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High Voltage

ORIGINAL RESEARCH

Multiple discharges before leader inception in long air gaps under positive switching impulses

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Abstract

There are multiple corona bursts before leader inception when the rising rate of the applied voltage or electric field is not sufficiently high enough in long positive sparks. In existing studies, no attention has been paid to whether these corona bursts occur in the same location, and they are mostly considered directly as belonging to the same discharge. However, this paper presents that in a typical rod-plate long air gap, the multiple corona bursts before leader inception are distributed in at least two different locations, and the highest probability of three discharges occurs. Also, the discharge occurs with the highest probability in the time sequence 'tip-tip-side-tip-other side' of the electrode in the first five corona bursts. For each discharge, the first corona current is a single, double exponential pulse, while the following corona currents are mostly a superposition of multiple pulses. The above findings are mainly based on experiments in a 1.4 m air gap under positive switching impulses, in which the voltage, current, and high-speed images were recorded simultaneously. Finally, based on the experimental results, this paper discusses the effects brought by ignoring the multiple discharges on key parameters of leader inception and makes some suggestions to optimise long spark experiments.

1 | INTRODUCTION

The study of long air gap discharges is of great value for designing external insulation of power systems and understanding the mechanisms of natural lightning [1–3]. In related studies, the experimental investigation is one of the most important tools. Many long air gap discharges have been observed under different conditions, for example, with the length ranging from tens of centimetres to more than 10 m [4–8], under the lightning impulse [9–12] or the switching impulse [5, 13–16], with the rod-plate [13, 17, 18], the rod-rod [19–21] or the plate-rod [22].

Due to the requirements of external insulation design and their similarities to the upward leader in lightning [23], long air gap discharges are always conducted under the positive switching impulse. The standard switching impulse has a rising time of 250 μs and a time to a half peak value of 2500 μs. The main chronological sequence of events composing the positive long air gap discharge in rod or sphere-plane geometry can be defined by the subsequent phases [24], that is, first corona inception, dark period, leader inception and development, and final jump. Researchers have proposed various numerical models for positive long air gap discharges [1, 25–29], and the prediction was in good agreement with the experiments.

In the long air gap discharge under positive switching impulses, there is a distinctive feature that the leader inception is always preceded by several corona bursts rather than just the first one, corresponding to some separated current pulses in the current waveform [22, 30]. Also, the recent study [31] showed multiple corona bursts before the upward leader initiated at the tower tip. For those observations in Ref. [22, 30, 31], the distance between the high-speed camera and the air gap is too large to identify the position of each corona from the images. Considering that the space charge generated by the corona bursts, the electric field at the electrode side is likely to be enhanced and triggers the corona burst there. If discharges at different locations are not differentiated, significant errors may occur in determining key main discharge parameters, such as the dark period, the voltage increment, the charge etc.

To this end, this paper investigates the characteristics of multiple discharges before leader inception and discusses its effect on determining several key discharge parameters. The rest of this paper is organised as follows: Section 2 introduces the experimental setup; Section 3 describes experimental results and is followed by discussions (Section 4) and conclusions (Section 5).

2 | EXPERIMENTAL SETUPS

The experiments presented in this paper were carried out on the same platform, as detailed in Ref. [32, 33]. For the sake of completeness, a brief description is as follows. Figure 1a demonstrates the top view of the experimental platform. The Marx generator generated a switching impulse with a rising time of 300 μs, which was applied to a 1.4 m point-plane air gap. This air gap was chosen because it was widely used in long laboratory discharges and also similar to the lightning rod under a thundercloud. Detailed dimensions of the anode are shown in Figure 1b. The discharge current was measured by a shunt resistor with a 25 Ω equivalent resistance, consisting of 8200 Ω non-inductive resistors connected in parallel. The current measurement module was located at the HV electrode, and the signals were transmitted via optical fibre to the low-voltage terminal. The discharge morphology was imaged by a high-speed camera (Phantom V1212) with a camera lens (Nikon, 50 mm, F1.4) located 2 m from the air gap. The camera was operated at a speed of 190 000 frames-per-second (fps) with an exposure time of 3.72 μs. The corresponding spatial resolution was 1.4 mm/pixel and the observation range was 180 × 360 mm^2. The voltage waveform was recorded by a digital oscilloscope (Tektronix DPO-4104B) through a voltage divider. All devices were triggered by the signal from the oscilloscope, and the data were processed synchronously in the way detailed in Ref. [34].

