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A Hybrid Lightning Strike Protection System

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Background

The first lightning protection system (LPS) went into operation over 250 years ago with the advent of the air terminal, a.k.a. lightning rod, attributed to Benjamin Franklin. Since that time there have been other systems that have approached the lightning event in a different manner and as a result offered different solution concepts depending on the users' needs. It is important to first discuss the lightning event itself, followed by whether a LPS should be implemented, the types of lightning protection systems and their methodology of protection, and finally, the hybrid approach.

The Lightning Strike Event

Lightning is the result of charge accumulation within a cloud cell exceeding the dielectric strength of the air and, as a result, the air beneath the cloud is no longer able to act an insulator between the charge and path to ground.

When there is no thunder cell in the area, the "fair weather" electric field is around 100 V/m. While the charge is being generated in the cloud cell, the related electrostatic field is inducing a charge on the earth's surface beneath it of equal but opposite polarity. It is much like an electrical shadow that moves with the cloud, as illustrated by figure 1. When the potential at the cloud base reaches approximately 10^6 volts, leaders form and move that voltage toward earth in "steps" as shown in figure 1. The stepped leaders move toward earth at velocities of between 1×10^5 and 3×10^6 meters per second. As the stepped leader approaches earth, the voltage between that leader tip and an earthbound facility rises to very high potentials; for example, the electric field beneath the cloud rises to become greater than 30 kV per meter of elevation above the earth. In a matter of a few milliseconds, the electrostatic voltage on a pointed rod elevated above earth by a mere 10 meters will rise from one hundred thousand volts to over a million volts. This potential will cause grounded pointed objects, such as air terminals, to first break into corona and then rapidly into upward rising streamers, as illustrated in the lower right panel of figure 1.

