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ASSESSMENT TO EFFECTIVENESS OF THE NEW EARLY STREAMER EMISSION LIGHTNING PROTECTION SYSTEM

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Abstract- A novel early streamer emission (ESE) lightning air terminal system is designed and fabricated. By comparing the intercepted artificial lightning striking numbers of the new ESE lightning protection device and the conventional lightning rod (CLR) lightning protection device in laboratory, the effectiveness of intercepting the artificial lightning strokes by the new ESE lightning protection device is superior to that by the conventional lightning rod lightning protection device. A modified Tesla Coil (TC) discharging by powering AC voltage up to 650 kV with the controlled triggering function generator is used to produce simulated lightning strokes. The top tips of both devices in the same horizontal plane are placed at the same distance to the modified TC during all the test processes. Exchanging their positions makes no obvious difference between the recorded results. The test data validate the effectiveness of the new ESE lightning protection device under the laboratory environment.

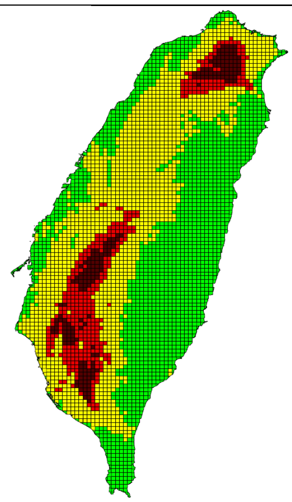
Index terms*:* Early streamer emission, electric field, zone of protection.

I. INTRODUCTION

Lightning strike in nature appears suddenly and may not be predictable in advance. It is a kind of physical phenomenon classified to impulsively electrostatic discharging caused by an electric storm. Lightning strokes to the earth ground could cause devastating consequences owing to high temperature and gigantic current of electricity all in a short time. They can result into severe injuries, including thermal burns from Coulomb heating to tissues or matters by the gigantic current in rather brief time, and dielectric breakdowns of nerves and muscles so as to change electro-permeabilization [1] under high voltage drop. Worth noticing, the mortality rate may be between 10% and 30%, and with up to 80% of survivors sustaining long-term injuries.[2] Besides killing human or animals by lightning striking, properties like buildings, equipments, buildings systems, electronics and vehicles could be also seriously damaged in extensive way.[3-8]

Table 1: Statistic data of lightning striking map in Taiwan from year 2003 to year 2010 [10]

Legend	Averaged annual GFD (#/km^2)		# of grids
Extreme	5.2 ~ 15.8	(4.90%)	203
Severe	3.2 ~ 5.20	(9.40%)	395
Mild	0.9 ~ 3.2	(38.9%)	1626
Light	0.0 ~ 0.9	(46.8%)	1980
			Total: 4204



During summer seasons in Taiwan, lots of local afternoon thunderstorms and a number of typhoons emerging from the Pacific Ocean torture this island each year. News that people get killed and properties suffer great losses by lightning strokes sounds familiar.[9-10] The unpredictable and fatal lightning strokes are more regular as the trend of global warming and lightning striking events will increase due to climate change. According to the official statistics from the report of Taiwan Power Company in 2014 [11], the lightning strokes took place more than 258,104 times recorded by the Total Lightning Detection System (TLDS) in Taiwan between year 2003 and year 2010. The statistic data are summarized in Table 1. The averaged annual ground flash density (GFD) map is classified by the nature breaks classification method. Each grid area is 9 km^2. The impressive striking number indicates the need of devices with effective protection under lightning strokes in Taiwan, not only for lives of people but also the properties of natives.

(a)

(b)

Figure 1. Examples of lightning rods made of copper, aluminum and their alloys deteriorated in the ambient: (a) rusty part surfaces by long term chemical/electrical corrosions and (b) structural deformation caused by typhoons due to insufficient material strengths

