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Experimental Study on Branch and Diffuse Type of Streamers in Leader Restrike of Long Air Gap Discharge*

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Abstract One of the main problems in the Ultra High Voltage (UHV) transmission project is to choose the external insulation distance, which requires a deep understanding of the long air gap discharge mechanism. The leader-streamer propagation is one of most important stages in long air gap discharge. In the conductor-tower lattice configuration, we have measured the voltage, the current on the high voltage side and the 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 front of the 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 the branch type streamer are greater than those of a diffuse type. We propose that the phenomenon results from the high humidity, which was 15.5-16.5 g/m^3 in our experiment.

Keywords: ultra high voltage, long air gap discharge, streamer, leader, restrike

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(Some figures may appear in colour only in the online journal)

1 Introduction

Ultra High Voltage (UHV) power transmission projects take a leading role to realize the cross-regional energy resource allocation, because large energy consumption areas are far away from the areas with abundant energy in China. UHV projects are also considered to be possible solutions to controlling air pollution, such as the haze problem [1]. One of the main issues in these projects is to choose an external insulation distance, such as the insulation design of the DC converter station or transmission line etc. It has been based on the full-scale simulation experiments of gap breakdown characteristics and there is still no applicable and reliable model of long air gap discharge [2]. Therefore, studying the discharge characteristics and its mechanism is the basis of external insulation. On the other hand, deep understanding of long air gap discharge helps to model natural lightning, which can be further used in lightning protection [3].

The physical processes of long air gap discharge were studied by the Les Renardières Group with various experiments under different laboratory conditions [4−6]. Fig. 1(a) shows a typical one-dimensional development of discharge by a streak camera. When the voltage of the anode electrode rises, first streamers form at the high electric field region around the tip, which looks like a tree structure. A large amount of electrons flow through the root of the streamers, which is called the "stem", and heat the stem by the Joule energy of the current. When the stem is heated to a critical temperature, 1500 K, it transforms to the leader channel. The temperature in the leader is so high that the electrons are detached from the negative ions and the conductivity is increased significantly. Thus, the leader channel brings the high electric potential to its tip and creates again a region with a high electric field. It will further facilitate the formation of streamers ahead of the leader tip. Then, the leader-streamer regions move forward together. When the streamer reaches the cathode, it comes to the final jump stage, in which the whole gap is soon bridged by the conducting spark with low resistance.

The leader-streamer system mainly decides the evolution of long sparks [7]. They observed that the leader-streamer region was diffuse according to the still camera as shown in Fig. 1(b). 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 prop-

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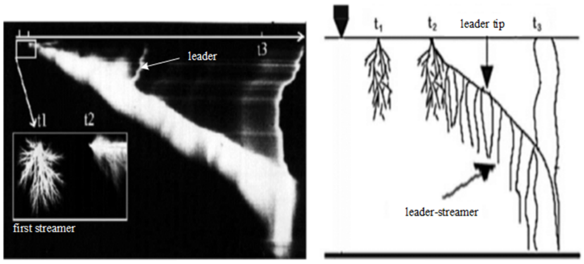
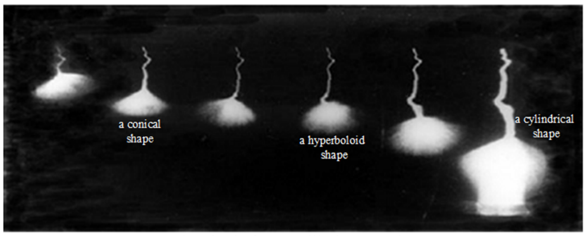
agation, the leader channel would sometimes suddenly brighten and lengthen, which was called re-illumination or restrike [5]. The mechanism of the restrike may play important part in the statistical variations of the discharge. It is also found that their probability is largely enhanced with the increasing of humidity. The upward leader model by Becerra and Cooray [8] assumed that the streamers split into many branches defining a conical volume. The charge accumulated was calculated by means of the charge simulation method. Bondiou and Gallimberti's model [9] 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.



(a) Streak photograph of discharge development



(b) Single frame still photograph

Fig.1 The temporal evolution of discharge in a 10 m rod-plane gap [7]

In this paper, the discharge development of an 8.45 m conductor-tower lattice gap is observed by a synchronized diagnostics system. We measured the voltage, the current in the high voltage side and the electric field outside the discharge channel. The leader restrike characteristics are studied in detail. Then we observe two different types of streamer, which are diffuse and branch type, ahead of the leader tip in the leader restrike process. Its physical mechanism is discussed to explain the two different streamer types.

