Return Stroke Initiated by the Contact between a Downward Negative Leader from the Aerosol Cloud and Upward Positive Leader from the Grounded Plane

M. G. Andreev[1], M. U. Bulatov[1, 4], A. Yu. Kostinskiy[2, 4], L. M. Makal'sky[3],
D. I. Sukharevsky[3], V. S. Syssoev[1, 4,*]

1. High-Voltage Research Center of the All-Russia Institute of Electrical Engineering, Istra, Moscow region, Russia
2. National Research University Higher School of Economics, Moscow, Russia
3. Power Engineering University of Moscow, Russia
4. Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia

ABSTRACT: For the first time a junction of two leaders one of which is formed in an aerosol cloud was recorded in a direct experiment, and it was shown that the parameters of the front of the current and its duration are very similar to those corresponding to the return stroke in resultant long spark discharges. The junction occurred between a downward negative leader from a cloud of negatively charged water aerosol and an upward positive leader from a grounded plane. Additional information about the characteristics of this process was obtained by means of high speed video and infrared cameras.

INTRODUCTION

The hypothesis that the physical nature of the discharge initiated by a cloud of negatively charged aerosol is similar to that of the return stroke in lightning and long spark discharges was first suggested by Antsupov et al. [1990]. The characteristics of the front of the discharge current growth and its duration turned out to be similar to those of the return stroke in lightning and long spark discharges, provided that the difference in characteristic scales is taken into account. Henceforth in this paper the term "return stroke" means a return stroke in a cloud of charged aerosol. It was concluded [Antsupov et al., 1990] that the return stroke appears as a result of the contact junction between a downward negative leader from an artificial cloud of negatively charged water aerosol and an upward positive leader from a metal ball situated on a grounded plane. The integral photograph of the process is shown in Fig. 1, where one can clearly see a tortuous channel of the upward positive leader moving to the cloud. The downward negative leader moves in the opposite direction at an angle to the trajectory of the upward positive leader. At the point where the distance between the channels of the two leaders is close enough, their streamer zones begin to interact strongly. The corresponding phase in lightning and long spark discharges is referred to as the final jump, and for the geometry of the leaders' trajectories seen in Fig.1 this phase ends with an

* Contact information: V. S. Syssoev, High-Voltage Research Center of the All-Russia Institute of Electrical Engineering, Istra, Moscow Region, Russia, Email: syssoev467@mail.ru.

almost perpendicular bridge between the two leaders (plasma bridge). In the image-converter camera record shown in Fig. 2 (adapted from Antsupov et al. [1990]) one can see an upward positive leader developing from the plane during a time interval of 30 μs. During this time interval the leader passes a distance of about 65 cm. At this point a sharp increase is seen in the brightness of the channels of the negative and positive leaders and the corona region connecting them, which indicates the beginning of the final jump of the discharge. About 1 μs later during the return stroke phase the channel becomes uniform. In Fig. 2 one can discern the final jump and the return stroke phase, but the downward negative leader cannot be seen, and at the beginning of the return stroke phase the distance between the two leaders is small. In Fig. 3 the time scan but not published in Antsupov et al. [1990] is shown, in which one can clearly see the head of the upward positive leader and what is presumably the head of the downward negative leader; the final jump and the bright channel of the return stroke are also clearly seen. However, the manner of the motion of the negative leader of a long spark discharge is much more complicated than that recorded in [Gorin and Shkilev, 1976], and this phenomenon itself needs to be explained. It appears that by 1990 there were reasons to believe that the junction of the two leaders one of which is formed in an aerosol cloud was documented.

Later (in 2007), using a similar cloud of negatively charged aerosol, the events similar to the meeting of the two leaders described above were recorded by means of single-frame shooting with a high-speed camera [Temnikov et al., 2007]. But in this case low resolution of the frames and very small distance between the two plasma formations did not make it possible to prove the existence of such a phenomenon. Time resolved images [Antsupov et al., 1990] and single-frame photos [Temnikov et al., 2007] did not yield clear records of the structure similar to that shown in Fig. 1, in which a discernible bridge between the two leaders occurs.

