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"Transient Lightning Protection of Outdoor Measurement and Control Circuits"

by

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Transient Lightning Protection of Outdoor Measurement and Control Systems.

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Abstract

This paper will discuss methods used for successfully protecting outdoor measurement and control circuits from the damaging effects of a direct lightning strike. In North America, surge protection system performance is evaluated by subjection to the ANSI/IEEE C62.41 voltage and current test waveforems. In addition to these standards the paper will discuss a new performance waveform described in the IEC (International Electrotechnical Commission) 1312 Lightning Protection standard as the
IEC 1024 10 x 350µS test waveform. This test waveform represents the amount of energy that could enter an outdoor control system due to a direct lightning strike. Based on these standards we will show new and unique technology described as the "Arc Chopping Principle" that can address this very stringent test waveform. This combined with proper networking and coordination of traditional surge suppression devices can safely protect an outdoor control installation form even a direct lightning strike. The discussion will cover various coupling methods for transients, and national and international standards that can help in evaluation and application of the surge protection network. Also discussed will be packaging available for easy installation of surge protection devices into new or existing power and control system applications. Focus will be given to control system applications specific to the Movable Bridge industry. The reader will end with an understanding of the need, application, and justification for installing a complete surge protection system for the protection of sensitive and costly equipment from the damaging effects of lightning.

Introduction

Technology advances in the world of semiconductors and microprocessors are increasing at a breathtaking pace. The density of transistor population on integrated circuits has increased at a rate unimaginable just a few years ago. The advantages are many: faster data acquisition, real time control, and fully automated processes, to name a few.

Semiconductor technology is also increasing its prevalence in field mounted instrumentation and control systems. Unfortunately, a tradeoff to the increased performance and efficiency is the susceptibility of these semiconductor devices to voltage and current transient events. The best case results could be unreliable instrumentation readings and operation, with periodic failures. The worst case results could be a completely destroyed instrumentation device. Figures published by electronics insurance companies show that the occurrence of damage to equipment of this kind due to surge voltage is doubling every three to four years. And the insurance companies are starting to tire of paying claims that can be avoided by proper installation of surge protection devices. Many insurance companies are starting to require residential, commercial, and industrial customers to install professional surge protection devices as a condition of their policies.

Such power surges are often the work of mother nature. Lightning, which according to the National Weather Service strikes some 40 million times annually in the U.S., is a leading cause of failure for instrumentation and control equipment. When these devices are field mounted the vulnerability greatly increases due to their remote location and outdoor installation.

It should be noted that although the most devastating source of transient voltage and current activity is lightning, there are other sources. Some of these include static buildup, human error, inductive load switching, and utility capacitor switching.

This paper explores lightning effects on instrumentation and control systems, and methodologies for preventing damage including lightning arrestor technology, shielding, grounding and surge protection devices (SPD). The discussion will also cover various coupling methods for transients, and national and international standards that can help in evaluation and application of the proper surge protection network.

Lightning Magnitude and Frequency

Most of the continental United States experiences at least two cloud to ground flashes per square kilometer per year. About one half of the United States will see three cloud to ground events per square kilometer per year. This is equivalent to about 10 discharges per square mile per year. An Isokeraunic map of thunderstorm days developed by ANSI/NFPA 780-1992 is shown in Figure #1. This shows the average number of thunderstorm days per year by geographic region. A relationship can be made between thunderstorm days and flash density (the number of lightning-to-ground flashes in a specified period over a certain area, expressed in flashes / km^2 [see Table 1]).

As can be seen, depending on the region, locations such as Tampa, Florida or Columbia, South Carolina can have over 70 thunderstorm days per year. This corresponds to about 25 flashes / km / year. Although this is on the high side, roughly one half of the continental U.S. experiences up to three cloud-to-ground events / km^2 / year, or equivalent to about ten discharges per square mile per year.