2 Experimental set-up

Experiments were conducted outdoors in the UHVDC Test Base of the State Grid Corporation of China. The conductor-tower lattice configuration was used, which can be seen in Fig. 2. 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 the 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 commonly-used rod-plane gap. The temperature was 23-28 °C and the absolute humidity was 15.5-16.5 g/m^3.

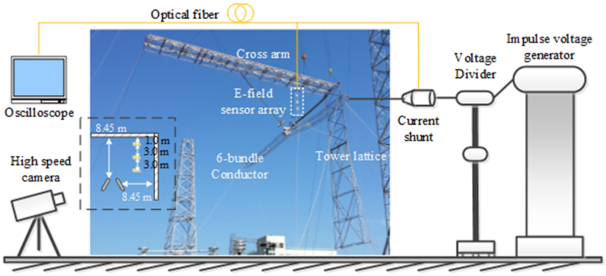


Fig.2 Conductor-tower lattice gap configuration and measurement devices

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 the current measurement was connected between the conductor and the high voltage lead. The current was sampled in a coaxial shunt and transmitted through optical fiber [10]. An integrated electro-optic E-field sensor was specifically developed and carefully calibrated [11]. The sensor can measure a field with a huge magnitude (up to MV/m) and a very short rise time (in nanosecond scale), which is suitable for a high space charge electric 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 sensors are 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, which is a fast diagnostics method for discharge study [12]. The discharge development was recorded as continuous photographs with 128×256 pixel resolution and 120000 frames per second.

3 Experimental results

3.1 Typical discharge development

In the experiment, the voltage with an average amplitude of 2060 kV was applied to the conductor. The typical discharge development is shown in Fig. 3. In order to get a better visual effect, the original grayscale images are transformed to color images according to the intensity.

There are three bright spots at t=83.2-91.52 μs, which indicates that the continuous leader firstly initiated from the corona ring. Then the leader channel begins to propagate with the streamer ahead of its tip

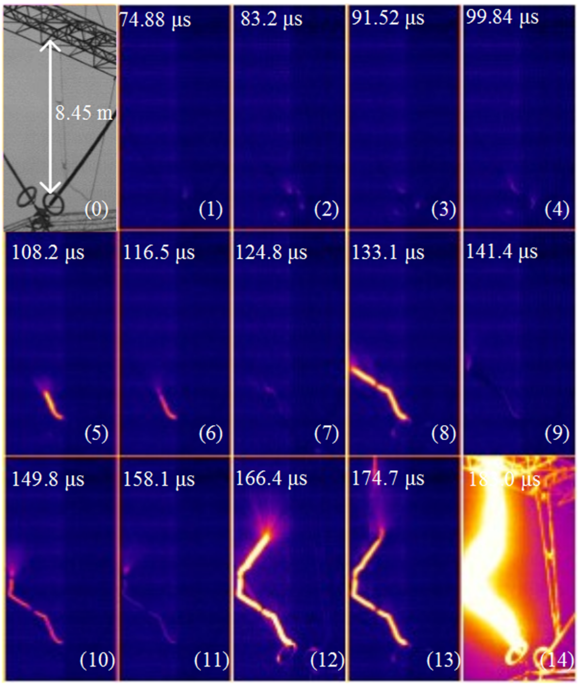


Fig.3 The time-resolved photographs of discharge development

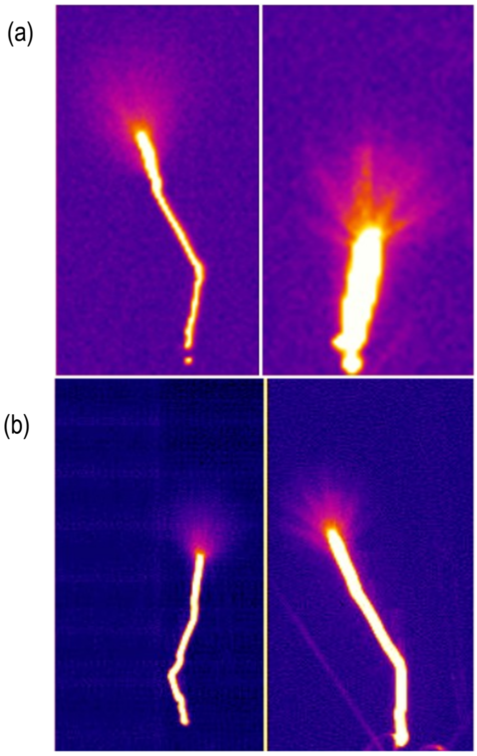


Fig.4 The typical results of high speed camera. (a) Diffuse type, (b) Branch type