This work is aimed at obtaining direct evidence of a contact between the two leaders, in which the parameters of the front of the current and its duration are similar to those of the return stroke in lightning and long spark discharges. Besides, additional information about the characteristics of such discharges was expected to be obtained using the high-speed video and infrared cameras with much higher resolution than those used in earlier experiments [Antsupov et al., 1990; Temnikov et al., 2007].

DESCRIPTION OF THE EXPERIMENTAL SETUP

The experimental setup for generating a charged aerosol cloud of negative polarity used in this work (see Fig. 4) is similar to the one described by Vereshchagin et al. [1998] and Antsupov et al. [1990]. The outlet nozzle (2.3) of the charged aerosol generator was located at the centre of a flat metal screen of 2 m in diameter with rounded edges (3). The charged aerosol generator consisted of the steam generator (2.1) and the charger (2.2). A steam-air jet from the steam pipe at a temperature of about 100-120 °C under a pressure of 0.2-0.6 MPa flew out from the nozzle (2.3) with an aperture angle of 28° at a velocity close to the speed of sound in the mixture (about 400-450 m/s), forming an adiabatically extending submerged jet. This produced a cloud of charged aerosol (1). As a result of rapid cooling, the steam condensed into droplets of about 0.5-1 μm. The ions charging the aerosol were formed in the corona discharge, between a thin pointed needle located in the nozzle (2.3) and the nozzle itself. A constant voltage of 10-20 kV with negative polarity was applied to the needle from the high-voltage source (2.2). The current of charge removal by the submerged jet was in the range of 60-150 μA. Long spark discharges occured spontaneously as a total charge of up to about 60 μC was accumulated in the aerosol cloud.

To measure the current, we used a shunt with 1 Ω resistance, the signal from which was fed to Tektronix DPO (13), a digital oscilloscope with 500 MHz band width. The shunt was connected to the receiving electrode in the form of a metal ball 5 cm in diameter (4), the uppermost point of which was 12 cm above the flat screen. The ball was 0.8-0.9 m away from the screen centre. As the current in the shunt exceeded a given value, an oscilloscope was triggered, which, in turn, generated a trigger pulse to FASTCAM SA4 (9), a high-speed camera in the visible range, and FLIR 7700M (10), an infrared camera. Colour camera FASTCAM SA4 was operated during the measurements in the loop recording mode at a rate of 50,000-500,000 frames per second (fps) and was stopped at the frame during which a synchronization pulse from the oscilloscope was received. To control the dynamics of the total charge of the aerosol cloud, we used an insulated copper ball 50 cm in diameter (6), connected through a 100 MΩ resistor to the oscilloscope (13). This allowed us to record the dynamics of the charge accumulation in the cloud and the fast processes of the charge removal from the cloud. The ball was at a distance of 6 m from the aerosol cloud. The dynamics of the discharge luminosity was recorded by a photomultiplier tube (11) in a visible range, and the overall picture of the discharge was recorded with Canon (12), a colour digital camera. The electric field at the surface of the grounded plane was measured by a fluxmeter (5).

RESULTS OF THE EXPERIMENTS

During the experiments the aerosol cloud was charged up to about 50-80 μC, when long spark discharges occurred spontaneously. As measured by the fluxmeter, the electric field generated by an aerosol cloud at the surface of the grounded screen at a distance of about 0.8 m from the jet axis was 4-5 kV/cm and slightly increased in the direction of the cloud. Positive streamer flashes and spark discharges occurred spontaneously from the surface of the ball.