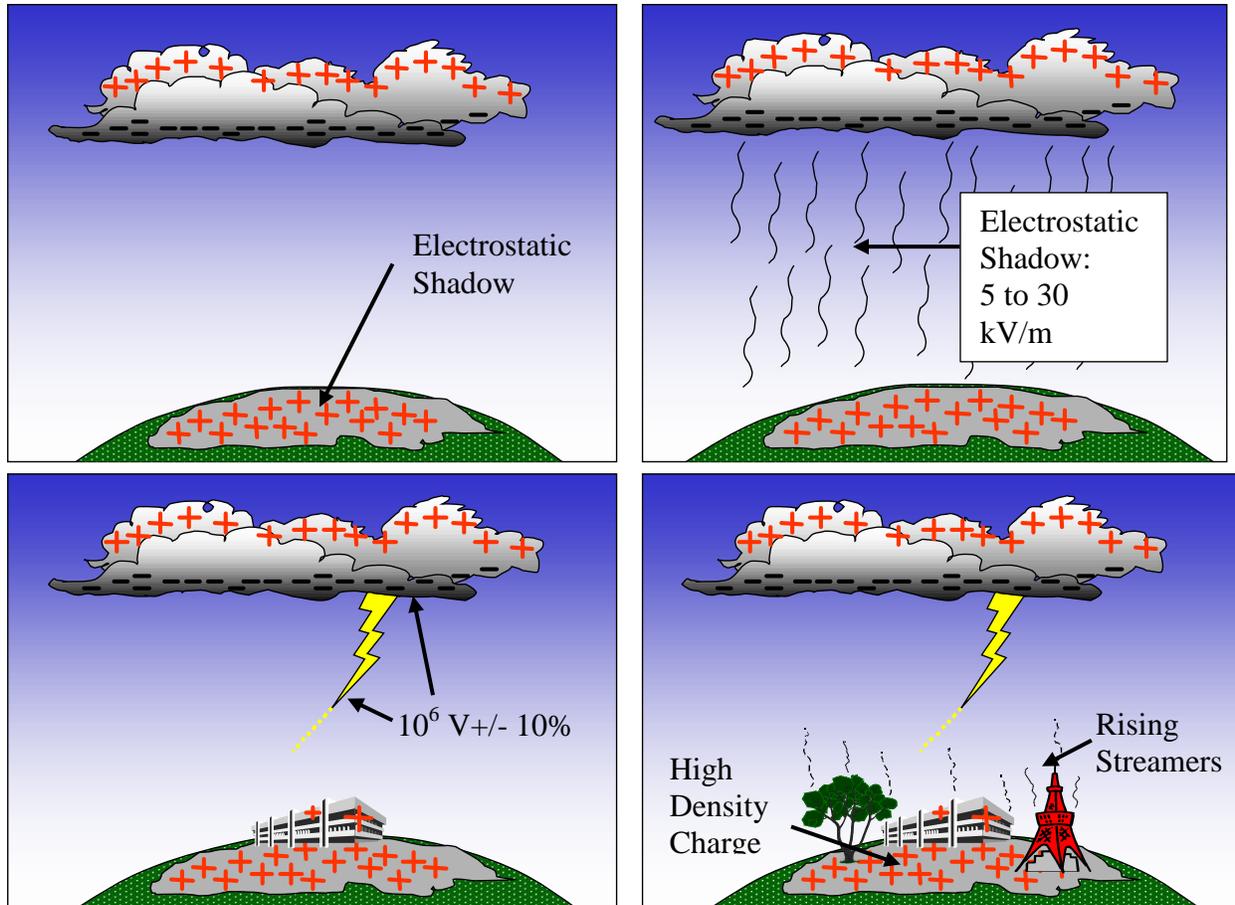


Figure 1: The Charged Cloud Impact

The early stages in the formation of upward streamers occur as result of what is called the point discharge phenomenon. The point discharge theory describes the ability for any grounded pointed object to give off discharge current. This point discharge current, or ionization, occurs with air terminals as well as with multipoint ionizers. Recent scientific testing has suggested that a multipoint ionizer will make that version of an air terminals self-protecting from lightning strikes at the early stages of the stroke development ¹.

When the leader connects with one of the upward streamers it is called a lightning stroke. This results in a discharge/neutralization process. The induced charge on the surface of the earth discharges or neutralizes with the rush of the induced charge through the channel formed by the creation of the stroke. This is illustrated in figure 2.

This discharge/strike can cause significant direct structural damage in forms such as fire and explosions. Associated with the direct damage, there can be additional damage caused by secondary effects. These secondary effects are caused by, in part, the rapid expansion and collapse of the electric field. This type of damage can have significant effects on nearby electrical systems and is commonly known as an electromagnetic pulse or EMP (see LEC paper The Secondary Effects of Lightning Activity, Rev. A - Carpenter, Lanzoni - April 2014)

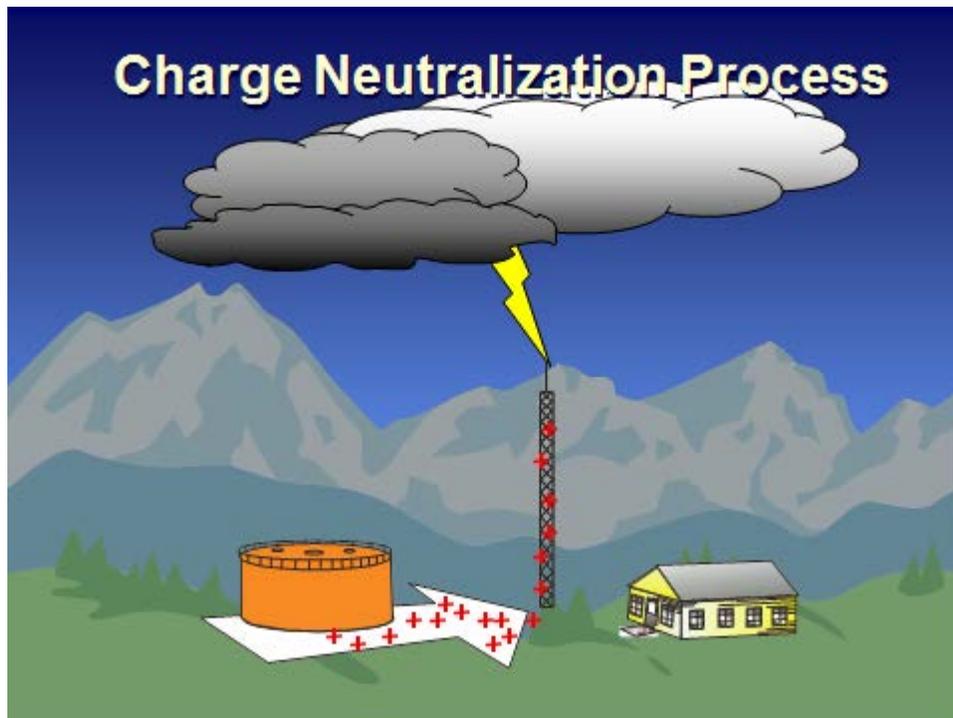


Figure 2: The stroke or discharge process

With all of the potential termination points for a downward stepped leader, a significant question is “Where will that stepped leader terminate?” Since a LPS is designed to control the damage due to the lightning event, it is important to know if a structure is at risk of naturally collecting a strike. To that end, a great deal of research has been accomplished and recorded. It seems that the stroke termination is a function of three definable factors.

