INITIATION AND DEVELOPMENT OF LIGHTNING DISCHARGE: PHYSICAL MECHANISM AND BASIC PROBLEMS

N.L. Aleksandrov¹, E.M. Bazelyan² and Yu.P. Raizer³

¹Moscow Institute of Physics & Technology, Dolgoprudny, Moscow region, Russia
²Krzhižanovskyy Power Engineering Institute, Moscow, Russia
³Institute for Problems in Mechanics, Russian Academy of Science, Moscow, Russia

ABSTRACT: This paper considers three interconnected problems: (i) initiation of a downward lightning in a thundercloud and that of an upward lightning near tall grounded structures; (ii) conditions for lightning development in the cloud-to-ground gap and the effects of lightning trajectory and branching on discharge parameters; and (iii) physical mechanism of the lightning return stroke and peculiarities of the propagation of current and voltage waves along the plasma channel with non-linear parameters. The focus is on the estimation of lightning discharge parameters required to solve applied problems including the simulation of lightning electromagnetic fields and frequency of lightning strokes to grounded and flying objects. Key problems of lightning physics which hinder the progress in practical lightning protection are posed.

INTRODUCTION

Lightning is a spark discharge with extreme parameters. Many details of its physical mechanism have never been quantified or, sometimes, even understood. A knowledge of lightning mechanism is required to predict lightning hazards, to calculate stroke frequency for protected structures, and to develop reliable systems of lightning protection. Lightning theory has not kept pace with demands of practical lightning protection. Conventional protection systems fail to provide a high reliability level necessary for high-rise buildings, large-dimension aircrafts, microelectronics devices and inflammable and explosive stores. This leads to a desire to use ‘non-conventional’ methods to act upon lightning. Unfortunately, an insufficient development of the theory clears the way to doubtful engineering proposals.

This paper makes an attempt to generalize available understanding (i) about lightning initiation, (ii) its development in a thundercloud electric field and (iii) impulse current forming after bridging the cloud-to-ground gap.

LIGHTNING INITIATION

Our consideration is based on observations of a long spark under laboratory conditions. We use a semiempirical model proposed by Bazelyan and Raizer [1997, 2000] which can give the conditions for the leader formation and its steady development in the gap of a given length. Under normal conditions, a leader is initiated in a long air gap only once the voltage drop across the length \( \Delta r \approx 1 \text{ m} \) near the electrode exceeds the critical voltage \( \Delta U_{cr} \approx 400 \text{ kV} \). Then, the energy deposited into the leader channel is sufficient to heat and maintain plasma in it. The leader current \( i_L \) and its velocity \( v_L \) are governed by the difference \( \Delta U(x) = U_{tip}(x) - U_0(x) \) between the leader tip potential \( U_{tip}(x) \) and the potential \( U_0(x) \) of an undisturbed external electric field at the tip point \( x \):

\[
\begin{align*}
  v_L &= a \sqrt{\Delta U} & a &= 15 \text{ m s}^{-1} \text{V}^{-1/2} \\
  i_L &= \tau_L v_L = C_1 \Delta U v_L & C_1 &= \frac{2\pi e_0}{\ln(L/R_{cov})} (1)
\end{align*}
\]

where \( C_1 \) is the capacitance per unit length of the leader, \( L \) is its length and \( R_{cov} \) is the effective radius of the space charge cover around the leader channel. Similar to an arc discharge, the channel has a falling voltage-current characteristic

\[
E_L = \frac{b}{i_L} \quad b = 3 \times 10^4 \text{ V m}^{-1} \text{A}^{-1} (2)
\]

In the atmosphere free of space charge, the condition for the initiation of a viable leader from the top of a vertical grounded conductor of the height \( h \) in the external electric field \( E_0 \) is written as [Bazelyan and Raizer, 2000]

\[
h \geq h_{\text{min}} \approx \frac{A}{E_0^{5/3}} \quad A \approx 1.9 \times 10^9 \text{ V}^{5/3} \text{m}^{-2/3} (3)
\]

For instance, this inequality is fulfilled for an ascending rocket with grounded wire (triggered lightning). It follows from (1) (see lower curve in figure 1) that a rocket gaining an altitude of \( \approx 200 \text{ m} \) has a high chance of initiating upward lightning in an external electric field of \( \approx 10 - 20 \text{ kV m}^{-1} \).
At the same time such an event rarely occurs near a fixed structure of a similar height. The reason is that the corona generates the space charge layer tens or hundreds metres in length around the top of a structure but has no time to develop a layer in front of the rocket ascending with a speed of ~100 m s⁻¹. It was theoretically shown by Aleksandrov et al. [2001] that the properties of a non-stationary corona under considered conditions differ greatly from those of a well-studied stationary corona. At present it is possible to numerically simulate the expansion of the space charge layer and the effect of coronae on the initiation and development of an upward leader. Figure 1 shows that this effect can double the critical height \( h_{\text{min}} \) for a given value of \( E_0 \).