In Fig. 5, the moment of the meeting of the two leaders is shown, as recorded by the high-speed camera FASTCAM SA4. The frame rate was 50,000 fps and the frame resolution at this rate was 320×192 pixels. In the first frame in Fig. 5 we see the upper part of the tortuous upward positive leader, and in the second frame we see how the downward negative leader interacts with the positive leader which has become a little longer. The leaders move in different planes, and one can clearly see the place of their meeting, the bridge perpendicular to both channels and similar to those recorded in static photographs (Fig. 2). At the moment of the contact the brightness of the channels increases sharply. In Fig.6 the oscillogram of the current corresponding to the event recorded in Fig. 5 is shown, which is similar to the oscillograms obtained before [Antsupov et al., 1990; Temnikov et al., 2007]. The current shown by the curve (1) flows through the ball and the shunt. According to the oscillogram, the process begins with a streamer corona flash with the duration of 50-100 ns and the current of about 5 A, after which the positive leader starts from the ball and during 25 μs moves upwards towards the aerosol cloud, the leader current falling down to 0.2 A. After a small the current steadily grows with an increasing rate until an abrupt jump to a maximum 18 A. The characteristics of this jump in the current are very similar to those of the return stroke in a long spark discharge in an electrode system, since the pulse front lies in the range 100-150 ns and the pulse width at half-peak is about 400 ns; the total duration of the pulse is 1.5-1.7 μs. In the current oscillogram, the first frame in Fig. 5 corresponds to the stage of the leader propagation (and low current), whereas the second frame corresponds to the abrupt jump in the current, the characteristics of which are similar to those of the return stroke of a long spark discharge. Curve (2) in Fig. 6 represents the charge removal from the negatively charged cloud during the propagation of the positive leader. At the moment of the return stroke a sharp increase in the charge removal occurs.

In Fig. 7, another discharge with a return stroke is shown, as recorded by a fast infrared camera. We were unable to record this event satisfactorily with the visible range camera (the image was blurred), because the entire channel was inside the cloud. The oscillograms corresponding to this event shown in Fig. 7 are similar to those shown in Fig. 6. The infrared image allows us to discern even more clearly the tortuous ascending channel of the positive leader, the less tortuous and slightly more wide descending channel of the negative leader, and the nearly straight bridge between them (as opposed to the perpendicular one in Fig. 6). The bridge is not merely an extension of the channel of the positive leader, which follows from the analysis of the radiation intensity (Fig. 7, right panel) of different parts of the structure looking like a single plasma channel (Fig. 7, left panel). The intensities of the infrared radiation from the positive (1) and negative (3) leaders are close to each other, and the intensity of the infrared radiation from the bridge (2) between the leaders is about five times greater than that of the leaders. Apart from this, the bridge is significantly wider than either of the leaders' channels.

CONCLUSIONS

For the first time, the junction of two leaders, one of which is formed in an aerosol cloud, was recorded in a direct experiment. This phenomenon is the cause of an abrupt increase in current, and the parameters of the front of the current and its duration are similar to those recorded during the return stroke in long spark discharges (which confirms the hypothesis suggested by Antsupov et al. [1990]). Inside the negatively charged aerosol cloud a plasma channel is formed, the descending part of which is a negative leader. As the negative leader meets the ascending positive leader, an abrupt increase in the current and energy release occurs, which is characteristic of the return stroke. The junction region is characterized by high energy release, which is several times greater than energy releases of the plasma channels of the positive and negative leaders.

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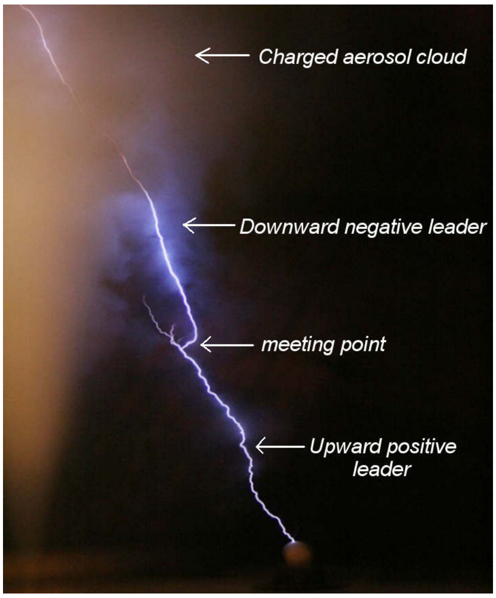

Fig. 1. Integral photograph of the meeting of the two leaders followed by a return stroke.

