Toward a New Understanding of Frequency- and Impedance-Related Failures in Grounding Systems

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Abstract – The importance of grounding in protecting structures and electrical systems has been known for over two centuries. However, there are two critical characteristics of damage-causing fault currents which have not been sufficiently explored by engineers in the design and installation of protective grounding strategies: This paper discusses the significant deficiencies in common grounding systems with respect to broadband fault current frequencies (including >60 MHz) and impedance “walls” created by inefficient ground-rod-to-soil interfaces. An examination of the dynamics of high frequencies and impedance mismatches in grounding systems is presented, demonstrating why these systems fail in spite of their adherence to commonly accepted design and testing standards. Broadcast Industry efforts to create a higher degree of damage prevention via grounding, therefore, requires a deeper analysis and understanding of fault current components, characteristics, and events.

Introduction

LaBarge *et al.* [1] argued that numerous aspects of analytic methods, national codes, industry standards, and measurement techniques of traditional electrical grounding (also referred to as earthing) are in need of very careful review, if not complete revision. In addition, it posited that grounding as a science has been largely ignored over the past several decades in favor of blind conformance to specifications based almost exclusively on the measurement of resistance-to-ground (RTG) as the sole determinant of sufficiency in grounding performance. This, in turn, has limited grounding system design preparation for the arrival of WiFi6, 5G, ATSC 3.0, and even applications of artificial intelligence while failing to address rising system and equipment costs and business risks.

If, in fact, the compendium of the accepted knowledge of electrical grounding were truly keeping pace with contemporary electronic innovation, the process of grounding would be very different today than it is. [2] Furthermore, if current grounding technology is indeed fully adequate, how can the annual disbursement of more than $1 billion in insurance claims payments – exclusively for lightning damage in the United States -- be explained?

In this paper, we will explore in much greater detail two essential elements of grounding system performance which are especially critical in the broadcasting industry, and that are almost entirely overlooked in traditional grounding solutions:

- Dissipation of high frequency fault currents, and
- Reduction or elimination of impedance mismatches

Failure to manage 1) high frequencies in fault currents, generally greater than 60 MHz, as well as 2) the disparity in the impedance of standard grounding hardware versus that of adjoining native soils, far too often result in excessive and sometimes catastrophic losses of critical broadcast equipment and systems. Therefore, a better understanding of the physics, and hence the behavior of fault currents entering grounding systems – specifically with respect to frequency and impedance characteristics, is clearly warranted.

Adverse Impacts of High Frequencies

For more than 50 years, the presence of a very broad range of high frequencies in lightning discharges and switching faults has been known. Much of this data has come from remote RF measurements taken during storms. [3] Additionally, the placement of these higher frequencies within the waveform of such faults has also been fully defined: the highest concentration of high frequencies (henceforth “HF”) in lightning [4, 5] and switching faults resides at the very leading edge of the wave – at what is often called a steep wave front. The leading edge of this nearly square wave event can contain a significant volume of frequencies from 60 MHz to well in excess of 200 MHz amongst a large and broad mix of other lower frequencies. Later in the pulse the higher frequencies are likely swamped by lower frequencies.

Anecdotal evidence supported by electro-physics seem to indicate that this high frequency rich front end of the current pulse is important in the early moments of a strike where a lightning bolt first interacts strongly with its new ground path. This means that the choice of grounding path route is being heavily influenced by high frequencies and any choke points for HF current can cause the entirety of the grounding path to change. Therefore, the surface area offered by electrical conductors in the grounding path can matter far more than generally understood.

In spite of being aware of HF content in fault currents, grounding system designers, for the most part, have not incorporated solutions with fully sufficient hardware or overall function to manage these inputs. Where HF fault mitigation is addressed in traditional grounding, the use of copper strap is the most common technique. This copper sheet functions as a very wide conductor either along the route to buried dissipation devices, or in some cases, as small “flanges” of copper sheet bonded to certain varieties of ground rods. As a routing conductor, various lengths and widths of strap – between 1 and 6 inches wide and often more than 6 feet long — are installed between antennae coax cable bulkheads on equipment structures, and the buried grounding array serving the structure. The concept behind this strategy is to provide a relatively large surface area to conduct HF faults to ground due to the known phenomenon of skin depth effect (SDE). HF current tends to travel upon or very near the surface of conductors.