- **Random chance** determines the path the leader will take until that leader reaches the “point of discrimination” as shown in figures 3A, 3B, and 3C.
- The **striking distance** is the distance from the lightning leader at which any earth-bound structure will generate an upward streamer as seen in Figures 3A and 3B. This radius is a statistical quantity dependent on the current intensity (current) of the ensuing lightning strike as shown in formula 1.1.
- The **point of discrimination** is the point where the force of attraction between the stepped leader and one of the upward streamers determines which upward streamer will generate the stroke channel between the leader and streamer. At this point, the leader is directed, in its final step, to the upward streamer with the greatest attraction force. This is shown in Figures 3B and 3C.

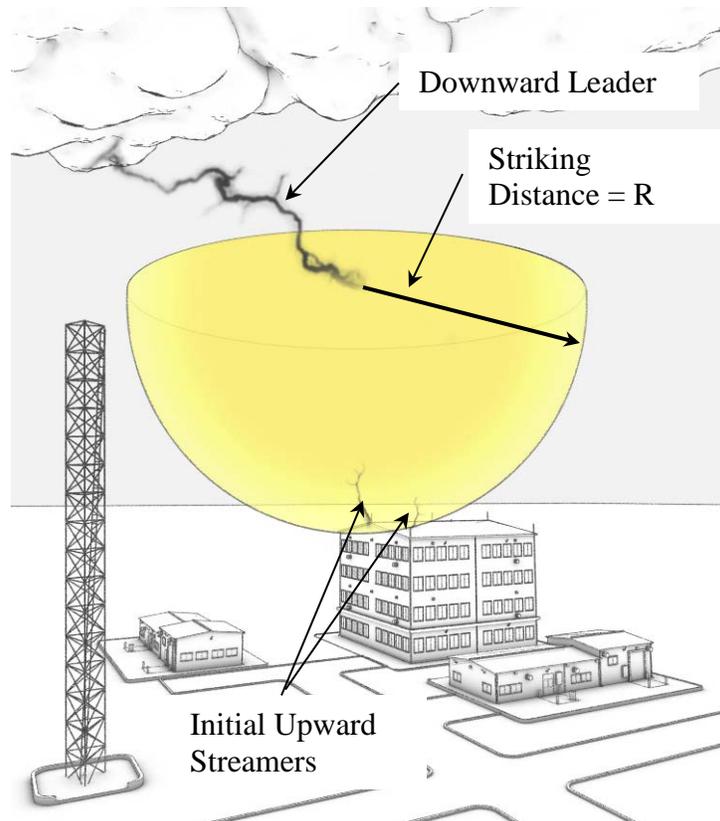


Figure 3A: Striking Distance

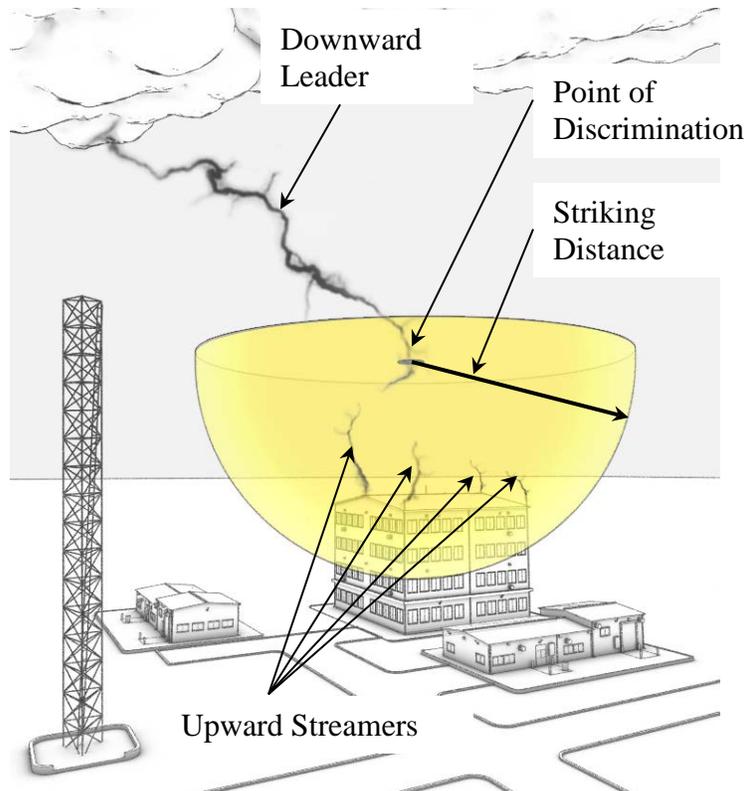


Figure 3B: Point of Discrimination

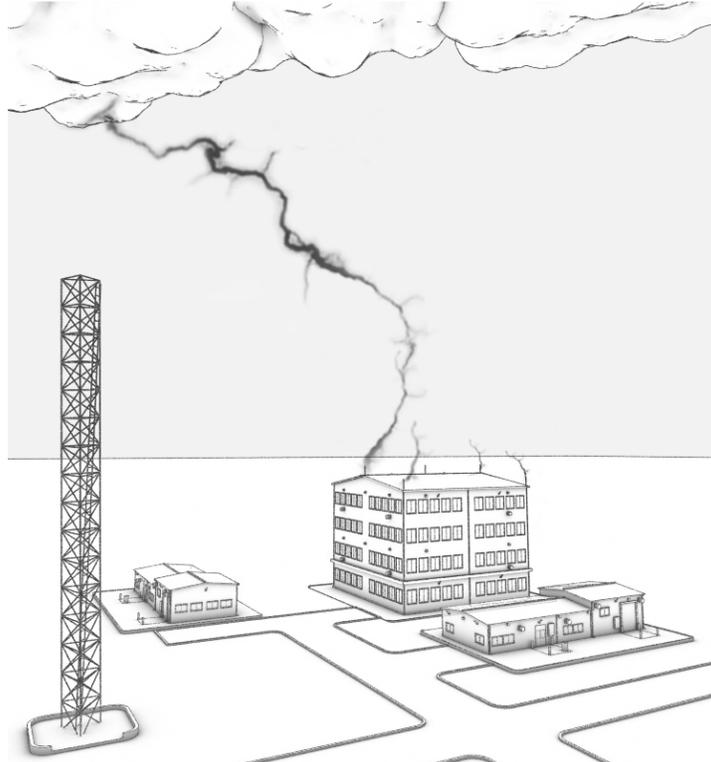


Figure 3C: Completed Stroke Channel

Figure 3A shows the striking distance of an example strike with striking distance R. Everything within the distance R from the leader tip is shaded yellow. This region is the shape of a hemisphere. The objects within the yellow hemisphere produce streamers while objects outside the area do not. This is true even if the structure is tall, as in the case of the tower on the left side of the figure.

As the leader progresses, the tip of the leader moves toward the point of discrimination and the “striking distance hemisphere” moves with it. Figure 3B portrays the leader shortly after the point of discrimination. As you can see, the hemisphere has moved since Figure 3A and now additional streamers are forming.

At this point of discrimination, the leader selects which will be the “winning” streamer and will move in its direction until contact is made. This change in movement can be seen right after the point of discrimination in Figure 3B. Figure 3C shows the final connection which is made between the leader and the streamer which was determined at the point of discrimination.

