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Environment

Proactive Lightning Protection Concepts

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Lightning Strike Protection

Introduction

"Struck by lightning" is a metaphor for sudden, unpredictable disaster. A large thunderstorm can produce over 100 lightning flashes a minute, and even a modest storm cloud can generate the energy of a small nuclear power plant (a few hundred megawatts) Not all lightning strikes the ground but, when it does, that energy can be devastating. For a drilling rig to be shut down for hours or days due to equipment damage, or a chemical plant to have fires started by lightning, is a costly and hazardous risk.

Until relatively recently, there was little that could be done to minimize this risk. Lightning strikes when and where it will. Traditional lightning protection has sought to collect and divert the energy of a lightning strike into the ground. While this may avoid some of the worst effects of a direct strike, it has some serious drawbacks.

None of the traditional systems are 100 percent effective, and all suffer from the secondary effects related to the close proximity of the electrostatic and electromagnetic fields. They are dangerous to flammables, explosives, and electronics.

The unanswered question is, why collect the strike in the first place, when strikes always create side effects that must be dealt with? New technologies have demonstrated that it is possible to eliminate the strike altogether, thereby avoiding all of the risks.

The Charge Transfer System (CTS) has proven its effectiveness as a system to prevent lightning from striking the protected area. Such as chemical plants, nuclear power plants, oil and petroleum facilities, off shore drilling rigs and many other installations. [1].

What is the Problem?

There is no question about the hazards posed by lightning strikes and their associated effects. Fires, injury or loss of life, damage and destruction of property, and the significant downtime and outage-related revenue losses due to equipment damage all make lightning a serious threat. While the direct effects of a strike are obvious, the secondary effects can be just as devastating. This is especially true for electrical power lines and facilities with sensitive electronic equipment.

Direct Effects

The direct effects of a lightning strike are physical destruction caused by the strike and subsequent fires. When a direct strike hits a facility where flammable materials are present, the flammables may be exposed to the lightning bolt itself, the stroke channel, or the heating effect of the lightning strike.

The petroleum industry's history provides ample evidence of the destructive nature of lightning activity. Millions of dollars of petrochemical products and facilities are destroyed each year by lightning-related phenomena in many parts of the world, and lives are lost when these facilities are ignited or explode. For example, in the Nigerian fire of 1990, a 670,000-barrel tank was set on fire by lightning. The tank full of light crude was lost, plus the tank itself, even though the Nigerian tank was "protected" with a conventional radio active system. Clearly, traditional protection systems are not sufficiently effective.

It is true that the risk of loss of one tank of product is small. But it is also true that preventing the loss of one tank and product in one country will usually pay for the protection of all the storage facilities in that country.

Secondary Effects

The secondary effects of a direct or nearby strike include the bound charge, electromagnetic pulse, electrostatic pulse, and earth currents. The bound charge (and subsequent secondary arc) is the most common. (These effects are discussed in greater detail in the next section on how lightning works.)

Statistics indicate that the secondary effects cause most of the petroleum-related fires, far more than are actually reported. These fires often self-extinguish after the free or isolated vapors are burned. For example, the electrostatic and electromagnetic pulses induce high-voltage transients onto any conductors within their sphere of influence. These transients will cause arcing between wires, pipes and earth. Again, arcs in the "right" place initiate both fires and explosions.

The secondary effects are not always easily identified as to cause or mechanism. Conventional protection will not influence any of these secondary effects other than to increase the risk of an event. Air terminals collect strikes and encourage a stroke termination in close proximity to flammable materials.

In addition, the trend toward micro-miniaturization in electronic systems development brings an increasing sensitivity to transient phenomena. Transients of less than 3 volts peak or energy levels as low as 10^{-7} Joules can damage or "confuse" these systems and their components.

Power Lines

Power line voltage anomalies are the greatest source of destructive and disruptive phenomena that electrical and electronic equipment experience in day-to-day operations.

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There are four basic sources of anomalies: lightning, the local utility, your neighbors, and your own equipment. Each of these creates its own form of anomaly. Of these sources, lightning is obviously the greatest normal threat in terms of potential destruction and disruptive phenomena. A direct strike to the power line at the service entrance can cause significant damage inside unprotected or improperly protected facilities. A facility adequately protected against lightning is also protected against other anomalies. In applications where the power is generated on site, like offshore drilling rigs, the likelihood of these transients is diminished, but there is still a possibility.

While the causes of power line anomalies may vary significantly with location, the results are the same. Either the equipment will fail immediately or degrade over a period of time. The failures may be catastrophic or some form of momentary or long-term lockup, requiring replacement, repair, reprogramming, or rerun of the program in progress. Any of these events can result in lost time and money. All of these events can be totally eliminated with the appropriate power conditioning equipment, properly installed and maintained. Most of these events can be eliminated through the correct use of relatively inexpensive protection equipment.