after the leader formation. Meantime, restrike appeared occasionally and two types of streamer region were captured. The first type was the same as the diffuse conical shape in Fig. 4(a) as found before. In Fig. 4(b), the streamers split into a few branches in front of the leader channel tip. Furthermore, the leader channel with the branch type streamer is much brighter and thicker than that of the diffuse type. Finally, the streamer region advances to the cross arm and it leads to gap breakdown.

3.2 Measured results of discharge parameters

A typical waveform of the voltage, current and electric field is shown in Fig. 5. The first large current pulse appears at t=82 μs and it indicates that the first corona initiates around the grading ring. But there is no electric field step in the measurement results. The electric field increases gradually as the voltage increases. After the continuous leader starts to propagate and advances near the E-field sensors, there are large field steps in the waveforms due to leader restrike. Large quantities of electrons suddenly flow into the leader channel and leave a positive space charge ahead of the leader. So these current pulses may correspond to the leader restrike phenomenon. It suggests that the leader restrike causes a large number of electron flux to the electrode. If the leader happens to propagate near the E-field sensor, the electric field would increase sharply accordingly. This phenomenon can be clearly seen in Fig. 5 at t=138 μs.

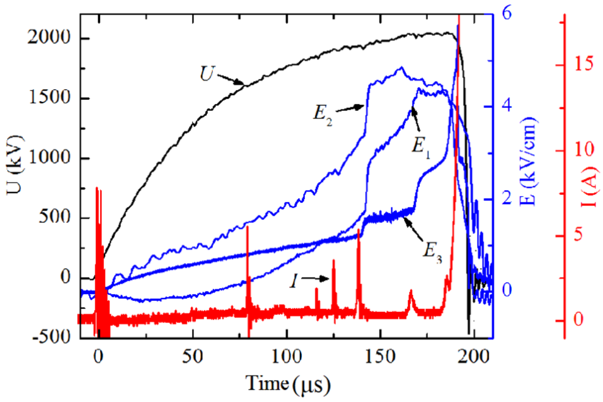


Fig.5 The typical waveform of voltage, current and electric field

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

$$v = \Delta l/\Delta t, \tag{1}$$

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.

Fig. 6 shows the leader velocity as a function of time for the same discharge in Fig. 3. The time value of the data is the midpoint in one frame and the origin refers to the start of the 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.

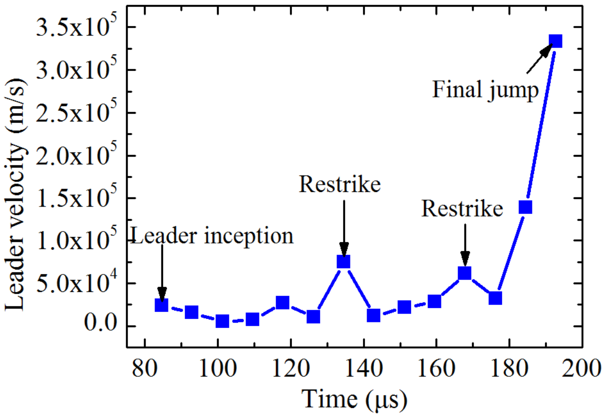


Fig.6 The leader velocity as a function of time

4 Discussion

4.1 The characteristics of leader restrike

The two-dimensional leader propagation velocities of 11 different discharges are calculated and shown in Fig. 7. Usually there is more than one leader advance alternatively during the discharge development. In the figure we only focus on the leader channel, which results in gap breakdown. It can be seen that leader velocities can be classified into three types according to their value i.e. 0-5 cm/μs, 5-20 cm/μs and greater than 30 cm/μs. They correspond to three stages of leader: stable stage, restrike stage and final jump stage. In the three stages, the velocities are very different and the average leader velocities of three stages are 2.2 cm/μs, 11.8 cm/μs and 37.8 cm/μs, respectively. As mentioned before, the leader restrike velocity is much higher than the stable development. This indicates that the electric field suddenly enhances due to the electron flux.

