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Observation and analysis of positive leader re-illumination in a 10 m ultra-high voltage transmission line gap under switching impulse voltages

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Abstract

The leader propagation is one of the most important stages in long air gap discharge. The mechanism behind leader re-illumination remains unclear. In high humidity conditions (20.0–30.1 g/m³), we have conducted experiments of long sparks in a 10 m ultra-high voltage (UHV) transmission line gap under switching impulse voltages. The positive leaders predominantly propagate discontinuously, with almost no significantly continuous propagation occurring. The leader channels are intensely luminous and each elongation segment is straight, with streamers resembling the "branch type" which differs from the "diffuse type" streamers at the front of continuous propagation leaders. The distribution of the propagation velocities is highly random (3.7–18.4 cm/μs), and the average velocity (9.2 cm/μs) significantly exceeds that of continuous propagation (1.5–2.0 cm/μs). Analysis suggests that the current-velocity models suitable for continuous leader propagation do not align well with the experimental data in re-illumination mode. Based on the discharge current waveforms and optical images, it is speculated that the newly elongated leader in re-illumination mode does not evolve gradually from the stem (about 1 cm) but rather evolves overall from a thermal channel much longer than stem.

Keywords: long air gap discharge, positive leader, re-illumination, discontinuous leader propagation

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

1. Introduction

The research on long air gap discharge is of great significance for the insulation design and lightning protection of ultra-high voltage (UHV) transmission lines [1–4]. Leader propagation is a crucial phase in long air gap discharge. While it is commonly considered that positive leader propagation is continuous, researches have shown that under conditions of slowly varying impulse voltages or high atmospheric humidity, leader propagation can be discontinuous. The period when ionization activity in the discharge channel vanishes is called the dark period [5]. Following the end of dark period, positive leader propagation is characterized by

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abrupt brightening and elongation of the leader channel, a phenomenon known as re-illumination [5, 6]. Due to the randomness and complexity of leader re-illumination, there is currently no consensus regarding the mechanism of leader re-illumination [7]. Therefore, experiments are necessary to observe the characteristics of leader re-illumination.

Among multiple experimental observation methods, the optical image observation is the most intuitive method to understand the propagation characteristics of the whole discharge, which has been widely utilized in the acquisition of crucial physical parameters during the discharge development [8–12]. In order to observe the development of leader, Zhou *et al* conducted a discharge experiment in a 6.1 m transmission tower gap and captured the propagation of leaders using a high-speed camera [13]. In the experiment, the leader re-illumination occasionally occurred during continuous propagation, and the velocity of the leaders in re-illumination mode was much higher than that of continuous propagation. But the researcher did not explore the optical and morphological characteristics of the leaders in further detail. Under the condition of absolute humidity of 15.5–16.5 g/m^3, Chen *et al* first discovered two types of streamers at the head of the leaders in re-illumination mode: "diffuse type" and "branch type" [14]. They speculated that the "branch type" streamer might be caused by high humidity. In literature [15], Kostinskiy *et al* used a two-frame, high-speed video camera with image enhancement to observe the properties of positive and negative leaders developing in 4–10 m air gaps. They found that in positive leader re-illumination mode, the morphological structures of the streamers resemble those of the negative leader. However, due to the limitation of the camera frame rate, they did not carry out further research on this observation. While researchers have observed some morphological structures of the leader-streamer system, the re-illumination happened by accident during the continuous leader propagation in the experiments, resulting in a lack of more comprehensive and coherent observation results of the whole leader propagation process in re-illumination mode.

