Get Grounded: Protecting Electrical Devices From Lightning Transients

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Lightning is one of the main paths for electrons to return from the atmosphere to the earth's surface. As in all electron flow, lightning is a form of current flow. Enormously high voltages (**Table 1**) between clouds and the ground cause breakdown of almost all insulator systems, leading to loud and brilliant arcing.

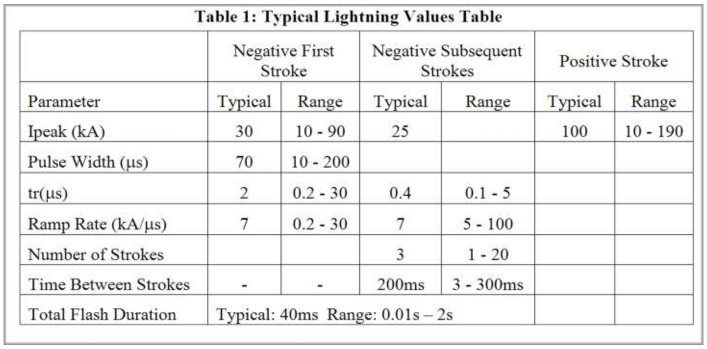

Table 1: Typical Lightning Values Table

	Negative First Stroke		Negative Subsequent Strokes		Positive Stroke	
Parameter	Typical	Range	Typical	Range	Typical	Range
Ipeak (kA)	30	10 - 90	25		100	10 - 190
Pulse Width (µs)	70	10 - 200				
tr(µs)	2	0.2 - 30	0.4	0.1 - 5		
Ramp Rate (kA/µs)	7	0.2 - 30	7	5 - 100		
Number of Strokes			3	1 - 20		
Time Between Strokes	-	-	200ms	3 - 300ms		
Total Flash Duration	Typical: 40ms Range: 0.01s – 2s					

Table 1

Providing a flow path for the lightning current is central to effective lightning protection. NexTek engineers are frequently asked why certain practices are important in grounding and bonding coaxial protectors. In this article we discuss some key parameters, and illustrate their role and importance. While the issues here are oriented towards grounding coaxial lightning protectors, the same concerns apply to general lightning protection practices.

Examining the frequency domain parameters is just as important as looking at the time domain profiles. Taking the 8x20 µs impulse as a very rough representative pulse, the harmonic contents show energy starting at 20 kHz to 100 kHz **Figure 1**); while the energy continues to diminish above 100 kHz to about 1 MHz, there is very little energy above 1 MHz.

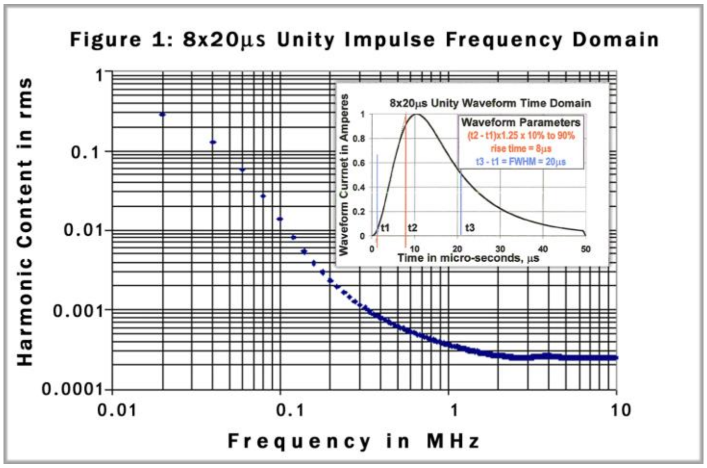

Figure 1: 8x20µs Unity Impulse Frequency Domain

Figure 1

Note that many waveforms (such as 10x350 and 6.7x70) are of longer duration, so that the harmonic content will be at lower frequencies.