While all of the copper in a normal 24 AWG wire (0.024” diameter) is used to carry 20 kHz, due to SDE only 68% of a 10 AWG wire (0.115” diameter) is used to carry current. [6] On the other hand, lower frequencies will travel through the core and on the surface of the conductor. The increased surface area in a sheet conductor versus wire cable allows greater transmittance of HF faults due to SDE and hence should deliver high frequencies to a grounding dissipation point more effectively than wire.

The theory, so far, is all good: maximizing surface area, and therefore SDE, carries HF faults better. This has been extensively empirically demonstrated. But in practice, this approach to HF grounding mitigation is poorly implemented. Far too frequently, extensive strap installations are ultimately connected to simple grounding rings and arrays of standard ground rods, all composed of materials with significantly less surface area per unit of length than the copper strap conveying fault current toward ground. These rings and arrays are, in turn, in direct contact with very high impedance soils — relative to the ring and rod conductors.

In more detail, most commercially available copper strap for grounding purposes in the United

States is either of 0.022 or 0.032 inches in thickness, and anywhere from 1 to 6 inches in width, with the most commonly used widths being 4- and 6-inch material. Therefore, the surface area per foot of length is 96 or 120 square inches for these two widths. By contrast, the per foot surface area of 4/0 copper wire — excluding the additional area created by stranding — is about 24 square inches. Stranding can create roughly 3.5 times the surface area per unit of length versus solid wire. Therefore, if 4/0 stranded wire is used, the effective surface area can be as much as 84 square inches per foot of length. Hence, at a maximum, this wire would still have only about 70%-87% of the surface area of 6-inch or 4-inch strap, respectively. [7]

Importantly, the vast majority of installations using copper strap as a grounding conductor incorporate multiple straps, generally one for each coax cable entering an equipment structure. Of course, while this additional surface area somewhat improves HF current handling, it is not an optimal broadband solution. But more critically, each strap eventually terminates this additional effective surface area in a bond to a single copper cable (often a grounding “ring”), which in turn leads to the system dissipation points — almost always an array of ground rods. Thus, the effective surface area for HF flow is reduced from the expansive area of possibly many copper straps down to only that area afforded by the conducting cable and ground rods.

As an example, if an equipment structure has a bulkhead connected to six 8-foot long, 6-inch wide copper straps, the combined total surface area available for HF flows would be 24 square feet (or 3,456 square inches). Per foot of length, the straps have 432 square inches of area. The ends of these straps all are connected (in a variety of formats) to the structure’s grounding ring of stranded 4/0 copper wire. As discussed above, typical 4/0 wire has an effective surface area of about 84 square inches per foot of length. This is an over five-times reduction from the copper straps.

The result of this reduction in available surface area is the creation of severe choke points for the dissipation of high energy HF fault current. While HF faults finding their way to a copper strap grounding design may move very easily along the strap, once reaching the end of the strap they face an exit point which has notably less surface area to carry the fault. This leads to a reflection of fault currents, whereby only a fraction of the HF can reach a dissipation device. The balance of the fault is rejected by the system, many times creating a major grounding system failure: very rapid heat generation along an inbound conductor of any type can cause conductor separation or disintegration. In copper strap, this often takes the form of a sublimation event.

With the “bridge being burned”, dissipation of the very large volume of lower frequency fault current yet to reach the grounding system becomes impossible. All systems, equipment, and structures upstream from the conductor break may now be energized with fault current and therefore are at extremely high risk.

