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"PROTECTION SYSTEM DESIGN FOR EQUIPMENT RELIABILITY AND LONGEVITY"

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Paper Title: PROTECTION SYSTEM DESIGN
FOR EQUIPMENT RELIABILITY AND LONGEVITY

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Mr. Kaiser also serves on the National Fire Protection Association Technical Committee on Lightning Protection, NFPA 780, and on the Technical Committee on Lightning Protection Systems Using Early Streamer Emission Air Terminals, NFPA 781.

PROTECTION SYSTEM DESIGN
FOR EQUIPMENT RELIABILITY AND LONGEVITY

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The reliability and longevity of sensitive microprocessor-based equipment can be enhanced dramatically by a simple and cost-effective approach to protection system design. As movable structures are updated to high-speed microprocessor-based control systems, they become as vulnerable to transients as the most sensitive computer facility.

The basis of transient protection is found in an effective lightning protection system consisting of properly designed bonding and grounding, transient voltage surge suppression, and structural lightning protection. If a facility can be protected from lightning, the most dramatic form of transient, it can be protected from more pedestrian transients, thus increasing equipment reliability and longevity.

BACKGROUND

The Lightning Phenomenon

As the storm cloud builds, various mechanisms create a stratified charge within the storm cloud, with an electrical charge at the base of the cloud. As the storm cloud travels through the atmosphere, it induces a "shadow" of opposite charge on the surface of the earth beneath it.

As the storm cloud travels above the earth's surface, it drags the ground charge along beneath it. When the ground charge reaches a structure, the storm cloud charge pulls it up on, and concentrates it upon, the structure. If, before the storm cloud travels away, it manages to concentrate enough ground charge so that the difference in potential between the storm cloud charge and structure exceeds the dielectric strength of the intervening air, the air breaks down electrically, and a potential equalizing arc occurs - a lightning strike.

When the intervening air breaks down, the strike itself begins with the propagation of stepped leaders. Stepped leaders originate within the cloud charge, and extend in jumps of fifty meters or so towards the earth. These are the wispy, downward reaching branches of light you see in a photograph of a strike. When the stepped leaders reach to within about one hundred and fifty meters of the ground, the rapidly building electrical field on the ground causes objects on the ground to break down electrically and respond by emitting streamers to jump upward toward the stepped leaders. When a stepped leader and a streamer meet, the ionized channel becomes the path for the main lightning discharge. The other stepped leaders and streamers never mature.

When the ionized path is completed, the current discharge occurs. 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 above description applies to a negative cloud-to-ground strike, which accounts for the vast majority of cloud-to-ground strikes

Lightning Damage

Lightning damage essentially takes four different forms; physical damage, secondary effect damage, electromagnetic effect damage and ground potential change damage.

Physical damage is caused by the current flow and heat of a lightning strike. An average lightning strike conveys anywhere from 20,000 to 45,000 amps (depending on the area of the country), and discharges of up to 200,000 amps can occur. The temperature at the core of the strike can reach 30,000 degrees Kelvin, or five times the surface temperature of the sun. This current flow and heat build-up can cause physical damage and fires. If the lightning current enters facility equipment, it can destroy components. If the heat is allowed to come in contact with an unprotected structure, it can damage the structure.

Secondary effect damage is caused by the motion of ground charge. During a lightning strike, the point on the surface of the earth at which the strike occurs is relatively vacated of ground 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 ground charge. 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 it takes place within a bearing, it can scar the bearing and cause premature wear. If the arc takes place on a circuit board, it can damage the circuit board.

The electromagnetic effect of lightning can induce transients in nearby conductors. A single lightning strike is actually made up of a series of flashes. This 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 surges can easily be sufficient to cause damage.

Changes in ground potential during a strike can introduce damage to equipment and components from the grounding system. If a facility is served by multiple services, i.e. AC power, TELCO, data, coaxial cable, etc., and the services are not commonly grounded, or if multiple chassis grounds exist, unwanted current flow can be introduced into facility wiring. When an area of ground charge moves onto a facility and there is a strike within that area of ground charge, because of the secondary effect the potential across the facility, and therefore the service and chassis grounds, changes dramatically and very quickly. Since current divides among available paths, this results in unwanted current flow along AC power, TELCO, data and RF wiring, and equipment damage can result.

