Collection versus Prevention:
Lightning Protection Technology Explained

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Summary

Though lightning rods are the oldest form of lightning protection and still used today, in the past few decades advancements in technology have provided more options. Two major types include the Early Streamer Emitter (ESE), similar in approach to the lightning rod, and the Charge Transfer System (CTS), which takes a completely opposite approach to lightning protection: collection versus prevention. A type of CTS, the Dissipation Array® System (DAS®), works to prevent a lightning strike in a specific area designated for protection.

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Introduction

When it comes to lightning protection, a common misconception is that the different types of solutions available are variations on the same technology. This is not necessarily the case—though the process may rely on the same natural phenomena, the result is entirely different. Although the lightning rod is the most commonly known form of lightning protection, there have been a great number of technological advances since the days of Benjamin Franklin.

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In addition to the antiquated technology of the lightning rod, two newer technologies are the Charge Transfer System (CTS) and the Early Streamer Emitter (ESE) air terminal. In reality, although both of these products are used for lightning protection, contrary to the public's understanding, they are very different. An ESE is a similar technology to the lightning rod, while CTS is an entirely different type of technology. The only similarity is that all three initially operate off of the same scientific principal or phenomenon, known as "Point Discharge." However, their actions diverge; the rod and ESE move toward streamer generation whereas the CTS utilizes a slow discharge process. Understanding the differences between these technologies is important. For example, it might not be ideal to collect lightning in areas that are highly volatile or indispensable, but instead to prevent it from striking altogether in these areas that are most important to protect. While lightning rods and ESE collect lightning, CTS prevents it from terminating in the area of protection.

What you will learn:

- How lightning is formed and its potential negative effects
- The history of lightning protection, starting with the lightning rod
- The types of modern lightning protection technologies, including ESE and CTS
- The key difference between these technologies and why it is important
- The basic physics behind Charge Transfer Technology

The Formation and Effects of Cloud to Ground Lightning

To better understand these different products and their approaches to lightning protection, it is first important to have an understanding of how lightning forms. During a storm, naturally occurring electric fields gain strength in the atmosphere. As the storm builds, paths of ionized air, known as stepped leaders, form and head toward the earth in a sort of stepped pattern. The electric field between the leader and ground intensifies as the leader descends, causing oppositely charged ions from the ground (or from buildings or trees, etc.) to group together, forming multiple "streamer"/"counter-leader" paths that head up toward the sky. When the leader connects with a streamer, a lightning strike forms. This natural phenomenon is unpredictable, and there is no way of knowing which leader-streamer connection will form.

Lightning strikes more often than many people realize. According to the National Weather Service, lightning strikes worldwide about 100 times per second.[1] Many of these strikes are harmless, but others can cause catastrophic damage. For example, in Kansas City in 2008, a storage tank holding 1.2 million gallons of gasoline caught fire after being struck by lightning, resulting in a $12 million loss. A similar incident in 2012 in East Malaysia resulted in a $40 million loss.

The strike is only part of the problem. The secondary surges that radiate outward from the ionic channel can also cause damage. When these surges pass over conductive elements such as electrical

[1] NOAA. (n.d.). Thunderstorms and Severe Weather Spotting. National Weather Service Eastern Region Headquarters. Available at http://www.erh.noaa.gov/lwx/swep/Spotting.html.

wires or metallic pipes, the result may not be fire and explosions, but it can lead to the destruction of electric appliances and motors as well as more delicate electronics. Though private home insurance claims for lightning strikes are down, the total paid out by the insurance industry has gone up—largely because of the sensitivity of common electronics to these surges. Ubiquitous electronics such as video game consoles and smart phones have led to an estimated additional $1 billion in insurance losses.

However, the effect of direct lightning strikes on industries such as oil and gas is at an incomparable scale to these individual losses. Potential damage comes not only from direct sources such as the loss of product and tanks as in the Kansas City and Malaysia examples (through destruction and fire), but also from downtime. For example, an ExxonMobil facility in Singapore lost nearly a day of work each week before installing lightning protection, due to crewmembers being forced to safety zones when the region's lightning alarm activated. In the Dominican Republic, lightning strikes caused a mine to lose the equivalent of 40 hours per worker per month. Other incidences include loss-time-events for offshore oil rigs and power generation stations where sensitive electronic systems were damaged. Downtime ranged from hours to months with loss of revenue ranging from a few thousand to millions of dollars.

A cost-benefit analysis taking into account these risks is what often leads industry decision-makers to implement some method of lightning protection. However, lightning protection itself has been around for a long time, which you will learn about in the next section.

The History of the Lightning Rod and Early Lightning Protection

The basic form of lightning protection that many people are familiar with is the lightning rod. When Benjamin Franklin first experimented with electric charges in the 1700s using a kite, a key, and some string, he originally proposed that lightning rods could reduce or eliminate lightning by relieving the imbalance between clouds and the ground.[2] However, he later realized that if the conductive metal rod was *struck* by lightning, then it worked to safely conduct lightning to the ground. In other words, the initial confusion was an issue of prevention versus collection. It turns out that Benjamin Franklin was correct, and prevention is indeed an option for lightning protection—but the technology would not be available for another 200 years.

Lightning rods do not prevent lightning, but instead essentially "collect" it. They serve as a preferred strike point in that they are an efficient streamer generator. Thus they collect strikes and convey the energy to the ground rather than to the building or structure that it is protecting. Lightning rods have been used for more than 200 years, mounted to the tops of buildings and electrically bonded to the ground, able to reroute lightning strikes away from important structures as a preferred strike point. They have served a good purpose, and over the years have protected many structures from the physical effects of a direct lightning strike, such as fire.

However, particularly in the past 40 years, new technologies have developed to protect against lightning—including one that takes the prevention approach that Franklin originally envisioned.

[2] Krider, E.P. (2006). Benjamin Franklin and Lightning Rods. *Physics Today*.

