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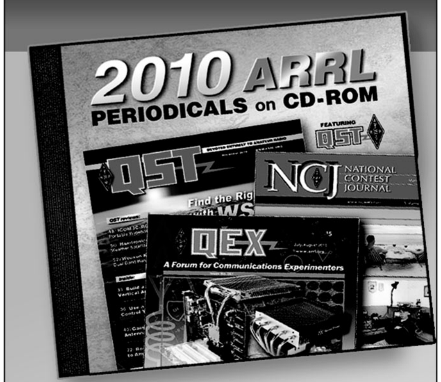

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Understand It or Suffer the Consequences

Part 2 — Inside your house. You can't keep lightning from happening — but by following the right practices, you can minimize damage.

Larry Scheff, W4QEJ

In Part 1 of this article we discussed what happens outside your house during a nearby lightning strike.[1] Now we'll discuss how lightning can affect what happens inside your house and what you can do to protect equipment during a nearby strike.

First let's put lightning-induced surges into two major categories — causative surges and resultant surges. We'll consider lightning-related surges that are generated outside your house to be causative surges. We'll consider resultant surges to be surges that result from interaction between the simultaneous causative surges that enter your house wiring from external sources and the ever-present 60 Hz ac waveforms in your house wiring.

Let's put those causative surges into two distinctly different sub-categories: above-ground causative surges and below-ground causative surges. We need to take very different measures to combat above-ground surges than we can use to combat below-ground surges. Let's examine the characteristics of those various lightning-related surges.

Getting Into the House

Figure 1 illustrates example characteristics of individual currents that flow through the stroke *arcs* during a cloud-to-earth lightning flash. We'll assume the soils of the earth are purely resistive having little, if any, inductance or reactance. Therefore the waveforms of the surge voltages developed between any two points on the earth's surface by earth currents of a nearby lightning strike should very closely mimic the waveforms of the earth-to-cloud currents in the individual lightning stroke arcs.

The waveforms of the transformer-like electromagnetic coupling fields between a lightning stroke and nearby above-ground wiring would also mimic the waveforms of the earth-to-cloud currents that produce that coupling. But it also seems logical that the parallel inductances in each such above-ground cable would produce a difficult-to-predict *store energy, then decay* type waveform for surges induced into that cable.

Further complicating things, power line surges will be electrostatically coupled from the primary winding to the secondary winding of the power company transformer that feeds your house, allowing them to enter your house through your load center panel.[2]

If I've Told You Once...

In Part 1 we determined that the only earth ground connection for everything inside your house should be through the ground terminal inside your load center panel. In addition, if you have more than one earth grounding electrode, then each and every one of those additional electrodes for all electrical and electronic equipment (including your tower, your station ground, your telephone service and cable TV service, for example) should be solidly bonded to your electric service grounding electrode.

We also learned that most above-ground lightning-induced surges originate as traveling waves that are introduced into outdoor above-ground wires or cables (power lines, phone lines, cable TV lines), and travel in both directions away from the point on the cable that's closest to the lightning bolt. Those lightning-induced traveling waves are line-to-ground voltage surges that are seeking a path to the ultimate ground of the lightning strike, not your ac service ground.

But each lightning-related below-ground causative surge is a ground-to-ground voltage that's created by lightning strike current flowing through the electrical resistance of the soils of the earth between two grounds. For instance, if your earth grounding system is improperly installed, with two earth grounding electrodes that are not properly bonded together, then there are three ground-to-ground surge voltages that you need to worry about — the voltage between the lightning touchdown point and one of your earth grounding electrodes (that we'll call electrode A), the voltage between A and your other grounding electrode (electrode B), and the voltage between electrode B and ultimate ground. In most instances the most harmful of those three surge voltages is the surge voltage developed between unbonded grounding electrodes, A and B.