It should be obvious that a properly designed lightning protection system must address all four types of lightning damage. Structural lightning protection provisions can divert the current and heat from strikes around the structure to ground. Secondary effect and ground potential change damage can be addressed with a system of single point ground potential referencing and proper equipment bonding. Electromagnetic effect damage can be mitigated by all-mode transient voltage surge suppression. All three sub-systems must be designed and installed in a complementary manner.

SYSTEM SOLUTION

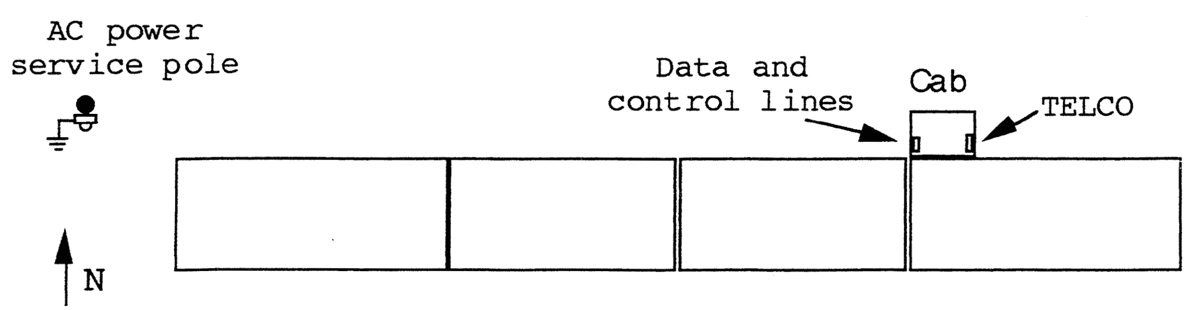
When we make recommendations as the result of a survey of a structure for transient protection, we are, in effect, comparing that structure to an ideal standard, and attempting to bring the surveyed system up to the standards of the ideal system.

What constitutes the ideal system and how can we design to that standard from the outset? In essence, the ideal system consists of three sub-systems: bonding and grounding, transient voltage surge suppression, and structural lightning protection. Let's look at each component separately.

Bonding and Grounding

Bonding is simply a matter of connecting all of the electrical and metallic masses within a structure so they are all at the same electrical potential. Grounding is simply a matter of bringing the potential of the bonded mass to the potential of the surface of the earth it occupies. What we found to be critical is the manner in which that connection is made.

A structure normally has several different services entering it: AC power, TELCO, and control and data lines. If these services enter the structure at multiple locations, and each service is grounded at that location, the difference in ground potential on those services during a nearby lightning strike can cause equipment damage. Consider the draw bridge example shown below.

