Relationship Between Brightness and Current of the Propagating Positive Leaders in Laboratory High Voltage Atmospheric Discharges

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ABSTRACT The discharge current of propagating lightning leaders is critical to understand lightning physics and to design lightning protection systems but almost impossible to be measured directly with present-day technology. In this paper, we have investigated the relationship between luminosity and discharge current of propagating positive leaders in laboratory high voltage atmospheric discharges. The continuously propagating positive leader channels were recorded by high-speed video frames. The brightness distribution of the propagating positive leader channel, which was evaluated by the gray value across the central line, obeyed a normal distribution. The mean grayscale pixel value of the propagating positive leader channel central lines obtained in high-speed video frames was compared with the average discharge current measured in the exposure duration of corresponding frames. There is a statistically significant linearity correlation between the discharge current and the channel luminosity of the propagating positive leader. The result further suggests a potential that the discharge current of propagating positive lightning leaders may be obtained based on the optical information observed in the time domain.

INDEX TERMS Lightning, leader, leader channel luminosity, discharge current, long air gap discharge.

I. INTRODUCTION

Lightning is the most impressive and commonly-experienced natural phenomenon. However, the cloud-to-ground (CG) lightning flashes, caused by electric charge imbalance between cloud and ground, are severe threats to the safety of ground facilities, especially for power systems. A CG flash could be comprised of two main components: the initial stage and the return stroke (RS) stage [1]. In the initial stage, the downward lightning leaders propagate from the thunder cloud to the ground, as a consequence, upward connecting leaders (UCLs) with opposite polarity initiate from the protruding ground objects, develop in the opposite direction with the downward leaders, eventually meet with the downward leaders. Then a channel connects the thunder cloud and the ground. In the RS stage, the electric charges with opposite polarities, accumulating in the thunder cloud and ground respectively, are neutralized through the channel formed in the initial stage resulting in a large RS current pulse [2]–[6].

In a CG flash, UCLs determine the lightning strike point. In natural CG flashes, most UCLs are positive leaders propagating continuously. So, understanding and modeling the dynamic process of positive UCLs is critical to design a proper lightning protection system. Several positive leader continuous propagation models have been proposed [7]–[10] and some of them have been applied to simulate the propagation of UCLs and analysis the efficiency of lightning protection measures [11]–[13]. In these models, the positive leader discharge current is an essential and fundamental feature.

Unfortunately, lightning’s occasional occurrence in space and time makes lightning particularly challenging to study [1]. Like many key features and processes of lightning leaders, the discharge current of propagating lightning leaders is almost impossible to be measured or obtained directly with...
This work shows that the brightness of propagating positive intensity and discharge current measured synchronously. The camera and to examine the correlation between the light and the optical observation date, the RS current peak could be calculated using the brightness ratios [17]. Recently, it was further reported that the distribution of branch currents could be calculated using the brightness ratios [17].

In the past, lightning optical observation data is provided mostly in the still graph form. The two components (the initial stage and the RS stage) of a CG are inseparable in a still lightning image, and indeed, the RS stage with larger electric current flowing along the plasma channel is more luminous. Therefore, the relationship between the intensity of emitted light in a lightning channel and its RS current pulse has been the main concern of static image-based research [15]–[19]. For the reasons mentioned above, even the RS current pulse is hard to measure directly in natural lightning observations. Meanwhile, lightning discharges have been proved to be governed by the same underlying mechanism as the laboratory high voltage atmospheric discharges [20]. Hence, the relationship between the return stroke current and optical signatures was mainly investigated in laboratory discharges or triggered lightning flashes. A strong correlation between the discharge channel luminosity and the RS current pulse peak has been reported in previous literature [15], [17], [18]. For the discharge channel with multiple branches, it was further reported that the distribution of branch currents may also be estimated based on the optical information obtained from the high-speed video frames.

In this work, we aimed to investigate the brightness of propagating positive leader channels in meter-scale laboratory high voltage atmospheric discharges using a high-speed camera and to examine the correlation between the light intensity and discharge current measured synchronously. This work shows that the brightness of propagating positive leaders is related to the leader discharge current. In the range of current magnitude relevant to this study, the relationship is approximately linear, suggesting a potential that the discharge current of propagating positive lightning leaders (like positive UCLs) may be obtained based on the optical information observed in the time domain.

