

# Lightning and Surge Protection Of Modern Electronic Systems



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## *Introduction*

In virtually all aspects of our modern lives, microprocessors and integrated circuits (ICs) are hard at work processing digital data, controlling critical systems and communicating information through ever-expanding global networks. These now common components have dramatically lowered system costs while increasing the power and flexibility of modern electronic systems in a manner unimaginable just a few years ago. Yet, few developers seem to appreciate the fact that these devices are critically susceptible to both externally and internally generated voltage transients and surges and especially those produced by lightning.

What would lead experienced system designers and engineers to attempt to manage transient voltage control and surge suppression for these modern systems by the use of protective technology designed for previous generations of electronics? The answers may lie in the following questions:

- Is there updated research available on the effects of lightning and voltage transients?
- Are widespread misconceptions regarding the “manageability” of lightning a factor?
- Have rapid advances in electronics out-paced the development of protective technology?

The purpose of this paper is to answer these basic questions and deal with the issues in an attempt to suggest a comprehensive but manageable approach for the design of modern protective systems.

## *Lightning – A Force to be Reckoned With*

In the introduction, the question was posed “Is there updated research available on the actual effects of lightning and voltage transients?”

The answer is a resounding YES! In the last ten years, prestigious research bodies including NASA, Sandia Laboratories, the University of Florida’s Lightning Research Group and many others have produced volumes of new information in the form of a number of published studies that greatly enhance the designers ability to understand the mechanics of lightning strikes and the resultant effects on electronic systems. The collection of truly meaningful data has been greatly improved through the use of satellite imagery, high-speed computer analysis of real-time data and advanced digital instrumentation. As we have learned more, the picture has gotten much clearer. For the first time, industry has available sufficient information to accurately predict the results of lightning induced transient events and to study the effects of protective technology.

## Knowledge is Power – An Overview of Lightning

### Strike Frequency

The National Oceanic and Atmospheric Administration (NOAA) reports at any single second there are over 2,000 thunderstorms occurring around the globe, and in that same instant, on average, lightning has struck somewhere in the U.S. six times. Figure 1 shows the five year average flash density.