Atmospheric conditions for all experiments were as follows: temperature = 307 K; absolute humidity = 23.4 g/m^3; relative air pressure = 1.0.

3 | EXPERIMENTAL RESULTS

3.1 | Typical experimental results

Figure 2 shows representative current and voltage waveforms, and associated high-speed images. From the current waveform in Figure 2a, multiple separated corona bursts (①–⑥) occur before t = 100 μs, and then the stable leader seems to initiate and develop continuously for about 60 μs. However, two errors in the above conclusion can be found in combination with the high-speed images in Figure 2b. First, the discharges are not at the same location. Three sequential discharges (called multiple discharges) were observed in this work. Second, the continuously propagating leader was not present. The superposition of discharges at different locations results in a cumulated current waveform during t = 100 ~ 160 μs, similar to that of a stable leader. In this paper, the discharges are numbered from #1 according to the chronological order of appearance. Taking the results in Figure 2b as an example, each discharge is numbered as #1 ~ #3. Discharge #1 initiates at the electrode tip where the electric field is the greatest before the discharge occurs. Discharges #2 and #3 both are on each electrode side. These three discharges do not show a significant difference in dominance before t = 145 μs, during which the three only alternates with each other, but the timing sequence is not characterised. Until t = 145 μs, discharge #1 dominates as the main channel and develops continuously for about 15 μs. After t = 160 μs, current pulses with an amplitude of less than 120 mA correspond to flicker phenomena in the discharge residual channel as detailed in Ref. [32], which are not accompanied by strong streamer discharge at the channel head. These phenomena can last for several hundred microseconds and are more pronounced during the falling phase of the applied impulse.

3.2 | Number and position of multiple discharges

Figure 3 presents the distribution of the number of multiple discharges under different impulses. In all experiments, there is more than one discharge. Furthermore, the probability of three discharges is greatest for all three applied voltages, that is, 83%, 59%, and 72% for the voltage with an amplitude of 235, 290, and 320 kV, respectively. However, the number of discharges and the voltage amplitude are not positively correlated, for example, four discharges are more likely to occur under the voltage with an amplitude of 290 kV than that of 320 kV. The reason could be that the location of subsequent discharges is not only related to the voltage but also to the shielding effect [13, 24] of the space charge generated by the preceding discharges.

As shown in Figure 4, the discharges are mainly located in two regions: (1) the electrode tip and (2) the electrode sides, where the diameter starts to decrease. From the high-speed image in Figure 4e, we can see that even if the initial corona burst initiates at a certain place behind the electrode, it will not be missed in the number counting as the streamer filaments are long enough. Therefore, the statistics in the number of discharges reported in this paper should be close to the true values.

3.3 | Timing of multiple discharges

For all current waveforms measured in our experiments, the first five pulses correspond separately to a discharge at a

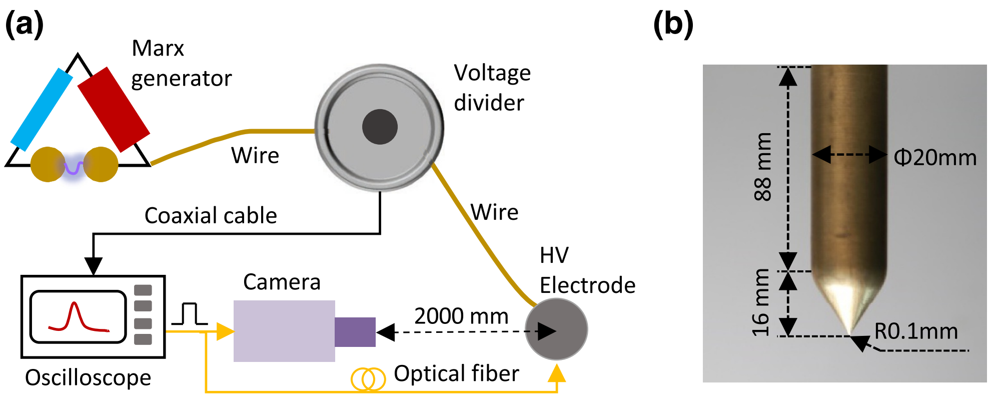

FIGURE 1 Experimental setups: (a) top view of the experimental arrangement (not to scale) and (b) electrode size