II. METHOD
A. EXPERIMENTAL SETUPS
The experiments were conducted at the ultra-high voltage laboratory of State Grid Corporation of China, Hefei. The experimental setups are shown in Figure 1. A 4 m meter scale rod-plane gap was employed to produce positive leader discharges. During the experiments, positive impulse voltage pulses with 250 $\mu$s front time and 2500 $\mu$s tail time were generated by a 4.8 MV Marx voltage generator and applied to the rod. Positive leaders initiated from the rod tip and then propagated to the plane. The applied voltage impulses were measured using a capacitor voltage divider and recorded by a digital oscilloscope. A current shunt with an equivalent resistance of 5 $\Omega$ and a digital acquisition system were embedded inside the high voltage rod electrode to measure the discharge current. The main performance parameters of the current measurement system were as follows: -3 dB frequency bandwidth, DC to 18.3 MHz; sample rate, 2 GHz. A high-speed video camera (Photron FASTCAM SA) was arranged to record the dynamic process of positive leader discharges. The high-speed video camera equipped with a Nikon lens (50mm F1.2) was operated at sampling rates of 225000 frames per second (FPS) with an exposure time of 4.44 $\mu$s per frame. The high-speed video camera is read out with 12-bit resolution. The length of the shooting range and the resolution of the high-speed video frames were 2.7 m and 128 x 256 pixels respectively.

To examine the correlation between the discharge current and the brightness obtained from the high-speed video frames of the propagating positive leaders, the measured discharge current is processed and the optical observation date, the RS current peak could be estimated based on the optical data.

With the development of optical measurement technology, high-speed cameras with high temporal resolution (up to millions frame per second) were utilized to observe natural lightning flashes [22]–[26]. The initial and RS stage of a CG flash can be distinguished in different high-speed video frames. If there is a correlation between the current and brightness of propagating positive leaders, the discharge current of propagating positive UCLs may also be estimated as a function of time using a sequence of high-speed video frames recording the development of positive UCLs.

Hence, it is of interest to know the relationship between the luminosity and discharge current of propagating positive leaders. However, there is a lack of research investigating the brightness-current relation of propagating positive leaders.

In this work, we aimed to investigate the brightness of propagating positive leader channels in meter-scale laboratory high voltage atmospheric discharges using a high-speed camera and to examine the correlation between the light intensity and discharge current measured synchronously. This work shows that the brightness of propagating positive leaders is related to the leader discharge current. In the range of current magnitude relevant to this study, the relationship is approximately linear, suggesting a potential that the discharge current of propagating positive lightning leaders (like positive UCLs) may be obtained based on the optical information observed in the time domain.

FIGURE 1. Schematic diagram of the experiment setup. The experiments were conducted at the ultra-high voltage laboratory of State Grid Corporation of China, Hefei. The experiments were conducted on 14 October 2019. The absolute humidity was 13 g/m$^3$.
current and the high-speed video frames should be synchronized in the time domain and then the discharge current measured in the exposure duration of a frame could be extracted. In order to realize synchronization (shown in Figure 2), the starting time is defined as the time when the impulse voltage waveform applied to the rod begins to rise.

**FIGURE 2.** Schematic of the timing sequence of observation instruments. $t_0$ is determined by the oscilloscope trigger level set before each measurement. $t_1$ and $t_2$ are transmission delays. If these delays are obtained, the applied voltage waveform, the discharge current waveform and the high-speed video frames could be synchronized.

The oscilloscope recording the impulse voltage waveform was first triggered. Then a signal generated by the oscilloscope was sent to the current measurement system and the high-speed video camera as a triggering signal. All trigger signals were converted into optical signals and transmitted by optical fiber to avoid electromagnetic interference. The delay $t_0$ was measured in each discharge event and the transmission delays $t_1$ and $t_2$ were premeasured before the experiments. These delays were corrected in the data processing stage.

**B. DATA PROCESSING**

The brightness of propagating positive leaders is obtained from the digital high-speed video frames showing the propagating leader channels. These frames are color and consist of R, G, and B components. To evaluate the brightness of the propagating leaders, we have first converted the digital color high-speed video frames to the grayscale images. The brightness evaluation is based on the gray values matrix $Y$.

The gray values $Y$ on one pixel could be calculated as:

$$Y = 0.2989R + 0.5870G + 0.1140B$$

(1)

where $R$, $G$, and $B$ are the pixel values of the R, G, and B components in a digital color video frame. The maximum grayscale pixel value is 4095 (in 4096 levels).

The row number of the starting and ending point of the channel in the matrix $Y$ could be read out using the high-speed video camera viewer software. In each row containing the channel information in matrix $Y$, the column numbers of pixels whose gray values are greater than the 60% of the maximum gray value in the row were extracted. Assuming that the propagating positive leader channel is a cylinder, pixels with minimum and maximum column numbers were defined as the channel edges and the pixel with the median column number was defined as the channel center in the row. Channel centers in all rows containing the channel information form the leader channel central line. Figure 3 shows the typical grayscale image converted from the high-speed video frames showing the propagating leader channel and the gray values at the leader channel central line. These grayscale pixel values vary in a certain range.

**FIGURE 3.** Typical grayscale image and the grayscale pixel values on the pixels at the leader channel central line in the image.