Under such devastating threats of lightning striking, the installation of lightning protection systems on constructions or objects has been becoming necessary. Lightning rods were the most used in the early days. Ironically, the first lightning rod invented by Benjamin Franklin in 1749 was not for lightning protection.[12] The conventional lightning rod (CLR), as a pointed lightning rod conductor also called lightning attractor or Franklin rod, was part of Franklin's groundbreaking exploration of electricity. Although not the first to suggest a correlation between electricity and lightning, Franklin was the first to propose a workable system for testing his hypothesis about electricity. The principle of the lightning rod was first detailed by Franklin in 1749.[13] In the subsequent years, his invention developed for household application was published in 1753 and further improvements became towards a reliable system around 1760. The lightning rod, which is a single component in a lightning protection system, requires a connection to earth as an effective dissipation sink of electricity power to perform its protective function. Commercial lightning rods appear in many different forms, including pointed, rounded, flat strips, hollow, solid or even bristle brush-like. The main attribute common to all lightning rods is that they are all made of conductive materials, such as copper and aluminum. Copper, aluminum and their alloys, the most common materials used in lightning protection, can be deteriorated by chemical and electrical corrosions in the ambient, as shown in Figure 1 (a). And, they may also suffer the insufficient problem of structural stiffness against gusty winds and typhoons, as illustrated in Figure 1 (b), owing to their inferior material strengths. Additionally, in order to reduce the burden of overheating to the wire connecting the lightning rod and the ground rod in earth due to huge surging current and high voltage drop, lightning arresters [14] may be served as part of a lightning protection system, in combination with air terminals and bonding, frequently used on electrical power systems and telecommunications systems to protect the insulation and conductors of the systems from the damaging effects of lightning. They limit the voltage increase, protecting the transmitter from dangerously high voltages, and are critically placed on a structure and connected to a lightning conductor and earthing system to safely receive a lightning stroke, safely conduct the lightning current to the earthing system and safely dissipate it in the earth. The typical lightning arrester has a high-voltage terminal and a ground terminal. A lightning arrester may be a spark gap or may have a high temperature block made of semiconducting material(s) such as silicon carbide or zinc oxide. When a lightning surge (or switching surge, which is very similar) travels along the power line to the arrester, the current from the surge is diverted through the arrester, in most cases to earth. Lightning arresters are rated by the peak current they can withstand, the amount of energy they can absorb, and the breakover voltage that they require to begin conduction.

Although Franklin rod is simple and inexpensive, the effective cross section to intercept lightning strokes is limited by less magnitude of electric field(s) on each tip for charge emission. In this study, we adopt the technique of early streamer emission lightning protection device [15], which can raise electric field(s) on each tip for charge emission. ESE lightning protection system is a proactive interception type of lightning strokes at early stages to reduce the probability of directly damaging other parts under protection except the base of ESE lightning protection system as lightning striking. ESE lightning protection device utilizes advanced streamer generating design elements to provide lightning protection to facilities that would otherwise be difficult or cost prohibitive to protect by conventional means. It is proactive and can be mounted externally on structure(s) or object(s) and designed to activate itself in the moments directly preceding an eminent direct stroke. These ESE lightning protection devices may be connected to a network of horizontal and vertical conductors that are terminated to the grounded lightning protection devices. The network of ESE lightning protection devices, conductors and earth terminals forms a Faraday cage to protect structure(s) or object(s) in a Faraday cage.

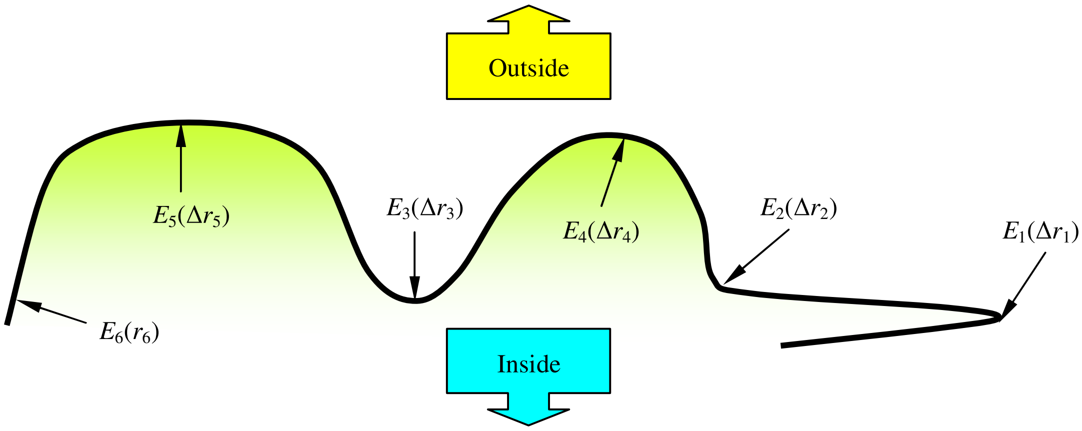
In this article, in order to effectively arrest possible injuries by lightning strokes [16], we have designed and built a new type ESE lightning protection device. Tests have been conducted for comparing its effectiveness to intercepting lightning strokes with a traditional Franklin rod and the results will be discussed.