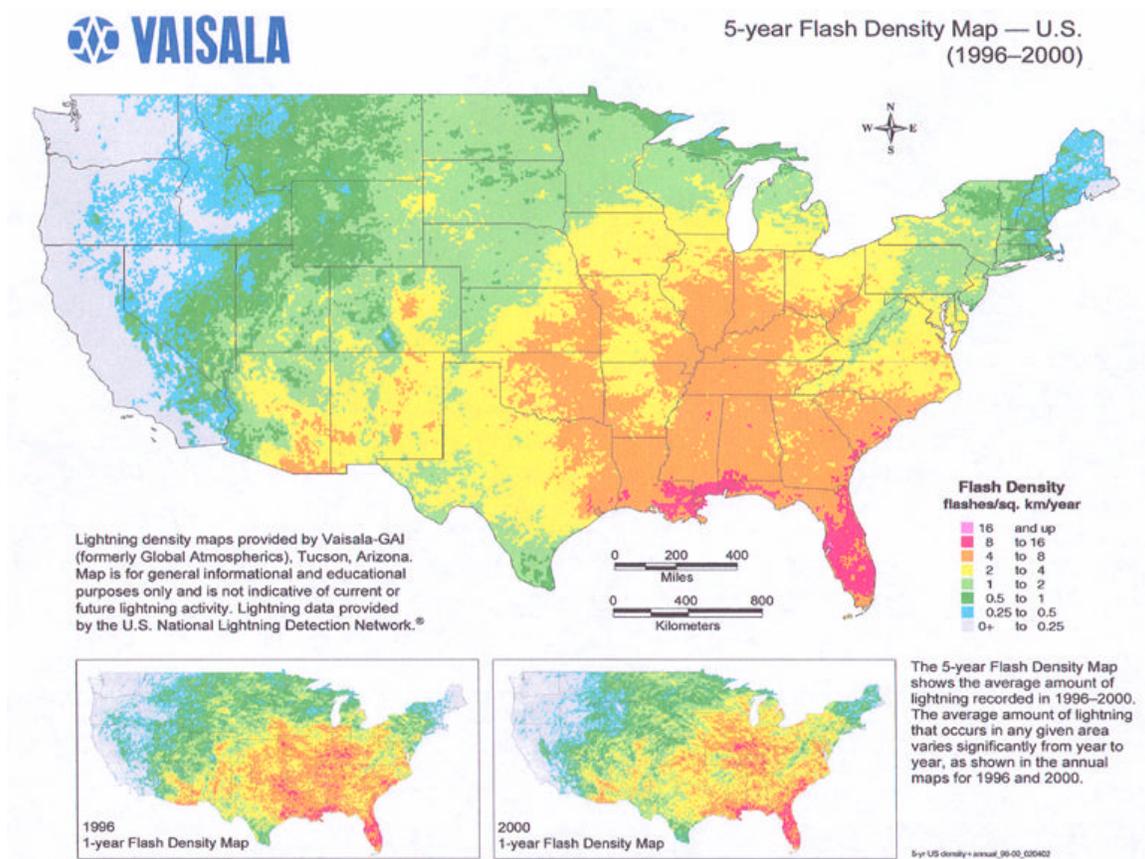


Figure 1 Lightning Flash Density Map  
(Courtesy of Vaisala-GAI)

### Lightning Statistics

- Cloud-To-Ground lightning strikes occur about 20 million times per year in the US.
- One in every 50 US Cloud-To-Ground strikes results in an insurance claim payout
- Estimated US annual damages from lightning: \$5,000,000,000.
- Lightning Strike Claims Paid per year (US) = \$820,000,000.00 \*\*
- Lightning claims represent approx. 7.5% of all US insurance company distributions.

#### Notes:

All data this page courtesy of the US Insurance Institute and is representative of private sector data only  
\*\* Claims paid per year listed above do not include US government property losses.

## The Nature of Lightning

Lightning is the natural equalization of charge potential that builds in thunderstorms between various regions of a cumulonimbus cloud and also the surface of the earth. The effect of updrafts acting upon water droplets and ice particles results in separation of charges in the upper and lower region of the cloud. In the typical thunderstorm, the lower region of the cloud becomes strongly negative and this in turn induces positive charging of the earth's surface below the cloud. When the charge potential between becomes large enough to break down the normally resistive characteristic of the air, a lightning bolt occurs. Bolts also frequently occur cloud-to-ground (CG), between various regions within a single cloud (IC), or between two clouds (CC) through similar actions. In all cases, this process repeats itself as long as the thunderstorm continues to receive sufficient energy in the form of heat to regenerate the charge separation/equalization process.

### Lightning Bolt Characteristics

- Voltage of up to 100,000,000 Volts and current as high as 300,000 Amperes
- The return stroke (main stroke) is approximately 30 microseconds in duration.
- There are typically 4 – 16 return strokes per lightning bolt.
- Typical bolt duration of 20 - 50 milliseconds.
- Temperature reaching to 50,000 degrees F (5 times hotter than the surface of the sun.)
- Radius of primary surface electrical influence = 60 feet.
- Power expended can be billions of Watts per bolt.
- Lightning displays characteristics of both Direct Current and Alternating Current in the form of Radio Frequency (RF) energy.

## How The Damage Is Done

Lightning damage falls into two main categories – Primary and Secondary Effects. These will be briefly described below:

- **Primary Effect** – Direct lightning strikes are a major cause of fire, instant destruction of property, electrocution injury and death. As one of the most common natural phenomenon known to man, there has been no practical method developed to prevent lightning strikes or to avoid damage caused by a direct hit. The most common technology for dealing with this effect is to divert the strike energy to a *properly* grounded lightning rod or cabling system.
- **Secondary Effects** – Approximately 1000 times more likely to occur than primary effects for any given facility, secondary effects are the damage caused to sensitive electronic devices, electrical networks and systems well outside of a CG strike point or as a result of Cloud-to-Cloud (CC) strike. There are three secondary effects that are most commonly observed – Direct Energization, Low Side Surge and ElectroMagnetic Pulse (EMP). These will be discussed below:

**Direct Energization:** This is the most obvious and potentially damaging effect of lightning. A strike on the electrical cabling or other conductive pathways routed to a facility can introduce dangerous energy surges into equipment connected at both ends of the pathway. Although the strike may be a considerable distance from the facility, it may be easily introduced into that facility by cabling, railroad tracks or even utility piping. Common surge suppression technology is not generally effective against lightning.

