Phenomena of Parallel Discharges and Flashovers in Lightning Triggered to Conventional and Non-conventional Lightning Rods

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Experiments of rocket-triggered lightning to a conventional lightning rod and a non-conventional Semiconductor Lightning Eliminator (SLE) were conducted in summers of 1998 and 1999 in southern China. Totally 16 lightning flashes were triggered and measured successfully. The measurements included photographs, currents and electrical fields. From the 5 lightning flashes triggered in altitude in 1998, it was found that these flashes tended to strike at the 4 m high conventional lightning rod rather than the 6 m high SLE located just 5 m away from the former. From the 11 lightning flashes triggered dedicatedly to the SLE in 1999, it was found that there were usually a phenomenon of parallel discharges between two or more SLE rods occurring during the developing stage of lightning. In addition, there were always flashovers occurred along the SLE rods struck by lightning. Current measurements on the grounding path of the SLE have been succeeded for only one case out of five struck the SLE, probably due to side-paths caused by flashovers. The peak current measured for that case was about 6.6 kilo-amperes. The results show that the SLE is neither superior to a traditional lightning rod in terms of provision of lightning attachment points and paths for the lightning current to flow into ground, nor capable to eliminate any possibility of lightning. The lightning current-limiting function of the SLE declared by the manufacturer was not confirmed by these experiments.

Keywords : triggered lightning, non-conventional lightning rod, parallel discharge, flash over

1. Introduction

In recent years, various nonconventional lightning protection systems have been deployed and applied to limit damage from lightning. However, there has been controversy about their working principle as well as their effectiveness in practice superior to conventional lightning rods. One typical example is the so-called Semi-conductor Lightning Eliminator (SLE) developed and applied in China recent years. The SEL is composed of several semiconductor rods distributed radically on a conductive base. Each rod is 5 m long with 4 metallic tips on its top and has a resistance of 35 kilo-ohms⁽¹⁾. The manufacturer declared that the SLE can eliminate upward going lightning discharge and lighten the damage of downward going lightning discharge due to its current-limiting function.

There are two basic approaches in examining a lightning protection facility. One is by means of long-gap discharges in high-voltage laboratories⁽²⁾⁻⁽⁴⁾. The laboratory gap discharge, however, is considerably smaller in both the scale and current than the natural lightning. In addition to the laboratorial test, the artificially triggered lightning technique, especially the triggered lightning in altitude provides a unique means for investigating the function and effectiveness of a lightning protection facility in

field⁽⁵⁾⁻⁽⁷⁾.

To test and compare the function of both the conventional lightning rod and the nonconventional SLE in field, experiments of triggered lightning were conducted in southern China in the summer of 1998 and 1999. This paper briefly reports the experiment results and some interesting phenomenon observed during the triggering lightning campaign.

2. Instrumentation and Measurements

In 1998, the so-called altitude-triggering lightning technique was adopted to compare the lightning acceptance between the SLE and conventional lightning rod. The conventional lightning rod was a 4 m high copper rod, with 6 launchers placed symmetrically around it (Figure 1). The SLE system was located 5m away to the right of the conventional lightning rod. The SLE was composed of

Fig. 1. The deployment of the conventional lightning rod and the rocket launchers around the lightning rod in 1998

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9 rods arranged orthogonally in two directions and was mounted on the ground through 4 isolators. Each rod was made of a special material, being 5m in length and 35 kilo-ohms in resistance, and had 4 metal tips with 20cm in length on its top. The resultant height of the SLE was about 6m, which is 2m higher than the conventional lightning rod. The altitude-triggering lightning technique used in the experiment was similar to that employed in the triggered lightning experiment at Camp Blanding, Florida⁽⁸⁾. After launching the rocket first spooled out about 100 m of electrically insulated nylon cable from the bobbin attached to the rocket tail, and then a steel wire (0.2 mm in diameter) was unreel. Photography and electrical field measurements were carried out at two sites. Site 1 was about 60m away from the launchers and site 2 about 1.3 km away from the launcher. Details of the measurement arrangements were given in that of Chen⁽⁹⁾.

