AMERICAN CONSULTING ENGINEERS COUNCIL'S

HEAVY MOVABLE STRUCTURES
MOVABLE BRIDGES AFFILIATE

3RD BIENNIAL SYMPOSIUM

NOVEMBER 12TH - 15TH, 1990

ST. PETERSBURG HILTON & TOWERS
ST. PETERSBURG, FLORIDA

SESSION
WORKSHOP NOTES

Session (1-7)
"Static Dissipation Lightning Protection", Bruce A. Kaiser, LightningMasters, Inc. Fl.

STATIC DISSIPATION LIGHTNING PROTECTION

FOR

HEAVY MOVABLE STRUCTURES AND MOVABLE BRIDGES

Prepared for:

HMS/MB
an ACEC Affiliate

3 rd Biennial Symposium
St. Petersburg, Florida
November 1990

At any given moment, there are some 1,800 active electrical storms throughout the world, producing 100 lightning flashes per second. On a per day basis, it is estimated these thunderstorms produce 8,000,000 lightning flashes. About 20%, or 2,000,000 of these flashes, are cloud to ground. All it takes is one strike to your property or equipment to ruin your whole day.

For the past 200 years, protection from direct lightning strikes has been centered around the traditional lightning rod. The lightning rod has come to represent lightning protection. When one installed an electrical or electronic system, one installed the basic lightning rod protection system, sometimes just to meet code, and sometimes in a conscious attempt to control damage from direct lightning strikes.

However, after doing all of the research and homework and going to all of the effort and expense of installing the best in traditional lightning protection systems, zap, a direct lightning strike still occasionally causes considerable damage. That's the bad news. The good news is that if you have gone to the effort and expense, you probably already have installed the basics of an effective lightning prevention system.

Over the past decade, a "new" technology has emerged. "Static dissipation" has become a buzz-word in lightning protection. What is static dissipation? Basically, it is the leaking-off of static ground charge from an object or structure to the atmosphere at a rate sufficient to maintain the potential on that object or structure below the threshold at which a lightning strike will be triggered, and retatding the formation of upward streamers from that protected structure.

Why is static dissipation technology kindling renewed interest among those concerned with lightning damage? Because, although the traditional approach controls the current flow and the physical damage from lightning, it does little to control the other aspects of lightning, aspects which cause most of the damage to modern electronic and electrical equipment.

THE LIGHTNING PHENOMENON

To understand lightning damage, it is necessary to have at least a basic understanding of the lightning phenomenon.

There remains disagreement among those dedicated to the study of electrical storms as to the exact mechanisms which create the conditions which cause lightning. However, there is agreement that the cause of the cloud-to-ground strike itself is the difference in electrical potential between the storm cloud charge and the charge on the surface of the earth and objects thereon. For the purposes of this discussion, the cause of that difference in electrical potential is not important. It is sufficient to recognize that it does exist, and that it is the cause of lightning.

The charged storm cloud, as it travels through the atmosphere, concentrates beneath it on the surface of the earth a "shadow" of opposite charge, commonly referred to as the "ground charge", or more accurately, the earth surface charge. This ground charge, interacting with the charge in the cloud, produces cloud-to-ground lightning. Since it is cloud-to-ground lightning we are attempting to prevent, and there is little or nothing we can do to affect the storm cloud, it is this ground charge and its behavior with which we must be concerned.

The stages and timing of the development of the actual strike itself are also subject to debate. However, it is generally agreed that, in the case of cloud-to-ground lightning, a stepped leader originates (most often) from the cloud charge, and extends in jumps of a few hundred feet at a time towards the earth. When the stepped leader is within several hundred feet of the ground, the rapidly building electrical field on the ground causes objects to respond by emitting streamers to jump upward from those objects. When a stepped leader and a streamer meet, the ionized channel becomes the path for the main lightning discharge.

