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TECHNICAL CORRESPONDENCE

LIGHTNING AND THE ELECTRICAL DISTRIBUTION SYSTEM

◊ I read the February 2008 *QST* article about lightning with interest (“Lightning: Understand It or Suffer the Consequences,” by Larry Scheff, W4QEJ, pp 40-44).

There are a couple of misstatements and errors in the article with regard to the power distribution system in the US and with National Electrical Code (NEC) requirements. The article says, “It’s fairly easy to understand the 60 Hz electrical ground for your house. Typically, the ac power source for a residence is the intentionally ungrounded center-tapped secondary winding of a ... power company single-phase transformer. This transformer supplies 120 V_{RMS} line to neutral from both sides of the center tap and 240 V_{RMS} from the entire secondary winding.” The statement that this transformer is ungrounded is wrong! Section 250 of the NEC (Grounds) and specifically Section 250.24 (2) Outdoor Transformer says “Where the transformer supplying the service is located outside the building at least one additional grounding connection shall be made from the grounded service conductor (neutral…Section 200 of NEC) to a grounding electrode either at the transformer or elsewhere outside the building.”

The next paragraph says there is no additional ground wire in the service cable (service drop or service lateral) so there is no wired ground connection between the secondary winding of the transformer and the load panel. It also says there is no wired ground connection between the transformer secondary winding and its primary winding. Again, this is wrong! See Section 250.24(2) of the NEC again. In a four-wire, three-phase electrical distribution system, the neutral is carried throughout the system and is also tied to the transformer secondary neutral, or center tap. This is called a “common neutral.” There is a ground rod at every transformer (single or three phase) to aid should the common neutral become broken or disconnected.

[Figure 1 in this Technical Correspondence column is a revised version of Figure 1 as it appeared in the February *QST* article. The resistances shown in the wires, including the pole ground wire, represent the lightning surge impedance of the wires. — *Ed.*]

What W4QEJ says is true in Delta derived transmission systems. There is no connection between the primary and secondary windings in that case, but this is not true on a Wye derived system, with the common neutral. Part of the country was changed to the four wire Delta system in the early 1950s, and this achieved a 73% capacity increase of the distribution system, and still used existing transformers.

The local power company in my area (Ohio Edison) even taps to the outer conductor in underground primary feeders every 600 feet or so, and buries about 20 feet of bare copper wire in the trench with the underground feeder. This establishes an extensive ground bed.

