THE SECONDARY EFFECTS OF LIGHTNING ACTIVITY

By Roy B. Carpenter, Jr. and Dr. Yinggang Tu
Lightning Eliminators and Consultants, Inc.
Boulder, Colorado, USA

Introduction

The trend toward micro-miniaturization in electronic systems development brings an increasing sensitivity to transient phenomena. Transients of less than 3 Volts peak or energy levels as low as 10^{-7} Joules can damage or "confuse" these systems and their components, as shown in Table 1.

TABLE 1 - RANGE OF DAMAGE THRESHOLDS OF ELECTRICAL DEVICES

DEVICE TYPE	JOULES
Relays	10^{-3} - 1
Resistors	10^{-3} - 1
Rectifier Diodes	5 x 10^{-4} 0.5
Medium & High-Power Transistors	10^{-4} 0.1
Low-Power Transistors	5 x 10^{-6} x 10^{-2}
Integrated Circuits	10^{-7} x 10^{-3}
Microwave Diodes	10^{-7} x 10^{-4}

One of the major causes of these phenomena is lightning activity within close proximity to electrical and electronic systems, which generates the destructive and disruptive secondary effects. These phenomena can be found both on the power source and on the communication lines, but at different magnitudes.

In order that effective protection technology can be developed and properly evaluated, one must first clarify 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 and not completely understood phenomenon. The process that creates a storm cell has not been completely defined, although there is general agreement as to the overall process.

Activity within the cloud cell causes charge separation within the cell. The cell develops an electrical charge between the top and its base. As a result, the cloud becomes an electrostatic battery where the upper levels are predominantly positively charged and the base of the cloud takes on a predominately negative charge (see Figure 1). That charge tends to concentrate at the base of the cloud cell, producing a very strong electrostatic field between the cloud and the earth's surface. Under a mature storm, that electrostatic field can achieve levels of between 10,000 and 30,000 Volts per meter of elevation above the earth's surface.

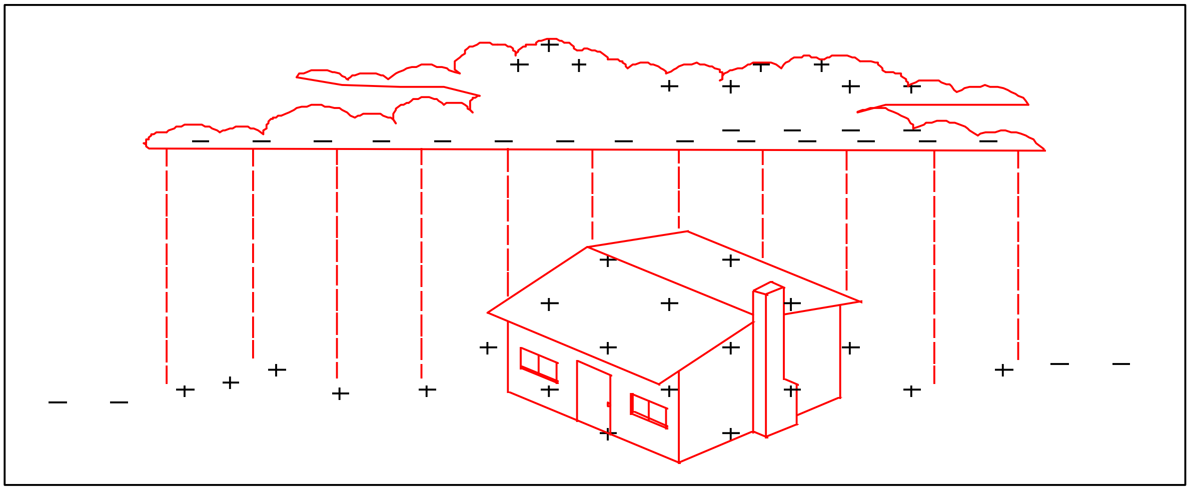

Figure 1: Charge Separation

The electrostatic field created by the storm cell induces a positive charge on the earth's surface between the cell that is of equal charge but of opposite polarity, normally positive.

NOTE:

> It should be pointed out that the ionosphere also creates an electrostatic field of about 150 Volts per meter, normally leaving a negative charge (with respect to the ionosphere) on the earth's surface.

