 MV. It is important to take into account that this value almost doubles reaching 3.8 MV at a more probable value of the atmospheric field of E_0 = 10 kV/m.

Thus, the control inevitably has to be associated with the use of megavoltage level voltage. It increases even more under real conditions, when it is necessary to take into account the redistribution of the electric field in the vicinity of the top of the considered electrode by the space charge of the ultra corona.

The results presented here characterize a corona formed from the tip of a rod electrode with a radius of 2 cm. It was assumed that the atmospheric field

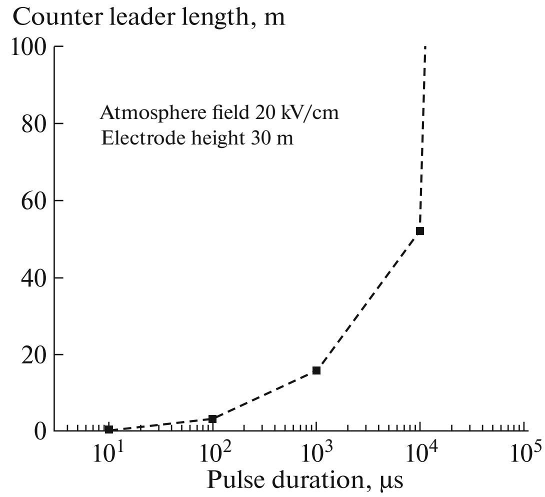

Fig. 4. Dependence of the length of the counter leader formed from the 30-m-high rod electrode under the action of the control voltage pulse with the amplitude of 2.5 MV of different durations.

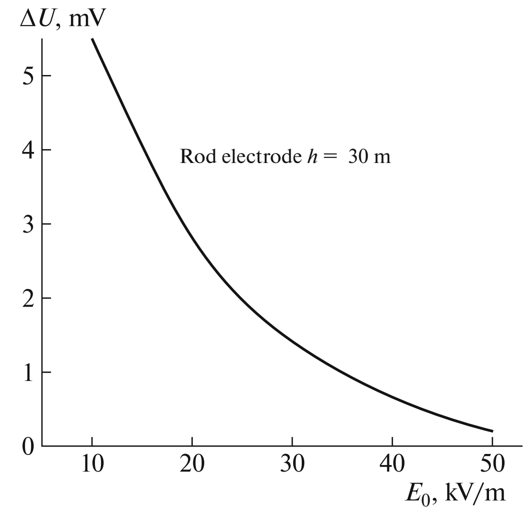

Fig. 5. Calculated amplitude of the effective control action on the counter leader from the 30-m-high rod electrode in different electric fields of the atmosphere.

increased linearly to an amplitude value of 20 kV/m for 10 s. The time on the order of 10 s seems to be the minimum for the relaxation of the charge in a thunderstorm cell after the next start of the lightning from it [25]. During this time, the leading front of the corona space charge moved away from the top by about 40 m regardless of the electrode height. However, the amount of the charge in the corona layer strongly depends on this height, which increases from 6.2×10^{-5} to 1.7×10^{-3} C as it increased from 10 to 100 m. The control voltage pulse in the model calculation had an unlimited duration. The computer calculation results in Fig. 3 show that due to the effect of the corona, the calculated level of the control voltage increased by about another 500 kV regardless of the height of the electrode.

It should be borne in mind when estimating the obtained results that the level of the control voltage, which guarantees the excitation of a steadily forming counter leader, which can produce an upward lightning similar to trigger lightning, is meant. The second important circumstance is the unlimited duration of the voltage pulse. Its efficiency depends strongly on this parameter (Fig. 4). In the case of an electrode with a height of 30 m in an electric field of 20 kV/cm, the control voltage (2.5 MV) found above could ensure the development of an upward leader for a length of only 3 m when the pulse duration is reduced to 100 μs (at the level of 0.5), and the effect of the voltage is negligible (~0.5 m) at the duration of 10 μs. The weakening of the control action at the reduction in the duration of the voltage pulse cannot be compensated for by increasing its amplitude within any reasonable range. For example, the action of a voltage pulse with the amplitude of 5 MV and the duration of 100 μs in the above calculation version made it possible to form a counter leader with a length of only 5.6 m.