Lightning damage to electronic equipment might be thought of as a remote possibility. Perhaps something that is as unlikely as winning the lottery. In fact the chances of winning the lottery in Florida are 1 in 14 million; the chances of getting hit by lightning are 1 in 600,000. The cost in equipment and property damage due to lightning is estimated at several hundred million dollars annually by The U.S. Department of Commerce.

Coupling Methods

Lightning effects can cause damage to sensitive electronic equipment in several ways, including: direct coupling, inductive coupling, and capacitive coupling. Direct coupling (Figure #2) is associated with lightning energies on the incoming conductors. Ground paths become saturated, and the transient energy seeks other direct paths to ground. Unfortunately, this is usually through unprotected electronic equipment such as instrumentation and control equipment.

An analogy can be made between direct coupling of lightning transients and flooding that occurs because of overfilled storm drains. Just as ground circuits become saturated with electrons in the case of a lightning strike, storm drains become saturated with fast flowing water in torrential downpours. The results are also similar in that the water seeks another path to ground which could be across a busy highway or through someone's backyard.

Inductive coupling (Figure #3) is produced by the magnetic flux lines generated during a lightning strike. As much as 70 V / meter of cable can be induced by lightning strikes that are more than a three-dimensional mile away. In other words, lightning does not have to strike the ground to inductively couple transients. Electronic equipment and measurement devices can experience inductive coupling from a cloud to cloud lightning event.

Shielding against inductive coupling with copper or aluminum foil shields is not effective. Magnetic flux lines penetrate through the small openings and apertures in the shield. Even with 100% coverage, flux lines penetrate through molecular openings in the shield. Only materials such as iron that have good magnetic conductivity are effective against inductive coupling. By deflecting the flux lines of the magnetic field, those materials keep the protected circuit outside of the magnetic field. Iron casing is one of the best materials to use, but its weight and lack of flexibility makes it an impractical material for shielding. The best defense against inductive coupling is accomplished by twisting the wires of the circuit together. This effectively reduces the area of the circuit to zero, limiting flux line penetration of the circuit, thereby minimizing voltage backup.

Capacitive coupling (Figure #4) is derived from positive or negative charged ions passing over conductors. Capacitive coupling is formed by the strength of the voltage field between the conductors of a circuit and the interfering source. The conductors of the circuit have a capacity to store electrons along their surface areas. As electrons collect along these surfaces, the strong voltage field of an interfering source can cause a migration of electrons to areas in the circuit with a lower voltage field strength. This migration constitutes a current to flow. The sudden appearance of a strong voltage field can cause enough current flow in the circuit to burn out most micro-electronic devices. Shielding is one method used to "bleed off" these charges to negate any capacitive coupling effects. However, to minimize ground-loop problems caused by potential differences along the cable shielding, it's best to ground the shielding on instrumentation signals only at one end.

Standards and Waveforms

Before microprocessor devices, engineers and technicians didn't have to worry about protecting their equipment from voltage and current transients. Since the proliferation of microprocessor based equipment, the need for protection against transients has become necessary. To define the areas of hazard, characteristics of transients, and protection product performance several national (ANSI/IEEE) and international (IEC) standards were created.

The ANSI/IEEE C62.41 is used primarily in North America as a guide for selection of surge protection devices (SPD). Table #2 shows the different equipment locations, test waveforms, open circuit voltage, and short circuit current specifications as defined by ANSI/IEEE C62.41. Factory floor measurement and control devices would be covered under Category B and field mounted instrumentation under Category C. The idea of the different categories is to define a surge susceptibility zone for different areas within a facility or installation. The Category C areas are those with the highest threat of direct strike energies, while the Category A areas are those located well within a facility, which is somewhat protected from the direct strike energy simply by their wiring distance and location away from the source.

The International Electrotechnical Commission (IEC) specification IEC 1312 defines several specifications related to lightning susceptibility. The basics of categorizations, test waveforms, voltage and current peaks are similar to the ANSI/IEEE C62.41. However, one unique classification of the IEC 1312 is the definition of a true lightning test waveform, the IEC 1024 x 350μS (Figure #5) waveform. The IEC 10 x 350μS waveform describes a transient current event with a 10μS rise time to 60kA and a 350μS decay to half energy or 30kA. This is approximately 200 times greater energy than ANSI/IEEE 8 x 20μS waveform (figure #5). The IEC 10 x 350μS allows a true lightning survivability test to be performed on a surge protection device. This will be discussed further in the following pages.