For short periods of time, the opposite can be true, but the positive earth charge predominates and the secondary effects are the same regardless of polarity. The charge tends to concentrate at or near the surfaces 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, plus or minus an order of magnitude, the air’s dielectric qualities degrade and conductive channels start forming, moving from the cell toward earth in steps. When one of these channels, called the "step leader", reaches earth, a short circuit is formed between the cell and earth. Scientists call the visible channel a "flash". This is when the charge neutralization process begins.

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

Earth current transients
Atmospheric transients
Electromagnetic pulse (EMP)
Bound charge - secondary arc phenomena

It should also be noted that the cloud-cell-to-cloud-cell discharges are more frequent and can create all of these secondary effects, though the mechanism is somewhat different.

Earth Current Transients

The 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).

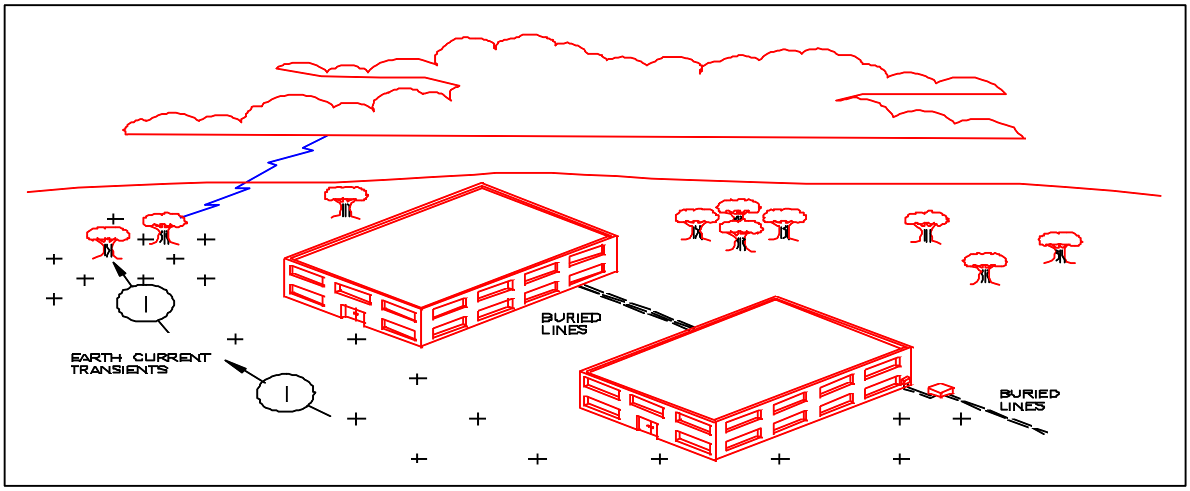

Figure 2: Earth Current Transients

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

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

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

> It may cause arcing through the soil to an adjacent gas pipeline, cable, or grounding system. (A 50 kV/m breakdown gradient is usually assumed(10). For example, the foot resistance of a power tower is 10 Ohms, the return stroke current is 200 kA, and the minimum separation distance is 40 meters).
>
> Surge current may be coupled by soil to the existing electronic grounding system for the electronic equipment which causes a non-uniform Ground Potential Rise (GPR) distribution in the ground system. For example, assume that two buried 10-meter ground wires with a grounding resistance of 31.8 Ohms are separated by five meters. If a 75 Ampere current is injected into one of the ground rods, the other rods will have a voltage rise of approximately 188 volts (11). The non-uniform GPR distribution caused by the surge injection can be analyzed using a program known as SPICE (12).

Atmospheric Transients

Atmospheric transients or electrostatic pulses 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 times the field strength) above local grade. For example, a distribution or telephone line suspended at an average of 10 meters above earth in an average electrostatic field during a storm will take on a potential of between 100 kV and 300 kV with respect to earth. When the discharge (stroke) occurs, that charge must move down the line searching for a path to earth. Any equipment connected to that line will provide the required path to earth. Unless that path is properly protected, it will be destroyed in the process of providing the neutralization path. The rising and falling electrostatic voltage is also referred to as the electrostatic pulse (ESP).