Figure 4 shows the statistical distribution of these gray values at the leader channel central line. The mean gray value obtained from the statistical distribution is defined as the mean gray value of the propagating leader channel and used to evaluate the brightness of the propagating leader channel in this study.

The exposure duration of each high-speed video frame lasts 4.44 µs. Thus, the mean gray value obtained above is determined by the time-domain integrated illuminance of the propagating leader in the exposure duration. However, the leader propagation is continuous, and thus the leader discharge current is continuous and varies with time in the exposure duration of each frame. Figure 5 shows the typical leader discharge current. To study the relationship between the propagating leader brightness evaluated based on discrete high-speed video frames and the continuous leader discharge current in time domain, the average discharge current in the exposure duration of the corresponding high-speed video frames is calculated as:

$$I_{ave} = \frac{\int_{t_1}^{t_2} i(t) \, dt}{(t_2 - t_1)}$$

(2)
where $t_1$ and $t_2$ are start time and end time of the exposure duration of the corresponding frame respectively (shown in Figure 5). The average discharge current is compared with the mean grayscale pixel value of the propagating leader obtained from the corresponding frame.

III. RESULTS

A. TYPICAL RESULT

The high-speed video frames and leader discharge current of a typical leader discharge is shown in Figure 6. The first corona discharge emerged from the rod electrode at about $t = 13 \mu s$ and was captured by the frame $a$. Then a dark period without any discharge activity appeared. In the dark period, the stem of the first corona continues to transit to the leader as the channel temperature increases. After the dark period, the positive leader initiated from the rod electrode at about $t = 21 \mu s$ and continuously propagated to the grounded plane. The dynamic process of the leader propagation was captured by the frames from $c$ to $y$. During the leader propagation, there were four restrikes characterized by the intense illumination, abrupt channel elongation, and large current pulse. The intense leader channel illuminations were captured by frame $j$, $m$, $p$ and $s$, and the current pulses were measured.
At $t = 54 \mu s$, $67 \mu s$, $79 \mu s$, and $90 \mu s$ respectively. At about $t = 120 \mu s$, the leader corona leading the propagation of the leader channel contacted with the grounded plane, then the leader discharge entered the phase termed final jump. At about $t = 126 \mu s$, the leader channel connected the rod electrode with about 1.2 MV high voltage and the grounded
plane with zero potential, a great current flew from rod electrode to the ground through the leader channel.

Before about $t = 120$ $\mu$s, the leader propagation is governed by the physics underlying the positive lightning leaders (such as UCLs) propagation. After about $t = 126$ $\mu$s, the phase is governed with the same physics with the RS stage of natural lightning. The relationship between the current and brightness of the RS stage have been researched in detail in natural lightening and in laboratory discharge experiments by previous studies. Only the positive leader propagation phase is the focus of this work.

From the high-speed video frames shown in Figure 6(b), it can be seen that the propagating leader channel emitted more light in some frames, such as $j$, $k$, and $s$. In the exposure duration of these frames, the amplitude of the discharge current was significantly larger than it in the exposure duration of other frames. It seems that the luminosity of the propagating leader channel is related to the leader discharge current. To examine the relationship between the luminosity and the discharge current of the propagating leader channel, the mean gray value of the propagating leader channel was obtained based on the statistical distribution of gray values on the pixels locating at the leader channel central line in high-speed video frames recording the leader propagation.

Figure 7 shows the gray values and its statistical distribution on the pixels locating at the leader channel central line in typical frames ($j$, $k$, $s$, and $w$), which records the leader propagation. The leader channel shown in frame $j$ and $k$ is brighter than the leader channel shown in frame $k$ and $w$. But in all frames shown in Figure 7, the statistical distribution of the gray values at the leader channel central line obeys a typical Gaussian distribution. That suggests that the type of the statistical distribution of gray values at the propagating leader channel central line is independent of the luminosity of the channel. The mean gray values of the propagating leader channel obtained from the frame $j$, $k$, $s$, and $w$ is 572, 86, 698.8, and 153, respectively.

Note that the head of the propagating leader channel was often the brightest part of the whole channel and the brightness of the rest of the propagating leader channel was generally uniform. But compared to the length of the rest of the leader channel, the length of the head of the propagating leader channel was usually short. The high gray value on the pixels locating at the leader tip has no significant effect on the Gaussian distribution.

