Lightning Problems in the Region and Semiconductor Lightning Current Extender (SLE)

PROGRAMME

1.30 pm	Arrival of Guests
1.50 pm	Arrival of Guest Speakers (1) Professor Liew Ah Choy (2) Professor Chen CiXuan Guests to be seated
2.00 pm	Welcome Address – Reuben Tan
2.05 pm	VCD Presentation
2.10 pm	Lightning Problems In The Region Professor Liew Ah Choy Chairman of Singapore Lightning Protection Code Committee
2.50 pm	An Introduction to SLE – A Revolutionary Concept to Lightning Protection Professor Chen CiXuan Co-Inventor of Semiconductor Lightning Current Extender (SLE)
3.15 pm	Questions and Answer Session
3.30 pm	Product Exhibition
3.40 pm	Buffet Reception
4.30 pm	End of Seminar

By

TopCan International Pte Ltd

LIGHTNING PROBLEMS IN THE REGION

AND

SEMICONDUCTOR LIGHTNING CURRENT EXTENDER

(SLE)

Triggered Lightning Test to a New Type of Lightning Rod

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Triggered Lightning Test to a New Type Lightning Rod

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Abstract

Conventional type of lightning rod has negligible small resistance. Once the lightning strikes the rod, the most charges in the cloud can instantly be discharged to the ground. Can the discharge current be limited by resistance, if the lightning rod has some finite value of resistance? As a lightning rod with large resistance, SLE (Semiconductor Lightning Eliminator) is reportedly applied in China. The authors have composed a prototype lightning rod with high resistance, taking into consideration of SLE. The outdoor tests were carried out by the rocket triggered lightning approach in which the lightning discharge was artificially conducted to top of the rod. When the flashover did not take place along the surface of the resistance element, small current was measured, which corresponds to the current limiting.

1 Concept of Current Limiting Rod

This new type lightning rod is based on SLE invented in China. Figure 1 shows the concept of current limiting by lightning rod with high resistance.

1. Due to the voltage drop across the resistance ($V_1 = RI_r$), the initiation of return stroke or the farther propagation of upward leader may be restricted, if the breakdown voltage V at the top of their channels is $|V_2 - V_1| < V$, where V_2 is the electric static potential at the same point.

2. Even if the upward leader reached the cloud, the big discharge so as to instantly neutralize the whole charge in the thundercloud may not occur because the discharge current is supposed to be limited and the further development of the leader into other clouds is also restricted by the resistance. Therefore, the limited lightning current will be flowing through the rod for comparatively long duration.

If the flashover occurred along the surface of the rod, however, current restriction cannot be expected any more because the resultant resistance of the rod becomes extremely small. In this experiment, the optimum value of resistance has been investigated by lightning discharge test using a rocket triggered approach. here, we used water including $CuSO_4$ as conductive material for the prototype lightning rod. Considering the long term use, such a high resistance lightning rod is recommended and must be made of ceramic materials to endure the lightning discharge current.

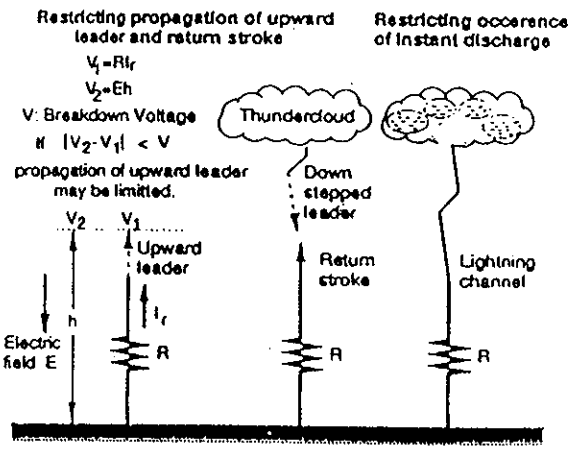

Figure 1: Concept of current limiting by a lightning rod with high resistance

2 Triggered Lightning to the Rod

Figure 2 shows the arrangements of the current limiting lightning rod. The lightning discharge is directly led to the top of the rod. The total length of the body was 4.25m. Outer and inner diameter was 70mm and 40mm, respectively. The body consists of polymer insulator, filled with water resistance inside. On the top of the rod a metal ball electrode was placed and the steel wire was directly connected. The pre-discharge

and main discharge currents were measured and data were recorded. Before the lightning discharge experiment, the laboratory test was carried out. Figure 3 shows the arrangements of laboratory test. Impulse voltage was applied. According to the results, the flashover voltages were almost constant around 500kV/m as shown in Figure 4. Figure 5 indicates the characteristics of the limited current vs. resistance in case of no flashover discharge. The critical current was very high under the value of 10kΩ/m

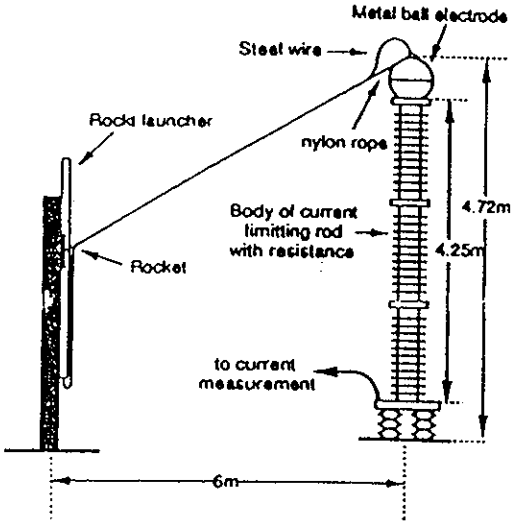

Figure 2: The arrangements of experiment for triggered lightning test

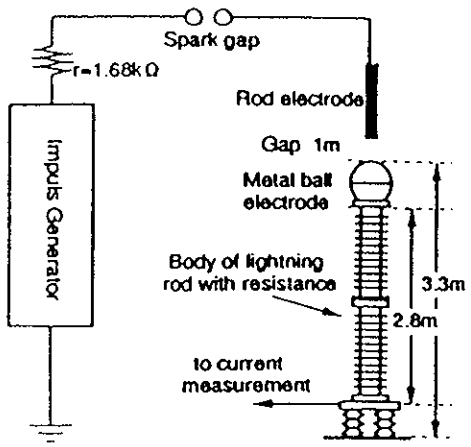

Figure 3: The arrangements of labratory test

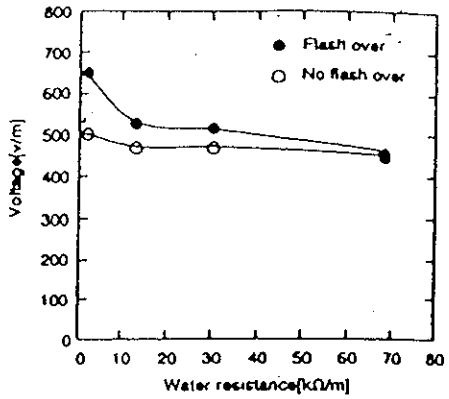

Figure 4 Characteristics of applied voltage per unit length and resistance per unit length

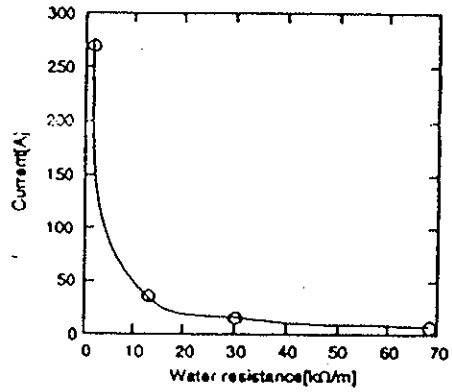

Figure 5: Characteristics of limited current and resistance per unit length, in case of no flashover discharge

3 Results

During one month period of triggered lightning experiment in each year during 1993-1995, four lightning discharges took place to the current limiting lightning rod. The resistance of around 30kΩ was applied, in 1993 experiment, and the 80kΩ in 1994, and 200kΩ in 1995. In case of No.9412, no flashover occurred and the current limiting was successful. The current waveform is shown in Figure 6, and the photograph is shown in Figure 7. The current continued for 310ms, with its maximum of −160A and the total charge of 30C. In the photograph, a straight line on the upper part is the lightning discharge channel, and flashover was not found along the rod body on the lower part. In the other cases, flashover occurred and the current limiting were failures. The current waveforms are shown in Figure 8 (No.9309), 9 (No.9315), and 10 (No.9511), the photograph of No.9511 is shown in

Figure 11. Figure 6 (No.9412) is quite different from other three currents. For example, the peak current is very smaller and less pulses than those of the others. Table 1 shows summary of triggered lightning experiments related to the lightning rod.

Table 1: Results of triggered lightning experiments to the current limiting lightning rod

No.	Date	R[kΩ]	s/f	Remark
9309	Nov,23,1993	25	×	Flashover
9315	Nov,28,1993	30	×	Flashover
9412	Nov,25,1994	80	○	No flashover
9511	Nov,24,1995	200	×	Flashover

○ : Success of current limiting
× : No success

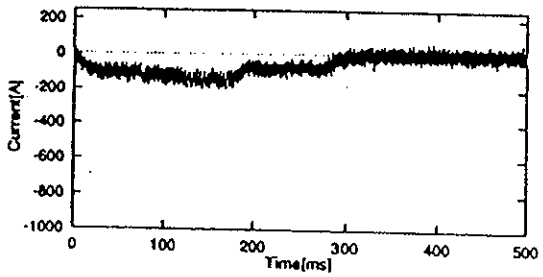

Figure 6: Current waveform(No.9412)

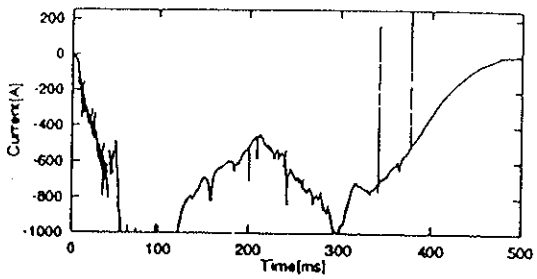

Figure 8: Current waveform(No.9309)

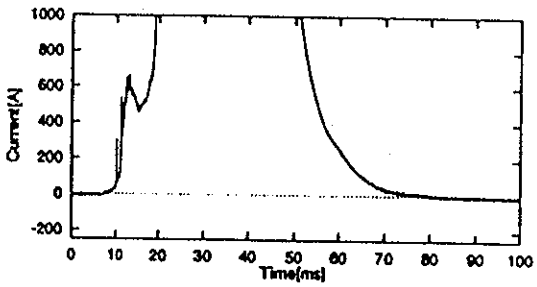

Figure 9: Current waveform(No.9315)

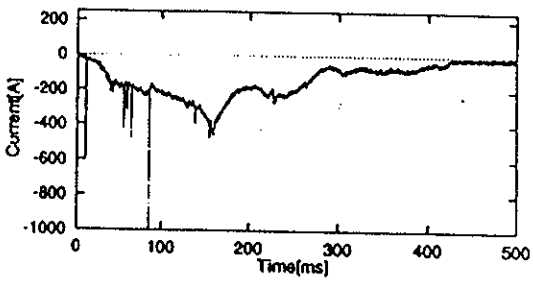

Figure 10: Current waveform(No.9511)

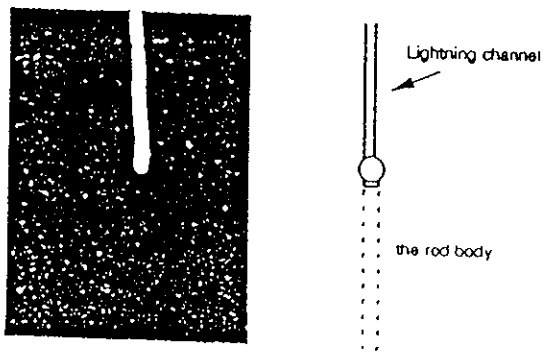

Figure 7: Photograph of triggered lightning to the rod in case of no flashover discharge (9412)

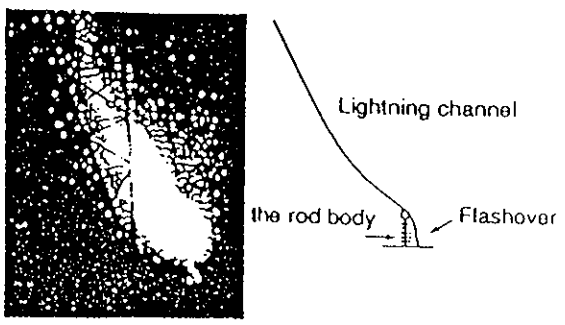

Figure 11: Photograph of triggered lightning to the rod in case of flashover discharge (9511)

4 Discussions

Discussing the reasons why no flashover occurred only in the case of No.9412, there are several aspects. First thing is that the rising part of the current is different from those of the other cases. Enlarged current waveforms are shown in Figure 12 (No.9412), 13 (No.9309), and 14 (No.9315). In the case of No.9412, only one pulse was observed, and then the current decreased to zero once again, and later the current gradually increased without any sharp pulses. In the case of No.9309 (Figure 13), the first pulse appeared at the time around 7ms which supposedly corresponds to the flashover initiation. After this first pulse, the current did not decrease to zero. This meahs that the flashover took place along the whole rod. The flashovered channel could limit no more the lightning current, then the current rapidly increased with many pulses. Similar current waveform was observed on the lightning to the positive charged clouds as indicated in Figure 14.

Second thing is the scale of thunderclouds. Figure 15 (No.9412) and 16 (No.9511) show the corona current waveforms measured by point corona current detector elected to the height of 5m on the ground. Figure 15 (No.9412) indicates the smaller corona current with short peiod of measurement compared to the current in Figure 16 (No.9511). It is suggested that the scale of thunderstorm corresponding to the lightning of No.9412 was smaller than that of No.9511.

Third thing is that there may be suitable value of resistance in order to realize the current limiting. In this experiment, the resistance of 80kΩ could limit the current, on the other, both of lower and higher resistance could not.

5 Conclusions

- In case of No.9412 (80kΩ), current limiting was successful without flashover along the lightning rod, in spite of the severe experiment such the lightning discharge was led directly to the top of the rod. In the cases of the lightning rod with smaller or larger resistance, current limiting was not successful because of flashover occurrence.
- Different current waveforms were observed in the cases of flashover and no flashover. First the current pulse appeared and it quickly decreased to zero, and later the current gradually increased without any sharp pulses.
- Photographs were taken clearly in both cases, flashover and no flashover.

Furthermore, we are going to continue such the suitable value of resistance.

Acknowledgement

We thank the member of triggered lightning experiment, Hokuriku Electric Power Co. Inc., Chubu Electric Power Co. Inc. for their supports on the triggered lightning experiment.

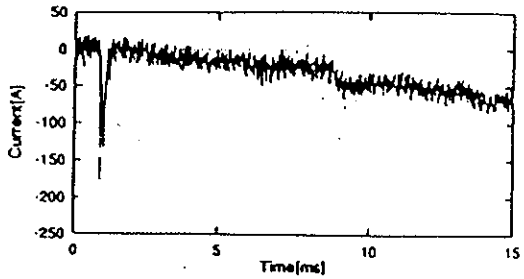

Figure 12: Enlarged current waveform (No.9412)

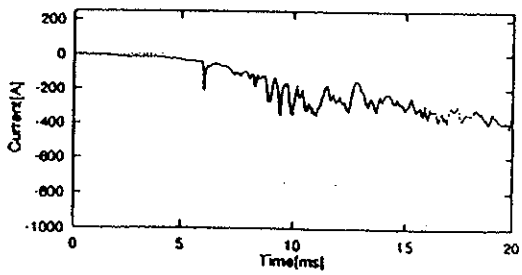

Figure 13: Enlarged current waveform (No.9309)

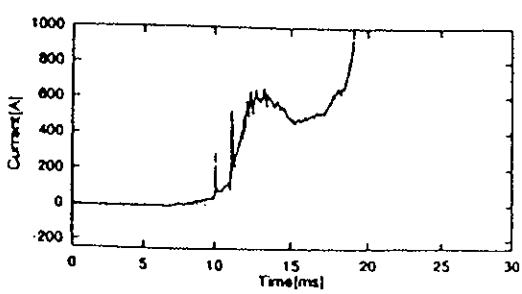

Figure 14: Enlarged current waveform (No.9315)

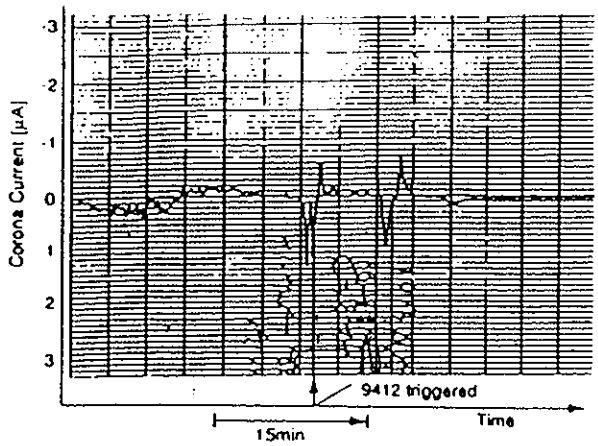

Figure 15 Corona discharge current measured(No 9412)

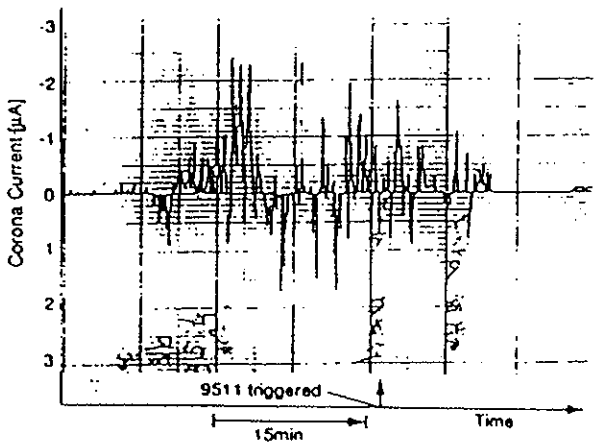

Figure 16 Corona discharge current measured(No 9511)

References

[1] K.Horii, K.Nakamura, Y Ikeda, R Matsuoka "Approach of current limiting lightning rod(Chinease type)" IEE, Japan, Proc. of Discharge and High-voltage Meeting, HV-93-59, 1993

[2] K.Horii "Consideration of Chinese type lightning rod" IEE, Japan, Proc of Discharge and High-voltage Meeting, HV-91-77, 1991

[3] K.Horii "Recent trend of cancel technique of lightning" IEE, Japan, Proc. of Discharge and High-voltage Meeting, HV-91-2, 1991

[4] K.Horii "Consideration of Chinese type lightning device" IEE, Japan, Proc of Discharge and High-voltage Meeting, HV-92-20, ED-92-82, 1992

[5] K.Horii, K.Nakamura, Y.Ikeda "Current limiting lightning rod" IEE, Japan, Proc of Discharge and High-voltage Meeting, HV-92-59, ED-92-173, 1992

Analysis of a Novel Method of Current Sharing in a Resistive Lightning Protection Terminal

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Analysis of a Novel Method of Current Sharing in a Resistive Lightning Protection Terminal

E. Pan and Ah Choy Liew, *Senior Member, IEEE*

Abstract—**A new method, which simulates the lighting channel as a series network of R–C circuits, has been proposed by the authors. It successfully calculates the return stroke current with various added resistance values at the base of the lightning channel. The calculation shows that the peak current and current risetime along the channel are strongly influenced by the added resistance element at ground level. However, the larger voltage across this resistance element may cause the flashover along its surface and result in failure of current limiting. This paper describes the analysis and simulation of a novel method of current sharing following the termination of a lightning stroke onto a resistive lightning protection terminal. Such a system of resistance elements is essential to ensure that surface flashover does not occur across lightning rods and current limiting is successful.**

Index Terms—**A resistive lightning protection terminal, flashover voltage, lightning discharge, peak current, return stroke current, voltage across rods, withstand voltage.**

I. Introduction

With increasing knowledge of lightning phenomena, several attempts have been made to improve the classical Franklin lightning rod protection systems. Recently, a novel kind of lightning rod, named the Semiconductor Lightning Eliminator (SLE) is fairly widely used in China: The SLE is developed based on a new principle termed the limitation theory of lightning current [1], [2]. Xie *et al.* considered that "rapid and violent neutralization" and "small resistance in discharge channel" are two necessary conditions for the formation of intense lightning current. Therefore, the SLE is designed consisting of several rods with high resistance values to destroy these conditions. These rods can connect automatically in parallel if the voltage across the SLE rod reaches the flashover voltage of the air gap between two adjacent rods. Rocket triggered lightning tests on a single semiconductor rod have been carried out in Japan in 1993–1995 [3]. When flashover did not take place along the surface of the resistance element, small currents were measured.

Whether a resistive lightning protection terminal can limit the large return stroke current is a very interesting question. Its result may influence traditional concepts relating to lightning protection terminal systems. In our previous work, a method has been provided to calculate return stroke currents at ground level [4]. Differing from other return stroke models, it is convenient for this method to obtain return stroke currents with various resistance values at the base of the channel.

The previous work has shown that peak current and risetime can be effectively limited by added resistance elements at the base of the channel. It means the return stroke current can be reduced when lightning strikes on a lightning rod with a high resistance value. However, in practice, the design of a suitable resistor for the purpose of limiting direct lightning stroke currents poses problems and difficulties. A large voltage drop across this lightning rod may be caused due to this resistance value. The authors' aim in this paper is to analyze and demonstrate a system, which can prevent surface flashover across lightning rods caused by this large voltage. A novel arrangement of lightning rods is hence introduced and the characteristic of the current sharing following the termination of a lightning stroke onto a resistive lightning protection terminal is discussed.

II. Return Stroke Currents

Many return stroke current models have been developed depending on different requirements, However, these models all assume infinite ground conductivity although return stroke currents may be influenced by the finite conductivity of the propagation path. In order to observe the effect of resistance on lightning return stroke current, a new method, which successfully fits a set observed lightning return stroke currents, has been proposed by the authors in [4]. A brief description of this method is given here.

A. Basic Assumptions and Parameters

1) The lightning stroke is modeled as a straight, vertical channel above a perfect conducting earth without branching. The stepped leader brings charge to travel along a thin conducting channel and stores it in the central core. This deposited charge expands radially to form a corona sheath, which surrounds the leader core. Hence, the leader channel is viewed to consist of two regions, the core (or breakdown) channel and the corona channel. Each of them is represented by several resistance-capacitance circuits. The model of stepped leader & return stroke channel and the equivalent circuit of leader channel are given in [4].
2) At the time $t = 0$, the return stroke starts at ground level. When the return stroke front reaches one of the sections, the switches in this section turn on and the charges stored here begin to discharge into the channel, and then discharge currents flow to the base of the channel. The upward velocity v of the return stroke front is assumed to be a constant (1.3×10^8 m/s) and the velocity of the current

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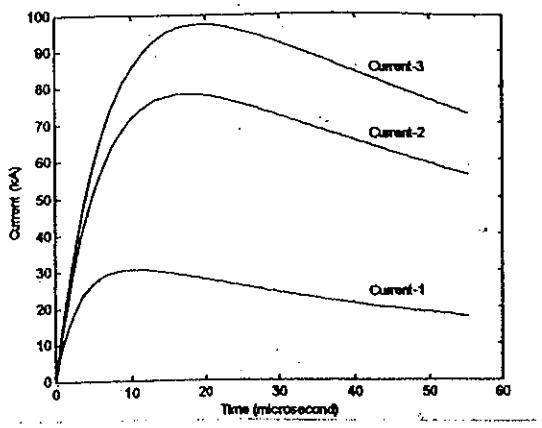

Fig. 1. Return stroke currents at ground level.

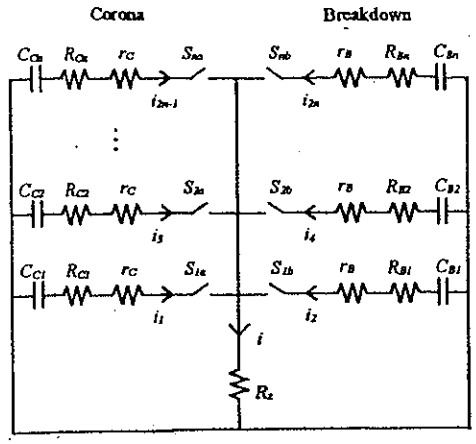

Fig. 2. Equivalent circuit of the lightning channel for $R_z \neq 0$.

flowing into the base of the channel is the speed of light c.

3) The total length of the channel H is assumed to be 5 km. The step length of each section l is selected to be 50 m. Hence, the number of sections simulated for the calculation is $n = H/l = 100$. We define a time delay constant w for each section, which is equal to $l(1/v + 1/c)$. It represents a time period from the return stroke front starting at the bottom of one section to the discharge current from this section flowing into the channel and returning to the bottom of this section.
4) The charge profile increases exponentially as the leader descends. The original voltage on capacitance element (U_0) increases with the charge in the channel and hence its ultimate return stroke current.
5) The range of the calculation is limited from 0 to $T(\mu s)$, where T is equal to $H(1/v + 1/c)$. At this time, the return stroke front reaches the top of the lightning channel and all switches in the R–C circuits are closed. It means that there is no longer any new discharge currents flowing into the channel after this time. The lightning discharge process after this time is not discussed in this paper.

B. Basic Return Stroke Currents

The return stroke current at the base of the channel is obtained by summing all the capacitance discharge currents, each section of which has a time delay. The curves shown in Fig. 1 are characteristic of typical lightning currents [5]. Return stroke currents at ground level (see Fig. 2 for illustrative model) are expressed as:

$$\begin{cases} i(0,\,t) = \displaystyle\sum_{n=1}^{H/l} (i_{2n-1}(t) + i_{2n}(t))u_n(t - nw) & (t \geq nw) \\ i(0,\,t) = 0 & (t < nw) \end{cases} \tag{1}$$

where $u(t)$, the unit step function is defined as:

$$u(t) = \begin{cases} 1 & (t \geq 0) \\ 0 & (t < 0) \end{cases} \tag{2}$$

Table I gives some parameters used to calculate return stroke currents. R_{Cn}, R_{Bn}, C_{Cn}, C_{Bn}, are resistance and capacitance values in the corona and breakdown channel in each section, respectively.

TABLE I
PARAMETERS USED TO CALCULATE RETURN STROKE CURRENTS

	Current-1	Current-2	Current-3
	$I_{max} = 30.26kA$	$I_{max} = 78.39kA$	$I_{max} = 97.46kA$
	$t_{max} = 10.47\mu s$	$t_{max} = 17.64\mu s$	$t_{max} = 19.29\mu s$
R_{Cn} (kΩ)	$1.8e^{n/800}$	$1.8e^{n/800}$	$1.8e^{n/800}$
C_{Cn} ($m\mu F$)	$3.75e^{-n/800}$	$9.18e^{-n/800}$	$11.0e^{-n/800}$
R_{Bn} (kΩ)	$0.273e^{n/70}$	$0.273e^{n/70}$	$0.273e^{n/70}$
C_{Bn} ($m\mu F$)	$10.0e^{-n/70}$	$21.25e^{-n/70}$	$25.0e^{-n/70}$
U_{0n} (MV)	$1.4e^{n/1200}$	$2.0e^{n/1200}$	$2.2e^{n/1200}$

C. Return Stroke Currents with Added Resistance Elements

The lightning current limiting by added resistance element or the resistance of lightning rods (R_z) at ground level is described in this section. When the resistance R_z, is added in the channel the normal intense neutralization in the lightning channel cannot be carried out; instead the neutralization process becomes weak due to this resistance element. Hence, besides R_z, another resistance r is considered in the channel, where r is taken to be 0.5 kΩ/m. For a 50-meter section, this resistance value is equal to 25 kΩ. Separating it into the corona channel and breakdown channel, each one is about 50 kΩ (i.e. r_C & r_B). The equivalent circuit is shown in Fig. 2.

Similar to the foregoing statement, the switches S_1 to S_n in the lightning channel are closed one by one with a delay time w after the return stroke starts at ground level. The return stroke is still modeled in the previous manner with the release of stored leader charge by a R–C circuit, where the resistance in each section has been modified in accordance with Fig. 2. The current at the base of the channel can be obtained by collecting all discharge currents through the resistance R_z in the channel. In other words, after each time w, two new circuits with original voltage U_0 are added into the circuit, and at the same time, the initial conditions of the previous R–C circuits are changed by the voltages of the capacitance from the previous interval. Equations (1) & (2) are still valid for this situation. The detailed calculation procedure is given in [4].

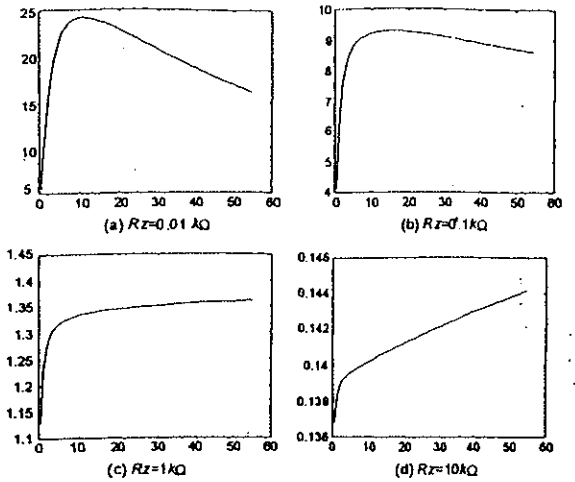

Fig. 3. Return stroke currents for various resistance values with the horizontal scales for time (μs) and the vertical scales for current (kA).

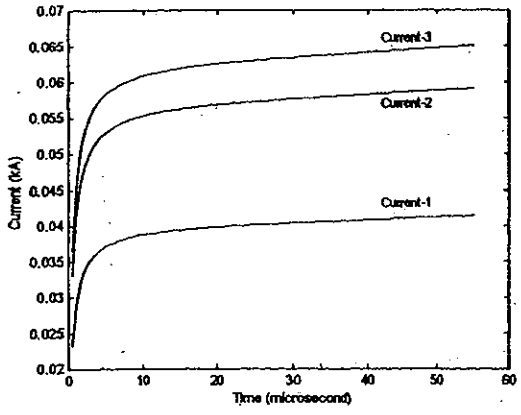

Fig. 4. Return stroke currents at ground level for $R_z = 35$ kΩ.

Fig. 3 compares return stroke currents for additional resistances R_z of 0.01 kΩ, 0.1 kΩ, 1 kΩ and 10 kΩ based on the same parameters as Current-1. It is clear that peak currents decrease markedly with increase of resistance R_z, i.e. peak currents change from 24 kA to 145 A when the values of resistance R_z increase from 0.01–1 kΩ. It means that the high resistance value at the base of the channel can effectively limit the return stroke current.

III. Current Sharing in a Resistive Lightning Protection Terminal

When lightning strikes on a lightning rod, the return stroke current can be reduced due to the high resistance value of this rod. Fig. 4 gives a group of the return stroke currents for the resistance $R_z = 35$ kΩ at ground level, in which the same data as those in Table I are adopted. However, a large voltage drop across this lightning rod occurs due to this resistance value. If this voltage is too large and exceeds the capability of the withstand voltage of the rod which is determined by its material and dimensions, flashover will occur along its surface. As a result current restriction cannot be expected any more because the resultant resistance of the rod becomes extremely small after being short-circuited by the flashover arc.

In order to cater for the larger currents without flashover across the surface of the lightning rod, a novel arrangement of resistance elements has been designed by Xie *et al.*, [1], [2]. A group of lightning rods substitutes for a single rod in the SLE. This group of rods is arranged as several fan-shaped groups. Each rod is required to have a withstand voltage (V_w) which is larger than the flashover voltage of the air gap between two adjacent rods (V_f). It means that the flashover will first occur in the air gap between two rods because this voltage is exceeded before the withstand voltage down the surface of the length of each rod. When this happens, the return stroke current is shared in two rods and the voltage across the lightning rods (V_{rod}) is also reduced. This process may be repeated if V_{rod} increases with increasing current to reach V_f again.

If a suitable number of rods is selected, the voltage across the rods can be controlled to be lower than its withstand voltage preventing flashover across the surface of the rods. This then allows the current limiting function of the resistance rod assembly of the device. However, once V_{rod} is larger than V_w, current limiting is not successful because of flashover occurrence along the surface of the lightning rod. The return stroke current may then reach a few kilo-amperes. This behavior is also confirmed in rocket triggered lightning tests done on a single resistance rod element [3].

A. Characteristic of the SLE

Clearly, it is important to provide more rods for the purpose of current sharing to prevent flashover across the resistance elements. The SLE comprises 13–19 semiconductor rods, which are 5 m in length with 4 metal tips on the top of each rod. The rods are distributed radially and form 2–3 fan-shaped surfaces. The angle between two adjacent rods in each fan-shaped surface is 20–25 degrees. The total resistance of lightning reduction resistor element is $R = R_C i^{\alpha}$, where $i(A)$ is current passing through SLE, $R_C = 35$ kΩ and $\alpha = 0.35$ [1], [2].

In order to prevent the flashover from occurring along the surface of the lightning rods, the SLE is designed in the way that the flashover voltage of the air gap between two adjacent rods is lower than the surface flashover voltage of the rod. These rods will then be automatically connected in parallel one after another as current rises [1], [2]. The photograph in Fig. 5 provided by Xie shows the laboratory test in progress illustrating how flashover on SLE rods will activate adjacent rods in parallel to spread the current This feature ensures the SLE rod's high resistance is maintained and current limiting capability is not compromised. Further, the SLE successfully protects buildings and all sensitive equipment in them.

B. Calculation and Analysis

The voltages across one lightning rod (35 kΩ) for different current amplitudes of basic return strokes are given in Fig. 6. For Current-1, V_{rod} is smaller than V_w so that it is successful for this single rod to limit the return stroke current. But for Current-2 & Current-3, the large voltage drop across the lightning rod causes V_{rod} to exceed the withstand voltage of the rod. The flashover therefore occurs along the surface of the rod and

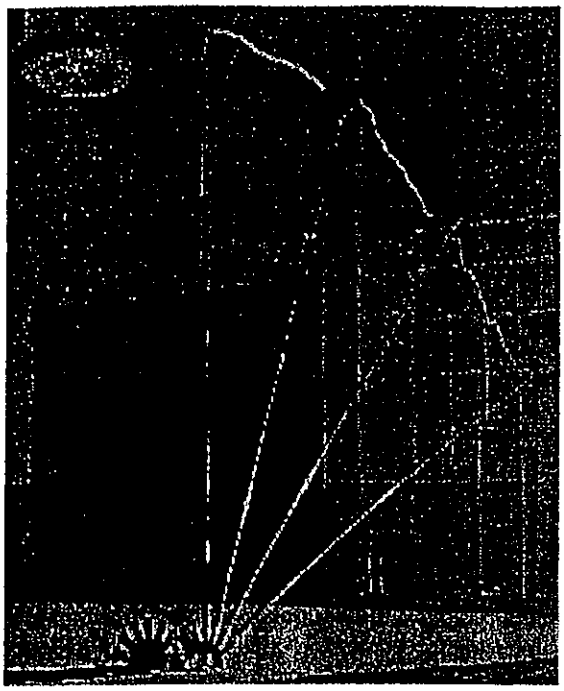

Fig. 5. Testing SLE's resistance and current limiting capabilities.

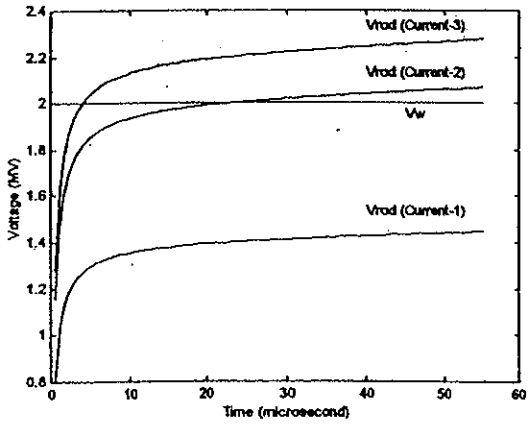

Fig. 6. Voltages across one lightning red for $R_s = 35$ kΩ.

the resistance of this short-circuited rod becomes very small. Hence, this short-circuited rod loses its effect for limiting return stroke current.

In order to avoid the surface flashover along the lightning rod, the structure of rods similar to the SLE is introduced in the following calculation and analysis. The parameters are chosen as follows: the number of rods is limited to 19, the resistance value of each rod is taken to be 35 kΩ (unlike the SLE with nonlinear resistance value) and the distance between two adjacent rods is 2 m. These values are designed to ensure that flashover across the air gap between the rods will occur before any possibility of flashover down the surface of the resistive rods. The principle of current sharing in this resistive lightning protection terminal is illustrated in Fig. 7.

The flashover voltage gradient of an air gap is about 0.7 MV/m [6]. For a 2 m gap, the flashover voltage across the air gap between the two rods will hence be 1.4 MV.

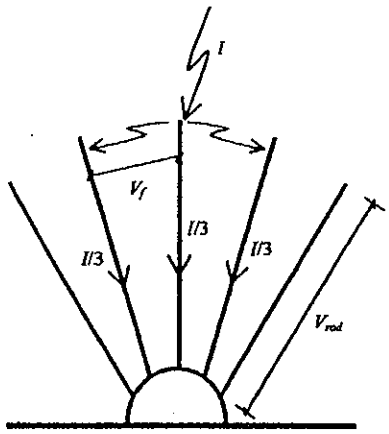

Fig. 7. Current sharing in three lightning rods.

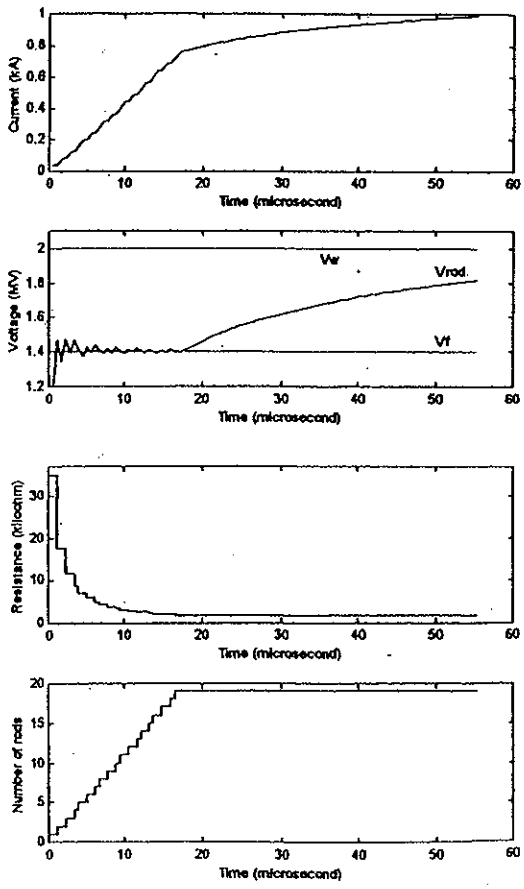

Fig. 8. Current, voltage & resistance behavior of the 19-rod resistance assembly of lightning terminal for Current-2.

The withstand voltage of the lightning rod is assumed to be 0.4 MV/m. For a 5 m rod, its withstand voltage is 5 m × 0.4 MV/m = 2.0 MV. It means that once V_{rod} exceeds this value, the flashover will occur along the surface of the rod. It is therefore crucial that this voltage be not exceeded to prevent the flashover. The voltage across the lightning rod is expressed as:

$$V_{rod}(0, t) = R_s i(0, t) \tag{3}$$

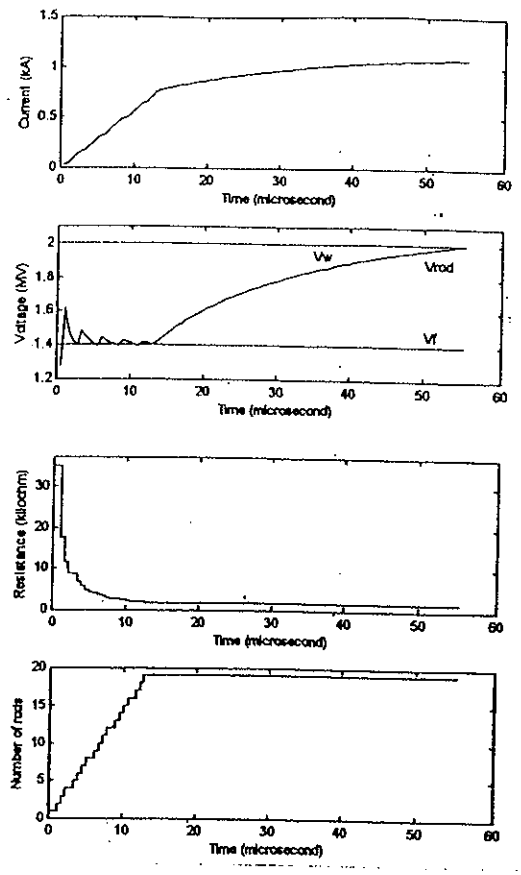

Fig. 9. Current, voltage & resistance behavior of the 19-rod resistance assembly of lightning terminal for Current-3.

Figs. 8 & 9 show current, voltage & resistance behavior of the 19-rod resistance assembly of lightning terminal for Current-2 and Current-3, respectively. In the beginning of the return stroke, the current increases with time; so does the voltage. Only one rod at the base of the channel is carrying the current during this period. When this voltage gradually increases to reach V_f, flashover between two rods occurs and the second rod connects with the first one in parallel automatically. Now the resistance value of the lightning rods becomes 17.5 kΩ. The change of the resistance value causes the current across the rods to rise and the voltage across the rods to drop suddenly. Subsequently, the voltage increases slowly again with increase of the channel current for $R_z = 17.5$ kΩ. When V_{rod} rises to reach V_f again, the same process will be repeated. The third rod shares the current of the lightning channel so that the resistance reduces again.

In Fig. 8, the voltage is finally limited to about 1.8 MV in the calculation range after 19 rods share the return stroke current, but the voltage in Fig. 9 almost reaches to 2.0 MV, i.e. the withstand voltage of the lightning rod. Compared to Fig. 6, the current sharing among the resistance elements is affected in both of them. It is also clear that a 19-rod unit is sufficient for a 78.39 kA prospective current. However, if the current in the lightning channel before being limited by the resistance is larger than 97.46 kA, a 19-rod unit is not sufficient to limit the voltage across the rods to be lower than the withstand voltage. Hence, more rods are needed to prevent the surface flashover from occurring along the rods under this condition.

IV. Conclusions & Discussion

The effectiveness of a multiple rod current sharing scheme is demonstrated and analyzed using our new developed method in this paper. A group of lightning rods is designed as a fan shaped structure. The air gap of the two adjacent rods flashes over first before the voltage across the rod reaches the withstand voltage of the rod itself so that the voltage across the rods is restricted by the change of the resistance value at the base of the lightning channel. Such a system of resistance elements is essential to ensure that surface flashover does not occur across lightning rods. In this system, the number of rods is determined by different prospective currents. Hence, proper design of the number of rods and its flashover characteristics is required to ensure success for any given current level.

The present analysis does not easily permit the incorporation of the inductance element although it is realized there will be some inherent inductance in the lightning channel. Typical values of a 5 km length of wire can amount to 5 mH representing amount 500 ohms for a 10 microseconds rise time and 5000 ohms for 1 microsecond. The values of resistance elements in the present model are high and of the order of 50 kΩ in each section. It is expected that the magnitude error is acceptable with neglecting of inductance in the analysis. The incorporation of inductance in the circuit model will be considered as a subject of continued study. The results predicted by such a model can then be used to verify all experimental tests and to study the best method for lightning current limitation and control.

References

[1] G. R. Xie, C. X Chen, Y. P. Chen, and Y. F. Zhang, "Mechanism of lightning current limitation of SLE after flashover," in *Proceedings of the EMPD'98*, 1998, pp. 340–345.

[2] G. R. Xie, C. X Chen, Y. P Chen, X. S. Wen, and J. H. Yu, "Theory and practice of semiconductor lightning eliminator," in *Proceedings of the EMPD'98*, 1998, pp. 532–537.

[3] M. Teramoto, T. Yamada, K. Nakamura, R. Matsuoka, S. Sumi, and K. Horii, "Triggered lightning test to a new type lightning rod," in *Proceedings of the ICEE'96*, 1996, pp. 779–783.

[4] E. Pan and A. C. Liew, "Effect of resistance on lightning return stroke current," *IEEE Trans. Power Delivery*, to be published.

[5] M. A. Uman, *The Lightning Discharge*: Academic Press, Inc., 1987.

[6] A. C. Monteith, H. R. Vaughan, and A. A. Johnson, "Insulation coordination," in *Electrical Transmission and Distribution Reference Book*, USA: Westinghouse Electric Corporation, 1950.



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Effect of Resistance on Lightning Return Stroke Current

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Effect of Resistance on Lightning Return Stroke Current

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Abstract—**This paper describes a new method of calculation to determine the return stroke current by integrating all discharge currents along the channel. Using this method, the effect of added resistance in the lightning discharge channel is calculated. We find that the values of peak current, current risetime, and current-time derivative along the channel are strongly influenced by an additional resistance at the base of the channel. This result is of importance in the behavior of lightning protection terminal systems.**

Index Terms—**Additional resistance, current risetime, lightning discharge, peak current, rate of change of current, return stroke current, stepped leader channel.**

I. Introduction

BEING one of the most spectacular events in nature, lightning has posed serious hazards to people, buildings, power transmission lines, and equipment. A lightning flash from cloud to ground usually consists of a series of separate discharges called strokes. It starts in the cloud and eventually neutralizes several coulombs of negative cloud charge. Each stroke is made up of leader and return strokes. The leader initiates the return stroke by lowering cloud charge and cloud potential toward the earth.

Many return stroke current models have been developed depending on different requirements. One type of these models is to calculate the temporal and spatial distribution of the current along the return stroke channel for a specified current at the base of the channel and a specified return-stroke speed. The Bruce–Golde (BG) model (Bruce and Golde, 1941), the transmission line (TL) model (Uman and McLain, 1969), the Lin–Uman–Standler (LUS) model (Lin *et al.* 1980), and the Diendorfer–Uman (DU) model [1] are of this type. In these models, it is assumed that the return stroke channel is a straight vertical channel above a perfect conducting ground plane and the return stroke is modeled to begin at the ground level. The return stroke current along the channel is considered as a function of height and time, from which remote electric and magnetic fields can be calculated.

Recently, a novel kind of lightning rod, named semiconductor lightning eliminator (SLE) is fairly widely used in China. Differing from traditional rods, the SLE is considered to be able to limit the main discharge current and reduce the rate of lightning current rising due to its high resistance value if no flashover occurs along its surface [2]. We are interested in this result caused by the resistance. Therefore, we reproduce the return stroke current curve that has been simulated in the DU model. Then, we will discuss how peak current, current risetime and current-time derivative are changed along the return stroke channel if there is a resistance at the base of the channel.

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II. Calculation and Analysis for Return Stroke Current

In order to obtain the relationship between the return stroke current and the additional resistance at the base of the channel, we attempt to reproduce a given current curve in the DU model. We will begin our calculation and analysis with a brief review of the DU model. This model is developed by Diendorfer and Uman in 1990. In their model, the current and charge are considered as a function of time and height. The current is the sum of two components: one called the breakdown current due to the discharge of the central core of the channel and the other named the corona current due to the discharge of the corona sheath around the leader core (Fig. 1). Each of the two components at the channel base is calculated using the analytical expression as follows [1]:

$$i(0, t) = \frac{I_0}{\mu} \frac{(t/\tau_1)^2}{[(t/\tau_1)^2 + 1]} e^{-t/\tau_2}. \quad (1)$$

For a specified current at ground strike point $i(0, t)$ and a discharge time constant τ_D, the current $i(z, t)$ at a height z is determined by:

$$i(z, t) = i(0, t + z/c) - i(0, z(1/v + 1/c))e^{-(t-z/v)/\tau_D} \quad (2)$$

where I_0, μ, τ_1 and τ_2 are current amplitude, amplitude correction factor, current rise time constant and current decay time constant, respectively.

In the DU model, the current waveform is similar to a stroke current measured in natural lighting. The model parameters, such as return stroke current at ground and velocity of the return stroke, are selected to fit the experimental data. The peak current amplitude is about 30 kA/μs and the maximum current-time derivative is about 80 kA/μs. This current is an approximation to an average first stroke. We will adopt the same parameters during our calculation procedure and compare the peak current and current-time derivative with the DU model.

During the lightning discharge process, the stepped leader is usually considered to originate from the cloud charge center and travels along the lightning channel, which is a straight, vertical channel above the earth. The stepped leader as a continuously moving charge distribution is modeled in many models. Thum *et al.* [5], [6] considered the stepped leader as a continuously

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descending conical structure with the apex of the cone at the cloud. Charge on the leader increases linearly from cloud toward the tip of the leader. Dellera *et al.* [3] modeled the leader as a continuously descending cylindrical charge distribution. In the DU model, the charge distribution along the channel depends on the base current as well as on the current-time derivative at ground. This stored leader charge at any height is discharged with a single exponential time constant τ_D into the channel [1]. Similar to them, charge in the leader channel is assumed to decrease exponentially with increasing of the channel height in our PL model (Pan–Liew model).

We also assume that the leader channel is made up of two regions as in the DU model, i.e., core channel (or called breakdown channel) and corona channel (Fig. 2). The stepped leader brings charge downward along the channel and stores it in the channel core. This deposited charge will not remain on this thin channel; instead it will create a radial electric field pushing the charge away from the channel, giving rise to the corona sheath, which is surrounding the leader core.

Energy is released during this expansion of the corona sheath, so the temperature of the channel is high close to the central core and decreases with increasing radial distance from the central core. Hot core and cold corona sheath cause the discharging process in the former to be faster than in the latter. Although some experimental observations show that the velocity of the return stroke decreases with the channel height, we will assume the return stroke front to move upward with a constant speed $\nu = 1.3 \times 10^8$ m/S.

