EXPERIMENTAL OBSERVATION OF TWO TYPES OF STREAMER REGION AHEAD OF LEADER IN LONG AIR GAP DISCHARGE

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ABSTRACT

The leader-streamer propagation is one of most important stage in long air gap discharge. In the conductor-tower lattice configuration, we have measured the voltage, current on high voltage side and electric field in the gap. While the streamer in the leader-streamer system presented a conical or hyperboloid diffuse shape, the clear branch structure streamer in the front of leader was firstly observed by a high speed camera in the experiment. Besides, it is found that the leader velocity, width and injected charge for branch type streamer are greater than those of diffuse type. We propose that this phenomenon results from high humidity which was 15.5~16.5 g/m^3 in our experiment.

1. INTRODUCTION

The mechanism of long air gap discharge is of great importance for the design of high voltage apparatus, insulation coordination and transmission line protection. The leader-streamer system mainly decides the evolution of long sparks.

Les Renardières Group carried out various experiments to study long air gap discharges under different laboratory conditions [1-2]. They observed that the leader-streamer region was diffuse according to the streak camera. In the first stage it had a conical shape. Then it gradually changed to a hyperboloid and, finally, the streamer extended the shape in a cylindrical form. During the leader-streamer's propagation, the leader channel would sometimes suddenly brighten and lengthen, which was called re-illumination or restrike. The mechanism of the restrike may play important part in the statistical variations of the discharge. It is also found that their probability is largely enhanced with the increasing of humidity. The upward leader model by Becerra and Cooray [3] assumed that the streamers split into many branches defining a conical volume. The charge accumulated was calculated by means of charge simulation method. Bondiou and Gallimberti's model [4] calculated the charge generated by the streamer formation with a simplification assumption. The charge was assumed to come from a single filament, therefore the charge for the total streamer area was estimated by multiplying the charge from a single streamer by a branching factor and by the number of filaments. The distribution and quantity of space charge in the streamer region are important to model the long air gap discharge.

In this paper, two different types of streamer, which are diffuse and branch type, ahead of leader tip were observed in conductor-tower lattice gap. We also measured the voltage, the current in the high voltage side and the electric field outsize the discharge channel so as to explain the mechanism.

2. EXPERIMENTAL SET-UP

In the present work, experiments were performed in the conductor-tower lattice configuration, which can be seen in *Fig 1*. The 6-bundle conductor is hung on the lattice by a V-shape insulator. The minimum distance between the corona ring in the middle of the conductor and the bottom or lateral side of tower was approximately 8.45 m. The original aim of the experiment was to obtain 50% breakdown voltage, thus providing guidance to the insulation design of ±800 kV HVDC transmission line. So it is the reason for choosing this complicated configuration instead of the common-used rod-plane gap. The temperature was 23~28 °C and the absolute humidity was 15.5~16.5 g/m^3.

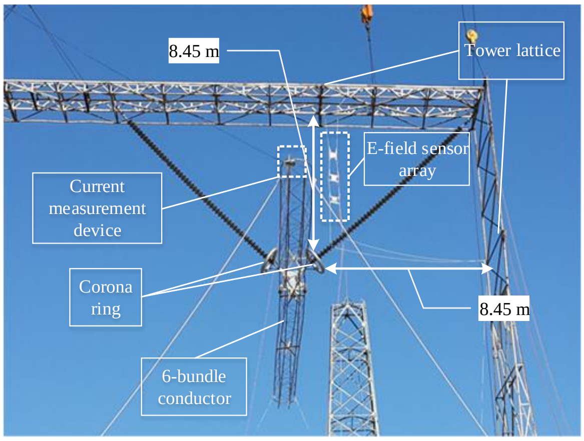
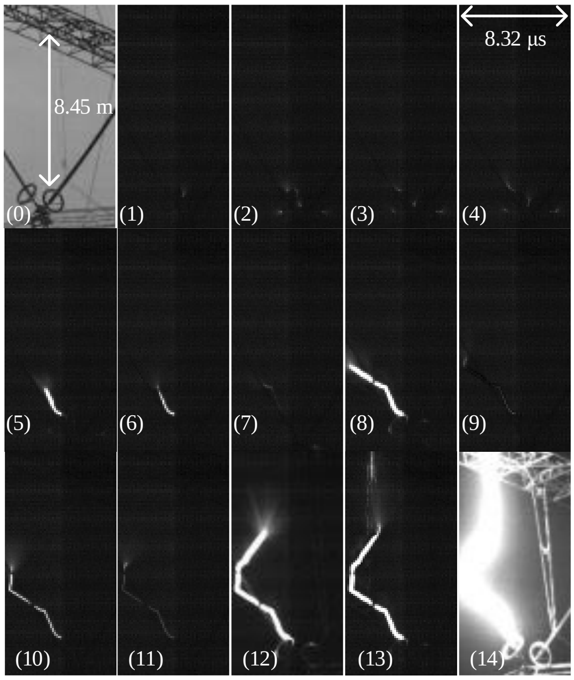