**Near Field Coupling (EMP):** Because the underside of a highly charged cloud usually carries a tremendous negative potential, an enormous electric field is developed in areas adjacent to the strike path at the moment of discharge. As a result, high currents (in tens to hundreds of kiloamperes) can develop along any electrically conductive paths to ground within the area affected by this field. The reader should note that these fields are developed in all lightning strikes including Cloud-To-Cloud events that do not directly contact earth. Remediation of these common effects cannot be accomplished through conventional grounding systems.

Example: Field strengths of 8000 volts/meter have been observed within 1 mile of a major CG lightning strike. Exposure of 10 meters of system cable to this field could produce an induced potential of 80,000 volts on system wiring.

**Ground Potential Rise (GPR):** This effect is a form of resistive coupling that occurs when a ground potential gradient forms in areas adjacent to the earth contact point of a CG strike. Low Side Surge (LSS) is the result and it is easily the most common point of introduction of damaging energy into sensitive control and monitoring circuitry. During a lightning induced GPR event, the ground reference point that electronic systems critically depend upon for diversion of “excess” energy can actually become a *source* of this energy. Commonly relied upon protective devices and their connected grounding systems are simply not designed to handle lightning related energy and may actually become the pathway for this destructive energy to enter the system. If an ideal low impedance single point grounding system (SPGS) existed in the facility, then resistive coupling due to GPR would be a non-issue. Since this is almost never the case in actual practice because of the relative size, complexity, and disparity of ages of different parts of the facility, most facility grounds tend to behave as a multipoint grounding system.

Example: A CG lightning strike of 100,000,000 Volts at 300,000 Amperes of current into ground having inductance of  $.5 \times 10^{-6}$  Henrys and a rise time of  $2 \times 10^{-6}$  Seconds could produce a Ground Potential Rise of 75,000 volts.

## Totaling Up The Risks

To recap some of the major points that what we have now learned about lightning, a brief review of the following may prove useful:

- Lightning does not have to *directly* strike a facility to do real damage.
- Protection currently in place may be fine for normal surges caused by load switching and utility transients, but will not be effective against lightning. They may even put system equipment at *greater* risk by providing a pathway through sensitive equipment.
- A typical facility ground will *not* provide necessary protection from lightning and may actually *contribute* to damage through Ground Potential Rise.
- To provide highly *reliable* protection, a lightning protection system design must address direct strikes, energization of all incoming lines, ElectroMagnetic Pulse, and the effects of Ground Potential Rise.

## Sensitivity of Microprocessors and Integrated Circuits

Microprocessors are subject to weakening damage from reverse electrical energy as little as one micro joule as can be seen in Figure 2 below. Integrated circuits are subject to damage from with as little as 10 microjoules. To conceptualize a microjoule, snap your fingers. This relatively tiny expenditure of mechanical energy is equivalent to approximately 10 micro joules of electrical energy, the limit for an IC and 10 times more energy than is required to damage a typical microprocessor.