Modern Lightning Protection Technologies

Early Streamer Emitter (ESE)

More similar to the conventional lightning rod, ESE systems are lightning collectors. However, according to their manufacturers, they are designed to trigger the early initiation of upward streamers, which increases the efficiency of lightning collection as a way to extend the effective range of protection far beyond that of lightning rods. ESE air terminals can typically be distinguished from ordinary lightning rods due to the presence of a small object near the top, a discharge trigger, and they also can be more geometrically complex. This discharge trigger increases the probability for initiating a "streamer" discharge at or near the tip of the rod when an ionized "leader" approaches. Increasing the probability of streamers and leaders meeting is how ESE systems serve as improved lightning collectors. According to the National Institute of Standards and Technology, it is difficult to judge ESE performance: "It is nearly impossible to make quantitatively meaningful statements on the relative performance of ESE devices and conventional Franklin rods. In fact, sufficient reliable quantitative data on the performance of conventional rods seem not to exist."[3]

Charge Transfer System (CTS)

Unlike lightning "collectors," CTS is specifically designed to *prevent* a lightning strike from terminating where it is not wanted—in a designated area of protection. This is the only system in which lightning strikes are actively discouraged, rather than encouraged. CTS technology is based on existing physics and mathematical principles. As noted by IEEE engineer Donald Zipse: "Proof of lightning rods' effectiveness lies mainly in empirical and anecdotal evidence. CTS technology, however, is based on existing electrical and physical formulas and mathematical basics."[4]

In order to prevent lightning from striking within a specified zone, a CTS collects the induced charge from thunderstorm clouds within this area and transfers it through an ionizer into the surrounding air, thus reducing the electric field strength in the protected zone. The resulting reduced electrical potential difference between the site and the cloud suppresses the formation of an upward streamer. With no leader-streamer connection, the strike is prevented.

In a commentary written by Dr. Al Gasiewski, professor at the University of Colorado, he states, "Such technology is based on the hypothesis that production of positive space charge in the region around the CTS reduces near-surface electric field strength to levels below which streamer formation is likely. With no streamers emanating from the structure of concern the leader is more likely to connect to streamers originating from either unprotected adjacent structures (both man-made and natural) or from any air terminals installed on these unprotected structures. The principle is consistent with Gauss' electric field

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[3] The authors of the quoted article are representatives of the National Institute of Standards and Technology, and it is based on a comprehensive bibliography of ESE lightning protection prepared at the request of the National Fire Protection Research Foundation. Van Brunt, R.J., Nelson, T.L., & Stricklett, K.L. (2000). Early Streamer Emission Lightning Protection Systems: An Overview. *IEEE Electrical Insulation Magazine 16*, 1.

[4] Zipse, D.W. (2001). Prevent Lightning Strikes with Charge Transfer Systems. *Electrical Construction & Maintenance Magazine*. Available at http://ecmweb.com/power-quality-archive/prevent-lightning-strikes-charge-transfer-systems.

divergence law, which states (in one dimension) that the vertical growth of the electric flux density is proportional to the space charge density. If this space charge density is positive near the surface (which is the typical case during a negatively-charged leader approach) then the electric field increases to its peak strength near the leader tip from a surface value near the protected equipment that is lower than if the space charge were not present. As a result of this lower near-surface field strength, there is less likelihood of streamer formation near the protected equipment, and hence less likelihood of leader-streamer connection. The principal of operation rests on the CTS being able to rapidly emit ample space charge during the time of leader approach. Accordingly, the CTS design attempts to maximize space charge emission, but without generating streamers of its own."

Dissipation Array System (DAS)

DAS is a specific type of CTS, invented and produced by Lightning Eliminators & Consultants, Inc. (LEC), engineered for optimum performance. Although available in varying shapes and sizes, the DAS system typically consists of a hemisphere of a large radius with an array of many thin metal splines with sharpened tips distributed evenly over the hemisphere's surface. Such DAS is usually installed on the top of the structure or structures to be protected.

Using a CTS "zone of protection," a DAS is able to completely isolate facilities from a direct lightning strike by bleeding off the induced charge in the protected area during the course of a thunderstorm, reducing it to a much lower level in relationship to the surrounding environment. When the naturally occurring electric field in a protected area is reduced, the upward streamers are suppressed and do not get enough energy from a storm to connect with downward leaders—thus, no lightning. This in turn eliminates the secondary effects of the lightning event and helps to mitigate the immediate loss of electronics and reduction in the mean-time-before-failure of all electronics. The proper application of Surge Protection Devices also prevents secondary effects to electronics caused by remote lightning strikes. This requires a thorough analysis of the configuration of the local electrical and electronic systems.

A CTS must be engineered to meet both operational and mechanical criteria. The proper design of a DAS for protection of a given area or structure is based on several factors. The major considerations include severe thunderstorm parameters, the configuration of the structure, local environmental conditions, structure construction methods, vulnerability of electrical and electronic systems, and the physical strength of the structure. All of these are taken into account in determining the best method to protect the structure.

A certain number of ionizing points are required to prevent direct strikes to the structure or area to be protected. Once the number of points is determined, these points are distributed as evenly as is practical across the area to be protected. Since taller structures are more prone to collecting a strike, the primary location for points to be distributed is on the tallest structures. Anything within the area of these taller structures will be protected since they are in the zone of protection of the DAS. The remaining points are distributed on any elevated structures in the area.

In one study that LEC conducted at a customer site, electric fields inside the protected area during thunderstorms were, on average, 55% weaker than those in the surrounding area. Tri-State Engineering, which installed DAS in the 1990s, has had its system checked and re-certified by LEC on schedule. They have never had another direct lightning strike in the protected area since installing a DAS.

Another revealing study can be seen in the Browns Ferry Nuclear Power Plant (BFN). In 1998 a DAS was installed on the off-gas stack, replacing a traditional LPS. Prior to DAS installation, lightning was repeatedly collected by the LPS on the off-gas stack and equipment on the stack and around its base was routinely damaged. A number of safety and financial issues ensued. As part of an internal review process, BFN consulted a database of lightning activity to determine the number and location of lightning strikes around the off-gas stack in the three years before and after DAS implementation. They compared the number and location of lightning strikes around the off-gas stack for these periods. The weighted data for strikes showed that although lightning frequency increased a nearly uniform 65% in 3, 6 and 10-mile radii around the stack, in the 3 years *after* DAS implementation there was an 80% reduction in lightning strikes within 500-meters of the off-gas stack. The result has been no lightning strikes to the off-gas stack since installation.