Grounding

One of the key factors to protect any sensitive industrial equipment is a low impedance earth ground. The National Electrical Code (NEC) targets 25 Ohms. However, 25 Ohms is a target. A ground resistance of 5 Ohms or less is preferred. Since the performance of any surge arrester is enhanced by a highly conductive path to earth ground, lightning currents are diverted from seeking other sensitive industrial equipment paths. The impedance of the earth ground consists of both a resistive and a reactive component of the grounding conductor. The formula V-IR + L(di/dt) can be used to show the voltage potential that a SPD must deal with when shunting transient energy to ground. The voltage drop is a function of the resistance (R) and the inductance (L). Skin effect and the path taken by the conductor (straight, bends, etc.) have a direct effect on the ground path inductance. A ground path of both low resistance and low inductance ensures the maximum performance of a SPD.

Protection Strategies

Surge protective device (SPD) is the common term used to describe products that protect sensitive electronic equipment from damaging transient voltages. A surge protective device acts as a high impedance connection between power or signal line and ground, under normal operating conditions. Upon sensing a fast rising voltage, the SPD becomes a low impedance "short circuit" to ground to divert the unwanted energy safely away from the sensitive electronic equipment. Since the transient condition occurs for a maximum time duration of approximately 20 microseconds, this short low impedance state occurs very quickly. After diverting the energy to ground the SPD then "resets" itself back to the normal high impedance state.

Industrial equipment, control systems, and electronic measurement devices can be damaged from lightning induced transients entering the control system through the power source. Also common is damage caused from such "back door" entrances as data communication lines, antenna connections, analog and digital I/O and phone modems. A typical Heavy Movable Structure control application could contain a variety of instrumentation systems. A common application would consist of a programmable logic controller (PLC) with standard 24V dc relay logic, 4-20mA field transmitter inputs and a radio modem for sending compressed data packets back to a central control station. The distributed I/O system utilizes an RS-422 full duplex data protocol. By evaluating this standard system shown in figure #6 we find that there is a potential for transient damage at any of the points from the data line to the power line.

The ANSI/IEEE C62.41 specifications shown in table 2 are a good guideline for selecting SPDs for protecting against the damage of *indirect* lightning effects. The components used by most SPD manufacturers include the independent use or a cascade use of Metal Oxide Varistors (MOVs), Silicon Avalanche Diodes (SADs) and Gas Tube technology. In our typical field mounted control system example *indirect* lightning effects are common on the 24V dc discrete I/O, the 4-20mA analog signals, the RS-422 data communication and the telephone modem applications.

For protecting the power system the effects of a *direct* lightning strike need to be considered. AC power lines are directly linked to the outside world. The use of larger gauge wire in power conductors allows these conductors to carry higher direct lightning surges. Because of these anticipated long duration lightning surges, a test standard using the IEC 1024 10 x 350μS waveform should be used when selecting the protection device. A "lightning arrester" utilizing an ARC Chopping Principle (figure #7) can safely divert this energy from AC power lines. A lightning arrester specified at 60kA based on the 10 x 350μS waveform will handle energy that would easily destroy one rated at 100kA to 150kA based on the ANSI/IEEE 8 x 20µS. A comparison of energy handling, response time, and clamping voltage for different protection components is shown in table 4.

Networked Approach

To safely protect outdoor measurement and control systems from the direct and indirect effects of lightning a networked approach is necessary. Unfortunately, you cannot simply install one product and protect everything. The internationally recommended practice is to build a networked surge suppression system. This includes a lightning arrester technology on the AC power lines, and SPDs on the analog and digital I/O, communication lines, and data lines.