Calculating Striking Distance

A common method to determine the striking distance is through the formula

$$r = 10 I^{0.65}$$

Formula 1.1 ²

Where:

r: striking distance in meters

I: peak current in kA

These steps and the striking distances vary from a low of approximately 15 meters to a high in excess of 200 meters. However, the average length is only about 50 meters for a negative stroke, which is the most common polarity. Positive strokes can have a striking distance of over 300 meters.

Risk Assessment

The need for a lightning protection system usually involves an analysis of risk and the following types of loss.

1. Loss of, or risk to, human life
2. Loss of production or service to the public
3. Loss of economic value
4. Loss of cultural heritage

Both the National Fire Protection Association (NFPA) and International Electrotechnical Commission (IEC) offer guidelines on risk assessment.

Standards

In the United States safety is the main determinate of most standards, and the National Fire Protection Association (NFPA) is no different in this regard. NFPA 780 put safety as the most important factor when addressing lightning protection. These standards are designed to address safety from a position of collecting the strike and discharging it in the ground as safe as possible. A determination of the location with the highest probability of collecting a lightning strike can be done using a rolling sphere method which is illustrated in figure 4. This method is endorsed by National Fire Protection Association (NFPA) which publishes the NFPA 780 Standard for Lightning Protection in the USA. Using this method whatever part of a structure that is touched by a sphere that is rolled all around and across the structure is subject to collect a lightning strike. Wherever the sphere touches the structure an LPS is deployed.