The high-speed video frames were aligned with the discharge current and the average discharge current in the exposure duration of each frame recording the leader propagation process was calculated using the method described above. The mean gray value of the propagating leader channel and the average discharge current obtained in the exposure duration of the same frame was compared. The mean gray values of the leader channel and the average discharge currents in the exposure duration of all frames recording the positive leader propagation are shown in Figure 8. The mean gray value of the leader channel shown in the frame $w$ was maximum, and it can be seen from Figure 6 that the leader discharge current measured in the exposure time of Frame $w$ was also the largest (the average discharge current in this duration was about 1.29 A). Correspondingly, the mean grayscale pixel value of the leader channel shown in the frame $k$ was minimal, and the leader discharge current measured in the exposure time of Frame $k$ was also the smallest (the average discharge current in this duration was about 0.51 A). It can be seen that the variety of the discharge current and the variety of the leader channel brightness show strong consistency, which implies that there is a linearity correlation between the channel luminosity and discharge current of the propagating positive leader.

**B. STATISTICAL RESULT**

To further examine the linearity correlation between the discharge currents and the channel luminosity in the propagation process of positive leaders, 5 positive leader discharge events were produced and observed in this study. In these events, 96 frames recording the propagation of positive leaders were obtained and the mean gray values of the leader channels were extracted. In the other 33 frames, the propagating leader channels are unfortunately out of the shooting range. Figure 9 shows the correlation of the propagating leader channel luminosity obtained from high-speed video frames and average discharge currents during the exposure duration of corresponding frames. In the range of current magnitude relevant to this study (from 0.2 A to 3 A). It seems that the relationship is approximately linear. The statistical analysis was conducted and the Pearson’s R value is 0.922. As the value is greater than 0.8, there is a statistically significant linearity correlation between the discharge current and the channel luminosity of the propagating positive leader.

**IV. DISCUSSIONS AND CONCLUSION**

During the propagation of leaders, the magnitude of currents (from several Amperes to tens of Amperes) is significantly
In summary, the results reported in this paper show the statistically significant linearity correlation between the discharge current and the channel luminosity of the propagating positive leader. The result further suggests that the discharge current of propagating positive lightning leaders, which is critical to establish the positive lightning leader propagation model evaluating the efficiency of lightning protection systems and almost impossible to be measured directly with present-day technology, may be obtained based on the inversion of leader channel luminosity which can be easily measured in the time domain.

\[ P = E \times I \times L \]  

(3)

where \( E \) is the electric field along the leader channel, \( I \) is the discharge current flowing the leader channel, and \( L \) is the length of the propagating leader channel segment. At different moments of the positive leader propagation, the length of the channel segment covering one pixel on different frames is constant. Assuming that 10% of \( P \) is released by light emission, the strong correlation between the brightness and discharge current of the propagating positive leader suggests that the electric field along the leader channel is constant. Previous studies had documented that the electric field along the positive leader channel is approximately constant (about 400~500 kV/m) [2]. Only when the positive leader channel is very long, the electric field along the channel will decrease significantly. As a result, some models evaluating the efficiency of lightning protection systems also accept the assumption that the electric field along the leader channel is constant [10], [29]. That can explain the results reported in this paper.

On the other hand, from the view of microphysics, the results reported in this paper can also be further understood. The current flows through the leader channel, the electron density in the channel is maintained at a certain level. The collisions between the electron and air molecules occur. A fraction of these collisions excites electronic states such as N2(B3Πg) and N2(C3Πu). These electronically excited states undergo radiative deactivation and produce emission known as First Positive System (FPS) and Second Positive System (SPS) respectively [30], [31]. When the current flowing through the leader channel is larger, the electron density in the channel will be larger, the collision will be more intense, and the emission process of light associated with the channel will be more intense. That may interpret that why the brightness of leaders is related to the leader discharge current.

A numerical model that can explain the linearity correlation between the luminosity and current of the propagating positive leader is critical to understand the physical mechanism underlying the relationship. Unfortunately, even for the RS stage, numerical models describing the relationship between the luminosity and RS current is still not perfect. Only in recent literature, a macroscopic physical model for calculations of RS currents and its optical emissions had been proposed [14]. The model assuming that 10% of the electric power energy consumed by the discharge channel is released by light emission according to the previous studies. For the leader channel segment, the consumed electric power energy is given by:

\[ P = E \times I \times L \]  

Where \( E \) is the electric field along the leader channel, \( I \) is the discharge current flowing the leader channel, and \( L \) is the length of the propagating leader channel segment. The model assuming that 10% of \( P \) is released by light emission, the strong correlation between the brightness and discharge current of the propagating positive leader suggests that the electric field along the leader channel is constant. Previous studies had documented that the electric field along the positive leader channel is approximately constant (about 400~500 kV/m) [2]. Only when the positive leader channel is very long, the electric field along the channel will decrease significantly. As a result, some models evaluating the efficiency of lightning protection systems also accept the assumption that the electric field along the leader channel is constant [10], [29]. That can explain the results reported in this paper.

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**FIGURE 9.** Correlation between the mean leader channel luminosity obtained from high-speed video frames and average discharge currents during the exposure duration of corresponding frames.
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