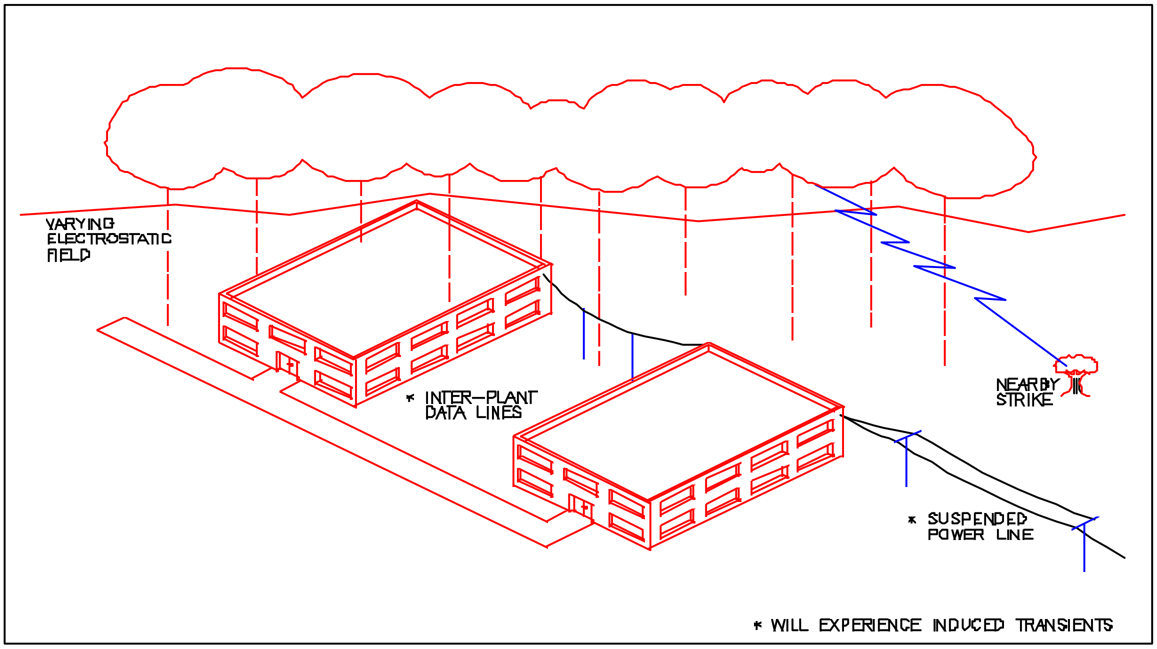

Figure 3: Electrostatic Pulses

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

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

Electromagnetic Pulse (EMP)

The electromagnetic pulse is the 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 like a wire. The neutralization current flows very rapidly, with the rate dependent on the channel path impedance and the charge within the cloud. The rate of rise of these current pulses varies by orders of magnitude. They have been measured at levels of up to 510 kA per microsecond. A practical average would be 100 kA per microsecond, as shown in Table 2.

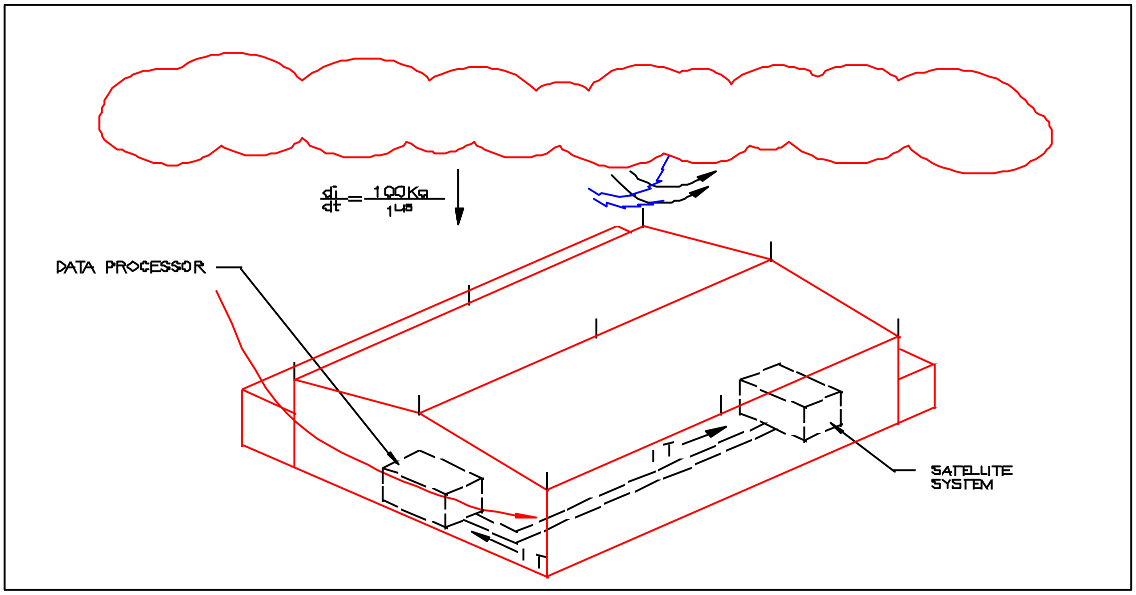

Figure 4: Stroke Channel EMP

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 achieve peak currents in the hundreds of thousands of amperes, the related magnetic pulse they create can be quite significant. The resulting induced voltage (EMP) within any mutually coupled wiring can also be significant.