How Lightning Works

Since the first awareness that lightning is an electrical discharge, scientists and engineers have studied thunderstorms and lightning extensively (although protection against lightning has not changed substantially since Benjamin Franklin's time). While centuries of study and new sophisticated instruments have greatly expanded our knowledge, there is still much about these phenomena that are not clearly understood. To understand how lightning protection works and which system is most appropriate for different applications, an overview of the phenomena is needed. [2]

Mechanics of the Strike

Thunderheads are electrically charged bodies suspended in an atmosphere that may be considered, at best, a poor conductor. During a storm, charge separation builds up within the cloud. The potential at the base of the cloud is generally assumed to be about one hundred million volts and the resulting electrostatic field about 10 kV per meter of elevation above earth. The charging action (or charge separation) within the storm cell usually leaves the base of the cloud with a negative charge, but in rare cases the opposite seems true.

This resulting charge induces a similar charge of opposite polarity on the earth, concentrated at its surface just under the cloud and of about the same size and shape as the cloud (see Figure 1).

As a storm builds in intensity, charge separation continues within the cloud until the air between the cloud and earth can no longer act as an insulator. The specific breakdown point varies with atmospheric conditions.
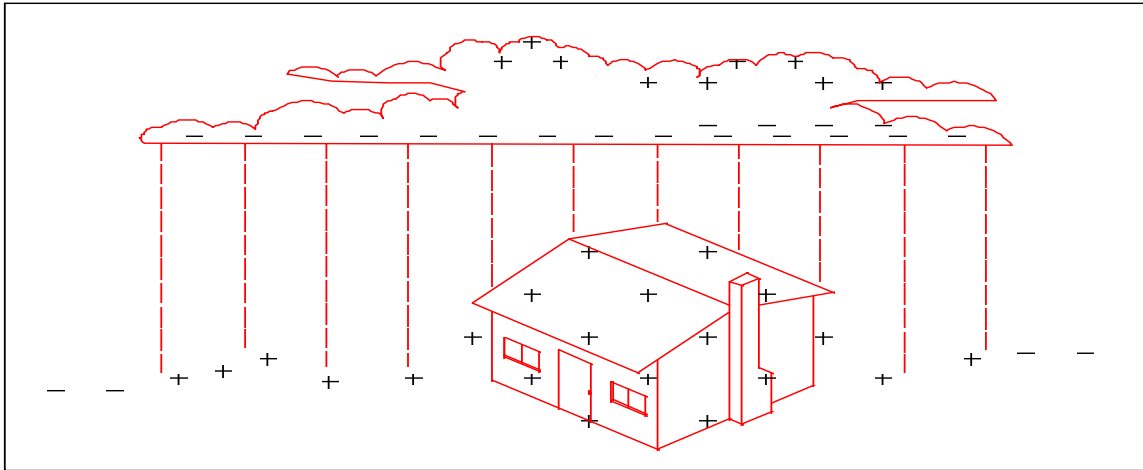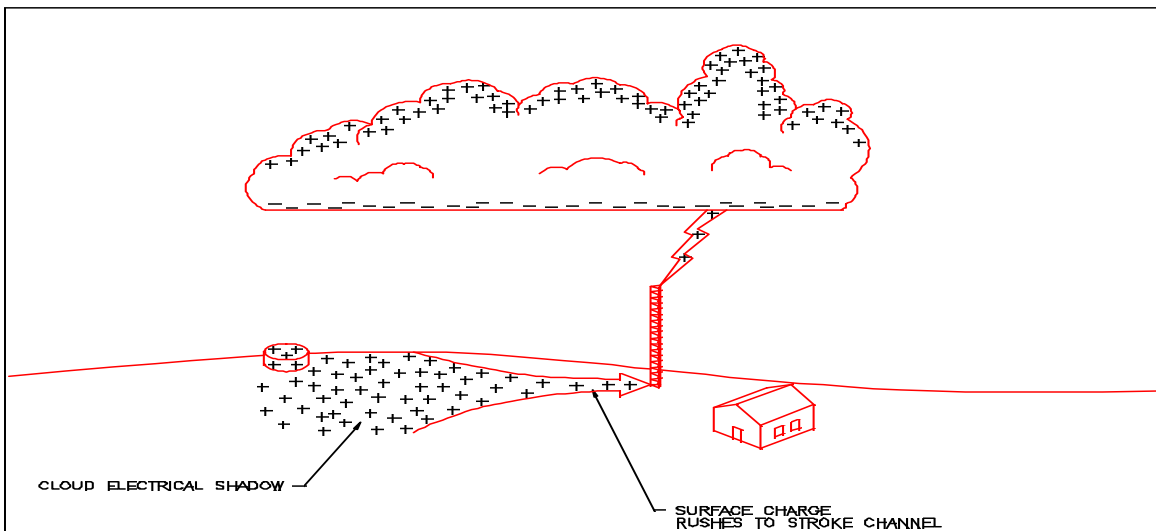