Although a lightning strike appears to be a single flash, it is actually a series of flashes. Lightning flashes for approximately one one-thousandth of a second then shuts off for about two one-hundredths of a second, flashes for one one-thousandth of a second then shuts off for about two one-hundredths of a second. This process repeats until the potential differential is no longer sufficient to continue the discharge. Occurrences of lightning flashing over forty times within a single strike have been recorded. The temperature of the channel of the strike can reach 30,000 degrees Kelvin; five times the surface temperature of the sun. An average strike conveys about 20,000 amps, and discharges of up to 200,000 amps can occur.

Having said that, I qualify it by saying that all of the above theory is subject to update as better and faster recording and analyzing techniques are developed.

Electrical storms and lightning are year-round phenomenon. The ingredients necessary for the formation of a thunderstorm are:

* moisture
* an unstable temperature lapse rate
* lifting action

Although they are more likely to be present during the traditional thunderstorm season, these ingredients can occur any time of year. Indeed, one of natures most awesome phenomena is lightning in a snow storm.

LIGHTNING DAMAGE

With a basic understanding of lightning, we can develop an understanding of the different types of lightning damage.

Lightning rods have been perceived to provide sufficient protection from the damage caused by lightning for over 200 years, since our main concern has always been the physical damage of a lightning strike, i.e. the current flow and resulting fire danger. Lightning rod systems are very effective at conducting the discharge current, and the associated heat, away from and around the protected structure to ground. Hence the reduction in fire insurance rates for a structure with an approved lightning rod system.

However, there are other types of damage from a lightning strike; the secondary effect, the electromagnetic effect and ground potential surges. While the lightning rod prevents most physical damage, it cannot mitigate these other types of damage.

The secondary effect can cause arcing and induced currents. During a lightning strike, the point at which the strike occurs is relatively vacated of charge. The area surrounding the point of the strike remains highly charged, causing an almost instantaneous potential gradient across the area. The surrounding area releases its charge to the point at which the strike occurred, causing a flow of current. This current flow can arc across any gaps in its path. If that arc takes place within a flammable material, it can cause a fire or explosion. If the arc takes place within a bearing, it can scar the bearing and cause premature wear. If it takes place on a circuit board, it can damage the circuit board.

The electromagnetic effect can induce currents in nearby wires or other conductors. The on-off-on-off action of a lightning strike causes the electromagnetic field surrounding the strike to expand and collapse with the series of flashes. This electromagnetic field motion can induce electrical currents in nearby conductors, including wires and electrical equipment. Older vacuum tube equipment was relatively less affected by these induced currents. Newer, solid-state electronic equipment is designed to operate on much lower internal currents, and the currents induced by electromagnetic surge can easily be sufficient to cause damage. In fact, microprocessors can be damaged by a nearby strike even if they are not in use or even connected to a power source.

On a typical structure, the structure ground is electrically bonded to the commercial AC electrical power neutral and ground at the service entrance. Indeed, electrical code and common sense require it in most cases. As the ambient ground charge potential rises and falls on the structure and the structure ground, the potential also rises and falls on the AC power neutral and ground. Electrical equipment operates on the difference in potential between the "hot" side and the neutral or ground. The absolute potential is not critical; it is the difference in potential which provides the power. Therefore, if the potential of the neutral (and ground) is varying with changes in the ambient ground charge, equipment damage, particularly computer glitches, can result. When the structure ground takes a direct strike to a lightning rod, the structure ground potential varies drastically over a very short period of time, possible resulting in severe damage to electrical equipment.

It is important to keep in mind that even if a structure is protected by a lightning rod system, and the lightning rod system is 100% effective at conveying all of the current of a direct strike to (or from) ground, electrical equipment in the structure can still be severely damaged by the secondary and electromagnetic effects, and ground potential surges. Particularly with the advent of microprocessors, it has become apparent that we must prevent the strike from occurring to control these types of damage.

LIGHTNING PROTECTION: A THREE-PRONGED ATTACK

Because of the nature of the lightning phenomenon and the different types of damage it can cause, a multi-part approach is necessary to control lightning damage. The first step is effective bonding and grounding. All metallic masses (structural members, buildings, radio racks, etc.) must be electrically bonded together. The primary reason is personnel safety. If an individual is touching two masses when a strike occurs, if there is no bonding between the masses, the individual becomes the path of equalization, often with disasterous results. The secondary reason is equipment protection. Again, if there is no bonding between masses when a strike occurs, the path of equalization often becomes your data or power lines, or arcing takes place. After all masses are bonded together, the electrical potential of the entire bonded mass must be brought to earth potential. Again, the primary reason if personnel safety. The secondary reason is equipment protection.