As the charges in the clouds peak, a downward step leader is initiated at the bottom of the thunderclouds. As the downward step leader approaches the ground, an upward step leader meets it, and the return stroke occurs. A huge amount of charge, as high as 100 Coulombs, accompanies this return. Table 2 shows the statistical data about lightning return strokes(1)(2).

TABLE 2 - LIGHTNING RETURN STROKE DATA

Return Current I	5 kA - 200 kA
di/dt	7.5 kA/ s to 500 kA/ s
Velocity	1/3 Speed of Light
Length (Height of Thunderclouds)	3-5 km Above Grade

A return stroke acts like a giant traveling wave antenna generating strong electromagnetic pulse waves. Therefore, lightning EMP can propagate over a long distance and affect large areas.

Using an antenna model of step currents, Uman et. al., modeled the EMP effects of a lightning return stroke (3). A lightning return stroke can induce high voltage on communication/data transmission lines and power lines(4)(5)(6).

According to numerical calculations, a return stroke of 11.5 kA, for example, can generate a vertical electrical field as high as 40 kV/m at 50 meters away. The induced peak voltage on a 10 meter-high power line is 82 kV(9). In 1980, Erickson measured induced voltage on a 1-km power line. The flash was 30 kA and 150 meters from the line, and the measured induced voltage was 70 kV(4).

Any elevated transmission or data line will also 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(7). Therefore, lightning EMP can penetrate the shielding and interfere with the system. The calculation of skin depth is well known and can be found in many electromagnetic text books(8)(9).

.

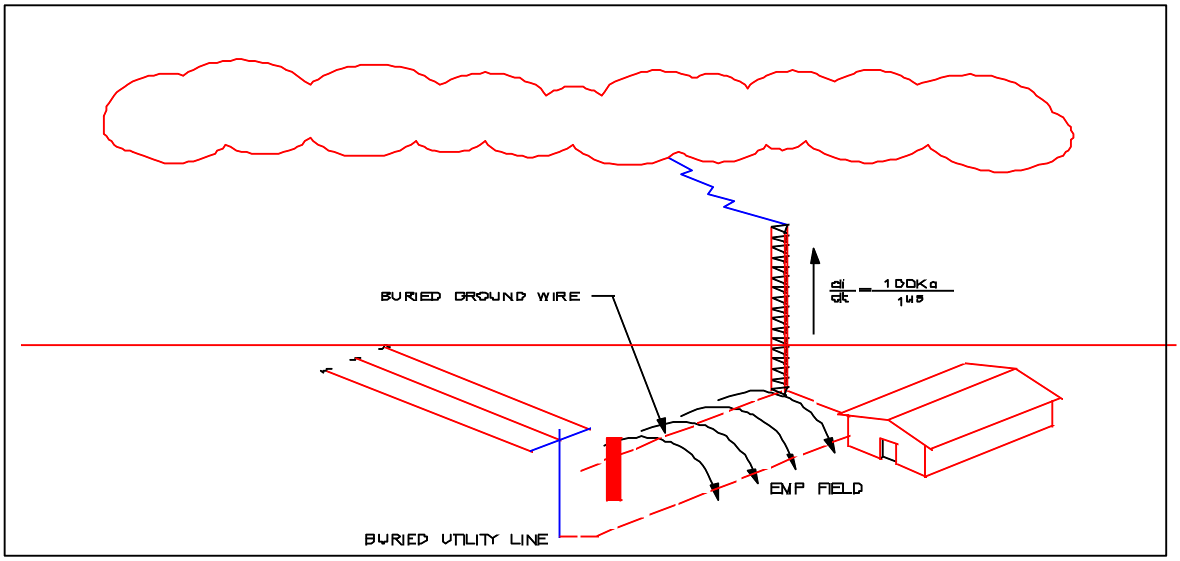

Figure 5: Grounding Current EMP

The EMP also has a related secondary effect as a result of the current flowing into the grounding 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 (within-ground) wiring that passes nearby, over or parallel to any part of the grounding system. Again, the mutual coupling results in the transfer of energy (EMP) into the underground wiring. That energy may not always be harmful to the entering electrical service; however, it will most likely be high enough to damage data circuits.