In 1999, the experiment was focused on testing the SLE itself and the current measuring system. Figure 2 shows the experiment setup. A set of SLE similar to that used in 1998 was mounted on an 8.5 m high steel tower through 4 isolators and was grounded by using a steel pipe down through the center of the tower. To facilitate the data analysis, we symbolized the SLE rods with numbers 1, 2, 3, 4 and 5 and letters a, b, c, d and e respectively as shown in the figure. The rockets used to trigger lightning were placed around the tower on the ground. The steel wire trailing by each rocket was connected to one of the SLE rods via a 6 m long nylon cable to ensure the SLE of being struck by triggered lightning. A Rogowski coil and a shunt with a resistance of 5.47milli-ohms were used to measure the lightning current flowing on the grounding steel pipe at the center of the tower. The signal from the Rogowski coil was recorded directly by an oscilloscope at a sampling rate of 400 kHz and a recording length of 150 milliseconds per event. The output of the shunt was transmitted through an optical fiber system to a tent located 90 m away from the SLE, and was recorded there on an oscilloscope at a sampling rate of 5 MHz and a recording length of 3.2 seconds per event. The electric field changes produced by the triggered

lightning were measured simultaneously at two sites (60 m and 1.3km away from the SLE respectively) by using two identical flat-plate slow antenna systems with a band-width of 4 Hz ~ 1.5 MHz, a sampling rate of 12.5 MHz, a digital resolution of 12 bit and a recording length of 2 Mega words per event). The optical images of lightning channel were recorded by using still cameras and video cameras in two orthogonal directions. A high speed video camera with a speed of 1000 frames per second was placed 1.3 km away from the SEL to observe the development of the whole lightning channel.

3. Data Analysis and Results

3.1 Attachment Process of Triggered Lightning to the Lightning Rod In 1998, total of 5 successfully triggered lightning flashes were obtained on 22 August during a period of 20 minutes when the electric field intensity on the ground was about -6 to -10 kV/m, corresponding to negative charge overhead. Table 1 is a summary of these flashes. Based on detailed analysis of the optical and electrical measurements in that of Chen⁽⁹⁾, it was found that these five triggered lightning flashes have similar developing process as following. When the rocket reaches a sufficient height, a bi-directional leader system initiates from the two extremities of the wire unreel from the rocket. That is a positive leader is initiated from the top of wire and propagates toward the cloud negatively charged, while a downward negative leader is initiated from the bottom of wire and propagates toward the ground. When the downward negative leader approaches the ground, an upward connecting positive leader is stimulated from the ground or the lightning rod. A mini-return stroke occurs when the downward negative leader meets the upward connecting leader. Then the mini-return stroke propagates along the trail of the melt wire and the positive leader previously initiated from the top of wire towards to the cloud. When the mini-return stroke wave reaches the charge center inside the cloud, a continuous current process is initiated. Following the continuous current process, some of downward dart leader/upward return stroke sequences traverse the same path. It is such a special developing process of altitude-triggered lightning that provides a close simulation of the downward leader and ground attachment processes in natural lightning.

Two triggered lightning discharges among them, 9802 and 9804, have struck the lightning rod. Figure 3(a) shows a still picture of case 9804 taken 1.3km away from the lightning rod. The bright straight part with a length of about 250m of the lightning channel is formed by the vaporized residue of the wire and the other parts are the lightning channel in the air. As seen from the figure, the very lower part of the lightning channel has changed the direction from a relative vertical one into a slant one at a height of about 30 m above ground. This lower 30 m channel bent is eventually due to an attachment process of the triggered lightning to the lightning rod there. Figure 3 (b) shows the still picture of case 9802 taken

Fig. 2. The deployment of the experiment in 1999 (SLE rod 3 and c are the same one)

Table 1. Summary of the 5 triggered lightning flashes in 1998

Flash No.	Triggered Time	Triggered Height(m)	Return Strokes	Attached to Lightning Rod
9801	16:41:48	276	2	No
9802	16:45:55	553	4	Yes
9803	16:52:22	387	0	No
9804	16:55:25	276	0	Yes
9805	17:00:48	332	9	No

60 m away from the lightning rod. It can be seen that when lightning path is approaching to the ground, it has changed the direction from vertical to slant towards the lightning rod at a height of about 15 m above and a horizontal distance of about 14 m away from the tip of the lightning rod. Three return strokes of this flash have changed the direction once again when they are at the height of 6 m above ground and have connected to the lightning rod eventually, and one return stroke has struck a rocket launcher 2 m away from the lightning rod. The change of the lightning path near the ground is obviously due to the attachment process between the lightning rod / launcher and the downward leader preceding each of the return strokes. It is worthwhile to mention that SLE was at just 5m away from the lightning rod and its top was taller than that of the lightning rod, but the triggered lightning would rather choose the lightning rod to strike. Nevertheless, some discharging sparks have been observed above the SLE rods when the electric field intensity on ground is more than -4 kV/m.