II. DESIGN PRINCIPLE

An ESE lightning protection device can manipulate emission of electric charges q_i (i = 1, 2, 3, ..., n) stationary in space at $\vec{r}_i$ in the absence of currents inside structure or object under protection into the ambient. Those electric charges form the electric field(s) based on the Coulomb's law, which is expressed as

$$\vec{E}(\vec{r}) = \frac{1}{4\pi\varepsilon_0}\sum_{i=1}^{n}\frac{q_i}{(\vec{r}-\vec{r}_i)^2}\hat{u}_{\Delta\vec{r}} , \quad (1)$$

where ε_0 denotes the permittivity of vacuum, $\vec{r}$ indicates the position in space, and $\hat{u}_{\Delta\vec{r}}$ represents unit vector of the distance $\Delta\vec{r}$ (= $\vec{r} - \vec{r}_i$). Figure 2 illustrates the radial dependence of electric field on the surface. Thus, we may facilitate the surface geometry to raise the electric field so as to increase electric charge emission for lightning protection devices.



$$\Delta r_1 < \Delta r_2 < \Delta r_3 < \Delta r_4 < \Delta r_5 < \Delta r_6$$

$$E_1(\Delta r_1) > E_2(\Delta r_2) > E_3(\Delta r_3) > E_4(\Delta r_4) > E_5(\Delta r_5) > E_6(\Delta r_6)$$

Figure 2. Radial dependence of electric field on the surface

Therefore, for a spherical object of radius R, $\Delta\vec{r}$ at the surface equals R, and its surface electric field is relative to the reciprocal of R^2 in accordance with the equation (1). With respect to a cylindrical object of infinite length and radius R, its radial surface electric field is inversely proportional to R. Since the superposition principle suits electric fields due to the linearity of Maxwell's equations, we may stack several electric fields up in series so as to further raise the strength of electric field on the top tip of ESE lightning protection device. Figure 3 demonstrates how to elevate the electric field of the top tip of ESE lightning protection device by manipulation of structural geometry. Away from the grounding is the higher place, the greater becomes the electric field. Besides, biased potential(s) (V_{bias} can be artificially set to be positive or negative opposite to clouds' electric field detected in advance by the grounded side tips) may be added to the grounding as shown in Figure 3 and the ESE lightning protection device to kick up the electric field of the top tip of ESE lightning protection device directly.

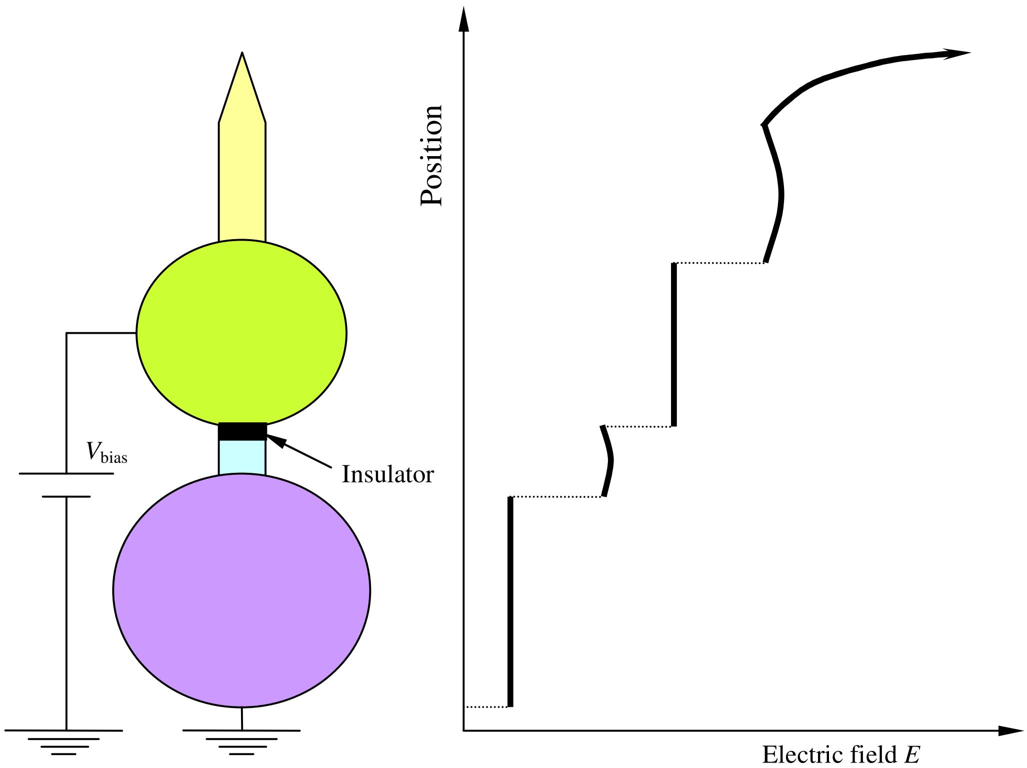
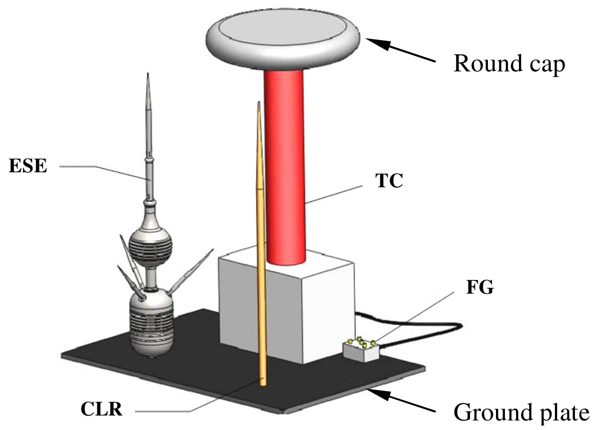