Given the particularity of the dark period compared with the continuous propagation leader, other scholars have also studied the gas temperature evolution of leader channels during the dark period in detail, to better understand the re-illumination phenomenon. Zhao *et al* proposed using quantitative Schlieren techniques to accurately measure the temperature of leader discharge channels [16]. They set up a calibrated Toepler's lens-type Schlieren system to measure the radial temperature profile of leader discharge channels and gave guidance on the use of quantitative Schlieren techniques. Some researchers investigated the decay and reactivation of positive leaders in long air gap discharges by an improved time resolved quantitative Schlieren observation system [17]. They found that when a positive leader begins to decay, the temperature drops below 3000 K. Besides, it is possible for a decaying leader to be reactivated before it transforms into an aborted leader and the temperature drops below 2000 K. Liu *et al* observed optical and thermal characteristics of discharge channels during dark periods by an integrated experimental platform. They noted weak luminosity of ionization activity in the leader channels during the dark period and observed a narrow thermal channel which may facilitate the subsequent re-illumination [18]. The above researches provide a detailed observation of the thermal evolution of leader channels during the dark period, deepening our understanding of the streamer-leader transition process. Unfortunately, due to the lack of corresponding refined and comprehensive optical images of the leader structures in re-illumination mode, the research results about streamer-leader transition have not been self-consistent.

In summary, in previous experiments, re-illumination events occurred accidentally during continuous leader propagation, making it challenging to observe leader structures carefully. Furthermore, previous studies primarily focused on the causes of dark period and the thermal evolution of leader channels during the dark period, without establishing a connection between the morphological characteristics of the leader-streamer system and the process of streamer-leader transition.

To comprehensively and meticulously observe the leader morphology in re-illumination mode, we conducted long sparks experiments in a 10 m UHV transmission line gap under 3376 kV switching impulse voltages of long wave front time (1000/5000 μs) in a high humidity environment (20.0–30.1 g/m^3). In this environment, the positive leaders predominantly propagated discontinuously, with almost no significantly continuous propagation occurring. Discharge current and voltage waveforms and optical morphological images of the leader-streamer system were captured by a comprehensive observation platform. Based on the analysis of the leader-streamer system characteristics, we proposed a hypothesis about streamer-leader transition in leader re-illumination mode.

2. Experimental configuration

2.1. Comprehensive observation platform

The comprehensive observation platform for long air gap discharge comprises an impulse voltage measurement system, a current measurement system, and a discharge optical morphology imaging system. Impulse voltage measurement is conducted using an impulse voltage divider, while discharge current measurement utilizes a coaxial shunt. The resistance of the coaxial shunt is 0.1 Ω. A CMOS (complementary metal oxide semiconductor) high-speed camera captures time-resolved images of the discharge process. In this experiment, the shooting frame rate of CMOS high-speed camera was set at 76086 fps, with a frame interval of 13.14 μs, an exposure time of 12.36 μs per frame, and an image size of 352×168 pixels. A schematic diagram of the comprehensive observation platform is shown in figure 1.

2.2. Experimental arrangements

In the experiment, two eight-bundled conductors were used,

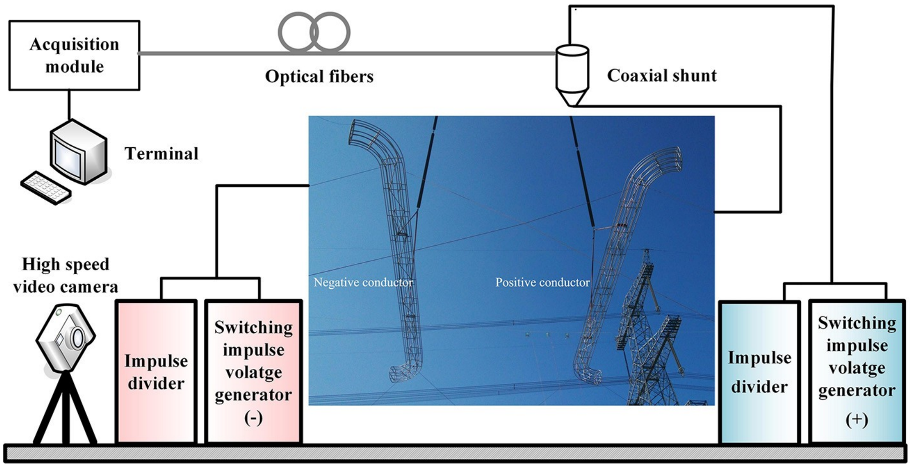

Figure 1. A schematic diagram of the comprehensive observation platform.

with a distance of 400 mm between adjacent sub-conductors and a diameter of 32 mm for the sub-conductors. These two conductors were arranged in parallel with an inter-phase gap of 10 m.