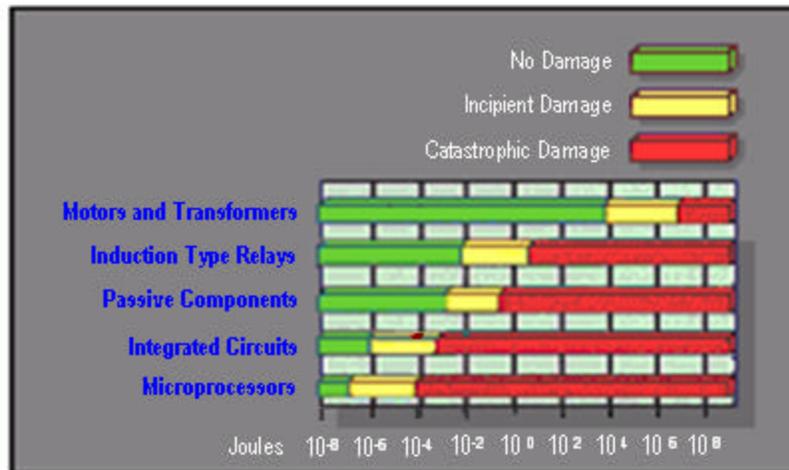


Figure 2 - Operating Limits of Electronic Components

With the above chart in mind, it's not difficult to visualize the relatively destructive effects of a 50,000 volt surge riding on the pin of an IC or microprocessor of a common digital device.

## Destruction, Damage, or Blue Sky Failures

Approximately 5% of digital device failures are due to catastrophic causes such as lightning strikes, transmission faults, or brownouts. The remaining 95% of failures are due to repeated degradation of the equipment from transients that fall into a category between safe or normal and catastrophic operation of a microprocessor or an IC.

The result of repeated attacks on solid state devices by transients, shown in Figure 3 below as short-duration "spikes" on otherwise normal waveforms, is the seemingly unexplained "blue sky" failures of the devices and a significant reduction in the mean-time-between-failures (MTBF) of the system components.

Although modern electronic systems include intricate circuitry designed to filter such transients, there is a limit to their effectiveness. If the effective surge is large enough, as in a lightning related event, damage will inevitably occur and performance will be affected. When the accumulated damage reaches a critical level, the component will fail.

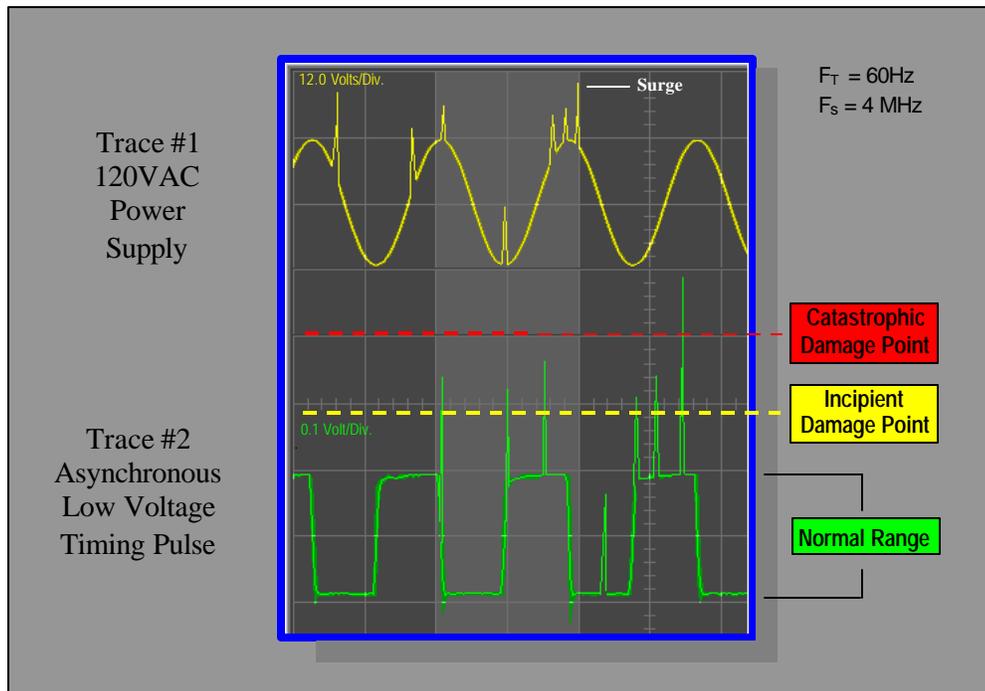


Figure 3

*Dual trace oscilloscope plot illustrating the effect that power line surges may have on connected low-voltage subsystem components. Surges are seen as “spikes” on otherwise normal waveforms.*

### **Characteristics of Affected Equipment**

Equipment damaged by long-term exposure to degrading surges and power transients displays a variety of typical behavior patterns. These are described below:

- Let's start with the obvious first. A facility that experiences frequent dimming of lights, brownouts, and partial or total disruption of electrical service during times of normal operation is a prime candidate for problems. Uninterruptable Power Supplies (UPS), Surge Suppression Devices and System Grounding should be considered possible suspect.
- Computer Systems – Symptoms of degraded performance include unexplained data loss, errors in data transmission for networked systems, bios errors on POST, system slowdowns, erratic behavior and unexplained lockups.
- Control Systems – Unexplained loss of Input/Output (I/O) sections of otherwise operational circuitry, I/O card failures in Programmable Logic Controllers (PLCs) or Distributed Control Systems (DCSs), data transmission errors, erratic behavior and the sudden onset of a frequent need to reboot key system components.
- CCTV Camera Systems – Sudden loss of input channels in otherwise operational devices, lines or pixel damage appearing in video monitors, data loss in recording systems.
- Audio Systems – Unexplained system noise including hum and hiss.

## *Hold The Phone! I Was Under The Impression ....*

At this point, we should address a few of those misconceptions that we talked about in the Introduction. Here are a few frequently asked questions:

### 1. Won't my National Electrical Code, Article 250 compliant ground protect our facility?

Not against lightning. Article 250 specifically addresses the danger of fire and the safety aspects associated with electrical faults in distribution wiring – typically 240VAC and down. In simply requiring a 25 ohm resistance (or lower) single point electrode system, it attempts to ensure that overcurrent can be safely diverted to ground. This it does very well. Article 250 was never intended to serve as an equipment reliability guideline.

In a lightning event, the total grounding system impedance is a much more critical factor than resistance and a simple grounding system presents itself as a very high impedance path. Simply put, the carrying capacity of the ground becomes insufficient to handle the energy levels and transient characteristics present in a lightning strike and this energy will always seek a lower impedance path to ground – often through critical equipment. Primarily due to the RF component of lightning and the high energy levels observed, the ground ceases to be a “safe harbor” for diverting excess energy during these events. As we will address later in this paper, isolation and electrical bonding become the strategy of choice for dealing with lightning.

### 2. My facility makes extensive use of Transient Voltage Surge Suppressors. Aren't these effective against lightning?

Probably not by themselves. Typically installed TVSS's operate through a variety of technologies. Most common systems based on Metal Oxide Varistors and similar technology work well enough for normal distribution surges, but are neither fast enough for high speed events like lightning nor can they handle the required energy levels. The danger must already be present in the system before they begin to react. Additionally, they degrade in performance with each protection event and can provide a ready path from ground for Low Side Surges that occur when GPR effects occur. These low-end devices should be avoided in all cases.

There is however, a class of upper-end transient suppression devices that operate at much higher energy levels in a normal (line to neutral) or a multimode (line to neutral/line to ground) configuration. These devices provide an excellent level of protection for AC line wiring and are highly recommended as part of a total system approach to lightning and surge suppression. These will be discussed later in this paper.

### 3. We've been operating for years with no apparent damage from lightning. Doesn't that mean that we aren't experiencing the effects described in this paper?

No. As will be discussed later in this paper, it is estimated that 95% of all electronic system failures are due to repeated degradation of the equipment from transients that fall into a category between safe (or normal) and catastrophic operation of a microprocessor or an IC. This is sometimes referred to as “electronic rust” due to it's cumulative effect. Eventually, the damage reaches a critical point and the equipment fails – seemingly without explanation. Facilities located in lightning prone areas and that experience unexplained or “blue sky” failures are most likely being affected. Automatic isolation is the key to preventing damage.

4. My facility is fully insured and the limit of our liability is only \$10,000. What incentive do I have to incur the cost of better lightning protection.

Limits of liability are usually confined to direct costs of system repair or component replacement in the event of a catastrophic lightning or surge event. As discussed in Question 4 above and later in this paper, it is estimated that these events represent less than 5% of all equipment failures. Consider the following:

- Blue Sky failures represent 95% of all electronic equipment repair or replacement and are nearly impossible to positively attribute to specific causal events for insurance purposes.
- Indirect costs of equipment down time – staff overtime, manual or extra security measures, loss of data, etc.
- Increased insurance premiums as a result of claims.
- Other costs.