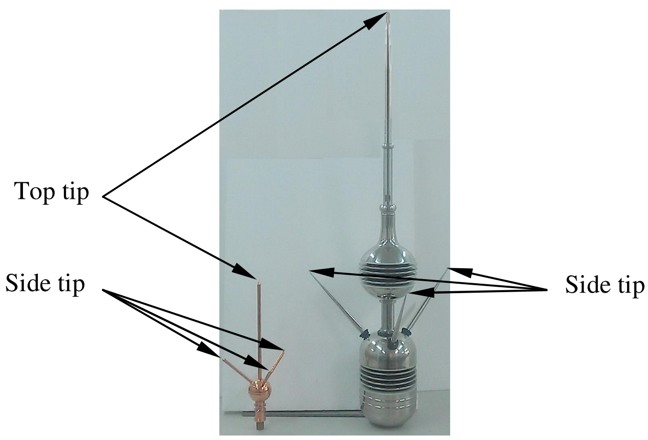
Figure 3. Schematic plot for elevation of electric field by manipulation of structural geometry

III. EXPERIMENTAL

A new ESE lightning protection device was designed and carried out. To reduce body corrosion during long term operation and enhance the overall strength for bearing gusty storm winds, the conducting parts of the ESE lightning protection device were made of stainless steels SUS304. The height of the assembled new ESE lightning protection device was 170 cm and its overall weight less than 25 kilograms. The configuration of our testing system is presented in Figure 4. A homemade Tesla coil discharging by powering AC voltage up to 650 kV was used to simulate lightning strokes. The TC was put on a metallic ground plate. Both the tested new ESE lightning protection device and Franklin rod were fixed on the same plane and keep good contact with the plane. As shown in Figure 5, a pointed aluminum rod replacing the round cap on the top of TC in Figure 4 (a) was put on the top of TC in order to accurately control discharge strokes from the same position during all the tests.[17-18] The relative positions in the test platform including a new ESE lightning protection device, the brass-made Franklin rod, as denoted by conventional lightning rod (CLR), and the modified TC are shown in Figure 4. The tip shape of the pointed aluminum rod was kept conformity with the French standard of NFC-17-102 [19] for lightning protection. The spark length made by the modified TC was no more than 40 cm. The two lightning protection devices were kept with the same height and were 0.5 m apart horizontally. The central lightning source above each lightning protection device kept the same distance of 0.3 m to each lightning protection device. Such arrangement of relative position was to make the two devices within the striking distance of the lightning and prevents the influence from static electric field of the ground plane.