From the point of view of applications, the most attention should be paid to the situation when the counter leader is formed the electric field that is significantly stronger than that in which the ultra corona started and developed. Such a calculated computer version reproduces the development of the counter discharge at the significant approach to the considered grounded electrode of the channel of the downward lightning leader, which transports a significant charge in the cover and on its surface. The results of model calculations shown in Fig. 5 demonstrate the dependence of the amplitude of the effective control voltage on the external electric field of the atmosphere for the 30-m-high electrode. It is assumed that the duration of the control pulse is not limited, and the ultra corona existed at the top with a radius of 2 cm for 10 s at the linear increase in the electric field of up to 20 kV/cm. According to the calculated data, it is sufficient to apply a voltage pulse of less than 1 MV to the electrode for the stable formation of the counter leader in the electric field of the atmosphere above 35 kV/m. However, in this case, the control efficiency depends strongly on the duration of the control pulse. The length of the counter leader was 3 m in the electric field of the atmosphere of 40 kV/ m at the voltage pulse of 600 kV, which is sufficient for the unlimited duration for the formation of the upward lightning from the 30-m-high electrode at the pulse duration of 100 μs, and it is only 1.8 m at 10 μs. The consequences of such impacts are hardly significant in practical terms.

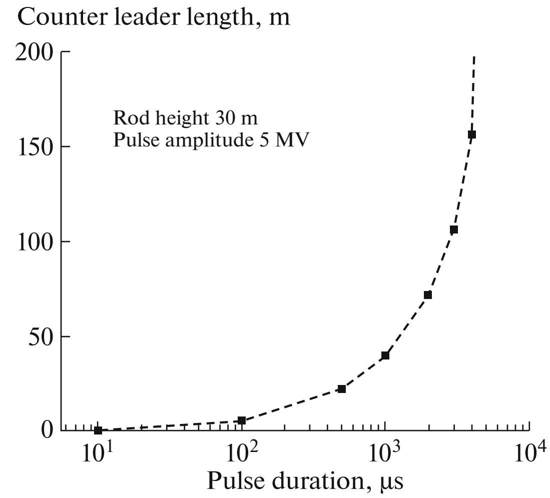

Fig. 6. Dependence of the length of the counter leader formed from the 30-m-high electrode under the action of the control pulse of 5 MV of different durations.

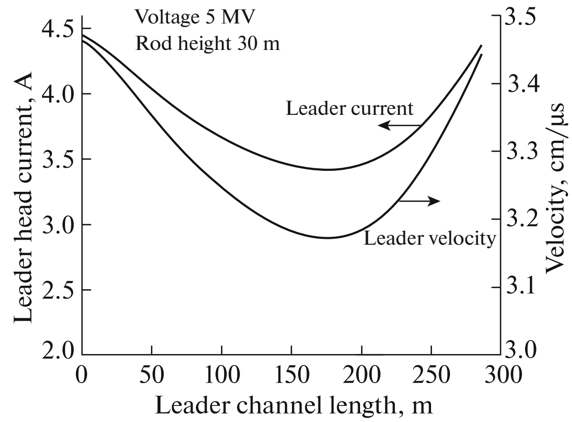

Fig. 7. Dynamics of the change in the rate of increase of the counter leader and the current of its head under the action of the control pulse with the amplitude of 5 MV and the duration of 5 ms. The electric field of the atmosphere is 20 kV/m.