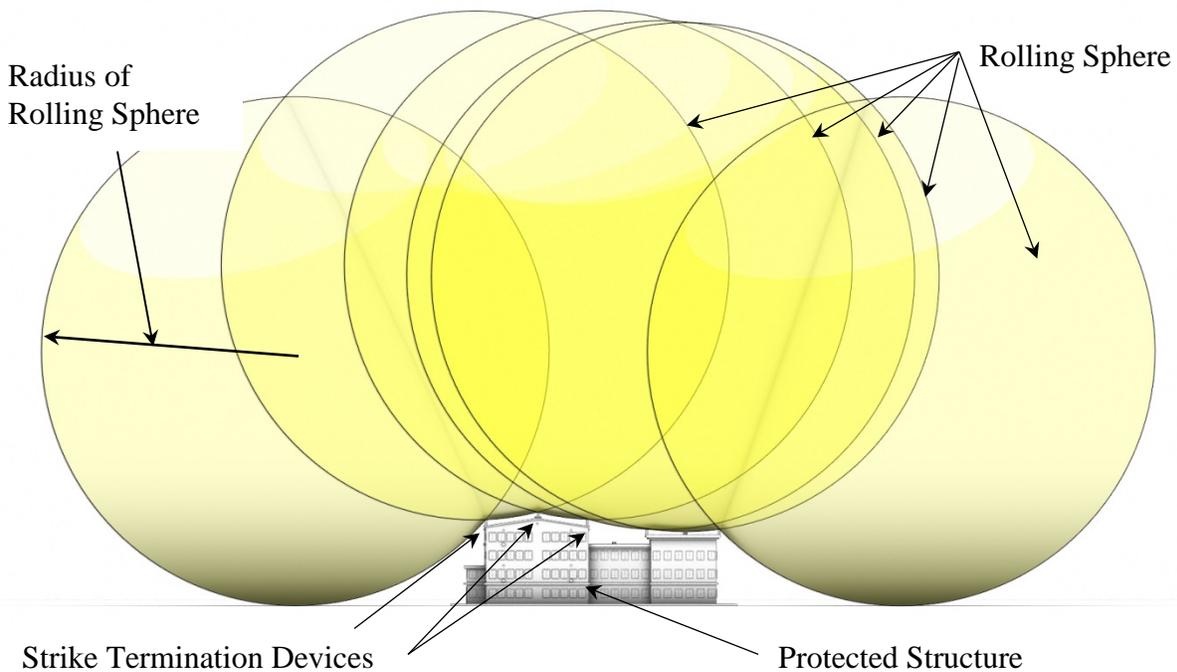


Figure 4: Rolling Sphere method of analysis

The radius of the sphere should indicate the striking distance based on the strike current. To maintain consistency, NFPA 780 uses a radius value of 150 feet (46 m) which equates to a strike current of approximately 35 kA. A limitation of using this method as detailed in NFPA 780 is that the rolling sphere method does not account for shorter strike distances than 150 feet (46 m), which would allow a strike to slip into the protected area, or competitive factors, which make some locations more likely to collect a strike than others.

Types of LPS

There are four general types of commercially available lightning protection systems, as follows:

1. Conventional air terminal lightning protection systems – designed to collect strikes
2. Early streamer emitting air terminal lightning protection systems– designed to collect strikes
3. Charge Transfer Systems – streamer delaying arrays that are that are designed to prevent all possible lightning strike collection
4. Hybrid System - streamer delaying air terminals that collect strikes only when charge transfer capacity is exceeded by dissipation requirements.

Each of these system types is comprised of two basic subsystems, as follows:

1. The devices that are installed on top of or above the structure or area to be protected. These devices may include single point air terminals, multipoint air terminals or arrays, shield wires, masts, ionizers, etc. Systems using these devices offer protection from direct strikes to objects

and structures that fall within a protected zone adjacent to and beneath the highest point of the devices.

2. A grounding electrode system designed to provide a sufficiently low resistance connection to earth. The lightning protection devices listed above must be bonded to the grounding system using conductors adequately sized for lightning currents.

The grounding subsystems for all four types of lightning protection systems are essentially identical. However, there are differences in the design and installation of the lightning protection devices, as described below:

Conventional Air Terminal Lightning Protection Systems

A conventional air terminal lightning protection system consists of installing a suitable number of air terminals (also called lightning rods), conducting masts or overhead shield wires above the structures or areas to be protected. These devices are then bonded to the grounding system. The air terminals, masts or shield wires are designed to collect incoming lightning strikes by generating upward streamers. Installation requirements and specific information about the protected zone can be found in NFPA 780, Standard for Lightning Protection. Note that NFPA 780 is a standard and not a national code which requires compliance.

Conventional air terminal lightning protection systems do not protect against indirect lightning currents or induced voltages. These effects are addressed by proper bonding and the application of surge protection devices.

Early Streamer Emission Air Terminal Lightning Protection System

An early streamer emitting (ESE) air terminal lightning protection system consists of a suitable number of ESE air terminals above the structures or areas to be protected. These devices are then bonded to the grounding system. ESE air terminals are designed to generate upward streamers that launch sooner, and with a greater collection zone, than conventional lightning rods, thus providing a more attractive point of termination and collection. Installation requirements and specific information about the protected zone is available from the systems' manufacturers. Early streamer emitting air terminal lightning protection systems do not protect against indirect lightning currents or induced voltages. These effects are addressed by proper bonding and the application of surge protection devices.