The hindering effect of corona space charge is of fundamental importance. Analytical analysis and computer simulation show that a high density of space charge is maintained in a layer several metres in depth near the tip of a grounded structure. It is most important for leader survival to escape from this region. Figure 2 shows that an ‘instantaneous’ elongation of a grounded conductor through the space charge layer leads to the development of a viable upward lightning. A rod can be ‘elongated’ by mounting a metal conductor, applying a high voltage impulse, or producing a laser spark or jet of thermal plasma. However, the action must be fast in order to prevent the compensation of the local enhancement of electric field by injected space charge. The required ‘elongation’ velocity is only ~20 m s⁻¹; therefore, in practice, to govern upward lightning is not an unsolvable problem.

Condition similar to (3) can also describe the lightning initiation from a flying conductive object (for instance, aircraft).

![Figure 1. The conductor height required for initiating a viable leader versus the external electric field](image)

Here, induced charges enhance the local electric field near two tips of the conductor; therefore, an object produces a bidirectional leader with positive and negative parts that move in opposite directions from its origin. Consequently, when considering condition (3) for an ungrounded object, one should keep in mind that \( h \) and \( h_{\text{min}} \) refer to a half length of the object. Then, it follows from (3) that a conductor ~ 1 m in length is sufficient to initiate lightning in an electric field of \( E_0 \sim 500 \text{ kV m}^{-1} \) near a thundercloud. Such a field is produced on the boundaries of a spherical charged region (thundercloud cell) of radius 500 m with the charge \( Q \sim 15 \text{ C} \). It is a maximum electric field in the case of a uniform distribution of charge. Therefore, it is reasonable to assume that, in a thundercloud, there is a way (for instance, due to a short-lived air vortex) (i) to locally enhance the density of space charge and, hence, local electric field up to the ionization threshold or (ii) to create a conductive object around 1 m in length. The latter can be caused by cosmic radiation. It follows from the balance of charges in a closed-loop system that a downward leader can develop only simultaneously with the development of an upward leader of opposite sign. It was Kasemir [1960] who first drew attention to this point.

**DEVELOPMENT OF LIGHTNING LEADER**

It is a common misunderstanding to believe that the difference in potential between the tip of a downward leader at ground level and a thundercloud is the voltage drop along the leader channel. It follows from (2) that the voltage drop along the channel does not exceed several megavolts for a downward leader current of 10 – 100 A. Therefore, the potential of the leader origin must be close to that of the leader tip at ground. However, a thundercloud cannot be considered as a metal electrode maintained at a constant potential of a high-voltage source. The cloud charge is scattered throughout the dielectric gas on small hydrometeors. In addition, lightning can start from a point with very high electric field near the cloud base rather than from the cloud interior. Then, at the instant a leader starts, the potential of its origin is close to the potential of the outer boundary of the charge region, \( U_{\text{cl}} = Q_{\text{cl}}(4\pi\varepsilon_0\varepsilon) \frac{1}{R_{\text{cl}}} \); however, later the potential of the origin will decrease. At any instant its magnitude will be equal to some potential averaged over the bidirectional channel elongated due to the development of a downward leader and upward one.

Inducing charges in a plasma channel in a non-uniform external electric field can be numerically simulated. In order to distinguish the effect of induced charges, figure 3 shows the evolution of the potential of a zero-resistance channel of a downward leader during its development to the earth. It was assumed that downward and upward leaders propagate strictly vertically from the base of a negatively charged.
region and show no branching. The initial value of the potential at the origin was assumed to be about 220 kV. Just before the downward leader reached the zero-potential ground, the upward leader tip covered only 760 m and came to a halt in the point in which the potential $U_0$ of a cloud dipole was around 100 MV. At that instant, the potential of the whole channel declined down to the same magnitude; that is, only 45% of the potential applied to the gap in the beginning was carried to the ground. It is important to emphasize that this is not associated with the voltage drop along the channel because the calculation assumed a zero channel resistance.

The fraction of the potential carried to the ground becomes several times lower when the leader trajectory is not vertical and has numerous branches, a typical situation for natural lightning. Estimates show that, at ground level, the potential of a lightning with numerous zigzags and branches can be as low as 10% of the potential of a thundercloud. It seems plausible that ultrahigh lightning currents are caused by the uncommon development of a vertical leader with no branching rather than by the lightning development from clouds with ultrahigh charge.

An upward leader came to a halt in a zero-potential point. Figure 4 shows that the leader velocity increased up to the centre of the lower negative charge of the cloud dipole and then decreased drastically.