(a)



(b)

Figure 4. The testing system for comparing protection effectiveness: (a) schematic drawing of the test platform, and (b) photograph of the new ESE lightning protection device and the CLR

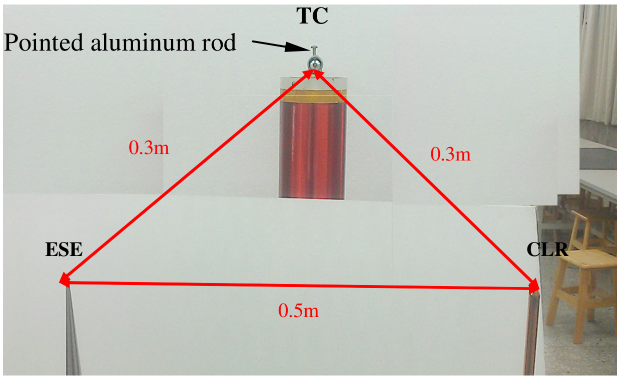
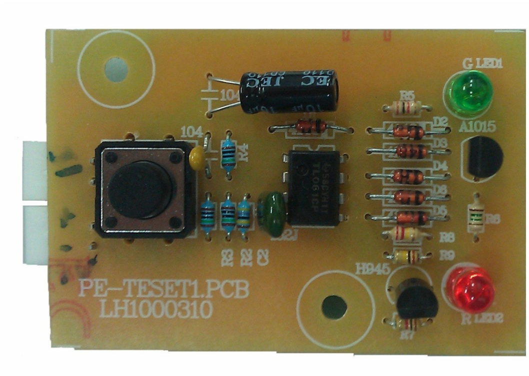
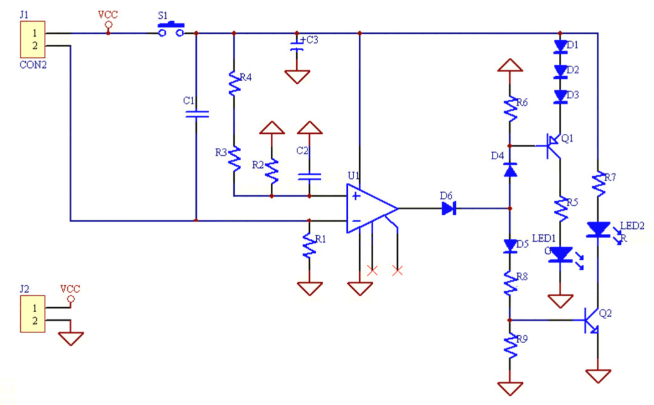


Figure 5. The relative positions of the new ESE lightning protection device, the CLR and the modified TC



(a)



(b)

Figure 6. The homemade counting system: (a) the circuit board and (b) the circuit diagram

Two counters for counting arrested strokes of the two devices were connected to the separated ground lines of the two devices. The controlled discharging of the TC simulated lightning strokes was triggered by the function generator (FG) with periodic pulses of voltage serial signals. In each test configuration, a total of 50 lightning strokes from the TC triggered by the function generator was recorded. The period between continuous triggering signals was assigned from one second to five seconds. Each intercepted impulse stroke on the test platform was recorded by a homemade counting system including an AC current sensor, an amplifier and an electromagnetic counter, as presented in Figure 6.[20]

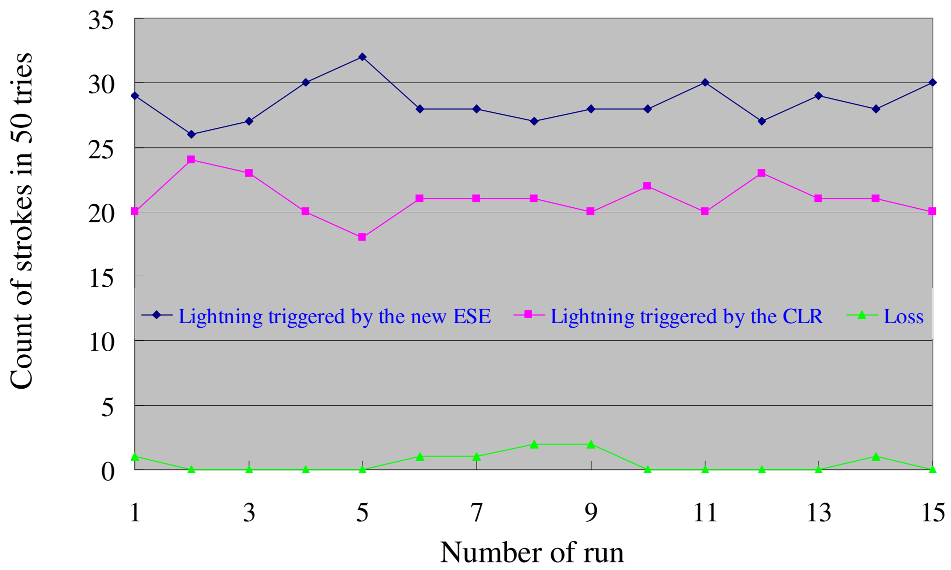


Figure 7. The test result of lightning strokes only intercepted by the top tips of the new ESE lightning protection device and the CLR (50 tries in total were delivered from the modified TC for each run.)