While most of the parameters are of a scale that technically oriented people can understand, perhaps the most difficult parameters to grasp are the huge currents of tens of kiloamperes flowing for only a few tenths of microseconds. To give a sense of these currents and times, consider that a bare 18 AWG (1 mm diameter) copper wire, in air, normally will conduct at least 10 amperes safely, with very low self-heating temperature rise. If the current slowly rises, the temperature will increase until the melting temperature of 1065° C (1950° F) is achieved at about 83 A. This same temperature could be reached "instantly" by an 8x20 µs pulse at a current of 61 kA. A 61 kA impulse is as much of an overload to a 10-amp extension cord as a continuous, 83-amp load. The effect might be just the same: molten copper, easily hot enough to start a fire.

A. Temperature rise of the grounding conductors

When high-current pulses flow in a wire, the temperature rises due to the heat created by the current flow through the resistance of the wire material. The integral of $i^2 dt$ is referred to as the *action integral*. The action integral, when multiplied by the resistance of the current flow path, is approximately the energy dissipated for that current flow (since $P = I^2R$ and $J = I^2Rt$.

During a current impulse, wire temperature increases due to several factors. For a given current impulse, the two most critical factors are the wire's resistivity and diameter. Temperature-rise parameters of secondary importance are the wire's density, specific heat, temperature coefficient of resistivity and the wire's initial temperature. **Figure 2** shows the impulse capability of wire with 8x20 µs current pulses.

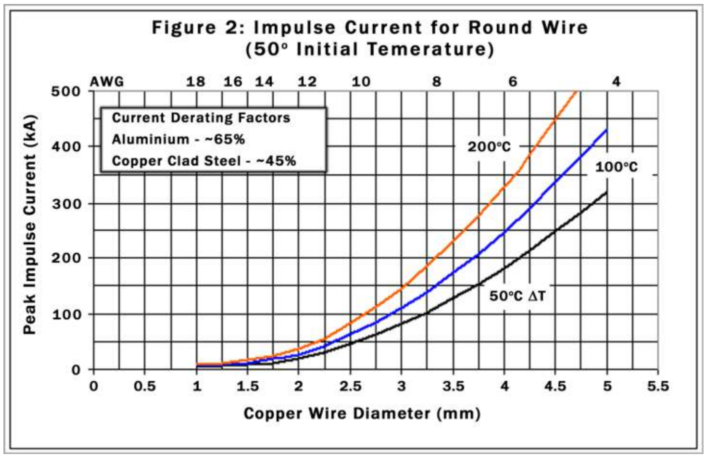

Figure 2

The wire's current capability is surprisingly high, even with a low temperature rise limit of 50° C. It appears that 4-mm diameter wire (~6 AWG) will withstand over 175 kA! So why are lightning grounding wires usually required to be larger?

B. Forces on a current-carrying conductor

Whenever current flows on a conductor in a magnetic field, Lorentz forces are created at right angles to the conductor. The magnetic field can originate from the earth or from the current flow in the wire itself. If the wire is straight, the force will tend to push the conductor sideways, or at right angles to the conductor direction. If the conductor is curved, then the force tends to put internal "hoop" tensile stress on the conductor.

Figure 3 shows samples of 12 AWG (0.080" or about 2 mm diameter) annealed copper wires after exposure to transient current pulses.

Figure 3

The top image shows the shape before the current pulse, with an inside bend radius of about 7/32" (~5mm). The middle wire, after exposure to a 55-kA, 8x20 µsec current pulse, shows that the internal hoop stresses have somewhat straightened the wire by smoothing out the relatively sharp bend. Repetitive current pulses of this magnitude would probably fracture this wire. The bottom wire has actually 'necked down' and fractured at the bend location, after a single 90-kA pulse.

According to the temperature-rise information above, impulse temperature rise was only slightly over 50° C, so wire softening or melting had no significant role in this fracture, even if follow-on or post-fracture current arcing occurred on the wire ends. The strength of the wire was exceeded by the internal forces.

Lorentz forces increase with sharper bends (lower radius) and are resisted by the size and strength of the wire material. As a rule, bends in lightning grounding wire should have at least a 10" or 30-cm radius. To eliminate bends, lugs should be positioned in line with the wire. Lugs which are in line with the ground wire are more effective than cosmetically satisfying lugs in line with an architectural component which force a directional change in the wire.

C. Terminations: It's not just the wire size; it's also the termination

Wire lug attachment (**Figure 4**) usually works better for continuous current than for transients.