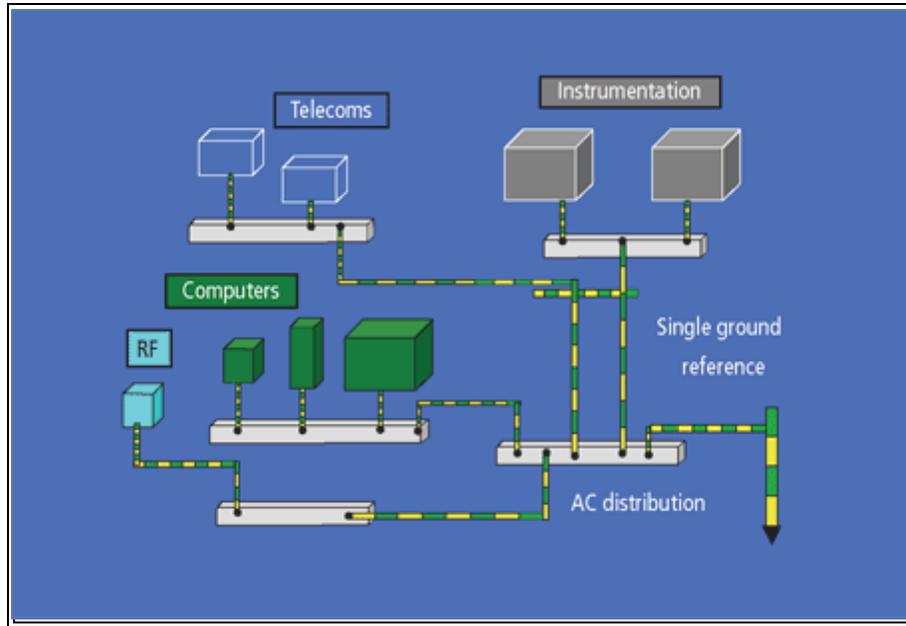
In the experience of the authors, the actual cost of lightning and surge damage almost always greatly exceeds the cost of a well-designed protection system for most facilities. In fact, many operators find that they actually reduce operating expenses through elimination of down time and repair costs as well as the ability to negotiate decreases in insurance premiums and lower limits of deductible liability.

## Grounding

Grounding and bonding in a modern facility is a complex issue beyond the scope of this paper. The reader can find vast amounts of data and opinions on the subject with even the most basic of research. In summary, guidelines that will prove generally acceptable in almost any application are as follows:

- **Divert surge current as soon as possible.** The longer a surge transient exists in a monitoring or control system, the more the potential for damage exists. Hence, it is imperative to detect and divert that pulse to a safe ground plane just as quickly as possible. Short, low resistance ground runs and fast suppression systems are the key to addressing this issue.
- **Use a dedicated low impedance connection for critical systems.** The importance of this is bond to the ground plane cannot be overemphasized. Ideally, the resistance to the ground plane should be less than 0.1 ohms. While this is rarely practical, it should be the goal. This is especially true for high frequency events such as lightning during which ground reactance becomes more important to system performance than simple resistance. A direct strike of 100,000 amperes to a lightning rod with a 10 ohm connection to the ground plane could easily produce a voltage across the entire electrical system of well over 1.5 million volts. By reducing the impedance of the connection to 0.1 ohms as recommended, the same lightning surge would theoretically produce a 10,500 volt pulse that would be much easier to manage with conventional suppression methods.

- Use a Single Point Ground System.** All the subsystems in the plant, instrumentation, communication, computers and control, and AC power, must connect to a single point ground system. This is typically referred to as "star point" grounding. Properly done, each subsystem ground is as short as possible and connects to the star point at only one point. Multiple paths to the ground plane from a subsystem inherently have different resistances. Different resistances to ground produce, again by Ohm's Law, different voltage potentials to the subsystem that result in transient surge damage to that system.