Figure 2 depicts the applied long wave front time impulse voltages (1000/5000 μs). Given that the distance between the conductors and the ground is only 20 m, in order to reduce the probability of breakdown between the conductors and the ground, we simultaneously applied positive impulse voltage to the positive conductor and negative impulse voltage to the negative conductor. The positive impulse voltage has an amplitude of 2010 kV, while the negative impulse voltage is 1366 kV, resulting in a total voltage amplitude of 3376 kV. The negative impulse voltage accounts for 40% of the total voltage amplitude. Throughout the experiment, the ambient temperature ranged between 32 °C and 34 °C, with an absolute humidity level of 20.0–30.1 g/m^3. The air pressure at the test site is 99.5–100.5 kPa, approximately equivalent to 1 atm.

3. Experimental results

3.1. Current and voltage measurements

The current and voltage waveforms of a typical discharge process are depicted in figure 3 (the letter labels in the figure correspond to the time intervals in figure 4). Positive and negative impulse voltages were initiated at 0 μs. Around 185 μs, the first notable current pulse emerged, signifying the formation of a leader (not the leader resulting in the final breakdown). The interval between two current pulses represents the dark period. Subsequently, multiple significant current pulses occurred, indicating a large number of electrons suddenly injecting into the leader channel, likely associated with the leader re-illumination. Approximately at 545 μs, the current sharply increased and then remained at about 10 A, indicating the final jump stage and subsequent arc-burning stage respectively.

Throughout the discharge process, the current mainly manifested as pulses exceeding 5 A, with no steady current. In contrast, during continuous leader propagation, the current is steady, typically ranging from 0.5 to 2 A [19]. Consequently, the leaders in the experiment mainly propagated discontinuously, which is completely different from the accidental leader re-illumination that occurs during continuous leader propagation in other experiments.

3.2. Observation of optical images

The typical discharge images of a gap breakdown process, which correspond to the current and voltage waveforms in

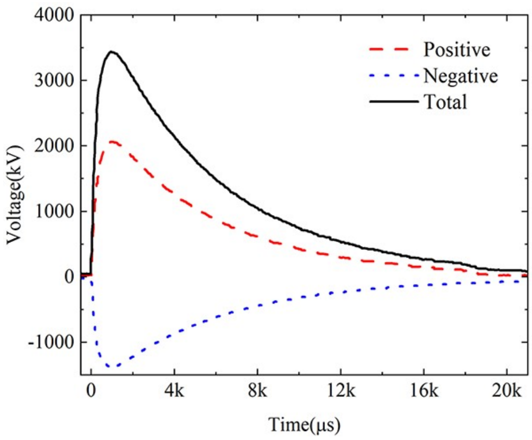

Figure 2. Waveforms of applied impulse voltages.

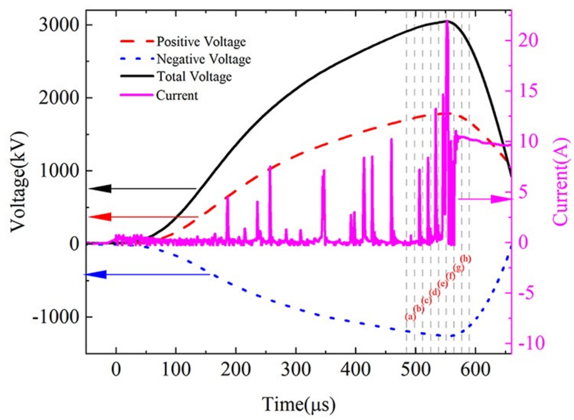

Figure 3. Actual measured waveforms of current and voltages.

figure 3, are shown in figure 4. In figure 4(a), the weak discharge was observed, corresponding to the initiation of the stable leader that led to the final breakdown. Subsequently, there was an obvious leader re-illumination, and the generation of streamers corresponded to the current pulse in figure 3(b). Then the leader propagated in a re-illumination mode, with each elongation corresponding to the current pulse in figures 3(c) and (d). In figure 4(e), it is evident that the streamers at the front of the leader reached the negative polarity conductor, marking the beginning of the final jump stage. Immediately afterwards, with the breakdown of the inter-phase gap, strong light emission was observed, followed by arc formation. Notably, the leader channel exhibits an intensely luminous and thick appearance, with each elongation segment being considerably straight and long. The characteristics differ significantly from those when the leader propagates continuously in a low humidity environment (4.4–10.0 g/m^3). As shown in figure 5, the leader channel in continuous propagation mode appears curved, significantly dimmer and thinner than that in re-illumination mode.