Fig 1. Conductor- tower lattice configuration

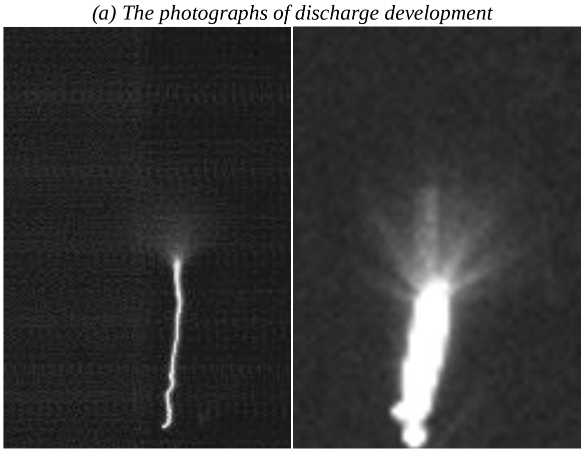
A positive 185/2290 μs switching impulse voltage generated by a 7.2 MV Marx generator was applied to the conductor. A coaxial shunt for current measurement was connected between the conductor and the high voltage lead. The current measurement device was also used in [5]. An integrated electro-optic E-field sensor was specifically developed and carefully calibrated [6]. The sensor can measure field with huge magnitude (up to MV/m) and very short rise time (in nanosecond scale), which is suitable for strong space discharge field. We aligned three sensors between the corona ring and the upper lattice. The topside sensor is 1 m away from the lattice and the other two sensor is 3 m away from the upper one. The discharge process was observed by a high speed CMOS camera aimed at the region above the conductor. The discharge development was recorded as continuous photographs with 128×256 pixel resolution.

3. EXPERIMENTAL RESULTS

In the experiment, the voltage with average amplitude of 2321 kV and 2060 kV was applied to the conductor. The typical discharge development is shown in *Fig. 2(a)*. The leader firstly initiated from the corona ring, then the leader channel begins to propagate with the streamer ahead of its tip after the leader formation. Meantime, restrike appeared occasionally and two types of streamer region were captured. The first type was the same as a diffuse conical shape in *Fig. 2(b)* as found before. In *Fig. 2(c)*, the streamers split into a few branches in front of the leader channel tip. Furthermore, the leader channel with branch type streamer is much brighter and thicker than that of diffuse type.



(a) The photographs of discharge development



(b) Diffuse type *(c) Branch type*

Fig 2: The typical results of high speed camera

The typical waveform of voltage, current and electric field is shown in *Fig. 3*. In the current waveform there are some current pulses which can correspond to the leader restrike in the photographs. If the leader happens to go by the E-field sensor, the electric field would increase sharply. This phenomenon can be clearly seen in *Fig. 3* at t=138 μs.