Figure 4

Consider a 4-mm diameter (~6 AWG) copper grounding wire and lug. The normal voltage drop of a crimp lug is about the same as the voltage drop of 50 mm (2 inches) of wire. However, the lug junction with the wire is usually less than 12 mm (1/2") long, so the lug's heat dissipation is about four times more concentrated than it is in the wire. Normal heat dissipation can use the full surface of the lug and wire to assist in cooling. With lightning transients, there is insufficient time for the same level of heat-spreading and cooling effects.

It is not uncommon for lug transient-temperature rises to be over twice that of the attached cable. Substantial de-rating is usually appropriate for crimp or compression connections. To get more of the wire's transient capability, it is helps to use redundant connections or long-barrel terminals and proper crimp tools. Avoid the vise-grip or hammer approach for field connections.

Welded connections can get all of the wire capability and allow the use of smaller diameter wire. These may be less expensive in total cost, especially when compared to longer, upsized copper conductors. Of course, don't use excellent or redundant lugs so you can use under-sized wire!

D. Aging effects

The above test results and calculations are based on using new materials and do not account for aging, the oxidation and corrosion effect on wires and lugs. In addition, galvanic-corrosion action, salt, or other chemical exposure and soil conditions can be even more aggressive. Vibration and other mechanical loading, including loading which occurs during maintenance, have to be considered. This is another reason why larger ground cables are specified for large primary-bonding wires (those wires that may exclusively take the lightning current).

In environmentally aggressive environments, use tin-plated wire and fittings, and place the ground wire in plastic conduit or coat exposed bare metal. Keep terminals and junctions away from, or above, standing water. Use copper wiring outdoors, and do not mix copper with aluminum, even with approved CuAl (dual use) fittings.

E. Mechanical Damage

While 10, 12 and even 14 AWG (2.6 to 1.6 mm diameter) copper wires have a significant transient capacity, they are not strong enough to survive accidental snagging, pulling, or other forces. Consequently, smaller ground cables have to be physically protected or be bronze- or copper-clad steel. However, high-strength bronze or steel does not approach the conductivity of copper. If significant risk of exposure to lightning is possible, it is better to use larger, copper ground wires, rather than smaller and stronger wires.

F. Impedance

When transient current is forced into a drain or ground wire, resistance and inductance combine to produce a voltage drop, **Equation 1**:

$$Z(\Omega) = (X_R{}^2 + X_L{}^2)^{½}$$

Where X_R is the resistance of the cable and X_L is the inductive impedance of the cable, both in ohms.

The resistance of the wires, shown in **Table 2**, is dependent upon the length and diameter of the wire (more on the electrode/earth resistance later).

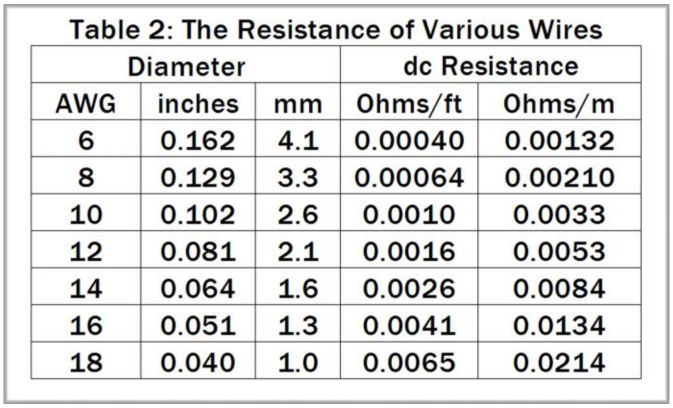

Table 2: The Resistance of Various Wires

Diameter			dc Resistance	
AWG	inches	mm	Ohms/ft	Ohms/m
6	0.162	4.1	0.00040	0.00132
8	0.129	3.3	0.00064	0.00210
10	0.102	2.6	0.0010	0.0033
12	0.081	2.1	0.0016	0.0053
14	0.064	1.6	0.0026	0.0084
16	0.051	1.3	0.0041	0.0134
18	0.040	1.0	0.0065	0.0214

Table 2

Here, the resistance is "dc resistance" since it is observed only in cases of direct (non-ac) current flow. The frequency (Hz) of the current has an indirect effect upon the resistance, due to the skin effect. When an alternating current flows in a conductor, a back EMF is created in the center of the conductor, which opposes the current flow. This restricts the current to flow only at the outer surface of the wire, effectively removing the core of the wire from the circuit.