The second part is surge supression. All lines, including power, telephone, data, etc., entering a facility or structure must be addressed in terms of preventing power surges from entering the facility. Electromagnetically induced power surges caused by strikes to or near power or telephone lines cause untold damage to electrical equipment. As a general rule, the lower the operating voltage of the equipment, the more susceptible it is to surge damage. One approach which can be very effective is to employ a very heavy-duty surge supressor at the service entrance of all incoming lines. This device will absorb the brunt of incoming surges. A second device should be installed at each critical load, as close to the load as possible. This secondary device should perform two functions. First, it should absorb whatever gets past the heavy-duty device, and secondly, it should catch surges induced in wiring between the service entrance and the load.

The third part is generally called structure lightning protection. This term describes what is most readily recognized as the conventional lightning rod system, with its associated bonding and grounding systems. The lightning rod system is designed to intercept any strike which would otherwise occur to the protected structures, and convey the current and resulting heat of the strike safely to ground. The remainder of this paper will address a technology which is essentially an improvement upon, and a outgrowth of, conventional lightning protection technology.

STATIC DISSIPATION FOR LIGHTNING PROTECTION

Static dissipators are relatively low-technology products; products based on technology as old as Ben Franklin. Patents covering the subject go back as far as 1839, with most progress having been made in the late 1920's and early 1930's.

One way to view a static dissipator is as a very efficient lightning rod. The traditional lightning rod offers protection in two ways. First, it dissipates static ground charge to the atmosphere, decreasing the build-up of voltage potential and reducing the possibility of a strike. However, a lightning rod has only one point and it is not sharp enough, electrically speaking, to be a very effective point dissipator. Therefore, when and if the build-up of charge exceeds the ability of the lightning rod to dissipate that charge, the lightning rod performs its secondary function, i.e. it attracts any strike which does occur and conveys it to ground. With a lightning rod you at least have the opportunity, to a certain extent, to designate the target.

One theory of static dissipator operation is that the static dissipator performs the first function of a lightning rod in a highly efficient manner. They bleed-off the ground charge, maintaining it at a value below that which is necessary to trigger a lightning strike. Static dissipators do not dissipate the storm or storm cloud charge to any appreciable extent.

When considering the operation of static dissipators, it is sometimes helpful to consider the nature of the static charge we are attempting to dissipate. It is not a directional current requiring a superb conductor. It is closer in nature to a static pressure. The engine driving the system is the storm cloud charge overhead attempting to pull the static charge off of the structure. One need only provide a low resistance escape for that static charge to the atmosphere. The discharge current produced is in the microampere range, typically under 100 microamps. Indeed, one may conceptually view a static dissipator as converting the 100,000 or so amps discharged over several hundredths of a second by a lightning strike to a current of under 100 microamps discharged over a much longer period of time.

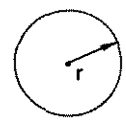
By installing a static dissipation array upon one structure, it does not follow that another nearby object or structure will be more likely to be struck by lightning. Since a static dissipation array functions by reducing the level of ground charge upon a protected structure to a value below that at which a lightning strike to that structure will occur, the likelihood of a strike to any object or structure upwind (or up-storm, if you will) of the protected structure will be unchanged. The likelihood of a strike to any structure downwind of the protected structure will be decreased, such protection decreasing with distance from the dissipator in which the ground charge can re-accumulate and re-build to the level at which a strike may occur.

Another theory of static dissipator operation is related to the formation of upward streamers. As a strike begins to occur, the approach of downward reaching stepped leaders from the cloud intensifies the ground charge, causing objects on the ground to emit upward reaching streamers. When a streamer and a stepped leader meet, the resulting ionized path conducts the main lightning discharge. Various objects on the ground exhibit different behavior in forming streamers, and we can use that to our advantage.