5. PRACTICAL OPPORTUNITIES OF CONTROL ACTIONS

Two fundamentally different ways of using control actions are of interest. On the one hand, it would have been desirable to abandon the work with launching small rockets and generate upward lightning on open high-voltage stands, using pulse ultra-high voltage generators (PVG) with a large capacitance in the shock for the control actions. Another task is associated with the increase in the radius of protection of the lightning rod with the help of an earlier start and active development of a counter leader from it. The technical requirements for the control voltage source are fundamentally different here due to various restrictions on energy intensity, output voltage, and most importantly, on dimensions.

As already noted, the electric field of a thunderstorm cloud near the Earth's surface with vegetation and various constructions can hardly exceed 20 kV/m. It is this electric field of the atmosphere that one has to orient oneself to when estimating the control voltage of ΔU, which, in principle, can excite the upward lightning. Typical heights of the PVG of an open facility are within 30 m. This is the second initial parameter of the estimating computer calculation. The design of most PVGs is oriented towards the repeated operation with the output voltage of 5 MV. This sets the limiting voltage of ΔU. There is no need to worry about the starting conditions for an upward leader. At a control voltage of a megavolt level, they are performed automatically when the starting electrode is placed on the PVG roof.

The computer calculation results in Fig. 6 demonstrate the length of the formed counter leader with different durations of the control pulse, which decreases exponentially. The computer simulations have shown that the duration of the control pulse should be at least 5 ms in order to produce the viable leader creating the upward lightning. The channel head current and the velocity of the upward leader do not decrease as it is formed after leaving the region filled with the ultra corona space charge only at such duration (Fig. 7).

According to the results of computer calculations, the average current of the control voltage source supplying energy to the channel of the upward leader is close to 1 A. The electric charge of about 7.5 mC was supplied to the 285-m-long leader in a time of about 8.75 ms. In this case, the voltage at the output of the control source decreased from 5.0 to 2.15 MV. To ensure such a mode of the operation of the control voltage source, its output capacitance should be at least 2000 pF. The requirement is provided without any problems by a modern PVG, assembled, e.g., according to the Fitch scheme [22], even taking into account the energy consumption for internal losses during the formation of such a long voltage pulse.

Thus, the excitation of the trigger lightning by means of high-voltage control actions seems to be possible in principle. Nevertheless, it should be noted that the technical possibilities of artificially exciting trigger lightning are greatly complicated when trying to work with a weaker electric field of the atmosphere. For example, it is impossible to use a source with the output voltage of 5 MV with the shock capacitance of less than 50–60 nF at the electric field strength of E_0 = 10 kV/m.

The task of this article does not include the analysis of possible technical solutions to reduce the permissible level of the electric field of the atmosphere with this initiation or to reduce the amplitude and duration of the control voltage. It suffices to note that this is possible due to the suppression of the ultra corona in the vicinity of the PVG and the rapid extension of the electrode up to 100 m high from its screen on the roof.

The extremely low prospects for increasing the efficiency of lightning rods due to the control voltage follows from the analysis already performed. It is generally accepted [24] that the radius of lightning contraction is proportional to the height of the rod lightning rod ($R_{at} = 3h_M$). The height of the lightning rod should be approximately doubled at the expense of the upward leader in order to increase the radius at least two times. It follows from the calculated data in Fig. 6 that to this end, the control voltage pulse with the amplitude of 5 MV and the duration of about 500 μs is required in the electric field of the atmosphere – absolutely unrealistic parameters for an ordinary lightning rod. The situation will not become noticeably more favorable in practical terms even if the synchronization system is provided and the control pulse is applied already with the significant increase in the electric field of the atmosphere by the charge of an approaching downward lightning. For example, according to the numerical simulation results in the atmospheric field of 40 kV/m, a pulse of the unlimited duration at the voltage of 600 kV, which can provide the development of the upward lightning from the 30-m-high electrode, produces the 3.2- and 1.8-m-long leader with the duration of 100 and 10 μs, respectively. This small increase in the effective height of the electrode cannot be of practical importance. In addition, the counter leader can grow to the length of 1.8 m from the grounded electrode and without control action in the atmospheric field of 40 kV/m under the considered conditions.