3.2 Parallel Discharges between SLE Rods In 1999, the triggered lightning experiment was dedicatedly conducted to test the SLE. The general information of the experiment is summarized in Table 2. Totally 11 triggered lightning events with meaningful data recorded (photographs, electrical field changes or/and currents) have been obtained. The range of electric fields on ground just before the launching of rockets was between -9 and -18 kV/m. The triggering heights were in a wide range between 25 m and 509 m. Among the 11 events, there are 8 cases with bright main discharging channels formed and 5 out of the 8 struck onto

the SLE. The other 3 cases have no main discharging channel formed but have local discharging sparks appeared at the SLE rods.

Figure 4 shows the video pictures taken 60m away from the launcher for event 9902 that has struck the SLE with main discharging channels formed. A local parallel discharge firstly occurred between the SLE rods 4 and 5 after the rocket was launched (Fig. 4(a)). One second later, the main lightning channel was formed and struck on another rod with flashovers occurred along the rod surface (Fig. 4(b)). Unfortunately the current of the discharge was not obtained probably due to that the current flew into the ground via the tower legs rather than the grounding pipe that was equipped with the current recording system.

It is interesting that for the 3 events 9905, 9909 and 9910, although no main discharging channels were formed, the so-called parallel discharges between SLE rods and flashovers along SLE rod surfaces have been still observed. In event 9905, the parallel discharge occurred between the rods c and d even lasted about 3.42 seconds. In event 9910, spark discharges at the tip of and flashovers along the surface of the rod e were observed by using a video camera at 60m away. The corresponding currents with small magnitude for the sparks in event 9910 were also recorded by the Rogowski coil systems (Fig. 5(a)). There are three pulses in the current waveform shown in the figure. The pulse A has a width of about 1.2 ms and a peak of 3.8 amperes (Fig. 5(b)). The pulse B appears about 130 ms later after the pulse A, with a width of 0.1ms and a peak of 4 amperes (Fig. 5(c)). The pulse C occurs about 70 ms later after the pulse B, with a width of more than 25

Fig. 3. The still camera pictures of (a) event 9804 taken at 1.3 km away from the lightning rod and (b) event 9802 taken at 60m away from the lightning rod, showing the attachment process of lightning on to the lightning rod

Fig. 4. Video pictures for event 9902, showing (a) the parallel discharge between rods 4 and 5 prior to the main discharge, and (b) the main discharge channel and the flashovers along the SLE rod formed 1 second later after the (a)

Table 2. Summary of the triggered lightning flashes for testing the SLE in 1999

Flash No.	Time, date	Wire spooled (Nylon + wire)	Main channel	Struck SLE	SLE responses (type: rod)	Triggered Height	Return Strokes	Current (kA)
9901	16:55:43, Jun 3	4m + 570m	yes	rod e	F: e	33m	0	
9902	16:57:47, Jun 3	5m + 630m	yes	rod c	F: c, PD: 4 & 5	145m	0	
9903	17:02:35, Jun 3	4m + 800m	yes	no	LD: SLE base		-	
9904	17:10:00, Jun 3	90m + 615m	yes	no	No		2	
9905	20:07:50, Jun 18	6m + 490m	no	-	PD: c & b, LD: SLE base		-	
9906	21:18:38, Jul 10	6m + 490m	yes	rod c	F: c	445m	2	
9907	21:54:12, Jul 10	6m + 35m plus 40m + 420m	yes	no	No	509m	-	
9908	22:08:25, Jul 10	6m + 488m	yes	rod 2	F: 2	131m	9	>2.8
9909	10:50:00, Jul 15	6m + 491m	no	-	F: 4, PD: 4 & -			
9910	15:59:49, Jul 18	6m + 492m	no	-	F: e	117m		
9911	16:01:52, Jul 18	6m + 497m	yes	rod c	F: c	25m	2	>6.6

* F: flashover, PD: parallel discharge, LD: local discharge.

Fig. 5. Currents for event 9910. (a) is the whole waveform and (b), (c) and (d) are expansions of pulses A, B and C in the (a) respectively

Fig. 6. Two video pictures for event 9908, showing the lightning firstly struck the steel tower (a) and then the base of the SLE with flashovers along the rod respectively

ms and a peak of 18 amperes, which is in consistent with a charge neutralization of about 0.18 columns (Fig. 5(d)). These current values may be seen, to some extent, as the thresholds for the occurrence of flashover / parallel discharges among the SLE rods. It can be inferred that as the rocket was rising, negative charges were accumulated at the bottom of wire spooled by the rocket and local electric field was intensified. It is this kind of intensive electric field that has triggered spark discharges on the SLE rods. The phenomenon of parallel discharges between SLE rods may be due to the large potential difference between the resistive rods under an intensive electrical field environment.

