LIGHTNING DAMAGE
AN ACT OF GOD OR ACT OF NEGLIGENCE?

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Abstract – Lightning is a natural phenomenon that cannot be stopped. However, it can be controlled and the energy diverted. Lightning is described and the induced energy is calculated. Adequate grounding and bonding are demonstrated. The effects of the configuration of metal are discussed. Actual photos illustrate problems with unbalanced and inadequate ground paths that have resulted in fires we have investigated.

INTRODUCTION

Lightning is at once fascinating, dangerous, and little understood by most. Lightning is considered an act of God by many, particularly in the legal community [1].

Think about other weather conditions such as rain and temperature. These are equally an act of God. However, we have learned to control them with buildings and other structures. Similarly, lightning can be controlled and directed by following industry practices and standards [2,3,4,5].

The origin of lightning, like other weather, is an act of God. However, damage due to lightning is an act of negligence or omission in most incidences we have investigated. The authors have written extensively about lightning and grounding. [6,7,8,9,10,11] These papers form the basis and background for the observations.

LIGHTNING MANAGEMENT

Lightning is simply the discharge of an electromagnetic (EM) field. Since lightning is electromagnetic energy, it can be managed as any other circuit.

Three measurements completely describe EM energy. Voltage is the potential or pressure. Current is the flow rate. Frequency is the inverse of the time for the signal. By controlling all three measures, lightning can be managed.

Voltage is clamped at a threshold level that precludes damage. Current is diverted to earth. Energy of a particular frequency is filtered from the conductor.

Energy that is developed in a cloud is attempting to return to earth or ground potential as lightning. Hence, an excellent ground "system" is the critical element of a lightning management system.

DIFFERENTIAL POTENTIAL

There is a voltage or potential between a cloud and the earth. The voltage is spread over the distance separating the two. The result is an electric field or voltage gradient measured in Volts per meter (V/m). The earth is nominally at zero volts.

Regardless of the presence of a thunderstorm, there is always a gradient in the air. In normal conditions, it is about 100 V/m. Under lightning conditions a typical gradient is 10 – 30 kV/m. Under this scenario, the head of a person would be ~6000 V above the foot. A chimney or peak of a house would be elevated about 20,000 V. A distribution power line would be ~30 kV. These are all examples of a vertical electric field.

Similarly, as a cloud moves over the surface of the earth, a horizontal potential develops between areas under the cloud charge and those outside the cloud. Furthermore, the earth resistance and the electrical ground are not uniform, which causes a horizontal potential [11].

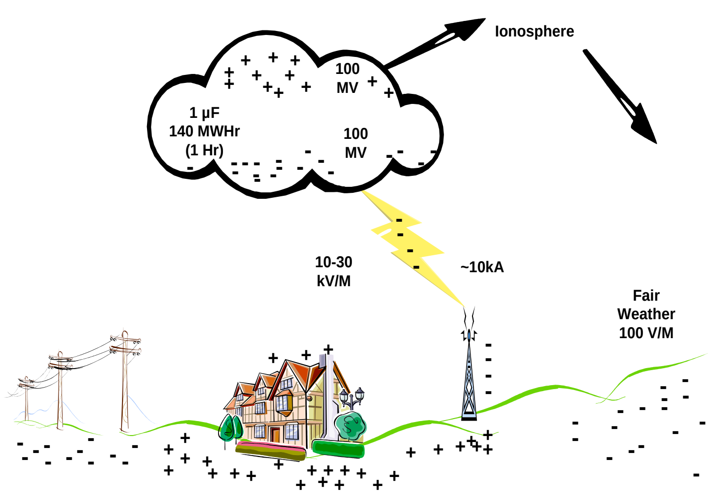

Figure 1: Potential gradients

Any potential difference, whether vertical or horizontal, can cause a discharge resulting in injury or damage.

EQUIPOTENTIAL

A dominant consideration for lightning management is to establish a uniform reference or ground. This is called an equal potential or equi-potential plane. The equal potential will only exist in the limited area designed for the purpose.