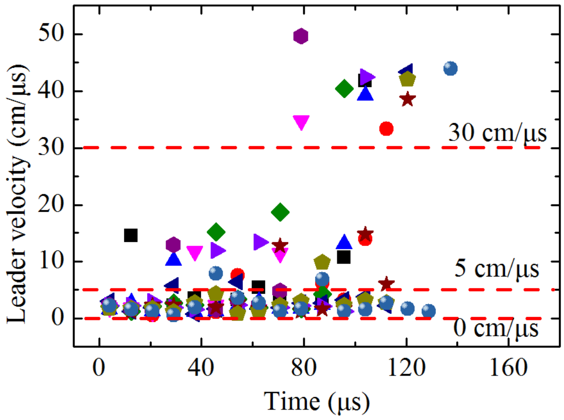


Fig.7 The leader velocity as a function of time

In order to see the change of linear charge density of the leader channel, we perform the integration of the current waveform to obtain the charge quantity. The influx of charge can be calculated as Eq. (2):

$$Q=\int_{t_1}^{t_2} I\mathrm{d}t, \tag{2}$$

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

The injected charge quantity Q as a function leader length L is illustrated in Fig. 8. The injected charge is proportional to the leader length. A linear fit Q=29.9 (μC/m)L can be made with the least square method. When we focus on a single curve, the injected charge increases sharply at some moments. This usually corresponds to the leader restrike because of the production of many charges in the streamer region and their transport to the leader tip.

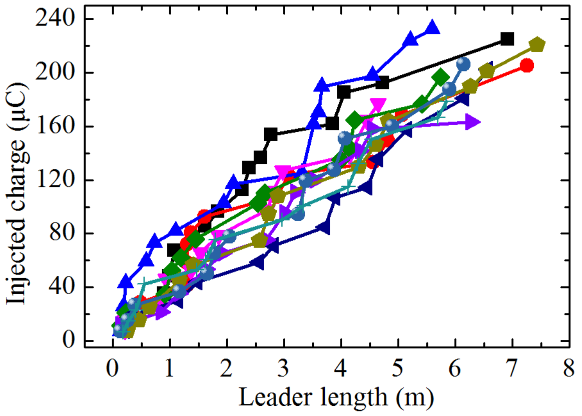


Fig.8 The injected charge as a function of leader length

4.2 Experimental comparison of two streamer types

The two types of streamer mentioned earlier 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 injected charge can be calculated by replacing t_1 and t_2 in Eq. (2) with the onset and terminal time of the current pulse.

The relationship between the injected charge and the leader velocity of the two types of streamer is shown in Fig. 9. The leader velocity and injected charge for branch type streamer are greater than those of the 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 $(1\text{-}2)\times10^4$ m/s. Furthermore, the figure indicates a positive correlation between the leader velocity and injected charge.

It can also be seen that the width of the leader channel is quite different in two types of streamer. The expansion of the leader channel is due to the current created by the streamers converging on the stem region. The energy input produces significant effects in the stem channel and causes a hydrodynamic expansion of leader channel width [13]. The energy input by the generator can be approximately obtained by Eq. (3):

$$W=\int_{t_1}^{t_2} UI\mathrm{d}t. \tag{3}$$

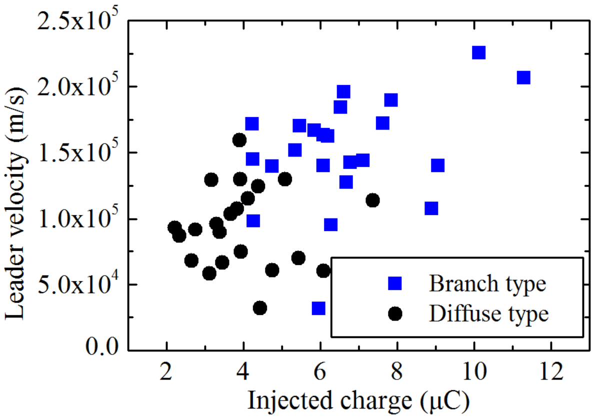


Fig.9 Leader velocity as a function of injected charge

The leader width can be measured in the photographs. The relationship between the leader width and the input energy is shown in Fig. 10. The leader width and input energy also presents a positive correlation. The input energy by branch type streamer is larger than that of the diffuse type and this ratio can be 5 times. Besides, some leader widths for the diffuse type are 1-2 pixels. The error would be very large and the real width would be smaller than 1 pixel.