A good analogy is presented by the debate over the relative value of blunt versus pointed lightning rods. A blunt rod will tend not to break down into ionization until under a relatively high potential, i.e. it is difficult for the cloud charge to pull ions off the blunt point. However, under the high potential of an approaching stepped leader, the blunt rod, when it finally breaks down, emits a relatively long streamer upward towards the approaching stepped leaders. A pointed rod, on the other hand, breaks down into ionization under a relatively lower potential, i.e. it is easy for the cloud charge to pull ions off the sharp point. The ionization, or high electric field intensity, around the sharp point does not allow a streamer to extend very far upward. Thus a sharply pointed rod is less likely to be struck.

The same effect explains the operation of a static dissipator. Since a dissipator employs a multiplicity of very sharp points, it does not allow the formation of upward streamers. The sharper the points employed, the greater the effect.

$$\mathcal{E} = \frac{Q}{4\pi\epsilon r^2} \quad \text{and} \quad D = \frac{Q}{4\pi\epsilon r}$$



SPHERE

where:
- $\mathcal{E}$ = electric field intensity
- Q = charge (in coulombs)
- ϵ = permittivity of medium
- r = radius
- D = flux density

These formula relate to point-discharge phenomenon. Point discharge theory holds that electrical discharge from the point of an electrode to a surrounding medium will follow predictable rules of behavior. That discharge creates an electric field around the electrode. The smaller the radius of the dissipator element (actually, the smaller the radius of the sphere of the end of the dissipator element) the greater the electric field intensity, or the greater the dissipation of the ground charge into the surrounding medium, which happens to be the atmosphere. As the dissipator radius approaches zero, the electric field intensity approaches infinity. This electric field intensity and flux density also preclude the formation of streamers.

THE STATIC DISSIPATOR

Ongoing investigation of static dissipation technology, and analysis of the theory and operation of static dissipators, has revealed that the key elements to successful performance are:

* RADIUS of dissipator electrode cross section
* NUMBER of dissipator electrodes
* DENSITY of dissipator electrodes
* CONFIGURATION of dissipator on structure to be protected
* dissipator construction MATERIAL

Electrode radius.

Static dissipation arrays work, as the name implies, by dissipating static charge. The radius of the dissipator electrode cross-section is critical because the phenomenon which enables dissipation of static ground charge to the atmosphere is related to electric field intensity (and flux density) surrounding the dissipator. We are attempting to provide, in effect, a "low resistance" route for the ground charge to reach the atmosphere, thus preventing a build-up of the ground charge to the value necessary to trigger a strike.

Since the electric field intensity will increase as electrode radius decreases, it makes sense to use the smallest radius electrodes possible consistent with structural integrity. In fact, by not using the smallest possible electrode cross section, one would entirely miss the "point" of point discharge. For instance, a dissipator electrode of .015" is not merely three times less efficient as a dissipator electrode of .005". As the above formulae indicate, the radius is squared, hence the factor is not three, but nine.

Number of dissipator electrodes.

Calculating the required number of dissipator points is not an exact science. One must not only dissipate the structure to be protected; one must also dissipate the ground charge, a function of the point on earth upon which the structure rests. The magnitude of the ground charge is a function of the strength and speed of the storm. (It is possible that an elevated structure creates somewhat of a "venturi" effect, drawing more ground charge than that which would normally occupy the point on earth upon which it rests. We have been unable to confirm or measure such an effect.)

Therefore, any formula for, or method of, calculating the required number of dissipator points would necessarily be based primarily on the properties of the storm charge and its accompanying ground charge, and only secondarily concerned with the object or structure upon which it is installed. The calculations would be based upon the absolute difference in potential which must be reduced through dissipation to prevent a strike, and the rate at which that dissipation must occur.

Since we are attempting to accommodate the ground charge produced by the strongest storm, it seems logical to provide as many discharge points as reasonably possible. By using a large number of points one can compensate for any loss of efficiency from the theoretical maximum, and spread the dissipator elements over more of the cross-section area of the structure.

Density of dissipator electrodes.