The velocity of the leader can be calculated by the photographs. The leader velocity v in one frame is defined as follows:

$$v = \Delta l / \Delta t \quad (1)$$

where Δl refers to the displacement of the luminous spot in leader tip between two adjacent frames, and Δt equals to the exposure time (8.32 μs) of each frame.

The leader velocity as a function of time in the same discharge in *Fig. 3* is shown *Fig. 4*. The time value of the data is the midpoint in one frame and the origin refers to the start of voltage. It should be noted that the velocity is the average value in one frame and is smaller than the real three dimensional velocity. At t=135 μs the leader velocity suddenly increases from 1.1×10^4 m/s to 7.5×10^4 m/s.

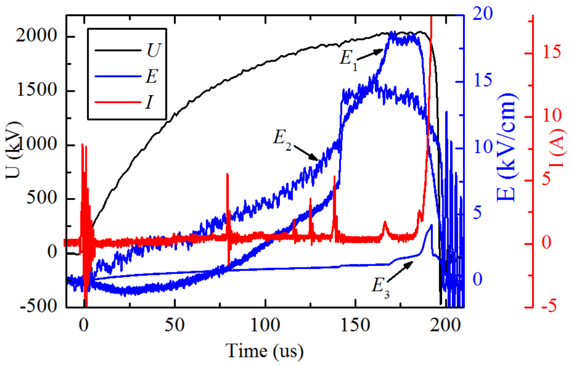


Fig 3: The typical waveform of voltage, current and electric field

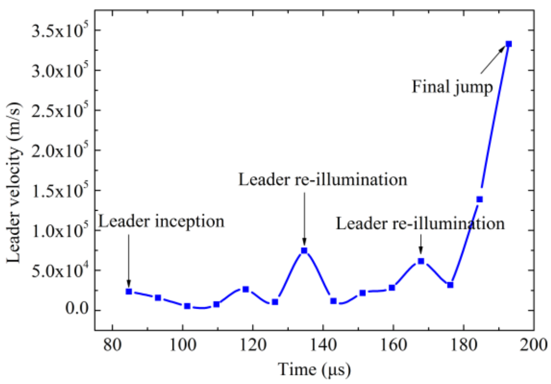


Fig 4: The leader velocity as a function of time

4. DISCUSSION

The two types of streamer can be observed in the leader restrike. The current and electric field results indicate that a large quantity of charges flowing into the leader channel. The influx of charge can be calculated as follows:

$$q = \int_{t_1}^{t_2} Idt \tag{2}$$

where I refers to current measurement value, t_1 and t_2 are the onset and terminal time of the current pulse.

The relationship between the injected charge and leader velocity of the two types of streamer is shown in *Fig 5*. The leader velocity and injected charge for branch type streamer are greater than those of diffuse type. The leader velocity can reach 2.3×10^5 m/s which is one order of magnitude faster than the normal leader velocity $1{\sim}2\times10^4$ m/s. Furthermore, the figure indicates a positive correlation between the leader velocity and injected charge.

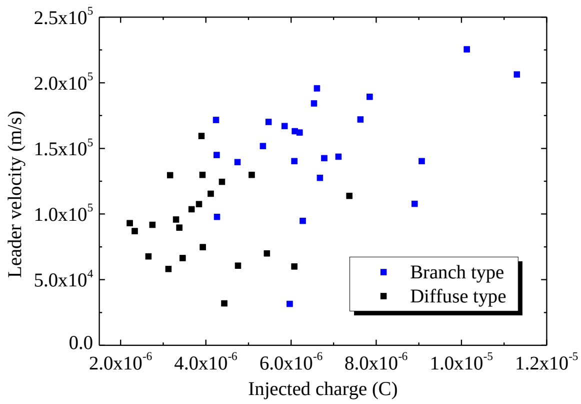


Fig 5: Leader velocity as function of injected charge

It is also can be seen from that the width of leader channel is quite different in two types of streamer. The expansion of leader channel is due to the current created by the streamers converge on the stem region. The energy input produces significant effects in the stem channel and causes a hydrodynamic expansion of leader channel width [7]. The energy input by the generator can be approximately obtain by equation (3):

$$W = \int_{t_1}^{t_2} UIdt \tag{3}$$

The leader width can be measured in the photographs. The relationship between the leader width and input energy is shown in *Fig 6*. The leader width and input energy also presents a positive correlation. The input energy by branch type streamer is larger than that of diffuse type and this ratio can be 5 times. Besides, some leader width for diffuse type is 1~2 pixels. The error would be very large and the real width would be smaller than 1 pixel.