Why? Let's apply Ohm's law ($E = I \times R$). Resistivity is defined as the electrical resistance per unit length of a substance with uniform cross section. Approximate earth soil resistivities range from 1000 Ω-cm for wet organic soil to 1,000,000 Ω-cm for bedrock. The average resistivity of pastoral, low hills, rich soil earth is 3000 Ω-cm.[3] Compare that with the resistivity of soft drawn copper of 1.724 μΩ-cm at 20° C and the resistivity of hard-drawn copper at 1.772 μΩ-cm.[4] A microhm is 1 millionth of an ohm so, comparing the average soil resistivity (3000 Ω-cm) to the more than 1.72 μΩ-cm resistivity of copper, it should be obvious that the voltage developed by surge current flowing between the point where most of the surge cur-

[1]Notes appear on page 34.

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rent of a very nearby lightning strike enters the earth and the service entrance ground would be very considerable.

If you have another earth grounding electrode that is not bonded to the service entrance ground, the surge voltage between those two electrodes created by that same earth current through the soils of the earth between those electrodes could be very dangerous. But when you install a ground bonding conductor having a low surge impedance between those electrodes it will, for most practical purposes, short out the surge voltages that would otherwise develop across the much, much higher resistance of the non-inductive soils of the earth between those two earth grounds. Of course that shorting conductor does have some impedance. But that impedance is very small compared to the virtually pure resistance of the soils of the earth between the two earth grounds.

Selecting Ground Bonding Conductors

Now let's set some rough guidelines for selecting and installing ground bonding conductors. You want each of those conductors to have as little surge impedance as possible when exposed to the extremely fast rise time lightning-induced surges so you want each of them to be as short and straight as you can make them. They should be of wire at least as large as the minimum 6 gauge size that's mandated by the National Electrical Code. They should be located outside the house to keep the surge currents out of the house.

All connections absolutely must be mechanically strong. Professionally welded connections are best, but UL-approved bolted clamps are permitted. Solder connections should never, never be used (and are prohibited by the National Electrical Code) because heat generated in those conductors during a lightning strike can destroy soldered connections.

The Genie Gets Out of the Bottle

Now let's see what happens when surges get into the house. No two lightning strikes are alike. Even if all strikes were alike and if you could make an accurate mathematical model that included the maze of wiring inside your house and the outdoor power, telephone, cable TV and other wires and cables that run into your house, it would be impossible to predict exactly where and when a nearby strike might occur, precisely what slightly varying 60 Hz voltage level would be coming from the power company, what equipment and devices would be turned on or off inside your house or how much the conductivity of the soils of the earth might change due to weather conditions. So such a mathematical analysis is impractical.

Now let's dispel what is probably the most common misconception about lightning damage from other than direct strikes. Many people seem to think lightning currents inside your house cause hard to explain damage. Generally it's the voltage peak of a lightning induced surge that triggers the damage to wiring or equipment inside the house. If the peak voltage of a surge exceeds the breakdown voltage of the wiring inside your house, it can cause arcing between wires to begin within that wiring, and that arcing may continue long after the surge has disappeared because the ever-present 120 V ac is sufficient to sustain arcing after the surge subsides.