Charge Transfer Systems

A charge transfer system consists of installing a suitable number of ionizing arrays and ionizing air terminals above the structures or areas to be protected. These arrays are then bonded to the grounding system. The arrays and supplemental terminals are designed to avoid the termination of incoming lightning strikes by lowering the electrostatic field thereby suppressing or delaying the formation of upward streamers. For more technical information see LEC paper Preventing Direct Lightning Strikes. Without the leader streamer connection, there is no strike. Installation requirements and specific information about the protected zone is available from the systems' manufacturers. Depending on the manufacture and product type, charge transfer systems will have some benefit in reducing indirect lightning currents or induced voltages. Some of these

products come with a performance guarantee. However, proper bonding and surge protection devices should still be provided.

Hybrid Systems

In addition to these three types of systems, there have been several attempts to improve the performance of air terminals by providing them with charge transfer capability. This capability allows hybrid ionizers to prevent or delay the formation of upward streamers in the same way that a full capacity charge transfer system would, but the terminal will collect the strike when the charge transfer capacity is exceeded by dissipation requirements. There is evidence that indicates that these devices do reduce the risk of a strike but with varying degrees. Furthermore, no hybrid system is 100% effective at lightning prevention. When a hybrid ionizer does fail to prevent a strike, it functions in an alternate mode as a stroke collector. Thus, the name “hybrid” has been applied to these designs because they share some of the benefits of a charge transfer system while performing no worse than an air terminal.

The ionizers presented in this paper include the Spline Ball Ionizer® (SBI®), the Spline Ball Terminal® (SBT®) and the Streamer Delaying Air Terminal (SDAT). These all comply with existing NFPA and Underwriters Laboratories (UL) standards and are a low cost option to the DAS.

Spline Ball Ionizer and Spline Ball Terminal

The LEC SBI® and SBT® were developed as optimized hybrid air terminals. Figures 10 and 11 illustrate the two configurations. Both the SBI and SBT provide the required point spacing to maximize the ionization current. At the same time, they provide a point oriented at least every 5 degrees in azimuth for the full 360 degrees in azimuth and a full 225 degrees in elevation. As a result, there is no direction from which a leader can approach that will not have a collective points oriented directly toward it and many backup points close by. The SBT differentiates itself from the SBI by a reduced number and shorter length of points thus it has a slight reduction in performance but is ideal solution for upgrading an existing lightning rod system. The SBI is the ideal solution for towers, large structures or vessels.



Figure 10: Deployed SBI



Figure 11: Deployed SBTs

Both the SBI and SBT have been reviewed by Underwriters Laboratories and have been listed as terminals, usable as such in any NFPA-780-based lightning protection where rod-type terminals are specified.

SDAT Systems

Similar to a SBIs and SBTs is the Streamer Delaying Air Terminal (SDAT). It works as a hybrid system with the goal of preventing the majority of the strikes while collecting the strikes that it can no longer prevent. The differentiating factor in the SDAT system is the number of points and the size of the wire. While the SBI and SBT use optimum point spacing the SDAT uses substantially more points essentially increasing the ionizing wire by a factor of 10. In theory this approached would lead to better result but it fails to address the issue of point spacing or crowding (point interference).



Figure 12: Deployed SDAT

The SDAT has been reviewed by Underwriters Laboratories and have been listed as terminals, usable as such in any NFPA-780-based lightning protection where rod-type terminals are specified.

Comparison of Multipoint Ionizers

The separation distance between points has been shown to be a significant factor in the charge transfer discharge current given off by each point ³.

LEC has conducted tests to determine the separation distance required to provide the optimal discharge (or ionization) current.

Further investigation by LEC into the ability of multipoint ionizers to generate ionization current resulted in a test of LEC's Spline Ball Terminal (SBT), Lightning Master's PP-31A (a fine point ionizer) and a 3/8" diameter lightning rod. The results of this test are shown in figure 5.