Protector Performance Requirements

The transients resulting from secondary effects must now be defined in terms of their characteristics. A great deal of research, monitoring of telephone and data lines, and testing were required to define the transient parameters. The results were used by the Institute of Electrical and Electronic Engineers (IEEE) Standards Committee on Transient Voltage Surge Suppression (TVSS) to prepare a standard. The results are recorded in an Underwriters Laboratory Standard, Number UL 96 and subsequent revisions. UL 96 was prepared to cover both power and data lines. Category B has been recommended as the appropriate definition for the performance requirements for data line protectors. As a result, protectors on the market should be evaluated against this standard. See Tables 3 and 4.

TABLE 3 - STANDARD SURGE GUIDELINES: CATEGORY B

	SURGE		
Location Category	**Wave Form**	**Med. Exposure Amplitude**	**Type of Specimen or Load Circuit**
Major feeders and	1.2 x 50 s	6 kV	High Impedance
short branch circuits	8 x 10 s	3 kA	Low Impedance
	0.5 s -100 kHz	6 kV	High Impedance
		500 A	Low Impedance

Unfortunately, standards are to some degree subjective opinion, tempered by limited knowledge and vested interest, resulting in a series of compromises. LEC has found that although the standard is satisfactory for the urban and most suburban situations, it is not representative of what is often found in rural areas or third world countries. These environments are much more severe, because they are the recipient of much more of the energy from the strike and are subject to poor voltage control. Data and telephone lines are frequently vaporized by the strike energy. Therefore, the protectors must be prepared to protect against that form of transient in order to be 100 percent effective.

Table 4 presents what is considered to be a more realistic list of performance requirements based on what may be considered the worst-case situation, or those hazards in excess of about the 99th percentile.

TABLE 4 - PROTECTOR PERFORMANCE REQUIREMENTS FOR DATA LINES, ETC.

Peak Current	10,000 Amperes
Peak Energy	500 Joules
Rise Time to 90%	50 Nanoseconds

NOTE:

> All grounds for data and power lines must be referenced to the same single point ground, preferably at the service entrance.

Rev. 1/97

REFERENCES

(1) "A Review of Natural Lightning: Experiment Data and Modeling," Martin A Uman et. al., IEEE Transaction on EMC, May 1982, p. 79-112.

(2) "Submicrosecond Characteristics of Lightning Return Stroke Current," Christiane Leteinturier et. al., IEEE Transaction on EMC, November 1991, p. 351-357.

(3) "Methods for Calculating the Electromagnetic Fields from a Known Source Distribution: Application to Lightning," Marcos Rubinstein et. al., IEEE Transactions on EMC May 19889, p. 183-189.

(4) "Lightning Induced Voltage on Overhead Distribution Lines," A. J. Erickson et. al., IEEE Transactions on PAS, April 1982, p. 960-968.

(5) "Lightning Induced Voltages on Power Lines: Experiment," Maneck Master et. al., IEEE Transactions on PAS, p. 2519-2529.

(6) "Induced Voltage on an Overhead Line Due to Nearby Lightning," Gerhard Diendorfer, IEEE Transactions on EMC, November 1990, p. 292-299.

(7) "Measured and Calculated Spectral Amplitude Distribution of Lightning Sferics," Luis L. OH, IEEE Transactions on EMC, November 1969, p. 125-130.

(8) "Electromagnetic Waves and Radiation Systems," E. C. Jordan, Prentice Hall Inc., 1968.

(9) "Fields and Waves in Communication Electronics," Simon Ramo et. al., John Wiley & Son, Inc., 1965.

(10) "Breakdown Gradient of the Soil under Lightning Discharge Condition," Abdul M. Mousa, 15th International Aerospace and Ground Conference on Lightning and Static Electricity, 1992, p. 67-71.

(11) "Power System Grounding and Transients," A.P. Sakis Meliopoulos, Marcel Dekker, Inc. 1988.

(12) "Current Distribution Calculation in Lightning Strike Structure in Presence of Nonlinear Impedance," S. Cristina et. al., 20th ICLP September, 1990, p. 3-11.