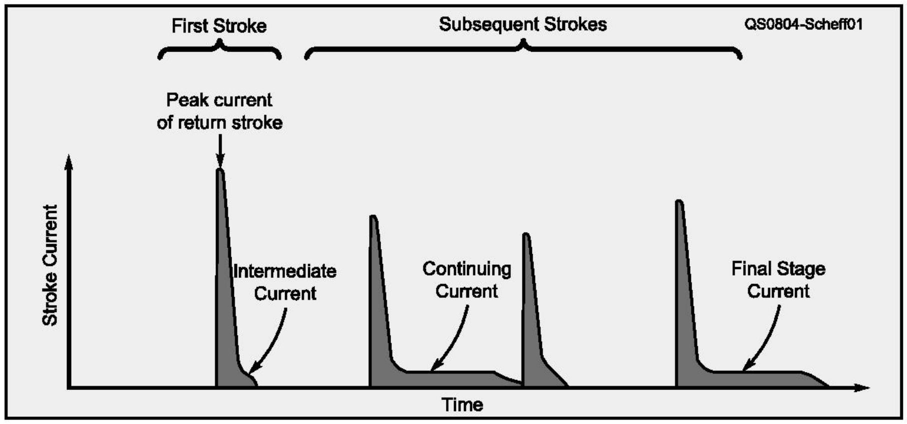

Figure 1 — Characteristics of individual currents that flow through the stroke arcs during a cloud-to-earth lightning flash. Note fast rise time and slower decay time.

Such arcing may ignite nearby flammable building materials causing a house fire. Even more likely but far less visibly detectable, if a voltage surge reaches, for instance, a transistor and the peak voltage of that surge exceeds the maximum voltage rating of that transistor, then that transistor or other component will probably be severely damaged or destroyed. If that doesn't worry you, just think about the even more microscopic innards of integrated circuits, especially complex microprocessors in our computers and modern transceivers.

Why don't the circuit breakers in your load center panel protect against such lightning-induced surges? Circuit breakers and fuses are *overcurrent* devices, not *overvoltage* devices. Even if the surge current is huge, breakers and fuses act much too slowly to do any good against lightning-induced currents. Typical lightning-induced surges inside your load center may reach their peak in only 8 millionths of a second.[5]

Since circuit breakers or fuses can't protect against lightning induced surges, we'd like to short out any line-to-ground traveling wave surge voltages from the electrical service entrance cable entering your home before those causative surges can enter the wires that distribute power throughout your house. We'd like to do it without also permanently shorting the 60 Hz voltages that provide power through the same electrical service entrance cable to ground. Sound impossible? Not at all, because the time durations of lightning-induced above-ground surges are almost infinitesimal compared to the time durations of a single cycle of 60 Hz ac power.

Surge Protection Devices

There are very fast-acting surge protection components and devices available that are designed to act like an open circuit when the voltage across them is below their clamping voltage, but act like a short circuit whenever a surge across them reaches or exceeds their clamping voltage. Such surge protection components may be divided into two basic types. One category includes crowbar type devices such as gas tube surge arrestors, spark gaps and silicon controlled rectifiers (SCRs). The other category includes clamp-type devices such as avalanche diodes, transient absorption Zener diodes, and metal oxide varistors (MOVs).

None of those components and no combination of components is a perfect solution to the problem of shorting out surges, so some compromises must be made in the design of surge protectors. We'll use MOVs in the following examples since the MOV is perhaps the most frequently used component in indoor surge protection equipment.

Different Protectors for Different Spots

Different types of surge protectors are used in different situations. Let's categorize the different kinds of pre-point-of-entry, point-of-entry and point-of-use surge protectors that may be used to protect equipment and devices inside your house as follows:

Heavy duty point-of-entry service entrance surge protectors, such as that shown in Figure 2, should be located at the load center panel of a residence and should be connected across the line, neutral and ground buses inside that panel. These protectors include specialized components (typically including banks of parallel-connected MOVs and some other components that are not shown in Figure 2) to instantaneously short out line-to-line surges, line-to-ground surges, line-to-neutral surges and, in some versions, neutral-to-ground surges inside the load center panel, preventing them from propagating

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farther into your house wiring.

Unfortunately, such devices were seldom included in older homes and are probably included in very few new homes. A really good service entrance ac surge protector may cost $500 or more, but compare that to the cost of replacing everything in your house that might be damaged by a very close lightning strike or a nearby direct hit on the power line that supplies power to your house.

If you add one of these, I'd strongly suggest that you to have a competent licensed electrician do the installation and insist that he follow the manufacturer's installation instructions. Some power companies now offer to provide such protectors for a monthly fee that's included in your power bill.