Historical Strike Data for BFN: Top Row is 3 Years Prior; Bottom Row is 3 Years Post DAS

Due to government regulations and requirements, as well as the nature of the nuclear materials, byproduct and sensitive electronics housed at the facility, Browns Ferry served as an excellent test case for this lightning protection technology. Since the science and methodology for protecting any type of facility is the same, it serves as a perfect example to all industries.

More recently, researchers presented an analysis of the physics behind charge transfer technology and DAS (called Lightning Protection Array System or LPAS in the paper) at the 2013 Asia-Pacific Conference on Lightning Protection (APL).[5] The following conclusions come from this paper:

1. The prevention of the lightning strikes to the object to be protected is possible by suppression of the initiation and/or propagation of the upward counter leader.
2. Two conditions must be met for the preventing a counter leader from initiation:
    a. the corona current must be less than critical value required for the suppressing the initiation of the streamers
    b. the voltage drop on the first meter of a streamer length must be below 400 kV
3. To suppress the counter leader propagation through the corona space charge cloud the voltage drop on the first meter of length of a streamer from the counter leader channel must be below 400 kV.
4. The design of the Lightning Protection Array System (LPAS) complies with the requirements to the strike prevention performance of the system.

The paper, titled "Preventing Lightning Strikes to the Protected Objects," is included as an addendum for the reader to review.

Differences in Lightning Protection Technologies

Conventional lightning rods and ESE have one major aspect in common: they collect lightning. ESE terminals arguably differ in effectiveness—an ESE terminal is equipped with a device that increases the probability that an initiated upward streamer will connect with a downward leader. Increasing this probability means that lightning is more likely to strike the terminal rather than unwanted areas.

However, CTS offers an entirely different approach than either of those technologies: the key difference is one of collecting versus preventing lightning strikes. The approach is essentially the complete opposite. Rather than *encouraging* the attraction between streamer and leader, a CTS *discourages* it, thus preventing the formation of lightning strikes in the protected area as opposed to collecting them.

This fundamental difference can be key for industries such as oil and gas, midstream storage tank farms, and energy producers of all types. These facilities often have many flammables and other sensitive materials where using a collector carries the risk of ignition or damage to electronic systems. As Zipse points out, "Is it wise to allow thousands of amperes to flow near sensitive electronics equipment, especially when charge transfer systems are available and can prevent strikes in protected areas?"[4] However, this is also true for any operation that would have little tolerance for downtime. A single strike of lightning, or even a secondary surge, could restart the "Days since the last downtime event" clock. By utilizing prevention rather than collection, CTS is the best option for facilities where a single spark could be catastrophic. LEC's Dissipation Array System (DAS) is the only commercially available solution for creating this zone of protection that guards against a lightning strike.

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[5] Drabkin, M.M, Endo, Y., Ong, L.M, & Mui, A.C.Y. (2013). Preventing Lightning Strikes to the Protected Objects. Asia-Pacific International Conference on Lightning. Seoul, Korea. Note
Note: Hitachi Critical Facilities Protection Pte. Ltd is a partner of Lightning Eliminators & Consultants, Inc.

Addendum

Preventing Lightning Strikes to the Protected Objects

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***Abstract*— This paper discusses in general the principles of performance of the Lightning Protection Array System (LPAS) preventing direct lightning strokes to the protected objects. The program of the intensive testing of the LPAS in natural conditions has been developed. The paper describes the testing field and devices to be used for recording the major parameters of the system performance such as the distribution of the electric field, currents through the system in different stages of the lightning activity, etc. The comparison between performance of the LPAS and the lightning rod will be also recorded.**

INTRODUCTION

Direct lightning strikes to the unprotected objects cause annually losses accounted in billions of dollars, deaf and/or injuries to people, forest fires, damage/destruction of the equipment and devices, malfunction of the computers, etc. Protection against direct lightning strikes is offered by the appropriate international and national lightning protection standards, codes and recommendations. The major means of the protection are the lightning rod installed on the top of the object to be protected or stand alone and overhead shield wire for power transmission and distribution lines.

Protection against direct lightning strikes by the lightning rod is quite reliable, simple, passive (does not requires any power supplies), inexpensive, and does not require any maintenance. In case of the lightning strike to the rod the heavy current of the lightning discharge flows through the lightning rod, grounding wire and grounding instead of the alternative path through the object protected by the lightning rod.

For many tens of years such a performance of lightning protection was quite satisfactory until latest fifty – sixty years with the fast progress in developing and implementation of the sensitive electronic equipment, computers, etc. The heavy returned lightning current in a stroke to the lightning rod produces a powerful electromagnetic wave, which induces in the nearby electrical/electronic circuits the dangerous voltages by far exceeding the safety level. The shielding, filtering and surge protection of the devices, which might be affected, were offered to mitigate this undesirable effect of the performance of the lightning rod. Still another measure to minimize the secondary effect of the lighting strike as well as to deal directly with the process of the lightning discharge itself was offered about forty years ago by introducing to the engineering practice the lightning protection array system (LPAS), which prevents lightning strokes into the protected object and itself instead of collecting the strikes.

I. THE PERFORMANCE BASICS OF THE LPAS

The lightning strikes preventing ability of the LPAS can be described as follows. In a typical case the lightning discharge starts from a downward lightning channel formed casually near the bottom of a thunderstorm cloud. This downward lightning leader lowers a part of a thundercloud cell charge, which is distributed along the channel. On the initial stage of its propagation it is impossible to predict the possible path of the downward lightning leader to the ground with so many steps and random changing the direction. The downward leader is “blind”, it does not “see” any objects on the ground as long as no counter leaders initiated from the objects on the ground. A downward leader has to come to the object as close enough as to initiate an upward counter lightning channel. Only then the interaction between the downward lightning leader and the object with the upward counter leader will start. The counter leader will propagates toward the downwards lightning leader and will get in touch with it, which will be a lightning stroke. So, formally lightning strikes not the object itself but the counter leader channel initiated from that object.

The lightning strike prevention ability of the LPAS based on the forcible prevention of the initiation and propagation of the upward counter lightning channel through the cloud of the local space charge injected to the air gap by the LPAS [1-6]. No the upward counter leader from the object (practically from the LPAS installed on the top of the protected object), no strike into the object.