To further investigate the characteristics of leader, figure 6(a) presents the optical image of leader-streamer system in continuous leader propagation mode, contrasted with that in re-illumination mode as shown in figure 6(b). It is evident from the images that, besides the differences of leader, the streamer region in re-illumination mode exhibits a branching shape resembling the "branch type" as described by Chen *et al* [14]. While during continuous leader propagation, the streamer at the front of the leader appears diffuse, resembling the "diffuse type".

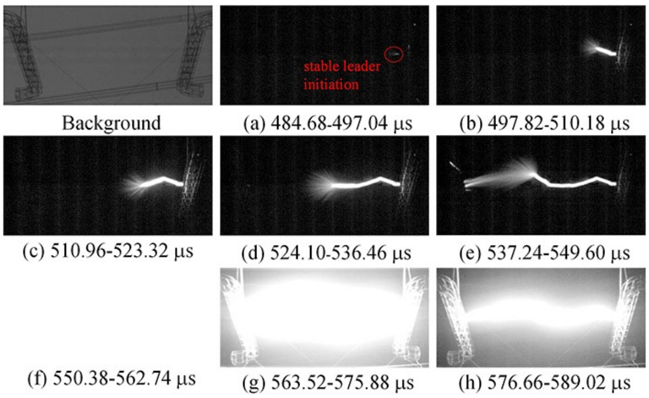

Figure 4. Optical images of discontinuous leader propagation in high humidity environment (with an exposure time of 12.36 μs).

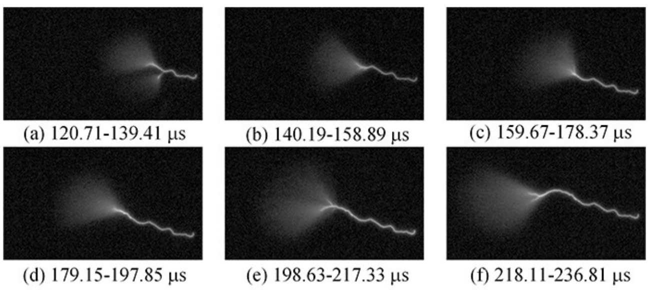

Figure 5. Optical images of continuous leader propagation in low humidity environment (with an exposure time of 18.70 μs).

Figure 7 provides other two images of the leader-streamer system in re-illumination mode. Within the exposure time of each image, two discharge pulses appeared, corresponding to two elongations of the leader. An interesting phenomenon is observed in the images: there are two separated streamer regions in each image, and no streamer is generated between the front and rear of the newly elongated leader. A detailed analysis of the phenomenon will be provided in the following sections.

3.3. Statistical results of data

By analyzing the time-resolved images, multiple sets of one-dimensional elongation lengths of the leaders in the experiment (excluding the final jump stage) were statistically obtained, as depicted in figure 8. Considering the wide variation in the formation time of the stable leaders (ranging from 250 to 750 μs), we designated the initiation time of each leader as time 0 in the figure to more intuitively represent the elongation lengths of the leaders. It is evident that within a frame interval of 13.14 μs, the leaders can achieve an elongation of up to 1 m or even greater, surpassing the elongation lengths observed in continuous leader propagation mode [13].

Figure 9 shows the statistical distribution of the one-dimensional velocities of multiple leaders under the same experimental condition (excluding the final jump stage). It is important to clarify that the velocities represent the average velocities of elongation over an exposure time, which does not signify continuous forward propagation at that speed. A

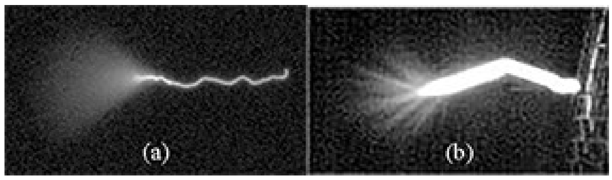

Figure 6. (a) Optical image of leader-streamer system in continuous leader propagation mode, (b) optical image of leader-streamer system in leader re-illumination mode.

