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ICCD Images of Leader Corona in a 4 m Rod-Plane Gap Discharge

Jianwei Gu[1,a], Shengxin Huang[1,b], Yufei Fu[2], Weidong Shi[1], Weijiang Chen[3,c,*]

[1]High Voltage Department, China Electric Power Research Institute, Beijing, China
[2]School of Electrical Engineering and Automation, Hefei University of Technology, Hefei, China
[3]State Grid Corporation of China, Beijing, China
[a]gujianwei13@163.com, [b]shengxin_huang@yeah.net, [c]wj_chen@yeah.net
**Corresponding author*

Abstract: *As the featured discharge pattern and widely present in lightning discharge channels, leader corona system is crucial for continuous leader propagations in long air gap discharges and natural lightning, which had attracted numerous studies experimentally or theoretically. In the simulation of discharge process and lightning attachment calculations, the vertex angle of streamer zone ahead of leader channel is the crucial parameter, which could only be obtained by discharge experiments. As a result, morphological researches on leader corona system gave an intuitive insight on the streamer zone ahead of the leader channel and helped comprehensive theoretical modeling studies especially in the calculation of electric field. In order to obtain the accurate shape features and provide the calculation parameter for model modification, in this paper, experiments of 4-m long air gap discharges were carried out based on a four-frame PCO.dicam C4 ICCD camera. Clear images of leader corona were observed. Results showed that the corona zone was assumed as conical and the average angle at the vertex was 75.2° which was less than the first corona during the stable leader propagation stage. Influences of exposure time and leader branching phenomenon were investigated in this paper. It was concluded that the competitive relationship of the branched leaders shrank the vertex angle of the conical corona zone. Results in this paper could instruct the future theoretical model researches on leader corona system and help to modify the existing lightning attachment models like SLIM or leader process model.*

Keywords: *Leader corona, ICCD image, Streamer, Long air discharge*

1. Introduction

Leader corona system exists both in natural lightning and insulation flashover in power systems, which is the crucial physical phenomenon. Due to the large dimensions in lightning and complexity in power systems, laboratory long air gap discharge experiments are the valid method to investigate lightning physics and external insulation in power system, which plays a significant role in protection design of transmission line, electric power apparatus and converter station [1]. Typical complete breakdown in laboratory consists of streamer and leader inception and propagation as well as final jump [2]. Among the subsequent processes, leader corona is the motivation of continuous leader propagation. Therefore, various investigations have been carried out to study the leader corona and their transition during last few decades [3].

Leader corona system consists of streamers at the tip, behaving diffuse glow pattern, leader filamentary channel connecting to the electrode, treated as luminous weakly ionized plasma channel, and transition zone between the leader channel and streamer tip. The streamer tip could be regarded as a column of space charge, where electrons, generated by avalanches and photoionization, converge into the leader tip and provide current for leader continuous propagation. Among the macroscopic physical characteristics of the streamer zone, such as spatial electric field distribution, current, the morphological features give an intuitive insight. Investigations on leader corona morphological characteristics help deep understanding of discharge continuous propagation. Optical observation is an effective way to capture features of leader corona system. The most common optical diagnosis utilized image converter camera and still camera [3]. However, due to the time resolution limits, few frame pictures were obtained. Gallimberti et al concluded that the corona zone behaved conical shape structure [2]. Various frame pictures under different gap distances and voltage waves showed that the corona zone kept constant during the discharge. Based on 10 m gap discharge frame photographs, Gallimberti et al reported that

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corona zone might have variable geometrical shapes in a complete breakdown discharge, which behaves conical in the first corona stage, hyperboloid during the leader propagation with the vertex angle of around 120 °and cylindrical at the final jump [4]. However, researches carried out by Lebedev et al found that the leader corona was a conical region with the vertex angle of less than 90 °[5], which differed from the first corona and the results obtained by Gallimberti. The difference in the above observations makes the streamer pattern vague. Recently, the development of optical devices with high precision and high temporal and spatial resolution had been utilized in long air gap discharge observations. The high-speed camera could overcome the problems of short recording time of image converter camera and had been utilized in many researches [6]. Based on the high-speed camera, more information about the leader corona had been revealed, such as leader velocity or leader length [7]. Intensified charge-coupled display (ICCD) camera is another apparatus to study the discharge features. But due to the difficulty on synchronous trigger of ICCD observation system and few frame numbers per discharge, ICCD camera was often adopted to study the streamer discharge during first corona stage [8]. As a result, experimental results based on ICCD camera were rarely reported.