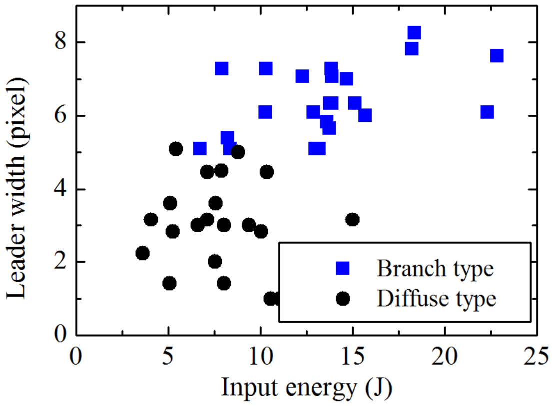


Fig.10 Leader width as a function of input energy

4.3 Physical mechanism of two streamer types

The clear branch structure streamer ahead of the 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, it is found that the restrike appears with the humidity increasing above about 8-10 g/m^3 [4]. At the higher humidity of 15.5-16.5 g/m^3 in our experiments, the photoionization efficiency is much decreased and the attachment coefficient is increased. It leads to the decreasing of the net ionization rate in the leader-streamer region [5]. 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 the 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 the streamer current causes a temperature increase of the gas molecules in the stem. The intense liberation of electrons by thermal detachment of the earlier-formed negative ions causes further conductivity growth [13]. To destroy O_2^- ions in dry air, a temperature T=1500 K is sufficient and detachment takes about 10^{-7} s [5]. But in humid air, a slightly higher temperature, up to 2000 K, is required for an appreciable detachment; because hydrated ions $O_2^-[H_2O]_n(n=1,$ 2, 3) are formed [14]. 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. 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 [15].

During the process that input current heating the leader channel, the tip width experiences a sharp increase because of the long streamer-leader transition time at high humidity. This is proved by the experimental data shown in Fig. 10. Hence the electric field distribution in the region near the tip becomes less non-uniform than the general condition. The thermal width of the leader channel was estimated 1-2 mm [5]. Around the thin leader tip the electric field is above breakdown field 30 kV/cm and in the over-volted region the existence of well separated streamers is unlikely [16]. However, with a thicker leader tip more streamer branches could initiate from it. More charge is thus injected into the leader as shown in Fig. 9. The above analysis can explain the formation of a branch type streamer ahead of the leader.

5 Conclusions

In this paper, we have observed two types of streamer ahead of the leader in the leader restrike process: the diffuse type and the branch type. The input energy by the branch type streamer is larger than that of the diffuse type and this ratio can be 5 times. The leader velocity and injected charge for the branch type streamer are also greater than those of the diffuse type. And the leader restrike velocity is 5-20 cm/μs, which can be one order greater than stable leader velocity.

The branch type streamer may result from the high humidity. Both the experiments results and theoretical analysis show that the leader tip becomes thicker due to the higher Joule power input of the streamer current because of the longer streamer-leader transition time at high humidity. Thus more streamer branches could further start from the leader tip. Therefore, it leads to the increasing charge and rapid leader elongations.

References

1 Liu Z Y. 2014, State Grid, 3: 16 (in Chinese)
2 Zeng R, Zhuang C, Yu Z, et al. 2014, High Voltage Engineering, 40: 2945
3 Zeng R, Zhou X, Wang Z, et al. 2015, High Voltage Engineering, 41: 13
4 Les Renardières Group. 1972, Electra, 23: 53
5 Les Renardières Group. 1974, Electra, 35: 49
6 Les Renardières Group. 1977, Electra, 53: 33
7 Gallimberti I. 1979, Journal de Physique Colloques, 40: 193
8 Becerra M, Cooray V. 2006, Journal of Physics D: Applied Physics, 39: 3708
9 Bondiou A, Gallimberti I. 1994, Journal of Physics D: Applied Physics, 27: 1252
10 Chen S, Zeng R, Zhuang C J. 2013, Journal of Physics D: Applied Physics, 46: 375203
11 Zeng R, Zhuang C J, Yu Z Q, et al. 2011, Applied Physics Letters, 99: 221503
12 Chen S, Zeng R, Zhuang C J, et al. 2013, IEEE Transactions on Dielectrics and Electrical Insulation, 20: 839
13 Gallimberti I, Bacchiega G, Bondiou-Clergerie A, et al. 2002, Comptes Rendus Physique, 3: 1335
14 Raizer Y P. 1991, Gas Discharge Physics. Springer, Berlin
15 Popov N A. 2009, Plasma Physics Reports, 35: 785
16 Sun A B, Teunissen J, Ebert U. 2013, Geophysical Research Letters, 40: 2417

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