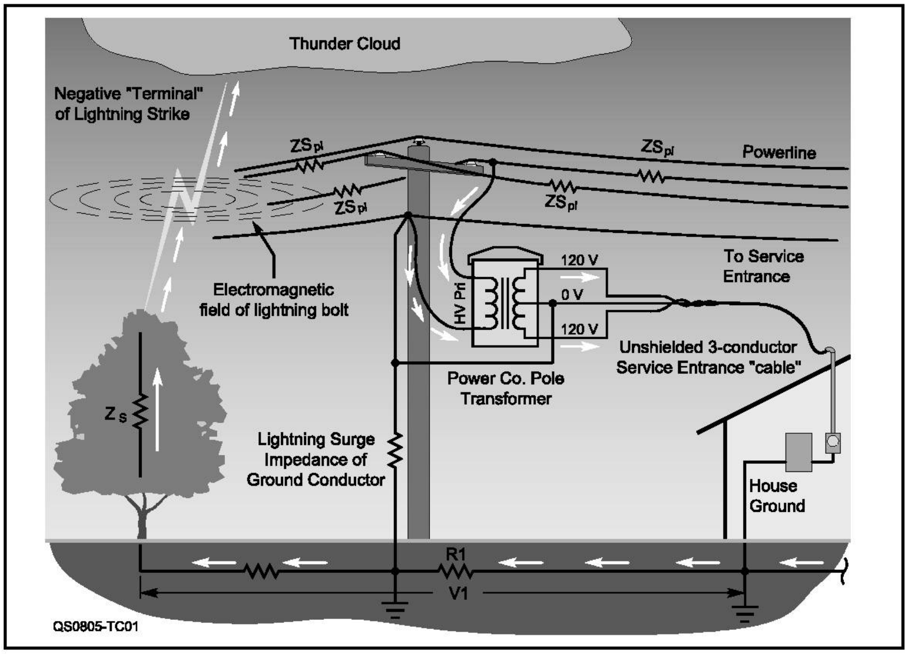

Figure 1 — This modified version of Figure 1 from “Lightning: Understand It or Suffer the Consequences,” in the February 2008 issue of *QST* shows the corrected electrical power distribution system. Sometimes in rural areas, only one phase of the distribution power, with the neutral ground wire is run to a small group of houses. Other groups of houses are fed from the other two phase lines, to maintain the load balance.

In Figure 2, the article states that the grounding electrode is improperly installed, and also indicates something called “Ultimate Ground.” What is the definition of a properly installed “made electrode”? My definition is what complies with Section 250 of the NEC. What is the definition of “Ultimate Ground”? My engineering handbooks make no mention of this term.— *Robert D. Spann, WA3QZK, 161 State Line Rd, E Palestine, OH 44413*; **wa3qzk@yahoo.com**

W4QEJ Responds:

After Part 1 of my article was published in the February 2008 *QST*, and before Part 2 was published in the April 2008 *QST*, several readers commented that the power company’s pole-mounted lightning arrestor, and/or pole “grounding conductor” were not shown or mentioned in the article. Their concern about that “omission” suggests two things to me; that many people believe that an arrestor offers a lot more surge protection to a residence than it really does; and they apparently think the pole “grounding conductor” which provides a good 60 Hz ground also provides an effective ground for lightning surges, but it does not.

Part 1 of my article was not intended to tell the whole story. Parts 1 and 2 have to be examined together to even begin to do that. And there’s a lot more to the overall subject than can be covered in any magazine article. The main “target” reader of the article is the typical ham who probably couldn’t care less about the details of things they can’t do anything about, but they should be vitally concerned about learning what they (not the power company) can and should do to reduce the vulnerability of their residence and the equipment inside to lightning-related damage.

Since the typical ham may live in a purely residential neighborhood, or in a mixed-use area (residential, commercial, apartment buildings, and so on), or in some other type area, that might be served by any of several different types of power company distribution lines, the representation of the power line in Figure 1 of Part 1 was intended to be as generic as practical, not representing any narrowly specific power line arrangement.

After digesting both parts of the article, readers should be aware that it does not rely on theoretical or hypothetical concepts to help the typical reader determine what can be done inside a home and on property to protect equipment from lightning-related damage. Part 2 presents empirically derived data from the real world. The data shown and/or quoted in Part 2 of the article is a small but representative portion of the data and information used by manufacturers to design, develop and test surge protectors that typical *QST* readers can purchase for use in their residences. That information is intended to help typical readers better understand those manufactured surge protection devices so they can choose the right ones to purchase and install in their residence.

That empirical data on surge levels that actually occur inside residential wiring should make it very clear that one should not assume that the power company's lightning arrestor will adequately protect from damaging surges that might enter a residence "from the power company." That's why I considered the power company's lightning arrestor to be virtually irrelevant to the scope of the article, and why it wasn't shown in Figure 1 of Part 1. If I had shown that lightning arrestor, I would have had to explain both what it should do and what it cannot do, but there simply wasn't enough space allocated for such an explanation.

The surge waveform shown in Figure 3 of Part 2 is an empirically derived ANSI/IEEE waveform that represents the combined effects (in and near the residence load center panel) of surges that "get through" that power company arrestor, pass through the residence service entrance cable and combine with the simultaneous "lightning ground surges" that enter the load center panel via the panel earth grounding conductor. Does a 3,000 A surge (as shown in Part 2, Figure 3) in your load center panel make you think the power company's pole-mounted lightning arrestor is adequately protecting you? I don't think so.