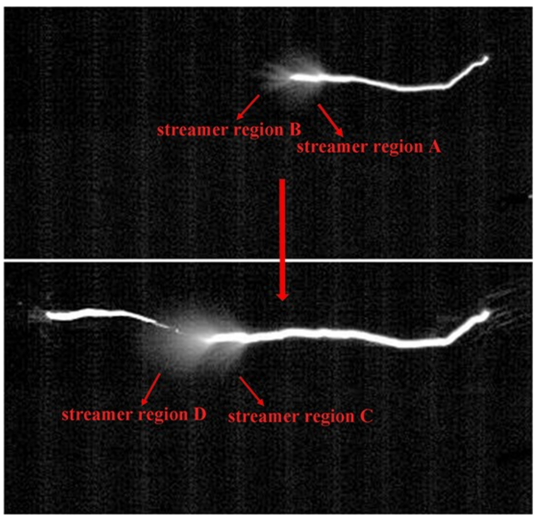

Figure 7. Two separated streamer regions.

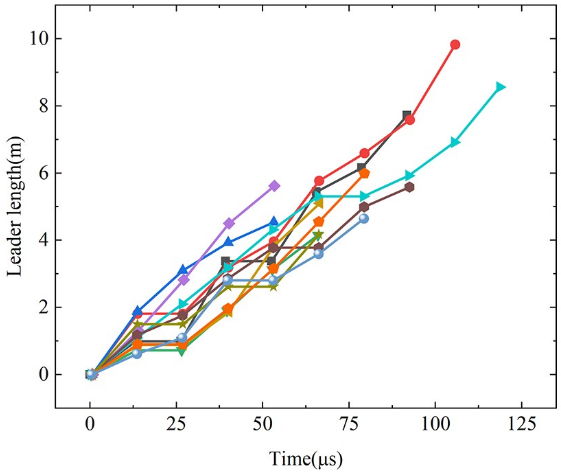

Figure 8. Elongation lengths of the leaders in re-illumination mode.

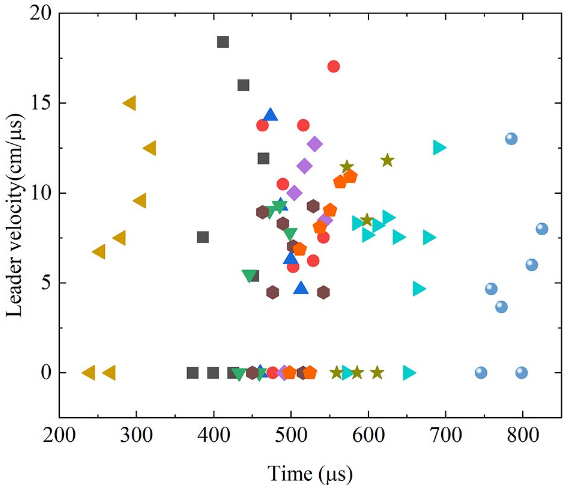

Figure 9. Distribution of leader velocities in re-illumination mode.

velocity of 0 indicates that the leader is in the dark period and has stopped propagating. In continuous propagation mode of the typical positive leader, the average velocities range from 1.7 to 2.2 cm/μs [13, 20]. However, in re-illumination mode, the distribution of the propagation velocities is highly random, ranging from 3.7 to 18.4 cm/μs. The coefficient of variation of velocities is as high as 36%. The average velocity (9.2 cm/μs) significantly exceeds that of continuous leader propagation (1.5–2.0 cm/μs [20]). Therefore, it is worth investigating whether mathematical models based on continuous leader propagation are still suitable for describing the discontinuous leader propagation.