Figure 1: Charge Separation

Low intensity sparks called "step leaders" form, moving from the base of the cloud toward earth. These steps are of about equal length, and that length is related to the charge in the storm cell as well as the peak current in the strike. These steps vary in length from about 10 meters to over 160 meters for a negative stroke. As the leaders approach earth, the electric field between leaders increases with each step. Finally, at about one step distance from earth (or an earthbound facility) a "strike zone" is established, as illustrated by Figure 2. A strike zone is hemispherical in shape, with the radius equal to one step length. The electric field within the strike zone is so high that it creates upward moving streamers from earthbound objects. The first streamer that reaches the step leader closes the circuit and starts the charge neutralization process.
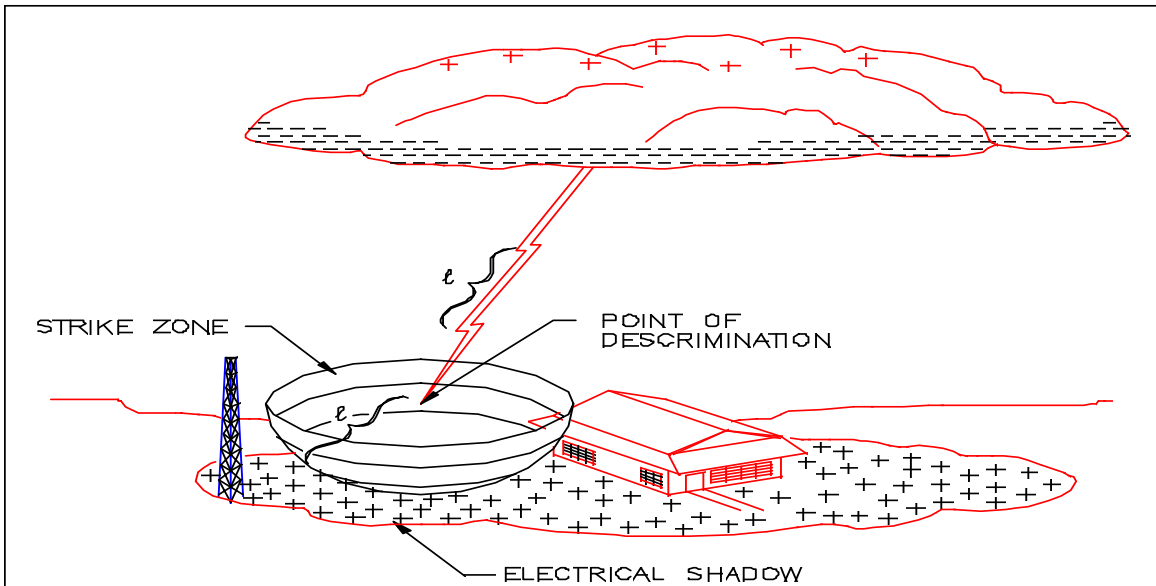
Figure 2: The Strike Zone

When structures intervene between the earth and the storm cells, the structures are also charged. Since they short out a portion of the separating air space, they can trigger a strike because the structure reduces a significant portion of the intervening air space.

Charge neutralization (the "strike") is caused by the flow of electrons from one body to the other, such that there is no resulting difference of potential between the two bodies (see Figure 3). The process creates the same result as shorting out the terminals of a battery.

Figure 3: Charge Neutralization ("Strike")

Secondary Effects

A flash is defined as the ionized channel resulting from the lightning discharge; a stroke is one surge of current in that channel. There are four separate secondary effects that accompany the flash. These are:

- Electromagnetic pulse (EMP)
- Electrostatic pulse
- Earth current transients
- Bound charge

Electromagnetic Pulse

The electromagnetic pulse is the result of the transient magnetic field that forms from the flow of current through the lightning stroke channel. After the lightning stroke channel is established between the cloud and earth, it then becomes a conductive path like a wire. The neutralization current commences to flow very rapidly, with the rate dependent on the channel path impedance and the charge within the cloud. The rate of rise of these current pulses varies by order of magnitude. They have been measured at levels of up to 510 kA per microsecond. A practical average would be 100 kA per microsecond.

Transient currents flowing through a conductor produce a related magnetic field. Since these discharge currents rise at such a rapid rate and achieve peak currents in the hundreds of thousands of amperes, the related magnetic pulse they create can be quite significant. The resulting induced voltage (EMP) within any mutually coupled wiring can also be significant (see Figure 4).
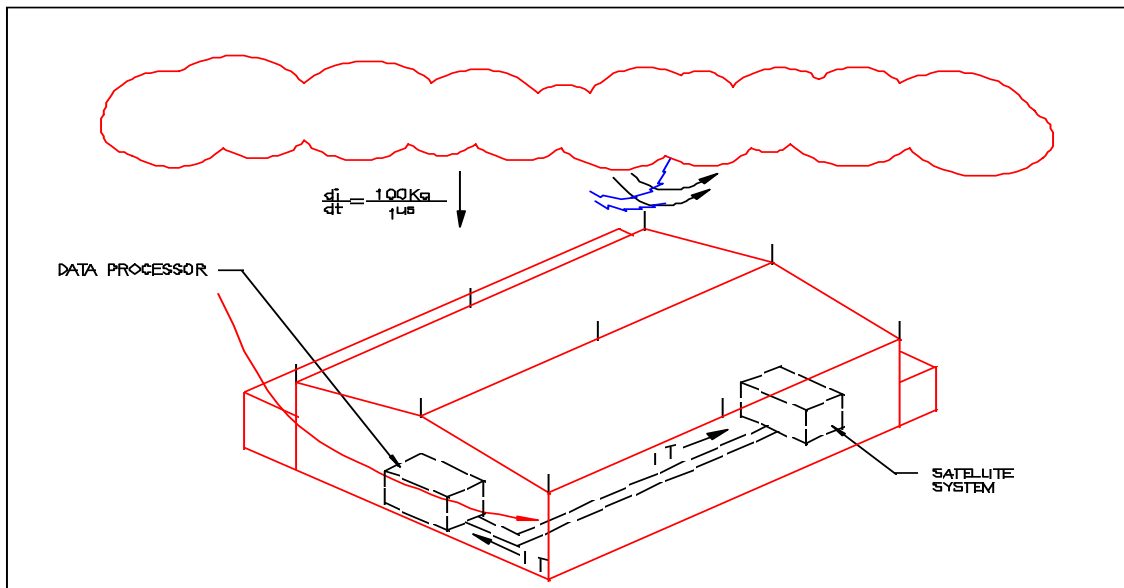