Therefore, our model is composed of two separate current components: 1) fast breakdown discharge current i_B and 2) slow corona discharge current i_C. The leader channel is divided into several small sections, and each one is equivalent to a capacitance-resistance circuit. The equivalent circuit is shown in Fig. 3. During the leader traveling downward in the channel, each capacitance stores charge at any height. When the leader arrives at ground, the return stroke starts at ground ($z = 0$) and propagates upward with a constant speed ν. The switches at each section are turned on when the return stroke front passes this section. The charge previously deposited in the leader channel at this part is discharged into the channel that extends to ground. The discharge current flows into the return stroke channel and is below the return stroke front. Its downward propagation is at the speed of light c. Finally, the return stroke current at ground is obtained by integrating all the discharge currents along the channel (breakdown and corona currents), and the current at any height is the sum of all discharge currents along the channel above this height. The current is zero above the return stroke wave front.

According to the circuit in Fig. 3, the discharge current in each section is:

$$\begin{aligned} i_n(t) &= i_{Cn}(t) + i_{Bn}(t) \\ &= \frac{U_0}{R_{Cn}} e^{-t/R_{Cn}C_{Cn}} + \frac{U_0}{R_{Bn}} e^{-t/R_{Bn}C_{Bn}} \end{aligned} \tag{3}$$

where U_0 = original voltage on capacitance of the leader channel element.

In order to obtain the return stroke current at ground, we sum the discharge currents of all sections in the channel. Each section current, which arrives at ground level, has a time delay. Detailed explanation about time delay constant w is given in the Appendix. Therefore, the total return stroke current at ground (Fig. 4) is given by:

$$\begin{cases} i(0,t) = \sum_{n=1}^{H/l} i_n(t - nw)u_n(t - nw) & (t \geq w) \\ i(0,t) = 0 & (t < w) \end{cases} \tag{4}$$

where

$$u(t) = \begin{cases} 1 & t \geq 0 \\ 0 & t < 0. \end{cases} \tag{5}$$

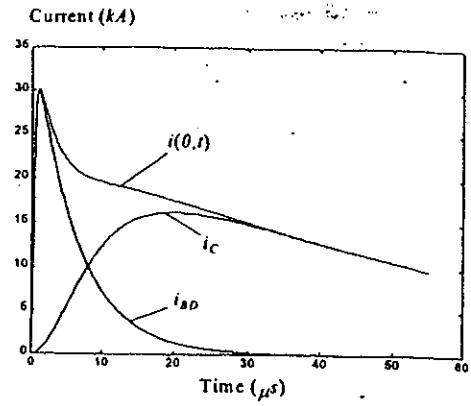

Fig. 1. Return stroke current at ground in the DU model.

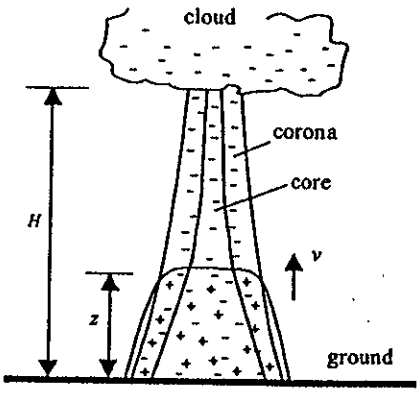

Fig. 2. Stepped leader and return stroke channel.

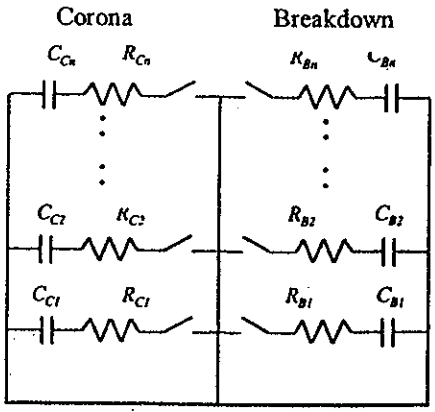

Fig. 3. Equivalent circuit of leader channel.

Parameters used to calculate the return stroke current are selected as given below: the height of the leader channel $H = 5000$ m, the step length $l = 5$ m, the original voltage on capacitance in the leader channel $U_0 = 1.97$ MV, the resistance in the section n of the corona channel $R_{Cn} = 6.4e^{7/1100}$ kΩ, the capacitance in the section n of the corona channel $C_{Cn} = 0.63e^{-n/1100}$ mμF, the resistance in the section n of the breakdown channel $R_{Bn} = 0.4e^{n/52}$ kΩ and the capacitance in the section n of the breakdown channel $C_{Bn} = 0.9e^{-n/52}$ mμF.

The charge at the tip of the leader does not have enough time to expand radially so that the charge deposited in the corona channel becomes less than the charge in the leader core at nearly the base of the channel. Therefore, at the beginning of the return stroke, most currents are from the leader core channel.

Fig. 5 shows the rate of change of the current at ground. The current has a peak value of 30 kA and the maximum current-time derivative is about 93 kA/μs.

The current waveforms at different channel heights ranging from 20–2000 m are plotted in Fig. 6. The return stroke current at any height z is the sum of all discharge currents along the channel above this height at a time z/v later. The current amplitude decreases with increasing of the channel height and the current risetime increases with increasing of the height. The equations to calculate the return stroke current at height z are expressed as:

$$\begin{cases} i(z,t) = \displaystyle\sum_{n=1+z/l}^{H/l} i_n(t - nw + z/c) \\ \qquad\qquad \cdot u_n(t - nw + z/c) \qquad (t \geq w + z/v) \\ i(z,t) = 0 \qquad\qquad\qquad\qquad (t < w + z/v). \end{cases} \tag{6}$$

III. Additional Resistance at the Channel Base

In most of the return stroke models, the lightning channel is considered as a perfect conductor above the earth. Typically, the return stroke produces a peak current of a few kiloamperes with a time from zero to peak of a few microseconds. The very large current and rapid rising rate of current are the cause of almost all the damages attributed to lightning.

How to limit the lightning current and reduce the rate of change of the current is very important on the lightning protection systems. The SLE is considered to be able to solve this problem due to its high resistance value. Now we discuss the effect of added resistance R_z on the lightning discharge current. On the basis of the above description, we attempt to add a linear resistance at the base of the channel although the SLE is a rod with a nonlinear resistance. The return stroke is still modeled as the behavior for the release of stored leader charge by a capacitance-resistance circuit, but the current is no longer the simple sum of the breakdown current and the corona current. The new equivalent circuit is given in Fig. 7. Fig. 8 shows the return stroke current at the channel base for $R_z = 35$ kΩ. This resistance does not influence the value of the charge stored in the leader channel. The calculation procedure for this situation is given in the appendix. The velocity of the return stroke current may decrease due to this resistance, but it is still considered as a constant in our calculation. The equation used to calculate

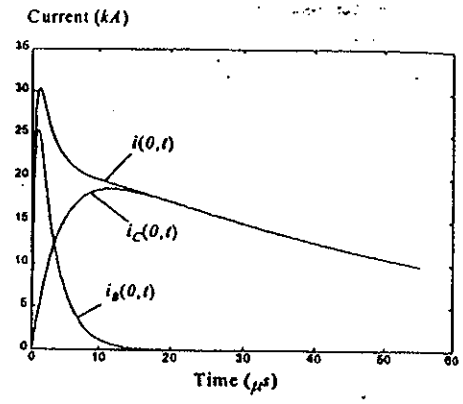

Fig. 4. Channel-base current waveform.

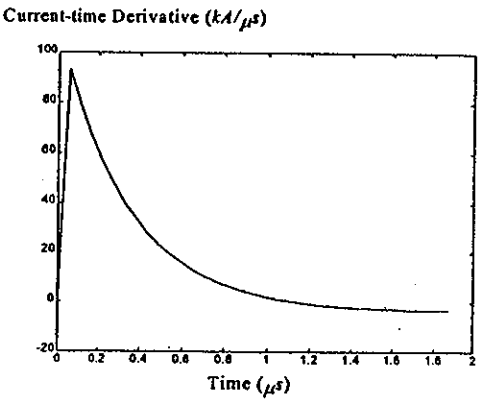

Fig. 5. Rate of change of current at ground.

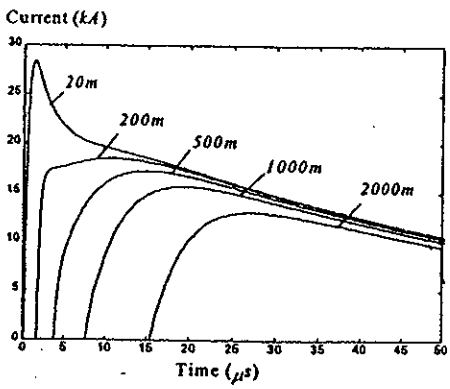

Fig. 6. Return stroke current at different heights z.

the total current along the channel with an additional resistance at the ground is represented by:

$$i(0,t) = \sum_{n=1}^{H/l} (i_{2n-1}(t) + i_{2n}(t)) u_n(t - nw) \qquad (0 < t < t_{n+1}). \tag{7}$$

The values of the peak current and the maximum current-time derivative for $R_z = 35$ kΩ are about 0.0562 kA and 1.01 kA/μs, respectively. Comparing with those values whose resistance R_z is equal to zero, both the peak current and the rate of rise of the current along the channel are decreased markedly. The relationship between the peak currents and the resistance values is

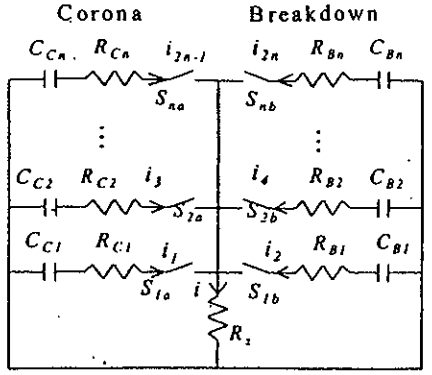

Fig. 7. Equivalent circuit of the leader channel for resistance R_z.

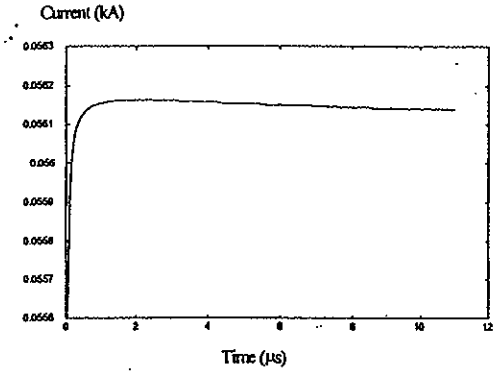

Fig. 8. Return stroke current at ground for $R_z = 35$ kΩ.

given in Table I. The peak current decreases with increasing of the resistance R_z.

The SLE can be considered to be a large nonlinear resistance added in the lightning discharging channel due to its structure. The data of lightning currents that were measured when the lightning strikes directly on the SLE by Xie *et al.* are given in Table II. As is evident from Tables II and III, more than 70% lightning currents are limited to be less than 100 A. After comparing the result of the calculation and the measurement, we find the return stroke current can be restricted if the resistance in the lightning discharging channel is increased.

IV. Conclusions

The return stroke current has been reproduced well in this paper. We split the current into two components: 1) a breakdown current from the leader core due to the release of charge that is stored during stepped leader process and 2) a corona current from discharging the corona sheath surrounding the leader core. The leader core and the corona sheath are assumed to make up of several capacitance-resistance circuits. Each circuit begins to discharge toward the earth when the return stroke front reaches this height. For assumed channel parameters, the return stroke current is obtained by integrating all discharge currents along the whole channel after a time delay. Although we only discuss the relationship between a linear resistance at the base of the channel and the return stroke current, the result still shows that the peak current and the rate of change of the current can be effectively limited depending on the value of the resistance at the base of the channel.

TABLE I
Peak Current with Different Resistance Values

R_z (kΩ)	0	1	2	5	10
I_{max} (kA)	30.2824	1.8311	0.9487	0.3880	0.1955
R_z (kΩ)	15	20	25	30	35
I_{max} (kA)	0.1307	0.0981	0.0786	0.0655	0.0562

TABLE II
Data of the Lightning Limitation Current [2]

No.	1	2	3	4	5	6	7	8
I (A)	-485	-26	-296	-362	-43	-346	-233	-335
No.	9	10	11	12	13	14	15	16
I (A)	-79	-485	-391	-28	-368	-346	-356	-204
No.	17	18	19	20	21	22	23	24
I (A)	-391	-348	143	-403	67	-303	47	278
No.	25	26	27	28	29	30	31	32
I (A)	-327	-628	-290	-991	-100	-100	-200	-100
No.	33	34	35	36	37	38		
I (A)	200	300	30	210	240	200		

TABLE III
Probability of Lightning Current Larger Than I (Absolute Value) [2]

I (A)	30	50	100	200	300
P (%)	92.1	86.8	73.7	63.2	42.1
I (A)	400	500	700	1000	
P (%)	13.2	5.3	2.6	0	

Appendix

To calculate the current distribution along the lightning channel after adding a resistance at the base of the channel, we assume that the return stroke starts at ground level when $t = 0$ and propagates upward with the leader channel. The equivalent circuit is shown in Fig. 7. Here the leader channel is separated into two parts (i.e., corona channel and breakdown channel). The parameters are selected in the foregoing statement and R_z is the resistance added at the base of the channel.

Assume that the height of each section is l and ν is the velocity of the return stroke front. After a time l/ν, the return stroke front reaches the height $z = l$. At this time, the first set of switches S_{1a} and S_{1b} are closed and the capacitances on this section are discharged. Then, the discharge currents flow into the channel base with the speed of light c. Therefore, during a time from l/ν to $(l/\nu + l/c)$, the discharging process has already started but the current has not yet arrived at the ground level until the time is $(l/\nu + l/c)$. We define a time delay constant w, which is equal to $(l/\nu + l/c)$. The 2nd set of switches S_{2a} and S_{2b} are closed after another time l/ν. It means the second discharge currents need a time delay $2w$ to arrive at ground. Finally, when the return stroke front passes the whole channel, all switches are closed. Now the channel currents are the sum of all capacitance discharge currents. The computer program is made based on following equations. U_0 and V_0 are the initial voltages on capacitance in the corona channel and the breakdown channel, respectively.

1) $0 \le t < t_1$ $(t_1 = w)$:

$$i(t) = 0. \tag{A1}$$

It means that no discharge current arrives at the ground during this time.

2) $t_1 \le t < t_2$ $(t_2 = 2w)$*:* The return stroke current at ground is only the first section discharging current. The initial voltages on capacitance C_{c1} and C_{B1} are:

$$U_1 = V_1 = U_0. \tag{A2}$$

The state equations of the 1st set circuit are given by:

$$\begin{cases} U_1 - \dfrac{1}{C_{C1}} \displaystyle\int_{t1}^{t2} (t)\,dt \\ \quad = R_z i(t) + R_{C1} i_1(t) \\ \quad = (R_z + R_{C1}) i_1(t) + R_z i_2(t) \\ V_1 - \dfrac{1}{C_{B1}} \displaystyle\int_{t1}^{t2} i_2(t)\,dt \\ \quad = R_z i(t) + R_{B1} i_2(t) \\ \quad = R_z i_1(t) + (R_z + R_{B1}) i_2(t) i(t) \\ \quad = i_1(t) + i_2(t). \end{cases} \tag{A3}$$

Differentiating the above equations:

$$\begin{cases} -\dfrac{1}{C_{C1}} i_1 = (R_z + R_{C1}) i_1' + R_z i_2' \\ -\dfrac{1}{C_{B1}} i_2 = R_z i_1' + (R_z + R_{B1}) i_2'. \end{cases} \tag{A4}$$

Rewriting (A4), we obtain

$$-\begin{bmatrix} 1/C_{C1} & 0 \\ 0 & 1/C_{B1} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} R_z + R_{C1} & R_z \\ R_z & R_z + R_{B1} \end{bmatrix} \begin{bmatrix} i_1' \\ i_2' \end{bmatrix}. \tag{A5}$$

Initial conditions of the differential equations are determined from the voltage of the capacitance from the previous interval. Therefore,

$$\begin{bmatrix} i_{10} \\ i_{20} \end{bmatrix} = \begin{bmatrix} R_z + R_{C1} & R_z \\ R_z & R_z + R_{B1} \end{bmatrix}^{-1} \begin{bmatrix} U_1 \\ V_1 \end{bmatrix}. \tag{A6}$$

3) $t_n \le t < t_{n+1}$*:* The switches from S_1 to Sn are closed. The channel currents are obtained by integrating all discharge currents along the channel. When $t = t_n$, the voltages on $C_{C1}, C_{C2}, \cdots, C_{C(n-1)}, C_{B1}, C_{B2}, \cdots, C_{B(n-1)}$ become:

$$\begin{cases} U_1 = R_z i(t_n) + R_{C1} i_1(t_n) \\ V_1 = R_z i(t_n) + R_{B1} i_2(t_n) \\ U_2 = R_z i(t_n) + R_{C2} i_3(t_n) \\ V_2 = R_z i(t_n) + R_{B2} i_4(t_n) \\ \quad \vdots \\ U_{n-1} = R_z i(t_n) + R_{C(n-1)} i_{2n-3}(t_n) \\ V_{n-1} = R_z i(t_n) + R_{B(n-1)} i_{2n-2}(t_n). \end{cases} \tag{A7}$$

The voltages on C_{Cn}, C_{Bn} are:

$$U_n = V_n = U_0. \tag{A8}$$

Therefore, the state equations of the circuit are given by:

$$\begin{cases} U_1 - \dfrac{1}{C_{C1}} \displaystyle\int_{t_n}^{t_{n+1}} i_1(t)\,dt \\ \quad = R_z i(t) + R_{C1} i_1(t) \\ \quad = (R_z + R_{C1}) i_1(t) + R_z i_2(t) + R_z i_3(t) \\ \quad\quad + R_z i_4(t) + \cdots + R_z i_{2n-1}(t) R_z i_{2n}(t) \\ V_1 - \dfrac{1}{C_{B1}} \displaystyle\int_{t_n}^{t_{n+1}} i_2(t)\,dt \\ \quad = R_z i(t) + R_{B1} i_2(t) \\ \quad = R_z i_1(t) + (R_z + R_{B1}) i_2(t) + R_z i_3(t) \\ \quad\quad + R_z i_4(t) + \cdots + R_z i_{2n-1}(t) + R_z i_{2n}(t) \\ U_2 - \dfrac{1}{C_{C2}} \displaystyle\int_{t_n}^{t_{n+1}} i_3(t)\,dt \\ \quad = R_z i(t) + R_{C2} i_3(t) \\ \quad = R_z i_1(t) + R_z i_2(t) + (R_z + R_{C2}) i_3(t) \\ \quad\quad + R_z i_4(t) + \cdots + R_z i_{2n-1}(t) + R_z i_{2n}(t) \\ V_2 - \dfrac{1}{C_{B2}} \displaystyle\int_{t_n}^{t_{n+1}} i_4(t)\,dt \\ \quad = R_z i(t) + R_{B2} i_4(t) \\ \quad = R_z i_1(t) R_z i_2(t) + R_z i_3(t) + (R_z + R_{B2}) i_4(t) \\ \quad\quad + \cdots + R_z i_{2n-1}(t) + R_z i_{2n}(t) \\ \quad\quad \vdots \\ U_n - \dfrac{1}{C_{cn}} \displaystyle\int_{t_n}^{t_{n+1}} i_{2n-1}(t)\,dt \\ \quad = R_z i(t) + R_{Cn} i_{2n-1}(t) \\ \quad = R_z i_1(t) + R_z i_2(t) + R_z i_3(t) \\ \quad\quad + R_z i_4(t) + \cdots + (R_z + R_{Cn}) i_{2n-1}(t) + R_z i_{2n}(t) \\ V_n - \dfrac{1}{C_{Bn}} \displaystyle\int_{t_n}^{t_{n+1}} i_{2n}(t)\,dt \\ \quad = R_z i(t) + R_{Bn} i_{2n}(t) \\ \quad = R_z i_1(t) + R_z i_2(t) + R_z i_3(t) + R_z i_4(t) \\ \quad\quad + \cdots + R_x i_{2n-1}(t) + (R_z + R_{Bn}) i_{2n}(t) \\ i(t) \\ \quad = i_1(t) + i_2(t) + i_3(t) + i_4(t) + \cdots + i_{2n-1}(t) i_{2n(t)} \end{cases} \tag{A9}$$

Differentiating (A9), we have (A10) shown at the top of the next page.

The initial conditions of the differential equations are shown in (A11), at the top of the next page.

$$-\begin{bmatrix} 1/C_{C1} & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 1/C_{B1} & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 1/C_{C2} & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & 1/C_{B2} & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 1/C_{Cn} & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 1/C_{Bn} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \\ \vdots \\ i_{2n-1} \\ i_{2n} \end{bmatrix}$$

$$= \begin{bmatrix} R_z + R_{C1} & R_z & R_z & R_z & \cdots & R_z & R_z \\ R_z & R_z + R_{B1} & R_z & R_z & \cdots & R_z & R_z \\ R_z & R_z & R_z + R_{C2} & R_z & \cdots & R_z & R_z \\ R_z & R_z & R_z & R_z + R_{B2} & \cdots & R_z & R_z \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ R_z & R_z & R_z & R_z & \cdots & R_z + R_{Cn} & R_z \\ R_z & R_z & R_z & R_z & \cdots & R_z & R_z + R_{Bn} \end{bmatrix} \begin{bmatrix} i'_1 \\ i'_2 \\ i'_3 \\ i'_4 \\ \vdots \\ i'_{2n-1} \\ i'_{n2} \end{bmatrix} \quad \text{(A10)}$$

$$\begin{bmatrix} i_{10} \\ i_{20} \\ i_{30} \\ i_{40} \\ \vdots \\ i_{(2n-1)0} \\ i_{2n0} \end{bmatrix} = \begin{bmatrix} R_z + R_{C1} & R_z & R_z & R_z & \cdots & R_z & R_z \\ R_z & R_z + R_{B1} & R_z & R_z & \cdots & R_z & R_z \\ R_z & R_z & R_z + R_{C2} & R_z & \cdots & R_z & R_z \\ R_z & R_z & R_z & R_z + R_{B2} & \cdots & R_z & R_z \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ R_z & R_z & R_z & R_z & \cdots & R_z + R_{Cn} & R_z \\ R_z & R_z & R_z & R_z & \cdots & R_z & R_z + R_{Bn} \end{bmatrix}^{-1} \begin{bmatrix} U_1 \\ V_1 \\ U_2 \\ V_2 \\ \vdots \\ U_n \\ V_n \end{bmatrix} \quad \text{(A11)}$$

Finally, we rewrite these equations as follows:

$$-[B]_{2n\times 2n}[I]_{2n\times 1} = [A]_{2n\times 2n}[I']_{2n\times 1} \quad \text{(A12)}$$

$$[I']_{2n\times 1} = -[A]^{-1}_{2n\times 2n}[B]_{2n\times 2n}[I]_{2n\times 1} \quad \text{(A13)}$$

$$[Io]_{2n\times 1} = [A]^{-1}_{2n\times 2n}[UV]^{T}_{2n\times 1}. \quad \text{(A14)}$$

The above differential equations are solved using Runge–Kutta formulas. $[Io]$ are the initial conditions of the differential equations.

The total current along the channel at the ground level is expressed by

$$i(0, t) = \sum_{n=1}^{H/l} (i_{2n-1}(t) + i_{2n}(t))u_n(t - nw) \quad (0 < t < t_{n+1}). \quad \text{(A15)}$$

REFERENCES

[1] G. Diendorfer and M. A. Uman, "An improved return stroke model with specified channel-base current," *J. Geophys. Res.*, vol. 95, no. D9, pp. 13621–13644, 1990.

[2] G. R. Xie, C. X. Chen, Y. P. Chen, X. S. Wen, and J. H. Yu, "Theory and practice of semiconductor lightning eliminator," in *Proceedings of the 1998 International Conference on EMPD'98*, 1998, pp. 532–537.

[3] L. Dellera and E. Gerbagnati, "Lightning stroke simulation by the leader progression model, Part I: Description of the model and evaluation of exposure of free-standing structure," *IEEE Trans. PWRD*, vol. 5, no. 5, pp. 2009–2022, 1990.

[4] M. A. Uman, *The Lightning Discharge*: Academic Press, Inc., 1987.

[5] P. C. Thum, A. C. Liew, and C. M. Wong, "Computer simulation of the initial stages of the lightning protection mechanism," *IEEE Trans. PAS*, vol. PAS-101, no. 11, pp. 4370–4377, 1982.

[6] ——, "Electrostatic field computation by an integral equation method," *Electric Power Systems Research*, pp. 259–275, 1982.

[7] R. H. Golde, *Lightning*. London, UK: Academic Press, Inc., 1977.

[8] S. J. Heckman and E. R. Williams, "Corona envelopes and lightning currents," *J. Geophys. Res.*, vol. 94, no. D11, pp. 13287–13294, 1989.

[9] V. Cooray, "A model for subsequent return strokes," *Journal of Electrostatics*, vol. 30, pp. 343–354, 1993.



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The Protection Characteristics of the Lightning Rod with Expanding Top

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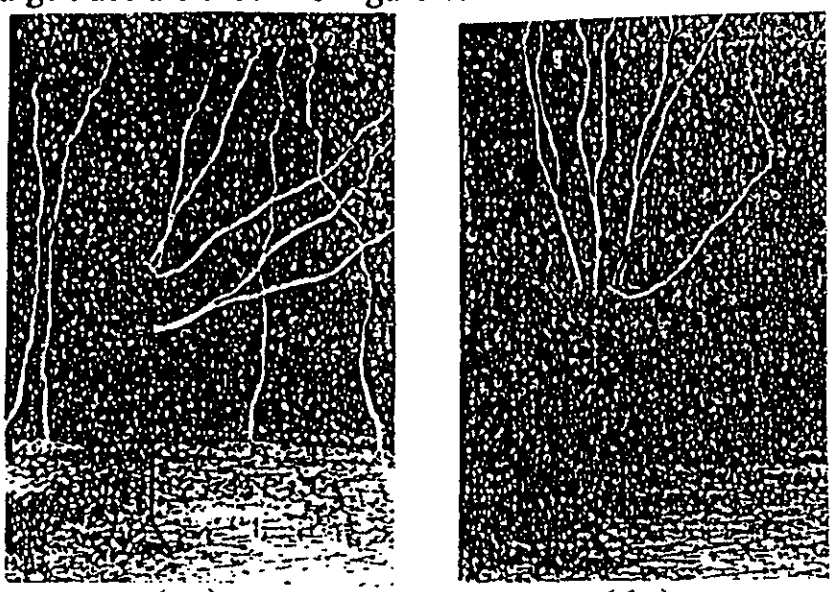
The law of lightning discharge should be understood in order to solve the problem on reliable and effective lightning prevention method. According to the analysis on lightning prevention condition in reference [1], we can draw the conclusion that the degree of the field distortion caused by leader discharge which is formed by objects on the ground has a determinant effect on the orientation of the lightning discharge channel. The degree of the field distortion caused by leader discharge is determined by the inductive charge of the objects on the ground and the charges which is formed near the objects during the process of the ionization. The more charges on the objects on the ground, the more electric displacement vectors start from the leader field and terminate at the objects on the ground. Therefore, the probability of the lightning stroke is enhanced. According to the hypothesis in reference [1], the probability of lightning stroke is determined by the number of the electric displacement vectors which terminate at the objects on the ground.

In order to increase the number the charge inducted on the lightning rod, the big volume lightning receiver with high capacitance to the ground can be installed on the top of the lightning rod. In order to protect devices, lightning rod should be struck firstly. A lot of charges are distributed on the lightning rod when the expanding receiver is installed on the top of it. Therefore, the probability of the lower part struck by lightning is decreased and the reliability of lightning prevention of the protected objects is increased.

This is approved by the experiments conducted in the outdoor highvoltage experiment site at Leningrad polytechnic Institute. In the experiment, high voltage electrode and lightning rod model are arranged coaxial, air gap is 10m. The high voltage electrode is applied with positive impluse voltage with slow wave front, the front time is 3500μs. This can simulate the developing process of the lightning accurately. The series test transformer is used as high voltage supply and the maximum peak value voltage is 2700KV.

The lightning rod model is made of the metal bar whose diameter is 2cm and whose height is 0.2 to 4m. The ring which is made of metal bar is mounted on the top of the lightning bar, the diameter of the metal bar is 0.5cm and the radius of the ring is 0.1m, 0.17m and 0.28m respectively. The h to H ratio h/H=0.1 ~ 0.35, when h is the height of the lightning rod and H is the distance of the air gap.

In the experiment, the discharge trace was photographed by the static camera. The location where the lightning rod was struck was photographed. Divide the discharge number n_0 of the lightning rod by total discharge number n (n=50~200) in the experiment, you will get the stroke probability ψ_0 of the lightning rod. The stroke probability of the lower parts ψ_{Hm} is defined as the value that the stroke number n_{Hm} of the lower parts divided by the discharge number n_0 of lightning rod . The typical pictures of the discharge trace are shown is Figure 1.



(a) (b)

Figure 1 pictures for typical discharge (air gap H=10m,the height of the lightning rod h=2.5m)
(a) without receiver
(b) with ring receiver and the radius of the ring R=0.28)

In the experiment, when the distance of air gap is 10m and the ground object height ratio h/H=0.3 ~ 0.4, we can observe that the lower parts of the lightning rod is struck by discharges many times (ψ_{Hm}=0.2) and the struck location is very low , which is (0.6 ~ 0.7)h.

The figure 2 shows the relationship curve between the stroke probability ψ_{Hm} of lower parts of the lightning rod and the height ratio h/H according to the experimental results. The three relation curves for three models show the variation law of the stroke probability of the lower parts with the height ratio h/H. The stroke probability of the lower part is very high for the lightning rod model without the receiver at the top (h/H=0.3 and ψ_{Hm} =0.26) . When the ring type receivers whose radius is 0.17m is installed on the top and h/H=0.2, the lower part will not be struck at all. If h/H=0.3, ψ_{Hm}=0.125, it decreases to the half of without receiver (curve 2 in

Figure 2). If the radius of the receiver is 0.28m and h/H<0.3, the lower part will not be struck, (curve 3 in Figure 2). If h/H=0.3 then ψ_{HB} =0.014, which is 1/8 of that for the radius of the receiver is 0.17m and 1/18 for the case of without receiver at the top. As can be seen from this, The radius of the receiver has an important effect on the stroke probability of the lower part. The lower part will not be struck if the receiver is installed on the top of the lightning rod and the size of the receiver need not to be very big.

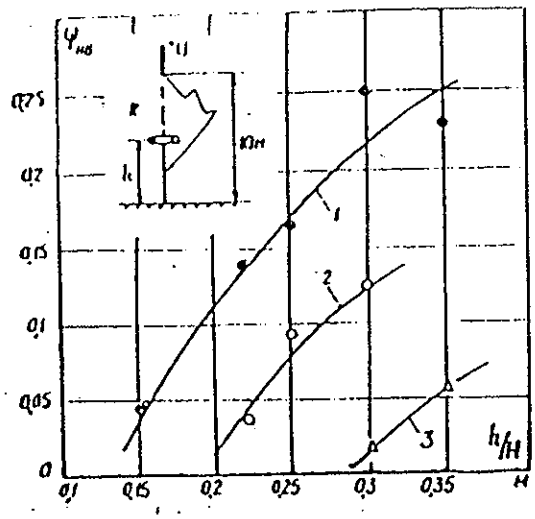


Figure 2. the relationship curve between the stroke probability ψ_{HB} of the lower parts of the lightning rod and the height ratio h/H
(air gap H=10m)

1—without ring receiver
2—with ring receiver and the radius of the ring R=0.17
3—with ring receiver and the radius of the ring R=0.28

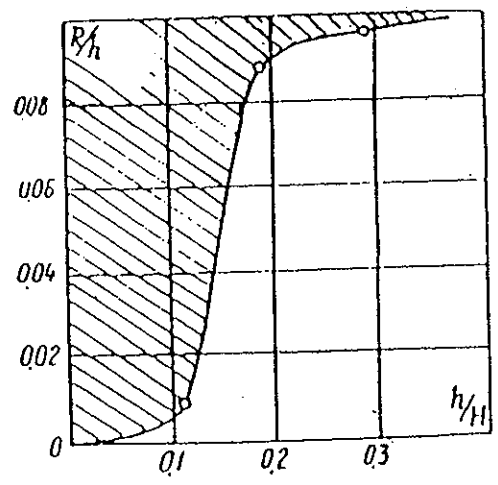


Figure 3. the relationship curve R/h= f(h/H)

In practical applications, the relationship curve R/h= f(h/H) (in Figure 3) is very important. The curve in Figure 2 is used when plotting this curve. As can be seen from these curves, when the ratio of the height of the lightning rod model h to the radius of the receiver R reaches some minimum value, the stroke probability of the lower part is very small. It can be seen from the Figure 2, if without receiver and h/H=0.15, ψ_{HB} =0.045; the radius of the ring receiver is 0.17m and h/H=0.22, then φ_{HB}=0.033; the radius is 0.28m and h/H=0.3, then ψ_{HB}=0.013. The curve in Figure 2 is extended outside within the range of small probability and this can get R/h=f(h/H) curve (In Figure 3). The area with oblique line above the curve is the R/h selection range where the lower part will not be struck when the value of h/H is fixed.

From the curve 3, when h/H is less than 0.11, the stroke probability is very low for the objects under the top of the lightning rod. In this case, as is expressed in reference [4], only if the protection range of the lightning rod is widened, the installation of the receiver is rational. When the value of h/H is from 0.11 to 0.3, the lower part will not be struck even if the size of the mounted receiver is very small. The radius of the ring receiver should be increased with the increase of the h/H. If h/H=0.3, then the radius R should not be greater than 10% of the height of the model.

The minimum value of the radius of the ring receiver can be expressed as follows for the curve in Figure 3.

$$R_{min}=0.1h[0.5+\phi(z)] \qquad (1)$$

R_{min}—the minimum value of the radius of the ring receiver, m

h—the height of the lightning rob, m

H—the length of the discharge gap, m

$\phi(z)=\frac{1}{\sqrt{2\pi}}\int_0^z e^{-\frac{y^2}{2}}dy$— Laplace function

Z=(h/H-0.15)× 33.3

In practical Engineering design of the lightning prevention, the radius of the receiver can be computed according to equation (1) and the lower part of the lightning rod will not be struck. The effect of the expanding parameter of the lightning rod on its protection characterics is studied after the electrode shape of top is selected. If the surface area of the top of the lightning rod is increased, the number of the charges accumulated on the electrode surface will be increased. Whereas, the wind load that is bears and the whole construction cast will also be increased. Therefore, it is guaranteed that the charge quantity on the unit surface area should be maximum when choosing the electrode. The ring type electrode is just suitable for this condition. The capacitance to the ground of it can be estimated as the following equation:

$$C_T = 4\pi^2 \varepsilon_0 R_0 (1 + \frac{r_T}{2R_0}) / [\ln \frac{8R_0}{r_T} (1 + \frac{r_T}{2R_0}) - \frac{\pi R_0}{H_T}] \qquad (2)$$

where R_0— of the ring pipe

H_T — the height to the ground of the axis

r_T— the radius of the ring pipe

The ratio of the capacitance of the ring to its surface area ($\Pi=4\pi^2 R_0 r_T$) is :

$$\frac{C_T}{\Pi} = (1 + \frac{r_T}{2R_0}) / r_T [\ln \frac{8R_0}{r_T} (1 + \frac{r_T}{2R_0}) - \frac{\pi R_0}{H_T}] \qquad (3)$$

and the ratio will increase with the reduction of the radius of the ring pipe r_T. Therefore, the thinnest ring pipe should be chosen if the requirement of the mechanical strength is satisfied. On the other hand, As can seen from the equation (2) that R_0 should be increased in order to raise the charge quantity.

In some cases, for example, the protected object is located at one side of the lightning rod and the lightning receiver is made in the form of short rod perpendicular to the lightning rod other than the ring type receiver. Therefore, the effectiveness of the ring type and the cantilever type receiver is studied and compared and the number of cantilever is different.

In the experiment, the high voltage electrode is the metal bar whose diameter and length are 5cm and 3m. The hanging height of the electrode is 10m. The applied voltage is the oscillation impluse voltage. The wave front time of the first positive half wave is 3500μs. The maximum value of the impluse voltage is set according to the following principle: the probability of the leader discharge in air gap is 0.95.

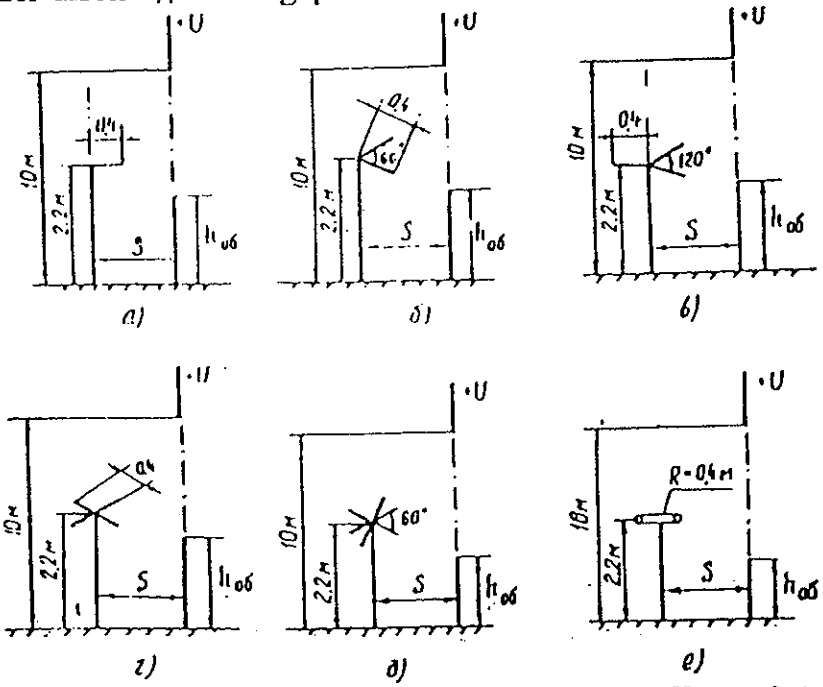


Figure 4. the arrangement diagram for testing the effect of the lighting receiver (the height of the protected object $h_{об}$=2m)

In research, the arrangement of the protected object and the lightning rod model is shown is figure 4.

The stick models of lightning rod are the metal bars whose diameter and height are 2cm and 2.2m. The top is installed with ning receiver whose radius is 0.1, 0.2, 0.3 and 0.4m respectively and the ring is made of metal thread whose diameter is 5mm. The other models are installed with the metal rods perpendicular to the lightning rod and the length and diameter of the cantilever are 0.4m and 5mm. The selection of the length of cantilever is on the basis of the actual dimension possibility of the lightning rod construction components.

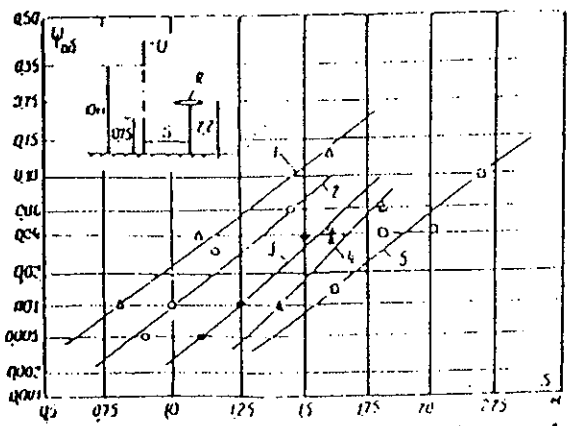
When testing the protection effect of the lightning rod with one centilever, The centilever is mounted at the side near the protected object (figure 4a) or at the opposite side.

When two centilevers are mounted on the top of the lightning rod, the included angle between them is 60^0. The protected object is between them.(figure 42).

If the number of the centilevers is 3, 4 and 6, the included angle is 120, 90^0, and 60^0 respectively. (figure 4.B.P.II)

The protected object is simulated by the standing stick , the diameter of it is 2cm and the height is 0.75m, 1m and 1.5m respectively.

The experimental result of the protection characteristic of the lightning rod can be expressed by the relationship curve of the stroke probability $\Psi_{o\delta}$ of the protected object and the distance S between the lightning rod and the protected object. The reference [2] suggests that the relationship curve $\Psi_{o\delta}=f(S)$ can be expressed by the normal distribution function of the random event, it can provide the stroke probability of the protected object is very small by making use of the obtained data.



The figure 5. the relationship curve of the stroke probability $\Psi_{o\delta}$ of the protected object and the distance S between the lightning rod and the protected object (the height of the protected object $h_{o\delta}$=0.75m)

1—without ring receiver

2—with ring receiver and the radius of the ring R=0.1

3—with ring receiver and the radius of the ring R=0.2
4—with ring receiver and the radius of the ring R=0.3
5—with ring receiver and the radius of the ring R=0.4

For the curve $\Psi_{o\delta}$=f(S) in figure 5, the height of the protected object is 0.75m, when the top of lightning rod is installed with receiver, the stroke probability of the protected object is decreased greatly. If the radius of the receiver is 0.2m and the height of the protected object is 0.75m and S=1.6m, the stroke probability can drop to $\Psi_{o\delta}$=0.04 from $\Psi_{o\delta}$=0.14 for the case with no receiver on the top, namely, it drops to 1/3 of the former. If the other conditions are not changed, the radius of the receiver is changed 0.4m, the stroke probabiling drops to $\Psi_{o\delta}$=0.015, which is 1/10 of the former. When the height of the protected object is 1.5m, the effect of the ring type receiver on decreasing stroke probability is more obvious. For example, when S=1m and the radius of the vine receiver is 0.4m, then the stroke probability $\Psi_{o\delta}$ is 0.01, which is 1/25 of that with no receiver.

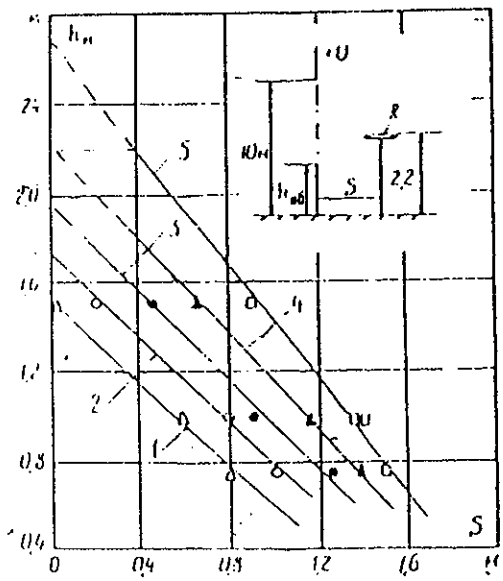


Figure 6. the protection region boundary of the lightning rod with the ring receiver ($\Psi_{o\delta}$=0.01)
1—without ring receiver
2—with ring receiver and the radius of the ring R=0.1
3—with ring receiver and the radius of the ring R=0.2
4—with ring receiver and the radius of the ring R=0.3
5—with ring receiver and the radius of the ring R=0.4

According to experimental data, figure 6 shows the boundary of the protection region for $\Psi_{o\delta}$=0.01. As can be seen from the figure, the

protection region of the lightning rod is widened due to the receiver on the top. Moreover, The longer the axis radius of the ring is, the wider the protection region is. The widening degree of protection region when the radius of receiver is increased is proportional to that when the height of the lightning rod is increased. The height of the protection region for the lightning rod with the ring type receiver on the top is determined by the point of intersection of this protection awl and the axis of the lightning rod . When the radius of the ring is 0.3m, the height of the protection region reses to 1.5 times of that without the receiver. When radius is 0.4m, it will rise to 1.8 times.

Because the protection region of the lightning rod with the ring receiver is heightened and widened, the height of the lightning rod can be lowered under the condition of the same distance between the lightning rod and the protected object and the same reliability of the lightning prevention.

Under the condition that stroke probability of the protected object $\Psi_{o\delta}$=0.01, if the ring receiver is installed, the relationship of $\Delta h_m/h_m$ and R_o/ h_m can be expressed as follows:

$$\Delta h_m/h_m = 2.5\ R_o/ h_m \qquad (4)$$

where $\Delta h_m/h_m$ is the lowered degree of the height of the lightning rod and R_o/ h_m is the ration of the radius of the ring to the height of the lightning rod.

The stroke probability of the column shape protected object is concerned with the number of the cantilevers when the top of the lightning rod is installed with the cantilevers. For example, the protected object is 1.5m high and located in the direction the cantilever, the distance between the lightning rod and the object is S=0.7m, then the stroke probability $\Psi_{o\delta}$=0.04. If the other two cantilevers are installed on the top and the included angle between then is 120^0, then $\Psi_{o\delta}$=0.01.

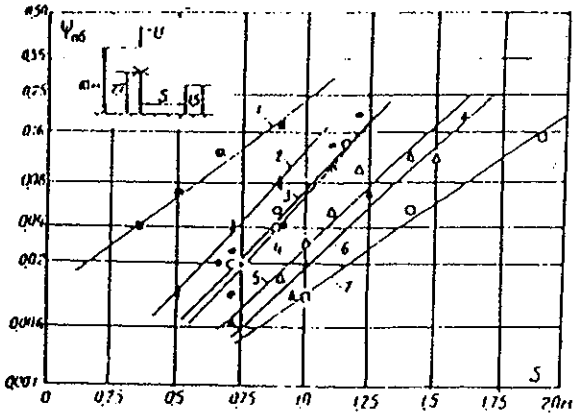
It must be paid attention that the stroke probability of the column shape protected object is concerned with the relative location of the cantilever and the object. When the protected object is located in the direction of the cantilever, the height of it is 1.5m and the distances between the lightning rod and it is 0.7m and 0.9m, then $\Psi_{o\delta}$=0.04 and 0.08. If the distance S is not changed, the protected object is located in the opposite direction of the cantilever, the $\Psi_{o\delta}$=0.14 and 0.22, this valne corresponds to that without the receiver. For the case of without receiver, if S=0.7m, then $\Psi_{o\delta}$=0.13.

It is very important that the protection effect of the two sides is not symmetry for the lightning rod with single cantilever. When the protected object is located in the direction of the cantilever, if the height of it is 1.5m

and the distance between the end of the cantilever and it is 0.5m, then $\Psi_{o\delta}$=0.08. If object is located at the opposite direction of the cantilever and the distance between the standing stick and it is 0.5m , then $\Psi_{o\delta}$=0.04.

When the top of the lightning rod is installed with two cantilevers (included angle is 60^0) and three cantilevers (included angle is 120^0), the stroke probability of the protected object is concerned with the relative location of the cantilevers and it. For example, the height of the object is 0.75m, the distance between standing stick and it is 1.5m, the number of the cantilevers is 3, if the protected object is located between two cantilevers, then $\Psi_{o\delta}$=0.04, if it is located in the direction of the cantilever, then $\Psi_{o\delta}$=0.02.

When the number of cantilevers is 4 and the included angle is 90^0, the protection effect becomes axial symmetry. When the protectod object is 1.5m high and the distance between the standing stick and it is constant, in the confidence interval, the stroke probability is the same whether the protected object is located in the direction of the cantilever or between the two cantilevers. When the column shape protected object is located between the cantilevers and the number of cantilevers is more than 3, the protection effect of the lighting rod is the best.



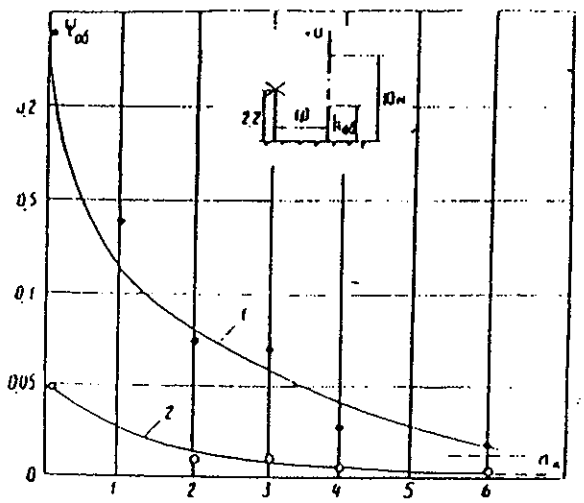
The figure 7. the relationship curve between the stroke probability $\Psi_{o\delta}$ of the protected object and the distance S between the lightning rod and it (with cantilever and $h_{o\delta}$=1.5m)

1—without receiver
2—with one cantilever
3—with 2 cantilevers
4—with 3 cantilevers
5—with 4 cantilevers
6—with 5 cantilevers
7—with 6 cantilevers

The figure 7 shows the relationship curve between the stroke

probability $\Psi_{o\delta}$ of the protected object and the distance between the lightning rod and it , the height of the object is 1.5m, the top of the lighting rod is installed with no receiver or with 1,2,3,4and 6 cantilevers or with the ring receiver whose diameter is 0.4m. As can be seen from the curve, the protection effect of the lighting rod with the cantilevers on the top is far better than that without cantilevers.

The shorter the distance between the protected object and the lightning rod is, the greater the difference of the protection effect is for the lightning rod with the cantilever and without cantilever. As can been seen from the relationship curve $\Psi_{o\delta}=f(S)$ in figure 7, the height of the proteoted object is 1.5m, when the distance S=1.0m, the stroke probability of the lightning rod with two cantilevers drops to 1/3 of that without cantilevers, if S=0.5m, then it will drop to 1/10 .



The figure 8. the relationship curve between the stroke probability $\Psi_{o\delta}$ of the protected object and the number n_k of the cantilevers (S=1m)

1—$h_{o\delta}$=1m 2—$h_{o\delta}$=1.5m

When the distance between the lightning rod and the protected object is constant, the stroke probability drops most fastly for the lightning rod with one or two cantilevers on the top (In Figure 8) .The stroke probability drops slowly when the number of the cantilevers is increased. When the number is increased to 6, the stroke probability can match with the lightning rod with the ring receiver on the top (the axis radius of the ring and the length of the cantilever is equal). Therefore, it is unreasonable when the number of the cantilever is more than 6.