**Star Point Grounding System**

### ***Instrument Solutions***

Focusing on the monitoring and control instrumentation required in modern process facilities, we find many similarities, problems, and solutions to transient surge elimination. The elements primarily are:

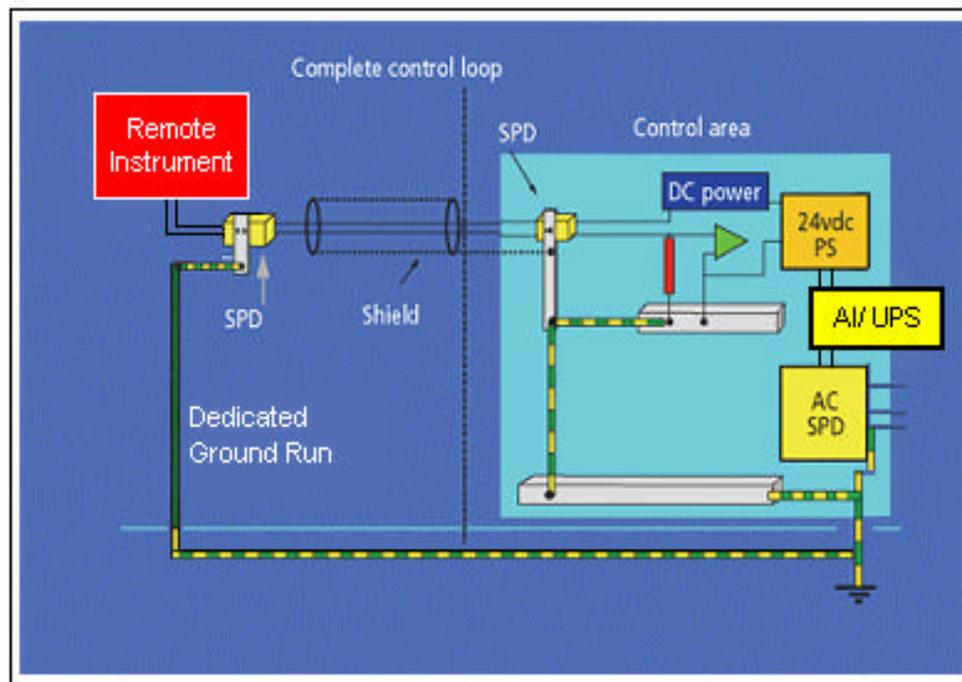
**Remote instruments and analyzers:** The problem is fairly well defined and very widespread. The most susceptible instruments in a typical process facility tend to fall into one of three general categories – analyzers, remote mounted instrumentation, and load/weight cells. These instruments generally employ highly sensitive microprocessors, ICs, or strain gage sensors and are often mounted on tall/isolated structures or the upper decks of process plants. Their isolation from other systems, greater mounting height (i.e. longest runs to ground) and general sensitivity make them the ideal targets for near-strike lightning effects. These devices typically require a minimum of two elements: power to operate and the means to communicate to a DCS or PLC I/O module located somewhere else in the plant. When designing applications that rely on these types of devices, it should be noted that manufacturers of these instruments rarely offer more than a minimum of surge protection as an option to the device.

**DCS or PLC control system:** This is where the control element, the brains of the system, resides. Again, DCS/PLC manufacturers offer only minimal surge protection devices.

The common element to both ends of the system is the signal and power wiring. These are the metallic power and information highways previously discussed. Once the surge couples onto this highway, at typically up to 7,500 Volts/15 Amperes for switching transients and up to 100 Million Volts/300,000 Amperes for a near lightning, it travels at 2/3 the speed of light in both directions on the conductor seeking low resistance pathways to ground.

Electronics at both ends of the control loop provide these pathways. Having isolation resistances far less than the transient surge, they break down instantaneously and often permanently under the high voltage/current and allow the current to dissipate through them to the ground plane. And by providing better grounding for the instruments at either end of the control/power loop, as many instrument manufacturers suggest or require, we have made the final destination of the surge pulse via the electronics that much more attractive!

What is the solution? To summarize, the most effective defense is a combination of Automatic Isolation systems, normal mode Surge Protection Devices installed at both ends of the loop and on every metallic conductor associated with the system, and a true low-impedance grounding system.



Automatic Isolation Used In Conjunction with Normal Mode TVSS