Figure 4: Stroke Channel EMP

As the charges build up in the clouds, a downward step leader is initiated at the bottom of the thunderclouds. As the downward step leader approaches the ground, an upward step leader meets it, and the return stroke occurs. A huge amount of charge accompanies this return stroke, which acts like a giant traveling wave antenna generating strong electromagnetic pulse waves. Therefore, lightning EMP can propagate for a long distance and affect large areas (see Table 2).

Table 2

Lightning Return Stroke Data

Return Current I	5 kA - 200 kA
di/dt	7.5 kA/µs to 500 kA/µs
Velocity	1/3 Speed of Light
Length (height of thunderclouds)	3-5 km above grade

Any elevated transmission/data line will also suffer from lightning EMP interference, regardless of the usual shielding. The lightning EMP has a very wide spectrum, and most of its energy is in the low frequency portion. Therefore, lightning EMP could penetrate the shielding and interfere with the system.

The EMP also has a related secondary effect resulting from the current flowing into the grounding system. In this situation, the fast-changing current in time (di/dt) creates a magnetic field which is now mutually coupled to any underground (within-ground) wiring that passes nearby, over or parallel to any part of that grounding system. Again, the mutual coupling results in the transfer of energy (EMP) into the underground wiring (see Figure 5). That energy may not always be harmful to the entering electrical service; however, it will most likely be high enough to damage data circuits.
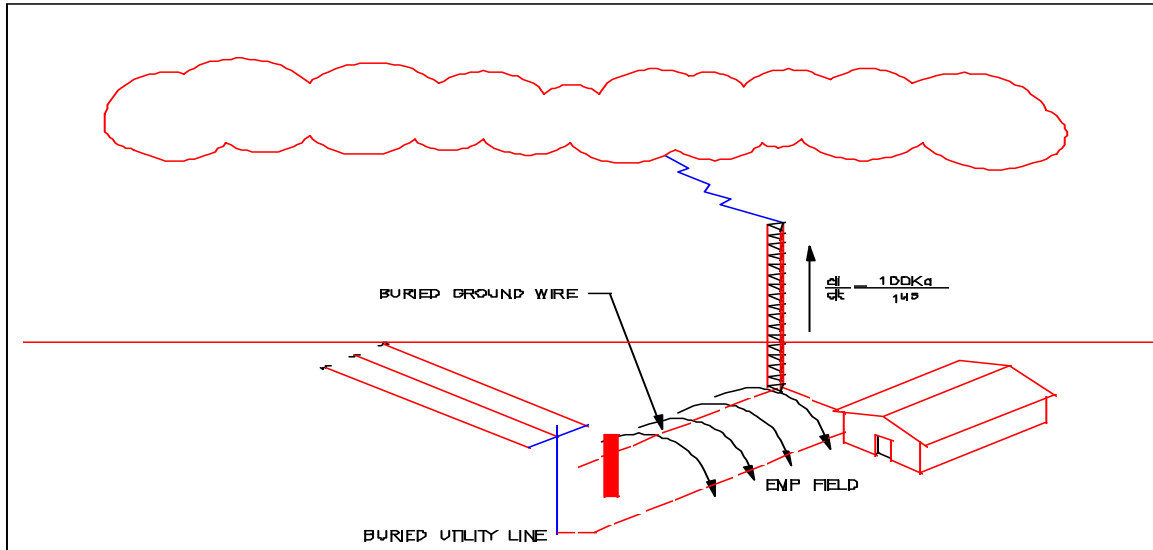
Figure 5: Grounding Current EMP

