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The Secondary Effects of Lightning Activity

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Background

The trend toward miniaturization in electronic systems brings an increased sensitivity to electrical transient phenomena. Transistors have shrunk, and dimensions are now on the order of five molecules thick. Most modern integrated circuits operate at very low voltages and, consequently, electrical transients of only a few volts can damage, disrupt or shorten the lifespan of these systems and their components.

One of the major causes of damage to and disruption of electrical and electronic equipment is lightning activity. Every lightning strike causes a number of indirect, secondary effects which can affect all nearby conductors and semi-conductive materials. These indirect or secondary phenomena can impact any type of conductor or semiconductor, including conductors being used for AC power, control systems, data transmission, instrumentation, communications circuits, etc. All of these conductors may be impacted, but at different magnitudes.

In order to effectively evaluate and implement effective protection technology, one must first clarify and understand how nearby lightning activity influences these systems. This paper examines these problems and provides the background information required to understand how to eliminate the secondary effects phenomena from electrical and electronic systems.

The Lightning Process

Lightning is a complex phenomenon but can be explained in a simplified abbreviated form as follows: Turbulence within a thundercloud generates electrostatic charge within the cloud. This charge tends to separate, thus forming a cell. In about 90% of thunderstorm situations, positive charge tends to accumulate in the upper regions of the cell and negative charge tends to accumulate on the bottom of the cell, as shown in the upper portion of figure 1.

The accumulation of charge on the bottom of the thundercloud will impress a resulting opposite charge (called an *electrostatic shadow*) on the surface of the earth and all grounded objects beneath the thundercloud, as shown in the lower portion of figure 1. As a result, the thundercloud has produced a very strong electrostatic field between itself and the earth's surface. Under a mature storm, that electrostatic field can achieve levels of between 5 and 30 kilovolts per meter of elevation above the earth's surface, prior to the initiation of a lightning strike.

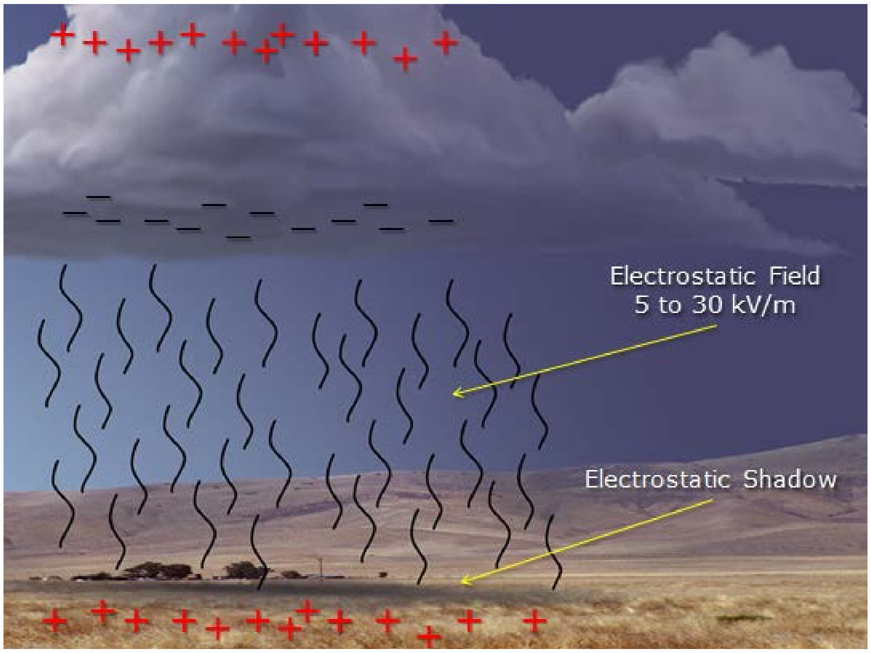

Figure 1: Charge separation within cloud and resulting *electrostatic shadow*

The electrostatic field created by the storm cell induces a charge on the earth's surface that is of equal charge but of opposite polarity to the charge in the base of the cloud. In about 90% of cases, a positively charged electrostatic shadow will be induced on the surface of the earth. In the other 10% of cases, the charge polarities are reversed, but the positive electrostatic shadow predominates and the secondary effects are the same regardless of polarity. The charge tends to concentrate at or near the surface of the earth and cloud base across the separating dielectric (air) because of the attractive force of the electrostatic field.