Based on experimental parameters, physical models of leader corona have been also proposed in literature [9]. No matter engineering models such as critical radius and leader inception critical voltage, or simplified models such as models proposed by Bondiou et al [10] and multi-parallel streamers model proposed by Geolian et al [11], are far from the actual pattern of leader corona and calculation errors were introduced in the simulations. The model carried out by Becerra et al [12] derived the geometrical shape of leader corona obtained by Gallimberti et al [4], but was found that simplifications still existed. Arevalo et al utilized Gauss's theorem and considered a variable streamer zone that changed with the applied electric field variations [1,9]. Because the experimental results Arevalo et al compared with were obtained from image converter camera with low time resolution and the streamers extended out from the central region simultaneously, streamers in the leader front might differ from real leader corona.

From the analysis above, it could be concluded that ambiguous points still exist when it comes to the geometrical shape of leader corona, which further affects the numerical model investigations. Observations on real shape of leader corona need to be carried out.

In this paper, to get high spatiotemporal resolution image of leader corona, long air gap discharge experiments with the distance of 4 m were carried out with the rod subjected to the positive switching voltage. A four frame ICCD camera with minimal exposure time of 4 ns was utilized. Three different exposure time were applied to capture the leader corona pattern. Finally, the effect of leader branching on the shape of corona zone was analyzed.

2. Experimental Setup

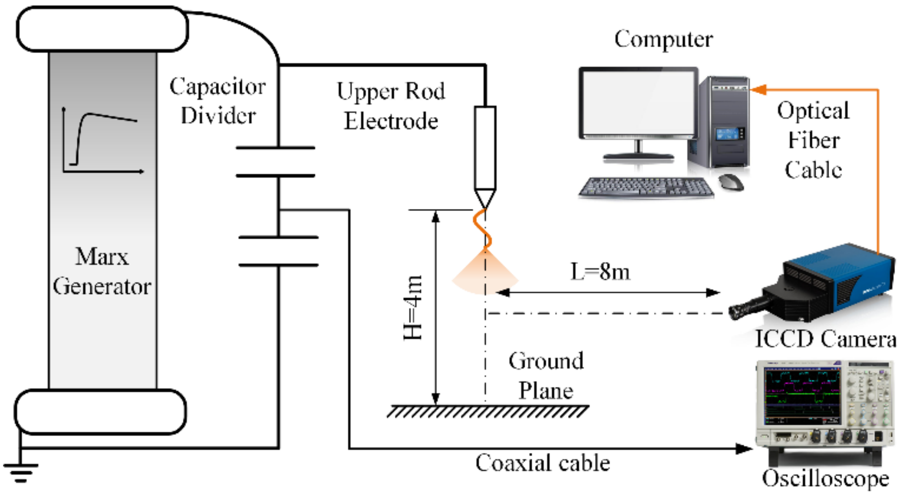

Figure 1: Schematic diagram of experimental setup.

The schematic diagram of experimental setup is illustrated in Figure 1. The positive switching impulse voltage with the rise and half peak time of 250 μs and 2500 μs respectively was generated by a 4.8 MV Marx generator. As shown in Figure 1, the voltage was applied to the upper rod electrode with a length of 2 m. The rod tip was a 1.5 cm diameter hemisphere. The rod electrode was suspended by insulators Distance between the upper rod electrode and the ground aluminum plane, which was 8 m×8

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m, was set to 4 m.

The voltage waveform was recorded by capacitor divider and connected to an oscilloscope by coaxial cable. In order to capture the whole gap, a PCO.dicam C4 ICCD camera with a Nikon lens (8-48 mm, f/1.0) was placed at the distance of 8 m away from the gap axis. The PCO.dicam C4 has 4-channel intensified CMOS cameras and four photographs could be taken continuously with the minimum exposure time of 4 ns and 2048×2048 pixels resolution. For leader corona capture, multiple experiments were carried out to find the reasonable trigger time interval of the ICCD camera. For better image quality, all experiments were performed in a dark environment with the ambient temperature of 10 ℃ and relative humidity of 64% corresponding to the absolute humidity of approximately 6 g/cm^3.

3. Results

A typical positive discharge subjected to the switching impulse is initiated with the formation of first corona which behaves the filamentary branched channels when the applied electric filed in the vicinity of the rod tip exceeds the threshold value, generally 3 MV/m [4]. One or more dark period might arise after the first corona according to the curvature radius of the rod tip, which the critical radius was called the critical radius. Subsequently, the second corona and transition from streamers to leader takes place after the Joule heating increases the temperature over the critical temperature [3,4]. Actually, the leader might vanish according to the crest time of the applied voltage. Then the leader propagates with the leader corona in front of the tip and this stage is the so-called stable leader propagation. Electrons generated by avalanches and photoionization in the streamer tip converge into the leader head and generate current determining the energy input and sustaining the transition from glow to leader channel. Based on this, leader corona is critical for leader propagation. For reasonable understanding of leader propagation and correct simulation of leader corona, accurate description of corona zone must be observed. According to the part of Introduction, parameters of the optical devices might have effects on the geometrical shape of the streamer zone. In this paper, effect of different exposure time and leader branching was investigated.