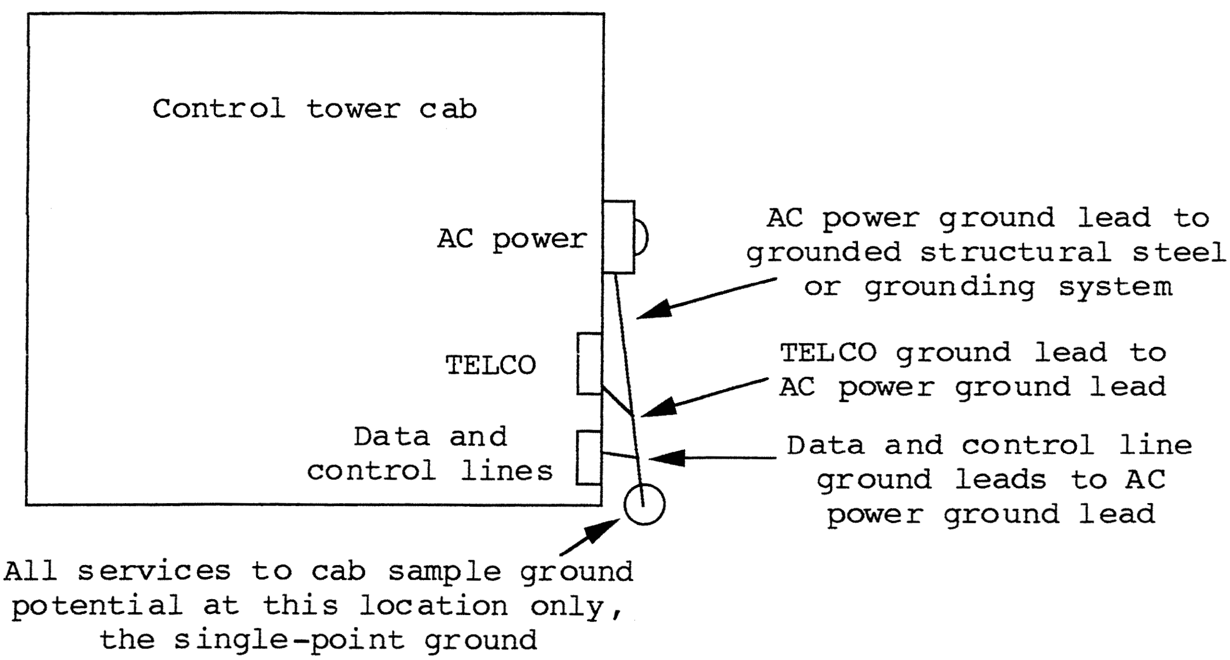


Draw Bridge
(plan view)

Each service is grounded at a different location: the AC power at the service pole off the west end of the bridge, TELCO at the east side of the cab to structural steel, and control and data lines at the west side of the cab.

When lightning strikes off in the woods near the site, the ground potential changes across the bridge due to secondary effect. The propagation rate of the ground charge causes a difference in ground potential at each service entrance ground. The equipment within the cab therefore sees a difference in potential between the data input at one potential, the AC power at a second potential, and TELCO at a third. That difference in potential is equalized across and within the equipment, causing damage and/or wear, i.e., a computer operating on AC power and communicating through a modem will see two different ground potentials.

The solution is to commonly ground all services to the facility.



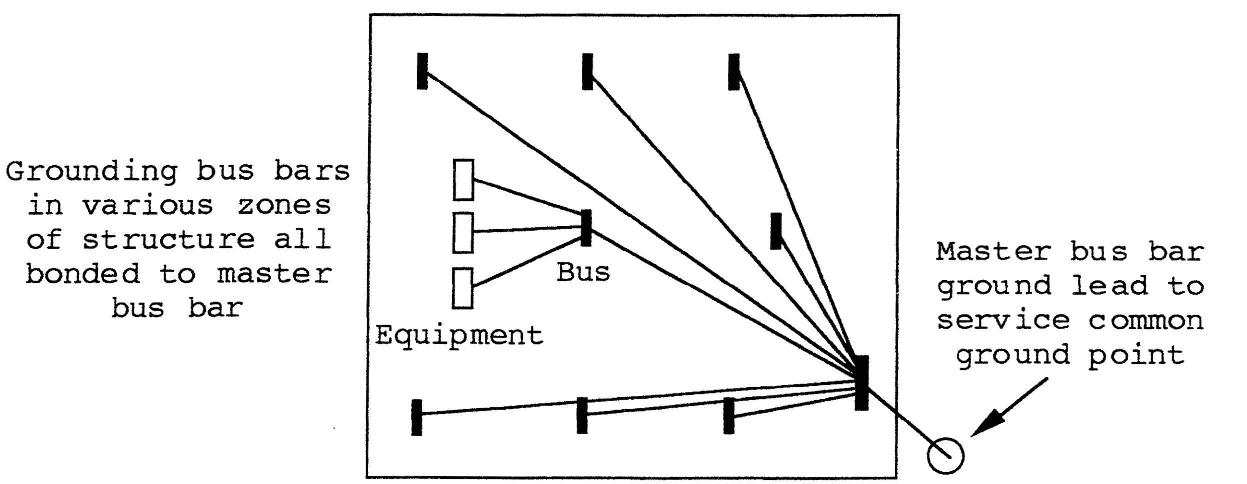
We establish the AC service as the reference ground. At the main disconnect, the AC neutral and ground are bonded together, and a ground lead extends from that box. This lead is grounded to structural steel, to a ground rod, or to the site grounding system, as appropriate, and becomes the reference ground for all services to the structure.

Then we route the TELCO service to the structure so it enters just to the side of the AC power service. We then take the ground lead extending from the TELCO service box, and also attach it to the ground lead from the AC power disconnect. This assures that the TELCO side of the site equipment will be at the same potential as the AC power service.