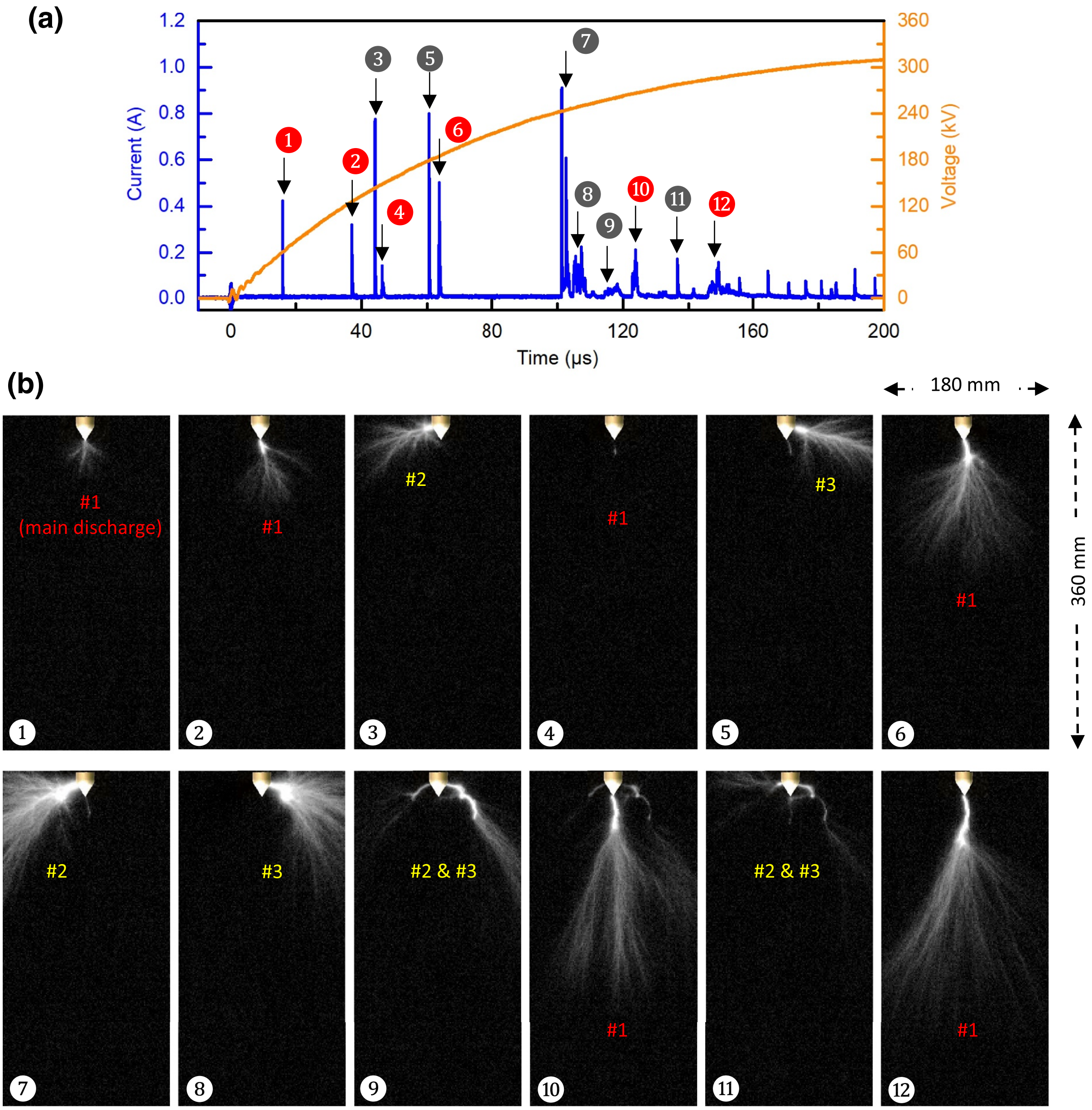

FIGURE 2 Typical experimental results. (a) Current and voltage waveforms. (b) High-speed images. The number of each frame corresponds to the current pulses marked with the same number in Figure 1a. Three discharges are numbered #1 ~ #3