AC Power Lines - Three Steps

Step One - Main Service Entrance. Facility AC power lines are the direct link to the outside world. Since the wire gauge of power conductors is large, so is the pathway for lightning induced surges. The IEC 1312 guidelines suggest that surge currents of up to 60,000 amps based on the IEC 1024 10 x 350µS waveform (figure 5) can be expected at the mains service disconnect. To take this initial hit a surge protection device utilizing the arc chopping principle must be employed. The ARC Chopping device is a new technology spark gap. The problem with traditional spark gap technology has been the susceptibility to follow-on currents which can cause nuisance tripping of upstream circuit breakers or fusing. The spark gap devices that feature the patented ARC Chopping Principle avoid this by their unique follow-on current extinguishing capabilities. The technology shown in figure #7 consists of two electrodes positioned opposite each other, held in place by a barrier and separated by a baffle. This arrangement and spacing of electrodes is called "ARC Chopping" and provides reliable ignition of the arc, which is then chopped by the baffle into several smaller arcs. This effect diverts the lightning current while self extinguishing the follow-on current before up stream circuit protection devices have time to trip. A protection system featuring this technology can be chosen in three phase enclosure systems with UL listing.

Step Two - Distribution and Sub-distribution Circuits. The lightning arrester just described will let through a residual transient of approximately 5kA which takes the form of the ANSI/IEEE 8 x 20µS waveform. The second step for protection of the AC power system will address this transient energy. A metal oxide varistor (MOV) based product with the capability to handle at least 40kA based on the 8 x 20µS waveform should then be installed at your critical power distribution circuits. Systems are available for all popular three phase and single phase power configurations. It is important to select a product that features pluggable and testable protection elements with failure indication. This is important because of the inherent characteristics of MOVs to fail over time. Each time a surge is discharged, the metal oxide crystals weaken and eventually form a direct short to ground. The rate at which MOVs fail is totally dependent on the number and magnitude of transients. If a MOV fails at this stage, the direct short to ground poses several problems. The least critical of which would be a circuit interrupt from an upstream breaker or fuse. More critical is a potential fire hazard. A MOV can actually leak enough current on an AC power line to heat up to the point of catching fire.

Step Three - Equipment Power Protection. The transient energy left after the step two protection should be too small to cause destructive damage to the power source of your sensitive equipment. However, it will still cause dissipative damage over time. Dissipative damage occurs when semiconductor materials are subjected to continuous small energy transient voltage. The semiconductor junctions are actually pitted away over time until pathways open and the device eventually fails. Transient protection at this stage should feature a hybrid protection circuit with MOV, gas tube, and surge arresting diode technology. The three stage hybrid circuit gives sufficient coarse protection with the gas tube and MOV, while providing fine protection with the surge arresting diode. Packaging is available in a convenient DIN-rail mounting format and with the option of removable protection elements. Also, features such as LED or remote warning contacts should be considered for indication of MOV failure.

Analog and Digital I/O Protection of Controllers and Instrumentation

A typical programmable controller or industrial computer has many areas of surge threat. We have just covered the power supply protection. However, there are several "back door" areas that also need to be considered. Signal lines typically run between a control device and a field mounted measurement and / or transmitter device. To have total coverage a surge protection device (SPD) should be installed at both ends of the I/O.

A digital I/O circuit can utilize MOVs in the circuit from line to ground. However, an analog circuit, which is a floating ground circuit, cannot be referenced to ground. As an MOV ages, it leaks to earth causing a ground reference that can damage or cause signal error. Since most digital or power supply I/O circuits are referenced to earth ground, there is no problem with designing protection circuits with MOVs in common mode, line to ground. The most effective digital or analog protection circuits utilize a three-stage protection scheme with MOV, suppresser diode and gas discharge tube. This hybrid circuit is in series with the application. Packaging is available in DIN-rail mounting for protecting the control side and also in a field mounted pipe nipple for protecting the field side.

Data and Telecommunication Circuits

Probably the most sensitive (and almost never protected) circuits are the data and telecommunication ports of control systems and electronic measurement devices. Any time a data or telecommunication line is routed through a facility or outdoors, it is susceptible to transient energies that can damage network cards and spread the damage through the entire control system.