We then route all data and control lines so they also enter the control cab near the AC power disconnect, and ground all of the control and data lines neutrals to a bus which is then grounded to the ground lead from the AC power disconnect.

Now, any difference in ground potential of the different services to the structure will be equalized at the single-point we have established, and the structure equipment will sample all ground potentials at one and only one point, the single-point ground. The same strike off in the woods produces the same step potential across the structure. However, since all equipment is attached to services sampling ground potential at only one point, and there is no other ground reference potential, the equipment sees no current flow across or within it to equalize potential. This arrangement is effective, and easy to design into a new structure, particularly during the design phase.

In a large structure, the same principle applies to grounding of equipment chassis within that structure. Bus bars should be established within the various zones of the structure, and each equipment chassis bonded to the appropriate bus bar with a direct run. Each zone bus bar should then be bonded back to a master bus bar, and the master bus bar bonded to the common ground of the structure services.



This method assures that not only will all services be sampling ground potential at one, common location, but also that all equipment will be sampling ground potential at the same location. Therefore, although there will be changes in ground potential, there will be no difference in ground potential across equipment, causing unwanted current flow through or between pieces of equipment.

Miscellaneous.

Movable structures present several challenges from a transient protection point-of-view since, by nature, they move. If a structure moves geographically, grounding may become a problem. If a structure moves on steel wheels on rails, the weight of the structure should provide an acceptable bond to the tracks, assuming the tracks are maintained in a reasonable clean condition. Then all that needs to be done is to ground the tracks. If the structure moves only occasionally, such as a gantry for a rocket, the grounding system may be attached with removable plugs disconnected either by the movement of the structure or by dedicated explosive charges or mechanical actuators.

In the event of a direct lightning strike to the structure, impedance, rather than solely resistance, to ground becomes the key factor. Techniques such as correct grounding lead routing become important.

If the structure moves in place around bearings, it is critical to install jumpers around the bearings, both as a low-impedance path for discharge currents to ground, and to protect the bearings from scarring due to internal arcing.

Transient Voltage Surge Suppression

To mitigate the effects of transients on wiring entering, leaving and within a structure, we recommend the use of transient voltage surge suppression (TVSS) devices. These devices limit the difference in potential between various wires, and between those wires and chassis ground, to acceptable values.

In most locations, the majority of equipment damage is not caused by lightning related transients, but rather by electric utility company switching and other transient-producing events, and from internally generated transients. Motors and other loads within a facility generate transients which are distributed throughout the wiring systems. This effect was not so much of a problem in the days of vacuum tubes which operated on high internal voltages. However, with the introduction of microprocessors which operate on very low internal voltages, it has become a very real problem. With the move towards faster, digital equipment, the problems will become more noticeable and expensive. Therefore, transient voltage surge suppression (TVSS) equipment is critical at all locations, even those which never experience lightning.

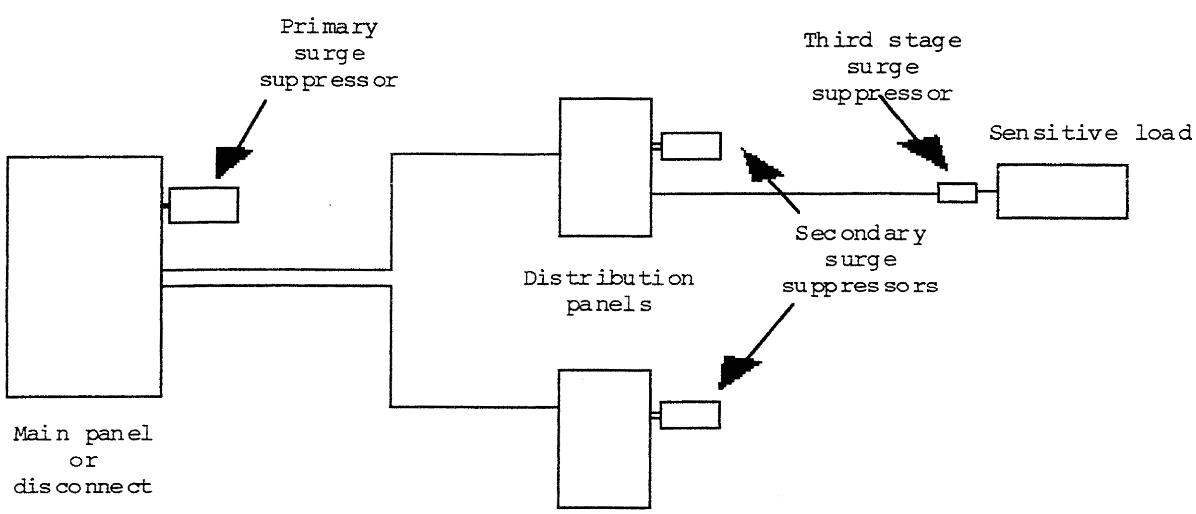
When designing a transient voltage surge suppression sub-system, there are several important factors and device features to consider.