As the storm cell matures, approaching potentials of about 10^8 volts, the air's dielectric qualities degrade and conductive channels, called *downward leaders*, form and begin to move downward from the cell toward the earth. When these downward leaders get within a few hundred meters from the earth, *upward streamers* are launched from location of accumulated charge within the electrostatic shadow and begin to move upward from the earth towards the downward leaders. Upward streamers are streams of electrical charge, similar to downward leaders but of opposite charge.

When one of the downward leaders connects with an upward streamer, an electrical short circuit is formed between the cloud and the earth, thus forming a lightning stroke. Several strokes typically occur within the same lightning channel, as current flows between the cloud and ground. Current will continue to flow between the cloud and ground until the cell between the cloud and ground is neutralized.

Scientists call a complete lightning discharge a lightning *flash*. A complete lightning flash may contain up to 30 component lightning strokes, with the average flash containing four strokes. It is important to note that every discreet lightning stroke within the flash will generate its own secondary effects. Some common parameters of lightning strikes are shown in table 1.

Table 1: Lightning strike parameters [Ref. 1 and 2]

Peak current, negative first strokes (50th percentile)	30,000 amps
Peak current, negative first strokes (95th percentile)	80,000 amps
Flash duration, negative flashes (50th percentile)	13 milliseconds
Flash duration, negative flashes (95th percentile)	1100 milliseconds
Charge, negative flashes (50th percentile)	7.5 coulombs
Charge, negative flashes (95th percentile)	40 coulombs
Range and average of strokes per flash	1 to 30 / 4
Peak temperature	> 50,000°F / 27,760°C

The Secondary Effects of Lightning

There are four separate secondary effects that accompany every lightning strike, each of which is described in the following sections:

1. Earth current transients
2. Atmospheric transients
3. Electromagnetic pulse (EMP), including Stroke Channel EMP and Ground Current EMP
4. Ground Potential Rise (GPR)

1. Earth Current Transients

An earth current transient is the direct result of the neutralization process that follows stroke termination as illustrated by figure 2. 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 (terminus). This induced charge is concentrated within the upper layer of soil, to a depth of only about three (3) feet. This depth also happens to be the typical depth of buried power, communication and instrument lines.

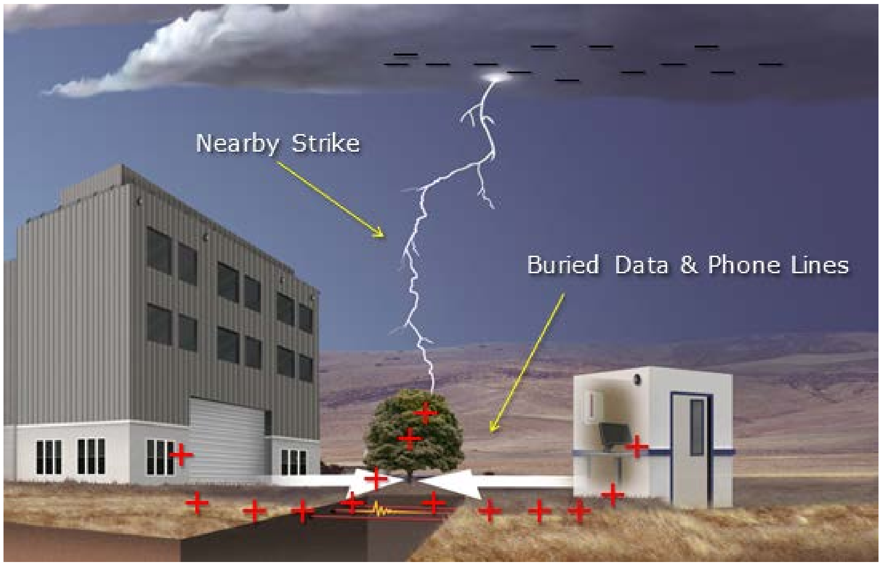

Figure 2: Earth current transients

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 and current on those conductors that is related to the charge which is, in turn, related to the proximity of the stroke terminus.