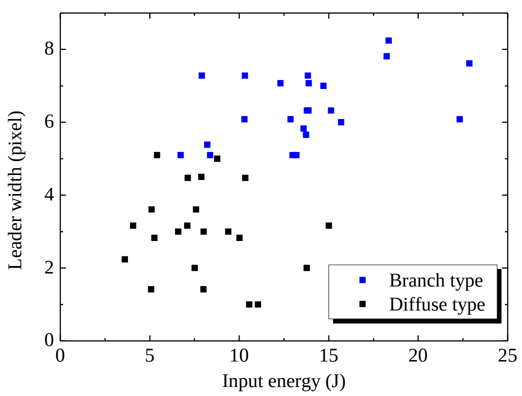


Fig 6: Leader width as function of input energy

The clear branch structure streamer ahead of leader was firstly captured in the experiment and always followed by a thick and bright leader channel. So it could be inferred that it appears in leader restrike. Since high humidity accounts for leader restrike and it is found that the restrike appears with the humidity increasing above about 8~10 g/m^3 [1]. At high humidity the photoionization efficiency is decreased and the attachment coefficient is increased. It leads to the decreasing of net ionization rate in the leader-streamer region [2]. Sometimes a particular situation can be reached in which the streamer activity is so low that the stable propagation condition is no longer satisfied and the current is practically reduced to zero.

Since the leader channel conductivity is very high, the potential of leader tip approaches that of the high voltage electrode. When the voltage continues to increase, the local field increases rapidly and a vigorous new streamer can initiate from the leader tip. The Joule power input due to streamer current cause a temperature increase of the gas molecules in the stem. The intense liberation of electrons by thermal detachment of earlier-formed negative ions causes further conductivity growth. To destroy O_2^- ions in dry air, a temperature T=1500 K is sufficient and detachment take about 10^{-7} s [2]. But in humid air, a slightly higher temperature, up to 2000 K, is required for appreciable detachment. Because hydrated ions $O_2^-[H_2O]_n$(n=1, 2, 3) are formed. In these ions, the bonding energy of the H_2O molecule $E_n(H_2O)$ decreases while the electron binding energy I_n^- increases with n [8]. Hydrated ions are progressively decomposed by successive separation of H_2O by successive molecular impacts, after which the electron is lost. The time required for detachment is 10^{-6}~10^{-5} s at T=1500~2000 K [9].

During the process that input current heating the leader channel, the tip width experiences a sharply increase because of long streamer-leader transition time at high humidity. This is proved by the experimental data shown in *Fig 6*. Hence the electric field distribution in the region near the tip becomes less non-uniform than the general condition. The thermal width of leader channel was estimated 1~2 mm [2]. Around the thin leader tip the electric field is above breakdown field 30 kV/cm and in overvolted region the existence of well separated streamers, as postulated in [10], is unlikely. However, with thicker leader tip more streamer branches could initiate from it. More charge thus injected into the leader as is shown in *Fig 5*. The above analysis can explain the formation of branch type streamer ahead of leader.

5. CONCLUSION

In this paper, we have observed two types of streamer ahead of leader: the diffuse type and branch type. The branch type streamer may result from the high humidity. Both the experiments results and theoretical analysis show that the leader tip become thicker due to higher Joule power input of streamer current. Thus more streamer branches could further start from the leader tip. Therefore it leads to the increasing charge and rapid leader elongations.

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