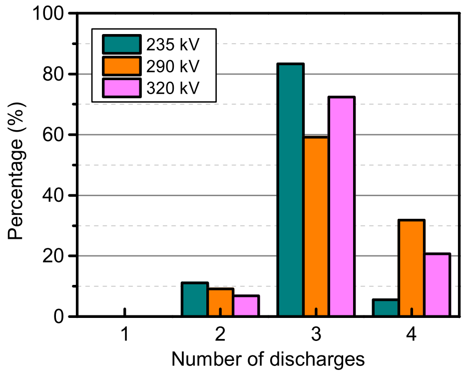

FIGURE 3 The ratio of the number of discharges for applied impulses with different amplitudes

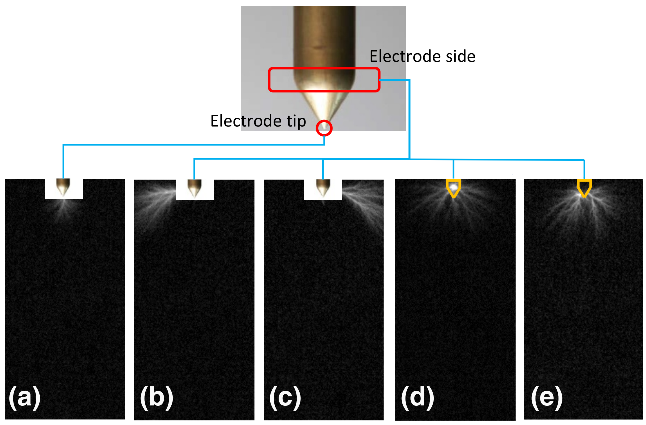

FIGURE 4 Typical locations where the discharge appears in the experiments: (a) electrode tip and (b)–(e) electrode sides

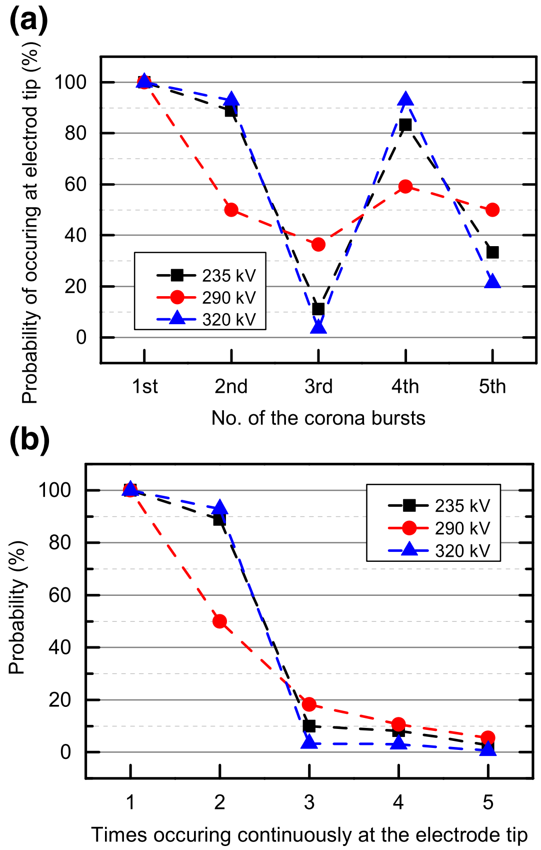

FIGURE 5 Probability of (a) first five corona bursts occurring at the electrode tip and (b) multiple consecutive corona bursts all occurring at the electrode tip

particular location, while subsequent pulses may be superimposed on multiple discharges, making it difficult to distinguish the timing of multiple discharges. For this reason, the first five corona bursts and their corresponding current pulses are chosen in the following analysis.

Figure 5a shows the probability of each of the first five corona bursts located at the electrode tip. The first corona burst always starts from the electrode tip (100% probability). The probability of subsequent corona bursts occurring at the electrode tip is less than 100% but will be larger for the second and fourth corona bursts than those for the third and fifth ones. The voltage amplitude has an effect on the probabilities whereas does not demonstrate a clear pattern. Figure 5b plots the probability of multiple consecutive discharges occurring at the electrode tip. The probability of five consecutive corona bursts in the same location is less than 10% and that of three consecutive ones is less than 20%.