Point-of-entry telecommunications surge protectors should be provided and installed by your telephone company, cable TV company or by any other telecommunications or data system provider, so you probably don't need to worry about what's inside them. These should be located at the point where such cables enter the house. But watch out! If the service installer does not securely bond that surge protector, and any separate ground rod he may install, to your electric service entrance ground, that protector can't really do its job.

Selecting Surge Protectors

How do you select a surge protector? First, you need to know something about the characteristics of the surges that the protector will have to protect against.

I'd recommend that you pay close attention to anything you can find relating to the latest versions of standards and certifications such as ANSI/IEEE C62.41, UL 1449 and UL497; these are updated periodically and might supersede some of the information I've researched for this article

Surge Characteristics

Above-ground causative surges that enter your load center panel from your electric service entrance will combine inside that panel with the below-ground causative surges from your earth grounding system. The characteristics of both those types of causative surges may vary considerably from lightning strike to lightning strike, however.

Empirically derived data indicates that a causative surge that gets into the wiring in your home can excite the natural resonant frequencies of the various conductors used to wire the house and the resulting surge waveforms are typically not just oscillatory, but may have different amplitudes and waveshapes at different locations in your house wiring.

The wires in and near your load center panel are relatively short, so the effects of such excitation are minimal there. The farther you get from the load center panel, however, the more pronounced will be the excitation of the natural resonant frequencies of the individual wires or cables.

Lightning Driven Waveforms

Using a wealth of empirically derived data, surge protection scientists and engineers have developed a number of representative surge waveforms that are commonly used as guides in the design, manufacture, application and testing of surge protection components, devices, equipment and systems.

We'll concentrate mostly on the characteristics of surges you can do something about rather than the characteristics of surges you'll have to rely on someone else (the telephone company, cable TV company, as examples) to do something about.

One of the more common of the industry standard waveshapes chosen by the professionals to represent a typical resultant surge that might appear in the wiring at, inside and near your load center panel is the combination wave shown in Figure 3. This is a unidirectional impulse waveform having a peak open circuit voltage of 6000 V with a rise time of 1.2 μs and a duration of 50 μs, and a peak short-circuit current of up to 3000 A with a rise time of 8 μs and a duration of 20 μs. This waveform is considered to be representative of resultant surges at the load center panel, in major feeders from circuit breakers in the load center panel, and in short branch feeders from circuit breakers in the load center panel.

How Big Does it Get?

Let's boil some of that gobbledygook down into simpler language. If you want to install a point-of-entry surge protector in your load center panel to block such surges from entering your house wiring, that protector should be capable of shorting out repetitive 6000 V surges and withstanding resulting repetitive 3000 A short-circuit currents without accumulating enough internal heat and/or damage from electromechanical shock to fail or self destruct. In order to not shut down the ac powered things in your house, each shorting out period should last only as long as each individual surge. Additionally, you want the clamping voltage of the protector to be low enough to adequately protect the downstream equipment from lightning induced surges but high enough that none of the normal peak voltage fluctuations of the 240/120 V power in the house will cause the protector to short out the ac supply voltage.

Translated to Protection Devices...

Since temporary power line overvoltage conditions sometimes do occur, I'd recommend using a two-pole circuit breaker as shown in Figure 2, having a trip current rating consistent with the surge protector manufacturer's recommendation, to trip only if the surge protector is subjected to a sustained ac overvoltage which would cause its MOVs to go into the short circuit mode resulting in overheating and destruction of the protector. Here, you should conform to the protector manufacturer's installation recommendations. I'd also suggest that, as a guide to determining what clamping voltage you really need, you make measurements to determine how much actual ac voltage variation occurs in