Electrostatic Pulse

Atmospheric transients or electrostatic pulses are the direct result of the varying electrostatic field that accompanies an electrical storm. Any wire suspended above the earth is immersed within an electrostatic field and will be charged to that potential related to its height (i.e. height times the field strength) above local grade. For example, a distribution or telephone line suspended at an average of 10 meters above earth in an average electrostatic field during a storm will take on a potential of between 100 kV and 300 kV with respect to earth. When the discharge (stroke) occurs, that charge must move down the line searching for a path to earth. Any equipment connected to that line will provide the required path to earth. Unless that path is properly protected, it will be destroyed in the process of providing the neutralization path. This phenomenon is known as the atmospherically induced transient. The rising and falling electrostatic voltage is also referred to as the Electrostatic Pulse (ESP). (See Figure 6.)
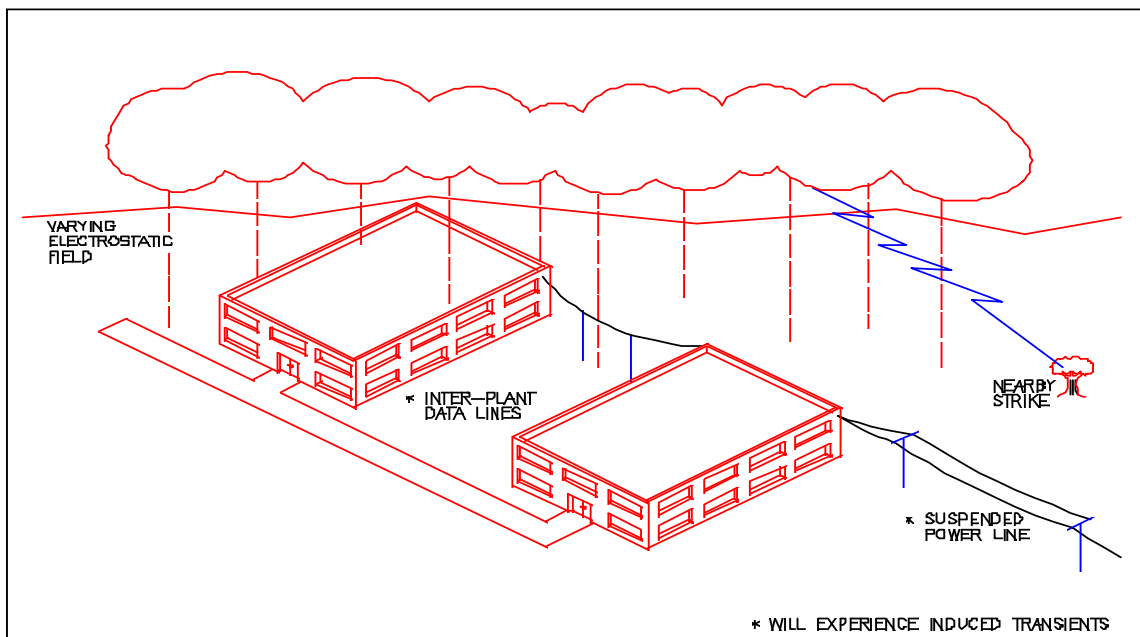
Figure 6: Electrostatic Pulses

According to electromagnetic theory, static charges build up on the surface of any object on the ground. The charge density is proportional to the magnitude of these static electrical fields. The higher the charge density, the higher the risk of a termination of the downward step leader.

A vertically erected metallic object immersed in these static electric fields, especially one having a sharp point, has a considerable potential difference with respect to ground. If the object is not grounded, it can cause sparks and in some hazardous locations ignite fire or upset sensitive electronic equipment.

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Earth Currents

The earth current transient is the direct result of the neutralization process that follows stroke termination. The process of neutralization is accomplished by the movement of the charge along or near the earth's surface from the location where the charge is induced to the point where the stroke terminates. Any conductors buried in the earth within or near the charge will provide a more conductive path from where it was induced to the point nearest the stroke terminus. This induces a voltage on those conductors that is related to the charge which is, in turn, related to the proximity of the stroke terminus.
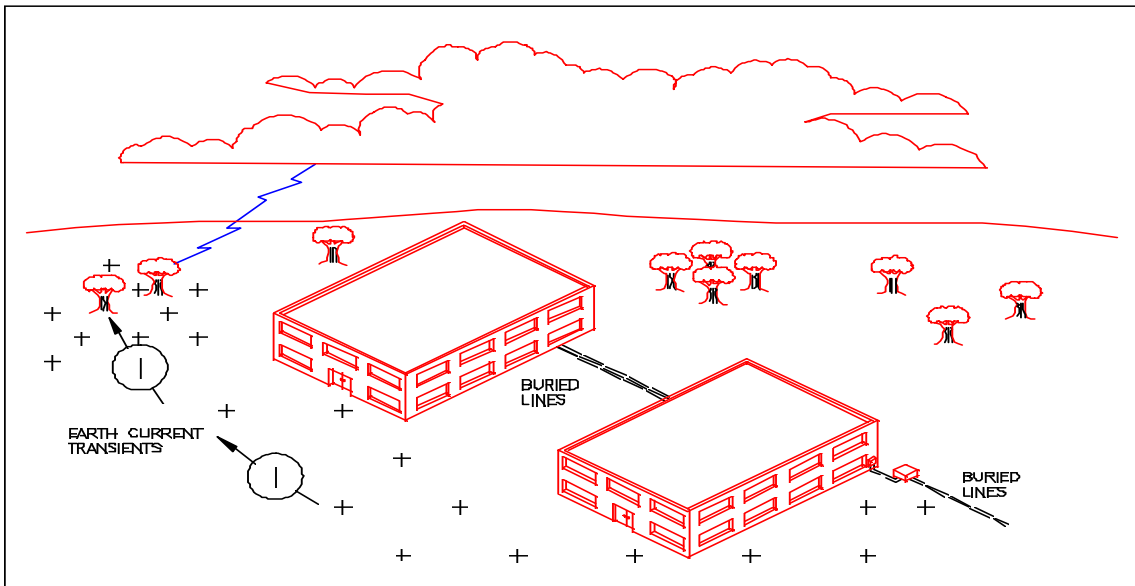
Figure 7: Earth Current Transients