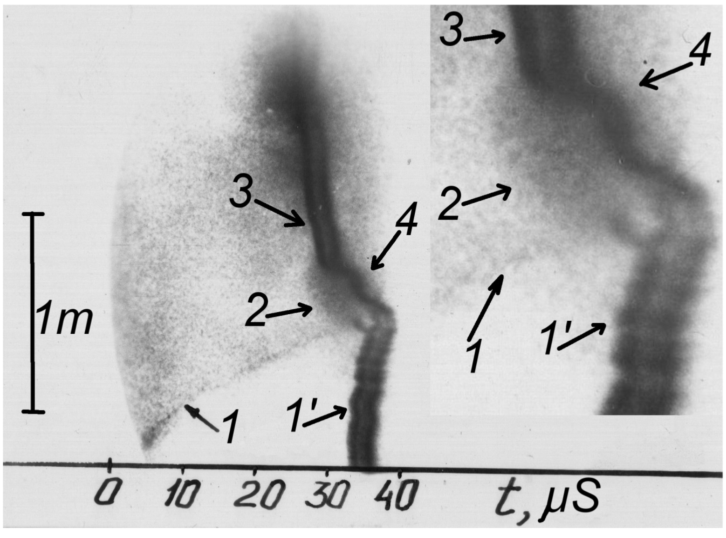

Fig. 2. Time-resolved image of the meeting of the two leaders: 1 – the head of the positive leader; 1' – the channel of the positive leader during the final jump; 2 – the glow of the corona during the final jump; 3 – the channel of the negative leader during the final jump; 4 – the channel of the discharge during the return stroke (adapted from Antsupov et al. [1990]).

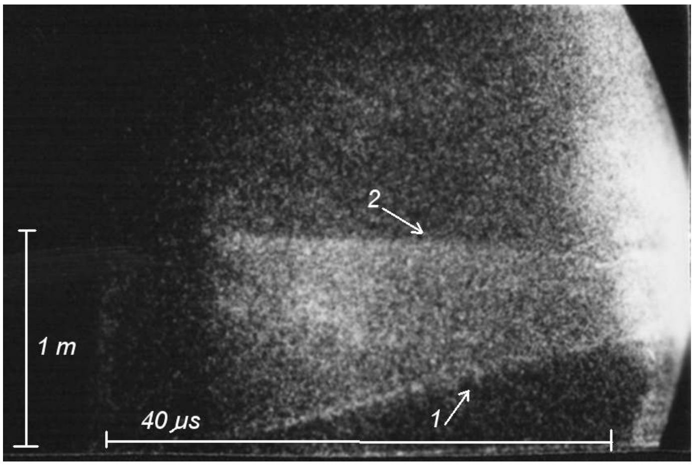

Fig. 3. Time-resolved image of the meeting of the two leaders: 1 – the head of the positive leader; 2 – the head of the negative leader.