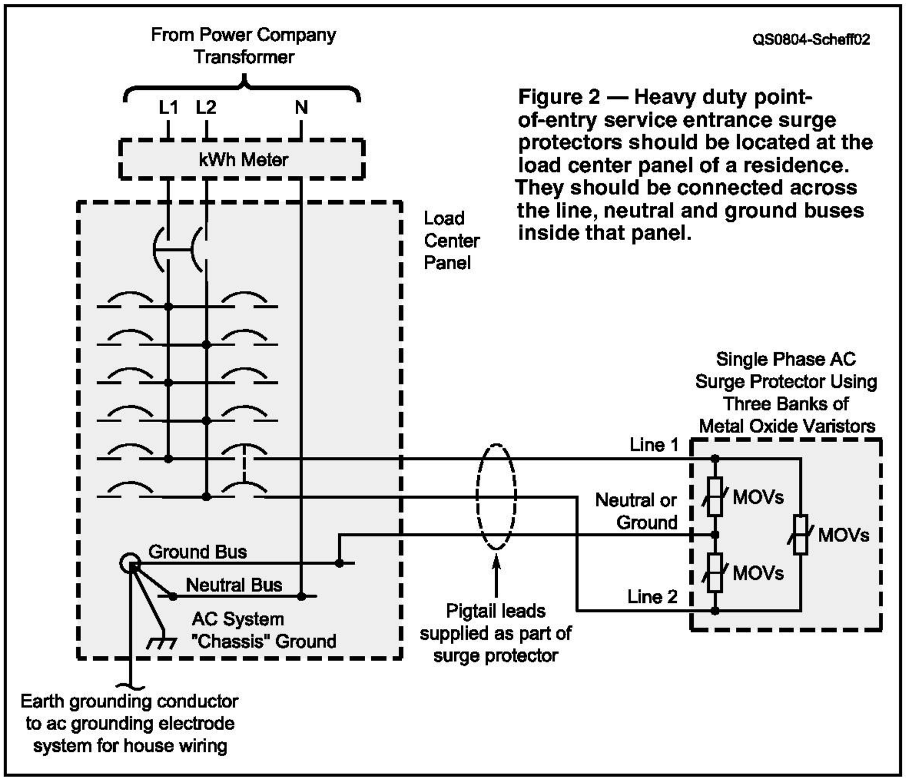

Figure 2 — Heavy duty point-of-entry service entrance surge protectors should be located at the load center panel of a residence. They should be connected across the line, neutral and ground buses inside that panel.

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your house at different times of day, week and season, and get a protector that will clamp at the lowest voltage level that's practical without being destroyed by normal ac voltage fluctuations.

Obviously we must consider the heat energy that's generated inside a surge protector. Using Figures 3 and 4 as an example, the amount of potentially damaging energy in a surge is proportional to what's often referred to as the area under the curve — in other words the area between a curve on a graph and its related horizontal 0 A or 0 V line. The larger that area, the more potentially damaging energy there is in the surge and the hotter some of the components inside a surge protector will get. How much of this destructive energy a protector can survive without self destructing is typically rated in joules. You may also apply this concept to the graphs that represent many other surges.

Beyond the Surge Arrestor

If Figure 3 represents resultant surges that occur in and near your load center panel, what about resultant surges that might occur in the rest of the house? Any causative surge that gets into the wiring in your home excites the natural resonant frequencies of the various conductors used to wire the house. The resulting surge waveforms are typically not just oscillatory, but may have different amplitudes and waveshapes at different locations in your house wiring. The wires in and near your load center panel are relatively short so the effects of such excitation are minimal. But the farther you get from the load center panel the more pronounced will be the excitation of the natural resonant frequencies of individual wires or cables.

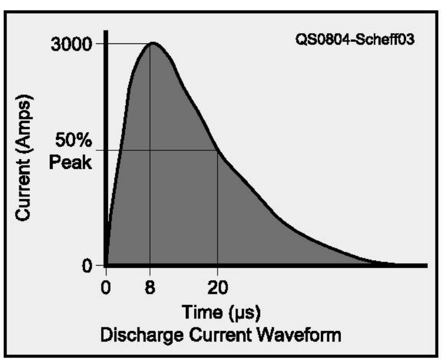

Figure 3 — Waveshapes representing a typical resultant surge that might appear in the wiring at a load center panel.