An equal potential ground is established not by the earth, but by a grid of electrical conductors bonded together [11].

The simplest grid is the rebar in the concrete of a structure. The *National Electrical Code (NEC)* Article 250.52(A)(3) requires the rebar to be bonded to the electrical system ground as an aid to an equal potential area [2]. In areas without concrete, a grid is created by copper electrical conductors bonded and buried in a network under and around a facility.

REFERENCE

An electrical grounding system uses a single point as a reference for all measurements. This is called the grounding electrode.

In an attempt to create minimum potential difference in the ground system, a grounding electrode system is mandated by *NEC* 250.50. "All grounding electrodes as described in 250.52(A)(1) through (A)(6) that are present at each building or structure served shall be bonded together to form the grounding electrode system."

The *NEC* 250.52 lists seven alternatives for the grounding electrode.

1. Metal underground water pipe
2. Metal frame of the building or structure
3. Concrete encased electrode, including rebar
4. Ground ring
5. Rod and pipe electrodes
6. Plate electrodes
7. Other metal underground systems or structures.

The *National Electrical Safety Code (NESC)* has a slightly different list consistent with a power distribution system [12].

The most familiar, but one of the least effective is the ground rod. As a minimum performance, the *National Electrical Code*, the *National Electrical Safety Code*, and the *IEEE Recommended Practice for Grounding* specifies a made electrode ground resistance of less than 25 Ohms (Ω) [13]. Otherwise, an additional electrode must be installed. Some jurisdictions now require two electrodes as a matter of course.

This high ground resistance is inadequate for communications, data, fire, and safety purposes. According to the *IEEE Green Book*, Section 4, "There is no implication that 25 ohm, per se, is a satisfactory level for a grounding system [13]." An engineered solution specifies a ground resistance of less than 6 Ohms [11].

An excellent ground resistance reference for electronic circuits can be obtained from the standards for intrinsically safe shunt diode barriers. In these systems, ground resistance from the furthest barrier cannot exceed one (1) Ohm. This requirement is incorporated into the *Code* by reference to *ANSI RP 12.6-1995* [14, 15]. The low ground resistance allows objectionable energy to be dissipated safely into the earth.

Metal gas pipe must not be used as a grounding electrode according to *NEC* 250.52(B)(1), but it must be bonded to the grounding system in *NEC* 250.104(B).

THE BOND

Assuming there is an adequate ground, bonding is crucial. Three factors impact the effectiveness of the grounding and bonding conductor.

First, conductor diameter should be AWG 4 or larger. Next, the distance from the bond to the ground should be less than 20 feet. This correlates to *NEC* 820.100(A)(4) requirements for communications circuits. Finally, the route must be as direct as possible with only sweeping bends. The first two factors impact resistance. All three impact inductance. We have previously shown that inductance is the critical factor [7].

A typical ground conductor has an inductance of 0.5 microhenries per foot. For a lightning impulse of 1 MHz, the inductive reactance is about 3 Ohms per foot.

$$X_L = 2\pi fL = 2\pi(1,000,000)(0.005) \approx 3\ \Omega/\text{ft}$$

This is 10,000 times great than the 0.0003 Ohm resistance for AWG 4. The voltage drop due to lightning increases dramatically. In effect, length greater than 30 feet is almost like no connection.

SIZE MATTERS

Lightning damage is the result of a discharge of electromagnetic energy from a conductive metal surface. Because of the electromagnetic field, a potential can be induced on a large surface area without a visible strike. These are called indirect discharges.

Lightning begins as a potential between a cloud and the earth or another cloud. To release the energy, a leader progresses from the cloud toward the earth [6]. The leader gets close enough to the earth in the order of 150 feet. Then a leader progresses up from the earth to create equilibrium. These meet in the air and the path continues on up the plasma trail to discharge in the cloud.

The electrical energy below a cloud has a charge density which is charge per area (Coulombs / meter^2). Think about the size of the metal surface. A larger size would develop a greater charge.