To show the timing of the first five corona bursts more clearly, the patterns that appear in all experiments are counted. Taking the results shown in Figure 2b as an example, the corresponding discharge sequence should be #1-#1-#2-#1-#3 (abbreviated as #11213). Note that discharge #1 refers to one occurred at the electrode tip. As shown in Figure 5, the probability of the first corona burst occurring is 100% in this paper. #2 and subsequently numbered discharges indicate those occurring around the electrode side and do not correspond to a specific location, for example, discharge #2 may refer to any of those shown in Figure 4b–e. According to this naming convention, the statistical results of all discharges are shown in Figure 6. The sequence #11213, that is, tip-tip-side-tip-other side, has the highest probability even under different switching impulses. The voltage amplitude has some effect on the time sequence of multiple discharge occurrence, for example, more types of sequences appear at 290 kV with the same discharge number. Moreover, the second discharge is more likely to occur at the tip than at the side, although there is space charge shielding after the first corona burst at the tip. The reason may be that the charge of the first corona burst is less than 0.1 μC, with most of them less than 0.05 μC, and the shielding effect is limited. As the voltage amplitude increases, the space charge moves away from the electrode tip, resulting in a rapid recovery of the electric field around the electrode head [35] and second corona burst initiation at that location. The enhanced shielding effect, which is due to the space charge generated by the first few corona bursts, can lead to an increased probability of subsequent discharges occurring elsewhere.

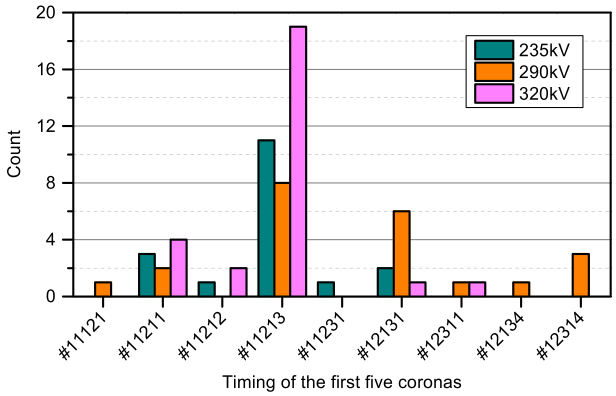

FIGURE 6 Patterns of discharge sequence for the first five corona bursts. Take #11121 for example, it is the abbreviation of #1-#1-#1-#2-#1. Discharge #1 can refer specifically to that at the electrode tip, while #2 and subsequent numbered discharges refer generally to those occurring around the electrode side and do not correspond to a specific location

3.4 | Characteristics of the first corona for each discharge

3.4.1 | Current waveforms

Figure 7a,c,e compare the enlarged current waveforms of first coronas for discharges #1–#3 (in Figure 2), respectively. For reference purposes, the current waveforms of second coronas are also presented in Figure 7b,d,f. The current waveforms of these three discharges exhibit similar pattern, that is, the first corona current is a single, double exponential pulse, while the second corona current is a superposition of multiple pulses, as also confirmed in other experimental results.

The rising time (t_r) and falling time (t_f) of the first corona current are determined by the method shown in Figure 7a. The time parameters of the first corona current for each discharge are shown in Figure 8. For discharge #1–#4, t_r (upper subfigures) increased gradually from 35.5 to 56.5 ns on average. Similarly, t_f (lower subfigures) increased from 352.9 to 821.7 ns. This implies that the later the discharge occurs, the longer time the streamers develop in the first corona.

3.4.2 | Charge

For discharges #1–#4 under different switching impulses, the charges of their first coronas are plotted in Figure 9. Note that the charge is obtained by current integration. At a given certain voltage amplitude, the average charge of the first corona for discharges #1–#4 gradually increases. For discharge #1 (red), there is no obvious relation between the first corona charge and the voltage amplitude, but as the voltage amplitude increases, the first corona initiates at an earlier time and the charge dispersion decreases. For discharges #2 and #3 (green and blue, respectively), the first corona charge is positively correlated with the voltage amplitude, for example, when the amplitude increases from 235 to 320 kV, the charge ranges from 0.087 to 0.100 μC and from 0.101 to 0.123 μC, respectively. Moreover, the average inception time of first coronas for discharges #2 and #3 is gradually advanced with an increase in amplitude. For discharge #4, it is not suitable for analysis due to the small number of experimental results. Overall, the first corona charge of discharges #2–#4 cannot be neglected relative to discharge #1 according to the results of our experiments.