What We're Left to Deal With

Empirical data indicates that the frequencies of such oscillatory surge waveforms may typically range from 5 kHz to more than 500 kHz, but a 30 to 100 kHz frequency range is a realistic measure of a typical surge for most residential and light indoor industrial wiring. So there's another very commonly used, empirically derived representative surge that's considered applicable to the 60 Hz ac wiring throughout your house that's not really close to your load center panel. It's the 0.5 μs risetime, 100 kHz ring wave shown in Figure 4. At the beginning of such a representative surge, the surge voltage rises from 0 to peak voltage in 0.5 μs, then decays while oscillating at 100 kHz with each peak voltage being about 60% of the peak that preceded it. The duration of such a surge is microscopic compared to the 16,666.67 μs duration of one cycle of 60 Hz ac power.

How it Gets From Here to There

How and why does such a resultant surge oscillate? One of the most common types of cable used to wire residences is a 600 V nonmetallic-sheathed cable containing two insulated wires (one for the line and one for neutral) and a single uninsulated bare ground wire sandwiched between the line and neutral wires. Those wires are very closely spaced inside the sheath, so there can be inductive and capacitive coupling between the wires. If a causative surge or a combination of causative surges gets into that cable, it will store electromagnetic and electrostatic energy in the inductance and capacitance of the cable as the resultant surge rises from zero to its peak voltage level. Then, while the causative surge decays, the stored energy in the cable will decay in an oscillatory manner until the combination of causative surge energy and the energy stored in the inductance and capacitance of the cable is dissipated.

Once initiated, such a resultant surge will propagate throughout your house wiring, being attenuated as it travels until all its energy is expended. The possibility of electromagnetic and electrostatic surge coupling between close-spaced cables should also be recognized. Perhaps the term ring wave originated by comparing this type of surge to an old-fashioned metal church bell that, once struck by its clapper, would continue to ring until the resulting vibrations died out.

Add it All Up

Now how does the waveform of any surge kind of surge combine with a 60 Hz waveform? On an oscilloscope, the surge would appear as a very narrow spike, perhaps as a straight vertical line, somewhere on top of the 60 Hz waveform. Whenever a surge voltage and a 60 Hz voltage combine, the instantaneous voltage at any time during the surge will be the algebraic sum of the instantaneous surge voltage and the instantaneous voltage of the 60 Hz waveform. Thus, it is often said that the surge voltage rides on top of the 60 Hz voltage.

Now see Figure 5. A red dashed horizontal line represents the ac supply zero voltage level of all the ground and neutral wires of the 120 V ac power wiring in house at the common point of connection to ground inside the load center panel. Also shown is the surge difference of potential between the service entrance ground and the lightning strike ultimate ground. Only if lightning strikes nearby is the difference of potential between those two grounds significant.

Lightning-induced surges occur at random times with respect to the 60 Hz power that's normally always present in your house wiring. As shown in Figure 5, if the arrival of a peak in positive surge voltage at some point in a circuit coincides exactly with a 60 Hz, 120 V sine wave positive voltage peak, then the total instantaneous line-to-neutral voltage level at that point will be 169.7 V (the instantaneous peak voltage of a 120 V_{RMS} waveform) plus the peak voltage level of the surge.

Under that condition, a mere 500 V surge superimposed on the 169.7 V peak of the 60 Hz supply voltage would produce an actual positive line-to-neutral peak voltage of 669.7 V, 69.7 V higher than the 600 V rating of typical house wiring.