This induced voltage and the associated current is called an earth current transient. It will be found on wires, pipes and any other type of conductor and semiconductor. If the wires are shielded, the internal wires will experience the first derivative of the shield current flow. Since the discharge process is extremely fast and the rise time to peak voltage is a few hundred microseconds, the induced voltage will be very high.

The termination of a lightning strike may cause, for example, shallowly buried telephone or power lines to have transient currents induced upon them, with the magnitudes of the transients proportional to the magnitude of and proximity to the strike.

2. Atmospheric Transients

Atmospheric transients are the direct result of the varying electrostatic field that accompanies an electrical storm. As illustrated in figure 3, 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 multiplied by the field strength) above local grade. For example, a distribution or telephone line suspended 10 meters above earth in an average electrostatic field during a storm will take on a potential of between 100kV and 300kV 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 may be destroyed in the process of providing the neutralization path.

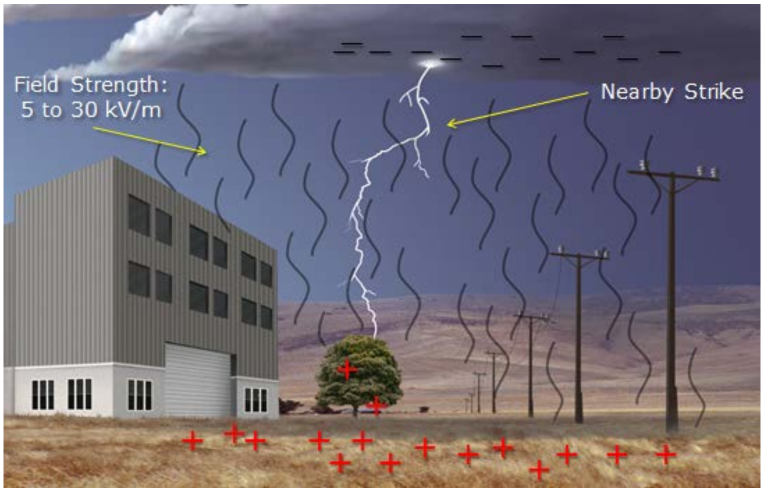

Figure 3: Atmospheric transients

3. Electromagnetic Pulse (EMP)

There are two categories of EMP that should be considered: Stroke Channel EMP and Ground Current EMP. *Stroke Channel EMP* is the direct result of the transient magnetic field that forms from the flow of current through the lightning stroke channel, as illustrated by figure 4. After the lightning stroke channel is established between the cloud and earth, it then becomes a conductive path between the cloud and earth. The lightning current then flows very rapidly, with the rate dependent on the channel path impedance and the charge within the cloud. The di/dt of a lightning strike may range up to 100 kiloamps per microsecond, as shown in figure 4.