Up to this point, we have indicated copper as the primary material used for grounding conductors and electrical charge dissipators. In practice, especially in commercial applications, this is nearly always true since, being relatively inert and highly conductive, copper metal [8] can provide for efficient dissipation of electrical charge even when buried in the ground for many years. While it is known that copper has limited abilities to carry frequencies over 100 kHz due to SDE [5], conducting current at even higher frequencies — those in excess of 100 MHz, for example, take specialized materials and structures. After all, there are good reasons that high frequency data and signals for WiFi6 and 5G are to be carried in coaxial cables with their own shielding and that these shields are moving away from copper and towards nanomaterials. [9] In that fault currents — including lightning — are now known to possibly contain a substantial amount of current at these frequencies, the extensive and sometimes exclusive use of copper as a grounding conductor is troubling. Just as mentioned above, if HF current cannot be fully carried to the point of dissipation, upstream damage becomes increasingly likely.

While nearly ideal for low frequency conductance and dissipation, the combination of surface area constriction, skin depth effect, and conductivity degradation due to introduction of very high frequencies paints copper as a less-than-perfect conductor for HF current. The authors of this paper have seen numerous cases of dissipation failures due to HF-overloading of traditional grounding systems at broadcast facilities across the United States. Yet in spite of the real (and expensive) damage being caused by such events, grounding system design continues to lag behind a very necessary, higher level of protection.

An enhanced approach to HF mitigation in grounding systems is overdue. To accomplish this goal, earthing of fault currents must be based on a view of these currents as a broadband collection of frequencies including high frequencies. This entire range must be managed in a way that not only allows, but encourages fault current to flow continually away from critical, expensive (and easily damaged) assets — harmlessly into the Earth. Particularly for high frequencies, every step along the path to dissipation must not hinder this “first-to-arrive” current. The reasoning is simple: if the first milliseconds of a fault event cause system failure, the balance of the “trainload” of fault current immediately following will certainly cause very undesirable damage.

Any grounding system design that throttles HF fault current prior to Earth dissipation results in a greatly increased probability of system failure than configurations which provide sufficient (and sequentially increasing) surface area / SDE capacity. Unfortunately, traditional grounding systems, which rarely incorporate consideration of HF fault management in their designs, fail to provide sufficient or increasing surface area entirely through the system to the point of dissipation. Sufficient surface area and skin depth capacity must become the norm.

Prudent risk management for contemporary broadcast facilities requires improved grounding management of high frequency faults.

Adverse Impacts of Conductor-to-Soil Impedance Mismatch

Present guidelines for the installation of grounding devices describe grounding as a *consistent and uniform* dispersal of current from buried rods, regardless of soil conditions and soil conductivity. With the massive expansion of electronics and micro-circuitry in contemporary broadcasting systems over the last several decades, the opportunities for expensive fault-related equipment replacements and system downtime has increased dramatically. Consequently, every broadcasting installation needs to have the most efficient current off-ramp possible from its grounding system.

As discussed above, traditional grounding systems generally employ extensive grids of heavy gauge copper conductor cable and multiple ground rods toward the goal of dissipating to Earth of high amperage, high voltage fault currents. These designs are expected to prevent damage to structures and equipment while adding a measure of safety to staff, electrical systems, and electronic devices. The shortcomings of this current system approach are plentiful [1] so it should not come as a surprise that these somewhat simplistic grounding systems suffer from a dramatic and significant mismatch of the impedance of their metal rods (usually copper or copper-clad) and the soil into which these rods have been driven. Even in very high conductivity soil, the disparity between the impedance of the grounding conductor [8] and the adjoining soil

[10] can be many orders of magnitude. The interface between a ground rod and local soil has always been inefficient; large current faults, most notably lightning, often simply exceed the ground rod's ability to dissipate electrical power across this high impedance interface.

Impedance mismatches are therefore present in the vast majority of traditional grounding systems yet they are rarely if ever discussed or recognized as important components of grounding system performance. Instead, guidelines for grounding designs concentrate nearly entirely on the number or total length of ground rods needed to reach a desired resistance-to-ground (RTG) value, as determined by various fall-of-potential or clamp-on ground resistance test instruments.