The effective depth of current flow is called the skin depth, and can be calculated by **Equation 2**

$$\delta = (2\rho/(2\pi f\mu_R\mu_o))^{1/2}$$

Where δ is the skin depth in mm, ρ is the resistivity of the conductor, f is the frequency in MHz, μ_R is the relative permeability of the conductor and μ_o is $4\pi\text{-}10^{-7}$ NA^2.

Table 3 lists the skin depth for copper wires at certain frequencies.

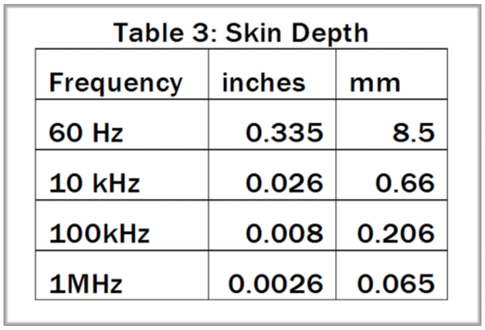

Table 3: Skin Depth

Frequency	inches	mm
60 Hz	0.335	8.5
10 kHz	0.026	0.66
100kHz	0.008	0.206
1MHz	0.0026	0.065

Table 3

Most lightning current energy is below 10 kHz. While there is some energy at 100 kHz, very little remains above 1 MHz. In this case, the design point for frequency might be at least 10 kHz, which means that conductors over 0.052" (1.3 mm) thick (representing a skin depth of 0.026" (0.66 mm) on each side of the conductor) have reduced conducting efficiency.

The 10-kHz resistance of the conductor, with only the outside 0.026" (0.66mm) of the conductor contributing to current flow, has a significant effect on larger-diameter cables. The effective conductor sectional area at 10 kHz, compared to the dc or actual area is given in the curve of **Figure 5**.

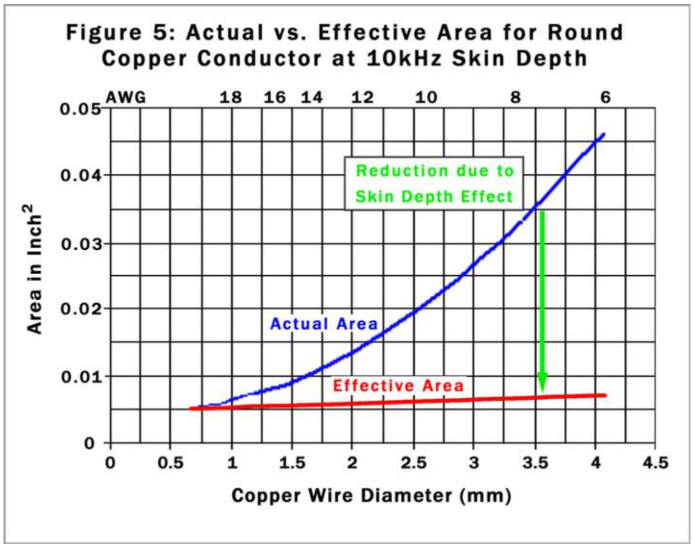

Figure 5

While increasing diameter increases the effective area, the increase in effective area is associated with the circumference of the wire, not the sectional area.

The skin-depth effect means that copper straps about 1/16" (1 mm) thick will tend to outperform round wire of the same cross-sectional area, since the full cross section of the strap will conduct high current. Admittedly, wire (particularly stranded wire) is much easier to install, join, and change direction than straps. Flat-braid cable is a good alternative for vibration resistant and highly efficient grounding, which is why it is commonly used in aircraft-grounding applications.