In order to design such a system, which will be able successfully suppressing the initiation and/or propagation of the upward lightning channel through the cloud of the local space charge, the characteristics of corona and its influence on the process of the lightning discharge must be clearly understood. The characteristics of the corona in the air gap between a grounded electrode and a thundercloud cell (non-stationary corona) is quite different from the characteristics of the stationary corona. The stationary regime of corona in the air gap between the earth and the thundercloud cell is

practically never achieved. The current of the non-stationary corona is determined not only by the instant value of the voltage across the gap, as in the case of the stationary corona, but also by the steepness of the voltage rise in the time as well. The electric field and amount of the space charge produced by corona are changing in time. The radius of the front of the space charge is also is changing in time because the charge is moving toward the thundercloud cell. As a result the current of the non-stationary corona may exceed many times the current of the stationary corona.

The process of the initiation of the upward lightning leader starts from the igniting the corona from the object subjected to the electric field of the thunderstorm cloud strong enough to initiate the corona current. The space charge produced by the corona current starts to move toward a thundercloud cell filling the air around the LPAS with ions of the sign opposite to the sign of the charge in the thundercloud cell. Typically it is positive ions with the negative main charge in the bottom of the thundercloud cell. The ion drift velocity in any given point is governed by the total electric field, which is the sum of the external electric field of the thundercloud cell, electric field originated by the charges induced in the LPAC and by space charge in the air gap.

The space charge distributed around the LPAS has a stabilizing effect on the electric field on the top of the LPAS. The electric field cannot go below the value E_c required to support the ionization, but it cannot also raise significantly above E_c because it will cause the acceleration of the emitting the ions from the electrode, increasing their density around the electrode until the electric field will return to the value of E_c. That means that the electric field at the top of the LPAS is self-regulating and maintained around the critical value, E_c supporting the ionization, delaying the transition of the glow streamer-free corona (ultra-corona) to the next form, corona with streamers. The value of E_c depends on the radius of the electrode and defined very well by the Peek formula. For example, for electrodes with radii 10 cm, 1 cm, and 0.1 cm E_c will be equal to 32, 43, and 75 kV/cm correspondently.

In order to initiate an upward counter leader from the LPAS a relatively week ultra-corona must go to the next stage – a corona with streamers. The specific of this new stage of the corona is the fast development of the streamer branches – thin ionized channels, started from the common place (stem) near the electrode. Each one individual streamer is cold and is not able to cause the initiation of a plasma channel (leader). It loses its conductivity very fast (in a fraction of 1 us), but in the conducting stage the streamer succeeds to contribute its current to the total current collected by the stem. The stem collects the total current of all the individual streamer strings and peak out the most of energy able at certain conditions to heat the air near the electrode to the temperature of several thousand degrees. That leads to the initiation of the counter leader channel.

While losing the conductivity the streamers leave their charges in shape of slow moving ions around the tip of the splines of the LPAS. They form the space-charge cover around the tips reducing the field on the surface of the LPAS and suppress the ability of the LPAS to extend the ionization zone.

The streamer-free (glow) corona can exist as long as the corona current will not exceed some value leading to the start of the streamers. When the corona current exceeds this value determined by the following formal condition $(dE/dt)_{r=r0} > 0$ the ionization zone will detach itself from the surface of the electrode and move inside the air gap to the point of the maximum electric field. The corona streamers will be developed at these conditions. Observations show that the bunches of streamers long of 1m or more are required for initiating at certain conditions the upward lightning channel. The electric field near the electrode must exceed the corona threshold E_c. It is achieved when the voltage maintaining the corona rises steeply and to the sufficiently high magnitude. Slowly drifting ions have no time at this condition to remove space charge from the ionization zone near the electrode.

Figure 1 shows the calculated distribution of electric field above a hemisphere of a radius of 1 m with a multitude of the splines in the absence of a downward leader as a function of the hemisphere position above ground level. The thundercloud electric field rises linearly up to 300 V/cm for 10 s.

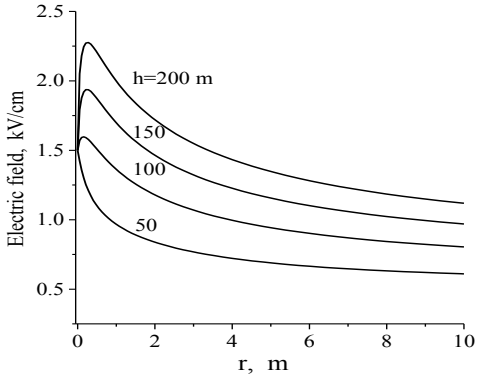

Figure 1. distribution of electric field above the LPAS of a radius of 1 m as a function of its position above ground level. The curves correspond to t = 10 s. The thundercloud electric field rises linearly up to 300 V/cm for 10 s.

The presented curves demonstrate the major advantage of the multi-point electrodes - the stabilization of electric field over the hemisphere surface at a level of around 1 kV/cm. As a result, an ionizing wave is not formed near the electrode surface when the region of high electric field is detached from the electrode and removed into the gap. Figure 1 shows that under considered conditions the maximum electric field is much less than the critical field corresponding to the ionization threshold; the maximum field is 2.3 kV/cm, an order of magnitude less than the critical field in air under standard conditions, even at the height h = 200 m for the hemisphere location. Of course, in this case, a streamer flash to be followed by the formation of an upward leader cannot be initiated.

Until corona current will not reach its critical value there will be no streamer flashes and as the consequence of that the counter leader will not start. It had been derived analytically

that streamers flashes will start when corona current exceeds value determined by the following expression:

$$i_c \geq 8\pi\varepsilon_0 \mu r_0 E_c^2 \qquad (1)$$

where μ is the ion mobility, and r_0 is the radius of the electrode.

For the conventional lightning rod with radius of the tip r_0 in range of 1 – 10 cm and typical ion mobility μ = 1.5 $cm^2(Vsec)^{-1}$ the corona current of the transition to the streamer form is estimated to be equal to 3 -30 mA. Such values are practically always produced under the influence of the electric field of the downward lightning leader.

In case of the multi-point corona producing electrode with a large radius like the described below the LPAS the total corona current is distributed evenly among the splines. Thus, it is relatively easy to control the corona current of the single spline and limit its value below the critical level even in the case of the extremely large total corona current. All that needs to be done is to increase accordingly the number of splines.