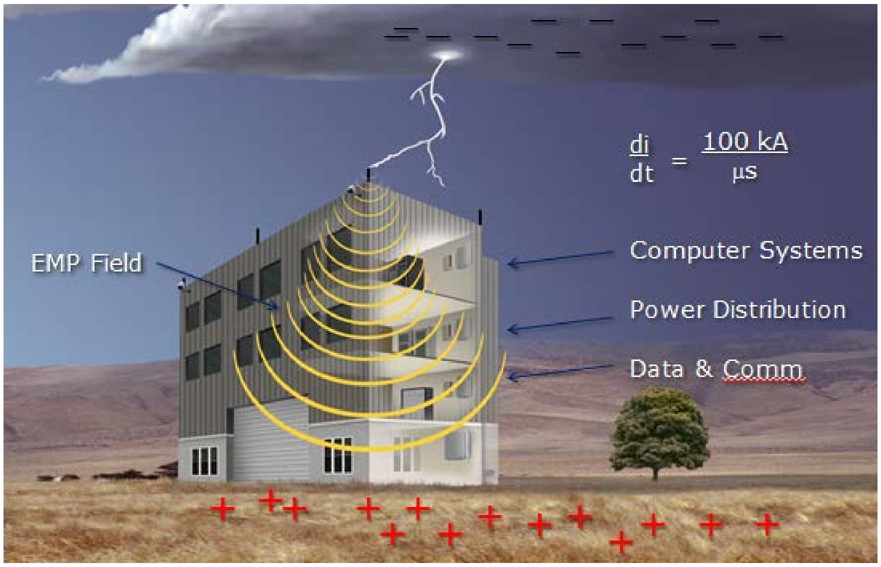

Figure 4: Stroke channel EMP

It is well known that transient currents flowing through a conductor produce a related magnetic field. Since these discharge currents rise at such a rapid rate and can achieve peak currents in the hundreds of thousands of amperes, the related magnetic pulse they create can be quite significant. The EMP caused by the lightning current will radiate outward in all directions away from the stroke channel. If this EMP should flow across another conductor, the resulting induced voltage within that second coupled conductor will be significant.

A lightning strike acts like a giant transmitting antenna, generating strong electromagnetic pulse waves. Therefore, lightning EMP can propagate over a long distance and affect large areas. The EMP from a lightning strike can induce high voltages on power lines, data lines and communications lines within the area of influence around that EMP field. Any elevated electrical, data or communications line in that area will suffer from lightning EMP interference, regardless of usual shielding. The lightning EMP has a very wide spectrum, and most of its energy is in the low-frequency portion. Therefore, lightning EMP can penetrate the shielding and interfere with the system.

Ground Current EMP is similar to the Stroke Current EMP except that it is applied to the earth's surface and buried conductors. When the lightning current is injected into the earth, such as when a grounding electrode system becomes energized from a lightning strike, the EMP radiates outward through the earth in all directions away from the grounding electrode system, as illustrated by figure 5. In this situation, the fast-changing current in time (di/dt) creates the magnetic field which is now mutually coupled to any underground wiring that passes nearby, over or parallel to any part of the grounding system. Again, the mutual coupling results in the transfer of energy via EMP onto the underground wiring, whether the wire is being used for power, data or communications circuits.

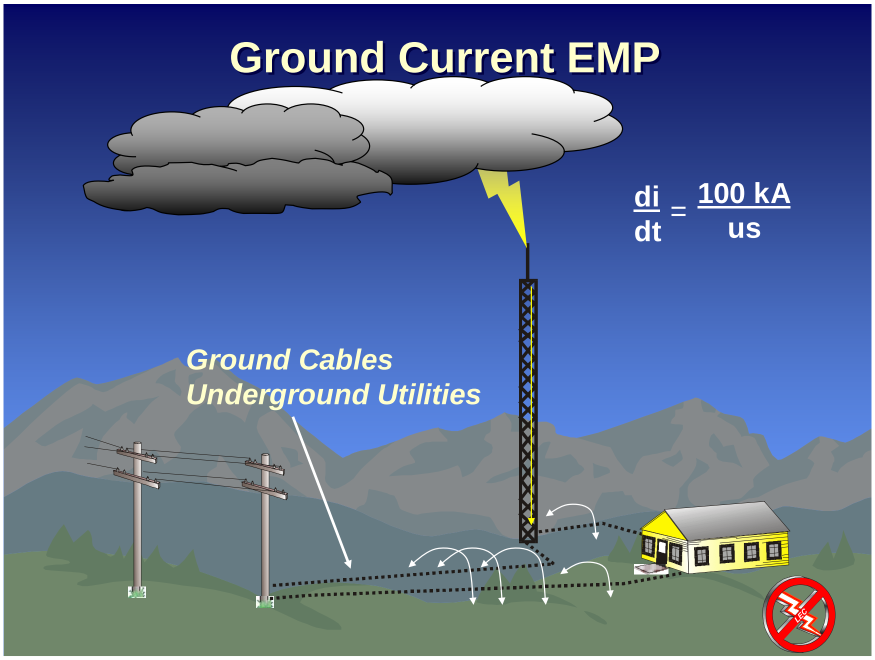

Figure 5: Ground current EMP

4. Ground Potential Rise (GPR)

Ground Potential Rise (GPR) occurs when lightning current is injected into ground or a grounded object. The strike current and inherent resistance of the earth or grounding system will cause a rise in potential of that location as compared to the surrounding area. This is not harmful *unless* there are humans in close proximity to the strike location or there are conductors between the area influenced by the GPR and another unaffected or less affected area. A lightning-related GPR will cause an undesirable current flow (a transient) in any conductor between the affected area and unaffected or less affected areas. This transient will propagate away from the GPR and may damage or disrupt any connected equipment. The intensity of the GPR resultant transient will be proportional to the conductor's proximity to the lightning strike terminus and the current magnitude of the strike.