The power line that serves your residence is designed to efficiently distribute 60 Hz ac power to your home and to neighboring residences. But if lightning strikes the power line, or strikes close enough to electromagnetically induce significant traveling wave surges into it, then the power line becomes not just a 60 Hz power distribution system — during the strike (an almost infinitesimal period of time compared to one 60 Hz cycle) it also simultaneously becomes a "lightning surge distribution system." So that power line is distributing both 60 Hz ac power and lightning surges at the same time. And that's an entirely different, dangerous ball game.

Such a "lightning surge distribution system" (including pole-mounted lightning arrestors, transformers, pole equipment "grounding," and also residence service entrance conductors, KWH meter current coils and potential coils, load center panels, and load center grounding) was illustrated in a figure titled, "Simplified Example Showing Direct Lightning Strike on Typical Electrical Utility Load Branch Circuit Feeding Residential Area" in the original nine-part version of the article that I submitted to *QST* for publication. I was asked to reduce that version to only two parts, and the article published in the February and April issues of *QST* is the result of that request. Obviously, a lot of information (including that figure) was sacrificed to reduce the article to only two parts.

That sacrificed figure was very different from a typical schematic diagram in that it showed the transformer windings, power line conductors, grounding electrodes, grounding conductors, and other equipment as surge impedances rather than using the usual standard device symbols. That was done to emphasize the fact that, during a lightning strike, those devices act far, far, far more like significant surge impedances than like "normal circuit components."

A Ground or Not a Ground

Apparently, many people, even many 60 Hz oriented engineers and technicians, assume that the "ground wire" that runs down a power pole, "connecting" the lightning arrestor, the "grounded neutral" side of that transformer's primary winding, and the center tap of the transformer's secondary winding, to an earth grounding electrode at the bottom of the pole serves as a good grounding conductor when lightning strikes the power line. That's a very mistaken assumption! That "ground wire" should provide a good 60 Hz "safety ground," but it becomes dangerous when lightning strikes because a tremendous instantaneous surge difference of potential may be developed across that "ground wire" during a lightning strike. Why? The resistance of that "ground wire" is the same for ac and for lightning surges, but even a simple straight wire has inductance. The inductance of that "ground wire" may be negligible at 60 Hz, but it becomes very, very significant when extremely instantaneous lightning-induced surges are present.

When the current in any wire or inductor is changing, the magnetic flux created in that inductance causes a voltage to be induced across that inductance. That induced voltage is proportional to the time rate-of-change if the permeability is constant. The constant of proportionality is called the self-inductance or the inductance of the wire or inductor. This relationship is often expressed mathematically as $v = L\,(di/dt)$, where v is in volts, di/dt (often called the rate-of-rise) is in amperes/second, and L is in henrys.[1, 2] Here it's important to realize that the smaller the diameter of a straight wire, the greater will be the inductance of that wire, so the smaller the diameter of a straight wire, the greater will be the surge voltage generated across that wire.

During a direct lightning strike to the power line, that "pole-ground wire" performs a function that's very similar to that of a "downcomer" used to connect a lightning rod system to an earth grounding electrode system. So, let's examine the results of an example calculation made by experts at Georgia Tech, showing that a typical lightning current of 20,000 A passing through a 0.894 cm (0.357 inch) diameter downcomer 30 m (98.43 feet) long and reaching its peak current in just one microsecond will develop a tremendous voltage drop of one million, fifty thousand volts across that "grounding" conductor.[3] That's a voltage drop of about 10,667 V per linear foot of downcomer. But the maximum rate-of-rise of a lightning stroke is taken to be 210,000 A/ms. So if you compare that maximum possible rate-of-rise to the mere 20,000A/µs rate-of-rise in the Georgia Tech calculation, you'll realize that the worst-case surge voltage at the top of such a "pole grounding wire" might be even more potentially devastating.