Larger pipes, flues, and vents are more prone to develop a significant charge than a single small-diameter wire in the same region. However, we have observed metal gussets, nails, and iron bed frames with a discharge of energy.

Two charged metals separated by some insulation called a dielectric form a capacitor. It is the capacitor discharge that damages.

The lightning waveform has the voltage on the top curve and the current on the bottom curve. These illustrate that the energy is a pulse with a very rapid rise and a slower decay time.

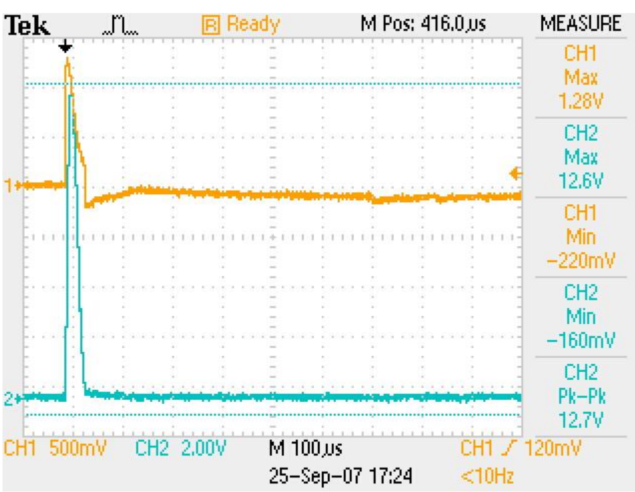

Figure 2: Voltage and current transients

ENTRY & EXIT WOUNDS

Since electrical energy requires a complete path or circuit, there will be a place where lightning energy enters the metal and where it leaves. However, with indirect strikes, the entry may be difficult to identify.

These are recognized by the direction of metal flow. The energy transfer creates heat causing the metal to flow inward at the entry and outward at the exit. The energy will severely damage or destroy high impedance locations between the points. This includes connections which are bolted or threaded.

The exit is to a ground path. Often this is to an electrical wire that crosses the metal containing the lightning charge.

Why does the path discharge to an electrical cable? All electrical circuits should have a path to a good ground. A standard 120 Volt circuit has three wires, two of which are connected to ground and provide a path to earth. Because of the potential in lightning, it can easily penetrate the 600 V cable insulation rating.

The conductor carrying the electromagnetic energy from lightning may be electrical or communications wires, a pipe, or other metal. The piece of metal conducting lightning energy must be as straight as possible. Lightning is a high frequency, high speed waveform. Sharp bends increase the inductance of the path.

The discharge of lightning has two distinct scenarios. A straight path or pipe that crosses a grounded conductor will have a relatively small failure from a kissing arc. Where a sharp turn is adjacent to a grounded path, there is more likely a rupture type failure due to the inductance kick. Hence any bends must be greater than an 8 inch radius on the inside of the curve.

The discharge from the metal to the ground conductor has more than adequate energy to ignite combustibles and create a fire if there is fuel.

GOOD GROUND PATH

Metal items that have a good path to earth potential are not damaged by lightning. There is no discharge. Simply connecting the metal to a ground rod does not assure a good ground. There must be a low impedance connection and an equal potential for the structure under the cloud charge. There must be a near zero impedance path in the horizontal and the vertical direction.

Think about a typical lightning strike with 10 kA current. A two-Ohm impedance creates a 20,000 Volt potential. That amount of energy discharge can be devastating.

As a counterpoint, consider a near zero impedance of 0.001 Ohms. The same lightning stroke would create a potential of 10 Volts, hardly enough to notice.

It is not a connection to ground that is important. It is how low the impedance is in the entire ground circuit that is crucial. This includes a low potential between all pieces of metal. A note in *NEC* 250.104(B)FPN states "Bonding all piping and metal air ducts within the premises will provide additional safety."

That is an understatement, bonding all metal is crucial to controlling lightning effects. Historically, when steel water lines were used, they provided a common reference with reduced lightning impact.