4 | DISCUSSIONS

To the best of our knowledge, multiple discharges at different locations before leader inception are still lacking in the existing long spark tests and computational models. One of the reasons may be that in most tests, the second corona starts and the leader initiates at the same location after the first corona [17], and multiple discharges before leader inception do not exist. Another reason may be that some observations are too far away from the air gap [30, 31], where in most cases, it is difficult to distinguish multiple discharges in a small region around the electrode. Although experiments in this paper are carried out under some specific conditions, it is reasonable to speculate that the same situation may occur in other experiments when the rising rate of voltage or electric field is sufficiently small. Once the phenomenon described in this paper occurs, it may bring huge errors to some key parameters for the leader inception if some corrections are not made to the conventional methods.

First, let us discuss the effect of not considering the multiple discharges on determining the dark period and the voltage increment. Note that these two parameters should be determined for the same discharge, which generally refers to the main one. Herein, we take the results in Figure 10 as an example. The first dark period and the corresponding voltage increment should be defined between the first two adjacent discharges #1, which are 42 μs and 99 kV, respectively. However, if the conventional method [24] is followed, the above two parameters would be determined between discharge #1 and discharge #2 at the initial time, which are 27 μs and 68 kV, with errors of 36% and 31%, respectively. These are huge errors.

Second, the effect of not considering multiple discharges on the charge estimation before leader inception is discussed. The corona charge can be a critical criterion for leader inception. Gallimberti [24] argued that the criterion is 1 μC, while Wu [36] proposed 0.2 ~ 0.3 μC. Moreover, Wu [36] argued that if there are several corona bursts before leader inception, the above criterion also applies, and the charge of all corona bursts can be summed up. The essence of corona charge as a criterion for leader inception is the heating of the channel as the electrons pass through it, resulting in a temperature increase to 1500 ~ 2000 K [37, 38]. However, in some experiments (including this work), not all electrons pass through the main streamer stem, that is, some electrons do not contribute to the heating of the main stem channel. It can be seen from Figure 9 that the charge of discharges #2–#4 is not negligible compared to that of the main discharge (#1). If the distinction

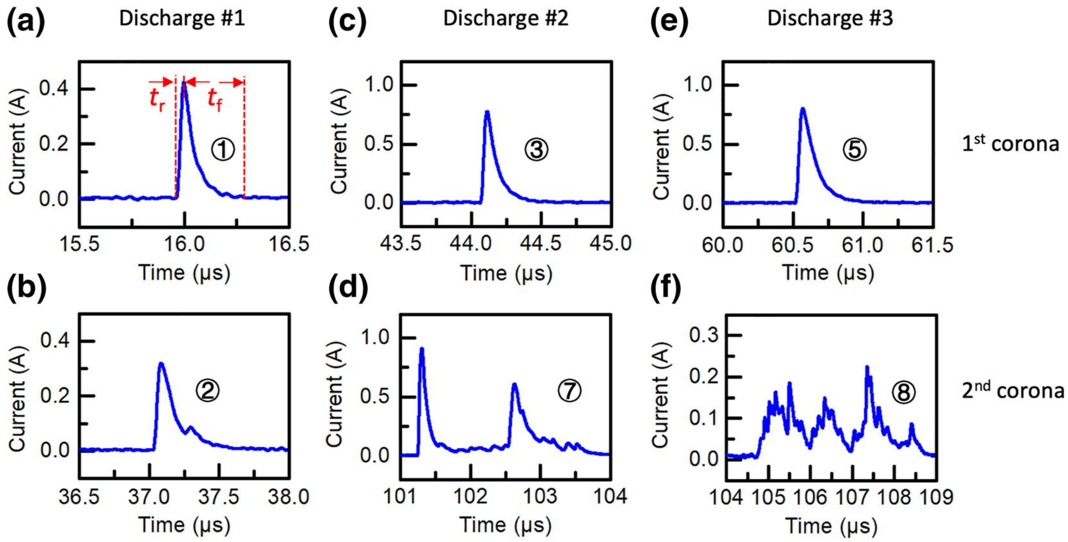

FIGURE 7 Typical current waveforms for (a) (c) (e) first corona and (b) (d) (f) second corona for each discharge. The number in each figure corresponds to the high-speed image marked with the same number in Figure 1b