4. Discussion

4.1. The reasons for re-illumination

High atmospheric humidity plays a crucial role in causing the re-illumination phenomenon [14, 21]. When the absolute humidity in the atmosphere is high, free electrons from the leader-streamer region are readily absorbed by electronegative water molecules. This absorption reduces the number of electrons that maintain electrical conductivity and temperature in the leader channel, resulting in a decrease in the net ionization rate [22]. If the ionization rate falls below the threshold required for continuous leader propagation, the current rapidly diminishes, causing the leader to cease propagation. Moreover, when the wave front time of the applied impulse voltage is prolonged, the voltage rise rate decreases. If the voltage increase is insufficient to counteract the shielding effect caused by net space charges, the electric field strength at the leader head diminishes, further reducing ionization activity in the streamer discharge region. Only when the voltage increment surpasses the shielding effect can the leader resume propagation.

In this experiment, the switching impulse voltages of long wave front time (1000 μs/5000 μs) were applied, and the absolute humidity in the environment reached levels as high as 20.0–30.1 g/m^3. Under these conditions, the leaders propagated mainly in the re-illumination mode, with almost no significantly continuous propagation occurring, which differs greatly from the conventional experimental phenomena.

4.2. Analysis of velocity models for leader propagation

The generally accepted theory regarding the streamer-leader transition mechanism is the thermal ionization theory. According to this theory, during the transition from a streamer to a leader, the free electrons produced in the head streamer regions converge at the root of the streamers (stem) and inject the electrode. Under the interaction of electrons and ions, the temperature in the region gradually rises. As the temperature in the transition region reaches a critical temperature of approximately 1500 K, negative ions in the stem detach in large quantities due to the elevated temperature. This process leads to a rapid increase in electron density and electrical conductivity in the stem, facilitating the gradual transition of the stem into an initial leader [23]. Popov proposed that the radius of the stem is 1 cm [24], indicating that the length of each streamer-leader transition is 1 cm. Building upon the theories above, many scholars put forward different mathematical models for the propagation of positive leaders [25]. Gallimberti *et al* suggested that the positive leader propagation velocity V_L is directly proportional to the current I_L and inversely proportional to the charge in leader channel per unit axial length q_L [23]:

$$V_L = \frac{I_L}{q_L}. \quad (1)$$

In the equation, the velocity V_L is measured in cm/μs, the current I_L is measured in amperes, and the charge in leader channel per unit axial length q_L is related to factors such as humidity, with a range of 20–50 μC/m. In this paper, the value of q_L is taken as 50 μC/m [26].

Andreev *et al* determined the dependence of the positive leader propagation velocity V_L (cm/μs) on the current I_L (A) in experiments of 8 m air gap [27]:

$$V_L = 1.88 \times I_L^{0.67}. \quad (2)$$

Gu *et al* obtained the relationship between the positive leader propagation velocity V_L (cm/μs) and the current I_L (A) through inversion of multiple discharge observation results [28]:

$$V_L = \left(ab + cI_L^d\right)\left(b + I_L^d\right)^{-1} \times 10^{-4}. \quad (3)$$

In the equation, $a = 189.40$; $b = 35.91$; $c = 5.59 \times 10^5$; $d = 0.66$.

To assess the validity of these models for leader re-illumination, we derived three sets of relationships between leader propagation length and charge by integrating equations (1)–(3) over time. These relationships were used to fit a set of typical experimental data on leader propagation length, as depicted in figure 10. The figure reveals that the mathematical models do not accurately predict the discontinuous leader propagation length, as the actual length exceeds the model predictions significantly. Therefore, these models suitable for continuous leader propagation are inadequate for describing leader re-illumination, suggesting that the mode of streamer-leader transition in re-illumination may be different from that in continuous leader propagation.

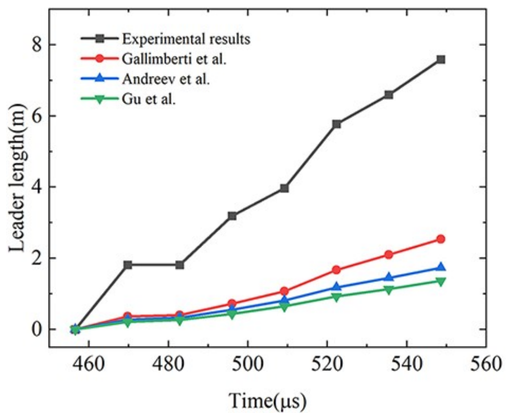

Figure 10. Fitting of the mathematical models to experimental data.