Particular interest in the amplitude and duration of the control action arises in connection with the estimate of the effectiveness of lightning rods with early streamer emission (ESE lightning rods) of various designs, which are especially actively advertised in the global and domestic markets for lightning protection means. It is claimed that the design is ahead of the start of the streamer flash from the lightning rod in comparison with the protected object due to the high-voltage pulse generated by the internal source at the top of the lightning rod. It gets the energy from the electric field of the atmosphere due to the current of the ultra corona, which is formed from the tips of the "active" nozzle. The volume of the nozzle, where the control voltage source is located, usually does not exceed a few liters. In the case of this volume, the source, which is assembled according to the classical Marx scheme, cannot provide the pulse duration of more than 1–3 μs at the amplitude close to 200 kV, which is declared in advertising brochures.

To analyze the results of such a short-term effect of voltage on the formation of the pulsed discharge, the numerical simulation results using the used computer models are not enough, since they disregard the effect of the space charge of the streamer flash itself, which

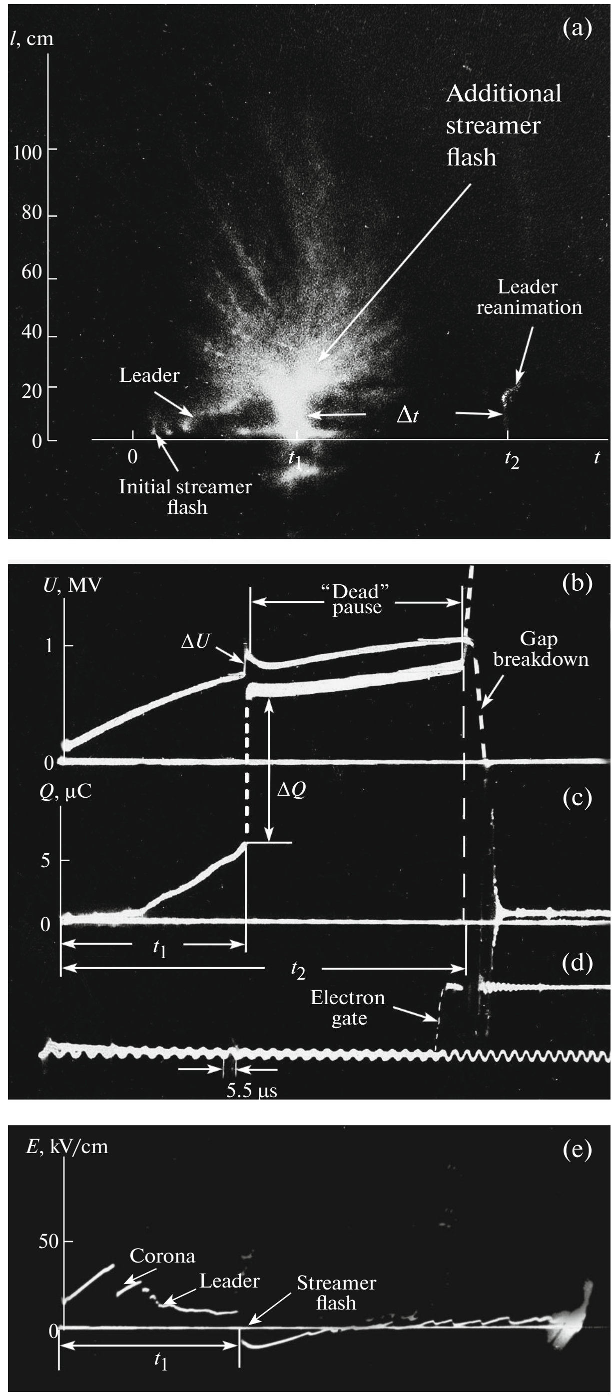

Fig. 8. Effect of the short-term control voltage pulse on the development of the counter discharge under conditions that simulate the electric field of the atmosphere in a thunderstorm. (a) Continuous photo-scan of the discharge; (b) time dependence of the voltage across the gap; (c) time dependence of the embedded space charge; (d) time calibration marks and an electronic shutter control pulse; and (e) electric field strength at the top of the electrode.