Another aspect of impedance is the series inductance and its effect on creating voltage drop. The inductance of a wire is predominately related to its length and weakly related to its diameter. An estimate of a wire's self-inductance is **Equation 3**:

$$L(\mu H) = 0.20\ [\ln(40{,}000\ L/d - 0.75]$$

Where L is the length in meters, and d is the diameter of the wire in mm. The inductance of some typical wire lengths and diameters is given in **Table 4**, along with the inductive impedance (calculated by 2**π**fL):

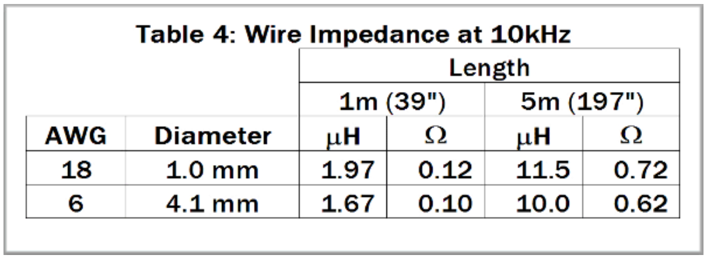

Table 4: Wire Impedance at 10kHz

		Length			
		1m (39")		5m (197")	
AWG	**Diameter**	**µH**	**Ω**	**µH**	**Ω**
18	1.0 mm	1.97	0.12	11.5	0.72
6	4.1 mm	1.67	0.10	10.0	0.62

Table 4

The length of the cable increases the impedance dramatically. Larger-diameter cables have slightly less impedance, due to the larger surface area. The benefit of larger diameter is less significant for resistive impedance, due to the skin-depth effects.

G. Bonding

Bonding refers to the electrical connection of metal objects with conductors that serve as a flow path for lightning current. Typical current-flow paths can include metal structural steel, reinforcing bar, metal conduit, dedicated lightning-protection system cables, metal plumbing and piping, power-grounding wires and electrical conductors. Since these metal objects may find themselves in the lightning path, just as in a cable, current-flow voltages can be created along their lengths due to resistance and inductance, so that the voltage nearest the current injection point is significantly higher than at other nearby metal objects. If a person or equipment is connected between these points, hazardous voltages can exist. Bonding of adjacent metal objects reduces this voltage, and provides a redundant current-flow path.

In many cases a protector should be bonded to a ground plane, which usually consists of at least a peripheral ground around the area to be protected. Often a ground grid is used to provide low impedance across the ground plane. To intercept lightning, overhead grounded shield wires can also be bonded to this ground plane.

The extent of bonding relates to the risk of a direct strike to the structure, susceptibility of equipment, and the likelihood of injury to personnel. Consult local codes and practices of other contemporary structures. Make sure that the bonding is made with appropriate wire and terminals, and is made between the appropriate objects. In some cases, "hidden" internal bonding, such as reinforcing bar, can be cost effective. However, testing with current injection is usually needed, particularly when the lightning protection infrastructure is unknown, or the building was not designed for high lightning-risk device deployments.

H. Grounding resistance: never low enough

Lightning is essentially a current impulse which is trying to return to earth. The term grounding sometimes means a wire connected to an equipment chassis that is run in parallel with the power lines, to assist in tripping over-current devices and reducing voltage on the chassis in case of power line faults. While these grounding wires are sometimes involved, grounding here refers to the connection to the soil, which (hopefully) will be the preferred path of lightning current.

Electrode resistance also deserves focused attention. For electrical power entry, a minimum of twenty-five ohms is sufficient in most locations. However, recommendations of 10Ω or 5Ω are common. In some deployments, the goal is an incredibly low 1 Ω. What value of electrode resistance is sufficient or able to solve our lightning problems?

Assume that we have to contend with a 90th-percentile lightning current of about 100 kA, and that using multiple current-flow paths we have managed to get the lightning current to share into five extremely low, 1Ω earth electrodes. This means that we would have about 20 kA into each electrode. The voltage of the 1Ω electrode would be approximately 20 kV (by $V = IR$). Now if you were spanning between this "ground" point and another more distantly "grounded" object, you would experience a very objectionable impulse. If electronics circuits span these "grounds", damage would most likely result (this voltage is sometimes called ground-potential rise).