The distribution of the electric field for the well-developed corona (when the front radius R of the space corona charge is many times larger than r_0) can be expressed as

$$E(r) \approx \sqrt{\frac{1}{6\pi\varepsilon_0 \mu r}} \qquad (2)$$

The voltage required for the initiation of streamer flash can be determined by the expression (3) as follows

$$U_{\max} \geq 2E_c r_0 \sqrt{\frac{6\mu E_c \tau}{r_0}} \qquad (3)$$

when the voltage rises linearly and reaches its maximum in τ seconds. For example for τ =10 s and r_0 = 5 cm, $U_{max} \approx$ 28 MV and the influence of electric field of the thundercloud alone is not enough for initiating the streamer flash for the object with any height. A fast growing electric field of the nearby downward lightning leader or mighty inter-cloud discharge may trigger the streamer flash.

Corona space charge injected to the air gap near the object changes qualitatively the process of lightning discharge between the thundercloud cell and the object on the ground. The air gap between them consists now of two different regions: the region filled with space corona space charge and the region free of space charge. The theoretical analysis of the electric field and potential distribution along the air gap in the presence of the space charge indicates the significant difference from the well-known distribution of these properties in the laboratory air gap without a space charge. The injected space charge smooths the radial potential distribution along the charged region of the air gap. Most of the applied voltage drops along the charge-free portion of the air gap and does not have any influence on the further process of the lightning discharge.

As result of the numerical simulation of the process the smoothest distribution of the potential along the charge portion of the air gap was obtained for electrodes with the radius of its hemispherical top with corona many times greater than the radius of the supporting the top grounding structure.

Figure 2 shows the calculated potential distribution for such a construction of the electrode of height 200 m and the hemispherical top with radius of 1 m. The electric field of the thundercloud cell raised to the magnitude of E_{0max} =200 V/cm during 10 s. Curves 2 and 3 on the Figure 2 show the potential distribution for the rod of the same height with the radius of 10 cm and the hemispherical top of the same radius of 10 cm with and without corona.

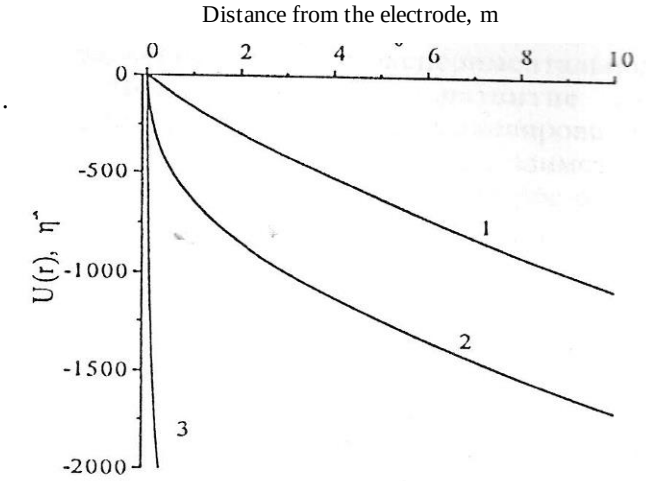

Figure 2. Potential distribution near the grounded electrode of height 200 m at time 10 s; 1 – hemisphere of radius 1m with a multitude of short splines; 2 – rod with radius of 10 cm; 3 – the same rod without corona.

The corresponding equations for potential distribution are as follows.

$$U(r) \approx U\left(1 - \frac{2}{3}\sqrt{\frac{r}{R}}\right); \quad U \equiv U(t) \approx 3E_f R \qquad (4)$$

for the hemispherical top with multitude of the short splines on its surface. R and E_f in equation (4) are the radius of the front of the space charge and the electrical field on it.

$$U(r) \approx U\left(1 - \frac{1}{3}\sqrt{\frac{r}{R}}\right) \qquad (5)$$

for the long electrode with radius of 10 cm in regime of the stationary corona in the air gap of the length R, and

$$U(r) \approx U_0 \frac{r_0}{R} \qquad (6)$$

for the same electrode without corona.

The front radius R of the corona space is increasing with propagation of the charge toward the thundercloud cell. The increase in R results in the more and more smooth redistribution of the potential along the charged region. Potential difference between electrode and point in gap with coordinate r is decreasing in time. It can be determined by the equation (7) as follows.

$$\Delta U(r) \approx U(0) - U(r) \approx \frac{2}{3} U_0(t) \sqrt{\frac{r}{R(t)}} \qquad (7),$$

Figure 3 shows the dependency between the voltage drop on the first meter from the top of the LPAS and the height of the LPAS.

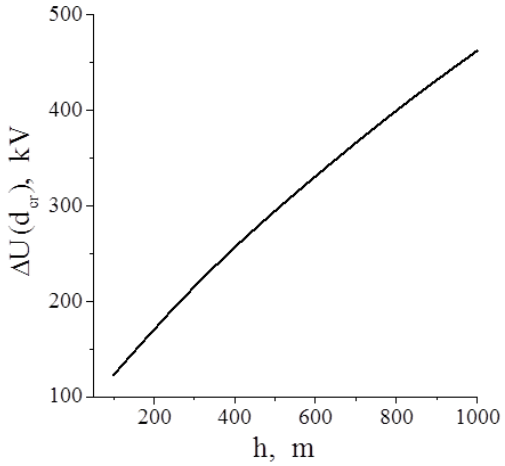

Figure 3. The voltage drop along d_{cr} = 1 m near the hemisphere of 1 m radius with numerous splines as a function of its height above the ground. Thunderstorm electric field rises up to 20 kV/cm during 10 seconds.