3.1. 4-m gap discharge

The representative ICCD image of 4 m gap discharge is illustrated in Figure 2 under standard 250/2500 μs switching impulse voltage. The photographs were taken at the exposure time of 58 ns and treated reversely to increase contrast, and the voltage waveform was shown in this figure too. Compared with the first corona in the literature [8], the leader corona behaved glow-like discharge and could be also treated as a conical area. Different from image converter camera pictures in literature [4], photos with the higher time resolution ICCD camera in this paper showed that the angle was less than 90° and the value in the figure was 73.30°. Actually, the mean value of our experiments was 75.2°.

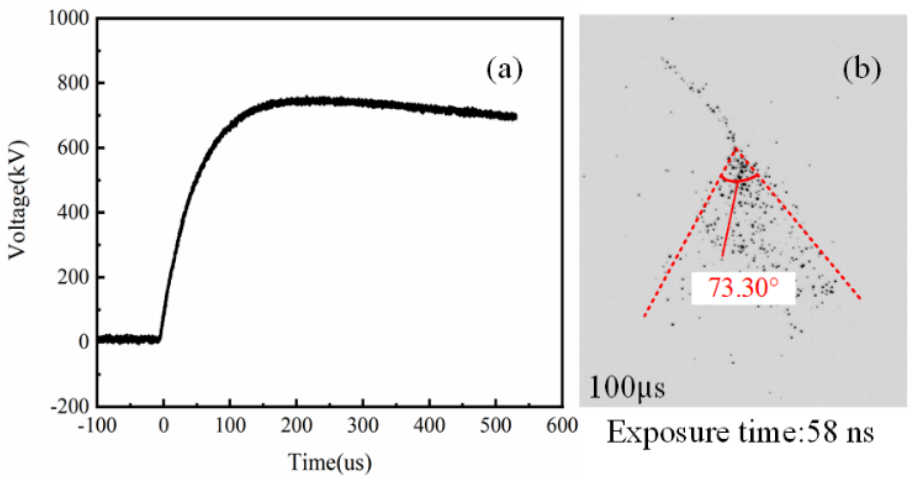

Figure 2: Voltage waveform and ICCD image of 4-m gap discharge.

3.2. Effect of exposure times

Different from the image converter camera, the ICCD camera have advantages in spatial and temporal resolution [7]. The ICCD camera in this paper could adjust the observation parameters according to the research requirements. In order to find the influence of observation parameters, the effect of exposure time on the geometrical shape of corona zone was investigated in this paper with three different exposure time, 58 ns, 100 ns and 200 ns, respectively. Figure 3 shows images of leader corona at the same time of discharge. It can be concluded from the figure that the vertex angle slightly reduced as the exposure time decreased from 200 ns to 58 ns. This could be attributed to the time integration of light signals collected during a single frame exposure time. The time resolution was enough to capture the real corona zone geometrical features, as a result, the exposure time had slightly influence on the geometrical feature such as the vertex angle of the corona zone.

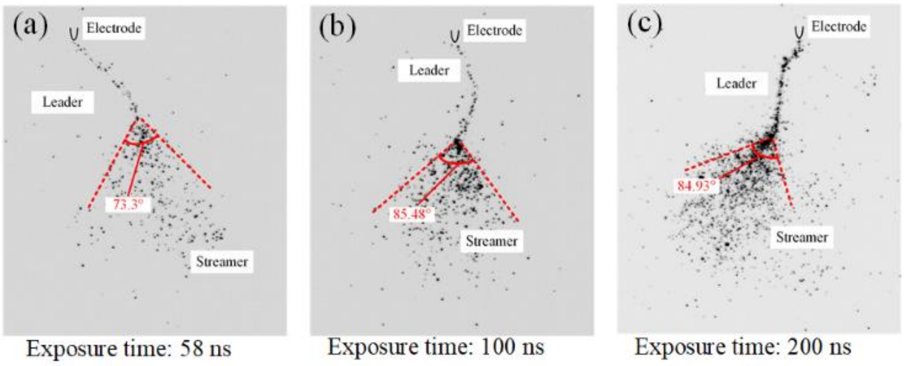

Figure 3: ICCD images of leader corona under different exposure time.