3.3 Flashover Current through the SLE Flashovers along the SLE rods have been observed for all the 5 events struck the SLE with main discharging channels formed and for 2 out of the 3 events with no main discharging channels. Among the 5 events struck the SLE, current waveforms have been recorded for only the events 9908 and 9911. A possible reason for no current records is probably that the currents for the other 3 events have flowed into the ground entirely via the tower legs due to flashovers between the SLE and the steel tower.

Figure 6 shows 2 video pictures for the event 9908. The lightning firstly struck onto the steel tower (Fig. 6(a)) and then onto the base of the SLE (Fig. 6(b)). The current waveform recorded has an abnormal shape with a peak of just about 2.8

Fig. 7. A video picture for event 9911, showing the lightning struck the SLE at rod c and the flashover occurred along the rod surface

Fig. 8. The current waveform recorded for event 9911

kilo-amperes, probably due to that most of the current has flowed into the ground via the tower legs.

Figure 7 is a video picture of the event 9911 showing the flashovers on the SLE rod c. The whole current waveform recorded for this event is shown in Figure 8. Further expansion of the current waveform shows that the discharge includes a mini-return stroke followed by a continuous current process and two return strokes with a total lasting time of about 500ms⁽¹⁰⁾. The mini-return stroke lasts about 3 microseconds with a peak current of 914 amperes, which is corresponding to a neutralized charge of just 1.5 milli-columns. The continuous current process, occurred 100 ms after the mini-return stroke, lasts about 435 ms with a peak current of 440 amperes, which is corresponding to a neutralized charge of about 58 columns. Some pulses superposed on the continuous current are believed to be M components and the largest one has a peak of about 300 amperes. There is a current quiet period of 36 ms after the continuous current. After that are 2 return strokes occurred successively in a time interval of 21ms. The first return stroke has a peak current of about 6 kilo-amperes with a front rising time of about 2 microseconds. The second return stroke has a peak current saturated at about 6.6 kilo-amperes. The detailed characteristics derived for these 2 return strokes are in agreement with that in natural lightning⁽¹¹⁾. The lightning current-limiting function of SLE claimed by its manufacturer has not been confirmed when it was struck by triggered lightning but the flashover phenomenon.

4. Summary and Discussion Altitude-triggered lightning experiment aimed to compare the response to lightning of the so-called "Semiconductor Lightning Eliminator (SLE)" with the traditional lightning rod was conducted in 1998. Two out of the 5 succeeded triggered lightning flashes have struck at the 4

m high lightning rod with clear attachment processes photographed. None has struck at the 6 m high SLE system located just 5m away from the lightning rod. Nevertheless, some discharging sparks have been observed on the SLE rods when the electric field on ground was more above -4kV/m . Such a result shows, at least for these 5 triggered lightning flashes, that the SLE is neither superior to a traditional lightning rod in terms of provision of lightning attachment points and paths for the lightning current to flow into ground, nor capable to eliminate any possibility of lightning within its protection zone. Similar views is given by Uman and Rakov⁽¹²⁾ who reviewed critically the nonconventional approaches to lightning protection including various dissipation array systems (DAS) or charge transfer systems (CTS) and early streamer emission (ESE) systems.

Triggered lightning experiment dedicated to test the performance of the SLE was conducted in 1999. Totally 11 triggered lightning events with data recordings have been obtained. Among these 8 events have bright main discharging channels formed with 5 struck the SLE rods. The other 3 events have no main discharging channels formed, however, have caused local spark discharges or flashovers at the SLE rods. Flashovers along the SLE rods have been observed for all the 5 cases struck the SLE and 3 other cases. In addition to flashovers, so-called parallel discharges between two or three SLE rods have been observed for 2 cases struck the SLE and 2 other cases. The phenomena of parallel discharges between and flashovers along the SLE rods are obviously due to the large potential gradient between / along the resistive rods when a current with certain amplitude flows on the SLE rods. Measurements of the current on grounding system of the SLE have been succeeded for only case, probably due to that the current paths in most cases are other than the grounding system because of flashovers. The peak current for one stroke recorded is more than 6.6 kilo-amperes. Similar experiments are those of Horii et al.⁽⁵⁾ and Teramoto et al.⁽⁶⁾ who tested the performance of the SLE rods and a sort of lightning rod with high resistance by using the triggered lightning technique in fields and the high voltage long-gap discharge technique in laboratories in Japan. Small currents were measured when the flashover did not occur along the surface of the resistance element in one out of four cases. However the initiations of upward leader from the tip of SLE were restrained in some extent and the some characteristics of triggering lightning discharges might be influenced due to the high resistance of the SLE. The experiments are not enough to obtain a certain answer for the effectiveness of the SLE. However, some phenomena observed are very helpful for the understanding of interaction between lightning and air terminals and for the improvement of existing lightning protection approaches.

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