This induced voltage is called an "earth current transient". It will be found on wires, pipes or other forms of conductors. If the wires are shielded, the internal wires will experience the first derivative of the shield current flow. Since the discharge process is fast (20 microseconds) and the rate of rise to peak is as little as 50 nanoseconds, the induced voltage will be very high (see Figure 7).

The termination of a return stroke on ground may cause the following effects:

1. It may cause arcing through the soil to an adjacent gas pipeline, cable, or grounding system. (A 50 kV/m breakdown gradient is usually assumed. For example, the foot resistance of a power tower is 10 Ohms, the return stroke current is 200 kA, and the minimum separation distance is 40 meters.)

2. Surge current may be coupled by soil to the existing electronic grounding system, which causes a non-uniform Ground Potential

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Rise (GPR) distribution in the ground system. For example, two buried 10 meter ground wires with a grounding resistance of 31.8 ohms are separated by 5 meters. As a 75 Ampere current is injected into one of the ground rods, the other rods will have a voltage rise of approximately 188 volts.

Bound Charge

The most common cause of lightning-related petroleum product fires is the phenomenon known as the "bound charge and resulting secondary arc" (BC/SA)

To understand the risk of the BC/SA, it is necessary to understand how the bound charge is formed and how the secondary arc results in a fire. The storm cell induces the charge on *everything* under it. That charge (ampere-seconds) is related to the charge in the storm cell. Since petroleum products are usually in a conductive metallic container, that container and everything in it takes on the charge and related potential of the local earth. Since the charging rate is slow, the product will take on the charge as well as the tank.

The earth is normally negative with respect to the ionosphere. When a storm cell intervenes between the ionosphere and earth, the induced positive charge replaces the normally negative charge with a much higher positive charge. The container (tank) is at earth potential, which is the same as the surroundings, positive before the strike, but instantly negative after the strike.

The secondary arc results from the sudden change in charge (20 microseconds) of the tank wall and the unchanged state of the contained product's charge.

Grounding will have no significant influence on the potential BC/SA phenomenon. Conventional lightning protection cannot prevent the bound charge/secondary arc because there is no discharge path available.

Solution

Since 1971, engineers have developed specialized expertise in the field of lightning protection. While traditional lightning strike protection methods may be adequate for some installations, when more complete protection is needed, custom designed systems meet more exacting requirements.

Engineering an appropriate solution is more complex than simply putting up a lightning rod. Each site is evaluated for risk factors, geography, soil type, and many other parameters before a protection plan can be implemented. For many reasons, there can be no "one size fits all" solution to lightning strikes.

Risk Factors

The Keraunic number (lightning days per year), or isokeraunic level, is a measure of exposure rate. The higher the Keraunic number, the greater the stroke activity encountered in that area. In the United States this number varies from a low of 1 to over 100. In other parts of the world, it is as high as 300. There is an average of 30 storm days per year across the United States, and many strokes occur in a single storm. Studies have shown that for an average area within the USA there can be between eight and eleven strokes per year to each square mile. Within the central Florida area, the risk is increased to between 37 and 38 strikes per square mile per year.

Structural characteristics such as height, shape, size, and orientation also influence this risk. For example, higher structures tend to collect the strokes from the surrounding area. The higher the structure, the more strokes it will collect. High structures will also trigger strokes that would not have otherwise occurred. Further, since storm clouds tend to travel at specific heights with their bases starting at five to ten thousand feet, structures in mountainous areas tend to trigger lightning even more readily.

The system exposure factor for a transmission line provides an example. Consider a 50-mile stretch of transmission line in central Florida. According to data from the IEEE Subcommittee on Lightning, there should be about 1500 strokes per year to the line (total to the static wire and phase conductors). Two hundred twenty-five of these will exceed 80,000 amperes, all in just one average year.

Prevention System Options

Since different facilities have different kinds of problems with lightning, it is important to understand the capabilities and limitations of each type of protection system. In most cases, one or more products can be adapted to solve any lightning protection problem. The following discussion briefly outlines features of the static ionizer, the Ground Current Collector (GCC), and various types of Transient Voltage Surge Suppression (TVSS).