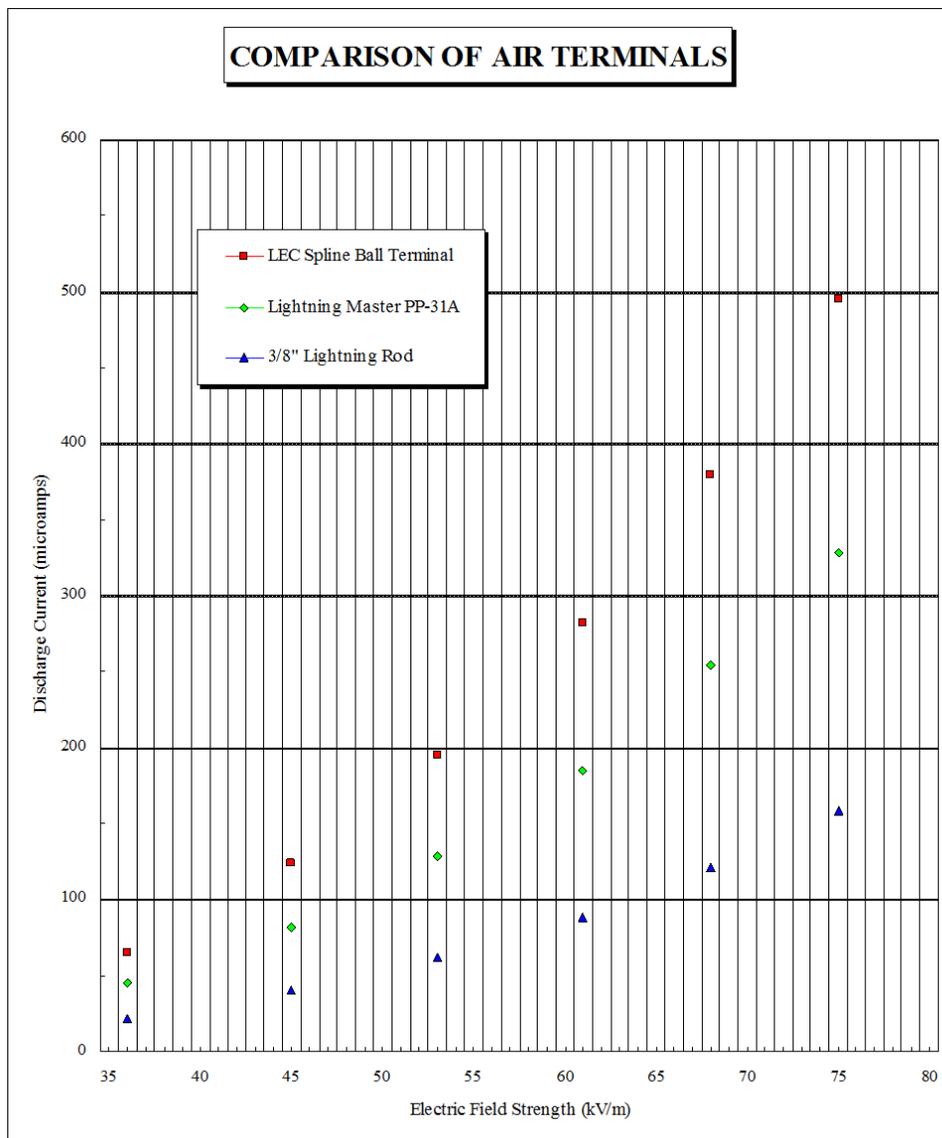


Figure 5: Comparison of Charge Transfer Ionization Capability

This test, performed at the LEC testing lab, shows that an LEC SBT has about 50% greater charge transfer current than the PP-31A fine point ionizer (similar to the SDAT) and over 2 times the charge transfer current than an air terminal when immersed in an electric field of 75 kV/m. This test indicates that multiple points ionize better than a single point and that proper point spacing is a factor when considering a multipoint terminal.

Major differences in the multipoint ionizers are the number of and spacing of the ionizing points. There are well over 100 ionizing points in the PP-31A which are closely spaced in a configuration similar to that of a shaving brush. The LEC SBT has a limited number of points spaced at 6" which has been shown to be an optimal spacing for the highest per point ionization current. As the chart above shows, there is a much greater ionization current for the greater spaced SBT over the PP-31A device, even though it has fewer points.

Multipoint (hybrid) ionizers will collect a strike, similar to a lightning rod, when they cannot dissipate (transfer) the charge fast enough. As the leader approaches, the terminal may eventually go into ion saturation and produce streamers and a subsequent stroke channel. When they produce streamers, some of them (when properly configured) become very efficient collectors.

Using the SBI, SBT, SDAT in Standards-Based Systems

Standards such as NFPA-780, UL96A, NAV FAC DM4, and Army 385-100 are based on the use of a single point lightning rod known as the air terminal or the stroke collector. However, since UL has listed the SBI®, SBT® and SDAT these assemblies can be used in place of the single-point terminal. In most cases, they can be used as a direct replacement. The SBT® and SDAT are designed to fit into the conventional lightning rod mounting plate.

Figure 12 illustrates a typical NFPA-780 building protection system that has been converted to a hybrid stroke protection system. Model SBT hybrids are used in the required locations around the periphery. SBI or SBT hybrids can be used in the required locations down the middle of the building.