Long air gap discharge results showed that the trajectory of leader channel is not simply straight line under switching impulse. In our researches, leader channel tortuosity was captured and shown in Fig. 4(a). The direction of leader channel changed in the process of advancement, leading to the superposition in space of streamer zone, and it could lead to larger vertex angle. The angle in the photograph was about 84.05°. What's more, the large vertex angle in Fig. 4(b) could be explained by the leader branching phenomenon. The leader tip split into two leader branches and the two streamer tips overlapped so that the angle became larger than the ones in Fig. 3. Moreover, the angle at the vertex in Fig. 4(b) was about 108.91 °. The influence of leader branching would be discussed in the following part.

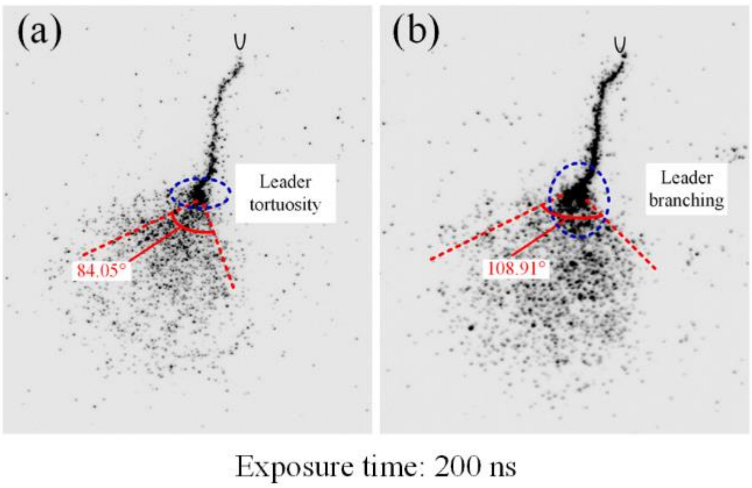

Figure 4: ICCD images of leader tortuosity and leader branching.

3.3. Effect of leader branching

The leader branching phenomenon widely exists in the leader propagation process [7]. In this paper, ICCD images of leader branching under the exposure time of 58 ns were observed and shown in Fig. 5. There existed two leader branches and the leader branches competed to grow towards the ground plane. Affected by the space electric field, leader branches might vanish before the final jump or reach the ground plane to finish the final jump. As shown in Fig. 5, both vertex angles of two corona zones were kept less than that in single leader channel discharge. After multiple discharges, we counted the mean value of different leader branches, and the average angles of left and right corona zone were 57.7 ° and 73 ° respectively, while the average vertex angle under single leader channel was 75.2 °. Actually, in our statistical results, only one branch completed gap breakdown if there existed two branches or more. With leader propagation, the branch leader that didn't finish the final jump became weaker but space charge still existed for a relatively long period. These space charge led to a distortion of space electric field which forced the corona zone of the other leader branch shrink. It's concluded that the vertex angle under leader branching discharges was less than single leader discharges, which should be taken into consideration for future theoretical researches.

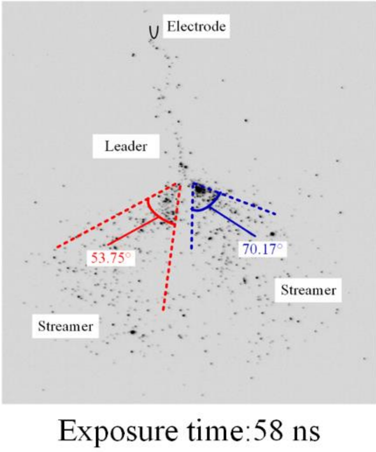

Figure 5: ICCD image of leader branching under the exposure time of 58 ns.

4. Conclusion

Leader corona system is the typical characteristics for continuous leader propagations in long air gap discharges and lightning. The existing simulation of lightning attachment process need the vertex angle of the leader corona zone to calculate space charge electric field or geometric coefficient. The shape of the streamer zone could be only obtained by discharge experiments. What's more, the streamer zone in front of the system provides current converging into the leader tip, which need to accurately observe. Existing studies have shown that there existed differences in the vertex angle of leader corona. To solve the above problems, in this paper, 4-m long air gap discharge experiments were carried out based on a four-frame ICCD camera. Clear images of leader corona were firstly obtained. The observation results showed that the corona zone had a geometrical feature of conical shape with the average vertex angle of 75.2 °under the exposure time of 58 ns. The exposure time had less influence on the vertex angle and the angle intended to decrease slightly with the exposure time decreasing. The leader branching phenomenon had apparently effects on the geometrical feature of the corona zones which could be attributed to the competitive relationship of different leader branches. Results in this paper showed that the angle of 75 ° during stable leader propagation stage could be chosen in the lightning attachment simulations.

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