With that in mind, take a good look at the "pole grounding wire" on the power company pole that provides power to your house and compare its length and diameter to that lightning rod system "downcomer." Then try to imagine how dangerously high the surge voltage developed across that "ground wire" might get during a nearby lightning strike or, even worse, during a direct strike to that power line. During some lightning strikes, you should expect the surge voltage drop across that "grounding conductor" to be tens of thousands of volts. And when that happens, everything connected together at the top of that "ground wire" may actually be tens of thousands of volts above "ground."

Now let's realize the profound difference between 60 Hz safety thinking and "surge impedance circuit thinking" relative to the wiring and equipment on that power pole. When no surges are present, the impedance of the pole's 60 Hz grounding conductor/lightning surge "downcomer" is very, very low — virtually ignorable. So the outer surface of the transformer tank and everything else that's connected to the top of that conductor is "60 Hz safety grounded." And the transformer is behaving normally, merely acting as a power transformer.

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[1] Further explanation of this relationship can be found in most any textbook on the basics of electrical engineering.

[2] Equations to calculate the inductance of a straight wire can be found on page 4.24 of the 2008 edition of *The ARRL Handbook.* ISBN: 0-87259-101-8, ARRL Order no. 1018. ARRL publications are available from your local ARRL dealer, or from the ARRL Bookstore. Telephone toll-free in the US 888-277-5289, or call 860-594-0355, fax 860-594-0303; **www.arrl.org/shop**; **pubsales@arrl.org**.

[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 2-1 to 2-4.

But when lightning strikes, everything changes — drastically! During a lightning-induced surge, each affected coil or transformer winding in that "lightning surge distribution system" has much higher inductance than any straight wire, so the surge voltage generated across it will be much higher than that developed across a straight wire. So, a very profound, very momentary functional change occurs inside the transformer. During a lightning surge, the transformer windings act far more like a weird capacitor and not much at all like a transformer. The transformer is designed to "step down" the 60 Hz voltage applied to its primary winding to the secondary voltage, 120-0-120 V. It's designed to perform its intended electromagnetic "transformer action" very efficiently at 60 Hz. When a lightning-derived surge, having a rise-time somewhere between a minimum of less than a microsecond and a maximum of only 30 microseconds, arrives at the transformer primary winding, then the resulting very high surge impedance of that winding will severely limit the electromagnetic energy that the surge can "pump" into the primary winding during the extremely fast rise-time of the surge. So, very little surge energy can be electromagnetically coupled from the transformer primary winding to its secondary winding.

But when lightning surges are present, the surface areas of the primary and secondary windings that "face each other" inside the transformer act like a capacitor.[4] The potential difference, *v*, across a capacitor is proportional to the charge on the capacitor. The constant of proportionality, *C*, is called the capacitance of the capacitor. The current through the capacitor, *i*, may be determined by the equation, $i = C\,(dv/dt)$, where *C* is in farads and dv/dt (often called the rate-of-rise) is in volts/second. So the bigger that "capacitor" is, and the faster the rate-of-rise, the greater will be the surge energy that can be capacitively coupled from the primary winding to the secondary winding, and from there through the surge impedances of the service entrance conductors and the relatively high surge impedances of the current coils inside the KWH meter, and from there into the load center panel inside the residence that is served by the transformer.

Lightning Surge Paths

From the pole that "feeds" ac power to your house, during a direct lightning strike to that pole, there are typically four different surge paths to "surge ground" (the "ultimate ground" of the lightning strike) from the common surge-elevated "grounded neutral" connections up on that pole. Three of those "ground" paths involve the power company lines, the power company equipment, and the other residences "fed" by those power lines. Those four paths are:

1) "Upstream" via the lightning surge impedances of the line and neutral conductors of the power line toward the power company transformer (or transformer bank) that's supplying the high voltage ac power to the power line. Surges traveling in this direction will be attenuated as they travel, because of the surge impedances of all the upstream line, neutral, and "grounding" conductors involved, and by the passage of surge currents into the earth at the bottom of each pole.