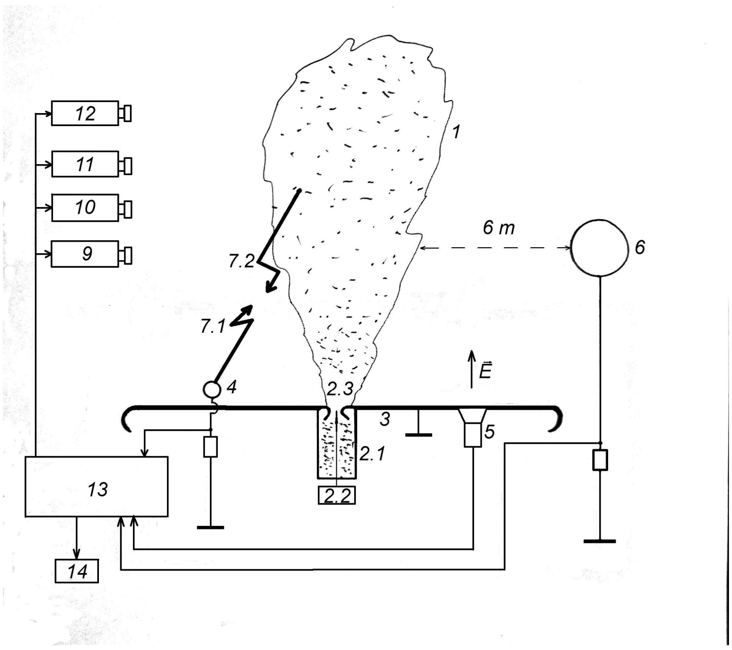

Fig. 4. The scheme of the experiment: 1 – a cloud of charged aerosol; 2.1 – steam-air jet generator; 2.2 – the source of high voltage applied to the needle in the nozzle; 2.3 – the nozzle through which the steam-air jet flows out with a corona needle in the middle; 3 – grounded metal plane; 4 – receiving electrode in the form of a metal ball 5 cm in diameter; 5 – slow electric field meter (fluxmeter); 6 – fast electric field probe (metal ball 50 cm in diameter); 7.1 – upward positive leader; 7.2 – downward negative leader; 9 – FASTCAM SA4, a high-speed video camera; 10 – FLIR 7700M, a high-speed infrared camera; 11 – photomultiplier tube; 12 – photo camera; 13 – signal synchronization and recording unit (Tektronix DPO 71004 oscilloscope and Tektronix AFG 3252 signal generator); 14 – data storage unit (PC).

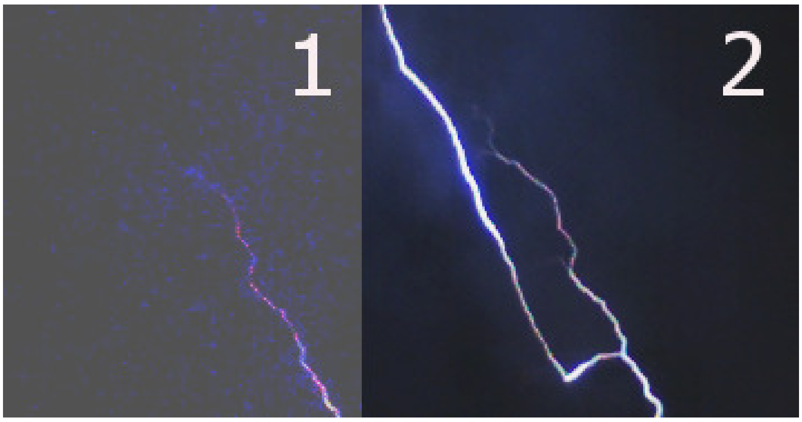

Fig. 5. 1 – the channel of the positive leader; 2 – the contact of the positive and negative leaders (as photographed by the colour camera FASTCAM SA4 at the frame rate of 50,000 fps and the frame resolution of 320×192 pixels).