Therefore, whether or not a lightning-induced 500 V surge in your house wiring will arc through wire insulation that's rated 600 V may depend upon when that surge occurs relative to the 60 Hz waveform. But remember — 6000 V surges may occur at or near your load center panel. And statistical data indicates that typically, in 120 V ac circuits, the occurrence of transient voltage levels of 3 kV may be expected to range from 0.01 to 10 per year at a given location. Voltage surges in the range of 1 kV to 2 kV are fairly common

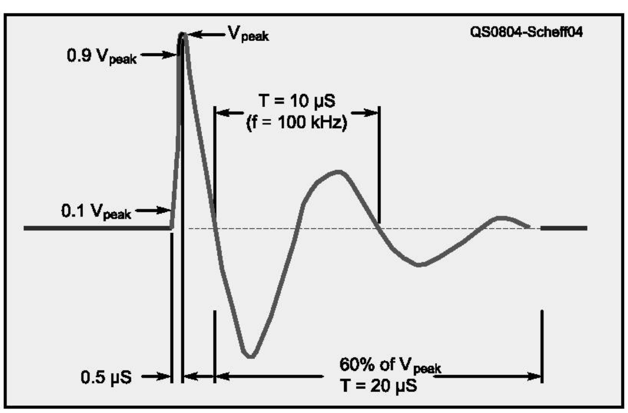

Figure 4 — The 0 V axis represents the instantaneous voltage level of 60 Hz ac waveform upon which this surge "rides." The quantity of energy in a surge is proportional to the area under the curve.

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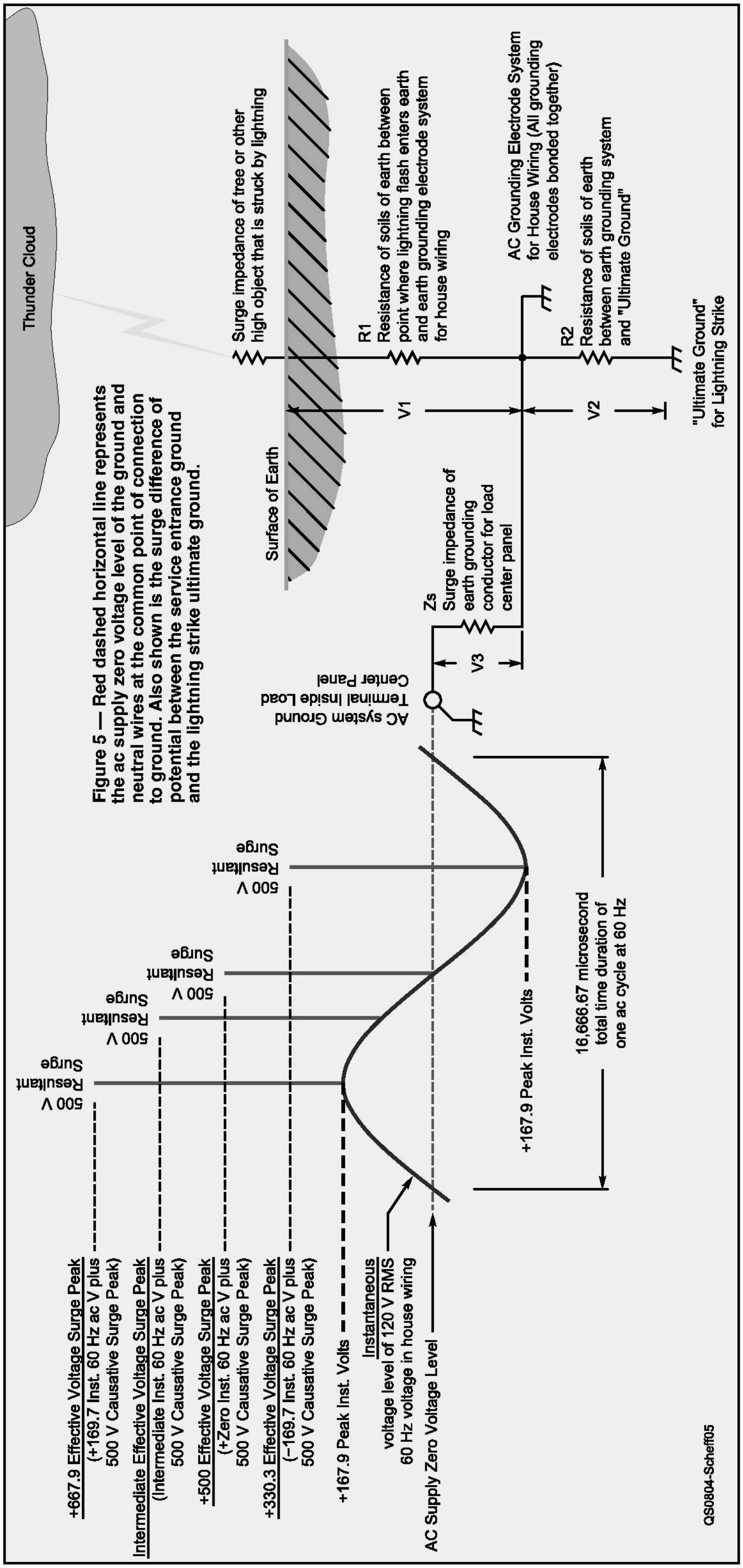