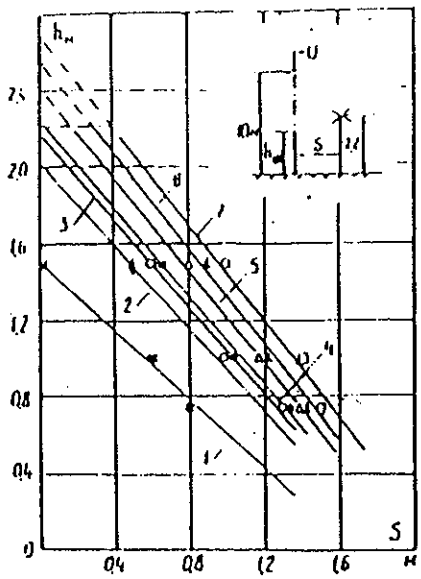


Figure 9. the protection region boundary of the lightning rod ($\Psi_{o\delta}$=0.01)
1—without cantilever 2—the number of cantilevers n_k=1
3—n_k=2 4—n_k=3 5—n_k=4 6—n_k=6
7—with ring receiver and the radius of it R=0.4m

The lightning rod is installed with the cantilever whose diameter is 0.4m and the number of the cantilevers is different, the protection region boundary is shown in figure 9 for the stroke probability $\Psi_{o\delta}$=0.01. As can be seen from the figure, the protection region is widened when one cantilever is installed on the top of the lightning rod. However, the protected object under the cantilever can be struck from the side by the lightning. When the lightning rod is installed with two cantilevers and the included angle between them is 60^0, the stroke from the side can be avoided. Thus, the interface of the protection region is close to the protection awl formed by the lightning rod.

It must be pointed out that the height of the protection region of the lightning rod with three cantilevers on the top is 1.5 times as much as that without cantilevers. If six cantilevers are installed, it is 1.7 times and close to that with ring receiver on the top (the axis radius of the ring is equal to the length of the cantilever).

The protection region of the lightning rod is widened greatly when the number of the cantilevers is more than two. Therefore, it is possible to

lower the height of the lightning rod under the condition that the protection level is kept constant. The lowered height is increased with the number n_k of cantilevers which are installed on the top until $n_k=6$, $\Delta h_m=0.41h_m$,which is close to $\Delta h_m=0.44h_m$ when the ring receiver is installed on the top (the axis radius is equal to the length of the cantilever).

The relationship $\Delta h_m/h_m=f(n_k)$ can be expressed approximately as follows:

$$\frac{\Delta h_m}{h_m}=0.21\sqrt[3]{n_k} \qquad (5)$$

The application range of this equation is $n_k \leqslant 10$, $l_k/h_m=0.18$(l_k is the length of the cantilever).

In order to be applied in arbitrary range of l_k/h_m , equation (4) is used and make $l_k=R_o$

$$\frac{\Delta h_m}{h_m}=\frac{2.5}{0.45}\frac{l_k}{h_m}0.21\sqrt[3]{n_k}=1.17\frac{l_k}{h_m}\sqrt[3]{n} \qquad (6)$$

For example, if $l_k/h_m=0.1$ and $n_k=6$, the lowered height of the lightning rod is $\Delta h_m=0.21h_m$.

The research reselts demonstrate the high effectiveness of the lightning rod with expanding top. Furthermore, the farer from the axis, the better (of course it should be economical), because the charge quantity on the top is proportional to the axis radius of the ring. Therefore, it is worthwhile to install some cantilevers on the ring which irritate outside. When the number of the cantilevers $n_k \geqslant 6$, it is equivalent that the axis radius of the ring is exended to the end of the cantilever.

Conclusion

1.The relationship between the stroke probability of the lower part of the lightning rod with the ring receiver on the top and the ring radius is given according to the experiment. The computaing formula of the ring radius is given under the condition that the lower part will not be struck.

2.The height of protection region of the lightning rod is increased with the increasement of the axis radius of the lightning rod with the ring receiver on the top. Conversely, when the lightning rod is installed with the ring receiver on the top, the height of it can be lowered and the lowered height is proportional to the ring radius. When the number of the cantilevers installed on the top is more than six, the protection effect is close to that with the ring receiver on the top.

References

[1] Александров Г.Н., Иванов В.Л., Кадзов Г.Д., Курилов В.А. О способах активного воздействия на ориентировку разрядов длинной искры. -Изв. вузов, Энергетика, 1980, Но 2.

[2] Александров Г.Н., Иванов В.Л., Костенко М.В. и др. Методика оценки защитного действия молниеотводов. -Труды ин-та "Тяжпромэлектропроект". М.: Энергия, 1972.

[3] Александров Г.Н., Иванов В.Л., Базелян Э.М., Садихова Е.Н. Об ориентировке канала длинной искры. -Электричество, 1973, Но 3, с. 63-66.

[4] Александров Г.Н.,Кадзов Г.Д.,О повышении эффективности молниезащиты. -Электричество, 1987, Но 2, с. 57-60.

[5] Александров Г.Н., Иванов В.Л. Изоляция электрических аппаратов высокого напряжения. -Л.: Энергоатомиздат, 1984.

[6] Александров Г.Н., Иванов В.Л., Кадзов Г.Д. Исследование влияния высокоионизированного канала, создаваемого мощным ОКГ, на развитие разряда в длинном воздушном промежутке. -ЖТФ, 1977, Но 10.

Theory and Practice of Semiconductor Lightning-current Extender (SLE)

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Theory and Practice of Semiconductor Lightning Eliminator

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Abstract The paper introduces the structure and function of the semiconductor lightning eliminator (SLE). It is pointed that SLE can limit the main discharge current and reduce the rate of lightning current rising. Therefore SLE is very available for the lightning protection of microelectronic equipment and flammable and explosive facilities.

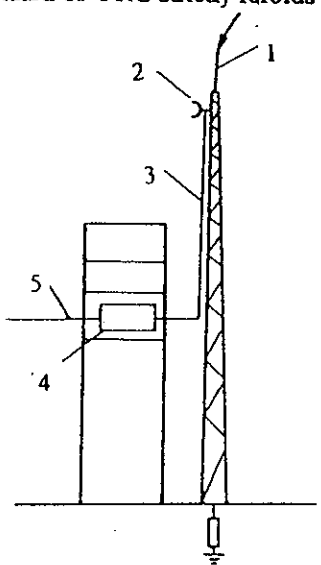
0. Introduction

It is well known that the damage caused by lightning stroke is because of the very large lightning current and its very rapid current changing rate. Conventionally Franklin rod is used as main equipment to prevent direct lightning stroke.

Fig. 1 shows a microwave station with a lightning rod. The potential of point A is

$$u_A = iR + L\frac{di}{dt}$$

which can reach hundred or thousand kilovolts and may destroy the microwave equipment. Therefore the National Standard of PRC strictly forbids to hang any low voltage wire (for example telephone lines, wired broadcast lines and power lines) on the lightning rod and its structure.



1—lightning rod 2—antenna 3—feedback line
4—microwave device 5—power line
Fig.1 Scheme of microwave station

People did lot of work to reduce the grounding resistance to decrease this overvoltage. However even if the grounding resistance can be reduced to zero, the inductance of the tower and rod, which can also produce high overvoltage, can not be reduced. Many of researches show that the essential measure to reduce the dangerous overvoltage is to reduce the amplitude and rising rate of lightning current. Semiconductor Lightning Eliminator was just invented according to such an idea in 1978 in PRC[1].

1. The function of SLE

1.1 Structure

Fig. 2 shows the structure of SLE. It is composed of 13—19 semiconductor rods, which is 5m length with 4 metal tips on the top of each rod. The rods are distributed radially and form 2—3 fan shaped surface. The angle between two neighbor rods in each fan-shaped surface is 20 to 25 degree. The total resistance of lightning eliminator is

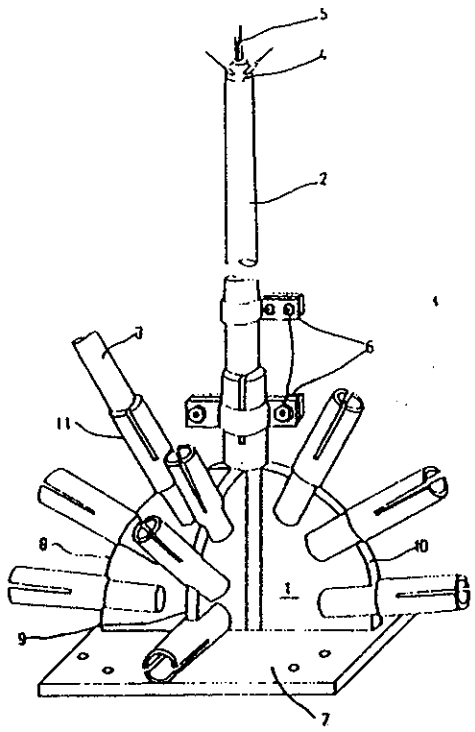
$$R = R_c i^{\alpha}$$

where R_c =35kΩ, α=0.35

1.2 Characteristic

(1) SLE can produce 3—14.5mA neutralizing current under the thunder cloud, and about 1—2m long spark discharge can occur on the top of the semiconductor rod when the thunder cloud is heavily charged. At that time the neutralizing current reaches about 1A up. Due to this function, SLE can eliminate about 25% of the total lightning strokes.

(2) SLE can completely eliminate the upward lightning strokes which constitute 50% up of the total number of the lightning strokes on high building or tower.



1— base 2, 3—semiconductor 4—top of rod
5—metal tips 6—fixture 7—base plane
8, 9, 10—fan plane 11—sleeve
Fig. 2 Sketch drawing of the structure of SLE

(3) SLE can reduce the current of the residual lightning strokes to a significantly low value, i.e., reduce the current of the residual lightning strokes to about 4 thousandth of the original value.

(4) The protective zone of the SLE is larger than that of the common lightning rod, its protective angle is 71^0 – 78^0.

(5) The rods of the SLE can bear the wind of 45m/s.

SLE should be installed on the top of the building or tower higher than 30m.

1.3 The guiding principle

Though the corona current of SLE under a thunder storm cloud is large, but it is not effective to neutralizing the charge in cloud, because there may be horizontal wind with velocity 10—20m/s, while the upward velocity of corona charge particle is only 1.4—5m/s (in the intensity of field 10—40kV/m). Therefore the guiding principle of SLE is not the "neutralization", but the "limitation of lightning current".

2. The investigation of SLE

2.1 The enlightenment of lightning withstanding characteristic of ancient Chinese Buddhistic pagodas[2].

In China quite a few thousand years old ancient pagodas have never been struck by the lightning. The lightning strokes of 160 ancient Chinese Buddhistic pagodas with total of 103904 pagoda-years have been counted up, only 45 lightning strokes are found out, while the total number of the theoretical lightning strokes is 10033. In Table 1 the lightning stroke rate (the ratio of the number of real lightning strokes to theoretical lightning strokes) of pagodas is listed according to its height. We can see from Table 1 that the lightning stroke rate is extremely low, especially of those pagodas higher than 40m. For the pagodas higher than 60m, the total lightning stroke rate is only 0.042%. It can be calculated that the lightning withstanding characteristic of the ancient Chinese Buddhistic pagoda is as high as 2,308 years (per pagoda). Again the damage of those pagodas struck directly by the lightning was slight. For example for the pagodas higher than 40m among the investigated ten lightning strokes only two result in collapsing of the pagoda top. This is really a great surprise to us. All these indicate that the ancient Chinese Buddhistic pagodas, which were made of semiconductor material, have a natural lightning protective property.

Table 1 The lightning stroke rate of pagodas according to its height

h(m)	N_1	N	N_2	$N_2/N(\%)$
10≤h<20	26	174	6	3.448
20≤h<30	59	1634	14	0.857
30≤h<40	39	2183	15	0.687
40≤h<50	16	1552	5	0.322
50≤h<60	12	2137	5	0.187
60≤h	8	2353	1	0.042
Sum	160	10033	45	0.449

where N_1 stands for the number of pagodas.
h stands for the height of pagodas.
N stands for the theoretical lightning stroke number.
N_2 stands for the real lightning stroke number.



Fig. 3 A part of tree struck by lightning

2.2 The enlightenment of lightning stroke on a tree

Fig. 3 shows a part of tree which was struck by a lightning in 5th April 1992 in Wuhan University campus. From this photo we can see that the tree trunk is split open only and there is no any flashover burn trace along its surface, i. e., the lightning current passed inside the tree trunk. The tree is semiconductor. This photo shows that under certain conditions, the lightning current can only pass inside the semiconductor and flashover can be avoid.

2.3 The experiment study

Fig. 4 shows the scheme of long air gap discharge experiments using Image Converter Camera (IMC). IMC has a scanning velocity of 1 mm/ns and the number of frame is 2×10^7 fps. DS is a double screened room. IG is a impulse generator rated 2400kV. R_1 is a decreasing discharge velocity resistance. r_1, r_2, r_3 are the current shunts. R_2 is the main discharge current limitation resistance, simulating the function of SLE. G is the spark gap.

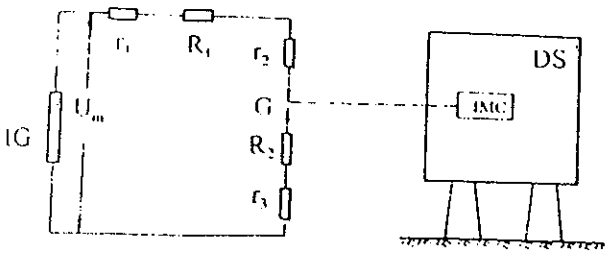


Fig. 4 Scheme of long air gap discharge experiment

In Table 2 one set of data is given. These data explain that the main discharge current limitation resistance R_2 can reduce the main discharge current and the leader velocity. Table 2 shows that when R_2 increases from 0 to 106kΩ, the main discharge current decreases from up 80A to only 3 A.

Table 2 One set of data from simulation experiment (R_1=106kΩ. The gap distance is 1m)

R_2(kΩ)	U_m (kV)	V_n (cm/μs)	I(A)
0	1128	4.9	80
35.3	1153	3.7	/
70.6	1142	3.4	/
106	1123	3.6	3

where V_n stands for the velocity of leader.

I stands for the main discharge current.

2.4 Theoretical analysis and computer simulation

(1) How to prevent flashover along SLE rod

The resistance of SLE can limit the lightning current so that the peak value of lightning current can be largely decreased. To prevent flashover along the semiconductor rod, the discharge voltage between two tops of the neighbor rods is adjusted to less than the flashover voltage U_f, i. e., the semiconductor rods can connect one another in parallel automatically step by step under the lightning

stroke. Under strokes, the resistance of SLE (R) is connected with the resistance of lightning leader channel (R_c) in series, so that the voltage acting on R is only $U=U_0\times R/(R+R_c)$, where U_0 is the voltage of storm cloud. The designing flashover voltage of semiconductor rod U_f is larger than 1700kV. If there are 3 rod tops connected in parallel, the resistance (R) will be $R=R_0/3=11.7k\Omega$. Assuming $U_0=50000kV$, the height of storm cloud is 1,000m and $R_c=0.5\times1,000=500k\Omega$. Therefore we get $U=50,000\times11.7/(11.7+500)=1,143kV$, which is less than U_f ($\geq1700kV$), i. e., the flashover should not occur.

(2) How to eliminate the upward lightning

The lightning observation shows that the rate of the upward lightning on the high buildings or towers is very high. According to Berger's statistics for a 70m high lightning rod on the St. Salvador Mountain, 70—80% of the lightning strokes is developed upward from the rod. Golde considered that total lightning strokes will be reduced evidently, if the upward lightning strokes are eliminated. Field measurement shows that the upward lightning occurs only if a upward leader current larger than 100A is provided. The resistance of the semiconductor rod has the ability to limit the upward leader current to few tens of amperes. This ability has been proved by theoretical calculation, laboratory experiment, computer simulation and field measurements. It is to say that SLE can destroy the condition of forming the upward leader, so that the upward lightning strokes can be totally eliminated.

(3) How to reduce the downward lightning strokes

It is the neutralization effect that makes SLE to reduce the downward lightning strokes. When the cloud is electrified, the number of the positive charge in thunder cloud is certainly equal to negative one, because the lightning is neutral before electrification. Practical observation shows that 90% of the lightning strokes to ground are negative and only 10% of them are positive. It seems that the negative charge will be accumulated in the earth. But a long period observation shows that the total amount of the negative charge in earth is unchanged (about 8.86×10^{-10} C/m^2). The only explanation is that a great part of positive charges in the cloud comes into the earth in a peaceful way (lightning elimination). The theoretical explanation of why the positive thunder cloud is easier to be neutralized in a peaceful way than the negative one is that the speed of the negative air ions rising up from the ground is 37.5% faster than the speed of the positive ones under the same electrical field intensity. It can be concluded therefrom that the lighting elimination effect is existent in the natural world. A great part of the charges in the thunder cloud is neutralized by the corona current that comes from the top of trees and buildings. The lightning which struck the ground is only a little remaining part of it.

It should be noticed that in order to reduce the field of the cloud to the level not enough to start a lightning stroke only a part of the charges in the thunder cloud need to be neutralized. Then the stroke will not happen.

Statistical data show that due to the neutralizing effect, SLE can eliminate about 25% of total number of lightning strokes.

(4) How to restrain the current of the main discharge of the downward lightning

When the electrification of the thunder cloud is so fast that the neutralizing current can not neutralize the charge in cloud in time, SLE is allowed being stroked by a downward lightning. This is the most conspicuous advantage of SLE. The main discharge can be restricted by the aid of semiconductor rod. The duration of the main discharge is extended from microseconds to milliseconds and the current of main discharge is reduced to about 4 thousandth of the original value. Sometimes main discharge will even not happen.

3. The field measurement result[3]

Three methods have been used to measure the direct lightning current. They are automatic lightning current measurement device YL0-1 in range 10A—100kA, ferromagnetic bar and the thermal crack on the protective lacquer membrane which can indicate the passing of a current of 10—35A through the semiconductor rod in millisecond duration.

Table 3 gives the data of measuring lightning current as the lightning strikes directly on SLE. The first 28 data (No. 1—28) recorded by lightning installation YL0-1 are obtained from 18 lightning discharges including 6 dual strokes and 2 triple strokes. The following 5 data (No.29—33) in which one is the positive stroke is

recorded by ferromagnetic bar, and the remained 5 data (No. 34—38) are recorded using the thermal crack method, so the polarity of which is unclear.

Table 4 shows the probability P of the lightning current larger than I (absolute value) as the lightning strikes directly on SLE.

Table 3 Data of the lightning limitation current

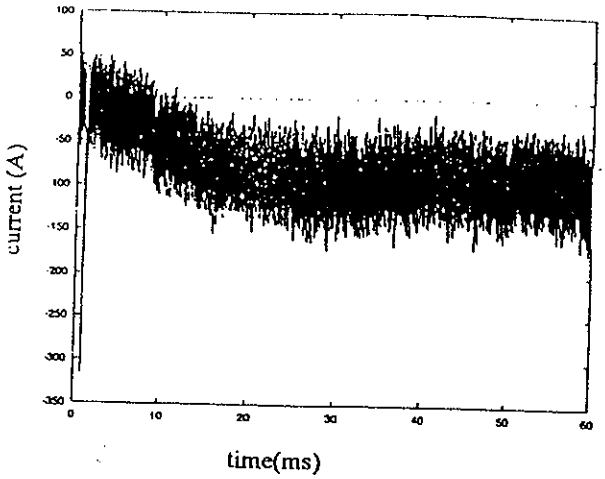
No	1	2	3	4	5	6
I(A)	-485	-26	-296	-362	-43	-346
No	7	8	9	10	11	12
I(A)	-233	-335	-79	-485	-391	-28
No	13	14	15	16	17	18
I(A)	-368	-346	-356	-204	-391	-348
No	19	20	21	22	23	24
I(A)	143	-403	+67	-303	+47	+278
No	25	26	27	28	29	30
I(A)	-327	-628	-290	-991	-100	-100
No	31	32	33	34	35	36
I(A)	-200	-100	+200	300	30	210
No	37	38	—	—	—	—
I(A)	240	200	—	—	—	—

Note : No. 4—5, No. 6—7, No. 8—9, No. 11—12, No. 18—19, No. 20—21 are dual strokes and No. 14—16, No. 22—24 are triple strokes.

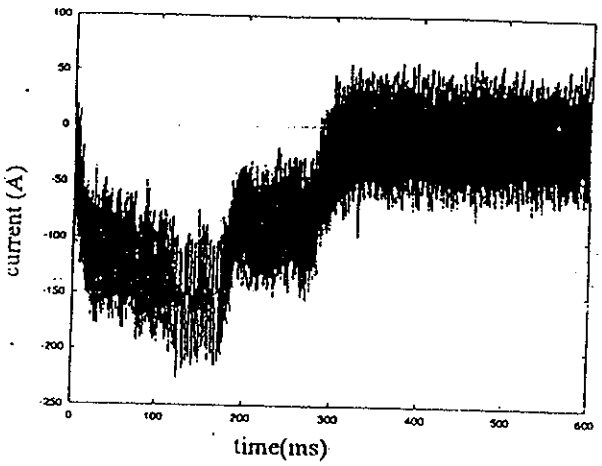
Table 4 Probability of lightning current larger than I

I(A)	30	50	100	200	300
P(%)	92.1	86.8	73.7	63.2	42.1
I(A)	400	500	700	1000	—
P(%)	13.2	5.3	2.6	0	—

The rocket triggered lightning test[4] on a single semiconductor rod (SLE consists of 13 semiconductor rods, its function is much better) had been carried in Japan in 1993—1996. Fig. 5, 6, 7, 8 are the oscillograms. From these figure we can find no matter the flashover occurs or not, the ΔT (time needed when the current increase from 0 to 200A) in the case of striking on single semiconductor rod is 300ms (No. 9412), 7ms (No. 9309), 10ms (No.9315) and 10ms (No. 9511) respectively, which is a larger tens times than that on ground. It means SLE can extend the duration of lightning and greatly decrease the rate of lightning current rising.

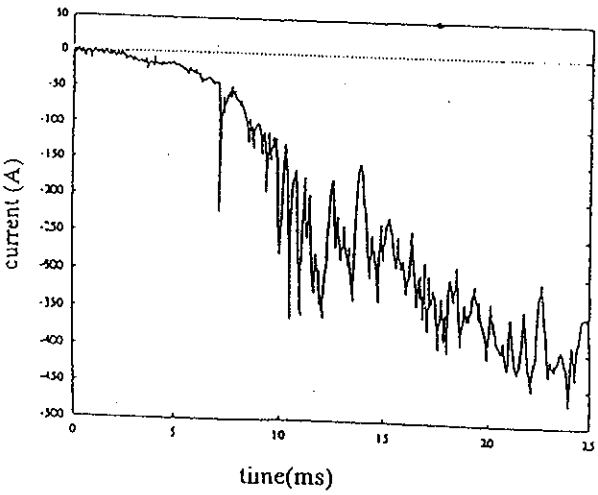


(a) Extended current waveform

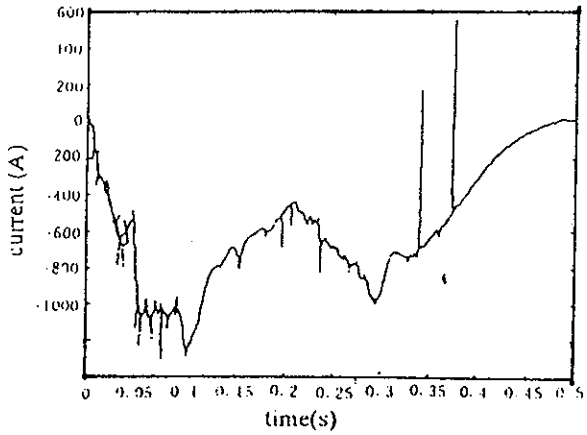


(b) Complete current waveform

Fig. 5 Oscillogram obtained from triggered lightning test (No. 9412)

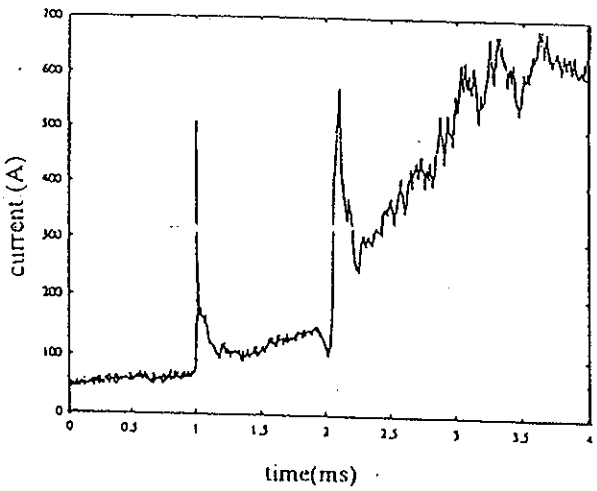


(a) Extended current waveform

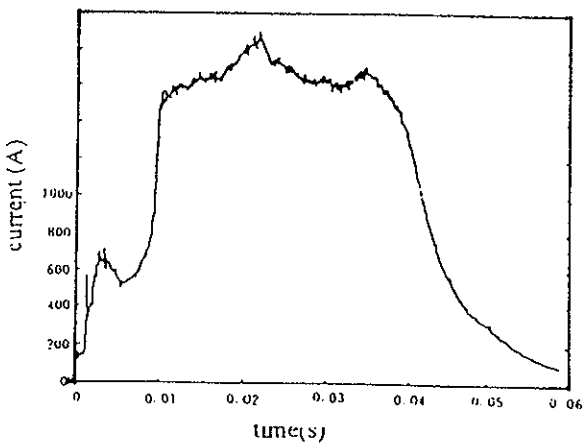


(b) Complete current waveform

Fig.6 Oscillogram obtained from triggered lightning test (No. 9309)



(a) Extended current waveform



(b) Complete current waveform

Fig. 7 Oscillogram obtained from triggered lightning test (No. 9315)

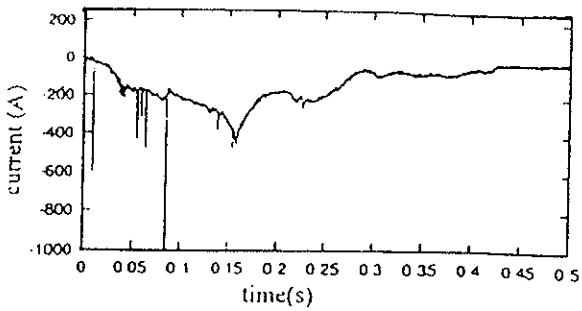


Fig. 8 Oscillogram obtained from triggered lightning test (No. 9511)

4. The practical experience

In China, SLE has been widely used for 13028 tower years by the end of summer of 1997. The successful experience of SLE includes CCTV center in Beijing, East Pearl television tower in Shanghai, rocket launching site in Xichang, oil storage tanks, refineries, computer centers and other places of telecommunication, radio and television . The rate of failure of SLE is less than 0.1%. It is very reliable.

5. Conclusion

(1) SLE can limit the lightning main discharge current and reduce the rate of lightning current rising.

(2) SLE is very available for the lightning protection of electronic equipment and flammable and explosive facilities.

References

1 Chen Cixuan, "Research and development of semiconductor lightning eliminator", Power system technology, No. 11, Nov. 1996. (in Chinese)

2. Xie Guangrun, et al, "The corona phenomena and lightning withstanding characteristics of the ancient Chinese Buddhistic pagodas", Proc. of the third Asian conf. on electrical discharge at Beijing, Sept. 1990.

3 Xie Guangrun , Yu Jianhui and Chen Cixuan , "The current limit capability of semiconductor lightning eliminator", Proc. of the 7th Asian conf. on electrical discharge at Xi'an, Oct. 1994.

4. K. Horri et al, "Triggered lightning test to a new type lightning rod", Electric power, Vol. 30, No. 5, May 1997. (In Chinese)

The Current Limit Capability of Semiconductor Lightning-current Extender (SLE)

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SEVENTH ASIAN CONFERENCE ON ELECTRICAL DISCHARGE
12－14 OCTOBER 1994 XI'AN CHINA

The Current Limit Capability of Semiconductor Lightning Eliminator

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ABSTRACT

Datums including 38 lightning current being restricted by the semiconductor lightining eliminator in practical operation are given in the paper. These datums are provided by automatical lightning current measurement device YL0－1 and ferromagnetic bar etc. Analysis shows that semiconductor lightning eliminator can reduce the lightning current to about 4 thousandth of its original value.

1. INTRODUCTION

The Chinese semiconductor lightning eliminator SLE－5 is composed of 13 ～ 19 semiconductor rods, 5 m in length with 4 metal tips on the top of each rod. The rods are distributed radially and form 2 ～ 3 fan－shaped surface. The angle between two neighbour rods in each fan－shaped surface is 25 degrees. The total resistance of eliminator is

$$R = R_0 i^{\alpha} \qquad (1)$$

where $R_0 = 35k\Omega$, $\alpha = 0.35$.

With the aid of the resistance of semiconductor rod, SLE can completely eliminate the upward lightning strokes which constitute 50% up of the total number of the lightning strokes on the high building or tower. And by the aid of corona discharge and herefrom the neutralizing effect and sheilding effect, SLE can reduce the number of downward lightning strokes. Statistical data indicate that due to the above two functions SLE can eliminate about 75% of the original toal number of direct cloud－to－ground strokes. As regard to the residual 25% lightning strokes SLE offers the characteristic of reducing the lightning stroke current to a significantly low value with the aid of semiconductor rods.

In order to obtain quantitatively the limit capability of SLE, values of lightning current recorded in the case when the lightning strokes directly on SLE in practical operation are given in the paper.

2. DATUMS FROM PRACTICAL OPERATION

Three methods have been used to measure the direct lightning stroke current. They are automatical lightning current measurement device YL0－1 in range of 10A ～ 200kA, ferromagnetic bar and the thermal crack on the protective lacquer membrance which can indicate the passing of a current of 10 ～ 35A through the semiconductor rod in millisecond duration.

Table 1 gives the datums of the measured lightning current as the lightning strokes directly on SLE. The first 28 datums (No.1 ～ 28) recorded by YL0－1 are obtained from 18 lightning discharges including 6 dual strokes and 2 triple strokes. The following 5 datums (No.29 ～ 33) in which one is the positive stroke are recorded by ferromagnetic bar, And the remained 5 datums (No.34 ～ 38) are recorded using the thermal crack method, so the polarity of which is unclear.

Table 1 Datums of the lightning current

No.	1	2	3	4	5	6	7	8	9	10	11
Lightning current (A)	－485	－26	－296	－362	－43	－346	－233	－335	－79	－485	－391
No.	12	13	14	15	16	17	18	19	20	21	22
Lightning current (A)	－28	－368	－346	－356	－204	－391	－348	＋143	－403	＋67	－303
No.	23	24	25	26	27	28	29	30	31	32	33
Lightning current (A)	＋47	＋278	－327	－628	－290	－991	－100	－100	－200	－100	＋200
No.	34	35	36	37	38						
Lightning current (A)	300	30	210	240	200						

Note: No. 4 ～ 5, No. 6 ～ 7, No. 8 ～ 9, No. 11 ～ 12, No. 18 ～ 19, No. 20 ～ 21 are dual strokes and No. 14 ～ 16, No. 22 ～ 24 are triple strokes.

Table 2 shows the probability of the lightning current larger than I (absolute value), as the lightning strokes directly on SLE. Fig. 1 is the probability curve.

Table 2 Probability of the lightning current larger than I

Lightning current I(A)	30	50	100	200	300	400	500	700	1000
Probability P(%)	92.1	86.8	73.7	63.2	42.1	13.2	5.3	2.6	0

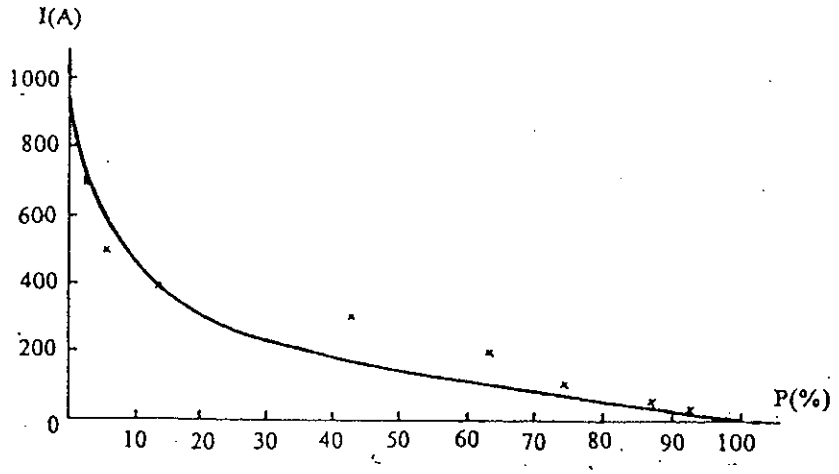

Fig.1 The probability of Lightning current as the lightning directly strokes on SLE

Using the logarithm pattern the probability of the lightning current being restricted by SLE can be expressed as

$$\lg P = -\frac{I}{0.44} \tag{2}$$

where I has the unit of kA. It can be seen that the lightning current corresponding to the probability of 10% is 0.44kA.

Statistical data in main land of China show that the probability of the lightning current P_0 is calculated by the following formula

$$\lg P_0 = -\frac{I}{108} \tag{3}$$

Comparing the above two formulas we can find that the current limit capability of SLE－5 to the direct lightning stroke is very great. SLE can reduce the direct lightning stroke current to about $\frac{0.44}{108} \approx 0.4\%$.

3. CONCLUSION

The Chinese semiconductor lightning eliminator type SLE－5 not only has the capability of reduce the number of lightning strokes but also can reduce the current of the residual lightning strokes to about 4 thousandth of the original value.

REFERENCES

[1] Liu Liben and Yu Jianhui, The significant effect of semiconductor lightning eliminator on the main building of Central China Electric Power Administration Bureau, High Voltage Eng. (1993) No.4 (in Chinese).

[2] Huangshi Power Supply Bereau, 3－times extinction of direct lightning stroke accident

on the microwave tower of Huangshi Power Supply Bereau by semiconductor lightning eliminator, High Voltage Eng. (1991) No.3 (in Chinese).

[3] Song Hongxi, Demonstration of the effect of semiconductor lightning eliminator, High Voltage Eng. (1993) No.1 (in Chinese).

[4] Xie Guangrun etc., The corona Phenomena and lightning withstanding characteristic of the ancient Chinese Buddhistic Pagodas, Proceedings of the third Asian conference on electrical discharge at Beijing, (1990) 9.

[5] Summarization of operation experience of semiconductor lightning eliminator, The dispatching department of Central China Electric Power Administration Bureau, (1989) 4 (Report in Chinese).

[6] An inspect report of the semiconductor lightning eliminator in danshuichi oil depot, Lightning protective group of Wuhan University of Hydraulic and electrical engineering, (1994) 3 (Report in Chinese).

Mechanism of Lightning Current Limitation of SLE after Flashover

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Mechanism of Lightning Current Limitation of SLE after Flashover

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Abstract The necessary condition for the formation of strong lightning current and the lightning discharge process before and after flashover of semiconductor lightning eliminator rod are given.It is indicated that SLE has the capability to limit the main discharge lightning current and its rapid current changing rate.The corresponding triggered test oscillograms are presented.

0. Introduction

Semiconductor Lightning Eliminator (SLE) is developed based on a brand new principle. SLE is composed of 13—19 semiconductor rods 5m in length with 4 metal tips on the top and has a resistance of 35kΩ. The rods are distributed radially and form 2—3 fan shaped surfaces.The angle between two adjacent rods in each fan shaped surface is 20—25 degrees. Once lightning strikes on one rod of SLE, the lightnig current can be limited by the resistance of SLE rod[1][2]. But as the current passing through the SLE rod rise to such a value causing the voltage dropped on the resistance arriving the surface flashover voltage of the SLE rod, flashover of the SLE rod will be occured.In order to prevent the surface flashover, SLE is designed in the way that the breakdown voltage of the air gap between two adjacent rods is lower than the surface flashover voltage of the SLE rod. Thus before the flashover of the original stroked rod, the adjacent air gap will breakdown first. It will make the adjacent rod connected automatically with the original one in parallel, i.e., the SLE rods can connected automatically in parallel one after another as the current rise. However if the lighting current is extremely large, flashover of SLE rod will finally happen. Will the SLE lose current limitation function after flashover and degrade to an ordinary Franklin lightning rod? The answer is "No". Even if the SLE flashovered, its strong current limitation function will remain. The mechanism of current limitation capability after flashover will be explained bellow.

1. The necessary condition for the formation of strong lighting current

It is well known that, when lighting strikes on Franklin rod, the current can not be restricted (See Fig.1), as there is no high value resistance, and a lot of opposite charges will go up quickly to meet with the charges in the leader channel. A "rapid and violent neutralization" and "strong thermal ionization" process will occurred accompanied with large and rapid changed main discharge current. The resistance of the

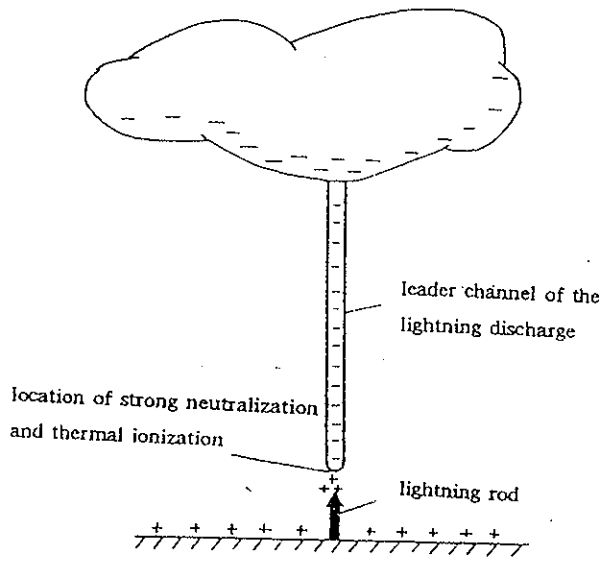


Fig. 1 Scheme of strong neutralization of lightning stroke on lightning rod

main discharge channel will become very small, due to strong neutralization and thermal ionization, so that the positive charges in ground can go up quickly along the main discharge channel and the strong neutralization process will continue, a large current (several ten kilo-amperes or several hundred kilo-

amperes) can be kept for a period of time, i.e., "rapid and violent neutralization" and "small resistance in discharge channel" are two necessary conditions for the formation of large lightning current. If these conditions are destroyed, strong lightning current can not be produced. Then the lightning current will be effectively limited.

2. The lightning discharge process before the flashover of SLE rods

In order to explain the mechanism of current limitation process after flashover, the discharge process before the flashover of SLE rods (see Fig. 2) must be classified first. When a lightning stoke occurred, the current in SLE rod increases from zero at the very beginning. Flashover will not happened before the voltage drop due to the current flowing reaches its flashover value. Hence the opposite charges enter the discharge channel slowly through SLE rod and the discharge current is only several ten amperes or several hundred amperes. As the current is small, the neutralization process will be mild, strong neutralization, and thermal ionization can not happen. So that the resistance of the neutralization and thermal ionization channel l_1 in Fig. 1 will maintain in a large value (about 500Ω/m). This process, starting from the beginning of the discharge and ended by the flashover

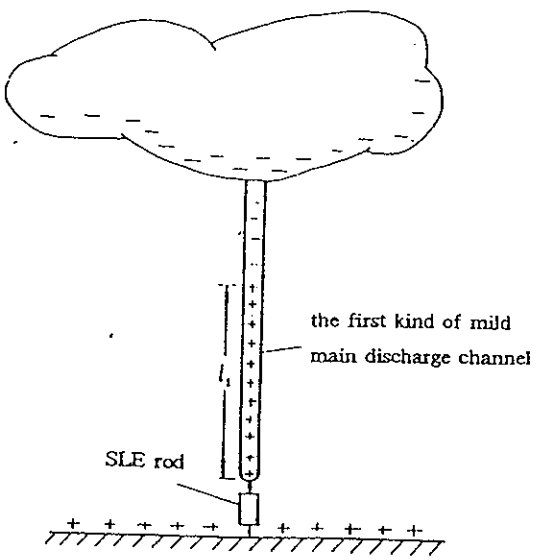


Fig. 2 Scheme of strong neutralization of lightning stroke on semiconductor rod before flashover

of the SLE rods, is called as first mild main discharge. This process can last about several ten miniseconds.

Evidently, the height of the first mild main discharge, l_1 depends on the velocity of the first mild main discharge. It is known that the velocity of the main discharge, generally within the range of 0.05—0.5 light velocity c[3], is the function of main discharge current. According to Wagner[4] the relation between discharging current I and velocity v can be written as

$$I = \frac{2 \times 10^6 v^2}{\ln \frac{2y}{b} - v^2 \ln \frac{2y}{a}} \qquad (1)$$

Where : a is the radius o f plasma discharge channel
b is the radius of the charge concentration area in the discharge channel
y is the height of main discharge.

Substitute relevant date into Equation (1). A curve shown in Fig. 3 can be drawn and some data obtained from the Fig. 3 is listed in Table 1.

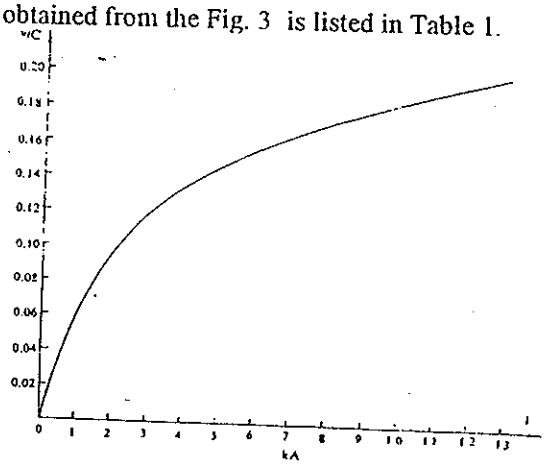


Fig 3 The relation between discharge current I and main discharge velocity v

Table 1 Some data of the main discharge current I and main discharge velocity v

I(A)	6	30	60	90	150	300	390
v(m/ms)	180	760	1500	2100	3600	6900	8400

Fig. 4, 5, and 6 show the practical oscilliograms obtained from the triggered lightning test to the single current limiting lightning rod (simulate the Chinese SLE rod) from 1993 to1995 in Japan[5]. The length of

the current limiting rod using in the triggered lightning test is 4.25m with a flashover voltage of about 1300kV. The resistance of the simulating rod for the test number 9309, 9315 and 9511 is 25kΩ, 30kΩ and 200kΩ respectively. From these oscillograms, the time interval t_1, during which the first mild main discharge exists, can be formed and listed in Table 2 accompanied with the corresponding mild main discharge current I and main discharge velocity v from Table 1. Therefrom the height of mild main discharge channel can be calculated and the results are listed in Table 2 too.

Table 2 : Interval of first mild main stroke current and height of mild main discharge channel

Test number	9309	9315	9511
I(A, average value)	30	60	6
t_1(ms)	7	1	15
v(m/ms)	760	1500	180
l_1(m)	5320	1500	2700

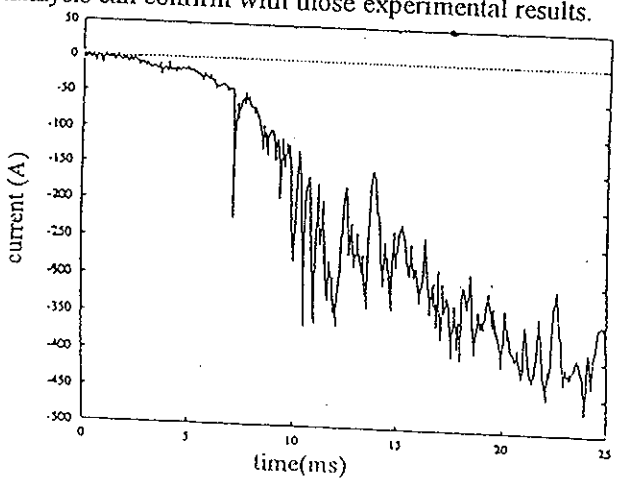
Although the values of l_1 are not very accurate, it will give us the idea that the height of mild main discharge channel is at least higher than 500m, before the flashover of SLE rod. It is necessary to stress again that the resistance in the channel l_1 is still very high (about 500 Ω/m), because the current is limited within the range of several ten amperes or several hundred amperes by semiconductor rod and violent neutraliztion does not occur. The negative charges in channel l_1 are instead by positive charges or the mixture of positive and negative charges.

3. The mechanism of current limitation after flashover

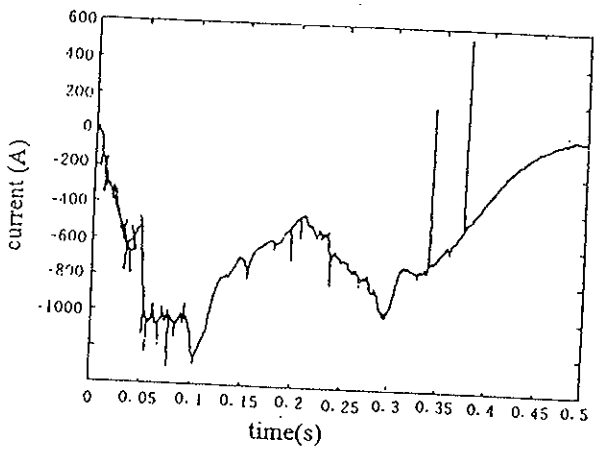
As the current through the rod of SLE increased over its threshold value or critical value, the voltage drop across the rod will happen (See Fig.7). It should be noticed that as the positive charges on the ground reach at the point N along the flashover path, not the negative charges but positives charges can meet. Also the channel, which the positive charges go into, is not a low resistance but the high resistance one.

Under this circumstance the necassary conditions for the formation of strong lightning current, i.e. "violent neutralization" and "channel with small resistance", can not be satisfied, so that large current can be avoided. Furthermore, because of the repelling effect of positive charges in channel. It is difficult for the positive charges to go up from the groumd.

A short impulse current caused by the capacity charging is occured to satisfy the sudden change of the electric potential at point N. Again the value of the short impulse current can not be very large because of the large resistance R_1 in the first mild main discharge. Or we can say, when the first surface flashover happened, only short impulse current of several hundred amperes is appeared and the current limitation capability will still exist. The corresponding impulse current in Fig. 4, 5 and 6 are 230A, 500A and 590A resipectively. It can be seen that this theoretical analysis can confirm with those experimental results.



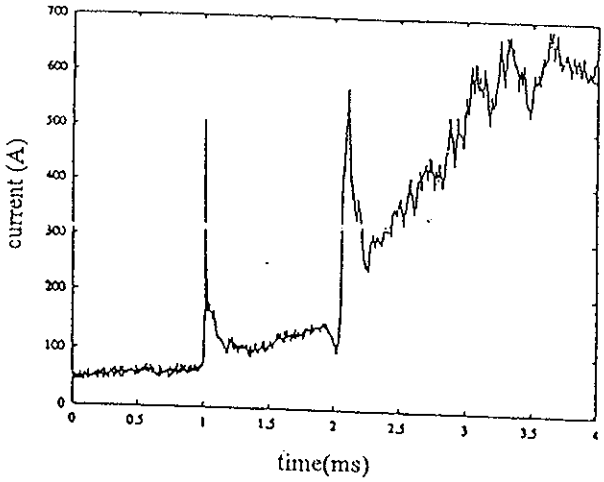
(a) partially expanded ocsillogram



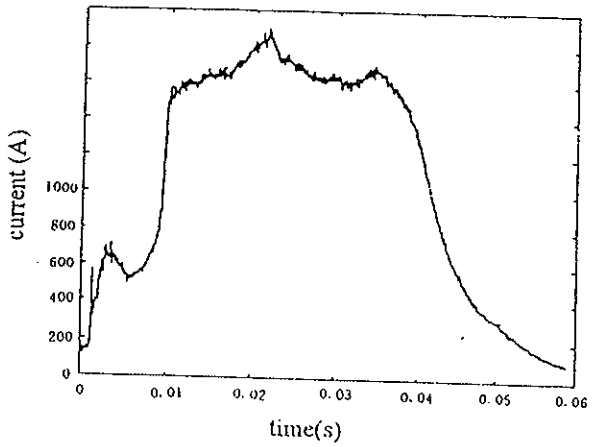
(b) full ocsillogram

Fig. 4 Oscillogram obtained from triggered lightning test (No. 9309) .

Because of the role of resistance R_1 the discharge process will restore to the situation before flashover after the first impulse. Then the current increases slowly or vibrates in low frequency.