IV. RESULTS AND DISCUSSION

Figure 7 demonstrates the result of 15 test runs comparing the lightning strokes intercepted by only the top tips of both the lightning protection devices without any side tips. Each test run contained 50 tries in total. Some strokes reaching none of the lightning protection devices were noted as the count of loss. Based on the result, the averaged ratio of the number caught by the new ESE lightning protection device to the number caught by the CLR is 1.36 (= 28.47:21) for all 15 runs. The new ESE lightning protection device shows 36% better than the CLR regarding the probability to intercept the strokes on all tests. The averaged ratio of intercepting the strokes vs. 50 tries on all tests is 56.9% for the new ESE lightning protection device and 42% for the CLR. The count of loss to intercept the strokes on all tests is averaged as 0.53, which is 1.9% for the new ESE lightning protection device and 2.4% for the CLR. The triggering time period from one to five seconds shows no apparent difference for the counts of lightning strokes and losses on all the tests. After switching the places of the two lightning protection devices with each other, no obvious difference could be observed.

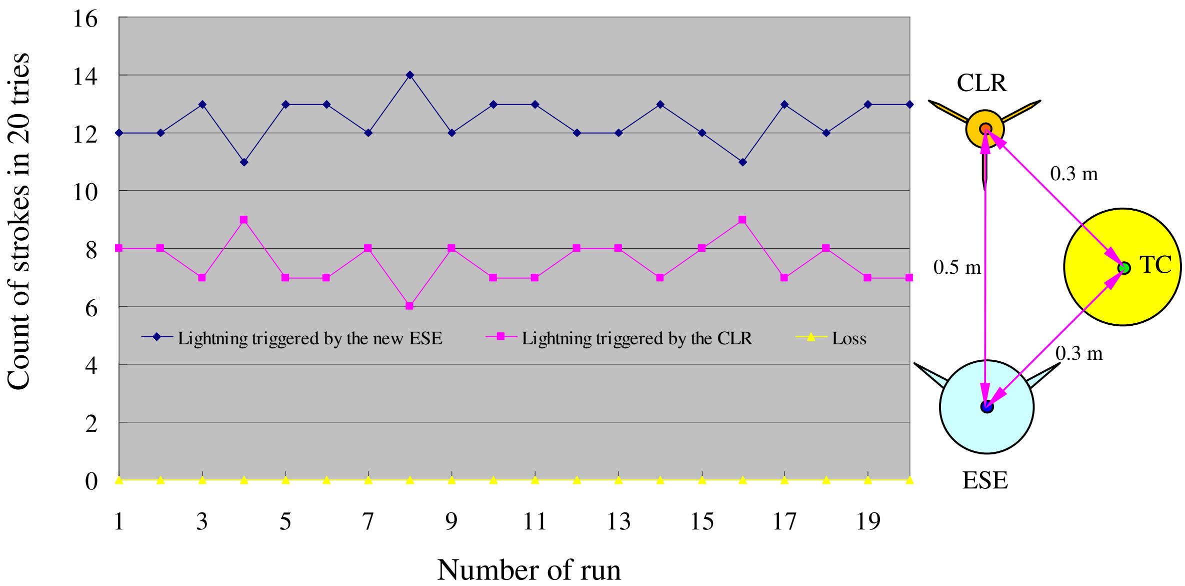


Figure 8. The test result of lightning strokes intercepted by the first type setup of top tips and side tips of the new ESE lightning protection device and the CLR (20 tries in total were delivered from the modified TC for each run.)

Figure 8 shows the result of 20 test runs comparing the lightning strokes intercepted by the first type setup of top tips and side tips of the new ESE lightning protection device and the CLR. Each test run contained 20 tries in total. No strokes reaching none of the lightning protection devices were recorded. Based on the result, the averaged ratio of the number caught by the new ESE lightning protection device to the number caught by the CLR is 1.65 (= 12.45:7.55) for all 20 runs. The new ESE lightning protection device shows 65% better than the CLR regarding the probability to intercept the strokes on all tests. The averaged ratio of intercepting the strokes vs. 20 tries on all tests is 62.2% for the new ESE lightning protection device and 37.8% for the CLR. The side tips improve 5.3% for the averaged ratio of intercepting the strokes vs. 20 tries on all tests to the new ESE lightning protection device and draw down 4.2% to the CLR, with respect to the data in Figure 7. Though the averaged ratio of the number caught by the new ESE lightning protection device to the number caught by the CLR in Figure 8 is better than that in Figure 7, the small difference about the averaged ratio of intercepting the lightning strokes vs. 20 tries on all the tests between the data in Figure 7 and Figure 8 shows that the first type setup of top tips casts the slight influence on the test result.