Charge Transfer System (CTS)

Lightning is the process of neutralizing the potential between the cloud base and earth. Any strike *prevention* system must facilitate this process slowly and continuously. The Dissipation Array® System (DAS®) is one of the most common configurations of a Charge Transfer System (CTS) and has been designed to prevent a lightning strike to both the protected area and the array itself. Some or all of these may be used in designing a particular protection system (see Figure 8).
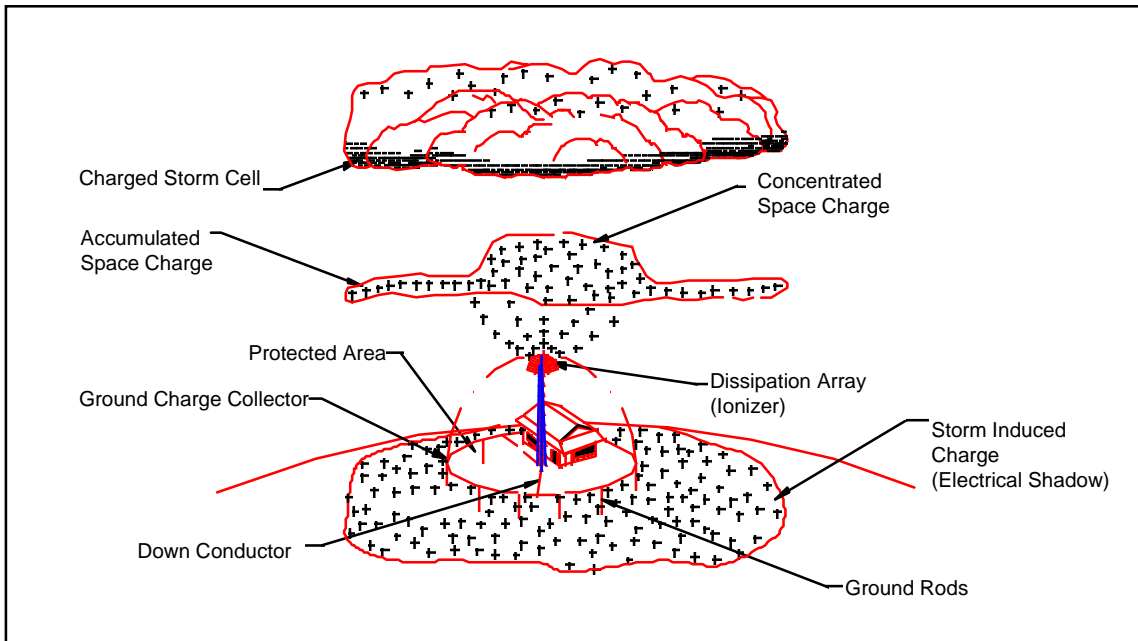
Figure 8: Dissipation Array Charge Transfer Concept

To prevent a lightning strike to a given area, a system must be able to reduce the potential between the site and the storm cloud cell, so that the potential is not high enough for a stroke to terminate within the area. That is, the protective system must release, or leak off, the charge induced in the area of concern to a level where a lightning stroke is impractical. (Charge induction comes about because of the strong electric field created by the storm and the insulating quality of the intervening air space.)

Atmospheric scientists have found that much of the storm's energy is dissipated through what is called natural dissipation, which is ionization produced by trees, grass, fences and other similar natural or man-made pointed objects that are earthbound and exposed to the electrostatic field created by a storm cell. For example, a storm cell over the ocean will produce more lightning than the same cell over land, because the natural dissipation of the land will reduce the storm's energy. Consequently, a multipoint ionizer is simply a more effective dissipation device, duplicating nature more efficiently.

The point discharge phenomenon was identified over one hundred years ago. It was found that a sharp point immersed in an electrostatic field where the potential was elevated above 10,000 volts would transfer a charge by ionizing the adjacent air molecules.

The Charge Transfer Systems are based on using the point discharge phenomenon as a charge transfer mechanism from the protected site to the surrounding air. The electrostatic field created by the storm cell will draw that charge away from the protected site, leaving that site at a lower potential than its surroundings.

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The DAS Ionizer

The DAS/SBI Ionizer is a multipoint device. It is designed to efficiently produce ions from many points simultaneously. As the electrostatic field increases, a single point will create streamers and encourage a strike. In contrast, the multipoint ionizer starts the ionization process at a somewhat higher potential; but as the potential increases, the ionization current increases exponentially. Since these ions are spread over a large area, no streamers are generated. In extreme situations, a luminous cloud of ions is produced, causing a momentary glow around the array and a sudden burst of current flow.

The ionizer assembly is very sensitive to a number of design parameters, some of which can be reduced to formulation, others which cannot. These factors include size, shape, elevation, point shape, point height above the array face, point spacing, range in wind velocity, plus the character and relationship of the surroundings. Thus, effective system design remains as much an art as a science.

Grounding System

The ionizer assembly alone, of course, is not sufficient. The system must be grounded. The Ground Current Collector (GCC) provides the source of charge to keep the ion current flowing through the array and discharge the site. The GCC in a land base application can be the existing ground gird if the ground grid contains horizontal bare interconnecting conductors commonly connected together and the earth contact (ground) is measured to be five (5) ohms or less.