To protect these data systems again requires protection at both ends of the transmission path. Twisted wire pairs and coaxial protection can be added to divert damaging transients from getting into the systems. These systems are usually high speed and cannot withstand high levels of line impedance. MOVs should never be designed into telecom or data circuits. They will lower and mis-shape data signals that travel on cables or phone lines. In many cases the signal will just stop transmitting if the wrong type of surge protection device is installed. Every data network is different. Specific surge arresters are designed to function properly with networks like ethernet and token ring. In industrial applications, networks that utilize RS-485 serial communications can be connected together by D-Sub style transient protection devices or hard wired data protection devices. To protect telecommunication lines, a multiple-pair protection system of single outlet protection devices can be utilized.

Conclusion

To properly protect outdoor measurement and control circuits from the direct and indirect effects of lightning a networked approach of lightning arrester and surge protective device technologies is required. Coupling methods, grounding, and surge protection device performance need to be considered. By addressing both the lightning energies and the I/O data structure, you can engineer a highly reliable protection network to safely protect your entire control systems from even a direct lightning strike.

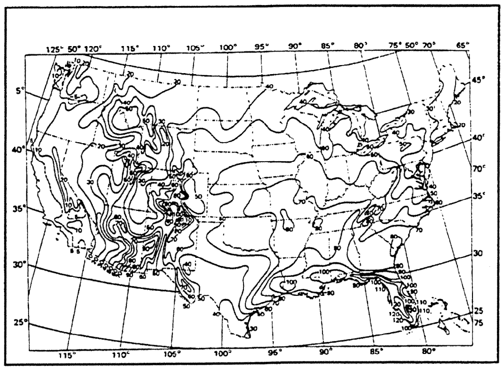

Figure #1. Isokeraunic Map Showing Mean Number of Thunderstorm Days per Year.

Number of Thunderstorm Days per Year	Flash Density per Square km per Year
10	1
25	4
40	10
80	30
100	50

Table #1. Relationship between thunderstorm days per year and number of lightning-to-ground strokes in a specified period and geographic area.

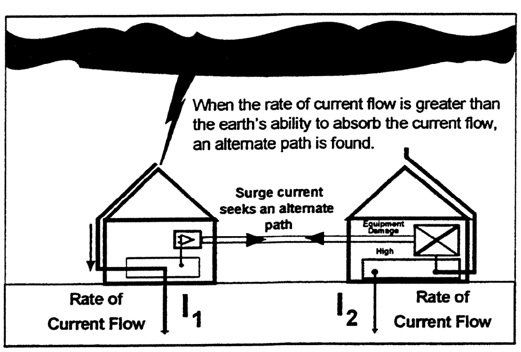

Figure #2. Direct coupling results from lightning energies on the incoming lines.

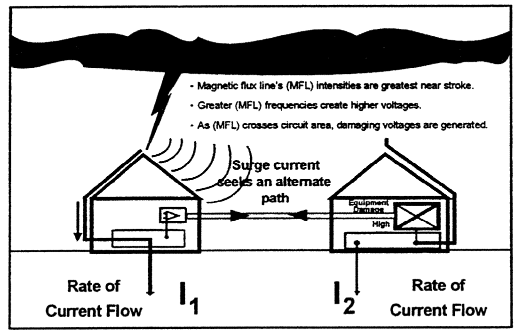

Figure #3. Inductive coupling is produced by the magnetic flux lines generated during a lightning strike.

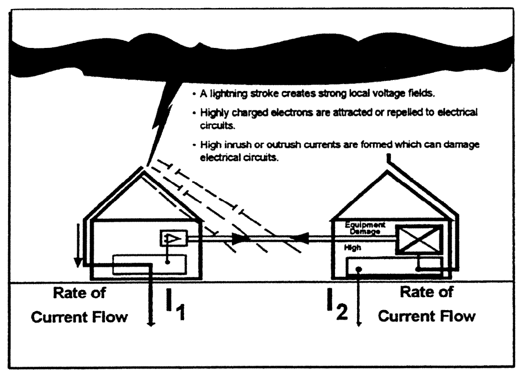

Figure #4. Capacitive coupling is derived from positive and negative charge ions passing over conductors.