For example, figure 6 shows a 30,000 amp lightning strike to an air terminal (lightning rod) on a commercial building with a 5 ohm ground resistance. Assuming the lightning rod is properly bonded to the grounding system, and the electrical system ground is properly bonded to the grounding system, then the facility grounding system (R1) will experience a 150 kilovolt GPR based on that 5 ohm ground resistance. Because the grounding system of the outlying shed (R2) is not bonded to R1, its potential will be different than that of R1, and the conductors between the building and shed (shown as red lines in figure 6) will experience transient current flows as these two individual grounding systems seek equalization.

It is not unusual to have two separate grounding systems within a facility: (i) an isolated ground for noise sensitive systems and (ii) the plant ground. This isolated ground (which may also be called the clean ground or technical ground) is normally used for grounding the computer or control room. The plant ground is normally used for the remaining grounding requirements, including the AC electrical systems, the lightning protection system, building steel, etc. As a matter of good grounding and bonding practices regarding lightning, all grounds at a facility should be bonded together to prevent or minimize the possibility of the GPR secondary effect.

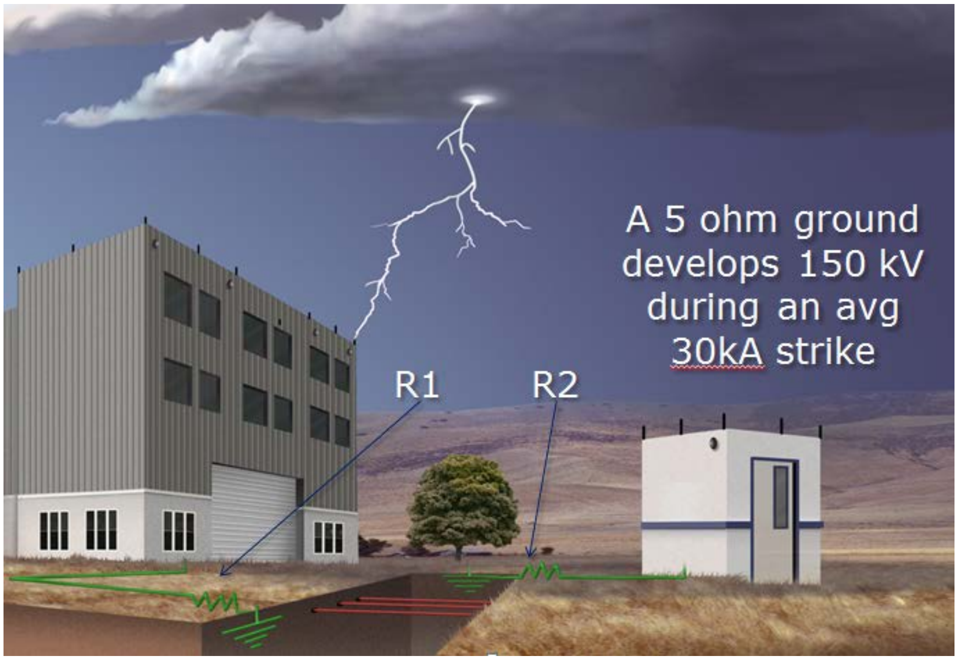

Figure 6: Ground potential rise

Protector Requirements for AC Power

The electrical transients resulting from secondary effects of lightning must now be defined in terms of their characteristics. A great deal of research and testing was required to define the transient parameters. The results were used by the Institute of Electrical and Electronic Engineers (IEEE) Standards Committee to prepare the following standards for surge protection devices (SPDs) for AC power applications: ANSI/IEEE C62.41.1, C62.41.2 and C62.45. The requirements set forth in these standards can be summarized in table 2.