2) "Downstream" via the lightning surge impedances of the line, neutral, and "grounding" conductors of the power line toward the last residence at the end of the line. Surges traveling in this direction will similarly be attenuated as they travel in a manner similar to what happens "upstream."

3) Down through the very high lightning surge impedance of the "pole downcomer" and into the earth at the bottom of the most affected pole (creating a very high voltage drop across that "pole downcomer."

4) The "ground" path that affects your house the most starts at the power company pole that "feeds" your house, runs through the lightning surge impedances of the neutral conductor in your service entrance cable and the KWH meter to the neutral and ground buses inside your load center panel; exposing those buses and the ac wiring inside your house to lightning surges from the power company; and then from there through lightning surge impedance of the load center grounding conductor to your service entrance grounding electrode system.

The power company's pole-mounted lightning arrestor has no effect at all until the surge voltage across it reaches or exceeds its "breakdown voltage" when, in effect; it becomes a "short circuit" across the primary winding of the pole-mounted transformer. That "short circuit" exposes the top of that pole's "ground wire" to the full unattenuated brunt of the lightning strike. Since the power pole end of the neutral conductor in the service entrance cable that "feeds" your house is also connected to that very highly "above ground" lightning surge voltage at the top of that pole "ground wire," that pole-mounted lightning arrestor can do little, if anything, to keep above-ground causative "power line surges" out of your load center panel. So obviously, that lightning arrestor should protect the pole-mounted transformer, but it cannot adequately protect your load center panel or what's inside your house.

Apparently many people, even many 60 Hz oriented engineers and technicians, simply don't understand the different ways that earth grounding and earth ground currents affect the surges that can occur inside a residence. The power source for the 60 Hz power distribution system that "feeds" your neighborhood is a secondary winding in a power company transformer or transformer bank having a corresponding primary winding that's connected into the power company system. And the neutral side of that transformer secondary winding is typically connected to an earth-grounding electrode that comprises the single 60 Hz source "ultimate ground" for the entire 60 Hz power distribution system that "feeds" your house. There are many "non-ultimate" power pole grounds within your neighborhood's 60 Hz power distribution system. But the "ultimate ground" for that entire "lightning surge distribution system" is the "ultimate ground" of the lightning strike that's explained and described in Part 1 of my article. Those two "ultimate grounds" (the one for the 60 Hz source and the one for the lightning strike) are not the same. And during a lightning strike to or near the pole that "feeds" your house, there's a significant lightning surge difference of potential between your service entrance grounding electrode system and the power company 60 Hz "grounding electrode" at the base of that pole. And that significant below-ground causative lightning surge difference of potential contributes to the resultant surge (Figure 3 in Part 2 of my article) that appears in and near your load center panel.

There are two related errors (my errors) in Part 1 of my article in February 2008 *QST*. In the last paragraph on page 40, the words "intentionally ungrounded" should not have been included in describing the secondary winding of the transformer. In the first full paragraph on page 41 the text that reads: "There's no wired connection between the transformer's secondary winding and its primary winding." was my goof, not a misprint. The sentence on page 41 should have read "There's no true lightning surge ground at either the transformer's secondary winding or its primary winding." I apologize for any confusion caused by that error. — *Larry Scheff, W4QEJ, 679 Creek View Dr, Lawrenceville, GA 30044*

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[4] Since the plates of a "normal" capacitor typically have smooth surfaces and the surface areas of the primary and secondary windings that "face each other" are actually partially exposed turns of insulated wire of a single layer on the primary winding and on the secondary winding, one would expect the "capacitor action" inside the transformer to be much more difficult to analyze than what happens in a "normal capacitor."