Location / Category	Waveform	Open Circuit Voltage	Short Circuit Current
Category A: Long Branch Circuits and Outlets, Data Wall Outlets.	0.5µs - 100kHz Ring Waveform Test	6,000V	200A
Category B: Major Feeders and Short Branch Circuits (Distribution Panels).	0.5µs - 100kHz Ring Waveform Test 1.2 x 50µs High Impedance Test 8 x 20µs Current Impulse Test	6,000V 6,000V n/a	500A n/a 3,000A
Category C: Outdoor Overhead Lines, Service Entrance.	8 x 20µs Current Impulse Test	n/a	10,000A

Table #2. ANSI/IEEE C62.41 Transient Environment Test Criteria.

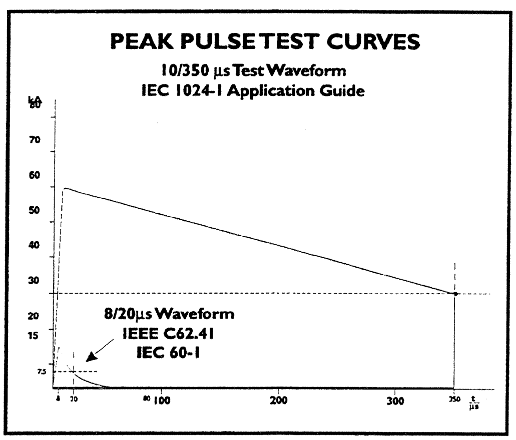

Figure #5. The IEC 1024 10 x 350µS waveform shown in comparison to the 8 x 20µS waveform. The IEC 10 x 350µS allows a true lightning survivability test to be performed on a SPD.

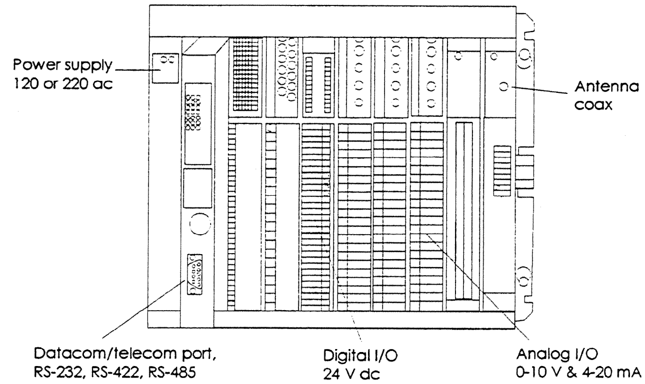

Figure #6. To be completely protected a typical remote terminal unit (RTU) requires protection for all copper pathways leading into the device.

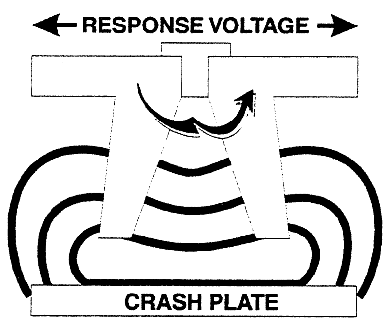

Figure #7. The ARC Chopping Principle. A lightning arrester technology which will handle a direct lightning strike condition (IEC 10 x 350µS) on the AC main service entrance while minimizing follow through current.

FLASHTRAB Spark Gap	Metal Oxide Varistor	Gas Discharge Tube	Suppressor Diode
60kA 10 x 350µS	**40kA** **8 x 20µS**	**10kA** **8 x 20µS**	**0.5kA** **8 x 20µS**
1,000V	**5V - 600V**	**90V**	**5V-300V**
rise time dependent	**nanosec.**	**microsec.**	**picosec.**

Table 4. Performance comparison of different SPD technologies.