(a) partially expanded ocsillogram



(b) full ocsillogram

Fig. 5 Oscillogram obtained from triggered lightning test (No. 9315)

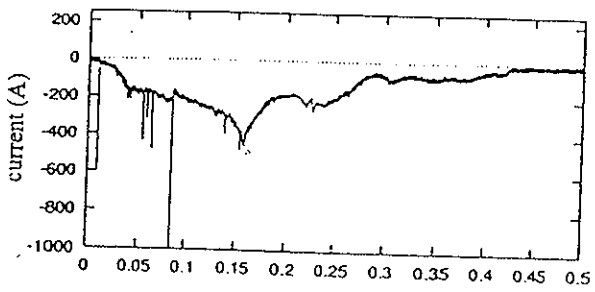


Fig. 6 Oscillogram obtained from triggered lightning test (No. 9511)

It is well known that there are multiple charge groups with same polarity or different polarity inside the storm cloud. Firstly, let's deal with the case that the sign of all charge groups is the same. While a part of the charges in the first charge group has been discharged, the second charge group may discharge toward the first group and move down along the previous mild main discharge channel to the ground. It should be noticed that, as the charge amounts of the second, the third,……groups are generally less than that of the first group, even if lighting strikes at a Franklin rod of which the resistance in the main discharge channel is relatively low, the discharge current of the second, the third,……groups ordinary only has a value of 20—30 kA, much more smaller than that of the first group. While SLE is used, the discharge current of the second, the third,……groups can still be limited, because of the large resistance in the first mild discharge current channel as well as the large resistance in the charge groups and the discharge path between the charge groups. As the charges of the second charge group going down, a gentle neutralizing process will be happened between the downward negative charges and the small amount of positive charges in the first mild main discharge channel. Thus forms the second mild main discharge channel. A relative large current may occur in the top of the channel. As the negative charges decrease gradually along its way to the ground, the current of the second lightning stroke will appear to be a short impulse current in Fig. 5 and Fig. 6. The value of these short impulse current is +560Aand -430A respectively. If there are more charge groups, the situation will be similar with the second discharge. For example, the third and the forth discharge current are limited to -320A and 500A in Fig. 6. Secondly, let's turn to the case that the polarity of the later charge group is opposite to that of the first charge group (see Fig. 8). Supposing the positive charge group P is discharging through path M to the previous discharge channel, because the polarity of the charges remained in the previous discharge channel is same with the charge group P, the discharge current can not be large. Furthermore, the resistance in the cloud path M is

fairly high, and the resistance of the previous channel is high as well, the discharge current of group P can also be limited to several hundred amperes. From Fig.4, it can be seen that there are two discharges of this type. It is the two positive impulse discharge. The currents are 150A and 540A respectively and the steep impulse of these currents is 826A and 1,000A.

4. After multiple discharge of the charge groups with the same polarity, a failure of current limitation may happen.

As explained above, after flashover the SLE can still limit the discharge current. However, if there exist several strong charge groups with the same polarity, after the discharge of these charge groups one by one, the discharge channel may be heated up repeatedly and the resistance of the channel will gradually lower down. In this case, current limitation capability will be decreased. According to practical measurement results, even if under this situation, the steep impulse discharge current is only several kilo-amperes or few ten kilo-amperes. As shown in Fig.6, for the first four times the steep impulse discharge current has been limited successfully after flashover, but the 5th one is not limited. The value of the 5th steep impulse current is out of the reading of oscilloscope and reaches 4.5kA measured by ferromagnetic bar.

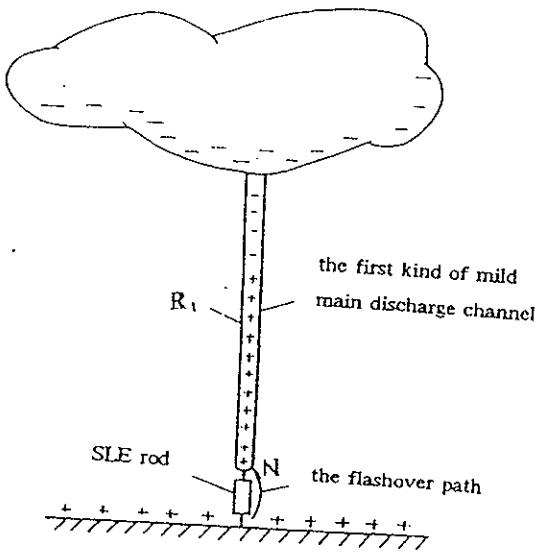


Fig. 7 Scheme of strong neutralization of lightning stroke on semiconductor rod after flashover

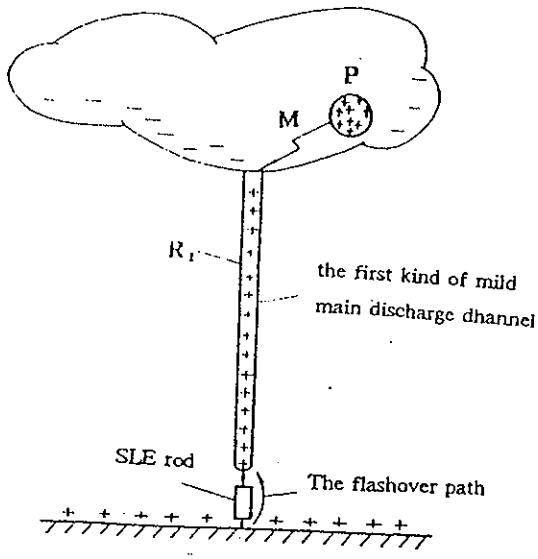


Fig. 8 Scheme of current limitation of lightning stroke on semiconductor rod in case of opposite polarity charge group

5. Conclusions

(1) SLE can effectively limit discharge current before flashover.

(2) Theoretical analysis and rocket trigger test show that SLE can effectively limit the steep impulse discharge current after flashover also. This is because the charges coming from ground will meet with the charge in the channel with the same polarity, and because the resistance of the channel is still very high. Hence the steep impulse discharge current under this circumstance may be only several hundred amperes too.

(3) After the first discharge, the later steep impulse discharge currents will be limited as well, their values may be within several hundred amperes.

(4) After mulitiple discharges of the followed discharge groups the discharge channel is gradually heated up and the resistance of the channel is reduced. Hence the current limitation may be failure and the steep impulse current value may reach several kilo-amperes or ten kilo-amperes.

References

1. Local dispatch division of Huangshi power supply bureau, "Three-times extinction of direct lightning stoke accident on the microwave tower of Huangshi Electric Utility by semiconductor lightning eliminator", High voltage technology, 17(3), pp. 80-81, 1991(in Chinese)
2. Xie Guangrun et al, "The current limit capability of semiconductor lightning eliminator", Proc. of the 7th Asian conf. on electrical discharge, pp.192-195, 1994
3. Xie Guangrun et al, "Overvoltage in power systems", Power Press, 1985(in Chinese)
4. Wagner O. F., "The relation between stroke current and the velocity of the return stroke", TIEEE PAS, 82(10), pp, 609-617, 1963
5. K.Horii et al, "Triggered lightning to a new type lightning rod", Electric power, 30(5), pp.57-59, 1997(in Chinese)

Thunder Observing Station with SLE

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Abstract: The paper introduces design of Thunder observing station with semiconductor lightning eliminator (SLE) for observing the operation characteristics of SLE. The set of device in the station uses the automatic recorder. It records automatically the neutralizing current under thunder cloud, flowing current in SLE and flash over current or the surface. It is satisfied with the supervision of operation of SLE.

Key words: semiconductor lightning eliminator (SLE)
thunder observing station(TOS)
measuring method

1.Introduction

Since professor Xie Guangrun in Wuhan University of Hydraulic and Electric Engineering invented semiconductor lightning eliminator (SLE) in 1978, SLE has been widely used in such fields as national defense, oil, weather, communication and broadcast, earthquake recording station and power system after it is improved continuously. Operation experience of 300 set × year is accumulated and no one direct lightning stroke accident has occurred. Theory analysis and field test data indicate that SLE has the function as follows: eliminating upward traveling thunder at 100%, producing higher neutralizing current and lowering main discharge current. The protection scope of SLE can reach 80^0 and it is the best lightning prevention apparatus. The setup of thunder observing station is on the basis of the measured data and theory analysis verified by test. According to actual conditions of the field, TOS is automatic and it is not necessary for operator to be on duty. Partial devices are installed in some places where field condition is very bad.

2.The Structure and construction of TOS

After SLE is installed on the tower, the tail part of SLE and the base of the tower should be connected electrically. The tower and its base should be insulated and the insulation level is designed according to actual required parameter and it is not necessary to be enhanced. When encountered with violent thunder and lightning, flashover is permissible to divide current. The down lead cable of SLE leads lightning current to the bottom of the tower where current flows into the ground through measuring resistance. According to the specification that the grounding resistance of

lightning rod should be below 10 Ω, so the sum of measuring resistance and grounding resistance should correspond to the requirement above-mentioned. Thus, signal detection channel is finished.

The signal detection devices of neutralizing current, limited flowing current and flash over current can be arranged in layers. Every layer consists of signal sensor, signal transmission, signal recording and storage transfer. Because the dynamic range of lightning current is very wide (from 100 μ A to 200kA), a central controller is provided to manage the devices of all layers so that they can operate normally. The function of Central Controller is composed of putting into which device layer according to range of current, the selection of operation state of storage transfer device and time detection during recording current.

When TOS is struck by direct stroke thunder, the rising of the ground potential and strong electromagnetic interference may damage the observing devices. Therefore, overvoltage protection measures must be taken. According to insulation level of all kinds of components, the overvoltage value is limited below the maximum working voltage for the integrated circuit. Input voltage of all devices should not exceed full extent scale . MOA, auxiliary gap and Zener-diode can be used to protect these unit circuit. The power supply of devices adopt floating construction and electromagnetic shielding.

Figure 1 shows the block diagram of TOS.

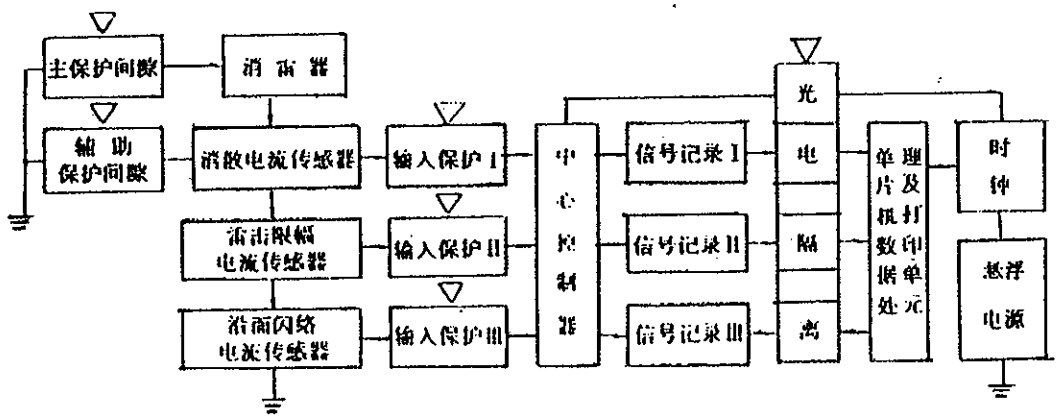

Figure 1. the structure and construction of the thunder observing station
▽—measures which are taken when considering overvoltage protection

3.recording device for neutralizing current

SLE can produce stable corona current (namely neutralizing current) under strong field strength of thundercloud. If acting time of current is t, the average current is I_1, then neutralizing and space shielding charge quantity

provided by SLE is:

$$Q=I_1 \cdot t \qquad (1)$$

According to practical measurement, varying scope of neutralizing current I_1 is less than 15mA generally. Considering the record tolerance, choosing I_{1max}=20mA. When I_1 is very low (in the case of sunshine weather), record significance is very small. Therefore, choosing lower limit value I_{1min}=100 μ A.

After peak value scope of neutralizing current is set, central controller should have such functions as follows:

a.It can start up recorder automatically when I_1 reaches lower limit record value.

b.The value of I_1 is divided into grades within the recording scope to improve recorded data's resolution and indication value of I_1 is given for every grade.

c.The absolute value of I_1 and control conditions are kept invariable when recording current of different polarity.

d.it can output standard current value to calibrate the recorder.

The neutralizing current recorder should be in the recording state for a long time. Generally two record modes can be chosen: pen-depicting and tape recording. XWD type electronic potential difference meter is a pen recorder (small long chart), different sensors should be connected to accordant transducers to record current. In Figure 4, I/V sensor is adopted, the maximum record extent scale is ± 100mV. Two pens of this recorder record simultaneously, one pen recording neutralizing current signal (blue pen) and the other indicating extent scale signal (red pen).

When current is beyond 20mA, the central controller will give an alarm to in form monitoring personnel and start up time record unit and printer to record initiating time when current exceeds the extents cale. Stopping tine will also be recorded after alarm is eliminated. Under the action of pulse current, alarm signal can not be given because recording time lag of recorder is very long. Over-extents cale signal is based on the upper limit switch of the potential difference meter. Once I_{1max}=20mA, upper limit switch will output a DC level, passing photo-electricity coupler, differential circuit and waveform transforming circuit, reaching the interrupt port of data treatment unit of computer. The computer reads current time Ts and sends it to the printer. When upper limit switch turn low, printer will give out end time T_E.

Individual clock which is composed of LM8361 and crystal oscillator gives out time setting of unit circuit and selection control.

In order to check normal logical functions of unit circuit, a reference current value output circuit is set up to complete the auto-check of the

central controller. The reference current value are set to be I_{10}=20 μ A, 5mAand 16mA respectively which coincide with the percentage of distance which is between location of pen and central line of the record paper. The percentage of distance for grade I is 20%, grade II 50% and grade III 80%. If the speed of recording is 80mm/h and length of recording of every grade is 10mm, total recording time t=2(± polarity)× 3(grades) × 7.5(time of recording for 10mm)=45minutes. Everyday's auto-check time can be set arbitrarily by clock.

4.recording device for limited flowing current

When lightning develops very fast and the neutralization of corona current can not suppress its development, the SLE will be struck and lightning current will flow through SLE. Because the non-linear resistance of the rod body can suppress main discharge process, flowing current is limited to about several hundreds Ampere and its rising rate drops markedly. In this case, the speed of recording can lower 1 ~ 2 quantity level compared with standard lightning impulse, the sampling rate can drop to 10^5 per second, this can meet the detection requirement.

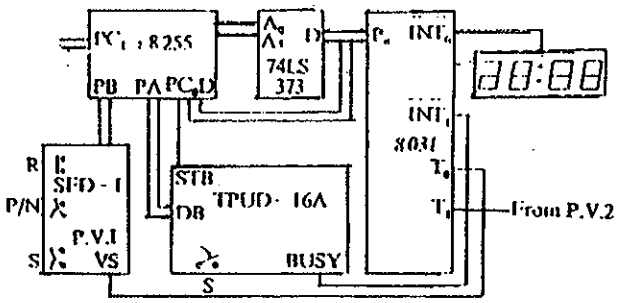

Figure 2. single chip processor data acquisition and print circuit

The recording of limited flowing current consists of wave shape recording and amplitude recording. Memory storage Oscilloscope is required in wave shape recording. Digital storage oscilloscope has a IEEE-488 interface through which waveshape stored in digital forms can be transmitted to external memory (for example, computer's memory, printer and tape recorder). The storage cube analog memory oscilloscope can not be adopted because it can not be connected to external devices. Because the flowing current amplitude is concerned about by people, peak value recorder is adopted. The recorder for peak value of flowing current in Figure 2 can output BCD code, it converts measured peak value into digital signal and sends it to single-chip processor system. Single chip processor converts BCD code into decimal code. Finally, it converts detected voltage value into flowing current value, then output it to printer.

recorder is in the record state of positive polarity.

After a lightning process is recorded, recorder outputs BCD code of peak value. Single chip processor receives data and treats it. At the time, it gives out reset signal which resets recorder and prepare for the next record.

The time of lightning stroke and peak value of flowing current are sompled by single chip processor simultaneously and they are both send to the printer.

5.recording device for flashover current

While SLE are in operation, when they are struck by strong lightning, the rods may flashover across its surface partially or mostly because current may not be divided rapidly. The flash over current may reach thousand of Ampere or ever stronger and acting time is very short (about several microseconds). Thence, recording device for flashover current should be adopted to record this flashover current.

Peak value current sensor uses symmetry-folding current divider, signal is sent to peak value voltmeter through I/V conversion, transmission cable and terminal matching resistor. Figure 4 shows the flashover current recording unit. The selection of the resistor of current shunt should coincide with the following principle: The peak value current of the beginning measured point is more than or equal to 1KA. The upper limit value is set to 200KA. If maximum measured value of the peak value recorder U_{3max} =100V, the value of R_{301} is only 0.5mΩ, it is very small. The fabrication and test of R_{301} are very difficult, it is also difficult to analyze measurement error. Therefore, matching resistor is used to divide voltage in order to measure maximum peak value. Assuming R_{301} is given, matching resistor R_{302}= Z_c (cable surge impedance), R_{302}/n is measurement resistor brought by connectim of instruments and meters. The relation of peak value current I_{3max} and measured voltage U_{3max} is:

$$i_{3\max} = \frac{u_{3\max}}{R_{302}/n} \cdot \frac{R_{301}+R_{302}}{R_{301}} \qquad (2)$$

If R_{301}=25mΩ, R_{302}=50Ω, then R_{302}/n =1.0005Ω, n=49.975

The parallel capacitor $C_{301}$of current shunt is used to eliminate spark discharge pulse of auxiliary gap G_3.

The control mode of the flashover current recorder is the same as the flowing current recorder. The data sent to the printer is selected by software of Single chip processor system:

a.If data recorded by flowing current recorder does not exceed the extent scale, printer records peak value of the flowing current.

b.If condition above is not satisfied, printer records flashover current.

6.auxiliary recording devices for flowing current

When very high current flows through rods, it is advisable to use cheap magnetic steel bar to detect current is order to lower the expense of TOS.

It would be best to install magnetic steel bar on every rod of SLE. If it is difficult to do so, steel bar can be installed on legs of iron tower. At this case, the effect of lead shout should be considered and the measured result should be corrected. When SLE is struck by lightning, the remanence of every magnetic steel bar is measured, total flowing current is the sum of the current which flows through every rods. If steel bars are installed on the lightning rods, the measurement error of steel bar can be within 10% after correction.

7.overvoltage protection of the observing devices

In thunder observing station, the measured current range is wide and insulation level of devices is different, so some protection measures must be taken.

In case high current flows into ground, the ground potential of observing devices rises greatly due to potential difference across the earthed resistance and lead inductance. Therefore, high amplitude ground potential will backflash to supply and damage the apparatus on the side of supply. In order to avoid backflash, isolation transformer is installed on the side of the supply. The extent of isolation is computed as the sum of potential difference across the earthen resistance and potential difference across the inductance between observing apparatus and the ground under the condition of maximum peak value current.

Low voltage MOA is mainly used as overvoltage protection components which are installed at input terminal of all devices. In Figure 4, residual voltage of MOA at point C, G and H is U_{c1}=24V, U_{c2}=U_{c3}=110V respectively when 1KA current flows through it. If potential of point C is 24V, maximum input voltage of small long chart recorder is 109mV, point C overload 9%, point G and H overload 10%. It is permissible for general recorders. When struck by strong lightning, discharge gap should be installed on the top of the tower to avoid damaging observing devices. Therefore, main current can be discharged and it is recorded by magnetic steel bar. Gap discharge voltage U_F can computed as follows: assuming I_{max} ≥200KA, the rise rate of lightning current di/dt= I_{max} /26, the distance between observing station and the top of the tower is H_t, then

$$u_F = \frac{L}{\tau} \cdot H_t \cdot \frac{I_{max}}{2.6} = 50 H_t \text{ kV} \qquad (3)$$

In equation (3), L/τ is equivalent resistance per meter under impluse.

The standard configuration of SLE is 13 rods, 40 metres high, each rod is 35k Ω, If field strength of ground surface is 40kV/m, flowing current of each rod is estimated as 40A. Maximum flowing current can reach 280A when SLE operate with 7 rods parallel connected, automatically, namely, the peak value of flowing current varies from tens of Ampere to hundreds of Ampere. The lower and upper limit measured value are set as I_{2min}=10A and I_{1max} =1kA respectively. Peak value current sensor adopts I/V conversion. When maximum permissible input voltage of peak value recorder is 100V, non-inductive sampling resistance R_{21}=100/1000=0.1 Ω.

Central Controller is in charge of putting peak value recorder into operation automatically. Because the motion speed of thundercloud mainly has something to do with the motion speed of upper airflow , the gathering time of thunder charge is longer than the response time of neutralizing current recorder, so we can control operation state of the peak value recorder according to intensity of neutralizing current. In Figure 3, the state-control value varies continuously from 0.3 to 1mA. When neutralizing current reaches the set value, the power supply of recorder is switched on after a time lag of 100mS, recorder is put into operation automatically. Attar neutralizing current descends, peak value recorder maintains operation for about half an hour. During this period, the operation state will return to initial state of being put into operation wherever current rises.

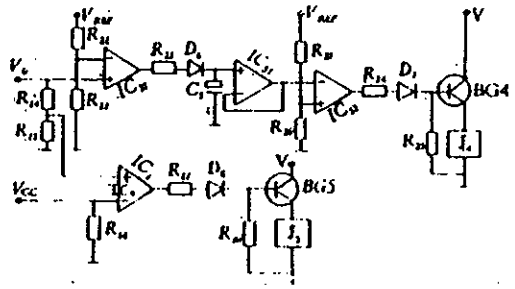

Figure 3. the control of the flowing current recorder

The polarity conversion of signal recorded by peak value recorder is controlled by polarity recognition circuit of central controller. Recognition signal I is actual neutralizing current which is connected to the reverse phase input terminal of the comparer(IC_4), Recognition signal II is half of the output of the absolute value circuit and it is connected to the same phase input terminal. After two signals are compared, output is a switch quantity. The next part is PNP transistor BG_S which drives relay circuit. Obviously, when the polarity of the neutralizing current is negative, Js doesn't act , peak value recorder is in the record state of negative polarity. Contrarily, after Js acts, polarity conversion switch is switched on and

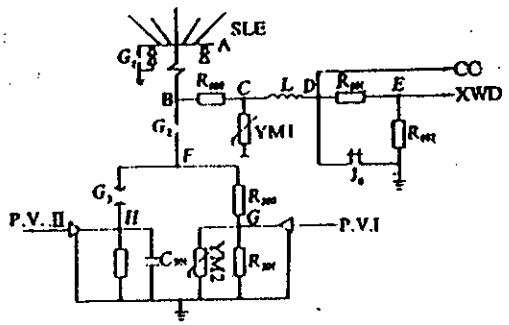

Figure 4. the principle diagram of the acquisition circuit

Figure 4 is the principle diagram of signal acquisition of the neutralizing current, limited flowing current and flashover current. The front of the neutralizing current recording channel is overvoltage and overcurrent protection circuit which is composed of R_{100} and L and MOA YM_1. R_{100} is high voltage isolation resistor which isolates the potential of point B when high current flow into the ground. L is high frequency choke coil, enhancing rise rate of potential of point C, suppressing instantaneous current. The acting threshold U_{y1} of Y M_1 is set as 24V. When I_{1max} is higher than 20MA, it will suppress rise of potential of point C. R_{101} the sampling resistor of control signal, R_{102} is the sampling resistor of record signal. When neutralizing current flows through SLE, neutralizing channel is in high resistance state, so the neutralizing current can be treated as constant current source. This current produces potential difference at every resistor, therefore control signal and record signal are also produced.

The discharge voltage of gap G_2 is regulated to 1000V, namely, the current which flows through R_{100} , $I_{1max}=(1000-U_{y1})/100=9.76A$, therefore, control circuit is ready to record flowing current. After G_2 breaks down, flowing current sampling circuit is put into operation. R_{201} is the sampling resistor of the current record signal, R_{200} is boosting voltage resistor, YM_2 is the component which protects R_{201} . Stray capacitance brought by YM_2 can filter incidental pulse produced by action of G_2. U_{y2} is set as 110V. When SLE is struck by lightning, shunt coefficient of neutralizing current branch can be computed as $\beta_{11}=5.73\%$. If it is about 1KA, the potential of point F is 6.1KV.

G_3 consists of a pair of copper sphere whose diameter is 2cm. Gap distance is 1.5mm. Under the atmospheric reference condition, discharge voltage of G_3 is 6.5KV. When rods flashover, R_{301} is connected into discharge circuit. The potential variation of point H is sent to flashover current recorder through cable, thus the measurement of I_{3max} is finished. The shunt coefficient of flowing current branch $\beta_{22}=1.21\%$, the shunt coefficient of neutralizing current branch $\beta_{21}=0.074\%$, so error correction problem brough by shunt coefficient should be taken into account when single chip processor treats data.

The computed value $L/\tau=0.65\Omega$.

If $H_t=20m$, then $U_{F20}=1000KV$, the discharge voltage is very high. So the sustaining insulator can be used as protection gap whose 50% impluse discharge voltage is 1000KV.

After supply is cut off, some measurement devices is forbidden input signal, otherwise input unit circuit may be damaged. Thus protection circuit should be installed at input terminal, it will work if supply is cut off. In figure 4, relay Jo which opens normally is located at point D. When the supply of devices is cut off, relay close up automatically. The input signal is short circuit and the back apparatus is protected.

When impulse current flows into the ground, strong space electromagnetic wave will be generated around down lead, it will interfere measurement circuit. In order to lower the measurement error of flowing current, coaxial cable is used as lead wire of signal and its placing direction is perpendicular to current carrier. The area circled by lead wire at interface should be small.

8.Conclusion

8.1 TOS can operate automatically, it solve some problems for thunder observing, that is long time, hard to catch signal manually and the danger . TOS can provide not only overall measured data of lightning but also operation and analysis result .

8.2 The recording devices for neutralizing current, flowing current and flashover current can automatically put into necessary apparatus and detect current signal under corresponding atmospheric condition. It can also provide calibration signal.

8.3 Single chip processor system is used to treat and print data, this can improve performance-to-price ratio of devices in TOS. Furthermore, single chip processor is put into measurement system and it provides evidence for good lightning prevention performance of SLE.

8.4 If possible, TOS should be equipped with pulse waveform storage and IBM computer, which can record and treat waveform of the current which flows through SLE. This will benefit to the improvement and development of SLE.

The Simulated Test for the Determination of Protective Zone of SLE

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The Simulated Test for the Determination of Protective Zone of Semiconductor Lightning Eliminator (SLE) Under Positive Polarity

The simulated test of protective zone of SLE was carried on by using 1200kV DC high Voltage generator under negative polarity in High voltage Laboratory of WUHEE. A test report was given in February 1997.

In condition of negative polarity we have negative downward leader electrode and positive lightning rod. In this case, discharge developed from positive lightning rod is rather easy in comparison with negative downward leader electrode, while this phenomenon does not exist in real lightning discharge, so that test for the comparison of protective zone between SLE and lightning rod can not be carried on under negative polarity .

In order to compare the protective effect between SLE and lightning rod, the polarity of 1200kV DC high voltage generator was transformed from negative to positive (see Fig. 1). After that the simulated test of protective zone for both SLE and lightning rod under positive polarity were carried on. The protective zone of SLE for ball top protected object and tip top protected object are given.

A 9cm high model lightning rod with a needle on the top and a 9cm high model SLE with 13 needles on the top were used as the protective device . Two kinds of protected object were used. One is the ball top protected object, of which the top is simulated by a Φ20 ball. The another is the tip top protected object, of which the top is simulated by a needle (see Fig. 2). The other test conditions are the same as in the test of negative polarity.

1. The simulated test of the protective zone of SLE for the ball top protected object under positive polarity.

In order to reveal the influence of the polarity on the protective zone , the ball top protected object with height h=6. 7cm, 5. 2cm and 3. 1cm are placed at the place with a horizontal distance L=7. 5cm, 12. 5cm and 20cm from SLE during tests. The tests show that under the above conditions the objects can be protected effectively by SLE as in the test under negative polarity. Some typical discharge photographs are given in Fig. 3.

2. The simulated test of the protective zone of SLE for the tip top protected object under positive polarity

In order to make clear the influence of the shape of protected object on the protective zone, the tip top protected object is placed on the place with distance L =7. 5cm, 12. 5cm and 20cm from SLE during tests. The test results are listed in Table 1. Some typical discharge photographs are given in Fig 4 and Fig 5. Fig. 4 shows that the objects can be protected in condition of L=20cm, h=2. 28cm and L=12. 5cm ,h=3. 96cm. Fig. 5 shows that the obects can not be protected effectively in condition of L=12. 5cm,h=4. 4cm and L=7. 5cm, h=6. 0cm. The comparison of the protective zone for ball top and tip top object is show in Fig. 6.

3. The comparison of the lightning attractive capability of SLE and lightning rod

In order to compare the lightning attractive capability of SLE and lightning rod, SLE model is placed at one side with a horizontal distance of 35cm from the downward leader electrode and lightning rod model is placed at another side of the downward leader electrode at the same distance. Fig. 7 (a) shows that the lightning strokes on the SLE model, while SLE model is placed on the left side of downward leader electrode. Fig. 7(b) shows that the lightning strokes on the SLE model too, while SLE moled is placed on the right side.

Thereby we can find that in comparison with lightning rod, SLE has a larger lightning attractive capability.

Table 1 The protective zone of SLE for tip top objects (under positive polarity)

The distance between protected object and SLE tower L(cm)	The height of protected object h(cm)	Total number of test	Stroke number on object
20	2.0	5	0
	2.13	4	3
	2.3	7	3
	2.42	5	1
	2.55	4	2
	2.65	4	2
12.5	3.77	5	0
	4.36	4	0
	4.48	5	2
	4.49	7	3
	4.53	3	3
7.5	5.8	10	0
	6.0	10	1
	6.2	7	1
	6.7	3	2

4. The simulated test of the protective zone of lightning rod

The test for the determination of protective zone of lightning rod was done only on the location of L=7.5cm and L=12.5cm, because of its smaller protective zone. Table 2 shows some of the test results. Some of the typical discharge photographs are given in Fig. 8. Fig. 9 shows the comparison of the protective zone between SLE and lightning rod.

Table 2 The protective zone of lightning rod for tip top objects

The distance between protected object and SLE tower L(cm)	The height of protected object h(cm)	Total number of test	Stroke number on object
12.5	1.96	10	0
	2.28	11	2
7.5	4.2	10	0
	4.5	11	1

It shoud be point out that it is quite difficult to make the simulate test corresponding strictly to the real nature phenomenon because of the small simulate scale. Firstly, the size of electron and molecule as well the distance between the molecules can not be reduced according to the simulate scale. Secondly the breakdown voltage of a 1m gap in simulate test is up to about 480kV, thus the test object has to withstand a field of 480kV/m, while in real nature the field intensity under the lightning cloud is only 20～40kV/m. All the above mentioned will be sure to influence the procces of discharge seriously. Finally the four 33cm long needles on the tip of the 5m lightning rod can not be added on because of the rather small simulate scale, and it certianly will make the protective zone of SLE smaller than it should be.

5. The influence of the resistance on protective zone

It shonld be indicated that the model needle of the SLE is made by metal due to the rather small simulate scale. In order to explain the influence of the resistance on protective zone, two tests of the protected zone were carried on . One is that the SLE model was directly grounded, another is that the SLE model was grounded through a 35kΩ resistor. The test results show that they both have the same protected radius on the ground. This result is supported by the field practice of SLE.

(1997,5)



Fig 1. The 1200kV DC high voltage generator in High Voltage laboratory of WUHEE.

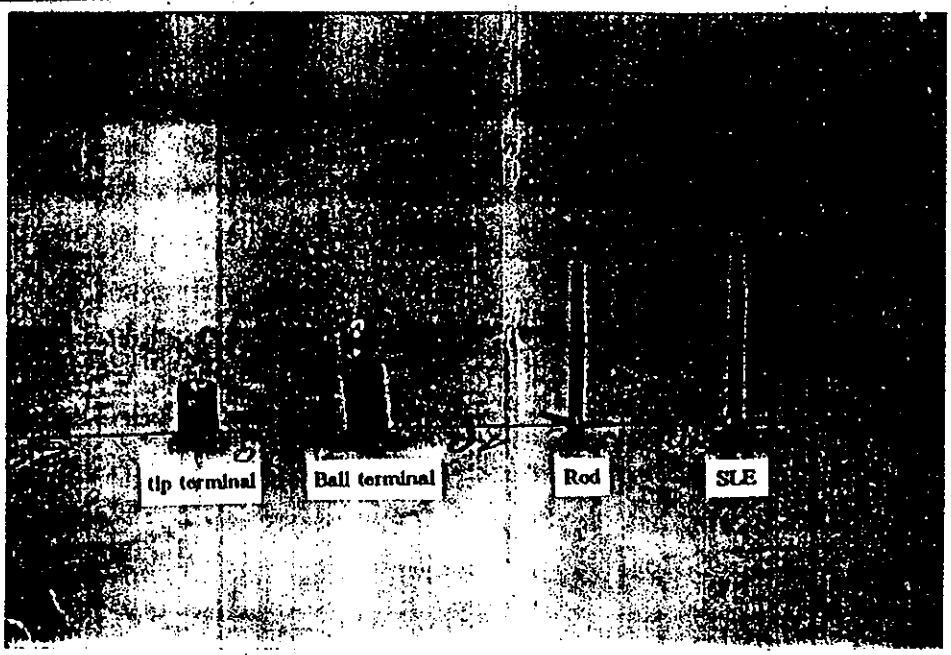
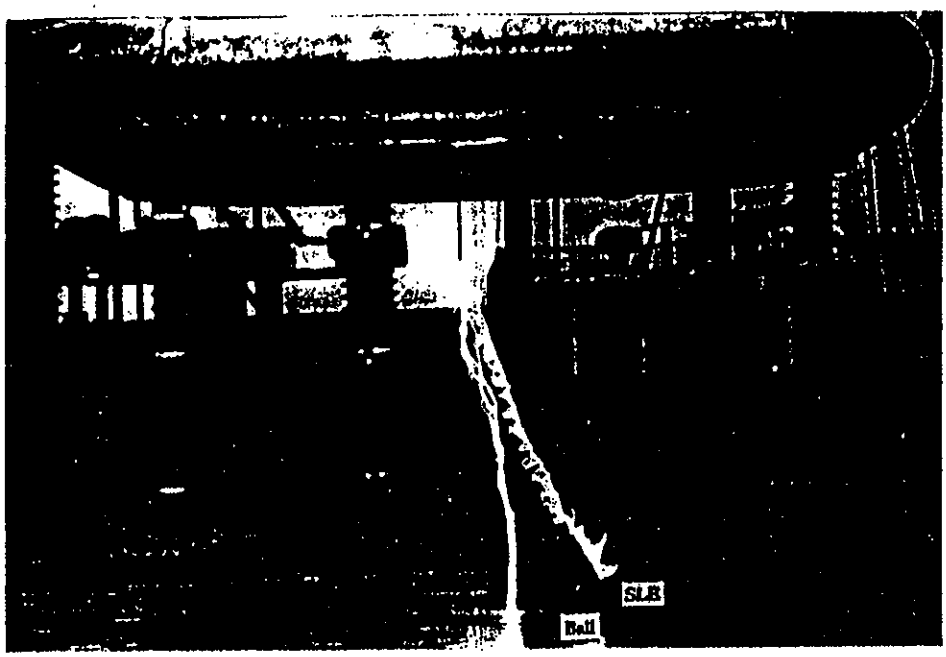


Fig 2. The model SLE, model lightning rod and model ball top and tip top protected object



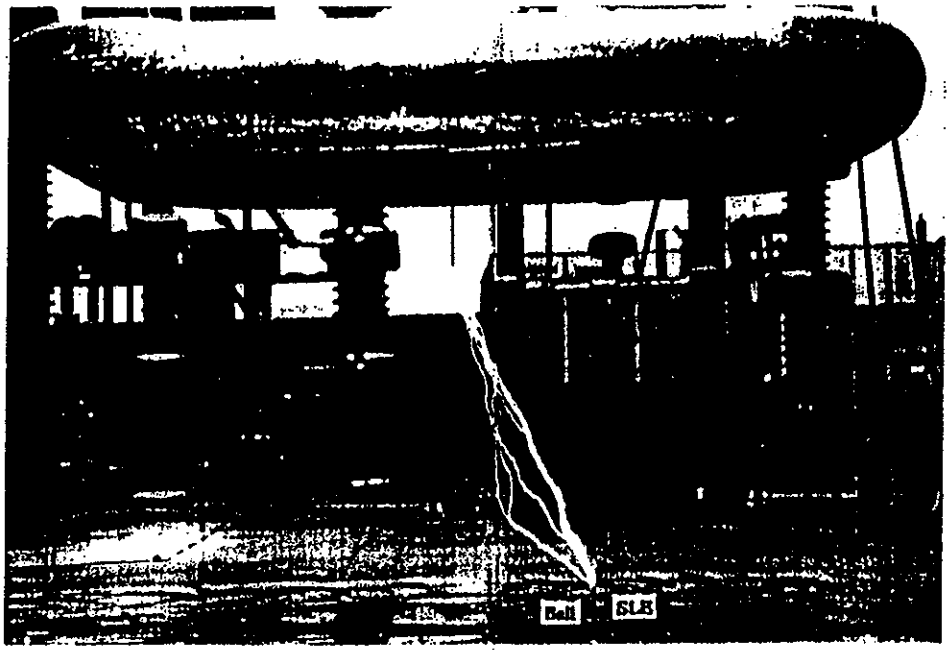
(a) lightning stroke on SLE tower and ground

(h=6. 7cm, L=7. 5cm)



(b)lightning stroke on SLE tower and ground

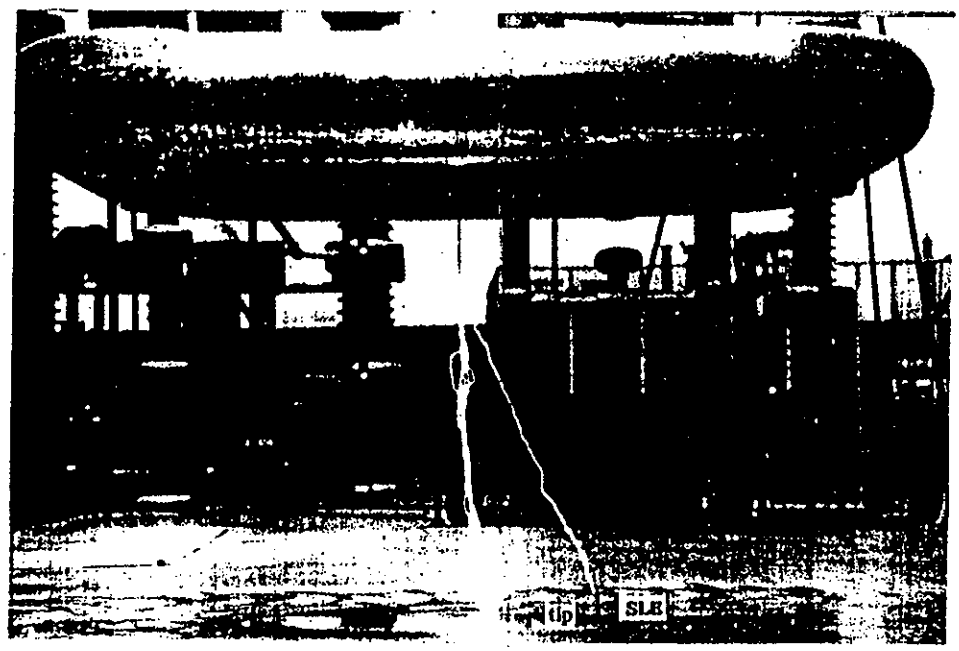
(h=5. 2cm, L=12. 5cm)



(c)lightning stroke on SLE tower

(h=3. 1cm, L=20cm)

Fig 3. The test of the protective zone of SLE for the ball top object (under positive polarity)



(a)lightning stroke on SLE tower and ground

(h=2. 28cm, L=20cm)

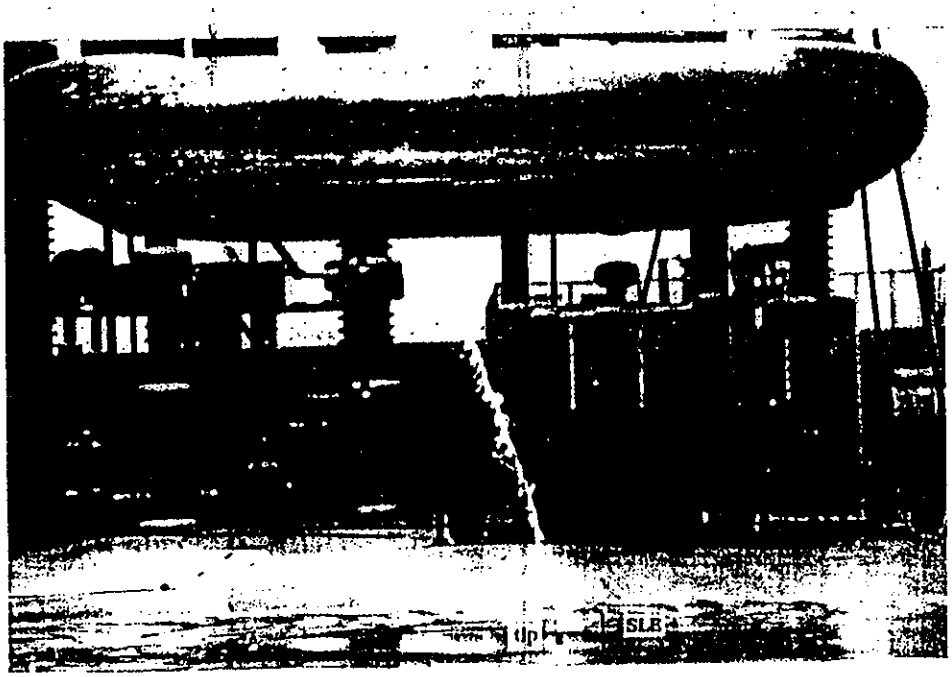


(b)lightning stroke on SLE tower and ground

(h=3.96cm, L=12.5cm)

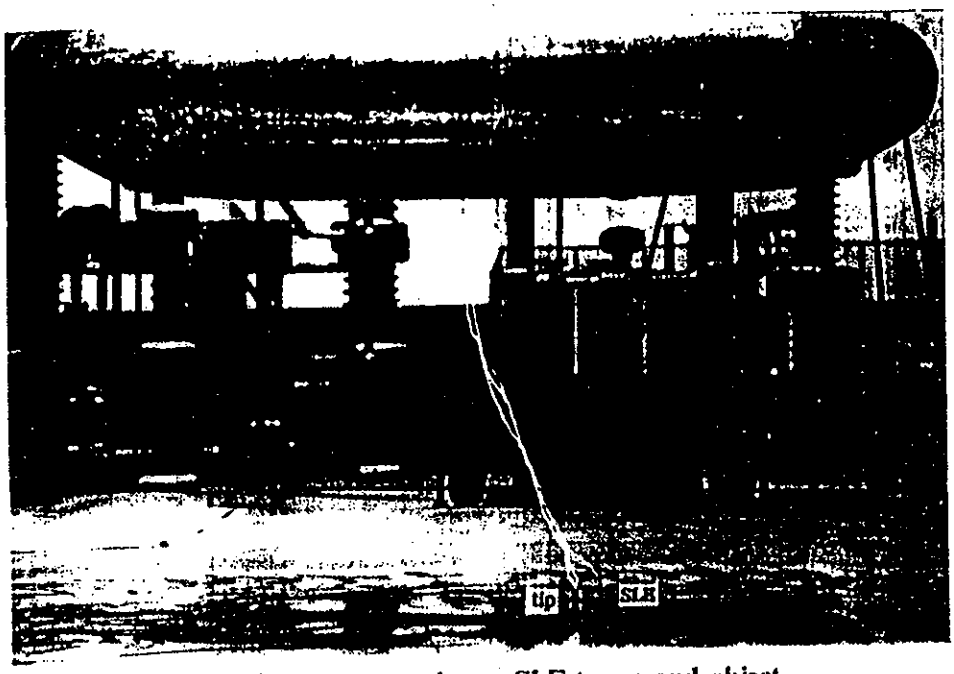
Fig. 4 The test of the protective zone of SLE for the tip top object

——the object can be protected (under positive polarity)



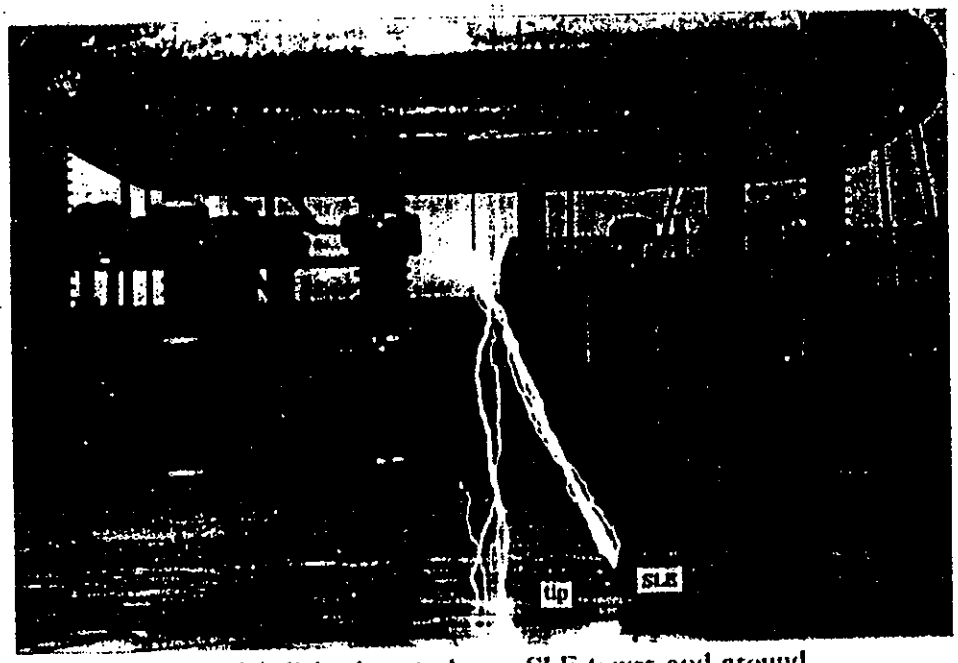
(a)lightning stroke on object

(h=4.4cm, L=12.5cm)



(b)lightning stroke on SLE tower and object

(h=6.0cm, L=7.5cm)



(c) lightning stroke on SLE tower and ground

same as (b), h=6.0cm, L=7.5cm

Fig. 5 The test of the protective zone of SLE for the tip top object

the object can not be protected effectively

(under positive polarity)

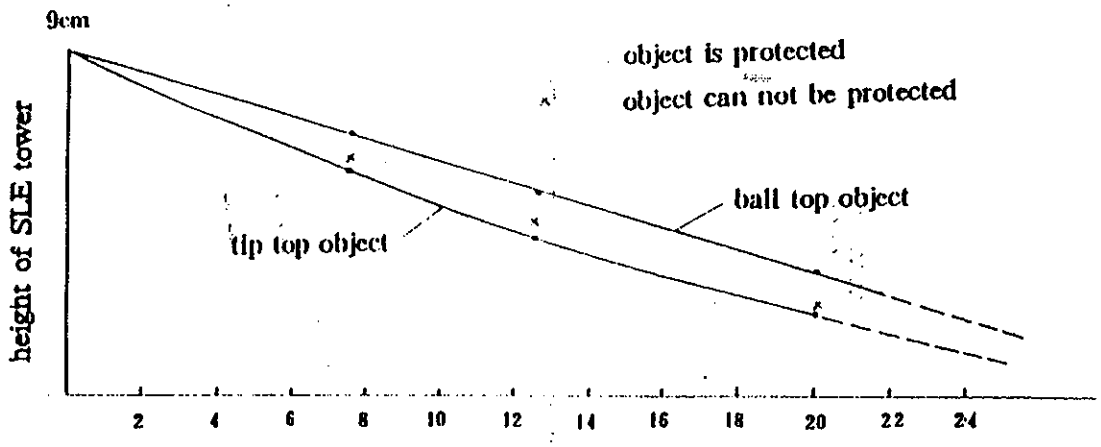
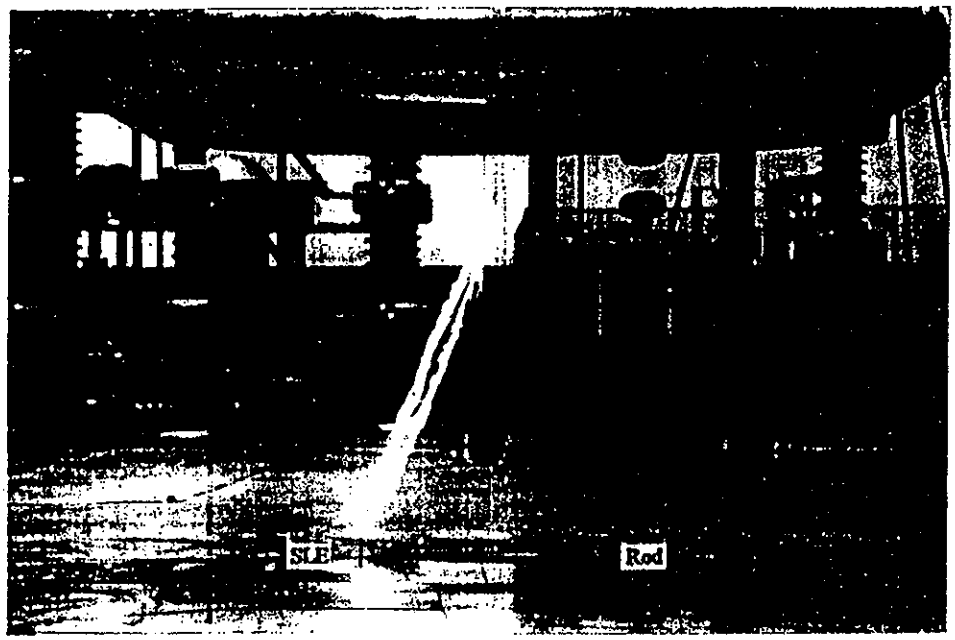
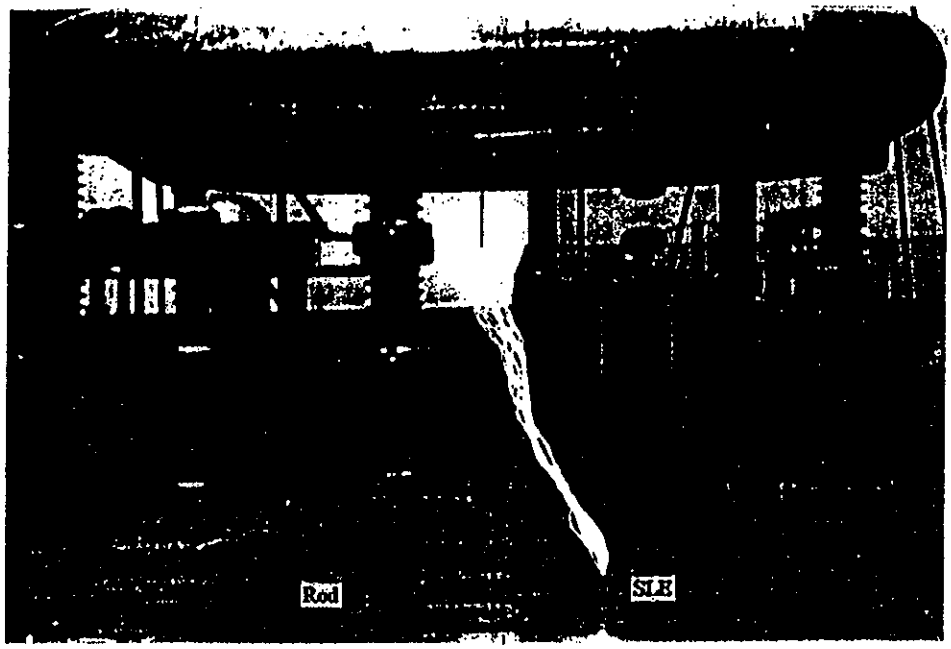