The *Code* 250.110(1) requirements for personnel safety grounding of fixed equipment is equally appropriate for controlling lightning. Any metallic conductor that may be energized by electrical or lightning energy must be bonded. Bond all metal within 8 feet vertically or 5 feet horizontally from ground or grounded metal objects.

These dimensions are to handle touch distance. The distance to discharge lightning energy is considerable shorter, but varies dramatically with humidity, surface area, and effectiveness of grounding.

ERRORS & OMISSIONS

The following are five preventable incidents that were investigated in a three-month period [16]. This is by no means a complete list of our lightning investigations for the year, but is representative of the types of errors that are related to lightning damage. The lightning was verified by witnesses or lightning reporting services.

Each of these scenarios is quite common and has been investigated by us multiple times in the past year. In addition to these, various other lightning scenarios have also been investigated.

CLEAR AIR AND END POLES

Must the lightning occur at the point of discharge? No, the charge can build up in one region and travel along a conductive path and discharge in another location. Further the charge can be distributed over a long area such as a power line.

Clear-day lightning may build up along an overhead power line. If there is not an alternate path, the discharge is typically at an end pole on the line.

At the end, the line is not terminated with characteristic impedance. Therefore, the open line causes a reflected wave equal to the incident wave. The resultant is two times as large. This potential will be adequate to discharge through any transformer or other device connected on the end of the line. The result is a huge transient that damages equipment and causes fires.

Although utilities accept this risk, engineers for critical production operations require one span to be built past any transformer bank with arrestors on the end poles. This moves the open line reflection away from the transformer.

Figure 3: Un-terminated electrical line

Lessons Learned: Lightning is a high frequency that prefers a straight, low impedance path. Un-terminated lines, whether power, communication or pipe will cause a reflected wave with increased magnitude. Energy can be shunted away from the line.

POOR GROUND ELECTRODE

What is the effect of a high resistance ground rod? Any fault current will take an alternate path to earth and will damage items in the path. A ground rod at a service meter pole had virtually no contact with earth. The resistance was 800 Ω, which is approaching no connection.

A transient fault occurred and took two identifiable paths. One path was another overhead triplex cable. The uninsulated grounded neutral carried excessive energy. This caused the insulation on the other two phase conductors to melt in the shape of the neutral. The insulation on the opposite side was unaffected.

The other path was to another grounding electrode conductor at a remote distribution panel. The grounding conductor had evidence of heat damage and electrical arcing. This energy resulted in ignition of combustibles and extensive damage to the structure.

Had there been an adequate ground at the service entrance, the energy would have been shunted to earth and the other damage would not have occurred.

Lessons Learned: Inadequate bonding provides an alternate path for discharge of energy that can ignite combustibles. A disconnected or floating neutral at the service entrance can result in a failure anywhere in the electrical system.

Figure 4: Damage from overheated neutral

REBAR

What is the effect of not bonding concrete encased rebar to the electrical ground system? The potential difference will damage the concrete and create enough discharge energy to ignite combustibles. The ground on the system met the letter of the *Code* but was not good. The resistance was 6.5 Ω, but sharp bends increased the inductance.

A lightning strike entered the structure at the peak above the second floor on the northwest side. The first contact with metal was a bundle of 21 non-metallic (NM) cables that were routed to the circuit breaker panel.

Rather than take the torturous path of the grounding electrode conductor with sharp bends, an alternate path was identified by arcing. The circuit breaker panel cover was removed during construction. The panel arced to a metal grate leaning against the panel. The grate arced to the panel cover setting on a concrete floor. The energy arced through the concrete creating sprawling.

Lessons Learned: The ground path to ground electrode (rod) must be low impedance with no sharp bends causing inductance. The ground electrode (rod) must have low contact resistance. The concrete is an excellent conductor. Rebar must be bonded to provide low potential difference. Any large surface metal provides a preferred path rather than the relatively small AWG 4 copper ground wire.

Figure 5: Damage from unbonded rebar

GAS PIPE

Should gas lines be grounded or bonded? The *Code* is clear that they as well as other metal piping should be, but some jurisdictions prohibit the connection. In many installations we have found that the connection simply was not made.