The energy of the streamer flashes is spent for heating the air mostly near the stem and along the streamer paths. The development of the plasma channel will become possible if the air temperature at this place will rise to about $5{,}000^0$ K. There is a clear physical relation between the minimum voltage drop ΔU_{min} along the streamer zone and the length d_{cr} of the streamer zone. There is no known direct experiments showing the effect of the parameters of the corona on the leader initiation in the cloud of the space charge, but the indirect observations of the discharge in the laboratory conditions give us the following. First, a new leader is never initiated and the already developed leader cannot survive in normal air when the voltage drop along the streamer zone is less than $\Delta U_{min} \approx 400$ kV. Second, during the breakdown of air gaps of length $d < d_{cr} \approx 1$ m between a positive stressed electrode and a grounded plane, streamers of the streamer zone of a leader reach the opposite electrode (plane) immediately after leader initiation. At $d > 1$ m the leader must cover some distance before the streamer zone contacts the opposite electrode leading to final jump. This means that the minimum length of the streamer zone required for maintaining leader development is $L_{S\,min} \approx 1$ m.

The value of ΔU_{min} provides the minimum energy $C_1(\Delta U_{min})^2/2$ (per unit leader length) required for air ionization and the heating the leader channel, where C_1 is the capacitance per unit length of the channel. Voltage drop $\Delta U \geq 400$ kV on the first meter of the streamer length will be sufficient to deliver such amount of energy. Therefore, the condition for the upward counter leader initiation is not only the transition of the streamer- free corona to the corona with streamers but also supplying voltage along the streamer path sufficient enough to initiate the plasma channel. In that sense the smoothing the potential distribution along the charged portion of the air gap became one of the major factors in suppressing the start of the counter leader from the object.

In the case of the well-developed corona the applied voltage U drops largely along the distance of the space charge cloud radius R rather than along the distance of about r_0. To initiate a leader in this case, the voltage drop along the distance d_{cr} with ΔU being a small part of the applied voltage U, must comply with the inequity $\Delta U \geq \Delta U_{min}$. This condition can be presented in the following form, which is valid at $d_{cr} >> r_0$.

$$U - U(r_0 + d_{cr}) \approx \tfrac{2}{3} U \sqrt{\tfrac{d_{cr}}{R}} \geq \Delta U_{\min}; \qquad (8)$$

Based on results of numerical simulation depicted on Figure 3 the height of the LPAS required to create 400 kV voltage drop on the first meter from its surface is about 800 m. That means that mounting the LPAS totally eliminates the initiation of the counter leaders from the protected object in a thundercloud electric field.

It is well-known fact that not every one leader being initiated will be able to cross the cloud of the space charge and arrive to the charge–free region of the air gap where is nothing hinders it anymore to reach the opposite side of the air gap. The analytical investigation and numerical modelling of that process are based on the theory of the long leader and published in [6].

All the important parameters of the a counter leader, which has started from the electrode, covered a distance of many meters and has not reached a tip of the downward leader or the base of the thundercloud cell are controlled by the difference $\Delta U_t = U_t - U_0$ between the leader tip potential U_t and the potential $U_0(x_t)$ of external electric field at the tip point x_t. The voltage drop ΔU_t controls the length $L_s = \Delta U_t / E_s$ of the streamer zone ($E_s \approx 450$ kV/m – the average electric field in the streamer zone), the leader velocity v_L, the charge τ_L per unit length of the leader, the electric current i_t behind the tip and the average electric field E_t in the channel of length L. We have

$$\tau_L = C_1(U_t - U_0); \;\; C_1 = \tfrac{2\pi\varepsilon_0}{\ln(L/R_{cov})} \qquad (9)$$

where C_1 is the capacitance per unit length of the leader and $R_{cov} \approx L_s$ is the effective radius of the space charge cover around the leader channel. And the electric current i_t behind the leader tip is equal to

$$i_t = \tau_L v_L = C_1 \Delta U_t v_L \qquad (10)$$

where $v_L = a(\Delta U_t)^{1/2}$ and a is a numerical constant
The average value of the electric field in the leader channel can be expressed by the equation $E_L \approx b/i_L$, where b is an another numerical constant.

During the leader propagation the voltage U is distributed between the channel of the leader of length L, the leader streamers zone of length L_s, and the charge-free part of the gap as follows

$$U = E_L L + \Delta U_t + U\left(1 - \frac{2}{3}\sqrt{\frac{L + \Delta U_t / E_s}{R}}\right) \qquad (11)$$

Using the relation between ΔU, i_L and E_L equation (10) can be transform to the equation (12)

$$\Delta U_t + \frac{bL}{C_1 a \Delta U_t^{3/2}} = \frac{2}{3} U \sqrt{\frac{L + \Delta U_t / E_s}{R}}, \qquad (12)$$

which is a relation between ΔU_t and the length L of the leader channel.

The solution of the equation (12) with the given length of the leader channel determines the voltage drop along the streamer zone, which allow after that to calculate the leader current and the speed of its propagation. The result of one of such numerical calculations is shown on Figure 4

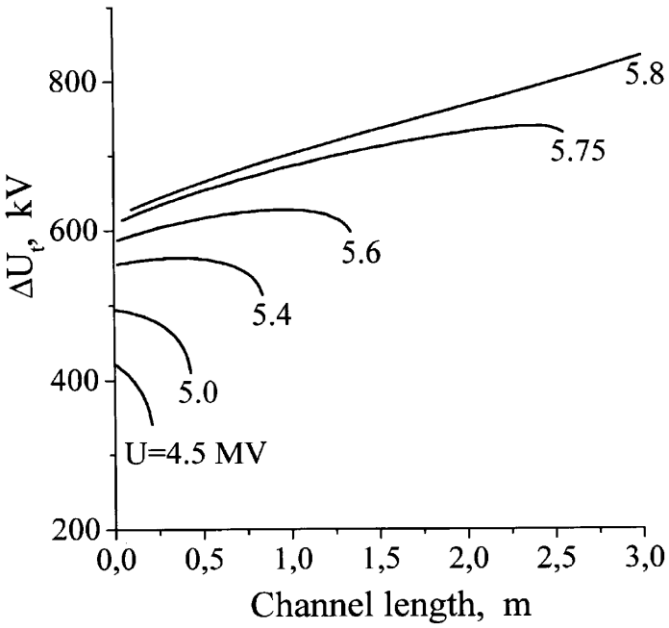

Figure 4. Voltage drop on the streamer zone of the leader propagating in the cloud of the space charge as a function of the leader length at different applied voltages.