But wait a minute! Even when we had five 1 Ω electrodes and developed 20 kV, as explained above, what's happening? The problem isn't the wires or the electrodes, it's the soil. Try as we might, it is virtually impossible to drain lightning into the soil with negligible voltage. So how do we protect people and electronics?

First, during high lighting current flow, the ground will be at an elevated voltage compared to other locations and grounds. There are three elements to a practical solution:

1. Extend your ground bonding plane to include all equipment required to be protected. This frequently means enclosing the protected equipment in a shielded structure, usually implemented as a "mesh" Faraday cage.

2. Ground this structure at numerous points to provide redundant and reduced, albeit imperfect, earthing.

3. Suppress or ground the entry of ALL conductors at this structure where they enter. Don't forget that water pipes, air conditioning lines, structural steel and other "on-electrical" conductors need the same grounding as signal and power lines.

Figure 6 represents various mounting configurations for installing in-line protectors.

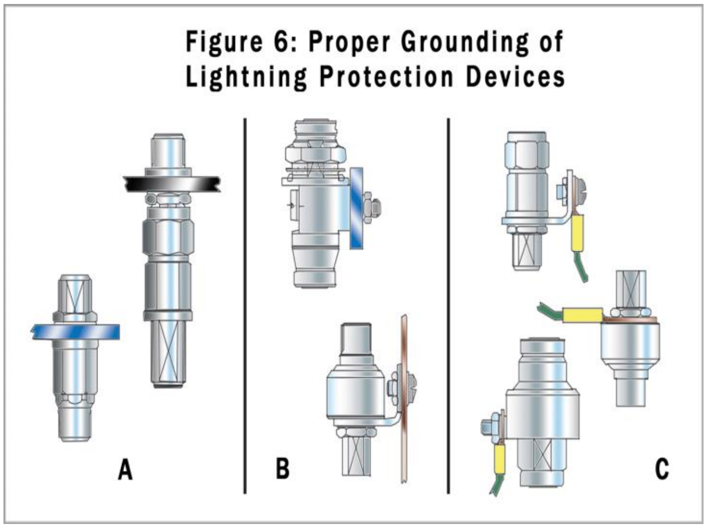

Figure 6

(A) Locating the protector in a panel or bulkhead provides the best grounding and shielding. A strain-relief loop is required for a rigid cable. The connector can also 'piggyback' on bulkhead feedthroughs.

(B) Attaching the protector to a ground bar or panel surface still provides superior grounding and enables high-density cable runs. The cable should include a drip/strain-relief loop. Mounting is usually accomplished with a bracket or M8 bolt.

(C) Grounding the protector with a wire jumper or strap still provides good grounding, and is the easiest method. A lug, bracket or M8 thread can be used. This method allows the cable to flex and run in any direction. A large ground wire should be used.

Unless properly protected, lightning transients can wreak havoc upon electronic systems. By understanding the role and importance of the key parameters discussed in this article and by following these design guidelines, it is possible to effectively mitigate the consequences of lightning transients and to protect electronic devices. Minimizing the impact of lightning transients not only extends electronic system life and reliability, it has the added benefits of reducing capital equipment, operating and maintenance costs.

References

Lightning-stroke parameters are varied due to variation in both instrumentation and location. Some representative profiles are available at:

1. http://www.weighing-systems.com/TechnologyCentre/Lightning1.pdf
2. http://www.sandia.gov/electromagnetics/New_Reports/reports/CaldwellEMC05.pdf
3. http://www.nextek.com/resources

About the author

George M. Kauffman is Vice President of Engineering at Nextek, Inc., Westford, MA (http://nextek.com/). For the past 10 years, he has overseen NexTek's engineering team, developing new lightning-arrestor and DC power-conditioning products. George is a recognized leader in the lightning-protection industry and holds multiple patents in the EMC field. His technical expertise assures that each product line exhibits optimal technical performance characteristics.

Prior to NexTek, George spent eighteen years at Digital Equipment Corporation in numerous roles including manufacturing, product development, product management and software development. George holds both a BS in Mechanical Engineering and an MS in Engineering Management from the University of Massachusetts/Amherst. He is registered in Massachusetts as a Professional Engineer.