Based on the electric field distribution, all points on the outer boundaries of positive and negative charge regions of a cloud dipole is expected to have the same probability of initiating lightning. However, the further discharge development is quite different. As an illustration we simulated lightning development from the top of the positive charge region. In this case the positive channel reaches the stratosphere, whereas the negative channel has no chance to attain the ground. Figure 5 shows the charge distribution along the bidirectional leader channel at $t = 50$ ms. At this instant the upward leader moved at an altitude of 14 km, whereas the negative channel has no chance to attain the ground. Figure 5 shows the charge distribution along the bidirectional leader channel at $t = 50$ ms. At this instant the upward leader moved at an altitude of 14 km, whereas the downward leader stopped its propagation covering only 1.5 km from the origin. It is very difficult to simulate the final phase of the downward leader development when the initiation of a new upward leader from the ground must be taken into account. According to widely accepted views, the development of an upward leader capable of intersecting a downward one determines the point of lightning stroke. An active action on lightning is generally associated with the initiation and development of an upward leader. We performed a numerical simulation of a corona discharge near a conventional lightning rod in the electric field on an approaching downward leaders. The simulation showed that the local electric field near the rod tip is enhanced by an approaching downward leader, in spite of the injection into the gap of an additional corona space charge. The rise of an electric field is so fast (rise time is ~ 1 ms) that the corona has no time to inject the space charge sufficient to prevent the local electric field enhancement. The current through the grounded rod rises up to 1 – 10 A and the initiation of an upward leader is inevitable. Nevertheless, the effect of coronae can be more important if the current is distributed over numerous (>10^3) coronating points. Then, the current through one point, being lower that 1 mA, will be insufficient to energize not only an upward leader but a streamer flash as well.

RETURN STROKE

The mechanism of the return stroke is well known. It is associated with discharging the downward leader channel which must change its potential from $U_{\text{tip}}$ to zero. This process can be modeled by the propagation of
a wave along a long line with L-R-C parameters that may vary with height and time, the evolution of linear resistance of the channel being most important. The wave of current leads to an increase in the gas temperature in the channel from 6000-7000 K (typical temperatures in the leader channel in long air gaps) to >30000 K and, consequently, to a drastic reduction of the linear channel resistance. There exists an effect of sharpening the wave front for powerful lightning discharges. The higher is the lightning current, the faster is the channel heating and, hence, the lower is the wave attenuation. As a result, powerful waves propagate faster and with lower attenuation (see figure 6). This is important for calculating electric and magnetic fields of lightning and for developing remote methods to measure lightning current.

PRESSING PROBLEMS

There are two problems regarding the return stroke. The case in hand is the boundary conditions at the point of contact of a downward leader and ground and near the upper tip of the channel in a thundercloud. The first condition affects the wavefront of lightning current, whereas the latter condition controls the shape and duration of the wavetail. A downward lightning makes a connection with the ground through the contact between its streamer zone and the streamer zone of an upward leader. To quantitatively describe an avalanche-like growth of lightning current, we need a reliable model of charge transport during the final jump of such a spark discharge. The second boundary condition affects the duration of the current impulse. Here, any assumption about an open-ended line leads to a sharp wavetail because of a reflected wave, in disagreement with available observations. Therefore, it is necessary to analyze models considering the effect of branching of the upper channel end which could lead to the attenuation of a reflected wave.

Mechanism of extremely long current impulses of positive lightning discharges is also poorly understood. Such discharges cannot be associated with wave processes. A hypothesis was proposed by Bazelyan and Raizer [2000] that the extremely long impulses are caused by a direct charge neutralization in positive charge regions in clouds. However, the hypothesis has had no numerical or experimental confirmation. The same can be said about the hypothesis considering the dart leader in multi-stroke flashes as a very long streamer propagating along the heated remains of the primary channel of the previous stroke. The streamer plasma is known to be cold and hence short-lived. A common streamer cannot be sufficiently heated during its development because of the radial ionizing wave spreading the deposited energy over a large volume. The heating of a streamer propagating along a pre-heated channel is much more efficient since the radial ionizing wave becomes slower in the ambient undisturbed air. The problem considered is of applied importance as it is associated with the fastest ionization process with an extremely sharp current impulse.

Finally, it is necessary to consider the initiation of an upward leader from a tall structure under the action of an approaching downward leader for various structure shapes and dimensions. This point is important for the development of efficient lightning rods. Obviously, it is possible to act on the initiation of an upward leader because it starts in a relatively low electric field. However, possible consequences and prospects for practical lightning protection are unclear. To answer these questions, a detailed study of a corona discharge in the electric field of an approaching downward leader is required.

REFERENCES