It was assumed in this sample that the applied voltage U *was* rising linearly and had reached its maximum value at time $t = \tau$, at which moment a leader was initiated. It can be seen from the Figure 4 that the ability of the leader to cross the space charge cloud and reach the charge-free part of the air gap, vitality of the leader in another words, is become clear on the first meters of its path. The leader moves with acceleration when the applied voltage raised to 5.8 MV based on the increasing of the voltage with the increase of the channel's length. The channel will not be able to move even to the length of 3 meters when the applied voltage was just one per cent less (5.75 MV)

Summarizing the basics of the strike prevention the following can be formulated as the performance requirements to the protection system able to prevent lightning strikes to the protected objects:

1. The system must produce corona as earlier as possible in the relatively week lightning electric field at ground level. It will provide sufficient time for the propagation of the developed space charge on many tens of meters from the object.
2. The system shall have a radius of its top large enough to support effectively the redistribution of the electric field and potential along the air gap in such a manner when voltage drop on the first meters of length of the corona streamers and counter leader streamers will not exceed 400 kV.
3. The corona current from single electrode (spline) should be maintained below its critical value defined by the formula (1) for preventing the corona streamers initiation.

The (LPAS) consists of a hemisphere of a large radius with many thin metal splines with sharpened tips distributed evenly over the hemisphere's surface. The LPAS is mounted on the top of the structure to be protected. Such design of the LPAS fully complies with the first requirement to the performance of the lightning strike prevention system.

Figure 5 shows the picture of one of the LPAS installed on the tall antenna tower.

Figure 5. The LPAS installed on the antenna tower

The electric field on the ground surface produced by the charges in the thunderstorm clouds is enhanced doubly. Firstly, the average field on the hemisphere surface is higher than the thundercloud electric field at the ground level by a factor of h/r_0, where h and r_0 are the height and radius of the hemisphere. Secondly, the electric field near the spline tips is higher than the electric field on the hemisphere surface by a factor of h_{spl}/r_t, where h_{spl} and r_t are the splines height and tip's radius.

The calculations made for the hemisphere with the multitude of the splines and the radius of 1 m installed on the tower of 100 m high show that just 12.5 V/cm of the lightning electric field is enough for the ignition of the corona from the hemisphere where electric field will reach threshold 30 kV/cm. The same hemisphere but without splines on its surface will have just 1.5 kV/cm – a value far below the magnitude required for the corona ignition.

The radius of the hemisphere usually varies in range from 1 to 5 meters. Such large radii of the hemisphere provide with the redistribution of the electric field and potentials along the gap with the significant reduced voltage drop on the first few meters of the gap.

The total corona current from the hemisphere is distributed almost evenly among the several thousand splines installed on the hemisphere surface and that keeps the corona current from the single spline well below the critical value required for the streamer initiation as long as the external electric field does not exceed the corona threshold value.

Each one spline starts to emit current under the influence of the electric field of the thundercloud cell as a solitary thin electrode. When the charges produced by those "solitary" splines have moved away from the hemisphere on the distance close to the radius of the hemisphere, the cloud of ions common to all the needles will be formed. This cloud will be moving in the electric field developed by the thundercloud cell, by the space charges of all the splines and by the charges on the surface of the hemisphere. Now this construction acts as a corona-producing smooth hemisphere with greatly decreased minimum value of the external electric field required for the igniting the corona.

The calculations show that the value of the critical electric field on the surface of the hemisphere of the LPAS with radius of 1 to 5 m and several thousands of the splines is in the range of 1.5 to 2.0 kV/cm is depending on the height of the installation. The field decreases with distance in the accordance with the equation (2). That means that the voltage drop on the first meter from the hemisphere will be $\Delta U(d_{cr}) < E_c d_{cr}$ = (1.5 – 2.0)x100 = 150 – 200 kV, which is substantially less than 400 kV required for the ignition of the counter leader. These low values of the voltage drop are remained even in very strong external electric field of the thundercloud cell.

It has been previously shown that for the initiating of a counter leader from the grounded electrode it is necessary to satisfy the condition that a streamer-free corona gives way to an intensive corona flash. In addition, the electric field must be sufficiently high to provide voltage drop $\Delta U \geq \Delta U_{min} \approx 400$ kV along a distance of ~ 1 m near the electrode surface. It has also been shown that the first condition is a more stringent one and it is never fulfilled for the LPAS in a slowly rising thundercloud electric field (with no downward leader creating a fast-rising electric field).

The initiation of a counter leader from the LPAS is associated with a joint electric field produced by thundercloud charges and charges of a not-too-distant downward leader, which appears at some distance from the electrode and drastically changes the situation. In order to clarify the effect of a downward leader on the initiation and development of a counter leader, it is necessary to simplify the problem by considering specific average downward leader parameters.

The average velocity of a downward leader and its linear charge are $(2\div3)\times10^5$ m/s and q_L ~ 1 mC/m, respectively. When compared to a thundercloud electric field, it is much more difficult to compensate the electric field of a downward leader near a grounded structure by the slow-moving ions carrying the corona space charge. These ions have no time to compensate totally a fast change in electric field.

The development of a downward leader (even during its initial phase when the leader is still far from a grounded object) induces a new corona process which develops against a background of the previous corona process initiated in a thundercloud electric field. The new corona is much more intensive because the rise rate of the electric field of a downward leader is many orders of magnitude higher than the rise rate of a thundercloud electric field. The total corona current through the surface of LPAS increases by several orders of magnitude and reach a few tens amperes at short distances between the downward leader and the LPAS.

The numerical simulation showed that in this case the initiation of the counter leader is determined by the conditions for the formation of streamer flashes. The streamer formation will inevitably be followed by the initiation and development of a counter leader, because under conditions considered the voltage drop along the distance of 1 m near the hemisphere is several times higher than the threshold $\Delta U_{min} \approx 400$ kV.

It is interesting to consider a downward leader trajectory that is displaced horizontally at distance Δy comparable with the height of a corona- producing system, *h* (Figure 6).