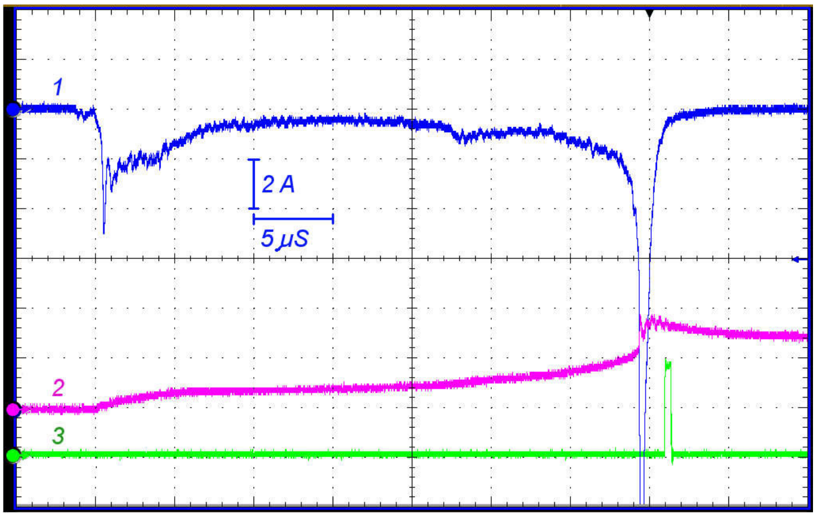

Fig. 6. The oscillograms of the event shown in Fig. 5: 1 – the current flowing through the ball at the plane from which the positive leader ascends; 2 – the current through the insulated copper ball 50 cm in diameter, which is proportional to the total charge of the aerosol cloud; 3 – the trigger signal to the high-speed camera.

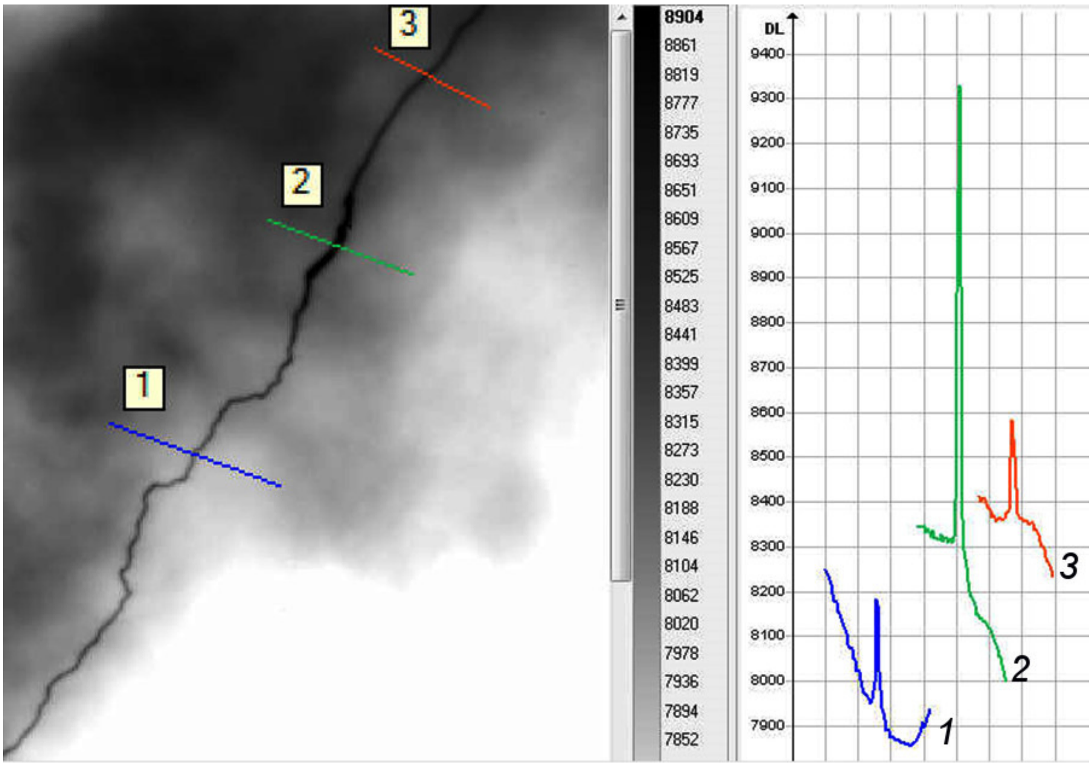

Fig. 7. On the left: The frame recorded by the infrared camera FLIR 7700M. The lines shown correspond to the positive leader (1), negative leader (2), and the region of the contact (the bridge) between the two leaders (3). The entire channel lies inside the aerosol cloud and is blurred in the visible range. On the right: The intensities of the radiation from different parts of the channel, in relative units.