4.3. Detailed process of streamer-leader transition in re-illumination mode

It is generally believed that in the continuous development mode, the leader originates from the continuous transition of the stem (about 1 cm [24]). However, this perspective does not explain the optical morphological characteristics of leader in re-illumination mode. When the leader channel continuously transforms from the stem, streamers will be generated from the corresponding leader tip at any moment of continuous leader propagation, indicating that the streamer regions should exhibit macroscopic continuity. In this case, the presence of two separated streamer regions at the front and rear of the leader, as shown in figure 7, would not occur. Additionally, due to the randomness in propagation direction, newly formed leader segments may curve rather than be so straight. In conclusion, the perspective that the leader originates from the continuous transition of the stem (about 1 cm) fails to account for the leader optical characteristics and the leader elongation in re-illumination, indicating different streamer-leader transition process in re-illumination mode compared to continuous leader propagation mode.

In the latest research, it was shown that the length of the stem is not constant [29], indicating the possibility of the region transitioning to the leader being longer. Based on the discharge current waveforms and optical images, we speculate that the newly elongated leader in re-illumination mode does not evolve gradually from the stem (about 1 cm) but rather evolves overall from a thermal channel much longer than stem.

Figures 11(a) and (b) illustrate the streamer-leader transition processes in continuous and discontinuous leader propagation mode, aligning well with the observed experimental phenomena. In continuous leader propagation mode, the stem undergoes continuous heating and development under stable current injection, resulting in the gradual extension of

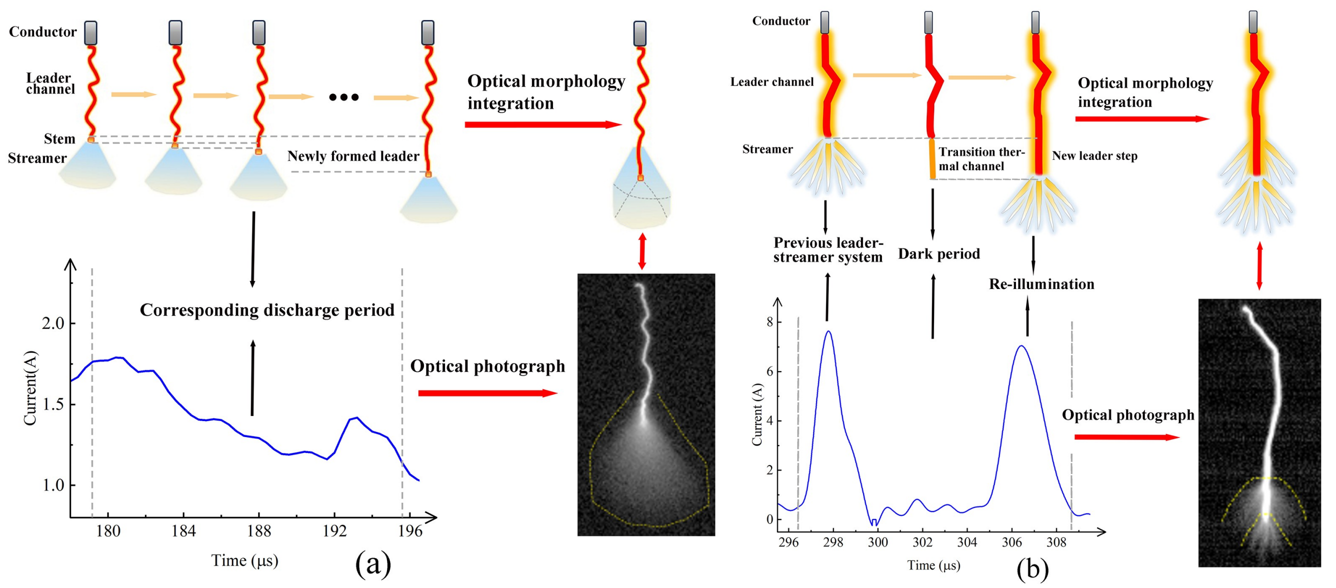

Figure 11. (a) The streamer-leader transition process in continuous propagation mode, (b) the streamer-leader transition process in discontinuous propagation mode.

the leader forward. At the head of each newly formed leader, streamer discharge occurs. Consequently, from the optical images captured during the exposure period, we observe streamers generated at every point along the newly elongated leader without interruption.