Lightning Arrestor vs. All-Mode Protection

Some devices sold as surge suppressors are actually lightning arrestors, that is, they offer only phase to ground (common mode) protection. When a transient comes down the phase wire, they divert it from the phase wire onto the ground wire. The surge will then travel on the ground wire back to the service entrance, where the ground and neutral are bonded together, and, unless your facility has a perfect, low resistance ground, some of it will reflect back into the facility on the neutral wire. Your equipment will then see a difference in potential between phase and neutral, the value on which equipment operates. All mode surge suppressors provide equalization of potential from phase to neutral (normal mode) as well as neutral to ground (common mode). When there is a change in potential on any one wire, the other wires change with it, protecting your equipment. So, specify all-mode TVSS devices.

Staged Protection

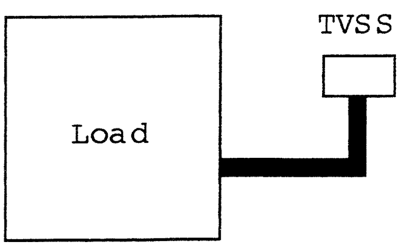
When designing a surge suppression system, the location of the devices within the facility is also important. The most effective way to install surge suppression is to employ the "staged protection" concept. That is, rather than install only one high energy device at the service entrance, it is more efficient to install multiple devices in stages.



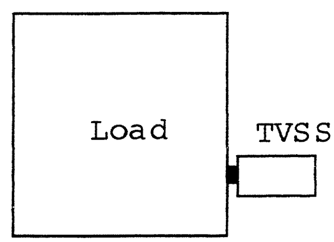
When a surge reaches your facility, some of the transient energy can make it through the primary surge suppressor at the service entrance. The higher the amperage of the surge, the higher the "let-through" voltage. Therefore, it is critical to have secondary devices downstream from the primary device to take care of the let-through voltage. The primary device should be located at the earliest possible location as a service enters your facility. With AC power, this could be your main disconnect. With telephone, data and cable, it could be at the service entrance. The secondary device should be located at least fifteen feet or so downstream from the primary device. With AC power, this could be your sub-panels. With telephone, data or cable, it could be near the loads. The inductance of the wiring between the devices then actually works in your favor, slowing the transient.

Lead Length

A device mounted several feet from the protected load or panel simply cannot work up to its rated values.



Long leads, high-impedance bends



Short, direct leads

Long leads and bends in those leads dramatically affect surge suppressor performance. For an 8/20 μs impulse, five feet of lead length can increase a five hundred volt clamping value to eighteen hundred volts, due to the inductance of the wiring. This increase in clamping voltage, dependent on the rise time of the surge impulse, is a function of the lead length, and does not reflect negatively on the efficiency of the device.

Surge Suppression Technology

To secure adequate levels of protection while keeping costs in line, we recommend employing the appropriate suppressor technology for the application. Having investigated the various suppressor technologies available, we recommend MOV-based technology for AC power protection, SAD-based technology for TELCO and data protection, gas tube technology for coaxial cable with DC power, and 1/4 wavelength shunt technology for unpowered coaxial and transmission line protection.

Miscellaneous

When planning system layout, it is important to avoid routing unprotected wires adjacent and parallel to protected wires, where transients can be coupled from the unprotected wires to the protected wires downstream of the surge suppressor, rendering it ineffective.

While engaged in installing TVSS devices, particularly in an existing facility, it is a good idea to check for correct wiring in all branch circuits. It is not at all unusual to discover basic wiring problems, such as neutral and ground wire reversal. This situation should be corrected to assure proper operation of both electrical equipment and TVSS devices.