Importantly, commonly used ground resistance meters don't "see" large impedance disparities in grounding systems for two key reasons: 1) the injected or induced current used by test meters to measure ground resistance is generally from a very low voltage power source and at a relatively very low frequency compared with large, high-energy faults, and 2) the input current is at a fixed voltage and frequency, hence the huge variations of voltage and frequency during a fault event cannot be modeled by test meters.

The combined effect of these two conditions is the effective blinding of the instrument to the dynamics of voltage, amperage, and frequency within a fault event over time. Therefore, the impact of impedance mismatches on grounding system performance are not properly presented by widely used ground resistance test instruments. To understand this further, it is valuable to look at what is very likely happening in a grounding system that has a large disparity between the impedance of the main grounding conductor and surrounding native soil.

At the initiation of a fault event, a very large amount of current is suddenly introduced into a grounding system. Because of its dramatically lower impedance relative to surrounding soil, current that reaches the ground rods of a grounding system will be carried primarily by the copper surface of these rods and will tend to stay on these surfaces to the tip at the end of the rods of the system. At this point, the initial fault current is either forced off the rod into adjoining soil by the charge pressure [11] of trailing current, or in the case of highly resistive soil, rejected entirely. If current rejection by the soil occurs, even for an instant, a blockage of sorts for current to continue flowing into the grounding system is created. In spite of the charges accumulating in the grounding system and their resultant need to exit the ground system and enter the adjoining soil, the effective wall created by a jump in impedance from conductor to soil of many orders of magnitude can be more than sufficient to prevent proper dissipation.

The passage of time during the fault, even though of extremely short duration, is also a key element in understanding the dynamics of impedance mismatches. With the nearly instantaneous rise in voltage and amperage entering a grounding system at the initiation of the event, the ability of the system to significantly route and release this current to Earth equally quickly is essential. Any delay, even a few milliseconds, causes significantly increased charge density upstream in the grounding system. Such a delay can and does occur when fault current must "scale the cliff" of an impedance mismatch. In this extremely short period of time, the trailing current of a fault event may find much lower resistance to dissipation at points upstream in the system. Unfortunately, these can be in the very structures and equipment a grounding system was designed and intended to protect.

In this manner, the existence of impedance mismatches in generally accepted grounding system designs — which additionally are not properly revealed by common testing procedures — are a likely source of grounding system failures. With all this said, how can the impact of impedance mismatches be minimized? For many years, various manufacturers of grounding devices (as well as countless lay- practitioners of grounding installation) have promoted the use of conductivity enhancing materials — primarily inorganic salts or carbon-based additives to solids surrounding grounding electrodes — to create a better bridge to soil dissipation of fault currents. In some applications, water retaining materials such as bentonite clays are used. Indeed, all these techniques are beneficial to grounding system performance to some degree. However, there are also notable limitations to each of these concepts with respect to more fully minimizing impedance mismatches. These include but are not limited to:

- Inorganic salts such as sodium chloride are highly corrosive to metals used in grounding electrodes.
- Many additives used to improve electrolytic characteristics of native soils are highly soluble in water and hence are dispersed to less than effective levels with rainfall over time. Recharging these systems to maintain their performance is required.
- Bentonite clays become insulative to fault current at high frequencies. [12]
- Conductive cements can be corrosive to metals used in grounding electrodes. [13]

Under ideal conditions, and especially immediately upon installation, each of these enhancement strategies can create a single additional step between the impedance of the grounding conductor and that of native soil therefore reducing the possibility of system failure at the initiation of a fault event. However, over time and in high energy faults containing high frequencies, drawbacks in their usage with respect to more effectively managing impedance mismatches become easily apparent.

To accomplish more efficient dissipation of fault currents, combined with use of very durable, non-corrosive grounding materials, a multi-step gradient in terms of overall system impedance structure should be considered. Further, the steps of this impedance gradient should be designed to handle a broad range of frequencies, as well as extremely high rates of variations in these frequencies. A stair-step approach where the impedance of each successive stage of dissipation is marginally higher — until reaching that of native soil, and where the various materials used are in combination capable of digesting broadband frequencies, would create a far higher probability of mitigation of an entire fault event.