Fig 6. The comparison of the protective zone of SLE for ball top and tip top object



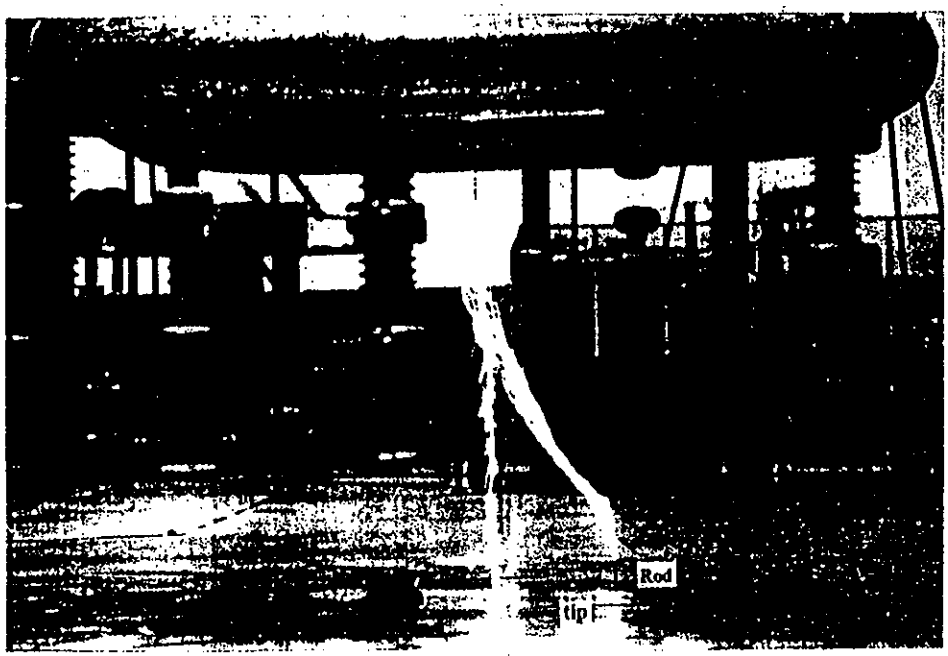
(a)SLE on left side and lightning rod on right side (lightning stroke on SLE tower)



(b)SLE on right side and lightning rod on left side

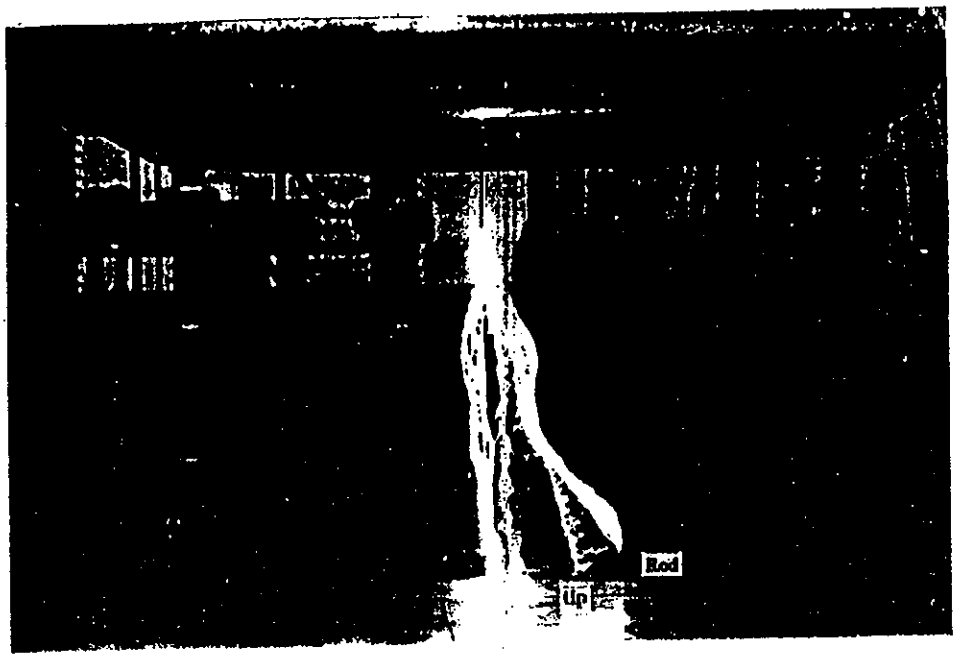
(lightning stroke on SLE tower)

Fig 7 The comparison of the lightning attractive capability of SLE and lightning rod (under positive polarity)



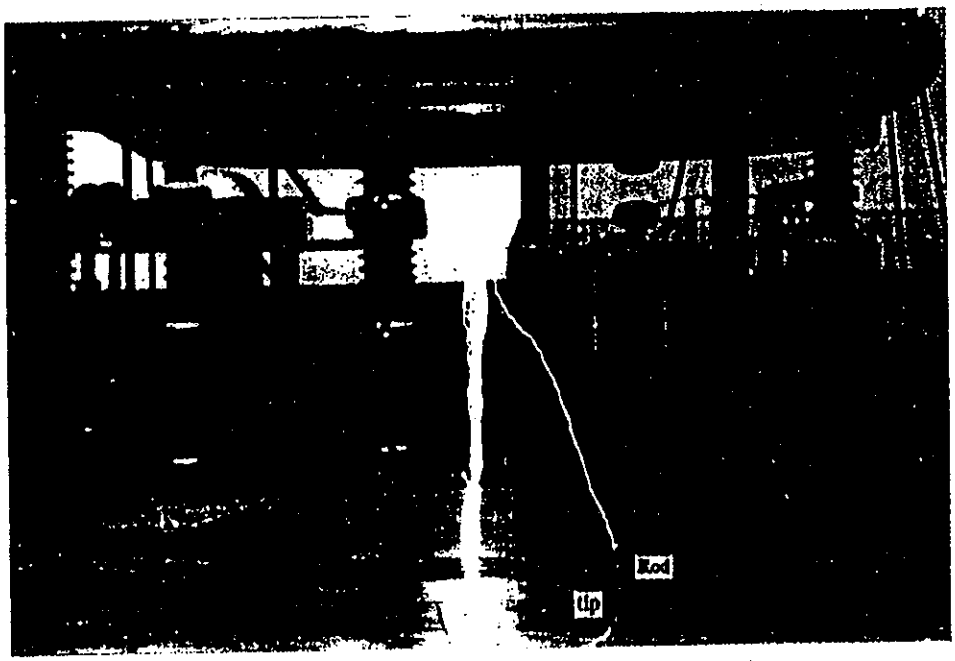
(a)lightning stroke on lightning rod and ground

(h=1.96cm, L=12.5cm)



(b)lightning stroke on lightning rod, ground and object

(h=2.28cm, L=12.5cm)



(c)lightning stroke on lightning rod and ground

(h=4.2cm, L=7.5cm)

Fig. 8 The test of the protective zone of lightning rod for tip top object(under positive polarity)

The Analysis on Current Limitation Function of SLE based on Practical Measurement Date

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The Analysis on Current Limitation Function of SLE Based on Practical Measurement Date

Three methods have been used to measure the direct lightning stroke current. They are automatic lightning current measurement device YL0-1, whose measurement range is 10A-200 KA, ferromagnetic bar and the thermal crack on the protection lacqure membrane which can indicate the passing of a current of 10-35A through the semiconductor rod in millisecond duration.

Table 1 gives the data of the measured lightning current as the lightning strokes directly on SLE.The first 28 data (No. 29-33) in which one is the positive stroke are recorded by ferromagnetic bar, and the remained 5 data (No. 34-38) are recorded using the thermal crack method, so the polarity of which is unclear.

Table 1 Practical Measurement Data of the Lightning Current through SLE

No	1	2	3	4	5	6	7	8	9	10	11
Lightning current(A)	-485	-26	-296	-362	-43	-346	-233	-335	-79	-485	-391
No	12	13	14	15	16	17	18	19	20	21	22
Lightning Current(A)	-28	-368	-364	-356	-204	-391	-348	143	-403	+67	-303
No.	23	24	25	26	27	28	29	30	31	32	33
Lightning Current(A)	47	278	-327	-628	-290	-991	-100	-100	-200	-100	200
No.	34	35	36	37	38						
Lightning Current(A)	300	30	210	240	200						

The probability distribution of the lightning current larger than I(absolute value) is shown in table 2 and corresponding curve is drawn in Fig. 1.

Table 2. The probability Distribution of lightning current larger than I.

Lightning Current	30	50	100	200	300	400	500	700	1000
Probability P(%)	92.1	86.8	73.7	63.2	42.1	13.2	5.3	2.6	0

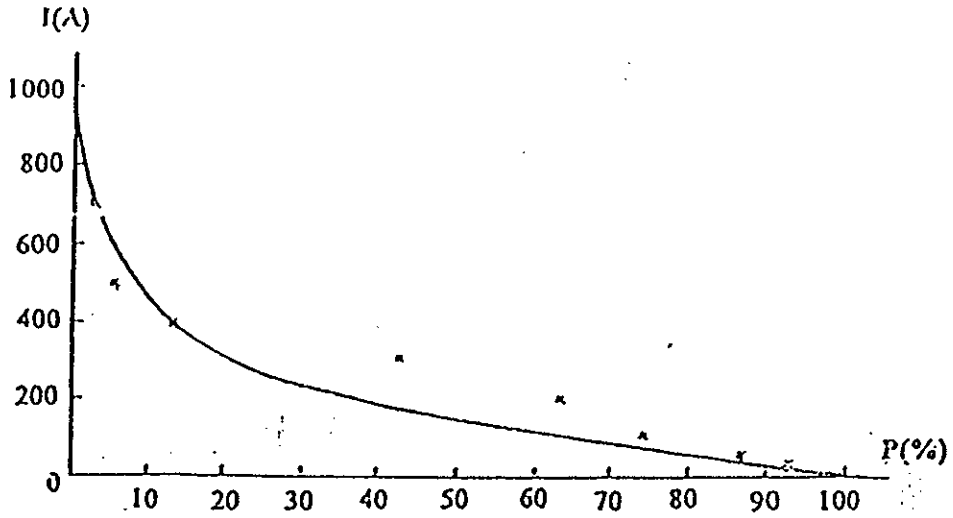

Fig. 1 The Probability Distribution Curve of Lightning Current as Lightning Directly Strokes on SLE

From the measured date the probability distribution of lightning current on SLE can be described by following formula:

$$\lg P = -I / 0.44 \qquad (2)$$

Where I is the current, kA.

From Eq. (2) we can calculated that the probability of current larger than 0.44 kA is 10%. According to the statistic date the probability distribution of lightning current on Franklin rod can be described by following formula:

$$\lg P = -I / 108 \qquad (3)$$

Where I is the current, kA. From Eq. (3) we can calculated that the probability of current larger than 108 kA is 10%. From above analysis we can conclude that SLE can reduce the lightning current to about

$$0.44 / 108 = 0.4\% \qquad (4)$$

The Experiment on the Protective Zone of Semiconductor Lightning-current Extender (SLE)

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The Experiment on the Protective Zone of Semiconductor Lightning Current-duration Extender (SLE)

By Zhong lianhong from Wuhan High-Voltage Institution
Chen Cixuan from Wuhan University of Hydraulic and Electrical Engineering

1 Introduction

It is well known that the effect of the lightning rod is attracting lightning. The operating experiences show even if the lightning rod is installed completely conforming to the regulations, heavy lightning accidents are still commonly occurred. For example, Taihua Mountain Weather Station in Yunnan were so frequently stuck by lightning every year that its power and equipment were destroyed though lightning rods are installed. The result is the radar is turned off in storm days which greatly affects the normal working of the weather station. The station operates normally in thunderstorm days after installation of SLE and all the equipment are protected . In order to compare the effect of lightning rod and SLE, Yunnan Electrical Experimental Institute replaced SLE with a lightning rod of the same height in May,1988, the result is that the weather station was twice stuck by lightning and image transcomputer and transmitter were broken during the period from August, 1988 to May,1990. This test shows obviously the advantage of SLE comparing with the traditional lightning rod.

The Semiconductor Lightning Current-duration Extender makes great inprovement based on the conductor Lightning eliminator, which can reduce the upwarding lightning and the main current of downwarding lightning besides keeping the role of "neutralization' and "Shieding" of the charges. The operating experiment shows the SLE has the following functions: a) It can100%eliminate lightning which develops from the earth; b) It can reduce about 75% of the total lightning strokes; c) It can reduce 81%~99.9% of the residual 25% lightning strokes; d) The protection zone of the SLE is very wide and definite. Its protective angle is as big as 80%, i.e. the ground protective radius is 5 times of the tower height.

The SLE has been widely used in the fields of national defense, petrolum. Earthquake test, telecommunications & broadcasting, meteology and electrical power in China. The operation experience has reached 300 tower year without any accident on lives and equipment. In order to further illustrate the SLE theory and improve its design, this paper put forward the protective zone of one-rod and two rod SLE based on the experiment and study on the problem of protective zone most concerned by the users.

2 Experiment method

The experiment is based on the simulated method. The simulate scale used is 1/300. DC voltage is applied in the experiment, as in comparing with the impulse voltage . DC voltage is more closer to the practical condition. The scheme of experiment is shown in Fig.1

Fig.1 Experiment Scheme
1---cloud plate (3.4x2.4m^2); H=1m;

2---shape rod for the simulating of the downward leader (10~25cm);
3---model of SLE;
h---the height of SLE model;
H---the height of cloud
The negative porarity is taken in experiment. A sheet of blank paper is put on the aluminuin plate under the simulating cloud to record the lightning stroke points. The experiement is carried on under the condition when the numbers of strokes to the tower and to the ground are almost equal. It is a rigorous test condition.

3. The result and analyses

3.1 The protective zone of an individual SLE

The model SLE for the experiment is made by 13 needles 1 cm in length(BS-3 type). The model tower is 10cm in high corresponding to a 50m high SLE tower. The number of voltage operating times in the experiment was 161,among which 83 times were striked on ground. The results obtained according to normal distribution regulation are given in table 1.

Table 1 The experiment results of the protective zone of an individual SLE

The range of stroke point L (cm)	L/h	The number of grounding strokes inside the range L / The total number of grounding strokes (according to normal distribution regulation)	The rate of grounding stroke inside range L (according to normal distribution regulation)	The rate of grounding stroke inside range L (according to real distribution regulation)
<40	4.0	0.0039	0. 00201	0
<49	4.9	0.0392	0. 0202	0
<50	5.0	0.0485	0. 0250	0. 0066
<53	5.3	0.0869	0. 0448	0. 0373
<55	5.5	0.1230	0. 0634	0. 0559
<60	6.0	0.2546	0. 1313	0. 1615
<65	6.5	0.4364	0. 2250	0. 2336
<70	7.0	0.6331	0. 3264	0. 3416
<80	8.0	0.9099	0. 4691	0. 4554
<90	9.0	0.9904	0. 5106	0. 5093
<91	9.1	0.9927	0. 5118	0. 5155

It can be concluded from Table 1 that the rate of ground stroke is 0.0066~0.025 within a grounding protective radius of 5 h, where h is the height of SLE.

As regard to a 50m high SLE tower, the number of lightning srokes in the area within a radius of 5 h can be caculated by the following equation:

$N = \gamma \cdot S \cdot T \cdot K = 0.015 \times 3.14 \times [5 \times 50/1000]^2 \times 40 \times 1$

$= 0.1178$ times/year

where γ =0.015 times/hundred kilometers/year,

T=40 days/year,

$S=\Pi(5h)^2 km^2$

K is the topography coefficient,using K=1 for the plain area.

Taking 0.025 as the rate of grounding stroke (according to normal distribution regulation), we can get the ground stroke number n is the area within radius of 5 h is

n=0.025x0.1177

=0.0029 times/year

i.e. one grounding stroke will occur every 1/n=1/0.0029=344.8 years.

Taking 0.066 as the rate of grounding stroke (according to real distribution), we can get

n=0.0066x0.1178

=0.0008 times/year

i.e. one grounding stroke will occur every 1250 years.

Fig.2 shows the grounding protective zone and protective rate of SLE. It ca be seen that the grounding stroke rate is 0.1% within a protective radius of 3.58 h, while the grounding stroke rate of the lightning rod is 0.5% within a protective radius of 1.5 h.

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It is worth to note that above results was get when conductor lightning eliminator was used. Rod resistance is not considered to influence the test results because resistance does not influence corona current. Moreover, contrast test also made by repeating the above mentioned test of grounding the above mentioned model through a resistance (35KΩ). The result shows that resistance does not influence the test results on the whole. That is to say that it does not influence the protective scope. So, it is believed that conductor rod in stead of semiconductor rod can be sued in protective scope test.

Above results show that conclusion of the simulation test is basically consistent with that of the operation test. The larger protective scope of the lightning eliminator depends on the shielding effect of the space-charge above it.

2. Result comparison of tests with different tower height and different rod number

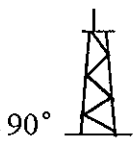
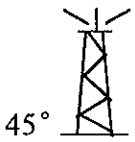
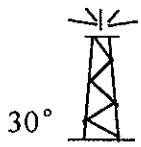
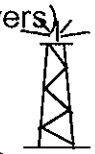
Table 2 and Table 3 respectively list the test results at different tower height (with 13 rods) and equal tower height (h=12cm) with different number of rods. The following fact should be noted: The compared model tower and the rod are rather rough with less pressurization times, so the results are rather dispersed, but still can be used for comparison. The table lists only the results of direct test.

Table 2: Test results at different tower heights

Stroke point range	Test result	h(cm)			
		8	10	12	14
		pressurization times			
		57	105	110	51
		land stroke times			

L (cm)		29	45	56	30
< 5h	Times Around stroke rate	1 0.0175	3 0.0286	11 0.1000	9 0.1765
< 4h	Times Round stroke rate	0 0	1 0.0095	4 0.0364	2 0.0392
< 3h	Times Round stroke rate	0 0	0 0	2 0.0182	1 0.0196
0 time point		4h	3.9h	2.9h	2.8h
1 time point		5h	5h	3.6h	2.9h

Table 3: Test results at different rod numbers

Stroke Point range L (cm)	Test results	Rod numbers and their diagrams			
		5(J_2type) 	9(J_2type) 	13(normal) 	17(two layers) 
		pressurization times/land stroke times			
		93/41	81/44	110/56	59/39
< 5h	Land stroke times Round stroke rate	11 0.1183	9 0.1111	11 0.1000	4 0.0678
< 4h	Land stroke times Round stroke rate	6 0.0645	4 0.0494	4 0.0364	0 0
3h	Land stroke times Round stroke rate	3 0.0323	2 0.0247	2 0.0182	0 0
0 time point		2.118h	2.5h	2.81h	4.33h

1 time point	2.5h	2.83h	2.92h	5h

We can see from table 2 that the higher the model is the higher the round stroke rate is. In other words, at the same rate of round stroke, the height (H) of the thundercloud is in direct proportion to the height (h) of the tower, the less the former, the less the later and the protective scope. So, if we select a rather lower thundercloud, for example 500m, the requirement to the test results will be even stricter.

We can see from table 3 that as we adding rods from 5 to 17 rods, the protective effect will become better and better. So, the customer can select suitable type of lightning eliminator according to the importance of the protected objects and their financial capacity.

We also made test with thundercloud at positive polarity. The result shows that the requirement with thundercloud at negative polarity is stricter.

3. Joint protection of twin lightning eliminators

When joint protection is adopted for twin lightning eliminators, the outside protective scope will be defined according to the standard of single lightning eliminator and the protective scope between the two lightning eliminators will be defined through test. In test,

the two model alike with H=10cm will be placed at both sides of the leading peak in balance respectively. Other requirements are the same of the test of single lightning eliminator. For symmetry, the land discharging point resulted from the test will be placed at one side, the other side will keep symmetrical with it. The distance between the two model towers (L) will be 100cm and 120cm. The results are shown in figure 3 and figure 4 (taking outside protective radius as 5h).

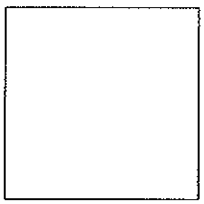


Figure 3: Test result when the distance between the twin towers (L) equals 100cm

In figure 3, the distance between the twin towers (L) equals 100cm, 10 times the tower height. The min. Protective breadth is 86cm, 8.6 times the tower height, e.g. S=8.h. In figure 4, L=12cm, 12 times the tower height, e.g. S=2h.

Figure 4: Test result when L=120cm

Joint protection scope of twin lightning eliminators is larger than the overlap of single eliminator protective scope because in joint protection the electric charge in the space is jointly shielded and prevented from striking the ground space between the two lightning eliminators. Joint protection of lightning eliminators can be adopted to protect large oil depot area and other important spots as well as power lines, especially the future EHV transmitting lines and cross-river towers. In joint protection of twin towers, the distance (L) can be set at 10-12 times of the tower height as shown in figure 3 and figure 4, with the min. protective breadth as S=8.6h and S=2h. Let's imitate the calculation of a lightning rod as follows: Imagine a lightning eliminator high (h_o) as shown in figure 5, and when L=10 times the tower height:

$$h_o = 8.6h/5x2 = 0.86h$$

By this we can calculate the protective breadth of the wire surface and design h as required. Experience in operation also shows that the semiconductor lightning eliminator is well suitable to power lines.

Figure 5: Analysis diagram of twin tower joint protection when L=10h

IV. Conclusion

1. Ground protective radium of single lightning eliminator is much larger than that of lightning rod. The protective radium and rate are shown in figure 2 and table 1, where the protective rate is 99.9-100% at 3.58h; 99.8-100% at 4h; and 97.5-99.3% at 5h. Test results basically tally with the operation experience.
2. Rod resistance does not impact the protective scope of the lightning eliminator.
3. In joint protection of twin lightning eliminator, the outside protective scope is counted according to that of a single one. Protective effect between the twin lightning eliminator is shown in figure 3 and figure 4.
4. Twin lightning eliminators can be used to protect transmitting lines and cross-river towers. They will be widely used especially for the protection of future EHV transmitting lines.

Fig.2 The grounding protective zone and protective rate of SLE

(the data on the left side is taken according to the normal distribution regulation, while the data on the right side is taken from the real distribution)

It should be indicated that the above results are obtained for the model SLE made by metal needles. But it does not influence the protective effect, because of the exist of resistance does not influence the corona current of SLE model. A consrast experiment was carried on to the model SLE, which was grounded through a 35kΩ resistor. The experiment shows that it has the same grounding proective radius as that of the model without resistance.

The above mentioned experiment result is supported by the field practice of SLE. The shielding effect of the space charge above SLE is the reason of the large protective zone of SLE.

3.2 The experiment results for different height of tower and different number of needles

Table 2 gives the results for different height of tower (13 needls). Table 3 gives the results for different number of needles under the same tower high (h=12cm).

We can see from the table 2 that the rate of grounding stroke increases as the height of the model tower increases. In other words, the protective

Calculation of Lightning Electromagnetic Interference on Microwave Station Equipment

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CALCULATION OF LIGHTNING ELECTROMAGNETIC INTERFERENCES ON MICROWAVE STATION EQUIPMENTS

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Abstract

The transient electromagnetic field in the free space due to lightning ground stroke is calculated according to the formula deduced from Maxwell and d'Alembert equation. The results are compared with that obtained simply from Ampere's Law. The dangerous distance curves related to the error operation and damage of electronic devices in the microwave station as well the malfunction probability and damage probability are given based on the calculated results. They can be used as the foundation of the lightning protective design in practical project.

Introduction

Microwave communication has been widely used in modern society. Equipments in microwave station are mainly computers and electronic equipments. The elements of these equipments have high integration but small working current during the message transmission. These equipments are extremely sensitive to the outer interferences such as lightning. Lightning electromagnetic field can disturb the normal work of equipments, turn bad the characteristic of components, confuse the logical systems, block off the transmission of signal, cause the error operation or even result in a permanent damage of equipments or components. Accident due to the interference of lightning transient electromagnetic field is of common occurrence in most of the microwave stations, especially those located in mountainous area or area with high Keraunic Number. The report of A/D—722675[1] indicates that when the lightning electromagnetic field reaches 0.07×10^{-4}T, error operation will occur and when it reaches 2.4×10^{-4}T, permanent damage of equipments or components will happen. This paper is related to the calculation of dangerous distance between lightning stroke point and the equipment. Furthermore the malfunction and damage probability are discussed.

Model for the calculation of electormagnetic field due to lightningground stroke

During the lightning ground stroke, a cloud-to- earth discharge channel is formed. Large current, up to tens or hundreds kilo- Amperes flows through the discharge channel from ground to cloud. A rapidly changed electromagnetic field is occured in the surrounding area.

Considering a straight vertical discharge channel above a perfect conducting ground plane as shown in Fig. 1 and assuming the current flows from ground to cloud is uniformly distributed along the line from the plane to a height vt expressed as the following fomula

$$i(z',t) = I_L u(t - z'/v) \tag{1}$$

where I_L is the lightning current, v is the current devolop speed, t is the time, z' is the vertical distance above the ground, function $u(\zeta)$ is defined as follows

$$u(\zeta) = \begin{cases} 0, & \zeta < 0 \\ 1, & \zeta > 0 \end{cases} \tag{2}$$

Equation for calculation of magnetic field in the surrounding area can be deduced from Maxwell and d'Alembert equation[2], ie.

$$B = \frac{\mu_0 I_L}{2\pi}\left[\frac{h}{d\,(h^2+d^2)^{1/2}} + \frac{d}{[c(h^2+d^2)/v + h(h^2+d^2)^{1/2}]}\right] \tag{3}$$

where B is the magnetic flux density, μ_0 is the permeability of free space, h is the height of the lightning current channel, d is the horizontal distance between the lightning current channel and the point of observation, c is the electromagnetic wave travel speed in free space.

Calculation of the dangerous distance curve

Since the height of the lightning current channel h is usually in the range of several thousands me-

ters, the magnetic flux density B for $h=1000$m, 2000m and 3000m are calculated at the distance $d=$ (6—3000)m according to equation (3). The results corresponding to lightning current $I=100$kA are shown in Table 1 and Fig 2. Results obtained simply from Ampere's Law, relevant to $h\to\infty$, are also

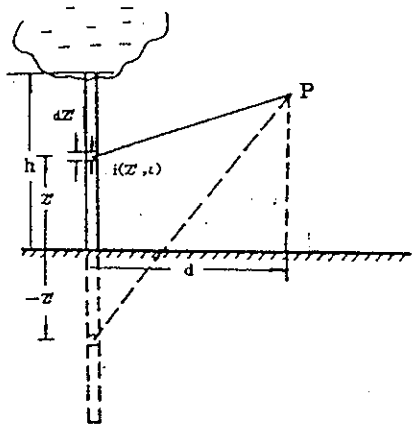

Fig 1 Model of lightning ground stroke

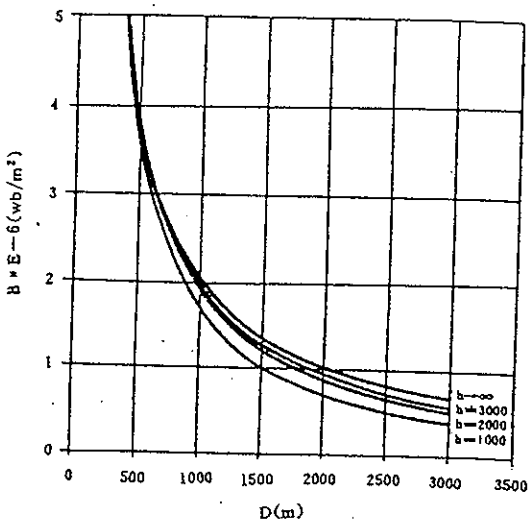

Fig 2 The magnetic flux density B versus distance

given for comparison. The equation is as follows.

$$B=\frac{\mu_0}{2\pi d}I_L \tag{4}$$

It can be seen that the results from equation(4) is larger than that from equation(3). The smaller the height of current channel is, the larger the difference among the results will be. The results also show that when the distance between the lightning stroke point and the equipment is less than 200m, the equation of Ampere's Law can be used for the approximate calculation of the magnetic field.

Table 1 Magnetic flux density B in different cases

corresponding to I =100kA (10^{-4}T)

B h (m) / d (m)	1000 [equ. (3)]	2000 [equ. (3)]	3000 [equ. (3)]	→∞ [equ. (4)]
6	33.3329	33.3331	33.3333	33.3333
100	1.9950	1.9988	1.9995	2.0000
200	0.9902	0.9975	0.9989	1.0000
300	0.6525	0.6620	0.6650	0.6667
500	0.3783	0.3939	0.3973	0.4000
1000	0.1684	0.1892	0.1948	0.2000
2000	0.0679	0.0842	0.0912	0.1000
2500	0.0502	0.0634	0.0702	0.0800
3000	0.0392	0.0499	0.0561	0.0677

Taking $B\geqslant 0.07\times10^{-4}$T as the malfunction range and $B\geqslant 2.4\times10^{-4}$T as the damage range, the

distance between lightning stroke point and the equipment under different lightning currents are listed in table 2. The dangerous distance curves related to the malfunction and damage of electronic device in the microwave station are shown in fig 3 and fig 4.

Table 2 Distance of the malfunction and damage limitation

d(m) B(10^{-4}T) / I_1(kA)	0.07	2.4
10	280	8.6
15	410	12.4
35	900	28
50	1060	41.6
100	1960	83.4
200	3250	166

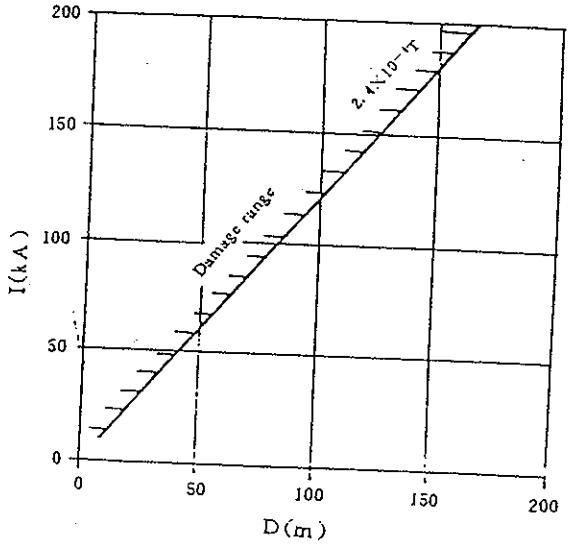

Fig 3 The damage distance curved for different height h corresponding to I=10kA.

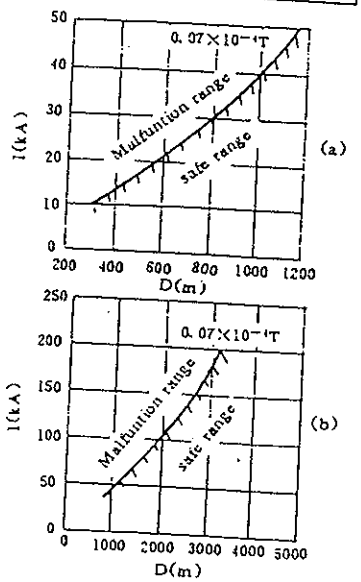

Fig 4 The malfunction distance curve
(a) for the range of 10—50kA
(b) for the range of 50—200kA

Usually the distance between the microwave tower and the main building equiped with microelectronic device is about 6m, so if the lightning strokes directly on the top of the microwave tower, the magnetic field caused by a small lightning current not exceed 10kA is enough to damage the device in the buiding. Early research[4] indicates that in order to avoid the damage of device a sheilding wire netting with meshes of 3cm×3cm is needed, but as regard of the error operation, even a wire netting of 6 meshes can not meet the safety requirment. We should pay special attention to this.

The malfunction and damage probability

According to the Chinese regulation[5], the probability of the lightning current is calculated by the following formula:

$$\lg P = -I/108 \tag{5}$$

where I is the amplitude of lightning current, kA; P is the probability of the case that the lightning current is larger than I.

As mentioned before the magnetic flux density B caused by the lightning current can be approximately calculated by Ampere's Law, thus we have

$$I = 2\pi d B \times 10^4/\mu_0 = dB \times 10^4/2 \quad (kA) \tag{6}$$

substituting (6) into (5), we obtain:

$$P = 10^{-dB} \times 10^4/2 \times 108 \tag{7}$$

Let B in (7) be 0.07×10^{-4}T and 2.4×10^{-4}T respectively, we can get the malfunction probability P_1, and damage probability P_2 as follows

$$P_1 = 10^{-0.07d}/2 \times 108 \tag{8}$$

$$P_2 = 10^{-2.4d}/2 \times 108 \tag{9}$$

Table 3 and Fig 5 give the probability P_1 and P_2 versus the distance between equipment and the lightning stroke point d.

Considering the probability of 0.04% as the safe range, the results show that in order to avoid the permenant damage a distance larger than 300m is needed. As regards the error operation, the malfunction probability corresponding to the distance of 300m, is as high as 79.9% and it remains a value of 10.7% even the distance raise to 3000m. We can see therefrom, it is quite difficult to ensure the safty operation of the microelectronic device in microwave station without a effecient protecting procedure.

Table 3 The malfunction probability P_1 and damage probability P_2

d(m)	5	10	50	200	300	500	1000	2000	3000
P_2(%)	88	77.4	27.8	0.6	0.04	0.002			
P_1(%)	99.6	99.2	96.3	86.1	79.9	68.9	47.4	22.5	10.7

Conclusions

1. When the distance between the lightning stroke point and the equipment is less than 200m, the equation of Ampere's Law can be used for the approximate calculation of the lightning electromagnetic field.

2. When the lightning strokes directly on the top of the microwave tower, the magnetic field caused by a lighting current not exceed 10kA is enough to damage the micro electronic device in the building.

3. In order to avoid the permenant damage of the microelectronic device, the distance between the lightning stroke point and the equipments need be larger than 300m, while the malfunction probability corresponding to the distance of 300m is as high as 79.9%.

Reference

1. Note on vulnerability of computers in lightning A/D—722 675
2. M.A Uman., Methods for calculating the electromagnetic Fields from aknown source distribution: Application to lightning, IEEE Transactionon EMC, vol. 31. No. 2. May 1989
3. Technical regulations of overvoltage protection for the electric power equipments SDJ 7—79, 1979(in Chinese)
4. Liu Dichen Xie Zifeng, The study of Lightning intereference on the dispatching and communication electronic equipment in electric power system, Proceedings of international Symposium on Electromagnetic compatibility, 1992, Beijing, China

An Introduction to Semiconductor Lightning-current Extender

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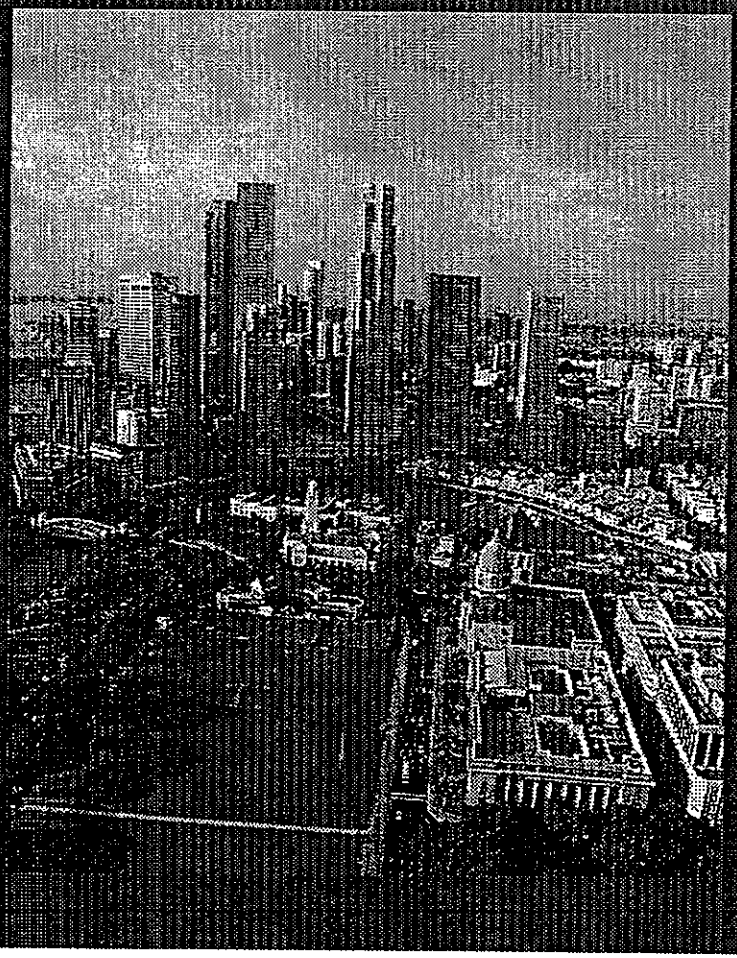

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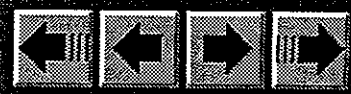

An Introduction to Semiconductor Lightning Current Duration Extender

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Abstract: A novel lightning protective device based on the principle of lightning current duration extension and current limitation is introduced in the paper. The design idea of this new device is explained accompanied with the enlightenment of natural phenomena. The experiment results including laboratory test, rocket triggered test and field measurement is also given.

Keywords: Lightning protection Lightning discharge
Lightning current limitation Semiconductor resistance

1. INTRODUCTION

The semiconductor lightning current duration extender (SLE) is a new device for prevention of the damage caused by direct lightning strokes.

It was developed in China in 1978 [1]. Recently SLE has been fairly widely used in China. About 13028 tower years field experiences have been accumulated by the end of 1997. SLE is developed based on the principles of ion neutralization and ions shielding, lightning current limitation and current duration extension, among them the lightning current limitation and current duration extension are the brand new ideas. The above mentioned functions are realized by a set of 5 m long semiconductor rods with 4 metal tips on each top. The rod, made of silicon rubber, epoxy resin and semiconductor materials, has a resistance of 35 kΩ. The rods are distributed radiately as shown in Fig.1.

These rods can connect automatically in parallel if the voltage across the SLE rod reaches the discharge voltage of the air gap between two adjacent rods. Fig.2 shows the case of 9 rods connected in parallel during the experiment.

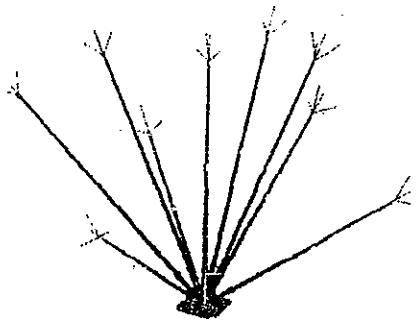

Fig.1 The scheme of a 9 rods SLE deice

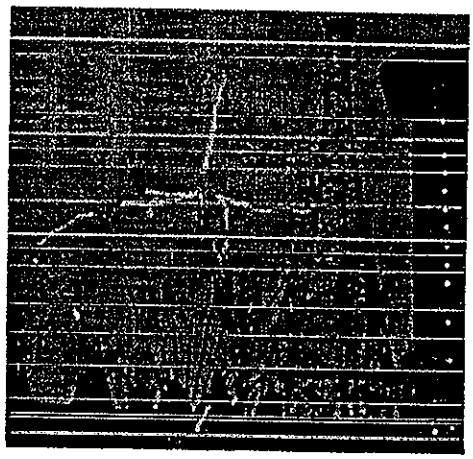

Fig.2 Nine SLE rods connected in paralleled

Applied voltage: 1.7 MV Wave form: +2 / 2000 μS
Current: 9.5 kA Air gap: 1.5 m

It is well known that the damage of lightning stroke is due to the intense lightning current and the rapid current changing rate. "Rapid and violent neutralization" and " small resistance in discharge channel" are considered to be two necessary conditions for the formation of intense lightning current. SLE can be considered to be a large nonlinear resistance added in series to the lightning discharge channel to destroy these conditions. Thus, lightning current will be effectively limited and the discharge duration will be significantly extended.

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2. ENLIGHTMENT OF NATURAL PHENOMENA

2.1 The 90% negative lightning stroke

Practical observations show that 90% of the ground lightning strokes are negative and only 10% of them are positive. However, when the clouds are electrified, positive and negative charges are equal in amount due to the fact that the clouds are neutral before electrification. It seems that the negative charges would be accumulated in the earth. But a long period observation shows that the total amount of negative charges in the earth is unchanged. The only explanation is that a great part of positive charges in clouds go down to the earth in a peaceful way, that is the natural lightning elimination.

We know that the negative air ion mobility k^- is 1.87 cm/s, while the positive air ion mobility k^+ is 1.36 cm/s. Let Q^+ and Q^- be the total amount of positive and negative charges in the cloud, Q_1^+ and Q_2^+ be the positive charges that go down to the ground in peaceful way and by lightning stroke respectively, Q_1^- and Q_2^- be the negative charges that go down to the ground in peaceful way and by lightning stroke respectively, the following equations can be written

$$Q_1^+ = 1.375 Q_1^- \quad (1)$$

$$Q_2^+ = 1/9\, Q_2^- \quad (2)$$

$$Q^+ = Q_1^+ + Q_2^+ \quad (3)$$

$$Q^- = Q_1^- + Q_2^- \quad (4)$$

$$Q^+ = Q^- = Q \quad (5)$$

By these equations we can get the negative natural lightning elimination rate

$$Q_1^- / Q = 70.3\% \quad (6)$$

and the positive lightning elimination rate is

$$Q_1^+ / Q = 96.7\% \quad (7)$$

It can be concluded that the lightning elimination effect is existent in the natural world. A great part of the charges in the thunder clouds are neutralized with the ions produced by the point discharges from the top of trees and buildings on the ground. The lightning striking down to ground is only a small remaining part. Thus the important thing we have to do is to find a way to increase the natural lightning elimination effect.

2.2 The lightning withstanding characteristic of ancient Chinese Buddhistic Pagodas

In China there are a great number of ancient Buddhistic pagodas. According to the historical records only a few of them were struck by lightning. An investigation was done on 160 ancient pagodas with 103904 pagodas-years [2]. The result indicates that only 45 lightning strokes were found out and the damage was insignificant, while the total number of theoretical lightning strokes N can be calculated to be 10033, i.e. the number of real lightning strokes is much less than that of the theoretical one. The ratio of the real lightning stroke number N_2 to theoretical lightning stroke number N_1 is given in Table 1 according to the pagoda height h. The higher the pagoda is, the smaller the ratio of N_2 / N_1 will be. In addtion there is no lack of records relevant to the luminous phenomena of pagodas in Chinese history books. The latest one happened in the year of 1960. On a thunderstorm night in Hangzhou, people discovered that fire rose continually from the top of Liuhe pagoda. The fire brigade was called. But the fire disappeared before the arrival of the fire engines.

All the above mentioned phenomena can be explained as follows.

Table 1 The lightning stroke ratio of pagodas according to its height

h (m)	n	N_1	N_2	N_2/N_1 (%)
10≤h<20	26	174	6	3.448
20≤h<30	59	1634	14	0.857
30≤h<40	39	2183	15	0.687
40≤h<50	16	1552	5	0.322
50≤h<60	12	2137	5	0.187
60≤h	8	2353	1	0.042
Sum	160	10033	45	0.449

Where n stands for the number of pagodas

The ancient Chinese pagodas are built by bricks and stones — a kind of semiconductor material. The pagodas are rather high and have a special shape. Due to the height and reasonable shape, great quantities of ions can be produced from the pagoda, which partially neutralize the charges in the clouds, thus eliminating a part of lightning strokes. By means of the resistance of the semiconductor material, the current of upward leader from the pagoda can be limited, thus eliminating the upward lightning strokes especially for those higher pagodas. Likely by means of the resistance of the semiconductor material, main discharge current of downward lightning stroke can be limited, thus decreasing the damage

of the downward lightning strokes. Therefore, by imitating the shape of ancient Chinese pagoda and adopting the semiconductor material, the new lightning protective device SLE was developed.

3. THE DESIGN IDEA

3.1 Point discharge function

Point discharge process will occur in all high objects with tip point in the electrostatic field under storm clouds. As ions produced by point discharge go up to the thunder clouds, a part of charges in the clouds can be neutralized. If the amount of charges in the cloud after neutralization can remain in a level not enough to start the downward leader, the downward stroke will not happen. As ions produced by point discharge spread over a large space above SLE, due to the shielding effect the field intensity on the top of SLE will evidently be reduced, thus reducing the probability of forming upward leader and facing leader from the SLE and its protected objects. The theoretical analysis shows that the height, shape and size of the discharge object influence the amount of ions to be produced by point discharge. In order to get large quantities of ions, the reasonable height and size of the discharge object and a reasonable number of discharge tips should be chosen. Accordingly the radially distributed 5 m long rods are used as the discharge object. Laboratory experiments show that the optimum number of discharge tips is in the range of 50 ~ 80, so 13 ~ 19 rod with 4 tips at the top are taken as the typical structure.

3.2 Eliminating upward lightning stroke

The field measurement shows that the upward lightning develops only if a upward leader current larger than 100A is provided. The motive power source for the formation of upward leader current is the potential U_0 determined by the product of the tower height h and average field intensity E_0 above the ground. For a tower of 60 m high, the field intensity needed to start the upward leader can be taken as 25 kV/m. Then we get U_0=1500 kV. Assume the upward leader current be 100A (in case of no SLE rod), the equivalent resistance R_0 that the upward leader current will meet with can be estimated as

$$R_0 = U_0 / 100 = 1500 / 100 = 15\ (\mathrm{k\Omega}) \qquad (8)$$

When the 35kΩ resistance of the SLE rod is added, the upward leader current will be limited to

$$I = U_0 / (35 + 15) = 1500 / 50 = 30\ (\mathrm{A}) \qquad (9)$$

Therefore SLE can destroy the condition for forming the upward leader, accordingly the upward lightning strokes can totally be eliminated.

3.3 Restricting main discharge current during downward lightning stroke

The resistance needed to restrict the main discharge current can be estimated as follows. We know that as the upward leader of the upward lightning goes up to the cloud, probably no main discharge process occur because of the large resistance in the cloud. Likely if the downward lightning strikes on the ground with large soil resistivitly (for example the dry sand), main discharge process will not occur either. Assuming that the soil resistivitly ρ is 2500 Ω·m, the downward lightning current I is 100A and the breakdown intensity E of the soil is 8.5kV/cm, the discharge radius of the lightning current in the soil can be calculated as

$$E = J\rho = I / 2\pi r^2 \rho \qquad (10)$$

$$r = \sqrt{I\rho / 2\pi E} = \sqrt{100 \times 2500 / (2\pi \times 8.5 \times 10^5)} = 0.216\ (\mathrm{m}) \qquad (11)$$

and the corresponding soil resistance R is

$$R = \rho / 2\pi r = 2500 / 2\pi \times 0.216 = 1.84\ (\mathrm{k\Omega}) \qquad (12)$$

i. e. a resistance of 1.84 kΩ might be enough to prevent the main discharge process of downward lightning. But as the current passing through the SLE rod reaches certain value, flashover of the SLE rod will occur. In order to prevent flashover, SLE is designed in such a way that the breakdown voltage of the air gap between two adjacent rods is lower than the surface flashover voltage of SLE rod. Thus before flashover of the initially struck rod, the adjacent air gap will breakdown, which will make the adjacent rod connected automatically with the initially struck one in parallel, i. e. the SLE rod can connected automatically one after another as the current rises, and the total resistance of SLE will go down as the current passing through SLE rises. For example, when 3 rods work in parallel, the voltage U acting on the SLE system during a lightning stroke can be calculated as follows

$$U = U_0 R / (R + R_0) \quad (13)$$

Where U_0 is the voltage of the storm cloud, R_0 is the resistance of lightning leader channel (about 500 Ω/m up) and R is the resistance of 3 rods connected in parallel. Assuming U_0 is 50000 kV, the height of the storm cloud is 1000 m, the voltage acting on SLE system will be

$$U = (5000 \times 35/3) / (500 + 35/3) = 1140 \text{ (kV)} \quad (14)$$

Which is less then the flashover voltage of SLE.

4. THE EXPERIMENT RESULTS

4.1 The laboratory experiment [3]

Fig.3 shows the scheme of long air gap discharge experiments using Image Converter Camera (IMC), which has a scanning velocity of 1 mm/ns and a number of frame of 2×10^7 fps. DS is a double-screened room. IG is an impulse generator rated 2400kV. R_1 is a decreasing discharge velocity resistance with a value of 106 kΩ. r_1, r_2, r_3 are the current shunts. R_2 is the main discharge current limitation resistance simulating the function of SLE. G is the 1 m long spark gap.

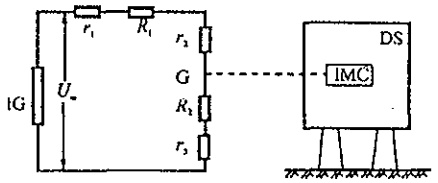


Fig.3 Scheme of long air gap discharge experiment

In Table 2 one set of data is given. These data show that when R_2 increases from 0 to 106 kΩ, the main discharge current decreases from 80A to only 3 A, i.e. the main discharge current limitation resistance R_2 can reduce the main discharge current and the leader velocity as well.