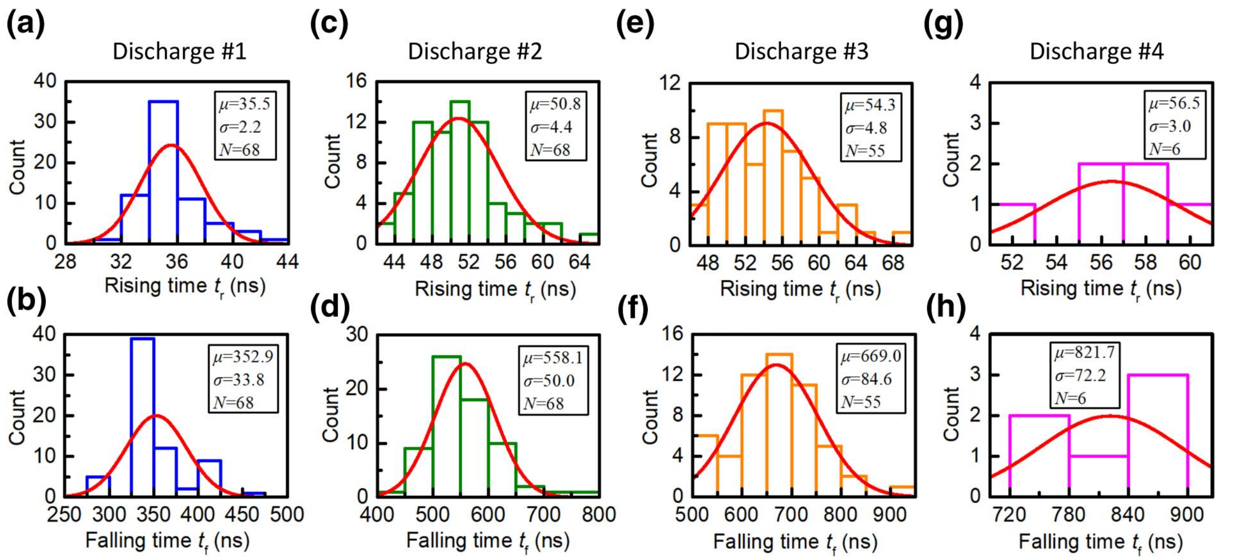

FIGURE 8 Histogram of the rising and falling times of the first corona current for (a)–(b) discharge #1, (c)–(d) discharge #2, (e)–(f) discharge #3, and (g)–(h) discharge #4: μ is the mean, σ is the standard deviation and N is the count

is not made, it may lead to a huge error for the corona charge counting before leader inception. Moreover, the discharges at other locations are closer to the main one, and the space charge there can affect the electric field at the main channel head, thus affecting the streamer discharge before the main leader inception. A detailed leader inception model, therefore, should consider all discharges and their complex interactions.

In summary, for the study on leader inception under positive switching impulses in the laboratory or upward leader initiation in natural lightning, this study suggests valuable recommendations. First, the photographic region should include the whole of the electrode and avoid focussing on only the electrode tip. This can help determine whether there are discharges in different locations. Second, if multiple discharges are unavoidable in the experiments, the influence of other discharges on the main one needs to be minimised in the subsequent analysis, especially for the validation of the leader inception model, which is usually not considered for multiple discharges. Third, the Schlieren photography is now widely used to study the thermal characteristics of discharge channels [39, 40]. The heating process of the channel is driven by the discharge current [37]. However, the observation range of Schlieren photography can only focus on an electrode tip area for better spatial and temporal resolutions, and it is somewhat challenging to determine whether other discharges are also present elsewhere. If multiple discharges exist and are not