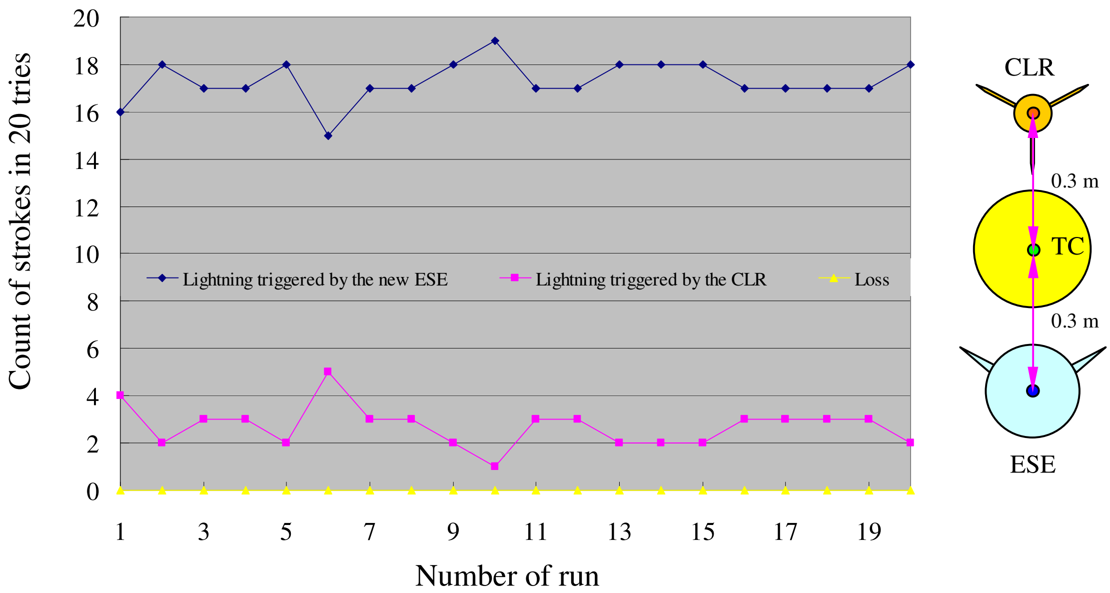


Figure 9. The test result of lightning strokes intercepted by the second type setup of top tips and side tips of the new ESE lightning protection device and the CLR (20 tries in total were delivered from the modified TC for each run.)

Figure 9 illustrates the result of 20 test runs comparing the lightning strokes intercepted by the second type setup of top tips and side tips of the new ESE lightning protection device and the CLR. Each test run contained 20 tries in total. No strokes reaching none of the lightning protection devices were recorded. Based on the result, the averaged ratio of the number caught by the new ESE lightning protection device to the number caught by the CLR is 6.41 (= 17.3:2.7) in average for all 20 runs. The new ESE lightning protection device shows 541% better than the

CLR regarding the probability to intercept the lightning strokes on all the tests. The averaged ratio of intercepting the strokes vs. 20 tries on all tests is 86.5% for the new ESE lightning protection device and 13.5% for the CLR. The side tips improve 29.6% for the averaged ratio of intercepting the strokes vs. 20 tries on all tests to the new ESE lightning protection device and draw down 28.5% to the CLR, with respect to the data in Figure 7. Since the averaged ratio of the number caught by the new ESE lightning protection device to the number caught by the CLR and the averaged ratio of intercepting the strokes vs. 20 tries on all tests between the data in Figure 7 and Figure 9 demonstrate the significant differences, the second type setup of top tips shows the great influence upon the test result. In other words, the interception to lightning strokes by the side tips of the CLR can be easily decreased by the surrounding condition, while that by the new ESE lightning protection device is only slightly influenced by the surrounding condition.