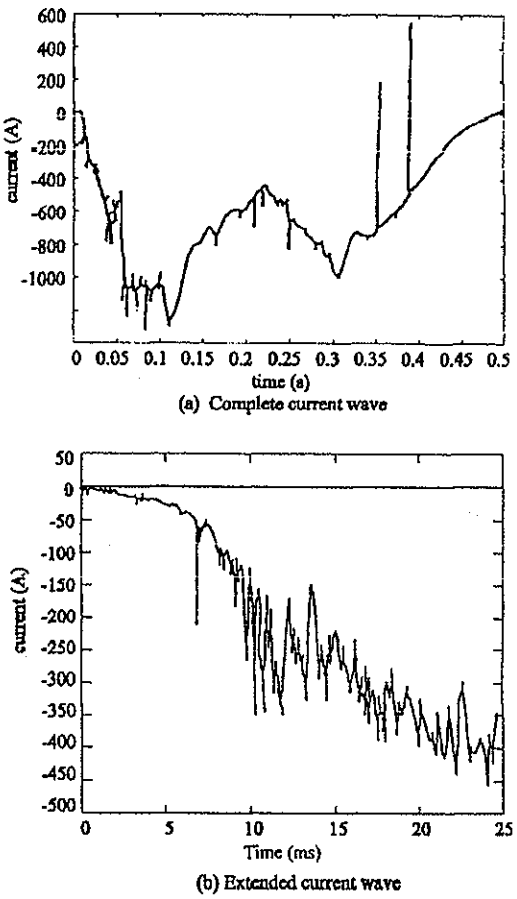
Table 2 One set of data from simulation experiment

R_2(kΩ)	U_m(kV)	V_g(cm/μs)	I(A)
0	1128	4.9	80
35.3	1153	3.7	/
70.6	1142	3.4	/
106	1123	3.6	3

Where V_g stands for the velocity of leader.
I stands for the main discharge current.

4.2 Rocket lightning triggered tests

The rocket triggered lightning test on current limiting lightning rod (i.e. single semiconductor rod) were carried out in Japan from 1993 to 1995 [4]. Four lightning current oscillograms with the testing number of 9309, 9315, 9412 and 9511 were obtained, of which No. 9309 is given in Fig 4. All results are shown in Table 3. A result of lightning triggered directly to ground without resistance (N0. 9509) is also given for comparison. Table 4 shows the amplitude of lightning current as lightning is triggered to the common lightning rod. It can be seen that as lightning is triggered to a rod with certain resistance the time needed for the current increase from 0 to 200A is much longer than that needed trigging to the ground without resistance and the amplitude of the lightning current is much smaller than that of triggering to the ground without resistance.



(a) Complete current wave

(b) Extended current wave

Fig .4 Oscillogram obtained from triggered lightning test (No.9309)

Table 3 Result of rocket lightning triggered tests

Test number	Resistance (kΩ)	Charge amount (C)	Amplitude of lightning current (kA)	Current duration (ms)	
				From 0 to 200 A	Total
9309	25	–293	–1.2	7	480
9315	30	57.5	1.65	3	60
9412	80	–30.2	–0.32	2	300
9511	200	–56.9	–4.5	10	430
9509	0	–56.3		0.4	210

Table 4 Lightning triggered on common lightning rod

Test number	Amplitude of lightning current (kA)
9310	32
9312	54
9319	132
9416	55
9421	39
9422	54
9501	102
9502	32

In the summer of 1999 the rocket triggered lightning test on 9 rods SLE device was carried out in China. In order to trigger the lightning stroke on SLE successfully, the rocket carried a bobbin on which only the metal wire is winded. Eight lightning strokes on SLE were obtained. The current in two of those strokes was very small (less than 150 A) and no lightning main discharge channel were found. The phenomena of 2 ~ 3 rods connected in parallel was recorded. The final report is under way.

4.3 Field measurement results

The automatic lightning current measuring device YLO–1 and ferromagnetic bar have been used to measure the direct lightning current [5]. Table 5 shows the results. Table 6 is the probability P of the lightning current larger than I (absolute value) as lightning strikes directly on SLE. Statistics indicates that as lightning strikes on a common lightning rod without current limiting capability, according to the Chinese formula $\lg P = -I / 108$, the lightning current corresponding to a probability of 6.1% is 131.2 kA. Comparing with the result in Table 6, the corresponding current is only 500 A, which indicates that SLE can limit the current of direct lightning stroke by about 0.4% of the original value and at the same time extend the current duration.

Table 5 Data of the lightning limitation current

No	1	2	3	4	5	6
I (A)	–485	–26	–296	–362	–43	–346
No	7	8	9	10	11	12
I (A)	–233	–335	–79	–485	–391	–28
NO	13	14	15	16	17	18
I (A)	–368	–346	–356	–204	–391	–348
No	19	20	21	22	23	24
I (A)	143	–403	+67	–303	+47	+278
No	25	26	27	28	29	30
I (A)	–327	–628	–290	–991	–100	–100
No	31	32	33			
I (A)	–200	–100	+200			

Table 6 Probability P of lightning current larger than I

I (A)	30	50	100	200	300
P (%)	90.9	84.8	70	63.6	45
I (A)	400	500	700	1000	
P (%)	15	6.1	3	0	

5. CONCIUSIONS

(1) The fact that of all the lightning stroke occurring in nature 90% are negative polarity indicates that there is neutralizing effect in natural world.

(2) The fact of the large discrepancy between the theoretical lightning stroke number and the real lightning strokes on ancient Chinese Buddhistic pagodas indicates that the ancient Chinese pagoda has a large lightning withstanding capability.

(3) SLE can provide large quantities of ions under lightning clouds to produce the ion neutralization and ion shielding effect due to its reasonable shape and size.

(4) With the resistance of semiconductor rod, SLE can eliminate the upward lightning stroke.

(5) With the resistance of semiconductor rod, the resistance of lightning leader channel and the automatical parallel connection characteristic of the rods, SLE can reduce the main discharge current to about 4 thousandth of the original value and extend the main discharge duration from microseconds to milliseconds.

0-7803-5938-0/00/$10.00 (c) 2000 IEEE

6. REFERENCES

[1] Chen Cixuan, et al., "The semiconductor lightning current duration extender." Proceedings of 24th ICLP, PP. 978~983,1998

[2] Xie Guangrun, Chen Cixuan and Lei Jinghuang. " The corona phenomena and lightning withstanding characteristic on the ancient Chinese buddhistic pagodas". Proceedings of the third Asian conference on electrical discharge at Beijing, PP.48–51, 1989

[3] X.S. Wen, et al. " Experimental study and a new model of long air gaps discharge." Proceedings of the 2nd Asian conference on electrical discharge at Kyushu, PP.65–68, August, 1989

[4] Teramoto M, et al. " Triggered lightning test to a new type lightning rod. " ICEE'96, PP.779–783

[5] Xie Guangrun, Yu Jianhui and Chen Xiuan. The current limit capability of semiconductor lightning eliminator. Proceedings of the 7th Asia Conference on Electrical Discharge at Xi'an, PP.192–195, October 1994.

7. BIOGRAPHIES



Chen Cixuan received her undergraduate education at Tsinghua University and her graduate education at Harbin University of Technology. She is currently a professor in the Electric Power Department of Wuhan University of Hydraulic and Electrical Engineering in China. Her research areas are in high voltage technique, electrical power system and electrical machine and apparatus.



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Xie Zifeng received the B. Eng. degree and Ph. D degree from the Wuhan University of Hydraulic and Electrical Engineering. She is currently a research associate in Department of Electrical Engineering and Applied Electronic Technology of Tsinghua University. Her research areas are in lightning interference and protection, surge suppression and electromagnetic compatibility.

The Calculation of the Protective Zone of SLE

Wuhan University of Hydraulic and Electrical Engineering, China

TopCan International Pte Ltd

The calculation of the protective zone of SLE

1. The protective zone of an individual SLE should be determined according to the following method (See Fig. 1)

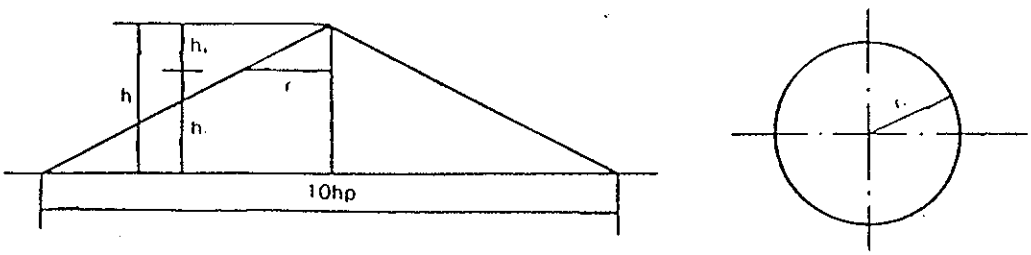


Fig. 1 The protective zone of an individual SLE

The protective radius r_x on the h_x lever of the protected object can be calculated by the following formula:

$$r_x = a(h - h_x) \cdot P = ah_a \cdot P \qquad (1)$$

Where:

h ---the height of the SLE, m
r_x ---the protective radius on the h_x level, m
h_x ---the height of the protected object, m
h_a ---the valid height of the SLE $h_a = h - h_x$, m
a --- for ammunition depot, a=1.5
for inflammable or explosive facilities, a=3.5
for others a=5
p --- the height influential coefficient: if $h \leq 64m$, p=1; and if $64m < h < 140m$, p=8/$\sqrt{h}$;

2 The protective zone of two SLEs with the same height should be determined according to the following method (See Fig. 2)

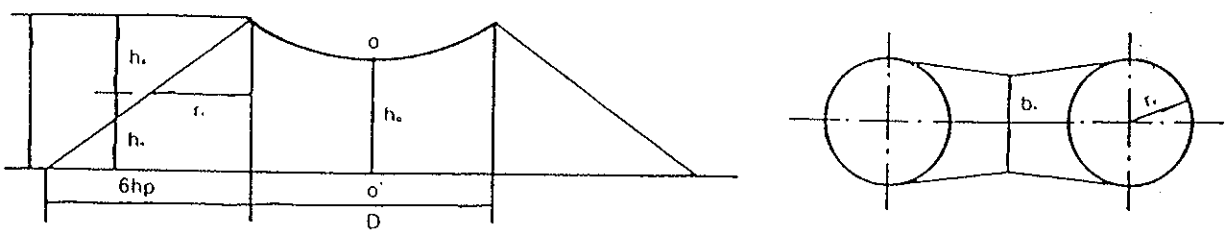


Fig.2 The protective zone of two SLEs with the same height

2.1 The outside protective of SLEs should be determined by the same method as that of an individual SLE.

2.2 As regard to the protective zone between the two SLEs, the upper side line is determined by the arc passing through the vertexes of the two SLEs and point o on the center line. The point o is the vertex of the assumed SLEs with a height h_0, which should be calculated by the following formula:

$$h_0=h-n_1D/P \qquad D\leq 10h \qquad (2)$$

where:

h_0---the height of the lowest point on the upper side line of the protective zone between the two SLEs, m

h--- the height of the SLE, m

D---distance between the two SLEs,m

n_1---for inflammable or explosive facilities, $n_1=0.02$, for others, $n_1=0.014$

p--- the height influential coefficient: if $h\leq 64m$, $p=1$, $64m<h<140m$, $p=8\sqrt{h}$

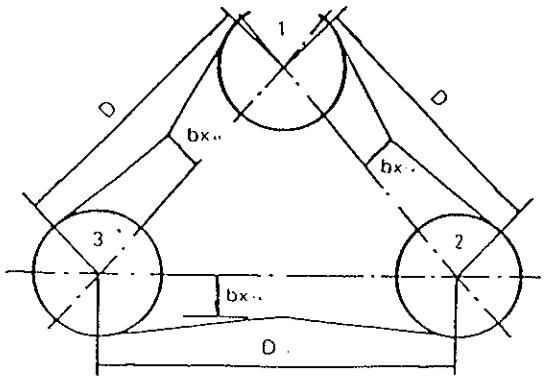
The smallest width b_x on h_x level at one side of the protective zone between two SLEs should be calculated by the following formula:

$$b_x=a(h_0-h_x)\cdot P \qquad (3)$$

Once b_x got, the protective zone of the two SLEs on the h_x level can be got from making a tangent line from this point to the protective circular of the two SLEs.

3. The protective zone of more than two SLEs should be determined according to the following method:

3.1 The outside protective zone of the triangle formed by three SLEs should be determined by the calculations of each two SLEs with the same height respectively. If all the b_x values are larger than 0, i.e. $b_x \geq 0$, all the objects with height h_x or below inside the areas can be protected.(See Fig 3)



Installation And Maintenance Manual

TopCan International Pte Ltd

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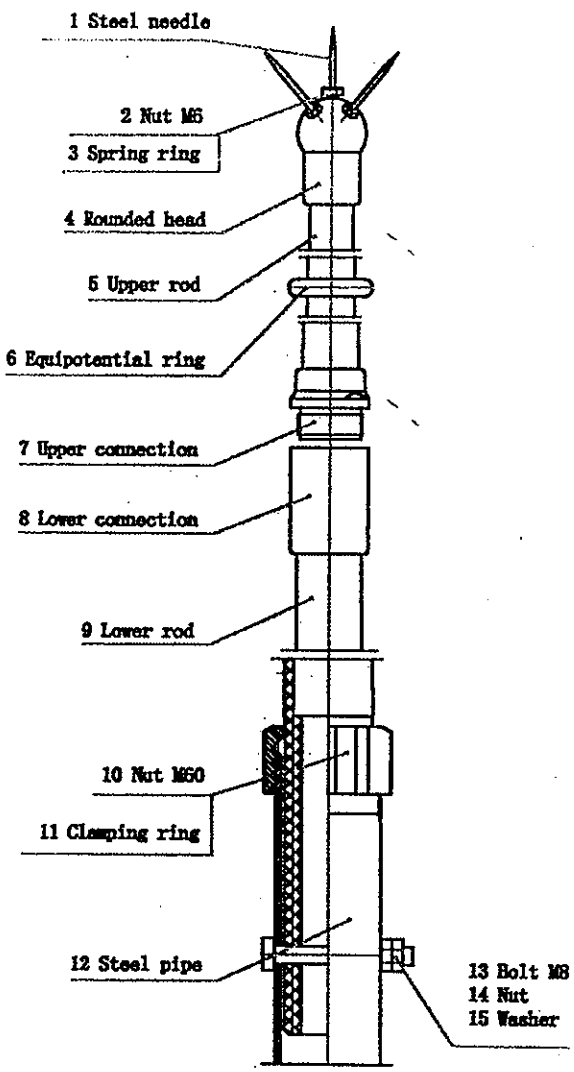
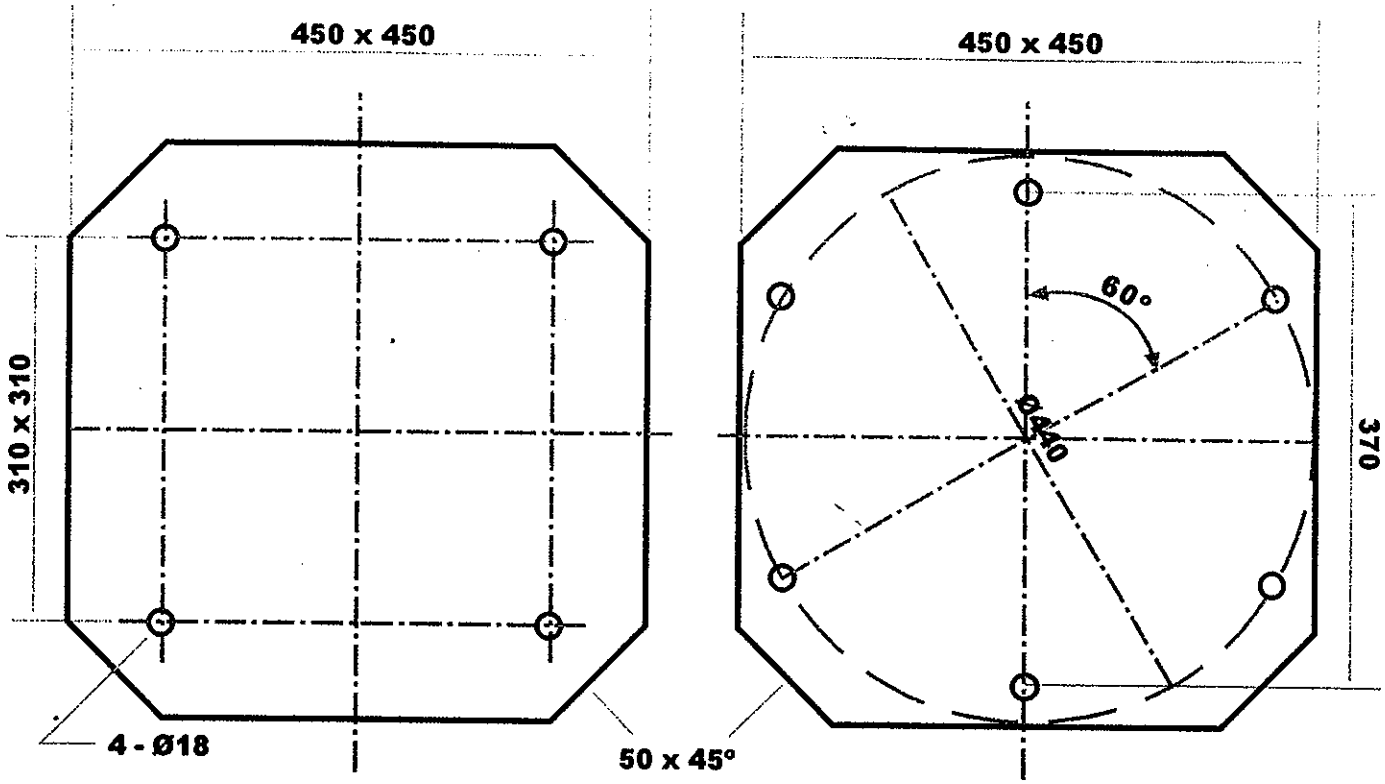


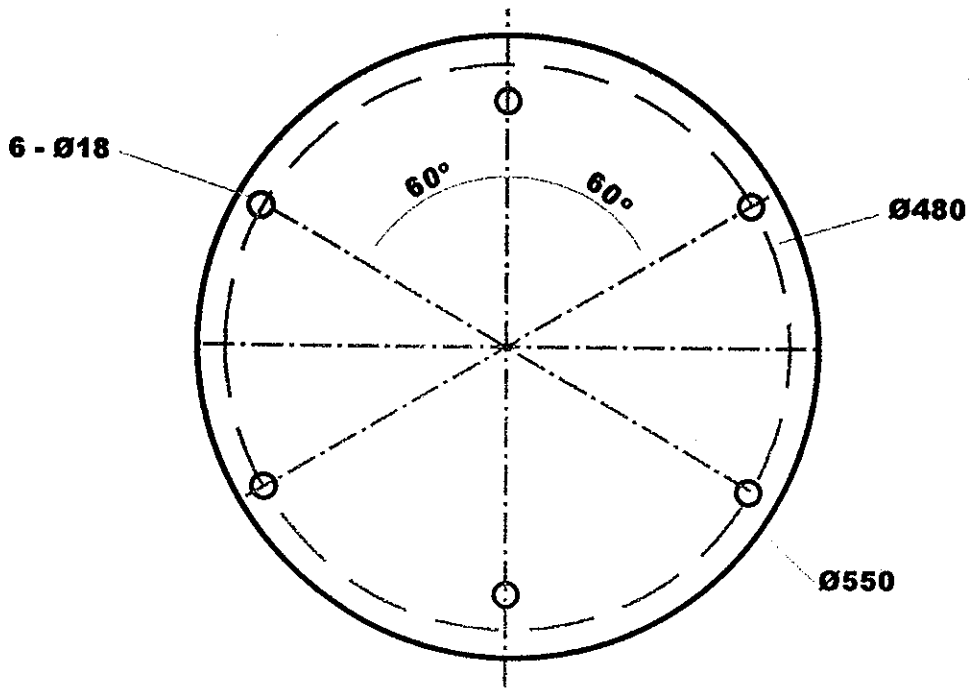
Figure 1: Assembling drawing of SLE

FIGURE 2: DIMENSION OF SUPPORTING BASE



SUPPORTING BASE OF SLE-V-5,9,13

SUPPORTING BASE OF SLE-V-19



SUPPORTING BASE OF SLE-V-25

THE INSTALLATION & MAINTENANCE MANUAL OF SEMICONDUCTOR LIGHTNING CURRENT EXTENDER (SLE)

FUNCTIONS OF THE SLE

The SLE is an air terminal lightning protection device. Its unique features include:

- Neutralization: The SLE is capable of eliminating upward lightning strokes
- Shield: It provides a wider protective shield that prevents lightning from making contacts with installations under its protection
- Current Limiting: Due to its non-linear design and high resistance rods made with semiconductor material, it has the ability not only to extend the duration of the flow of lightning current but also to reduce the amplitude of the lightning discharge
- Sustain Flashover: The umbrella design of the SLE is made for the purpose of sustaining the flashover effects of excessive lightning current

PRE-INSTALLATION PREPARATION

Please check the specification of the SLE before installing the SLE. All installation process must be carried out according to instruction and requirement listed in this manual.
Should there be any doubts concerning installation, please contact the TopCan International Pte Ltd at Blk 8 Lorong Bakar Batu #02-04 Singapore 348743, Telephone: (65) 7474695 Facsimile: (65) 7470025.

Assembling The SLE Rods

Figure 1 shows the assembly drawing of SLE.

Make sure all the parts are complete according to the parts list.

Each box that contains the semiconductor rod should consist of an upper and a lower rod part.

Assemble and fasten the semiconductor rods according to the drawing.

When removing the rods from the packaging, please handle the parts with care.

Loosen the screws at the tip of the lower rod and connect it to the bottom tip of the upper rod. Tighten the connection with screws.

Installation of steel needles

Place the nut M6 (2) and the spring ring (3) on the end of the steel needle (1)

Insert the nut M6 (2) into the rounded head (4) and tighten it.

Place the 4 steel needles onto the tip of each semiconductor rod.

Installing The SLE Base

Figure 2 shows the dimensions of its supporting base.

Loosen the self-locking nut M60 (10) before the supporting base is mounted.

Loosen the clamping rings (11) of the steel pipes (12) on the supporting base and remove the bolts M8 (13), nuts (14) and washers (15).

Place the supporting base (12) on the mounting location, and fix it with bolts or weld if necessary.

Insert the semiconductor rods into the steel pipes (12) on the supporting base.

Align the drilled holes on both components and assemble them with bolts M8, nuts and washers.

The protected objects must be 1.5 metres below the base of SLE and situated in the protective zone of SLE.

NOTE: Avoid any impact of the semiconductor rod on the supporting base and the tower. Prevent any scratches on the surface of semiconductor rod

Maintenance Procedure

We recommend the regular check up of the SLE to be performed before and after the rainy season.

Please comply with the following procedures.

Regular Checking of the SLE rods

The SLE contains several semiconductor rods. Each rod is 5 metres long with 4 copper needles on the tip of the rod.

Please check for cracks on surface of the semiconductor rods. Telescopes can be used for this purpose.

The surface of the semiconductor rod is coated with a protective membrane to avoid aging of the semiconductor material.

Regular check up for supporting base

Check whether the supporting base is connected tightly and whether the tower of the SLE is corroded. Treat it if necessary.

DOs AND DON'Ts FOR THE SLE

DOs

- Regular checking must be conducted by our engineers only
- Keep proper records of the counter
- Replace faulty parts as soon as possible
- Report any unusual incident that concerns the SLE system
- Keep all the climbing rungs in the trunk of the SLE Mast after use

DON'Ts

- The highest points of all other objects within the SLE protection zone must be at least 1.5m below the base of the SLE
- Never install any object on any part of the SLE system (e.g. hanging of cables & etc.)
- Air warning lights must stay within 1.5m away from the base of the SLE
- The SLE and its supporting mast must always stay connected to the 2 points of the lightning bands or bonding tapes
- Self-replacement of any part of the SLE system is strictly prohibited. Consult TopCan International Pte Ltd instead for any replacements.

Technical Information of Comprehensive Lightning Protection

TopCan International Pte Ltd

1. Characteristics of Lightning

1.1 Lightning Flashover

1.1.1 Process of Lightning Flashover

(A) Basic Process of cloud-to-ground flashover

I) Accumulating negative charges in thundercloud and including positive charges on the nearby ground at the same time.

II) When the local electric field intensity between the thundercloud and ground is greater than the critical electric field intensity for atmosphere ionization, a local flashover channel begin to develop from the edge of the thundercloud to the ground (leading flashover as shown in figure 1a).

III) When the leading channel develops close to the ground, the local space electric field intensity is increased and a positive leading flashover will be developed from the bulge of the ground to the sky (head on head as shown in figure 1b).

IV) When the leading channel reaches the ground or meet with the head-on-head, a plasma channel with high conductivity is formed, and then the negative charges in the leading channel and thundercloud neutralize the positive charges on the ground rapidly (main flashover process as shown in figure 1c).

V) The main flashover finishes when it reaches the height of the clouds; the remnant charges in the cloud flow down through the main flashover channel (after light flashover as shown in figure 1d).

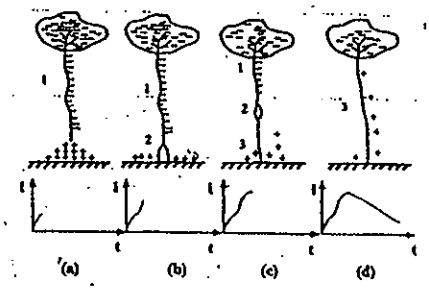


Figure 1 Basic process of Lightning Flashover

(B) Types of cloud-to-ground flashover

I) A process of negative cloud-to-ground flashover (downward negative flashover)

II) Starting from the bulge of ground or (top of a tower or hill), a flashover caused by an upward development of a positive lead which discharges into the negative zone in cloud (upward negative flashover)

III) Downward positive flashover

IV) Upward positive flashover

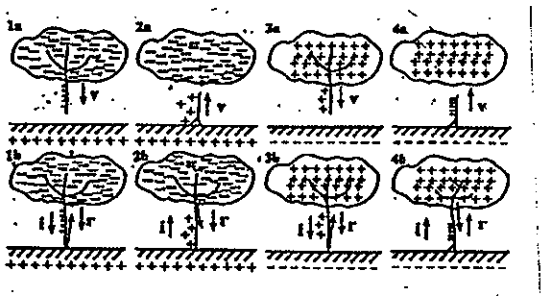


Figure 2 Types of cloud-to-ground flashover

1.2 Parameters of Lightning

1.2.1) Waveform and polarity of lightning current: the waveform of lightning current is a single polarity pulse; 75% ~90% of the lightning current is of negative polarity.

1.2.2) Amplitude, wavehead, wavelength, and gradient.

1.2.2a) Probability distribution of the amplitudes of lightning currents I: According to the analysis of 1205 statistic data measured in our country, the probability of I ≥ 40kA is 45%; that of I≥ 80kA is 17%, and that of I≥ 108kA is 10%, only 0.1% of the amplitude of the lightning currents was I= 330kA. Figure 3 shows the probability distribution curve of the lightning current amplitude in our country. For example, 12% of the lightning current present I≥100kA.

The formula is lg = - I / 108 or lg = - I / 54 (for less than 20 thunder days)

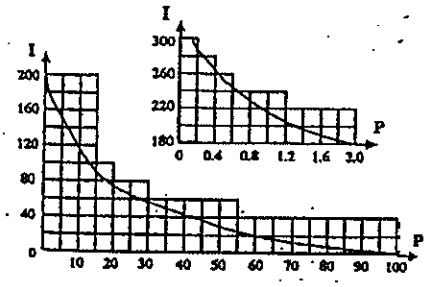


Figure 3 The probability curve of lightning current amplitude used in China.

1.2.2b). Wave head and wavelength
In general, the length of wave head is 1-5μs, average is 2-2.5μs; recommended value is 2.6μs in our country. The wavelength of the lightning current is 20-100μs, the average is about 50μs; 18%~30% of them exceed 50μs. 2.6/50μs waveform is used for direct lightning stroke protection design.
1.2.2c). The gradient of lightning current: rising variation rate of the lightning current versus time.
As the variation of the wave head of the lightning current is rather small, a fixed wave head of 2.6 μs is adopted

$$a = -\frac{I}{2.6}(kA/\mu s)$$

That is, the lightning current with greater amplitude has greater gradient.

1.2.3). Repeated impulse number and total duration of the lightning flashover
According to the analysis of about 6000 statistic records based on practical measurement in the world, 55% of the lightning include two more impulses; 25% include 3~5 impulses; 4% include ten impulses and more; average is 3 and the highest record is 42.

1.2.4).Thunder Days (thunderstorm days)
Thunder days T: days of a year in which thunder occurred in certain area.
When T>90, the area is defined as strong thunder area; when T>40, the area is more thunderous area; when T<15, the area is less thundery area. The design of lightning protection shall be in accordance with the thunder days.
1.2.5) Density of ground lightning strokes γ :average lightning strokes in one square kilometer ground per thunder day.

It is not distinguished between the lightning of cloud-to-cloud that of cloud-to-ground for the statistic of thunder days and thunder hours. The ratio of cloud-to-cloud lightning strokes to cloud-to-ground lightning strokes: about 1.5~3.0 for temperate zones, 3~6 for torrid zones.
By regulation: γ =0.015/km.d
In foreign countries: γ =0.1_0.2/km.d

2. The invading path of transient over-voltage

2.1. The invading path of lightning stroke

2.1.1) Direct lightning stroke can result in personal casualties because some tens to 100~200 KA thunder impulse current has tremendous electromagnetic, mechanical and heat effects. Huge voltage pulse is formed when the current flows through the hit object, causing damage of equipment insulation; the electro-dynamic effect of the impulse current will result in blowout of the object; the impulse current can also cause temperature rise and melting of the conductors and metal objects etc. suddenly. Most severe destroy always occurred in the first case mentioned above.
Because the cable between the power source and electronic system or that between electronic systems uses same grounding system together with the building, the thunder current will result in very high potential on the grounding network and lead wire (concrete bars in general) when the thunder current flows into the ground through the lead wire at the time when the building is struck by the lightning. This will result in different potential on the micro-electronic devices in different positions in the building as well as the transient wave of over-voltage and over-current on the lines between the devices, invading into the devices and causing damages as shown in figure 4.

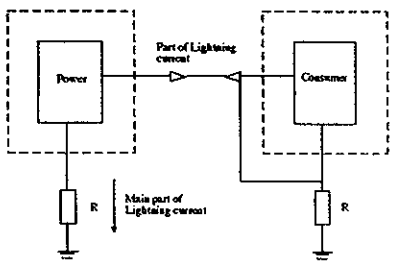


Figure 4 Possible transient overvoltage in power system when lightning stroke occurred on the building

2.1.2) Lightning stroke on a line

When the lightning stroke occurred on an overhead transmission line, communication line, metal conduit of every kind or antenna far from the building, the thunder impulse wave with high potential and current generated on the line will invade into the building along the conductors. This is called thunder invasion wave. Even overhead lightning lines and lightning protectors etc. are used (see figure 5), the lightning transient over-voltage cannot be eliminated completely and a part of over-voltage with lower amplitude can still threaten the equipment in low voltage systems, especially computers, electronic systems and home electric appliances.

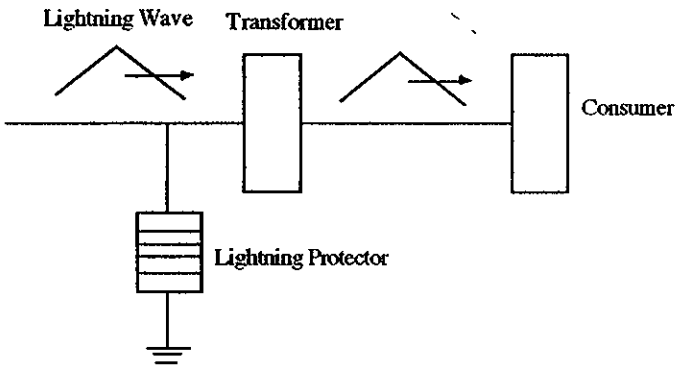


Figure 5 The low voltage power system is invaded by Lightning wave

2.1.3) Induction over-voltage caused by lightning stroke

(a) Induction over-voltage on lines

When the nearby ground is struck by lightning, the leading channel is fully charged negatively, which can attract positive charges onto the conductor nearest to the channel from other conductors by electrostatic induction, becoming bounded charges. In the process of main flashover, the negative charges in the channel are neutralized rapidly, and the corresponding electric-field intensity is weakened and disappeared rapidly, as a result, the positive charges is released from the bandage of the electric-field and become free charges, producing voltage wave spreading to both directions and causing very high over-voltage as shown in figure 6.

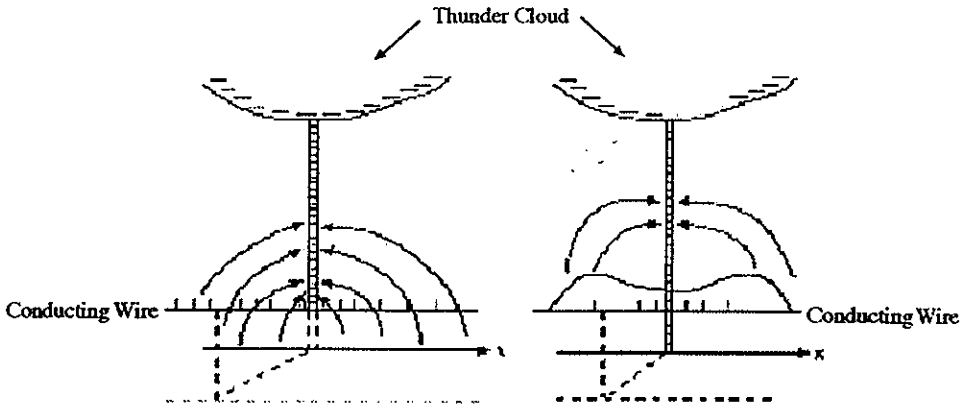


Figure 6 Sketch Map of inductive over-voltage
Formation caused by electrostatic induction

2.1.3b) The induction over-voltage of nearby conductor when the lightning rod is struck by lightning

As shown in figure 7, when lightning stroke occurred on the top of a lightning rod, the potential of each point (point N) on the lightning rod u_N

$$u_N = L_0 h\frac{di}{dt} + ir + iR$$

L_0 = 1.67μH/m, when h=10m, L_0h=16.7μH, R=10Ω, r is ignored, take I=100kA, τ =2.6μs, then

$$u_N \approx L_0 h\frac{di}{dt} + iR = 1.67 \times 10 \times \frac{100}{2.6} + 100 \times 10 \approx 1641(kV)$$

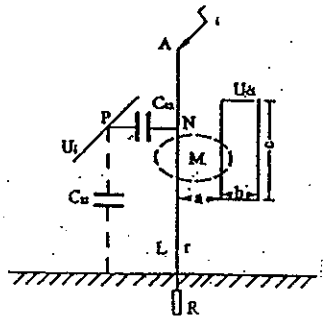


Figure 7 Inductive over-voltage caused by lightning stroke on lightning rod

Under the influence of the high potential along the rod body, the electro-static inductive over-voltage u_j will be produced on nearby line:

$$u_j = u_N \frac{C_{12}}{C_{12} + C_{22}}$$

At the same time, there will be inductive over-voltage u_{ci} at the opening of unfolded metal ring near the rod

$$u_{ci} = M\frac{di}{dt} = 0.2c(\ln\frac{a+b}{a})\frac{di}{dt}$$

when a=b=1m, c=10m, I=100kA,

$$u_{ci} = 0.2c(\ln\frac{a+b}{a})\frac{di}{dt} = (0.2 \times 10 \times \ln 2) \times 100/2.6 \approx 53.3(kV)$$

This can break through the air gap.

2.1.3c) When the lightning stroke is occurred on a building, the potential at the point of ground where the lightning current enters will be driven up and the stronger electromagnetic pulse will be formed in the space around the flashover channel at the same time. If there are communication lines, signal and control lines and radio frequency transmission lines near the lightning stroke point, the lightning will produce transient over-voltages on these lines by voltage beat-back or electromagnetic coupling. The over-voltage will spread along the lines in the form of flowing-wave and invade micro electronic devices.

2.2) Internal over-voltage

Internal over-voltage is caused by the changes of system internal state such as operation, turning on and off a load or system fault in power system. The system parameters are changed and then a transient process of electromagnetic energy conversion or transfer occurs in these cases.

Causes of internal over-voltage:

a) Turning on or off heavy load, such as elevator, large air-conditioner, freezer, medical equipment and large equipment.

b) Turning on or off inductive load, such as motor or relay coil, loaded transformer.

c) Turning on or off capacitors used for power factor compensation.

d) Operation of circuit-cutter or fuse.

e) Short-circuit fault.

2.3) Nucleo-electronic pulse (NEMP)

NEMP is one of the four major effects of nuclear weapon explosion. The execution of shock wave, ray radiation and nuclear radiation weaken quickly along with distance, but the electromagnetic pulse can be spread extensively, especially in the case of high altitude explosion. High energy γ-ray caused by high altitude explosion can be spread at light speed and produce Compton dispersion when meeting with the air molecules in aerosphere. The scattered electrons (Compton electrons) get energy from the γ-ray and move out at a speed of about light, forming Compton current. The Compton electrons collide and ionize the air molecules, producing large amount of secondary electrons and positive ions. The speed of secondary electrons decreases level by level, meanwhile, the electromagnetic field is radiated toward each sides. During high altitude explosion, on the boundary between outer space and atmosphere, there are asymmetries for both earth magnetic field and nuclear device itself, this will cause movement deflection for the Compton electrons, thus the contrail of the Compton current is not globally asymmetrical, as a result, the electromagnetic field can be radiated far away, forming NEMP, as shown in figure 8.

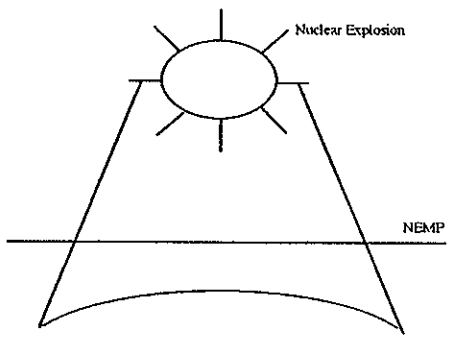


Figure 8 Incurrence of NEMP

High over-voltage will be produced in the power network by the coupling effect resulted from the NEMP, causing lots of semi-conductor devices and integrated circuits out of order or suffered from destroy. As large amount of semi-conductor devices and integrated circuits are adopted in modern weapon control systems, war commanding, control and communication systems, they are highly sensitive to the NEMP. As long as the coupling energy greater than 10^{-10}_10^{-9}J_the system will be disabled or destroyed.

3. Arrow's comprehensive lightning protection theory

3.1) Protection of direct lightning stroke

Traditional lightning rod: consisted of lightning acceptor, down-lead and grounded body, as shown in figure 10.

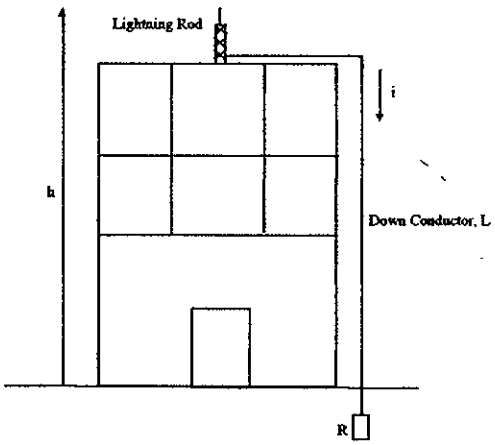


Figure 10 Sketch map of lightning rod installation and its protection function

When the lightning rod is struck by lightning, a large amount of current i flows into the ground through the building body (or down-lead) L and grounded body (grounding resistance R) and produces electric potential u_h at each point along the path of lightning current. $u_h = L_0 h\frac{di}{dt} + iR$

For example: According to the regulation, take the amplitude of lightning current I= 100 kA, and τ =2.6μs, L_0 = 1.67μH/m, R=10Ω if h=40m, then the potential at the point at 40m height will be

$$u_h = L_0 h\frac{di}{dt} + iR = 1.67 \times 40 \times \frac{10C}{2.6} + 100 \times 10 \approx 3570(kV)$$

the ground potential will be u_R = iR = 100 x 10 = 1000(kV)

When the lightning current with large amplitude disperses through down-lead and grounded body, the potential of down-lead and grounded body will be driven up, causing the high potential and large current to be introduced into the building. In the other word, by the effect of the electric and magnetic field impulses, the electric equipment in the building will be interfered through conduction, hinge and coupling. The primary interference forms include the lightning invading wave action on the microelectronic devices with the lightning waves existing on the peripheral equipment and its lines, the voltage counter-strike to the power source

due to potential increase of the grounded body and the influences caused by the coupling between the magnetic chain around the lightning current channel and the chips of the micro-electronic devices.
According to the test on site, there were about 10% of impulse current introduced into the building through wave-guide tubes. Even though the lightning current is only 10 kA, the lightning current introduced by the wave-guide tube will be 1KA, obviously high enough to make the electronic devices burned out.
We cannot overlook the damage caused by the secondary effect on the micro-electronic devices and its chips when large current flowing into the ground.
Assume that the amplitude of the lightning current is I, and *R* is the horizontal distance between the electronic device and the current-carrying conductor (or the downward lead), the maximum magnetic field intensity B_m produced by I at the spot of the device will be:

$$B_m = \frac{I}{2\pi kR} \text{ (Gs)}$$

Where the scaling coefficient k=79.3.
When B_m reaches 0.07 Gs (or 2.4 Gs), the devices will be out of order (or destroyed). This is equivalent to the damaged caused by a lightning strike of I=100kA happening at the place apart from 2.8kM (or 83m). In other words, when I=2kA, within a range of 50m, the unshielded microelectronic devices will be out of order; if I=60KA, they will be destroyed. As the probability of I>60kA is 57%, that is, greater than 1/2, the unshielded microelectronic devices will be of malfunctioning or destroyed when the chips are coupled with the magnetic flux produced by large current impulses once the lightning rod on the top of a building is hit by lightning.

3.2) Protecting measures against Direct Lightning strike

a) Protection: Conventional measure is to install lightning rod, lightning belt or a lightning net.
b) Reduction of the grounding resistance R: according to the regulation, the grounding resistance for lightning protection must be limited to be 10Ω or less.
c) Restrict the amplitude of lightning current I: even though the grounding resistance has been lowered to approximate zero, the voltage drop on the down-lead will still be close to million volts, which can introduce high potential and large current into the building. Therefore, it can effectively lower the voltage drop on the down-lead and grounding resistance and eliminate the action of secondary effect by restricting the amplitude of the lightning current and its gradient.
d) Shielding: To shield the micro-electronic devices from the electromagnetic field and set up Farad cage can strengthen the capability of the micro-electronic devices against over-voltages.
e) Voltage balance and iso-potential: Lightning accidents may easily happen to the structure of "one ground with two network (lightning protection grounding and operational grounding)" if the two networks are not connected automatically. The only safe way is to adopt the common grounding network –a voltage balance and

iso-potential method to realize "the boat on a river will be raised as the water rises in the river."
f) Safety distance: A high potential will be produced by lightning current flowing through the downward lead and grounding devices. Certain distance of safety shall be kept between the downward-lead or/and grounding devices and the grounded objects in order to prevent the counter-strike caused by the high potential against the protected buildings or all their connected metal substances.

3.3) Modern Direct Lightning strike protectors

3.3.1) Principle of AR lightning rod

The resistance of traditional lightning rod is very small, and can be forgotten. Once the lightning rod is hit by thunder, most of the electric charges in the thundercloud can be discharged immediately to the earth, but its fault is its huge voltage drop on downward-lead and grounding resistance that produces very strong the secondary effect after the lightning. The AR lightning rod features a high resistance that may restrict the lightning discharge current. Its basic principle is shown in figure 11.

As the voltage drop of the resistance $U_1=Ri_r$, if the disruptive voltage for counter-strike and upward-led is U>U2-U1 at the top of the resistance (where U_2 is the electrostatic potential at the same point), the occurrence of voltage counter-strike and the transmission of upward lead may be restricted. Even though the upward lead reaches the thundercloud, the strong discharging cannot be produced to instantly neutralize all the thundercloud charges because discharging current is restricted. It restricts the further development of the lead toward other thunderclouds. Therefore, the restricted thunder current will take longer time to flow through the AR lightning rod.

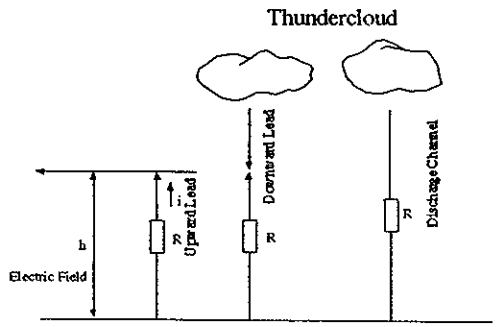


Figure 11 The current restriction principle of AR lightning rod

3.3.2) Verification result of AR lightning rod

a) The current waveform of lightning leading test is shown in figure 12(a), and (b). In figure (a), a current appears at first and rapidly attenuates to zero, and then increases gradually without any peak pulse. Figure (b) shows a part of the enlarged current waveform, where pulse discharge occurs at 1ms, but the current increases slowly after that, with 160A as maximum value and total duration of 321ms for the current.

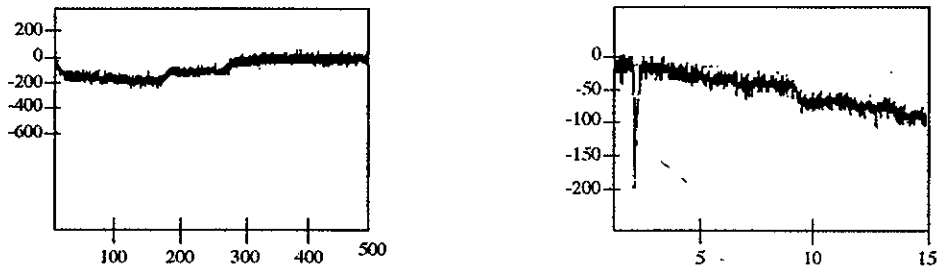


Figure 12 Current waveform of lightning leading test and a part of enlarged current waveform

According to the test, the average amplitude of lightning current pulse is 1407A when the AR lightning rod is stricken by lightning. However, when an iron tower lightning rod is stricken, the amplitude of lightning pulse is 54900A. Obviously, the current restriction effect of AR lightning rod is significant, being 2.5% of the original value.

b) The tolerable energy density of the current restriction resistor is $W=1.033J/mm^3$, its tolerable quantity of permeable electric charges is $Q=0.04215C/mm^2$, and the energy-carrying capability of an AR lightning rod is 5127.5 kJ.

c) The head of the acceptor of AR lightning rod is made of a steel sheet of thickness 4mm, which can withstand a lightning strike of 300C quantity of electricity without melting. Golde indicates that it is rarely seen in the real test for the value is greater than 100C and the average of all the real tested values is 8C for every institution. The inner and outer diameters of AR lightning rod are 83mm and 75mm respectively, and section area is $992.7mm^2$,therefore, so the tolerable quantity of permeable electric charges is 41.84C for AR lightning rod.

d) AR lightning rod can normally operate in the wind of a speed 43.5m/s.

3.3.3) Functions

a) Restrict the development of upward lightning on the skyscrapers.
b) Restrict the amplitude of lightning current and lower its gradient, to effectively reduce the secondary effect caused by lightning.
c) Counting function of lightning strikes
d) Strong resisting capability against wind up to force 12.
e) Easy to install, 10-year life time, maintenance free.

Appearance and Parameter Table of AR Lightning Rod (Please refer to Brochure)

3.3.4) Design, installation and maintenance

a) The design of AR is in compliance with the standards "The design standard for lightning protection on buildings (GB50057-94)" and "The design standard of the over-voltage protection for industrial and civil power facilities (GB64-83)".
b) Telephone line, broadcasting line, antenna and low voltage power line are strictly prohibited from being hung on AR lightning rod.
c) When the rod may affect any signal lights and antenna, it shall be installed on the iron tower and their down-leads shall be passed through steel pipes at least 1.5m apart above the bottom of the base of AR lightning rod before entering the building.
d) In general, the grounding resistance shall be lass than 10_.
e) AR lightning rod is a device free from maintenance. The connections of AR lightning rod, down-lead and grounding body should be checked before each raining season to ensure their reliability.

3.4 Protection of the invasion wave from power line

3.4.1) The disadvantage of traditional protection of power transmission line

To prevent the insulation of the distribution transformer from being damaged by the lightning impulse from power line, a lightning protector should be installed near the transformer, as shown in figure 13. As the insulation level of 3~10kV distribution line is relatively low, the lightning disasters cannot be avoided by simply installing the lightning protectors on high voltage circuit. If there is no protector installed on the low voltage side, the insulation near the neutral point of the high voltage side of the transformer and the vertical insulation on the high voltage side of the transformer would be broken down when the impulse invaded from either high voltage side or low voltage side. Therefore, it is necessary to install a protector on each phase of the low voltage side.