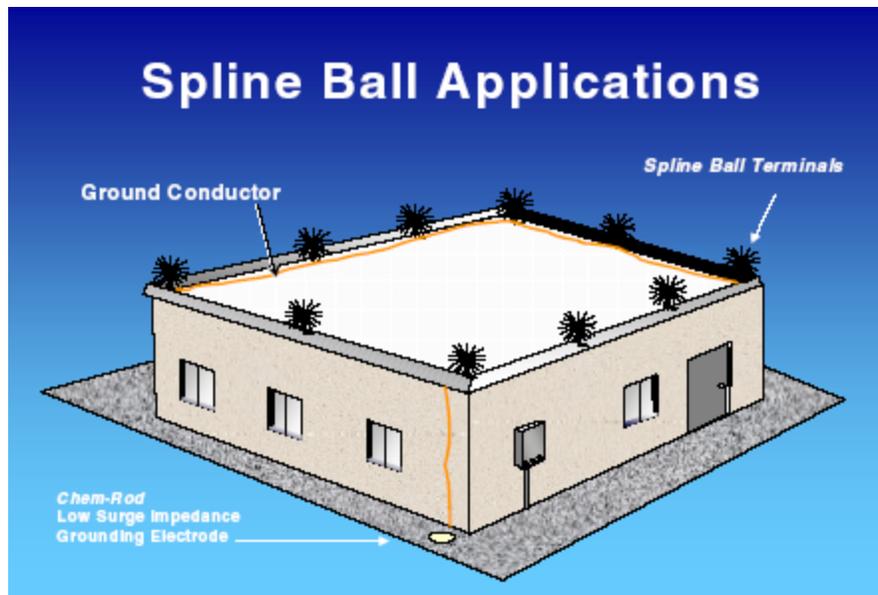


Figure 12: SBT's Deployed in Standard 780 Layout

Choosing a System

When assessing the three biggest risk factors

1. Loss of, or risk to, human life
2. Loss of production or service to the public
3. Loss of economic value

The cost of lightning related damages may be significant. This may be especially true in an oil/gas facility or chemical processing plant where a strike can cause a substantial loss of product and equipment. In these cases, the risk to human life cannot be ignored.

If there is an appreciable economic and or safety loss associated with lightning activity, it may be worthwhile to implement a no-strike, Charge Transfer type, LPS. However, since the cost of this type of system can be high, a cost-benefit analysis should be performed. If the cost-benefit analysis shows that a no-strike LPS is unwarranted, a lower cost hybrid LPS may provide the ideal solution.

A hybrid LPS functions on the same principles as a no-strike LPS but cannot prevent a direct strike to the protected area or structure under all conditions. It will, however, reduce the number of terminations and thereby increase safety and lower the damaging effects on the electrical and electronic equipment.

Grounding

If the lightning stroke is allowed to seek its own path to ground, it may cause significant direct damage to the stricken object and damage due to secondary effects. An LPS is designed to provide the lowest impedance path to ground for the lightning current.

For a conventional LPS, the termination device provides a generator of the upward streamer and a highly conductive location for the lightning current to begin its path to ground when it is struck.

If there is not a low impedance path to ground provided by the ground conductor, the high current values will take the lowest resistance path to ground which may be through the structure causing significant personal and property damage.

Since the lightning current must transfer current through the earth, a low impedance connection to earth must be established. This earth connection must be able to spread the current out over a large area of earth to prevent localized high current values. To do this a low earth resistance must be obtained and maintained or a low resistance ground grid must be installed.

Surge protection

Surge protection devices usually deal with the secondary effects of the strike. These effects result in earth current transients, atmospheric transients, electromagnetic pulses and the bound charge phenomenon. The most common of these secondary effects cause problems associated with over voltages on copper wires. Proper grounding design and application is also essential in minimizing this threat.

Conclusion

In the industry of lightning protection, options must be considered to determine what system best fits the user's needs. Understanding the lightning event, the motivations for LPS implementation and the types of systems all play a significant role in ensuring the user's goals are met and an unintended event is prevented. A hybrid lightning protection system can meet the basic requirements of the user over a traditional system as well as provide an economic advantage over a full capacity charge transfer system.

Based on a cost benefit analysis, in many commercial or industrial applications, these hybrid lightning protection systems are the preferred cost effective lightning protection option.

A properly designed and installed standards-based system that includes the use of the LEC hybrid terminals will provide two modes of protection:

1. A stroke prevention mode that reduces the risk of a strike to the protected facility using the size and number of SBI/SBTs and or SDATs in proportion to the size of the facility.
2. A stroke collector-diverter system that is far superior to any system now in use because it collects strokes entering the "protected" area from any direction and angle.

References

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