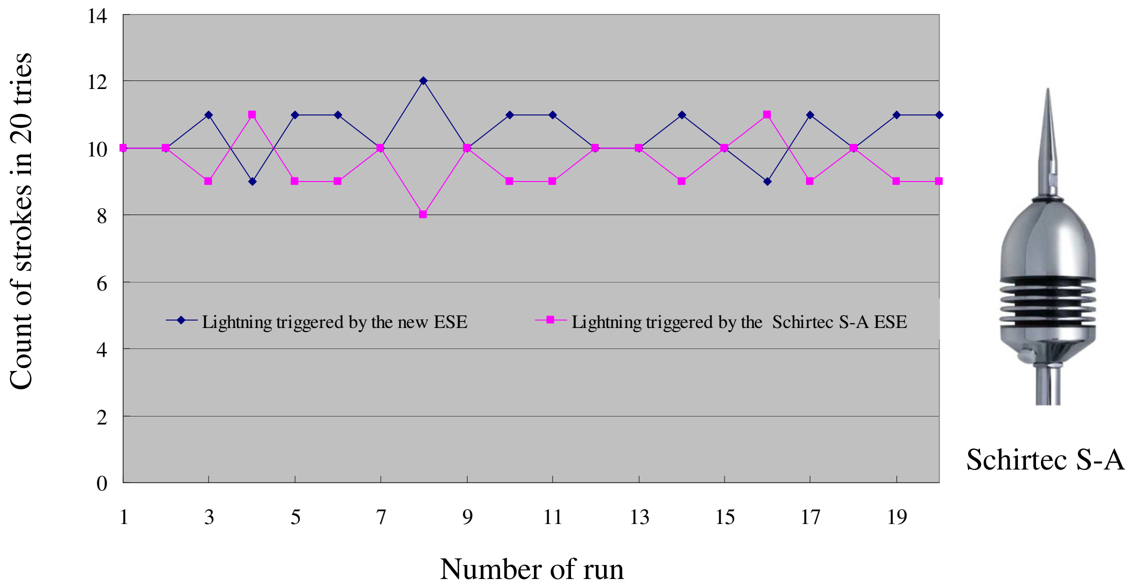


Figure 10. The test result of lightning strokes intercepted by the top tips of the new ESE lightning protection device and the commercial Schirtec S-A ESE lightning protection device (20 tries in total were delivered from the modified TC for each run.)

Besides, in order to realize the geometric effect of main body for interception of lightning strokes, we made the comparison of the new ESE lightning protection device and the commercial Schirtec S-A ESE lightning protection device. Figure 10 presents the result of 20 test runs comparing the lightning strokes intercepted by the top tips of the new ESE lightning protection device and the commercial Schirtec S-A ESE lightning protection device. Each test run contained 20 tries in total. No strokes reaching none of the lightning protection devices were recorded. Based on the result, the averaged ratio of the number caught by the new ESE lightning protection device to the number caught by the commercial Schirtec S-A ESE lightning protection device is 1.094 (= 10.45:9.55) in average for all 20 runs. The new ESE lightning protection device shows 9.4% better than the commercial Schirtec S-A ESE lightning protection device about the probability to intercept the lightning strokes on all the tests. The averaged ratio of intercepting the strokes vs. 20 tries on all tests is 52.3% for the new ESE lightning protection device and 47.8% for the commercial Schirtec S-A ESE lightning protection device. The averaged percentage of intercepting the lighting strokes to the commercial Schirtec S-A ESE lightning protection device is still greater than the CLR, after multiplying a weighting factor 0.918 to the percentage of the data in Figure 7.That is, the interception percentages to lightning strokes by the new ESE lightning protection device and the commercial Schirtec S-A ESE lightning protection device are better than that of the CLR.

Finally, since raising the electric field of the new ESE lightning protection device can upwardly lift the equipotential lines of the same magnitudes in the electric field, intercepting downward lightning strokes, its outwardly expanded "zone of protection" [21] may increase the probability of interception to lightning strokes. Hence, both the new ESE lightning protection device and commercial Schirtec S-A ESE lightning protection device are able to provide better protection of interception to lightning strokes than that of the CLR. That is, the "zone of protection" of the new ESE lightning protection device as well as the commercial Schirtec S-A ESE lightning protection device is superior to the CLR.

V. CONCLUSION

In this work is presented assessing the effectiveness to intercept lightning strokes by comparing the new ESE lightning protection device and the CLR. The new ESE lightning protection device is designed and fabricated in our laboratory for evaluating its effectiveness to lightning protection with the conventional lightning rod. The simulated lightning strokes on the lightning devices are produced from the modified Tesla coil with electrical resonant transformer circuit invented by Nikola Tesla.[22] The configuration setup of the side tips of the conventional lightning rod relative to the surrounding can significantly lower the probability of interception to lightning strokes. The result of recorded lightning strokes numbers intercepted by both the devices proves the superiority of the new ESE lightning protection device over the conventional lightning rod protection device.

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