However, one cannot emulate the patient who, upon being told that three pills was good for him, decided that thirty pills must be better. Concerning the number of dissipator electrodes, there is a point at which more is less.

The density of the dissipator electrodes is critical because of the possibility of interference between points. If the dissipator electrodes are held too close to one another, the points interfere with one another's ability to dissipate.

Experimentation indicates that the smaller the radius of the dissipator electrodes, the closer they can be arranged without interference.

Moderately close spacing of extremely small radius electrodes, while it may lead to some inter-point interference and limited loss of efficiency by individual points, more than compensates for any such loss by providing a greater overall number of points and greater overall dissipating capacity than fewer points spaced further apart. At the extremes, too close spacing results in the dissipating capacity of the array, under heavy discharge, approaching that of a a solid surface, be it a cylinder, plane or toroid: all very poor dissipators. On the other hand, if the dissipator points are too widely spaced, the result is unnecessary supporting structure with resulting excess weight, wind loading, and cost. If dissipator points cease to interfere at a given distance, there is nothing to be gained by increasing that distance.

Assume, for a moment, that there is no problem of interference between dissipator points located in very close proximity to one another. Another limiting factor arises; the ability of the volume of atmosphere surrounding the dissipator points to accept the charge. Therefore, the points must not only be separated to prevent interference, but also be separated to provide a sufficient volume of surrounding atmosphere to avoid "saturating" that surrounding volume of atmosphere. Of course, this does not take into account the effect of wind, usually present in abundance during peak dissipator discharge. Wind presents constantly renewing surrounding volumes of atmosphere, and, if the dissipator electrodes are sufficiently flexible, continuous movement of the points in relation to one another providing momentary increases in spacing.

Configuration of dissipator on protected structure.

All objects have natural dissipation points. On a structure, charge tends to gather at, and dissipate from, the top of the structure (the ultimate point) and from corners. The most effective way to mount a dissipator, in terms of structure, weight, wind loading, cost and aesthetics, is to enhance this natural dissipation by supporting the dissipator from the structure itself at these natural dissipation points. The dissipator itself should be designed to accommodate the ground charge which must be dissipated as it accumulates upon an object or structure. The installation of the dissipator should be designed to enhance the natural dissipation of the object or structure, as opposed to attempting to re-direct that natural dissipation through a structure dedicated to supporting the dissipator elements. In other words, the installation of the dissipator should be tailored to the structure, not vice versa.

On a building or other structure normally protected by air terminals (lightning rods) and the associated bonding and grounding system, existing industry accepted lightning rod system design provides an adequate and proven method and arrangement for mounting static dissipators. One may enhance the system by installing dissipators over, or in place of, the air terminals. The problem with most static dissipation systems is that they lack Underwriters Laboratories listing or other industry accepted accreditation. The installation thereof does not allow insurance and other benefits associated with such accredited systems. However, there is now a line of static dissipating air terminals on the market which are Underwriters Laboratories listed air terminals and offer static dissipating properties. Now a user can enjoy both the benefits of a "Master Label" installation to meet both building codes and insurance carrier requirements, and the benefits of a true static dissipating system.

It was once believed critical to effectiveness that a dissipator be the absolute highest point on a structure. Practical experience has proven it need not be. Indeed, mounting a dissipator too high above the structure in an effort to clear all appurtenances can reduce the level of protection by allowing charge to continue to accumulate at the structure's natural dissipation points, thus allowing a strike to occur at those points.

In certain applications such as electrically floating broadcast towers, it is inadvisable to install anything, including a static dissipator, above the top of the tower. A dissipator which changes the length or other characteristics of a radiating antenna may cause a change in the signal or pattern radiated by that antenna or antennae array, necessitating expensive and time consuming test proofs, retuning and subsequent test proofs.

Dissipator construction material.

The critical qualities of the material used in dissipators are conductivity and durability. The dissipator must be a good conductor to provide maximum discharge of current during normal operation, and, in the unlikely event of a direct strike, a path for current flow in its role as a lightning rod. At the same time, the dissipator must provide a long and trouble-free service life, combining light weight and low wind resistance with durability. Construction material should consist of high quality stainless steel, unless UL requires otherwise. All dissipators should be designed in such a manner that normal dissipation currents are easily accommodated, and, if dissipating capacity is ever exceeded and a direct lightning strike is sustained, they will function as lightning rods.