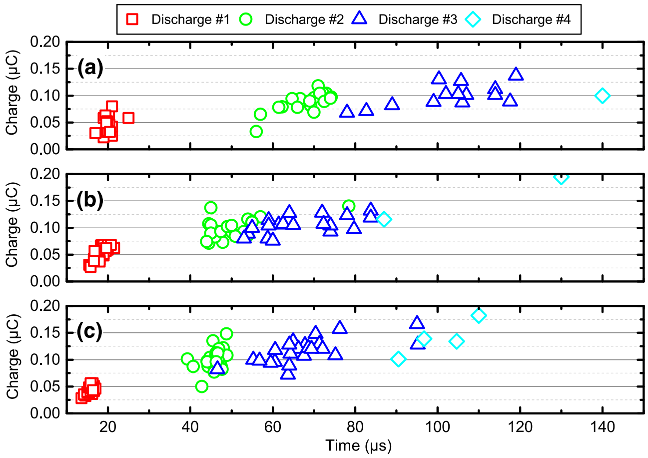

FIGURE 9 Charge of the first corona for each discharge under the impulses with different amplitudes: (a) U_m = 235 kV, (b) U_m = 290 kV and (c) U_m = 320 kV

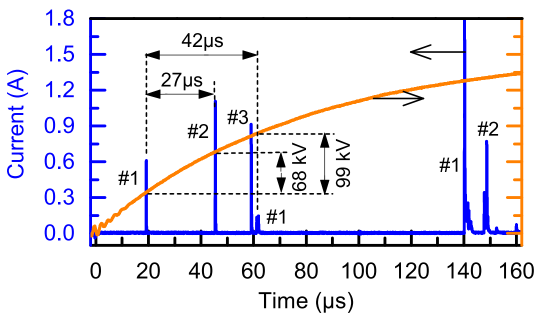

FIGURE 10 Current and voltage waveforms illustrating the statistical errors for the dark period and voltage increment

distinguished, all measured currents may be incorrectly used as excitation sources to simulate the thermal processes of the main channel. Therefore, it is recommended that the Schlieren photography and the direct photography should be applied together in long gap discharge observations.

The focus of this paper is to discuss the effect of multiple discharges on the experimental results of leader inception characteristics and to provide several practical suggestions. The premise of the above findings is that it is possible to identify the discharges at different locations. The best way to determine this is by means of high-speed images. However, the exposure time of high-speed images is less than the capture time of each frame, resulting in a dead time, for example, 1.54 μs in our experiments. If the discharge happens to be in the dead time, a misjudgement will happen based on the high-speed image alone. In this case, the current waveform can be used as a supplementary tool. As shown in Figure 7, there is a difference between the initial corona current and the subsequent current for each discharge. When the current has a single, double exponential pulse waveform, the first corona of a discharge at a particular location can be initially determined.

Multiple corona bursts under specific experimental conditions have been studied in this paper, with the aim of exploring its possible implications for studies on leader inception and dark period. The same phenomenon has also been reported in Ref. [41], where a lightning impulse voltage with a rise time of 1.2 μs was applied to a cone-shaped electrode of a different configuration to that used in this paper. From this, it can be inferred that the voltage waveform and electrode configuration can affect the characteristics of multiple corona bursts. The shorter the rise time of applied voltage, the more favourably multiple corona bursts occur. However, the effect of electrode configuration on the performance of multiple corona bursts is still unknown. Also, the influence of environmental factors is not clear. More experimental studies are needed to answer these questions.

5 | CONCLUSION

Experiments were carried out to study the multiple discharges before leader inception in a 1.4 m point-plane air gap subjected to positive switching impulses. The following conclusions can be obtained from the experimental results in this paper.

(1) In all experiments, the multiple corona bursts before leader inception are distributed in at least two different locations, and the highest probability of three discharges occurs.
(2) For the first five corona bursts, their positions with the highest probability are 'tip-tip-side-tip-other side' of the electrode. The probability of the first three corona bursts occurring at the electrode tip is less than 20% and that of the first five is less than 10%.
(3) For each discharge at different locations, the first corona current is a single, double exponential pulse, while the subsequent corona current is mostly a superposition of multiple pulses. Moreover, the later the discharge occurs, the greater the rising and falling times of the first corona current, where the average rising time varies from 35.5 to 56.5 ns and the average falling time correspondingly varies from 352.9 to 821.7 ns.

Although the above conclusions are based on the specific experimental conditions of this paper, it is reasonable to speculate that such phenomena would be relatively common in the long spark under the switching impulses with a long front time in the laboratory or the upward leader in natural lightning. To avoid unacceptable errors in the statistical results when studying the leader inception, it is suggested to distinguish the main discharge from other discharges through direct photography and current waveforms.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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