The electrical ground resistance was excellent with 0.7 Ohms. The flue to a heater is a large metal surface area that protrudes above a structure. It is a ready entrance for lightning energy, whether direct or indirect. A direct strike will penetrate the cap with nail size holes. Arcing is noted along the pipe joints.

The lightning energizes any metal connected to the unit. This includes gas line, copper air-conditioning lines, and electrical conductors. Seldom does rigid steel gas pipe have a failure. However, flexible metal lines will be penetrated if crossing another metal conductor including insulated electrical wires. The *NFPA Standard for Lightning Installation* affirms that adequate thickness steel cannot be damaged by lightning [3].

There are multiple paths for energy from the source. Each path has different impedance. With a relative low lightning current of 10 kA, even a 0.1 Ohm difference will create a potential of 1000 V and a power across the point up to 10 Megawatts. That is enough to blow up virtually any metal and cause fire.

$$V = IZ = (10000)(0.1) = 1000 \text{ V}$$

$$P = VI = (1000)(10,000) = 10 \text{ MW}$$

Lessons Learned: Excellent bonding is critical to minimize differences in impedance and potential. The relatively thin wall of flexible tubing and pipe is penetrated by lightning energy. The widening and narrowing of tubing creates an un-terminated waveguide for electro-magnetic energy resulting in reflected waves and doubling of the waveform. Local bonding is necessary to any metal within about a foot.

Figure 6: Damage from unbonded gas pipe

SATELLITE DISH & CABLE

Will coax cable carry enough energy to cause a fire? Must satellite dish and coax cable be grounded and bonded? Coaxial cable is designed to carry high frequency electromagnetic energy in the form of television signals. Lightning is a high frequency signal with substantially more energy.

Lightning struck the post of an ungrounded dish mounted to a roof. A hole was blown in the steel post. The cable splitter was destroyed at the terminations. The cable jacket was split but otherwise appeared intact. The foam filler, shield, and copper had become plasma and vaporized.

Figure 7: Damage from ungrounded satellite dish

Two different coax lines crossed electrical cables at 30 feet and 33 feet away. Both coax cables discharged to the electrical ground in the power cables. The coax was not destroyed past the electrical cable faults.

In similar scenarios, the braided shield had tiny beads on each strand. The foam filler was melted and had flowed due to the energy.

Figure 8: Damage from ungrounded coaxial cable

Lessons Learned: Lightning damage will result in coax foam being melted or vaporized. Beading may be found on individual braids or the conductor. Grounding of the dish and coax is necessary and required by *NEC* 810. The ground should be within 20 feet with sweeping bends. The ground must be bonded to the electrical grounding system.

CONSIDERATIONS

Lightning damage is more likely when any of the following conditions exist.

1. Large metal surfaces
2. Metal surfaces protrude above other grounded surfaces
3. Metal conductors have sharp changes in direction, including corrugation
4. Thin metal
5. Ungrounded metal
6. Inadequate bonding between metal
7. End of line or metal conductor.

CAN IT BE DONE?

Is it really possible to protect from lightning damage? The Empire State Building is a well recognized, metal frame structure protruding into the New York skyline. The structure has been struck by lightning an average of 100 times per year, since its construction in 1931. Yet the building is still there [17].

Figure 9: No damage to Empire State Building

This is a very visible demonstration that with adequate design, installation, and maintenance, lightning can be managed. Lightning discharges cannot be prevented. They are an act of God. However, they can be controlled. Not doing so may tend to be an act of negligence.

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VITAE

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He has been awarded numerous times for the over 117 technical papers he has authored. He has published seven books used in university level classes. He is acclaimed in Who's Who of American Teachers, National Registry of Who's Who, Who's Who of the Petroleum and Chemical Industry of the IEEE, Who's Who in Executives and Professionals, Who's Who Registry of Business Leaders, Congressional Businessman of the Year, and Presidential Committee Medal of Honor. Honorary recognition includes Phi Kappa Phi, Tau Beta Pi, and Eta Kappa Nu.

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