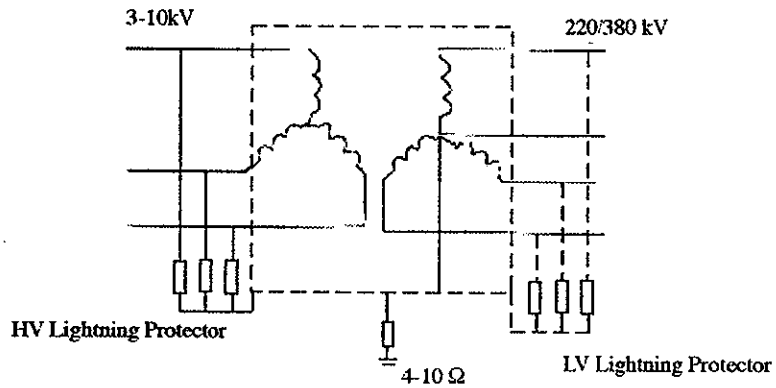


Figure 13 Wiring for protection of distribution transformer

3.4.2) Technical measures for restricting the traveling waves from the power lines

According to the electromagnetic theory, a protected zone may be protected from outside to inside according to the their dangerous scales. The outmost area shall be most most dangerous from direct lightning strike; the deeper into the internal of a building the less dangerous from lightning.
The raid of high voltage and large current happens mainly through lines. The boundaries of outer and inner lightning protection areas are formed by the shields that are made of direct lightning strike protection system, reinforced concrete and metal covering. Electric conduits and metal pipes pass through these boundaries. It is recommended by IEC that 50% of the lightning current will flow directly into ground through grounded body, and the other 50% will evenly flow into all the electric channels (e.g. power lines, signal lines and metal conduits etc.) when the lightning rod is stricken by lightning on the building.

The relevant regulations in China, by taking the lightning protection into account, have made all the stipulations of current disconcentration, voltage balancing, shielding, grounding and protection etc for lightning protection in telecommunication sectors. Current disconcentration is very important for restricting the waves from line. Because the amplitude of direct lightning strike current is considerably high, common electric equipment cannot withstand the over-voltage caused by it. This is the case where current disconcentration is applied. To disconcentrate lightning current means to set up multiple current distribution channels under multiple-stage lightning protection so as to discharge the lightning current stage by stage, and thus to guarantee the amplitude and gradient of the lightning current being reduced to the tolerable level before entering the equipment.
An over-voltage protection device or surge absorber that is used extensively nowadays for protecting power lines is one of the current disconcentration measures. At the same time, the power lines leading into a building must pass through underground steel conduits before entering the building and being connecting to the main switch-gear box. Therefore, the over-all lightning protection of a building must be implemented stage by stage; For the equipment connected to the power line, power distribution over-voltage protection devices with staged protectors must be installed so that the over-voltage coming from line is reduced to the acceptable level for the protected equipment

3.4.3) Power Distribution System Over-Voltage Protectors (DSOP)

3.4.3.1) The principle of Distribution System Over-voltage Protection (DSOP)

The main part of DSOP is a fast response module that realizes restriction function on over-voltage with its excellent nonlinear features, completely overcoming the limitation of traditional "air gap" and "gas discharge tube".

Generally, DSOP is parallel connected to the line of power source. The fast response module will present a high resistance under normal operation status so as to reduce current leakage current to the minimum. When over-voltage appears on the line, the current passing through the fast response module will rapidly increase and the module present a low resistance, allowing one part of the over-voltage energy to be released into the ground through the module and the other part of the energy to be absorbed by the module, transferred into thermal energy and dissipating into the environment. Thus the over-voltage is restricted.

3.4.3.2) Characteristics of DSOP

a) Modularized design has been made
Standardized design is adopted for DSOP and the fast response module is packaged into a module. The module is packed with glue-casting technology, and is connected into the circuit by bolts, so as to ensure firmness and easy to make maintenance.

b) Kevin's connection method is used in circuit design

Under the effect of over-voltage, the downward-lead of DSOP has an inductance characteristic, and the voltage drop is harmful to the insulation of the protected equipment (micro-electronic equipment in particular). According to the test of down-lead impulse, when the amplitude of impulsive current is 460A and wave-head length is 0.85μs, the voltage drop on the lead could be up to 5V/cm; when the amplitude is 2.94kA and wave-head length is 3.5μs, the voltage drop could be up to 8.7V/cm.
As seen from figure 16(A), when DSOP operates, the voltage on the protected equipment is a sum of DSOP's residual voltages and the voltage drop of down-lead. The voltage drop of down-lead will result in increase of the voltage that is applied on the protected equipment. This will still endanger the insulation of the electric and micro-electronic equipment. To eliminate the influence of the voltage drop of down-lead, the company adopts Kevin's connection method for the comprehensive design of DSOP, as seen in figure 16(B). This most remarkable feature makes our over-voltage protection product to be superior to the other similar products.

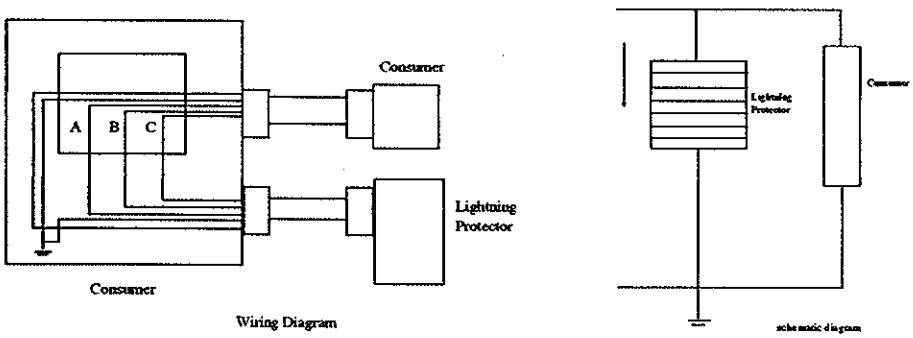


Figure 16(A) Traditional parallel connection

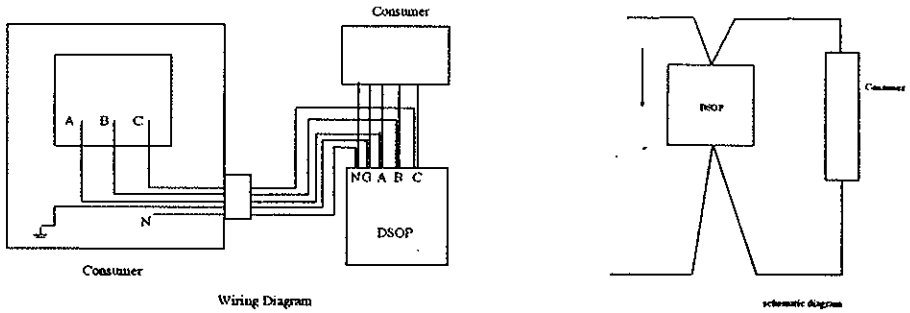


Figure 16(B) Kevin's connection

This device is easy to install and maintain and is equipped with special parallel terminals for easy implementation of Kevin's connection to eliminate the influence of the inductance of down-lead, improving its protection performance, making the residual voltage to be reduced to lowest level. On the other hand, use of the parallel terminals can also bring convenience and simplicity of installation and disassembly without interrupt of power supply.

3.4.3.3) Characteristic of fast response module

- Large surge current capacity

The surge current capacity for each phase is as high as 200kA; Each phase module is consisted of several fast response modules with 25kA surge current capacity each.

- Strong over-voltage energy absorption

Up to 180J/cm^3 in general, 240J/cm^3 maximum.

- Without power frequency continuation current, can withstand repeated operations

The continuation current is in micro-amperes, actually, it can be treated as null. Under the effect of lightning or internal over-voltage, it absorbs the energy of over-voltage only, no energy of continuation current has to be absorbed, therefore, it can withstand multi-lightning strike and repeated internal over-voltage.

- High response speed

As its response time is in nanoseconds, the over-voltage energy can be released in time, and avoid the over-voltage exceeding the volt-second characteristic because of fast response, therefore, the reliability of the protection is improved.

- High stability, strong anti-age ability

DSOP, consisted of multi fast response modules, reserves abundance capacity space as against its rated surge current capacity. After testing with 10kA lightning current for 1000 times, the residual voltage characteristic of 25kA module changes only a little. Its high reliability makes the module could last at least 8 years.

Low impedance bus-bar

AS the DSOP adopts low impedance bus-bar, it can eliminate the needs of using high impedance conductor as down-lead and the consequences arising from. As

a result, the durability of the device is improved, and its low residual voltage is guaranteed as well.

Maximum continuous operation voltage
Instead of lowering the rated voltage of the adopted fast response module, we reduce the influence of the voltage drop on the inductance of downward-lead to cut down the residual voltage. Therefore, the life time of the module is guaranteed even the system voltage goes up (e.g. in the case of smaller load).

State indicator
There is a state indicator on each module for monitoring the operative state of the power system. If the module is in normal condition, the indicator lit up; if the module fails, the indicator extinguished and has to be changed. Similar indicators are also installed on the state monitor panel of the device for easy detecting and finding faults.

State monitor
DSOP is provided with a state monitor. The monitoring signal emits from each state indicator of the module. Once the module of any phase in the device fails, the state monitor panel will notice the operator with sound-optic signal for dealing with and clear the fault, as shown in figure 17.

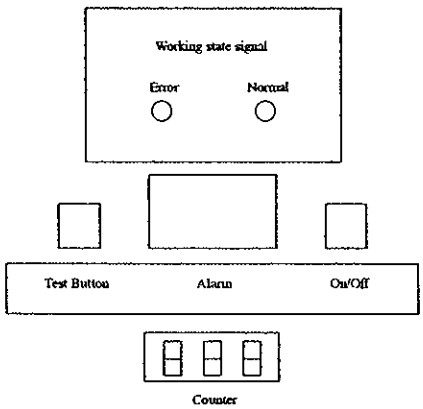


Figure 17 State monitor

Operation counter
It can record the actions when the over-voltage is applied on the input terminal. This can be used to verify the restriction result. The counter is provided with a battery used as backup power source, so as to work continuously when the utility power supply is interrupted.

Remote signal contacts
There are remote contacts prearranged in DSOP for unattended stations.

Easy operative conditions

The DSOP requires pretty easy operative conditions, it can work regularly in the following conditions: 40~63 Hz frequency, -40°C to +50°C temperature and 0-95% relative humidity. Its operative noise is 45dB at a distance of 1.5m, without environment pollution, applicable to the places where the noise limit is requested.

Appearance of DSOP series and Parameter table of DSOP series (Please refer to Brochure)

3.4.3.3) Validation result of DSOP series devices
a) The company was authorized as a technique support unit for "High-energy surge voltage suppressor" under "State level key project of science and technology for spreading" project by the State Science and Technology Commission in 1995.
b) The company took the lead in passing the test and inspection report of special safety product for computer information system under the Ministry of Public Security in September 1998: (98) TH GA-#013, (98) TH GA-#014; The company was the first one to be granted with sales permission certificate of special safety product for computer information system in the country in September 1998: the certificate numbers are: XKA11001, XKA11002_
c) The company passed the quality inspection and test procedure by the Preventing Technology Maintenance and Support Center of the Ministry of Posts & Telecommunication in April 1998. The test report number is: BLX-980423_
d) The People's Insurance Corporation of China, Wu Han sub-corporation is charged with the liability insurance for this product.

Computer Information System Security Examination Report of The Ministry of Public Security for the Special-purpose Products
Inspection result:
1. Rated pass-through voltage U_n(by regulation: $U_n \geq 2.2 \times 380V$) is 597V-623V; the change rate (≤10%)of the rated pass-through voltage U_n is 0.2%-2.2% before and after surge current capacity test;
2. Impulse leakage current is 11μA-35μA;
3. Restrictive voltage U_r (wave form 8/20μs, amplitude 3kA) is 961V-992V;
4. Surge current capacity I_n (wave form 8/20μs, amplitude 20kA,twice) without disorder, qualified;
5. The inspected items are accord with the relevant technical requirement in standard GA173-1998. The surge current capacity and restrictive voltage are decided as third class (highest class).

Test result:

- Four phases of the tested sample to ground, without damage after 5 positive polarity and 5 negative polarity 25kA, 8/20μs surge current tests; residual voltage: 1.25kV-1.5kV;
- Phase C to ground, phase B to ground, 8/20μs wave head, test 5 times for 10kA surge current, once for 15kA surge current, 980V and 1140V residual voltages were recorded correspondingly;
- The average values of voltage-sensitive voltage and leakage current of each phase are 552V and 40μA; the changing rate was less than 3% for voltage-sensitive voltage, 7μA for leakage current respectively.
- Performed counter tests 4 times for phase C of the tested sample, passed.

3.4.3.4) Design, installation and maintenance

a) The design of DSOP is accord with relevant national standards and industrial standards {Classification of electric and electronic equipment according to electric shock preventing (GB/T12501-1997)}, {Voltage-sensitive resistor for electronic equipment (GB/T10194-1997)} and {Technical regulation for lightning protection of the power system of communication engineering (YD5078-98)}

b) During installation, all connections shall be performed by full time electric technicians; the conductors used should be of standard cables or conductive wires.

c) DSOP shall be installed close to the protected equipment as far as possible. Space about 1 meter in front of the DSOP for easy access and daily maintenance.

d) It is recommended to adopt "kelvin's connection"; if use traditional parallel connection, the length of down-lead shouldn't be greater than 3m for optimum protection.

e) The device is properly structured, featuring stable performance and high reliability, therefore, nothing special maintenance is needed; the operator and inspector should record the actions of the counter when make his rounds.

f) When the protective performance declines or the device is out of order, the audio-optic warning signal will be emitted from the panel of the device; if the green light is extinguished and the red light lit up, which means the device has to be repaired.

g) In the case of fault, open the front cover and find out the module on which the indicator was extinguished; cut off the module from the circuit and replace it.

3.5 Protection of communication lines

3.3.1 Deficiency of communication line protection

The buildings have been protected effectively since the lightning rod was invented by Franklin. Since then, the lightning protection and safety are considered to be a task of architects, need not to worry about--people have the sense of security. In recent 20 years, suddenly, new problems about lightning disasters appeared frequently. Persons and things in the building cannot be protected effectively even the building was protected by traditional lightning rod. The micro-electronic devices including host computers, servers and terminals etc. in the machine room suffered from the attacks of lightning over-voltage waves more frequently.

Modern science and technology are rapidly developing. With LSI and VLSI as a kernel, the electronic products including measurement, protection, monitoring, communication and computer etc. are applied extensively in electric power, aviation, aerospace, defense, medicine and other areas of modern life. IC circuits with much higher logic density have driven the processing speed up to one billion times per second. Along with the improvement of IC's function, the ICs become more sensitive to the transient impulse. The transient impulse not only can result in mal-function of electronic equipment, but also can cause permanent damage of them. The essential reason which makes the micro-electronic equipment damaged is that the energy applied on these equipment has exceeded its permitted limit.

Table of critical energy by which a semi-conductor device can be damaged

type of semi-conductor	energy limit(joule)	destroy energy(joule)
digital Ics	10^{-9}	10^{-6}
analog Ics	10^{-8}	10^{-6}
Low noise transistor and diode	10^{-7}	10^{-6}
high speed transistor and ICs	10^{-6}	10^{-5}
small power transistor and signal diode	10^{-5}	10^{-4}
medium power transistor	10^{-4}	10^{-3}
voltage stabilizing tube and rectifier	10^{-3}	10^{-2}
large power transistor	10^{-2}	10^{-1}
power controlled silicon rectifier and power diode	10^{-1}	10^{-0}

Therefore, if we can release the energy of the transient invading wave in time, and make it below the limit at which the micro-electronic equipment will be damaged, proper protection will be obtained. To realize this objective, we design and produce the signal protector series products elaborately.

1. Technical measures for restricting invading wave from communication line

At present, there are three reasons of failures or damages, they are: high potential, large current invasion by conducting and magnetic hinge and capacitance coupling. As the communication equipment itself can to some extent screen static electricity, high potential and large current blocking and magnetic screen shall be properly resolved when the lightning strike protection is considered

According to theoretical calculation and test study, the anti-over-voltage capacity of the LSI chips in micro-electronic equipment is very low. After adopting electromagnetic screen around the machine room, it will be conducive to resolve the problem of inductive over-voltage. But electromagnetic screen cannot revolve the problem of voltage beat-back caused by conduction invasion of high voltage and large current as well as the problem of the invasion of the lightning wave along the signal line.

The invasion of the lightning wave along different lines will result in damage of relevant equipment, therefore, line protective devices shall be installed between communication line and host computer and at the interface of remote communication terminal. Accordingly, the lightning faults caused by the wave from line will be restricted and reduced roundly.

2. The signal protector in communication line

The principle of signal protector

The signal protector is connected serially between the line and protected equipment, it has three major functions: discharge high energy, current limited and clamping.

There are two parallel modules and a serial module included in a signal protector. The first parallel module is for high energy discharge, absorbing and discharging most part of the energy in transient wave; the second one is for voltage-restriction, strictly preventing any clutter which is higher than the clamping voltage and transient rising-pulse from entering the protected equipment. The serial module is a current-restriction module. It is in the status being connected in normal operative condition. When the surge wave comes, it presents high resistance and reserve the energy of the surge wave, making the energy discharges into ground through the high-energy discharge module before it, protecting the voltage-module and equipment and prolonging the life-time of the voltage-restriction module.

Features of signal protector
Self-recoverable, with high reliability
With extremely short response time, and action time of several ns's
Insertion loss is less than 0.5dB
No special requirements for operative environment
Frequency range: 0~2.5GHz; normal temperature: -40°C~50°C; normal relative humidity: 0~95%; and maximum altitude: 2000m.

Appearances of DLP, TLP, HFP and CSP and Parameter table of DLP, TLP, HFP and CSP (Please refer to Brochure)

1. Inspection and test result of signal protectors

Signal protector of Type CSP-100L has passed the inspection test according to stipulations of "Computer Information System Lightning Protectors", and the test is completed by the Product Quality Supervision and Inspection Center of the Ministry of Railways under authorization of the Ministry of Public Security. Inspection report is (99)TH (Zi) No. GA-017. The items in the inspection include rated action voltage, surge protection voltage, restriction voltage, surge current capacity, insertion consumption and stationary wave ratio.

2. Design, installation and maintenance

1 The signal protectors can be classified into four major classes, i.e. audio frequency line protectors of TLP series, data line protectors of DLP series, high frequency signal protectors of HFP series and coaxial cable protectors of CSP series.

TLP, DLP, HFP or CSP series is selected according to different protected objects. TLP series is applicable to protecting the equipment connected with audio lines, including programmable switching exchange, telephone, fax machine and modem etc.; DLP is applicable to protecting computers and other micro-electronic equipment connected with data and signal lines. HFP and CSP series are suitable to the common-mode amplitude over-voltage caused by lightning strike or lightning induction on the antenna feeder to the ground, and is to protect the communication equipment from being damaged by the over-voltage.

Signal protectors series products are classified into seven types: 7.5V, 12V, 30V, 75V, 100V, 150V and 200V.

2 TLP shall be serially connected between audio line and protected equipment; its input terminal shall be connected to outward audio line, and its output terminal shall be connected to the protected equipment. Never make them be upside down. The grounded terminal should be properly connected to the ground.

3 Each TLP can be composed of many several units to form a protector made of many pairs of lines.

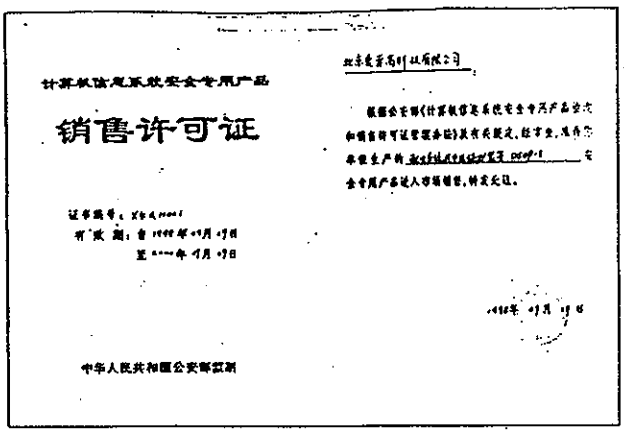
4 For easy installation, use universal connectors of audio lines or RJ45, RJ11 jacks for TLP.

5 DLP shall be serially connected among data line, signal line and protected equipment; its input terminal shall be connected to outward data line, and its output terminal shall be connected to the protected equipment. Never make them be upside down. The grounded terminal should be properly connected to the ground.

6 The number of lines of each data line protector indicates the lines could be protected by the protector. 1~8 lines are available for option.

7 HFP, CSP series shall be serially connected between antenna feeder and communication equipment, using L16, Q9 standard interfaces; select the interfaces according to the needs of input or output; special forms of interfaces will provide upon user's requests; and its grounded terminal shall be connected to the nearest grounded point at the machine room.

3.6 Quality Certificate



计算机信息系统安全专用产品

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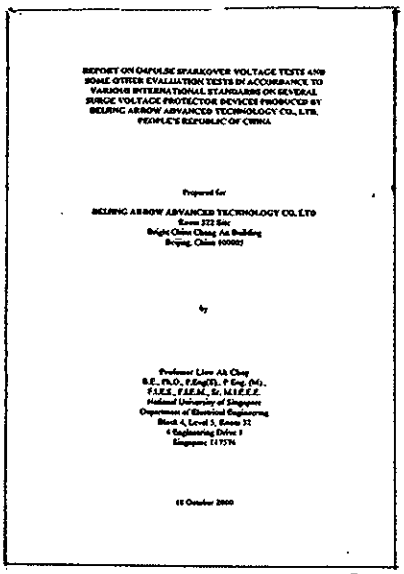


REPORT ON IMPULSE SPARKOVER VOLTAGE TESTS AND SOME OTHER EVALUATION TESTS IN ACCORDANCE TO VARIOUS INTERNATIONAL STANDARDS ON SEVERAL SURGE VOLTAGE PROTECTOR DEVICES PRODUCED BY BEIJING ARROW ADVANCED TECHNOLOGY CO., LTD. PEOPLE'S REPUBLIC OF CHINA

Prepared for

BEIJING ARROW ADVANCED TECHNOLOGY CO. LTD

by

Semiconductor Lightning Current-duration Extender (SLE) Technical Documents

TopCan International Pte Ltd

Semiconductor Lightning Current-duration Extender (SLE)

Technical Documents

Lightning Generation and Its Harms

I.Thundercloud Generation

When ground temperature is very high, water elements on ground are vaporized, and meanwhile, ground air becomes lightened and ascends because of being heated. The vapor in ascending airflow condenses into water droplets. And besides, when cold and warm air current moving horizontally encounters each other, the cold air mass descends while the warm air mass ascends. The vapor condenses into water droplets in the sky, and forms up frontal cumulus as wide as several kilometers, which may lead to lightning harms in a large area.

Dark clouds are formed when many water droplets suspending in the clouds. Three theories have been invented for the principles of electricity generation in dark clouds, which can be employed to explain a certain phenomena respectively: ① Water droplet breakup effect: Struck by strong airflow, the water drops in clouds break into larger water droplets with positive charge and smaller water droplets with negative charge, and the latter are carried away by airflow. Therefor clouds carry different charges respectively because of charge separation. ② Charge absorption effect: Under the action of cosmic rays, two types of ions exist in the atmosphere. Because of the electric field existing in the space from the sky to ground, electric charges accumulate in clouds with negative ones on the top and positive ones on the bottom. Cloud layers separate under the action of air currents, which causes electrification of clouds. ③ Water droplet freezing effect: It is discovered that, in lightning clouds, positive charges exist in the clouds consisting of ice crystals while negative charges exist in the clouds of water droplets. Therefore it is also believed that electrification of clouds is caused by the electric charges released in icing up of water droplets. When ascending air currents in ice-crystal areas carry away water from ice grains, positive and negative charges are separated and electrification of clouds comes into being.

II. Forming of lightning

Electric charges in lighting clouds are not evenly distributed,. Instead, they form up many accumulating centers. Therefore, the intensity of electric fields is not equal at all places, no matter it is among the clouds or between the clouds and ground. When the electric fields at the places where electric charges are dense in the clouds reaching 25~30 kV/cm, the clouds will forerun discharge against ground (for high buildings, lightning can start from the ground surface and then run upward, which forms up-going lightning). When the front of forerunning path approaches ground, it can induce head-on precursor (usually starting from a protruding place on the ground). When the forerunner joints with the head-on precursor, a strong ionized path is formed up and massive currents occur. This is the main discharging period of lightning, and it is accompanied with thunder and flashes. Its duration is as short as 50~100 μ s, and its process develops reversely to that of the forerunning path with a speed 1/20~1/2 of light velocity. The current of

main discharge can be as high as one hundred thousand amperes, which is the fundamental part of the lightning current. When it reaches the clouds, the main discharging process comes to an end. Then the residual charges flow downward along the main discharging path, and this is called residual glowing phase. Due to higher resistance in clouds, the discharging current in this phase is not very strong (about several hundreds amperes) with a comparatively longer duration (0.03s~0.15s). Several accumulating centers of electric charges may exist simultaneously in the clouds, so after the completion of the first accumulating center's discharge, a second and third center may discharge into the first center's discharging path. Therefore, one time of lightning usually consists of multiple discharges with an interval of 600 μ s to 800 ms among them. It contains 2~3 times of discharge in one time of lightning on average. Its generation is illustrated in Fig.1.

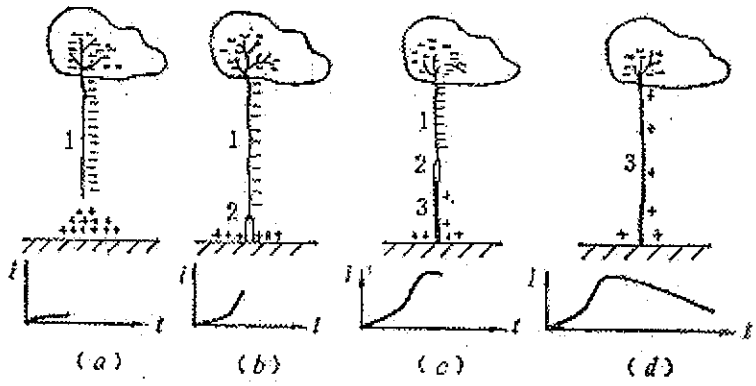


Fig. 1 Generation of Lightning

III. Harms of lightning

It is well known that lightning can cause severe destruction. Its voltage can reach as high as several million to several ten million volts and its current can reach several hundred thousand amperes. With the development of high technologies, electronic elements are widely adopted in various equipment, such as the weaken current elements in computers, communication systems, broadcast TV systems, electronic navigation systems, power supply systems, meteorology instruments. Lightning can seriously damage these equipment or cause miss operation. Traditional lightning rod can not meet the requirements of lightning protection for modern equipment. Lightning harms caused by adoption of traditional lightning rod for lightning protection in practice frequently occur. In modern life, lightning still constitutes vital harms to human and animal life, and severe threats to communication, oil, power, meteorology, air and space aviation and other national economy departments and cause severe loss. The following are some examples:

1.Oil system

January 18, 1972, Yokohama, Japan, A company's one 10-thousand-cubic-meter vault steel oil tank equipped with lightning rod then was directly struck by lightning and burst into fire.

September 24, 1977, Chicago, America, U oil company's one 38-thousand-cubic-meter vault steel oil tank equipped with lightning rod then was directly struck by lightning and burst into fire.

May 3, 1978, American Mississippi P oil company's 58-thousand-cubic-meter floater steel oil

tank equipped with lightning rod then was directly struck by lightning and burst into fire.

April 18, 1981, Singapore, S Oil Company's 58-thousuand-cubic-meter floater steel oil tank equipped with lightning rod then was directly struck by lightning and burst into fire.

In July, 1987, Qianfa Base, Hokkaido, Japan, a three-thousand-two-hundred-cubic-meter underground copper tank equipped with lightning rod then was directly struck by lightning and burst into fire.

In August, 1989, China, a 76-thousand-cubic-meter underground reinforced concrete oil tank in Huangdao Oil Depot equipped with lightning rod and shielding covered with 0.5 m thick earth then was directly struck by lightning, it burst into fire and exploded.

2.Electric power system

One transformer substation in Guangdong, China was struck by lightning, causing power cut in a wide area.

In July, 1988, lightning struck the lightning rod on a microwave tower on one microwave communicating station adjacent to a 110 kV transformer substation in a county in Hebei Province, causing an accident in which many communicating and electrical equipment including the microwave communication station, transformer substation, and 35 and 10 kV power lines connecting with it, and the county's power dispatching chamber are damaged. It took about one hour to recover the communication.

In July, 1991, one transformer substation in Beijing was struck by lightning, causing power failure at one large liquid gas station in several days.

From March to July, 1992, a microwave communicating tower in a 500 kV transformer substation in Hunan Province, China was struck twice by lightning, causing failure of the communication equipment and break of communication, and trip of the transformer substation's static compensation system.

3.Broadcast TV system

In 1977, lightning struck the top a TV tower located on a hill in Guangxi Province. Many people witnessed that flames burst out of the top of tower. It damaged the micro-electronic equipment. And the lightning electric wave sent high potential into the transmitter room along the leading wires from the tower top, which caused sparks on cable terminals and severe damage of transmitter, carrier equipment and power supplies. TV broadcast halted in many days. Its tested grounding resistance is 10.6 Ω.

In 1986, one TV station at Wulingshan in Hebei Province halted from broadcast repeatedly in lightning strike. The wire lines coming down from hills led over-voltage of lightning into rooms and the station master and one technician were struck and lost consciousness。

In May, 1990, lightning struck one TV station in Yunnan, China, and caused a severe accident.

In September, 1991, one TV station in Hongkong was struck by lightning and stopped from broadcasting in two of its channels.

In the summer of 1994, Tongshan County in Jiangsu Province was struck by lightning and halted its broadcast in a period of time.

4.Communication system

In August, 1981, Changzhou Microwave Station in Jiangsu Province were struck by lightning, three rectifier diodes in the end device of power carrier were broken down, and the contacting point between the outer layer of lead covered cables and earth screen was burnt.

In August, 1987, the communication equipment room of a microwave communication station in a high building in a city in Henan Province was struck by lightning and 12 microwave communicating lines were cut off and 16 electronic boards were turned useless.

In 1987～1990, the 605 microwave stations of the national wide power systems encountered 57 lightning strike accidents, and 240 computer boards were damaged.

In 1992, the microwave communicating stations' loss caused by lightning strike amounted to 0.4 million yuan in Anhui province. The radio station of the provincial Public Security Department was damaged repeatedly.

In June, 1994, a hotel in Kunming, Yunnan Province was struck by lightning, all the program controlled switching system and computers were damaged.

5.Air and space aviation, and national defense system

In September, 1992, 5 of the 25 sets of navigating equipment at Shenzhen International Airport were damaged by lightning. The airport was nearly at a standstill.

In 1993, lightning struck Huanghua Airport in Changsha, Hunan Province. Some electronic equipment was damaged, and some of the flights had to be postponed.

In the summer of 1994, a military airport in Inner Mongolia was struck twice by lightning and the computers' modems were damaged. Also in the same year, a military airport in Zhejiang Province was struck by lightning and the navigating radar was out of order.

In June , 1995, lightning struck Fenghuangshan navigation radar of Baiyun Airport, Guangzhou, and caused communication troubles. Over 120 air flights could not land.

In the summer of 1995, 5 among the 6 sets of equipment installed in a military airport in Hebei Province were damaged by lightning. The only set left undamaged which was installed at the meteorology station was equipped with lightning arrester.

In August, 1996, at Chongqing Jiangbei Airport, lightening dug three pits on the runways. The airport's telephones failed to work completely, and some of the radar facilities are damaged. the airport had to be shut up for 13 hours.

6.Meteorology system

In May, 1994, Guangzhou Regional Meteorology Center's operating system was struck by lightning. Many electronic equipment of the regional center's computer networks, fax between Guangzhou and Hongkong, and Zhujiang Delta automatic station networks were damaged to different extents.

In July, 1994, Sichuan Meteorology Bureau was struck twice by lightning. Many of the electronic facilities in CQS system and the regional center computer network that was under construction as well as the weather radar, satellite data receiving system, short wave radio station were damaged to different degrees.

In July, 1995, Shaanxi Huashang Meteorology Station was struck by lightning. The power supply wires, sockets, storage batteries and radio sets in the duty room sparked with harsh electric shock noise. Two radio sets entrusted to the station by Weinan City Flood Control Office and Sanmenxia Gorge Management Bureau were also damaged.

7.Finance and securities system

In 1993, Guangxi People's Bank Securities Center was hit by lightning. 16 computers were damaged. The loss reached 110 thousand yuan. It also caused damage to the computer networks of two specialized banks and the program controlled system of the telecommunication office in NanningCity.

In August, 1994, the computers in a bank in Hunan Province were damaged by lightning. It caused 750-thousand-yuan direct economic loss and the bank's service had to be halted for 7 days. the economic loss related to the accident amounted to several million yuan.

In the summer of 1995, a bank in Shunde City, Guangdong Province was struck by a induced lightning, which damaged its computer equipment and caused 880 thousand yuan direct economic loss.

In June, 1995, a lightning struck the Agriculture Bank Securities Exchange of Taiyuan City in Shanxi province and damaged the computers and network cards.

In June, 1995, a 33-storey building of China People's Bank Liquidation Center in Guangdong province was struck by lightning and halted its networks' operation for 3 days. Several hundred billion of fund could not be operated and interest loss exceeded 2 billion yuan.

Lightning Protection Measures

Lightning threatens human being and causes severe losses. In the whole world, many specialists have been devoting themselves to the study of lightning protection. Modern lightning protection equipment can be classified into two types: lightening protectors and lighting eliminators. The former type includes the traditional Franklin lightning rod, lightning band and Faraday Net, dynamic ball lightning protector, radiation lightning rod, and high frequency impulse lightning rod. The latter can be further classified into conductor and semiconductor kinds. The conductor kind includes short pin Dissipation Array System and Semiconductor Lightning Current-duration Extender(SLE) invented by American LEA Company in 1971, and the semiconductor kind includes the semiconductor lightning current-duration extender invented by a professors of China Wuhan Water Conservancy and Hydropower University in 1978.

Currently, most of the countries in the world adopt the lightning protection measures based upon the principles of Franklin lightning rod. It works on the principles that attracts lightening and withstands lightning strike instead of the protected object by making use of its altitude to distort the electric field under lightning clouds. This measure has been in use for a history of over 200 years. With the development of science and technology, it is far from being able to meet the requirements of modern lightning protection measures. The problems can be summed up as follows:

A. Protecting scope of lightning rod

Many lightning specialists in the world have made researches on the protecting scope provided by lightning rod to its adjacent buildings with the following conclusion drawn: The protecting scope of a vertical lightning rod is not definite. The facts in practical operation of lightning rods also verify the problems of lightning rod's protecting scope. For example: One oil depot in China adopted over ten lightning rods to provide combined protection over the oil tank area. But it did not work,. Instead, lightning caused explosion. One transformer substation in Guangdong Province was equipped with 5 lightning rods for combined protection, but one bus line within the protected scope was still struck by lightning, which caused power failure in a large area in Guangdong. The 537-meter-high TV tower in Moscow was once struck by by-pass strike lightning. The lightning struck at the places on the tower 200 and 300 meters from the top, and it even struck the ground 150 meters away from the tower horizontally, as illustrated in Fig. 2. It is reported that accidents in which by-pass strike lightning damaged the equipment happened repeatedly, besides the tower itself attracts lightning. The lightning strike rate in the area within 1.5 km from the tower is 2.5~4 times higher than that in the other areas in Moscow. All the events show that lightening rod can not protect the lower section of itself, not to mention the regions nearby. On the contrary, it functions negatively.

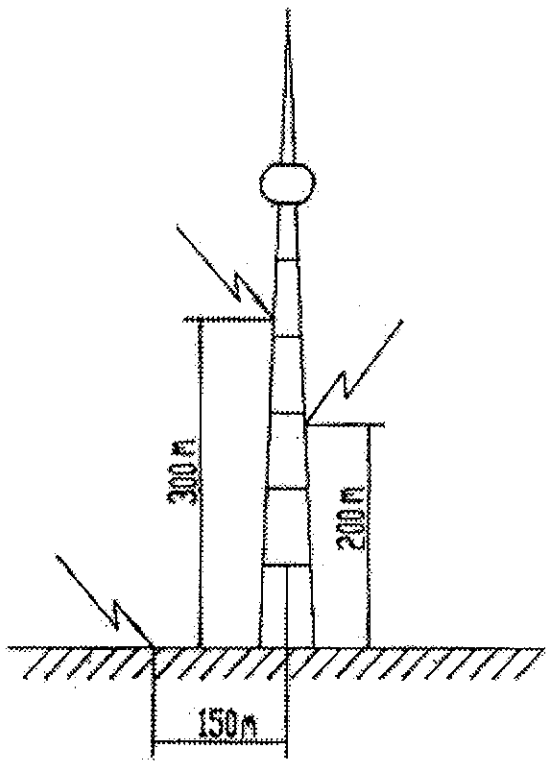


Fig. 2 A By-pass Strike Lightning Struck the Tower and the Ground Nearby

After 1982, German Regulation DIN57185 introduced rolling ball method to determine the protecting scope. Then, after 1985, British Regulation BS-6651 introduced the method. And China's Building Lightning Protection Design Standards (GB50057-94) also adopted the method.

B. Induced over-voltage

Traditional lightning rods can function to attract lightning electricity, therefore, lightning strike frequencies thus increase. Even though lightning is completely attracted onto lightning

rod instead of falling onto protected object, when strong current flows downward into the earth along lightning rod, it can still induce over-voltage in protected object and cause accidents. Electromagnetic inductance over-voltage is induced by the magnetic field around lightning current, and it is in direct proportion to lightning current and varying velocity while in reverse proportion to the range of lightning strike spot. When lightning electricity magnetic field reaches 0.07 Gs in intensity, integrate circuit elements might miss operation. And when the magnetic field intensity reaches 2.4 Gs, it might cause permanent damage to weak current facilities. The natural shielding in some buildings now, such as reinforcing bar net in buildings, can do nothing in shielding against electromagnetic induction and electromagnetic interference. The effective shielding (above 60 db) requires fully enclosed hexahedron made with double-layered 100 holes / $inch^2$ copper net. It is obviously hard to realize. Many damages of weak current equipment and lightning-caused fire in oil tank areas are resulted from induced over-voltage. It should be pointed out that the 3cm×3cm single-layered steel sheet net hexahedron shielding measures currently adopted in engineering can not effectively shield lightning interference. Microwave and computer equipment can still be caused to miss operation.

C. Reverse strike

When lightning is attracted onto lightning rod, several dozen or several hundred kilo-ampere high frequency lightning current flows through lightning rod and its leading-down wire and grounding device. In such a case, the lightning rod and leading-down wire carry very high potential. It the range between the lightning rod and the protected object is shorter than the safe range, it will incur reverse strike from the rod against the protected object and damage the object. China's regulations stipulate that the range in the air between the rod and the protected object S_K should be $\geq$ 5m, and the range in the earth between the rod and the protected object grounding device S_d should be $\geq$ 3 m. In fact it is hard to achieve the requirements in many cases. A survey shows that in most cases, power lines, telephone lines broadcast lines and various antennas are just laid very near to lightning rods and their leading-down wires, and some of them are even directly tied to the rods of leading-down wires. When microwave towers and TV set common antennas are equipped with lightning rods, it will cause more lightning strike, and it also might be possible that lightning is led onto microwave equipment and TV sets along wave guide tubes and TV signal feeding wires, which as illustrated in Fig. 3. is like to lead lightning into rooms.

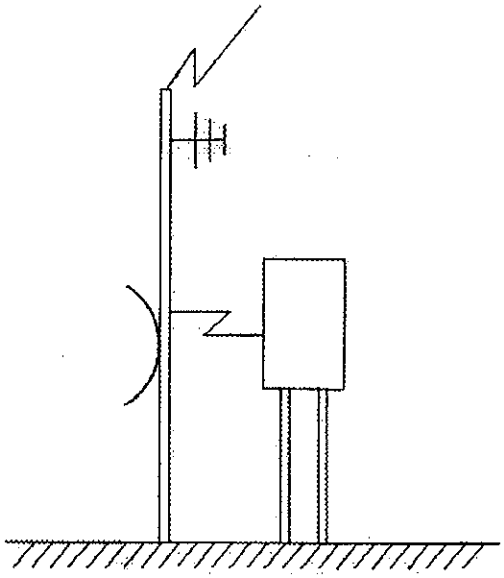


Fig. 3 Reverse Strike when Lightning Strikes at Lightning Rod

D. Contact voltage and step voltage

When someone touches an object which is being struck by lightning, a potential difference U is formed up from the one's highest contacting point along his body to the ground, as illustrated in Fig. 4. This is called contact voltage and it can cause danger to human body.

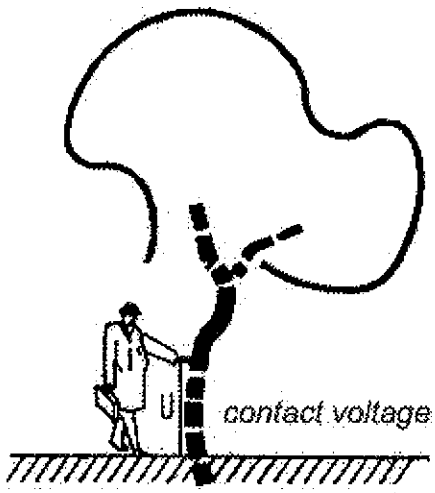


Fig. 4

When lightning strikes against lightning rod, lightning current will form up different potentials at different points along the radii in which the lightening current diffuses in the earth. Therefore, if someone bestrides nearby, high step voltage will be formed up between his feet. It will bring danger to human being and livestock, as shown in Fig. 5.

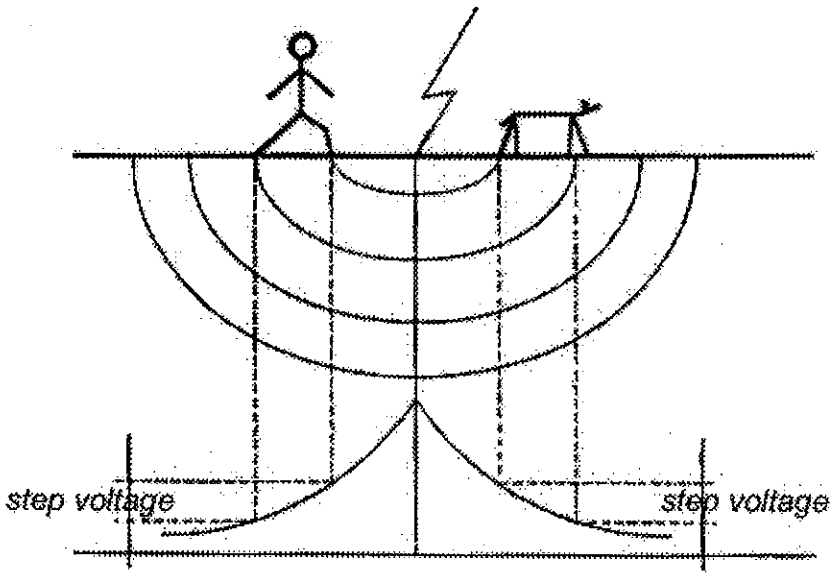


Fig. 5

In order to avoid the danger brought forth by contact voltage and step voltage, people and animals should be kept 3~5 m away from lightning rod. But for some buildings, such as public places, office buildings, and dormitories, it is hard to satisfy this requirement. Some lightning rods are just laid beside roads. All these cases are quite dangerous.

E. Lightning rod is especially unsuitable in protecting inflammable and explosive materials and weak current equipment

When traditional lightning rod is employed to protect inflammable and explosive materials, the heavy lightning current flowing through it might produce sparks at poorly-welded joints of the grounding lead wire, or break down the air and discharge against a conductor within 1~2 m. Heavy lightning current can also cause sparks at the opening a nearby metal ring. All these can lead to explosions or fire disasters. For example, When lightning struck China Huangdao Oil Depot in August, 1989, though the oil tank area was equipped with over 10 lightning rods, the lightning rods failed to function as protecting device, which led to a fire and explosion disaster. For weak current equipment, their electric withstanding capability is very weak. When the nearby lightening rods are struck by lightning, the induced voltage will cause malfunction among the equipment. The aftermath will be even worse when by-pass strike or reverse strike occurs.

It proves that it is imperfect to adopt traditional lightning rods for lightning protection. All lightning protectors, including overhead ground wire, lightening band, radioelement lightning protector, high-frequency rod, and dynamic ball, can not be free from the bondage of conductor-attracting-lightning characteristics. They all have the above mentioned problems, and therefore can not meet the requirements of modern lightning protection.

Conductor lightning eliminating device can reduce lightning strike frequency relying on its corona current neutralization and shielding effects. In 1977, Professor Xie Guangrun invented

a conductor lightning current-duration extender. Its corona current can reach 15 mA when the ground field intensity is 40 kV / m, which is 47 times stronger than that of American dissipation array system. It performances are also much superior to American dissipation array system. But it has no such function of current limit, therefore, it might also encounter the problems existing in the above-mentioned lightning protectors. Then, in June, 1978, Professor Xie Guangrun invented Semiconductor Lightning Current-duration Extender(SLE). It basically solves the problems existing in the lightning protectors relying upon its strong current limit capability. With more than ten years and several product generations of research, comparison, modification, it has now become the best protecting measures against direct lightning strike.

A Brief Introduction to Semiconductor Lightening Current-duration Extender

Semiconductor Lightning Current-duration Extender (SLE) was developed on the basis of lightning rod. Its characters are: It adopts semiconductor resistors to suppress the development of up-going lightning, and reduce lightning main discharging current amplitude and abruptness effectively, so as to overcome the shortcomings of lightning protectors and other conductor protectors against direct strike lightning, i.e., it reaches the main purposes to "limit current" with semiconductor materials and concurrent the function of neutralization with increasing neutralizing current with a few long pins. It is an advanced lightning protection device in the world. Its unique technical performances help to realize some of the technical conceiving that were impossible to become true in the past. The technical performances have been approved with mathematical calculation on theory, computer simulation, various simulating test, and magnetic steel rod measure performed by Huangshi Power Supply Bureau, rest with YL01-I lightning observing station practiced by Central China Power Management Bureau and Japanese missile-inducing-lightning test. It has also been in real operation in China with a record of over 10,000 tower-year test. The results achieved are satisfying and have passed experts' authentication.

SLE functions:

1. It suppresses the development of up-going lightning. It can limit the forerunning current of up-going current under 100 A, so as to prevent the development of up-going forerunner.
2. Taking "current limit" as the main purpose, SLE can effectively reduce lightning main discharging current in down-going lightning strike against ground (down-going lightning).
3. With their radiating pattern design and rational included angle, multiple pins can connect themselves in parallel automatically so as to realize the purpose of combined "current limit" when lightning current is too strong.
4. SLE's inner "current limiting" abilities can retard lightning discharging time, reduce lightning current amplitude and abruptness in a large extent so as to reduce secondary effect of lightning strike. Therefore, it becomes easy to achieve protection against secondary effect of lightning.
5. In suitable weather conditions (such as no wind coming horizontally), when the averaged

ground electric field under lightning clouds reaches 40 kV / m, it can produce neutralizing current at milliampere level. It can generate corona sparks with neutralizing current reaching Ampere level, i.e., with concurrent "neutralizing" function when there are strong lightning clouds in the sky. So it can greatly reduce the probabilities of lightning strike.

6. The protecting scope is large. The ratio of SLE installation height h to its protecting radius r is 1:5, and its protecting angle is 80 degrees. It ground protection range is 11 times of that of lightning protectors of its same height.

7. In high earth resistance regions, the shock grounding resistance can be reasonably larger, but it should not exceed 30 Ω.

8. The semiconductor pin sets can withstand 45 m/s wind, and out-door temperature between -40°C~56°C.

SLE consists of multiple semiconductor pins and a base. Each 5 m long semiconductor pin consists of a lightning receiver formed up with a metal ball head and steel pins (four metal forked pin tips) and a current eliminator made of semiconductor resistors.

Technical Instructions of Semiconductor Lightning Current-duration Extender

1. SLE's suppression against up-going lightning

   Observations show that up-going lightning from high buildings and towers takes a very high ratio. For example, according Berger's statistics, 70~80% lightning on the 70 m high lightning rod on St. Salvatore Hill develop upward from tip of the lightning rod. British Golde, a lightning protection authority in the world, believes that, if up-going lightning can be eliminated, the total number of lightning strikes against high towers will be reduced enormously. Therefore, a well-designed lightning protector against direct strike lightning should be provided with the capabilities of eliminating the development of up-going lightning. Real test shows that, up-going lightning can not be developed until up-going forerunning current exceeds 100 A. In accordance with theoretical calculation, laboratory simulating test, computer simulation and operation experience, SLE's semiconductor resistors are capable of suppressing up-going forerunning current to the level lower than a hundred ampere, so that it controls the development of up-going lighting forerunner and suppresses up-going lightning's coming into being. So it can limit the development of up-going lightning.

2. SLE's limit to lightning main discharging current

   When lightning activity develops too fast for the lightning-eliminating device to suppress lightning development with its corona current's neutralizing functions, discharge from clouds to ground will occur. In such a case, the lightning eliminator can be subject to strike of lightning. In lightning strike, the pins of the lightning eliminator can function to limit current, which gives prominence to the principles of SLE to take "current limit" as the main purpose. SLE's special structure ensures that, when it is subject to lightning strike, it can connect non-linear resistors in series into its ionized channel (the main discharging channel), so as to limit lightning main discharge, and prolong the main discharging time from microsecond level to

millisecond level, which can effectively reduce main discharging amplitude and abruptness and avoid appearance of lightning main discharging current. Real test approves that , when lightning strikes in high resistance zone or desert, lightning current is just about 100 amperes, and there is no main discharging process. Therefore, it is possible to suppress the main discharging process from clouds to ground with properly selected non-linear semiconductors of suitable resistance value. The results of magnetic steel rod test performed by Huangshi Power Supply Bureau and test of YLO-I lightning observing station practiced by Central China Dispatching Building show that SLE can reduce several dozens to several hundreds of kiloamperes of main discharging current to several dozens to several hundreds of amperes.