Figure 5 — Red dashed horizontal line represents the ac supply zero voltage level of the ground and neutral wires at the common point of connection to ground. Also shown is the surge difference of potential between the service entrance ground and the lightning strike ultimate ground.

in residential circuits.[6] So you probably need better surge protection than you already have.

It's Not Just the Power System

How dangerous are the above-ground causative surges that come from your telephone cable, cable TV service or from any other telecommunications or data system? I've found little published data on those surges but I have found one mention of an open circuit voltage peak of nearly 18,000 V at the end of a telecommunications system cable entering a central office 2.75 miles from the point where a 100,000 A lightning stroke hit the cable. There was indication that such a surge may reach about 355 A of available current.[7]

Your service supplier's installation should include a proper point-of-entry surge protector and assurance that it will do the job. But just in case they don't install it right or it really doesn't do the job, I'd strongly recommend that you also install, for each of your susceptible devices, a point-of-use protector that includes line-to-neutral, line-to-ground and neutral-to-ground protection plus signal-to-ground protection.

When you've done all you can do to prevent such lightning damage, then cross your fingers and hope you don't get a direct strike!

Notes

1. L. Scheff, W4QEJ, "Lightning: Understand It or Suffer the Consequences — *Part 1, QST,* Feb 2008, pp 40-44.
2. A load center panel is often called a circuit breaker box or, in older homes, a fuse box.
3. H. Denny, L. Holland, S. Robinette, and J. Woody, *Grounding, Bonding, and Shielding Practices and Procedures for Electronic Equipments and Facilities, Volume 1 — Fundamental Considerations,* US Department of Transportation, Federal Aviation Administration Systems Research and Development Service, by the Engineering Experiment Station of the Georgia Institute of Technology, Atlanta, Georgia as US Department of Commerce, National Technical Information Service publication AD-A022 332. pp 1-9. In subsequent footnotes, this publication will be referred to as *GB&S.*
4. W. Timbie, V. Bush and G. Hoadly, *Principles of Electrical Engineering* — Fourth Edition, 1955, John Wiley & Sons Inc, New York, p 37.
5. Inertia is the resistance of a body at rest to being set in motion or of a body in motion to any change of speed or of direction of motion.
6. *Transient Voltage Suppression, Application Note 9769 — The Development of a Guide on Surge Voltages in Low Voltage ac Power Circuits*, Harris Semiconductor, 1998.
7. *Application Note 9774 Surgetectors for Telecommunications Systems*, Harris Suppression Products, p 11-162.

Larry Scheff has been licensed as W4QEJ continuously since 1950, except for a 1963 to 1966 move to Massachusetts that necessitated a call sign change to W1ASW. He also held the call sign KR6PU while on Okinawa.

Read the details of Larry's bio in his February 2008 article. You can reach him at 679 Creek View Dr, Lawrenceville, GA 30044.

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