Table 2: IEEE surge protector requirements for AC power

Location Category	Location Description	Current (amperes)
A	User circuits	500
B	Subpanels and branch circuits	3,000
C – low exposure	Service entrance	3,000
C – high exposure	Service entrance	10,000

Unfortunately, these SPD requirements are to some degree the result of subjective opinions and a series of compromises. These requirements may be satisfactory for urban and suburban situations with low lightning frequency. However, these SPD requirements are **not** satisfactory for rural areas, areas with high lightning frequency and for applications in underdeveloped locations.

These environments are much more severe, because they are the recipients of much more of the lightning strike energy and, in underdeveloped locations, are subject to poor voltage control.

For example, suppose there is a power line running to an industrial plant in a rural area, and a lightning strike induces a transient onto the incoming power line. This transient would be delivered directly to the plant, instead of being shared by many users as it would in an urban area. In addition, when a transient arrives at the end of a single-user line, it reflects back upon itself, effectively doubling its voltage.

Therefore, because the capacity of surge protectors can be increased inexpensively, surge protectors with capacities greater than the IEEE requirements should be installed to protect modern facilities. For example, the surge capacity of a given SPD can often be doubled for about a 30 to 40 percent increase in cost. In addition, the value and capacity of the SPD should reflect the value of the equipment being protected. For example, one should not protect a $100,000 system or process with a $100 SPD.

In order to acknowledge the relatively low cost of SPDs, the increased sensitivity of modern equipment and the high energy levels caused by direct and nearby lightning strikes, a prudent engineer should specify SPDs with capabilities greater than that required by the IEEE standards. These greater SPD surge capacities are shown in table 3. These greater surge current capabilities not only provide for the possibility of significant lightning strike currents beyond that specified by IEEE, it also provides for greater reliability and better performance of the SPD.

Table 3: LEC's recommended SPD surge capacities for AC power

Location Description	LEC Recommended Surge Capacity (amperes)
User circuits	10,000
Subpanels and branch circuits	50,000
Small service entrances and subpanels	100,000
Service entrance – low exposure/low value	200,000
Service entrance – high exposure/high value	400,000

Protector Requirements for Low Voltage Lines

Data, instrumentation, communications and other types of low voltage lines are frequently damaged by lightning strike energy. SPDs for these applications must be designed to protect against lightning-related surges and transients in order to provide reliability to their connected systems. Many SPDs for low voltage lines provide only a small amount of surge capacity to reduce cost, even though a nearby lightning strike may induce thousands of amperes into these lines. In addition, it is not prudent to use a low capacity SPD to protect a device which may be controlling a continuous process operation, whose disruption would be extremely costly.

Therefore, LEC recommends that SPDs for low voltage lines provide at least 10,000 amperes of surge capacity for *every* conductor being protected. In addition, because a series SPD will provide better control over the incoming signal than a parallel SPD, series-hybrid SPDs are recommended for low voltage lines with low operating currents, such as those operating at less than one or two amps.

Conclusion

Every lightning strike will generate a number of indirect, secondary effects. These secondary effects will typically contain enough energy to disrupt or damage any nearby electrical or electronic equipment. The secondary effects are (1) earth current transients, (2) atmospheric transients, (3) the electromagnetic pulse, including both (a) stroke channel EMP and (b) ground current EMP and (4) ground potential rise.

Surge protection devices (SPDs) should be installed on all conductors leading to the vulnerable equipment, regardless of the purpose of the conductor. Because one cannot predict the direction of the resulting transient current flow, SPDs should be installed on *both* ends of all connected wires. Series-hybrid SPDs should be used for all low voltage, low current applications, such as on instrument, data and communications lines, whereas parallel SPDs can be used on AC power lines. These SPDs should be designed and selected to provide high surge capacities to reflect the value of the equipment and operation being protected. SPDs with higher surge capacities should be used at locations that are remote, unmanned and/or at the end of a power distribution line.

References

1. Uman, Martin, *The Lightning Discharge*, Table 7.2, page 124.

2. Uman, Martin, *All About Lightning*, page 41.