As the complexity, sensitivity, and expense of contemporary broadcasting equipment and facilities increases, employment of grounding strategies which manage impedance disparities more effectively should be considered.

Summary

Careful analysis of present and common grounding techniques reveals serious shortcomings in frequency and impedance management in grounding systems. Further, it is entirely possible that in spite of achieving low resistance-to-ground measurements gathered using accepted testing techniques, strategies which rely entirely on low resistance-to-ground measurement may indeed fail to provide sufficient protection from fault events. Incorporating continuous high-frequency dissipation and an impedance gradient throughout the grounding system design all the way through to the native soil can provide *all three* of these essential elements of a high-performance grounding system:

- Low RTG,
- Improved HF dissipation, and
- Reduced return current reflections

In this way, professional Broadcast Engineers who become keenly aware of these aspects of a fully effective modern grounding design can provide their broadcast facilities with safe and consistent operation.

References

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[3] Ulman, M. A., “Comparison of RF Frequency Spectra of HEMP and Lightning,” DTIC DNA-TR-90-001, March 1991. Ulman also references relevant earlier reports from Schafer and Goodall (1939) and Alya (1955).

[4] Grcev, L., “High-Frequency Grounding,” in *Lightning Protection*, Vernon Cooray, editor, London: Institution of Engineering and Technology, 2010, page 504.

[5] Romero, C., *et al.*, “A statistical analysis on the risetime of lightning current pulses in negative upward flashes measured at Säntis tower,” 2012 International Conference on Lightning Protection (ICLP), 2-7 Sept. 2012. The authors report values from 0.3 to 0.37 microseconds, much lower than the commonly stated 1-10 microseconds.

[6] Lampen, S., “Understanding Skin Effect and Frequency.” Retrieved from https://www.belden.com/blog/broadcast/understanding-skin-effect-and-frequency on 23 January 2020.

[7] At about 84 square inches of surface area per foot of stranded 4/0 wire and about 120 square inches of surface area per foot of 6-inch wide strap, the 4/0 stranded wire only has about 70% of the surface area of the 6-inch wide strap (84 divided by 120 is 0.7). Similarly, the same 4/0 stranded wire would have about 87% of the surface area of a 4-inch wide strap (84 divided by 120 is 0.875).

[8] Helmenstine, A. M., “Table of Electrical Resistivity and Conductivity.” Retrieved from https://www.thoughtco.com/table-of-electrical-resistivity-conductivity-608499 on 23 January 2020.

[9] Behabtu, N., *et al.*, "Strong, Light, Multifunctional Fibers of Carbon Nanotubes with Ultrahigh Conductivity," Science, vol. 339, No. 182 (2013). This article shows that carbon nanostructures can be almost as conductive as Cu, Al, and Ag even at low frequencies.

[10] Kouchaki, B. M., “Laboratory Resistivity Measurements for Soil Characterization,” Ph.D. Thesis, University of Arkansas, Fayetteville, page 3. Table 2 shows 1,000 Ohm-cm and higher for various soil types.

[11] Note that like charges repel each other causing their accumulation in one location to result in what acts like pressure for these charges to move away from their peers.

[12] Sabry, R. Z. *et al*, “Frequency Dependent Permittivity of Soil and Bentonite: For Lightning Protection and High Frequency Earthing Systems,” International Symposium on Lightning Protection, São Paulo, Brazil, 30th September – 4th October 2019. This article shows that the electrical properties of mixes with Bentonite clay vary significantly over frequency and moisture variations. It can be inferred that at high frequencies moisture content will not mitigate high resistivity of poor soil.

[13] Depending on the chemical makeup of “conductive cement” (containing coke breeze or other amorphous forms of carbon), encased copper conductors can suffer significant corrosion over time to the point where the continuity of a grounding system to its dissipation points fails. The possible presence of iron impurities and chlorine ions in these products can exacerbate this process.