In offshore applications, the grounding approach is different as there is no ground to interface with. But, in these applications, the only criteria is to make a positive contact with the ocean/water. Because of the conductive elements in the water, once this contact is made with this conductive body, the grounding requirements are achieved. In order to ensure a long-term low-impedance contact there should be at least two redundant connections for the CTS to the grounding system.

Transient Voltage Surge Suppression (TVSS)

As mentioned earlier, voltage line anomalies are the greatest source of destructive and disruptive phenomena that electrical and electronic equipment experience in day-to-day operations. These anomalies can be prevented or mitigated in electrical substations, along power lines, at the entrance to an individual facility, or on internal data lines. LEC's surge suppression devices address all of these applications. A protective system must both prevent instant loss or catastrophic failures and protect the system's reliability.

Power Lines

Two classes of protectors are used to protect power lines against lightning-related anomalies:

- **Parallel Protectors** are installed between phase conductor(s) and ground (or neutral). They may include gas tubes, metal oxide varistors, and avalanche diodes, used in some parallel configuration. Often more than one device is used. The positive benefits are that they are easy to install and relatively inexpensive, but they typically involve some compromises in performance.

- **Series Hybrid Protectors** are installed in series with the phase conductors, with several parallel devices used to dissipate the surge energy and limit the peak voltage. The major benefit is performance. By inserting a series inductor in the power line, a high impedance at mid-range is set to the frequency of the lightning-related impulse (average equals 1 MHz). This expedites turning on the primary elements, shunting the bulk of the surge to ground, and allowing the secondary protection to clip off any remaining let-through voltage transient.

In and On Buildings

The IEEE (Institute of Electrical and Electronic Engineers, Inc.) C62.41-1991 standard was generated to establish surge guidelines to which electronic equipment would be exposed in a field environment, depending on their installation location. This standard was revised in 1991 to reflect the effects of location on system exposure. For example, a product in Florida (number of lightning days per year = 100) would not have the same exposure risk as the same product would have in California (number of lightning days per year = 5).

When testing any product, such as a computer or a surge protector, it is imperative that the proper tests be performed. Most engineers will only think of a surge existing either hot-to-ground or hot-to-neutral. In reality, a surge can be induced in all four modes: hot-to-ground, hot-to-neutral, neutral-to-ground and hot-and-neutral-to-ground. For example, if a standard plug-in surge protector is only providing hot-to-neutral protection, the device is vulnerable to impulses applied on the other modes. When reviewing specifications on plug-in surge protectors, be careful to check that all modes are protected.

The IEEE standard separates the impulse tests by location, defined as Category A, B, and C. Category C is for service entrance installations. This includes any device installed outside the building or as the power enters the building near the service disconnect, or for runs between the meter and distribution panel. Category B includes major feeder and short branch circuits, such as distribution panels more than 30 feet inside the building, or lines that are run for heavy appliances. Category A includes

long branch circuits and all outlets more than 30 feet from Category B with wire size ranging from #14AWG to #10AWG.

NOTE: All electronic equipment surge suppressors must be evaluated based on installation location.

Conclusion

The risks from lightning are real, and traditional lightning protection devices do not adequately cover all the risks. The secondary effects which cause much of the damage are in fact increased by collecting strikes.

Over the last 30 years there have been newly developed proven CTS technologies which can eliminate lightning strikes from a protected area. When eliminating the strike to the protected zone and the associated structure, the secondary effects of lightning are, if not completely eliminated, reduced. If a lightning strike could put a facility out of business, or even out of action for a few hours, consider whether the cost of preventing all future risks from lightning would not easily offset the cost of installing a CTS lightning elimination system. It is inexpensive insurance.

Selected Bibliography

Carpenter, Roy B. "Lightning Prevention for Transmission and Distribution Systems", American Power Conference, Chicago, IL, Vol. 49, 1987.

.... "Lightning Strike Protection, Criteria, Concepts and Configuration", Report No. LEC-01-86, Revised 1993.

.... "New and More Effective Strike Protection for Transmission Distribution Systems", 1992.

Chalmers, Alton. "Atmospheric Electricity", Pergamon Press, 1967.

Davis, Charles. "Lightning and Fiber Optics, Transmission and Distribution", World Expo 92, Indianapolis, IN, 1992.

Eriksson, A. J. "The Incidence of Lightning Strikes to Power Lines", IEEE Transactions on Power Delivery, 3 July 1987.

Golde, R. H. "Lightning Performance of High Voltage Distribution Systems", Proceedings of the IEEE, 113 No. 4, April 1966.

Grzybowski, Stan. "Effectiveness of Dissipators Used for Lightning Protection on 115 kV Distribution Lines", (Rev. 1) Final Report dated Jan. 1992.

Lightning Protection Manual for Rural Electric Systems, NRECA Research Project 82-5, Washington, DC, 1983.

Merrit, S. "Design Charts to Relate Transmission Line Parameters to Flashover Probability", Union Camp Paper, Franklin, VA, 1988.

Uman, Martin. "The Lightning Discharge", Academic Press, 1987.

Williams, Earle. "The Electrification of Thunderstorms", in The Enigma of Weather, Scientific American, 1994.