When looking at wiring diagrams of large, spread-out structures, it becomes obvious that the data and control lines, since they may be grounded at both the control and sensor/actuator ends, can carry significant transient energy. Therefore, each line must have all-mode transient voltage surge suppression installed at both ends to prevent damage from different ground potentials. If ground loop noise becomes a problem, the ground at one end can be provided through a mode of surge suppression, becoming conductive only during the transient.

If a structure is moved with electric motors, it is important to protect both ends of all electrical wires to those motors. Transients induced on wires or resulting from secondary effect may travel both directions, damaging both the motors and the controllers.

Structural Lightning Protection

When designing a structural lightning protection system for a facility, it helps to keep in mind that which you are trying to accomplish. It should be noted that the purpose of a conventional lightning rod system is to keep the structure from burning down. That is why lightning protection system design is a function of the National Fire Protection Association. That was fine back in the days when we were trying to protect barns filled with hay and horses. The barn would be struck, and the lightning protection system would convey the heat and energy around the structure and dissipate it in the earth. Then we took the hay and horses out, and filled the barn with computers. The barn took a strike, and the lightning protection system performed as advertised. However, after the strike, none of the microprocessor-based equipment worked, victim of the near-field electromagnetic effect damage of the strike.

Therefore, when designing a structural lightning protection system, it is worthwhile to consider employing one of the new technologies available to reduce the incidence of direct strikes to the structure. These technologies are based on the functioning of the air terminal (lightning rod) portion of the lightning protection system. In the world of air terminals, there is a spectrum of how they operate, ranging from early streamer-emitting air terminals designed to attract lightning, through conventional lightning rods, to streamer-delaying air terminals which are designed to reduce direct lightning strikes.

Streamer-delaying air terminals operate by reducing the accumulation of static ground charge on the structure, and by delaying the formation of the lightning-completing streamers from the protected structure, thus reducing the likelihood of streamers from the protected structure reaching the stepped leaders first and completing the strike.

Since it is conceptually a good idea to specify a system which will keep lightning off of the structure, we recommend a structural lightning protection system employing streamer-delaying technology be installed on the structure itself. The system should be installed on any portions of the structure upon which ground charge would tend to accumulate and streamers tend to form. For example, on a draw bridge, we recommend installing streamer delaying systems on the control tower cab, the light poles, signs, traffic gates and bridge spans. Since it will most likely be occupied during electrical storms, we require the use of all Underwriters Laboratories UL Listed components installed to the standards of UL 96A on the cab.

When designing the layout of the structural lightning protection system on a movable structure, it is important to keep in mind that the structure must be protect in all possible configurations which may be presented during an electrical storm. This may entail multiple, interconnected systems so that all charge accumulation points are protected. Or, if a structure covers or moves over a very large area, it may be advantageous to consider a hybrid system consisting of streamer-delaying technology on the critical portions of the structure, and early streamer emitting technology in areas where lightning can be harmlessly dissipated to ground.

CONCLUSION

When an engineer designs a movable structure, his or her primary goal is to make it work as a movable structure. Unfortunately, lightning and transient protection is sometimes not considered in the overall design picture. The design approach described above considers primarily lightning and transient protection. Both approaches, taken together, produce a system which operates as intended and is immune to the effects of lightning and other transients.

As microprocessor-based equipment becomes faster, the transient problem will become worse. It is not possible to speed up electricity. In order to make the microprocessor faster, internal distances must be reduced. As distances between components are reduced, arc-over voltages become lower, and transient tolerance is reduced.

Much of the benefit accrued from a properly designed equipment protection system is not readily observable. In addition to protecting against catastrophic damage, the system also protects against day-to-day transients which, taken separately, are not sufficient in magnitude to cause equipment damage, but taken cumulatively, do cause wear and damage which may result in unreliability and random operation or premature failure.

The optimum time to review protection system design is when the facility design is still on paper or in the computer. At that point, corrections and upgrades can be made by merely moving lines or making several keystrokes, instead of relocating services, moving structures, re-routing wiring or digging up parking lots or drive lanes.

The path to equipment reliability and longevity is based on a three-part approach consisting of bonding and grounding, transient voltage surge suppression and structural lightning protection. This system approach is not theoretical; it was developed at various movable structures and large fixed structures in Florida, the ultimate lightning laboratory. Its simple, its easy to accomplish, and it works.