STATIC DISSIPATOR EFFECTIVENESS

Lightning related phenomena are difficult to measure in the field or to recreate in the laboratory. Proof that static dissipators perform reliably and effectively is elusive and depends upon one's definition of proof. Empirical proof is difficult to obtain since successful performance of a static dissipator is evidenced by the absence of results.

Anecdotal evidence, both positive and negative, is readily available from users of static dissipators and those who have studied this method of reducing the incidence of lightning strikes to a particular installation.

Perhaps the most pertinent type of evidence is statistical evidence. Users who have tracked expenditures of funds due to direct lightning strikes for a reasonable period of time before and after an installation can provide the most useful data, since cost savings is what this particular application of the technology is all about. Manufacturer customer reference lists provide a starting point for obtaining this information, but are obviously limited, since a manufacturer will usually provide only positive referrals.

The problem with a guarantee of effectiveness is developing an accurate understanding of the phenomenon with which we are dealing. If one can accurately describe, for all occurences, the precise nature, cause, and series of events and conditions leading to a lightning strike, as well as the magnitude and rise time of the potential difference which triggers it, along with such other variables as the ability of the atmosphere to absorb dissipated charge, then we can more accurately tailor a particular dissipator to a particular application. Until then, we just do what has historically and cost-effectively worked.

FACTORS SPECIFIC TO HEAVY MOVABLE STRUCTURES

Designing effective lightning protection for heavy movable structures can be best addressed by considering each part of the three-pronged approach to lightning protection discussed above.

Step one, bonding and grounding can present specific problems. Because of the movable nature of the structures, it is critical that steps be taken to assure an adequate and continuous electrical path between components and between all components and ground. This includes components separated be some fixed or changing distance, or components which move upon one another or angularly to one another. In many cases, flexible bonding jumpers can be employed. In other cases, "plug-in" mechanical bonds which require connection by operating personnel can be used, although the problem arises of assuring that the bonds are adequate when and if they are attached.

Step two, surge supression, should not present undue challenges, since the surge supressors should be permanently mounted on the structures.

Step three, static dissipation lightning protection, can be tailored to the structures involved. Careful planning can result in a static dissipation lightning protection system which is effective and aesthetically acceptable. Provisions must be made to accomodate the structures in all possible configurations. By analyzing natural dissipation patterns of the structures in all configurations possible during an electrical storm, a system can be designed to attach directly to the structure and operate at acceptable levels of efficience in all structure configurations.

SUMMARY

Effective lightning protection consists of three complementary facets; bonding and grounding, surge supression, and structure lightning protection. There are two structure lightning protection methods of dealing with direct lightning strikes: lightning rods with a bonding and grounding system to attract and conduct the strike to ground; and, dissipation to the atmosphere of the static ground charge which causes the strike, thereby reducing the likelihood of the strike. The lightning rod system only controls the physical damage of the strike; it does nothing to control the secondary and electromagnetic effect, or AC ground reference potential change damage. Static dissipators, when properly designed, constructed and installed, have all of the benefits of the lightning rod. They also reduce the likelihood of the strike ever occurring, thereby controlling secondary and electromagnetic effect damage.

From the above discussion, it is clear that static dissipation technology can provide a high level of lightning strike protection for heavy movable structures and movable bridges. It is also clear that care must be exercised in dissipator design and installation. It is not, however, an impossible or even very difficult mission, and the technology has been successfully applied on a variety structures with diverse properties similar to many structures you may operate, as well as on movable bridges here in Florida.

Static dissipation technology, when realistically applied in conjunction with bonding and grounding and effective surge supression, can be a cost-effective means of reducing expenditures for damage due to direct lightning strikes. The technology has a remarkable track record of sucess in the field. A properly designed, constructed, configured and installed dissipator can help save you money. However, it is not a stand-alone solution, but must be used as part of the three-pronged attack on lightning.

08/15/90