In discontinuous leader propagation mode, the streamers exhibit a "branch type" appearance with noticeable luminous intensity contrast compared to the more uniform luminous intensity of the "diffuse type" streamers. Chen *et al* proposed that the differences between the two types of streamers are due to high humidity [14], but they did not investigate the connection between the streamer structure and streamer-leader transition process. Now, we offer our perspective as follows: in the process of streamer-leader transition, the branches with strong luminous intensity inject a relatively large amount of charge, thereby generating significant heating effects, enough to form the initial thermal channel. Due to the short duration of the pulse current generated by streamers, the vibrational temperature of gas molecules within the channel has not reached equilibrium with the translational temperature, with the former surpassing the latter. During the dark period, the temperature of the thermal channel gradually rises due to vibrational-translational relaxation (V-T relaxation), leading to the increase of conductivity. When the applied voltage reaches a sufficient level to initiate the next streamer discharge, the thermal channel, which is much longer than stem, completes the transition to the leader as a whole. This process explains why the elongated segment of the leader appears so straight and long in re-illumination mode. Immediately following the transition, new streamers emerge from the head of the new leader. Therefore, during the discontinuous propagation of the leader, the streamer regions are discontinuous, corresponding to figure 7 showing the two separated streamer regions.

In reference [30], under the slow varying ambient electric field, Huang *et al* discovered a discharge that emits faint light at the halted leader tip before the intense reillumination by using a high-speed video camera and a synchronized electrical parameter measurement system. They believed that the discharge causing the faint illumination leads to the leader elongation in the pre-reillumination stage, and the leader channel actually restarts and extends forward before the intense re-illumination. This discovery points out that there is leader formation and development in the dark period, which is consistent with our hypothesis that the transformation to the leader takes place in the dark period. However, since we did not observe any clear discharge phenomena during the dark period in our experiments, we are inclined to believe that the leader transformation process during dark period is the overall heating transformation of a thermal channel rather than a gradual progression.

5. Conclusions

In a high humidity environment, we conducted long spark experiments in a 10 m UHV transmission line gap under switching impulse voltages of long wave front time. Discharge current and voltage waveforms and optical morphological images of the leader-streamer system in re-illumination mode were captured by a comprehensive observation platform. The conclusions are as follows:

(1) Under the conditions of high humidity environment (20.0–30.1 g/m^3) and with the application of 3376 kV slowly varying impulse voltages (wave front time of 1000/5000 μs) to a 10 m UHV transmission line gap, positive leaders mainly propagate discontinuously, with almost no significantly continuous propagation occurring. The main reason for this phenomenon is that the electronegative water molecules absorb a large number of free electrons from the leader-streamer region, causing the ionization rate falling below the threshold required for continuous leader propagation. Furthermore, the applied impulse voltages of long wave front time are not conducive to counteract the shielding effect caused by net space charges, thereby exacerbating the discontinuity in leader propagation.

(2) There are significant differences between continuous propagation leaders and discontinuous propagation leaders. In terms of morphology, leaders in re-illumination mode appear intensely luminous with straight elongation segment, and feature "branch type" streamers, while the leaders during continuous propagation appear curved characteristics and "diffuse type" streamers. In terms of development status, the distribution of leader propagation velocities in re-illumination mode is highly random, ranging from 3.7 to 18.4 cm/μs. The coefficient of variation of velocities is as high as 36%, and the average velocity is 9.2 cm/μs, significantly higher than that of continuous propagation mode (1.5–2.0 cm/μs).

(3) Based on the characteristics of straight leader elongation segment accompanied by "branch type" streamers and the phenomenon of two separated streamer regions in re-illumination mode, it is speculated that the newly elongated leader in re-illumination mode does not evolve gradually from the stem (about 1 cm) but rather evolves overall from a thermal channel much longer than stem.

Acknowledgments

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