precedes the start of the counter leader. The dual nature of this effect should be borne in mind. First, it was already noted that the streamer flash current heats up its stem, where, at a certain energy input, the onset of the counter leader channel is possible. Second, the charge of the streamer branches reduces sharply the electric field in the near-electrode region, delaying the advancement of the emerging leader channel for the time required to recover the field due to the additional voltage increase and as a result of the space charge drift into the depth of the discharge gap. The screening effect is very significant. According to the experimental data [22], the change in the streamer flash charge from 0.4 to 1.4 μC led to the increase in the start voltage of a viable leader from the rod electrode with the radius of 1.5 cm from 400 to 800 kV.

The experiment, the results of which are shown in Fig. 8, makes it possible to estimate the specific result of the short-term voltage exposure under conditions similar to the operating conditions of ESE lightning rods. The 3-m-high rod electrode with the hemispherical apex 1.5 cm in radius was mounted on the grounded surface and contacted it through a resistor, on which the positive voltage pulse with the duration of 3 μs with a steep front was formed. The pulse amplitude reached 300 kV. The negative voltage with the amplitude of up to 1.2 MV with the rise time of ~200 μs on a plane raised to the height of 6 m above the ground level simulated the electric field of the atmosphere in the discharge gap caused by the charge of the downward lightning leader. The optical picture of the discharge was recorded by an electronic-optical converter with a multi-alkaline cathode with continuous scanning of the image together with oscillograms of the voltage across the gap, the introduced space charge, and the electric field strength at the top of the rod. The time of the supply of the short-term control pulse could be varied within wide limits. It can be seen that a powerful streamer flash with the charge of about 10 μC was excited under its impact. This streamer flash screened the electric field at the top of the rod electrode, reduced it down to zero and further until the polarity was reversed. Thereby the formation of a counter discharge was completely interrupted in about 80 μs. As a result, the dielectric strength of the tested air gap not only did not decrease due to the additional effect of the voltage, but, on the contrary, increased by 20–25%. Taking this fact into account, the results of testing ESE lightning rods in field and laboratory conditions [5, 6] become understandable, which showed their significantly lower efficiency compared to that of conventional rod ones of the same height, which is more than a convincing reason for refusing to use them in lightning protection practice.

6. CONCLUSIONS

(i) The analysis of the mechanisms of the development of the counter discharge from ground constructions in a thunderstorm situation showed that the control action of the high voltage should be aimed at changing the start time and ensuring the stability of the development of the counter leader. The change in the conditions for the occurrence of a streamer flash alone is not effective.

(ii) An analytical expression is obtained for estimating the control action on the counter leader in the atmosphere free of the space charge of the ultra corona. In a typical thunderstorm field of 20 kV/m, the required amplitude of the control pulse of unlimited duration that excites the trigger lightning decreases from 2.4 to 0.6 MV at the increase in the height of the grounded rod electrode within 10–100 m.

(iii) Under conditions similar to those presented in Section 2, taking into account the space charge of the ultra corona according to the results of computer simulation increases the amplitude of the effective control pulse by another 0.5 MV, regardless of the electrode height.

(iv) Modern open-circuit PVG with the output voltage of 5 MV or more are suitable for initiating upward trigger lightning in a thunderstorm environment.

(v) A sharp decrease in the effectiveness of control actions on the counter leader at the reduction in the voltage pulse duration excludes their use in practical lightning protection to expand the radius of protection of lightning rods.

(vi) The use of an internal voltage source in an ESE lightning rod, which generates voltage pulses with the duration of a few microseconds, leads to the decrease in the protection radius, and not to its expansion, as stated by their manufacturers. For this reason, the use of ESE lightning rods in the practice of lightning protection cannot be considered acceptable.

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Translated by L. Mosina