A Japanese scientific research group headed by K. Horii conducted missile-inducing-lightning experiment continuously in Okushishiku Mountain in Ishikawa County of Japan in 1993～1995. The group employed missile-inducing-lightning methods to test the current-limiting effect of current limiting pins on the spot. They achieved four times of success within the three years. The successful test numbers are respectively 9309, 9315, 9412, and 9511. Fig. 6 illustrates the current waveforms of missile-inducing-lightning test numbered as 9412. Even in the extremely unfavorable conditions, the lightning main discharging pulses of the four times of successful tests were under effective control: the discharging currents were just a few amperes while the discharging processes were extended very long. The following-on currents could not cause so serious harms as the main discharging currents, because their frequencies were very low. In the on-the-spot tests, the following-on current of 9412 was 220 A, which is lower than the main discharging current. In tests 9309 and 9315, the following-on currents were limited under 2kA, though they were higher than the main discharging currents. Therefore, the current limit is successful. The scientific group believes that current limiting pins can function to suppress sharp increase of lightning current, and under the conditions of the same amount of lightning discharge, if sharp ascending can be reduced into retarded ascending, lightning harms caused by induction can be decreased then. Therefore, current-limiting pins can be regarded as useful.

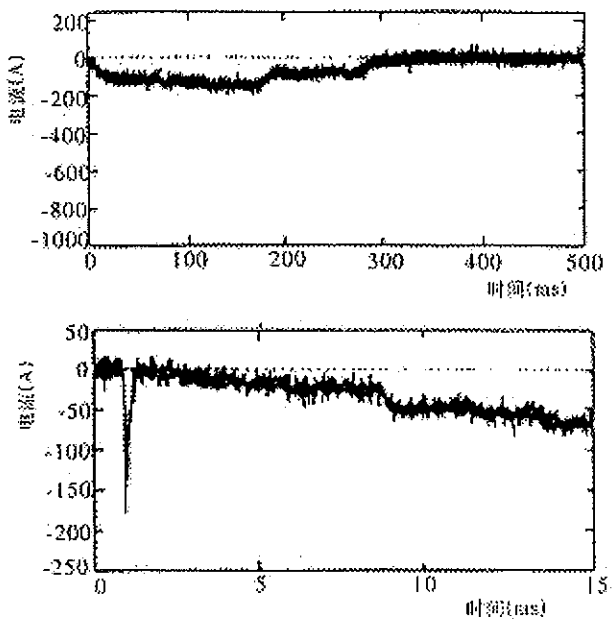


Fig. 6 Current Waveforms of Test Number 9412

and Part of Its Deployed Current Waveform

When lightning strikes SLE, the semiconductor pins can function to limit lightning current with their resistance if the pins do not produce surface flashover. In order to prevent the semiconductors from producing surface flashover, the discharging voltage between SLE's adjacent pins is designed lower than the semiconductor pins' surface flashover-voltage, in this way, before one semiconductor pin produces surface flashover, it adjacent semiconductor pin will be connected in parallel automatically so as to prevent surface flashover of the former pin. Each semiconductor pin's designed lightning resistance is 8 kA (limited to 30 A after current limit). When lightning current is especially strong, it can still cause semiconductor pin flashover. For example: when lightning current I exceeds 8 kA/pin × 13 pins=104 kA (taking the 13-pin type as an example), the semiconductor pins will produce flashover. But the semiconductor pins can still function to limit current after producing flashover. This is because:

As illustrated in Fig. 7, when lightning strikes SLE, current arises from 0 and flashover does not occur yet at this moment. Therefore, the current of different charges entering forerunning path via semiconductor pin is very low, as low as from several dozens to several hundred amperes. In such a case, the neutralizing function in lightning path is limited and it is impossible for fierce neutralization and thermal dissociation to happen. That is to say, the resistance in neutralizing section length l_1 is still very high, roughly keeps the value in the original forerunning phase (about 500 Ω). This process lasts about 1 to over 10 milliseconds, till the voltage drop on semiconductor pins produced by the current flowing through the pins exceeds its flashover-voltage. The current limiting process before flashover is called "the first type slow neutralizing process", and its corresponding discharge is called "the first type mild main discharge". Within the reverse strike height l_1 of the "the first type mild main discharge" , it will not produce fierce neutralization because the reverse strike current is limited to several dozens to several hundreds of amperes by the semiconductor pin resistors. Therefore, resistance R_1 in channel l_1 is still very high (about 500 Ω/m). So it possesses strong current limit functions by itself obviously.

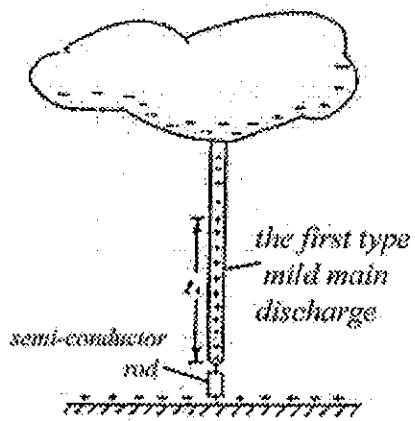


Fig. 7 Current Limit Illustration before Lightning Strike on SLE

When voltage drop produced by the above-mentioned current I on SLE reaches its surface flashover, surface flashover discharge is obviously about to happen, as it is shown in Fig. 8. When the ground charges ascend along the flashover path to the space point N above the semiconductor pin, they meet positive charges instead of negative ones, and a channel with high resistance R_1

instead of low resistance. i.e., the conditions for " instant and fierce neutralization among different charges " and "very low resistance in the channel" do not exist. Therefore, it is impossible for heavy current to occur. What's more, expelled by the charges of the same polarity, it is difficult for the ground charges to ascend. So, at this moment, what can happen is just the transitory charging current to point N incurred by abrupt change of the potential difference at point N. And the value of charging current can not be very strong because it encounters high resistance R_1 in "the first type mild main discharge channel". So, in its first flashover, the semiconductor pins can still function effectively to limit lightning current, and turn it into short pulses with the value of several hundred amperes. the short pulses illustrated in Fig. 9 and Fig. 10 are respectively –230 A and +500 A. It completely approves the above theoretical analysis, i.e., semiconductor pins still possess strong current-limiting functions after their first flashover. Upon completion of charging to space point N, the reverse strike current passing through the flashover path restores the value similar to that before the flashover under the limit of high resistance R_1 of "the first type mild main discharging channel", and ascends slowly in a long time. It also might happen low frequency oscillation. Therefore, SLE still possesses current limiting functions after flashover.

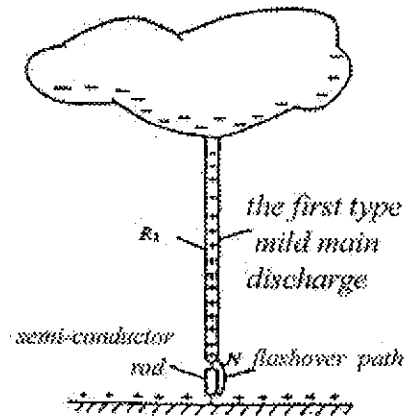
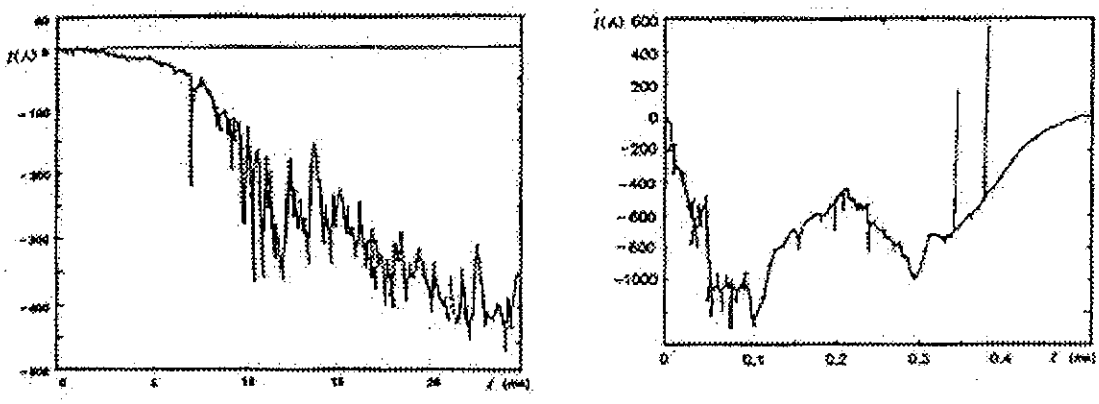
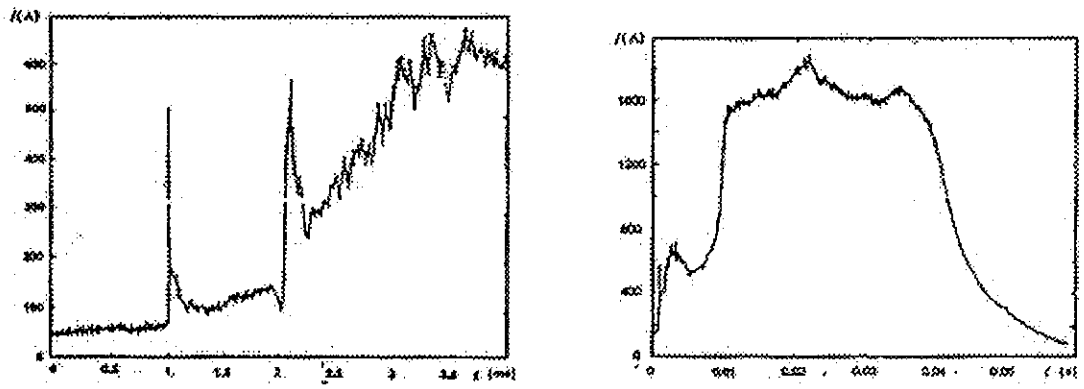


Fig. 8 Current Limit of SLE after Flashover



(a) part of the chart (b) whole chart

Fig. 9 Current Limit Illustration of Semiconductor Pins in Lightning Strike No. 9309 (25 kΩ)



(a) part of the chart (b) whole chart

Fig. 10 Current Limit Illustration of Semiconductor Pins in Lightning Strike No. 9315 (30 kΩ)

SLE is designed to weaken direct lightning strike and its secondary effects, and it can be used to replace the traditional lightning protectors. The difference between SLE and traditional lightning protectors lies in the fact that traditional lightning protectors are just metal conductors with no current-limiting functions. When a traditional lightning protector is struck by lightning, heavy and abrupt current will flow through the lightning rod and lead wire to the ground. Its secondary effects (such as reverse strike, high potential leading-in, and electromagnetic induction, and so on) will bring forth great threats to microelectronic equipment and inflammable and explosive facilities. And it is hard to guard against the secondary effects. But SLE is provided with current-limiting capabilities. It can enormously decrease lightning current amplitude and abruptness when it is subject to lightning strike so that the secondary effects of lightning strike can be greatly reduced, and make it easy to guard against the secondary effects of lightning strike.

3. SLE's functions to decrease lightning strike frequency

SLE relies upon its shielding effect of neutralizing space charges with corona current to decrease lightning strike frequency.

Thunderclouds are neutral before generation of electricity, while the positive and negative charges in the clouds are equal after electrification. In electric discharge from clouds to ground, polarities of lightning refer to the polarities of the charges down-going from thunderclouds to ground. Lightning observances show that, both in the aspects of discharge frequencies and discharge amount, 90% of the down-going lightning are negative and only 10% are positive. So this might cause that the earth carries more and more negative charges. But long-term survey shows that the amount of negative charges carried by the earth is stable (about 8.86×10^{-10} Coulomb/m^2 on the ground). Therefore, the only explanation for it is that the main portion of lightning positive charges is transferred to the earth in a peaceful mode (Positive thunderclouds are more apt to be neutralized against ground in a peaceful way than negative thunderclouds. And the theoretical explanation is: under the same electric field intensity, negative ions in the air flow 37.5% faster than positive ions). Upon this explanation we can know that various corona current existing in the nature can neutralized part of the charges in thunderclouds, the lightning we can see is just the remaining part of natural neutralization. So, the principle of neutralization stands. And the natural protection of ancient towers also proves this point. The result of a survey performed on 160 brick or wood structure ancient towers distributed in 18 provinces (municipalities) in China in 103,904 tower-years

shows that the total numbers of theoretical lightning strike on the ancient towers should amount to 10,033 times, but only 45 times are recorded in the history and their lightning damages were also slight.

It has been approved with theoretical calculations, laboratory simulations and on-the-spot tests that it can not generate strong neutralizing currents to take radioactive source or laser as the power source on lightning eliminators, and what can generate strong neutralizing currents are thunderclouds' electric fields themselves. Depending upon its structure and design, SEL makes full use of the strong power of thunderclouds electric fields so as to produce strong neutralizing currents. For example: when a thunderclouds electric field intensity E=40 kV/m, a lightning eliminator with 70 m installation height can generate corona currents as strong as that generated under 2,800 kV voltage. When you notice that 220 kV power lines can produce strong corona in wet days, it is not difficult to understand that SLE can produce long time of corona spark discharge and very strong corona currents when 2,800 kV is applied on it.

On-the-spot tests show that, when the thunderclouds averaged electric field intensity E=40 kV/m, SLE can generate 15 mA neutralizing current. When there are heavy thunderclouds in the sky, SLE can produce 1~2 m long corona sparks and the neutralizing current generated by it can be over ampere level. As long as the electric charges equivalent to the corona current can neutralize a small portion of thunderclouds charges to lower the thunderclouds' electric field intensity to the level below discharging limit, then it is possible to effectively prevent lightning strike from happening. The space electric charges equivalent to the corona current are distributed in the space over SLE and they can decrease the intensity of the electric field over SLE and the protected object, so that it is hard for the frontal forerunner to generate, so as to decrease the frequencies of down-going lightning strikes.

Although the function of "neutralization" can decrease lightning strike frequencies, the fatal week point of "neutralizing" thunderclouds electric charges is wind. This is because the ascending velocity of neutralizing electric charges is determined by the averaged intensity of thundercloud electric fields and mobility. Let's take negative thunderclouds as an example. The ascending velocity of positive electric charges in the air ascending from the ground is 1.36~5.44 m/s, while the wind velocity in the regions where oceanic monsoons can reach can be 10~20 m/s (equivalent to wind force grades 5~8), sometimes even 33 m/s (wind force grade 11). Therefore, the neutralizing charges are blown away before they can reach the thunderclouds. So it has remained as a great mistake to take "neutralization" as the key point in 200 years of researches for the direct strike lightning protecting devices, because "neutralization" can never happen in strong wind, no matter what measures are taken to increase tip discharging current. However, if the direct lightning strike protecting devices are employed in thunderstorms in the regions where horizontal wind velocity is not high and comparatively strong ascending airflows are available, they can still achieve a certain effects. Therefore, SLE takes "current limit" as the key point with concurrent function of "neutralization". Statistics show that, with the above-mentioned two functions, SLE can enormously decrease lightning strike frequencies provided that wind velocity is not high.

4. SLE's protecting scope

SLE's protecting scope refers to the specific space range nearby SLE in which direct lightning

strike accidents do not (or rarely) happen.

SLE sends electric charges of different polarity into the nearby space under thunderclouds, which results to effectively decrease the field intensity near the lightning-eliminating tower, so that up-going "frontal forerunner" can not be formed up from the ground nearby the lightning-eliminating tower. So the possibilities of lightning strike against the ground can be decrease enormously. SLE's protecting scope is much larger than that of lighting rod of the same height, and it is approved by on-the-spot test records that ground field intensity tends to decrease as the corona current increases.

The outcomes of SLE protecting scope test performed in laboratory show that, when SLE protecting range r is 5 times of tower height h, i.e., the protecting angle is 79°, the by-pass strike rate is 0.7%, and when r is 4 times of h, i.e., the protecting angle is 76°, by-pass strike rate is 0. In practical operation, the protecting angle is 83°~85°. So the ground protecting range can be 5 times of tower height, or 80° of protecting angle in practical use. When SLE is employed to protect important facilities, such as oil depots and arsenals, the ground protecting range and protecting angle can be reduced reasonably so as to intensify its safety. When combined protecting-angle with two lightning eliminating towers is adopted, the outer protecting edge can be considered respectively according to each tower, and protecting width of the two towers is determined by the space between them. When the space between two lightning towers is 10 h, the ground protecting range can be determine in accordance with the illustration in Fig. 11.

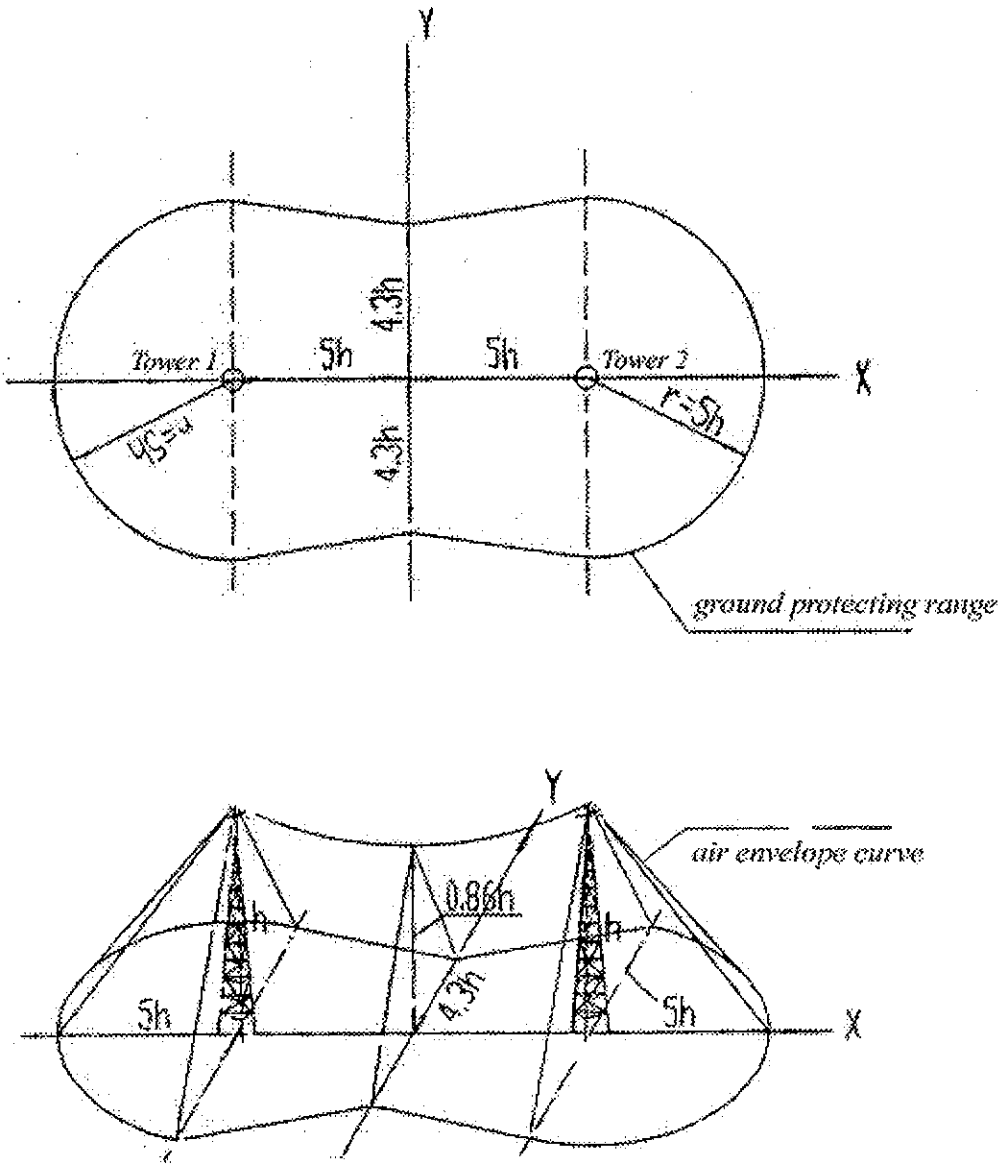


Fig.11 Protecting Range When the Space

Between Two Lightning Eliminating Towers of the Same Height Is 10 h

5. SLE's grounding system

In order to avoid the harms caused by lightning, sufficient grounding system must be arranged in lightning protection design so as to lead lightning current into ground. Because of the existence of grounding resistance, when massive current flows through the grounding device, the voltage drop on grounding resistance caused by the current will lead to increase of grounding potential. So, equipment might be damaged by the over-voltage reverse strike. It also forms large potential differences on the ground, which might cause life casualties when human body is subject to large transit step voltage. Therefore, the grounding resistance must be limited. China's concerning regulations require that grounding resistance of lightning protection should not exceed 10 Ω.

SLE can massively decrease the main discharging current, so that it enormously lowers voltage drop on grounding resistance. Its requirements on grounding resistance are not so

strict. The shock grounding resistance of the grounding device should comply with the requirements of place, and it can be reasonably larger but should not exceed 30 Ω. The calculation of grounding device power frequency grounding resistance should comply with the stipulations of GBJ65-83 and its conversion with shock grounding resistance should comply with the stipulations of GB50057-94.

6. Precautions

1. Since the first generation of conductor lightning eliminators were invented in 1977, the products have been under promotion continuously both in structure and quality. Beijing Arrow Advanced Technology Co., Ltd. recently pushed its sixth generation of SLV (SLV-VI) into markets. One of its outstanding characteristics is: it can withstand 150 kA strong current, 50% higher than the value of 100 kA stipulated in the national standards.

2. SLE can decrease direct strike lightning and reduce induced lightning so as to enormously reduce lightning secondary effects. Besides, it can also lower the occurrence probability of ball lightning (Up to now, people have not yet found out the generating principles of ball lightning. in some special cases, ball lightning can appear when it is fine).

3. SLE can only weaken direct strike lightning and its secondary effects. It can not protect against the direct lightning led in by power supply lines, communication lines, signal wires, or induced lightning over-voltage, nor can it eliminate ball lightning. So, do not neglect the other lightning protecting measures stipulated in the concerning regulations after adoption of SLE.

4. In order to prevent lightning over-voltage coming along overhead lines from distance, the low voltage distribution system networks should be equipped with distribution system over-voltage protector (DSOP) besides lighting protectors installed at both high voltage and low voltage sides of the transformer. DSOP can effectively suppress the transit over-voltage occurring in the power networks and absorb the energy of transit over-voltage. The combined application of SLE and DSOP can improve the reliability of lightning protection to a large extent.

5. The voltage withstanding ability of micro–electronic equipment is just about 10 V. It is suggested that the users should adopt reliable shielding measures besides SLE and DSOP so as to avoid electromagnetic inductance caused by lightning 300~1,000 m away.

6. In order to increase integrated lightning protection effects, measures must be taken to guard against electromagnetic inductance over-voltage of signal lines. DC surge absorbing device, and audio line, data line and antenna feeding wire protectors should be installed in accordance with the conditions of different wires.

Instructions to Design and Model Selection of SLE

Foreword: With wide application of high-tech lightning protecting series products of SLE-V, the design and model selection of the products in various engineering becomes more and more

important. The concerned instructions are provided here for users' reference.

I. General:

1. All the protected buildings, facilities and equipment must be completely located in SLE protecting range. It generally requires to build a small iron frame structure when SLE is installed on a building. The frame structure's top is coordinately connected with SLE base.

   ① For the protected objects like buildings, microwave communication towers, broadcast TV towers, SLE protecting range is calculated according to h : r = 1 : 5 (h: the difference between SLE installation height and the protected object height, r: SLE protecting radius. It is the same in the following paragraphs)

   ② For inflammable and explosive locales, such as oil depots, chemical works, row cotton warehouses, the protecting range is calculated according to h : r = 1 : 3.5 .

   ③ For the protected objects like arsenals, the protecting range is calculated according to h : r =1 : 1.5

   ④ The highest point of other objects installed on SLE iron frame structure should be at least 1.5 m lower than the SLE base.

2. SLE usually makes use of the frame structure itself and the main reinforcing bar as its lead-down wire. When SLE is installed on the top of a building, SLE frame structure should be connected with building's main reinforcing bars or parapet wall lightning protection bars at two places at least. The connecting cross-section area should not be smaller than 48 m^2 and the connecting wires should be flat steel bars or 8 mm-diameter round steel bars.

3. In ordinary buildings, SLE can make use of the main reinforcing bars as its lead-down wire and it is not necessary to lay independent lead wire. If it requires independent lead-down wire, the requirements on the lead-down wire are the same as that mentioned above.

4. All lead-down wires' corrosion-proof requirements should comply with the state's stipulations.

5. The protected object grounding resistance should be lower than 10 Ω. In high soil resistance regions, the shock grounding resistance can be reasonably higher, but can not exceed 30 Ω.

II. SLE model selection for different protected objects

1. Buildings

No.	Building	Height	SLE Selection Model		
			Building Class 1	Building Class 2	Building Class 3
①	Multi-story building	h<30m	SLE-V-13	SLE-V-9	SLE-V-5
②	Mid-high building	30m≤h≤50m	SLE-V-19	SLE-V-13	SLE-V-9
③	High building	0m≤h<80m	SLE-V-19	SLE-V-13	SLE-V-9
④	Very high building	80m≤h<200m	(T)SLV-V-25	SLE-V-19	
⑤	Ultra high building	h≥200m	(T)SLE-V-25	SLE-V-19	

2. Broadcast TV and microwave communication towers

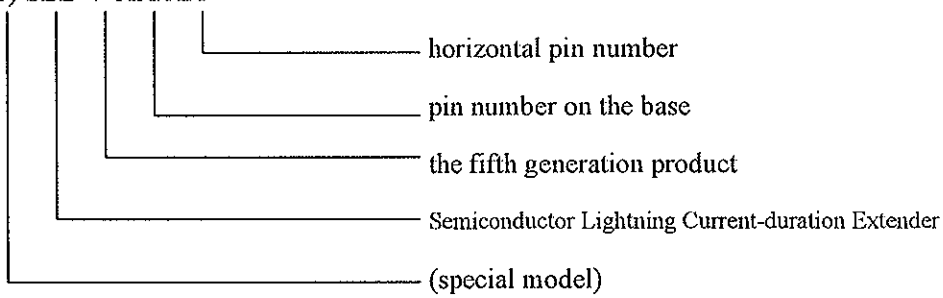
No.	Tower Height	SLE Selection Model		
		Strong lightning region	Frequent lightning region	Rare lightning region
①	h<30m	SLE-V-19	SLE-V-13	SLE-V-9
②	30m≤h<60m	SLE-V-19	SLE-V-19	SLE-V-13
③	60m≤h<80m	SLE-V-19/8	SLE-V-19/8	SLE-V-13/8
④	80m≤h<100m	SLV-V-19/16	SLE-V-19/16	SLE-V-13/16
⑤	100m≤h<150m	SLE-V-19/24		SLE-V-13/24
⑥	* h≥150m	(T) SLE-V-25		SLE-V-13/19

* The installation number of horizontal pins on ultra high towers should be specially designed according to the specific situations.

3. Power lines

No.	Voltage level	SLE Selection Model		
		Strong lightning region	Frequent lightning region	Rare lightning region
①	10, 35 kV lines	SLE-V-5	SLE-V-3	SLE-V-2
②	110, 220 kV lines	SLE-V-8	SLE-V-7	SLE-V-5
③	330, 500 kV lines	SLE-V-8	SLE-V-7	SLE-V-7

Note: ① (T) SLE-V-XX/XX



② For an independent tower higher than 60 m, a layer of horizontal pins should be installed at the place of 30-50 m high.

③ For 80-100 m high towers, two layers of horizontal pins should be installed respectively at the places of about 45m and 65 m high with 20-30 m space between the two layers of pins.

④ Towers higher than 100 m require three or more than three layers of horizontal pins, and the space between each layers is the same as above-mentioned.

⑤ Models of SLEs with more than 13 pins should be selected for protection of inflammable and explosive locales such as oil depots, chemical works, arsenals and row cotton warehouses.

⑥ In accordance with the concerning stipulations of the state:

Rare lightning region: the annual averaged lightning days don't exceed 15 days

Frequent lightning region: the annual averaged lightning days range between 15-30 days

Strong lightning region: the annual averaged lightning days exceed 30 day.

III. SLE protecting region calculation

1. The protecting range of a single SLE should be calculated with the following methods (See Fig.12)

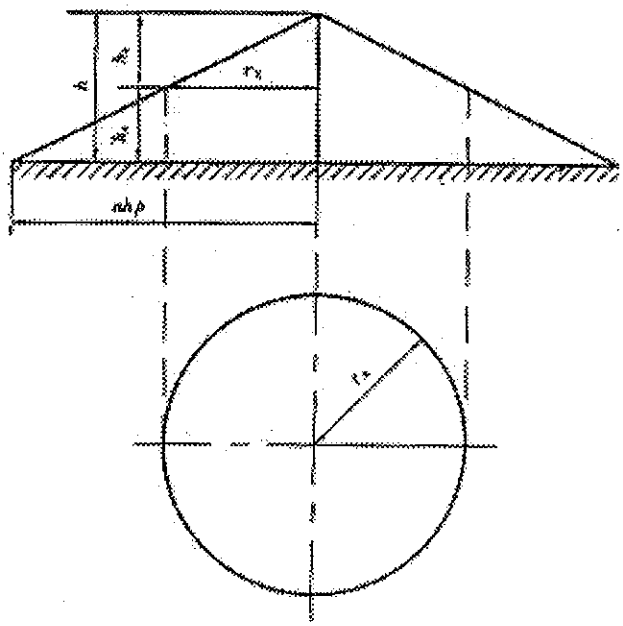


Fig. 12 Protecting Range of a single SLE

The protecting radius r_x on the horizontal plane at the protected object height of h is determine with the following formula:

$$r_x = n (h - h_x) p = n h_a p \quad \text{.....(12)}$$

where:

h-----height of SLE, m

r_x ----SLE protecting radius on the plane of h_x , m

h_x ----height of the protected object, m

h_a ---- effective height of SLE, m

n----- for inflammables and explosives, n=3.5 (by-pass strike probability is below 0.1%), for other facilities, n=5 (by-pass strike probability is 1%)

p----- height effecting coefficient: when h≤64m, p=1, and when 64m≤h<140m, p=8/$\sqrt{h}$

2. The protecting range of two SLEs of the same height should be determined as follows (See Fig. 13)

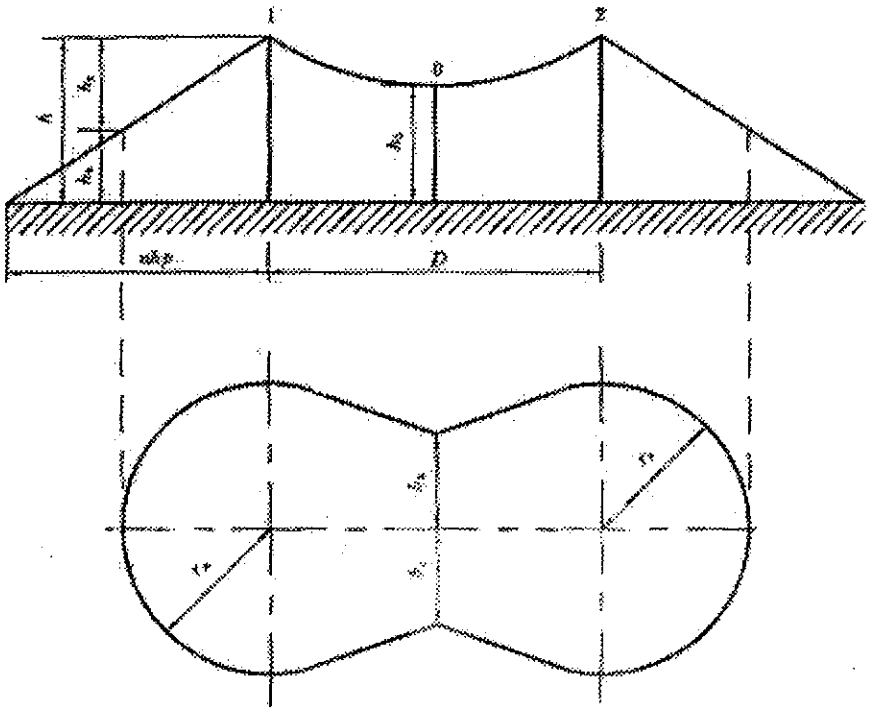


Fig. 13 Protecting Range of Two SLEs of the Same Height

13.① The outer protecting range of two SLEs should be determined in accordance the calculation methods of a singe SLE.

13.② The upper edge of two SLEs' protecting scope is determined with the arc passing the apexes of the two SLEs and point O on the center line. Point O is a fictitious lightning eliminator's apex, and its height should be calculated with the following formula:

$$h_0 = h - n_1 D / p \quad D<10\ h \qquad \text{.....(13)}$$

where:

h_0-----the height of the lowest point of two SLEs protecting scope upper edge

D-----distance between two SLEs

n_1-----for inflammables and explosives, n_1=0.02, and for other facilities, n_1=0.014

The protecting range on h_x plane between two SLEs is calculated with the formula as follows:

$$b_x = n\ (h_0 - h_x) P \qquad \text{.....(14)}$$

Upon having obtained b_x , draw tangent lines from this point to the two protecting circles at both sides so as to determine two SLEs' protecting range on h_x plane.

14. The protecting scope of multiple SLEs of the same height is determined with the following methods

14 ① The outer protecting range of the triangle formed with three SLES of the same height should be calculated respectively with the same methods of two ALEs of the same height. On the

plane of the protected object's height h_2 within the triangle, if b_x not smaller than 0, i.e., $b_x \geq 0$, the protected object is completely under protection (See 14).

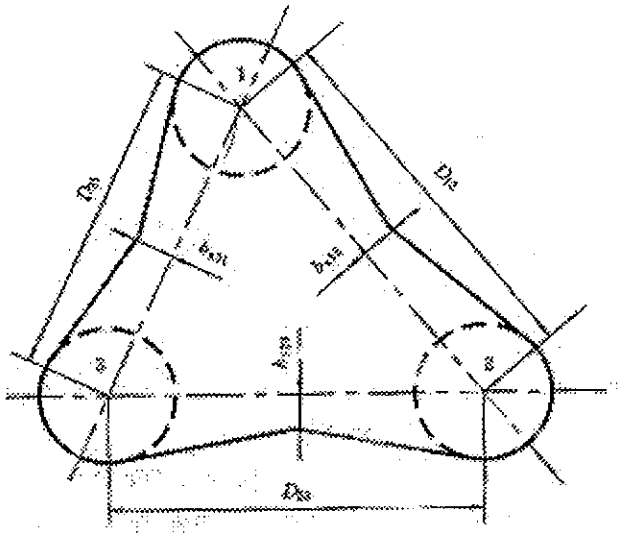


Fig. 14 The protecting Scope of Three SLEs of the Same Height

14. ② When determining the protecting scope of quadrilateral or polygon formed up with four or above four SLEs of the same height, it can be divided into two or more triangles, then calculate with the same method for three SLEs of the same height. If all b_x bigger than 0, i.e., $b \geq 0$, then on the plane of the protected object height h_x, all the areas within the polygon are under protection.

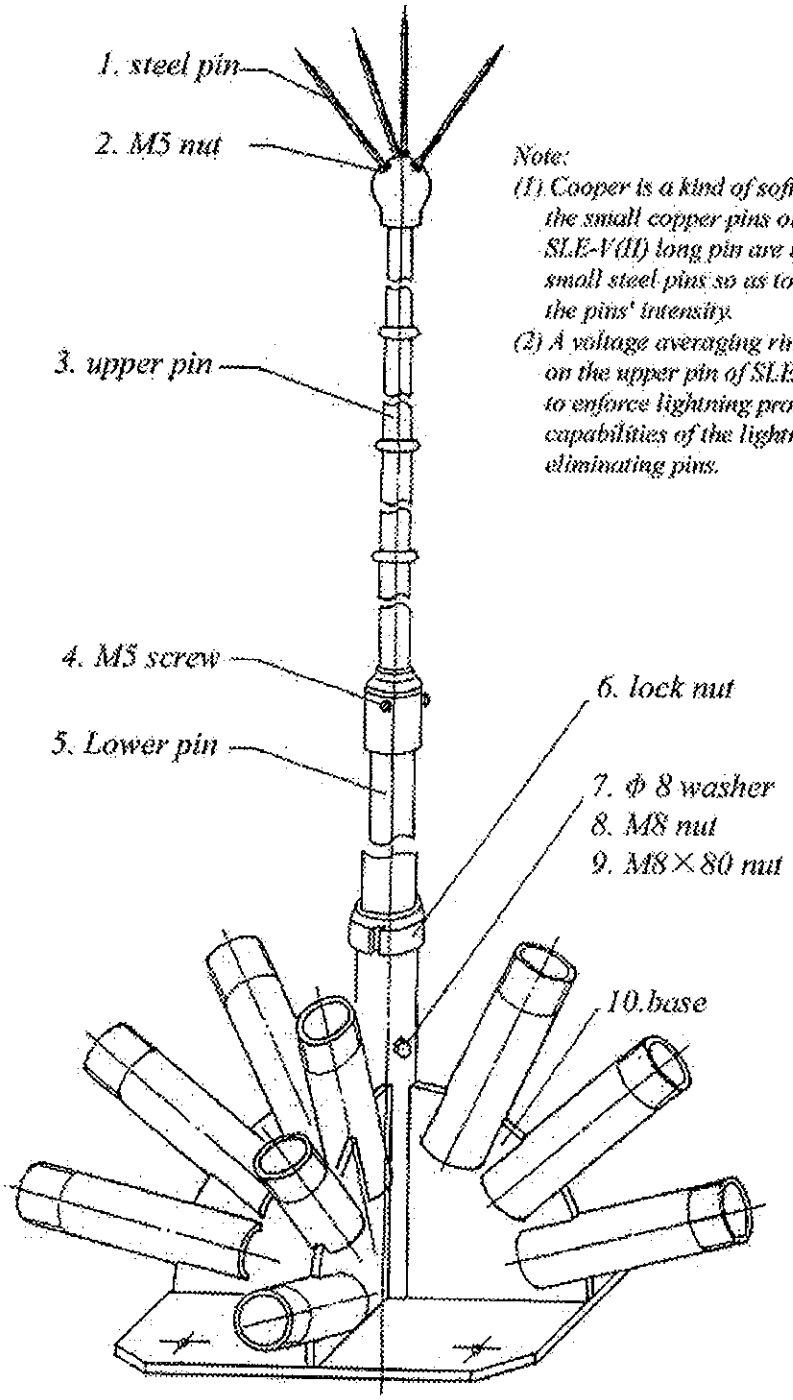
14. ③ The protecting scope of SLEs of different heights should be calculated with the following methods:

14.3.1The outer protecting scope of two SLEs of different heights should be determined respectively with the methods of a single SLE.

14.3.2 For the protecting scope between two SLEs of different heights, determine the higher SLE's protecting scope with the calculating methods of a single SLE, then draw a horizontal line from the apex of the lower SLE and the line intersects with the protecting range of the higher SLE. Take the intersecting point as the apex of equivalent SLE, then determine the protecting ranges of both the lower SLE and the equivalent SLE with the calculating methods for two SLEs of the same height.

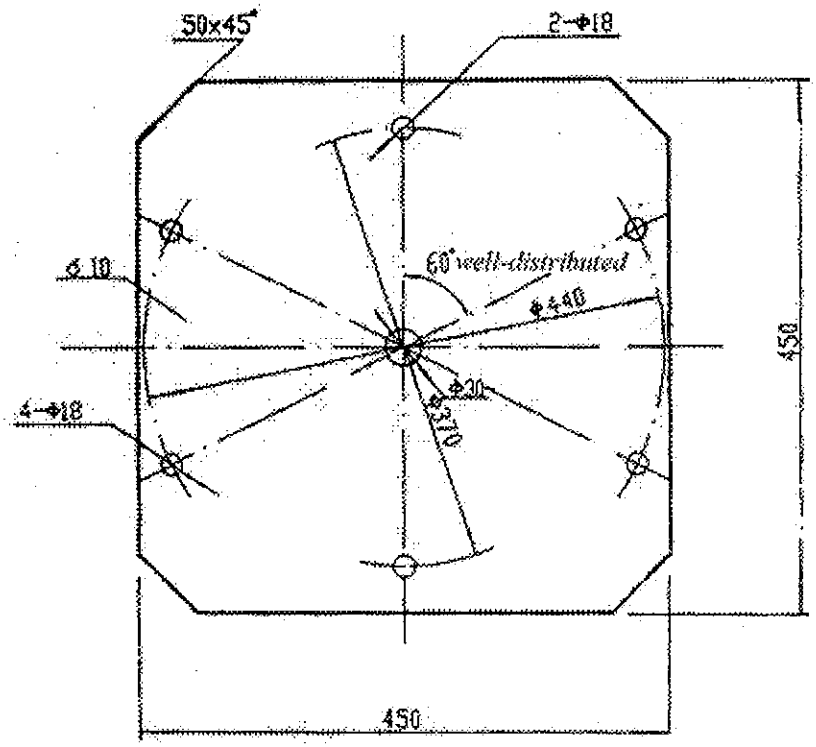
14.3.3 For multiple SLEs, the outer protecting range of each two adjacent SLEs can be determined with the calculating methods for two SLEs of different height. On the plane of the protected object's maximum height h_x within the polygon, if the minimum width at the side of the protecting range between each two adjacent SLEs $b_x \geq 0$, then all the areas are under protection.

An Illustration of SLE

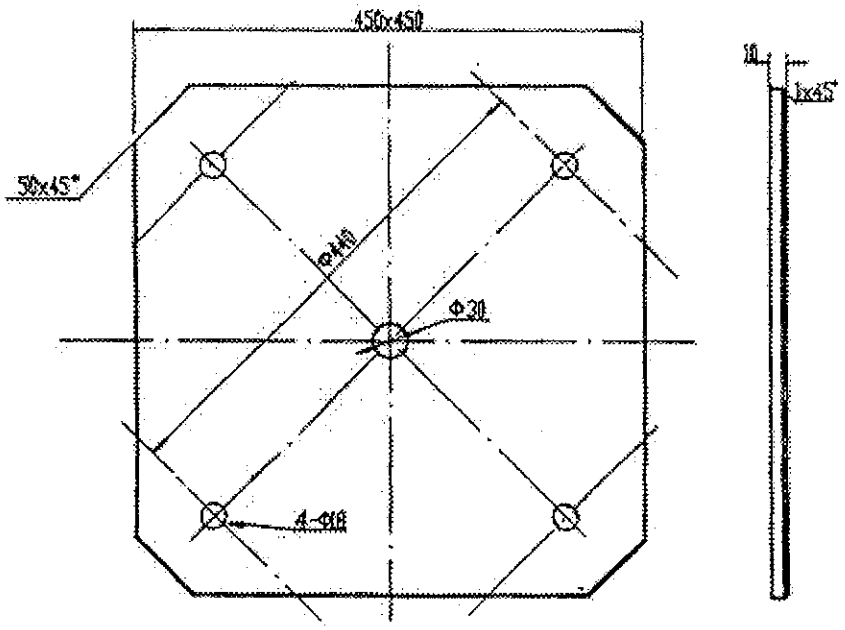


Note:
(1) Cooper is a kind of soft metal, so the small copper pins on the top of SLE-V(II) long pin are replaced with small steel pins so as to reinforce the pins' intensity.
(2) A voltage averaging ring is added on the upper pin of SLE-V(II) so as to enforce lightning protection capabilities of the lightning eliminating pins.

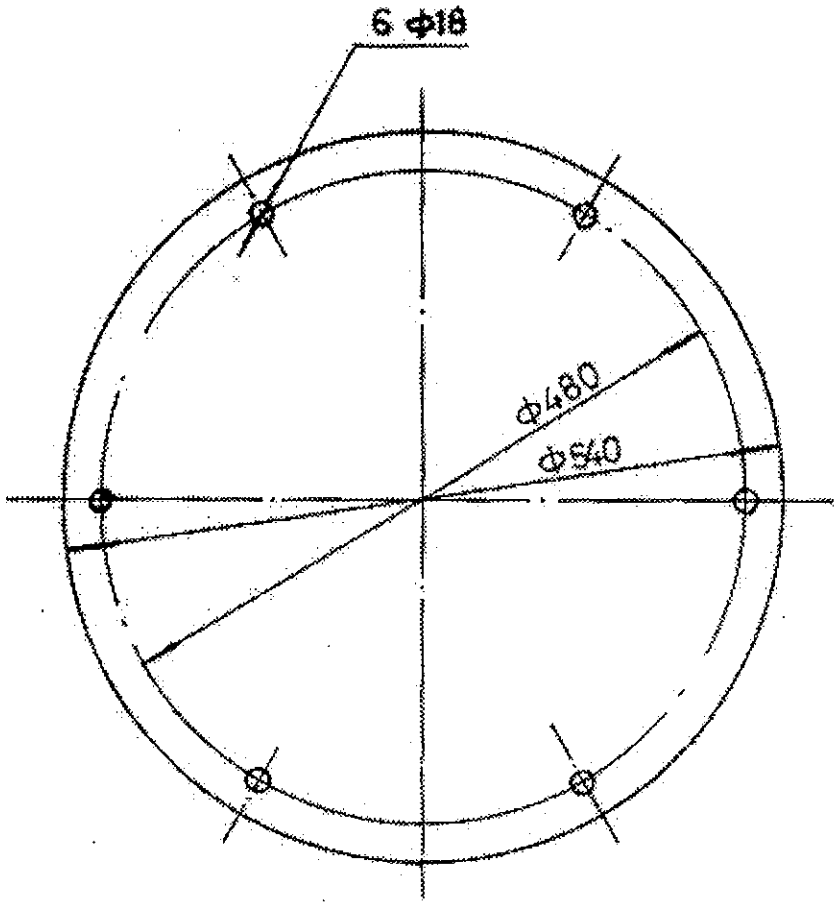
Base Plate Illustration



SLV-V-19 (19 pins) Base Plate Illustration Material 14:d=10

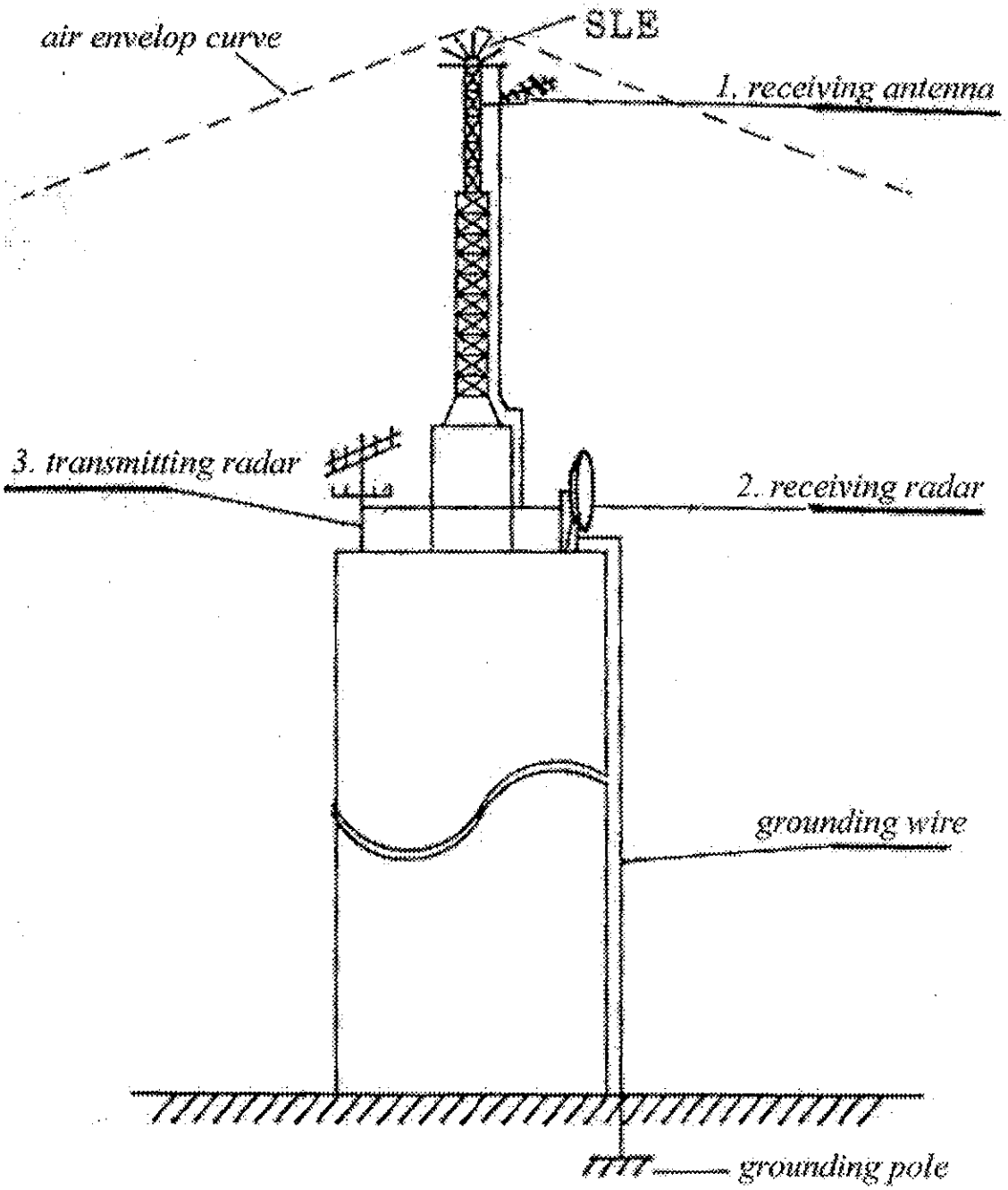


SLV-V-9.13 (9 pins, 13 pins) Base Plate Illustration Material 14:d=10
Note: Make reference to this illustration when designing SLE base.



SLE-V-25 (25 pins) Base Plate Illustration Material 14:δ=10

SLE Installation Illustration



Note:

① The dotted lines indicate protecting range

② The apex of the protected object's outer edge must be located in the protecting range

③ The distance between the apex of the protected object and SLE base must be ≥1.5 m