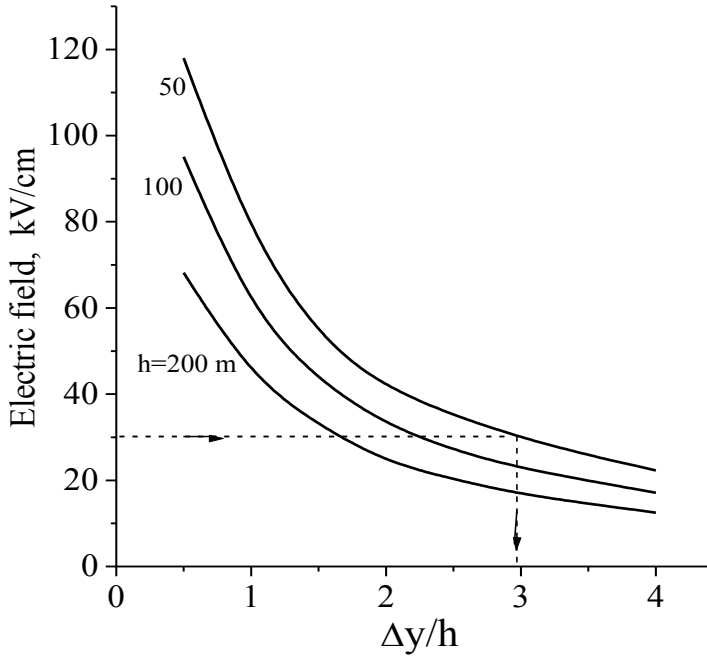

Figure 6. The maximum electric field near the surface of a hemisphere of 1 m radius with numerous splines placed at the height *h* above ground as a function of the minimum distance from the horizontal displacement of a downward leader. The thundercloud electric field rises linearly up to 200 V/cm for 20 s. A downward leader is initiated at t = 20 s (the instant the thundercloud field reaches its maximum) at a height of 3 km above ground; the leader velocity is 2×10^5 m/s and its linear charge is 1 mC/m.

In this case, a counter leader could be totally suppressed if the radius of the LPAS and the number of the splines were chosen in a proper way.

III. THE LPAS TEST BED

In order to verify the performance of the LPAS, field test equipment as shown in Fig.3 is installed in Singapore.
Electric field mills for measuring the electric field strength are installed in a straight line in flat field of about 210m length

and 110m width. The two iron towers of 20m in height and 100m distance are installed in the straight line. Also, weather sensor unit to measure the various weather data is located in the middle of the field. The video cameras to observe the corona discharge and lightning are placed on both sides of this straight line (Not shown).

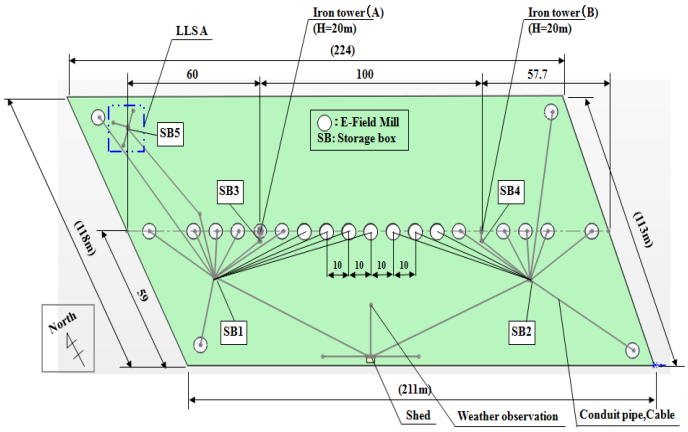

Figure 7. Arrangement of field test equipments on LPAS verification site

Figure 4 shows an example of actually measured data. This data is the state in which two towers are not installed. In this example, the field strength is varied ±2 kV/m. When a change in the electric field strength, it is observed that the temperature is dropping, the humidity is rising; the wind is stronger and it is raining.

In the future, various measurements are scheduled in sequence. Eventually, the major parameters of the LPAS performance will be recorded and analyzed.

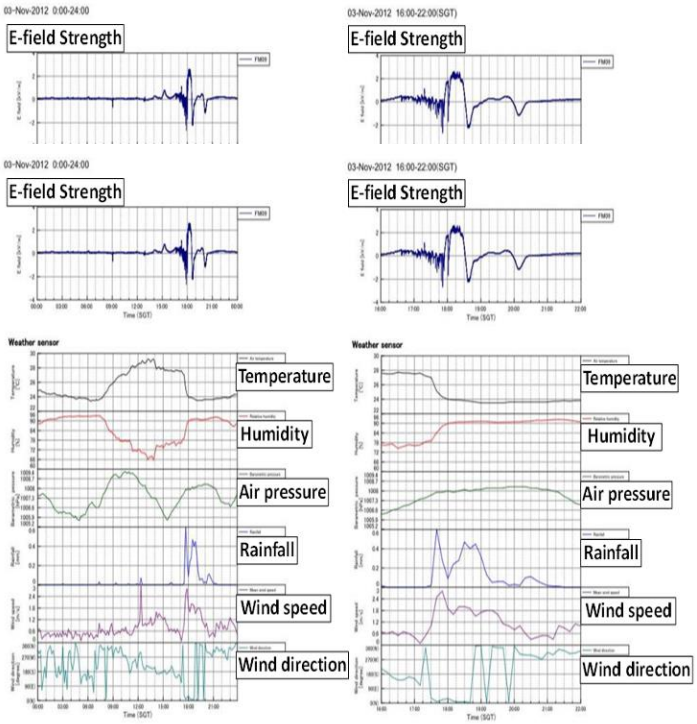

Figure 4. Example of measured data

Figure 8. Examples of measured data.

III. CONCLUSIONS

1. The prevention of the lightning strikes to the object to be protected is possible by suppression of the initiation and/or propagation of the upward counter leader.
2. Two conditions must be met for the preventing a counter leader from initiation:
   a) the corona current less than critical value required for the suppressing the initiation of the streamers
   b) the voltage drop on the first meter of a streamer length must be below 400 kV
3. To suppress the counter leader propagation through the corona space charge cloud the voltage drop on the first meter of length of a streamer from the counter leader channel must be below 400 kV.
4. The design of the Lightning Protection Array System (LPAS) complies with the requirements to the strike prevention performance of the system
5. Verification of the LPAS performance under natural weather conditions is planned to carry out in Singapore.
6. Electric field strength by the EFM, air pressure, temperature, humidity, rainfall, and wind speed etc. by meteorological sensors are obtained at the same time.

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