Substation Control House Design Considerations for the Increased Presence of Networked Devices

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***Abstract*—In recent years, utilities have increasingly been installing technologies and devices in substation control buildings that were once almost exclusively found in data centers. Not all of these new devices meet IEEE Standard 1613, as some of the equipment has been recommended and installed by persons not familiar with the substation environment. Remote monitoring and management of power system parameters such as Synchrophasor technologies, have become mission-critical. SCADA, security, and now the increased presence of Cyber-Security appliances are all becoming mission-critical to operating and maintaining the Grid.**

This paper and presentation are intended to review some of the changes we've all seen in the technologies and systems now being installed in our substation control buildings. Design practices will be recommended in properly designing and installing grounding, bonding, and cable management systems in order to provide an environment in which the new technologies and systems can perform as reliably as our protection & control systems. Now is a good time to pause and consider the effects which new cyber-inspired devices might be requiring a response from engineers and designers of control buildings. The presence of these devices are certainly weaving their way into the fabric of our substation space. How are we, as P&C engineers, designers, and commissioning engineers adapting to these new technologies? By considering the recommended methods in control building design, a more reliable 'Smart" power transmission and distribution grid can be achieved.

Keywords—component; formatting; style; styling; insert (key words)

I. Introduction (*Heading 1*)

Most devices presently installed in substation Control Equipment Enclosures (CEEs) come standard with at least one communication port. Serial communications connections are likely to remain as an alternative for SCADA, data transfer, and substation-to-substation protective relay interfaces. However, many utilities have chosen Ethernet as a more common method of transferring data and controls messages both within the substation and outside the confines of the station fence. While Cyber-Security requirements have only increased, Ethernet remains a high speed and flexible method of providing communications connectivity and remains likely to have an ever-increasing presence as a mainstream communications method.

At the same time, utility companies have hired Chief Technical Officers, Chief Information Officers, and other high level technology related professionals from the general IT and telecom industries. While well versed in various blends of legal, financial, networking, software applications, Cyber, and other skills, most remain unfamiliar with the substation environment and the special challenges that most protection & control and substation professionals have learned to design in. Thus, network designs, circuit leasing agreements, even Cyber Security applications may have been designed without considering the environment into which security appliances, network equipment, or even leased circuits will be installed.

Another special challenge for a design engineer is that current-state IT-Telecom technologies are frequently installed in legacy CEEs, where cable management and grounding and bonding techniques were applied strictly from a safety point of view. As our discussion continues, certain observations will be made for consideration when designing the installation of current-state IT/Telecom devices in a CEE that may never have been designed for anything but legacy Pilot Wire schemes or systems and electro-mechanical relays, meters, and SCADA equipment. Some discussion will also be made to recognize green field opportunities to design CEE grounding and bonding with not only safety, but also with current-state communications reliability in mind.

During the author's research, text books, IEEE, TIA, IEC or other industry standards have not fully addressed grounding and bonding for the substation CEE. While the National Electric Code could be cited in terms of specific grounding electrode connections, a more holistic concept of applying grounding and bonding as an equipotential plane within a CEE will be introduced in this paper as the start of discussion and healthy technical debate on methods and techniques of not only assuring personnel safety, but also data reliability.

II. From Hard Contacts And Transducers to Protocol-Centric Devices

In the past fifteen years, the protection & controls community has witnessed career-changing advances and opportunities in the SCADA and communications applications. Equipment status, alarms, and controls have been communicated to energy control centers using hard contacts, analog transducers, and

interposing relays quite literally since the dawn of SCADA systems at utility substations.
Long rows of interposing relays installed on racks formed from Unistrut materials were applied in the design to achieve isolation between equipment in the substation yard and the RTU, and to provide trip/operate-duty ratings. At the same time, analog transducers converted one or both of voltages and currents into analog signals which legacy Remote Terminal Unit (RTU) A/D converters translated and then converted to protocol to communicate Watts, VARs, Volts, Amps, Tap Position, and other values to energy control centers. For many years, the only protocols that existed were proprietary and served to connect the RTU to the energy control center. Technology today has changed to a point where most analog, status, and control points are connected by protocol-based connections to their end devices to an interposing IED, or in the case of IEC-61850 designs, to the yard equipment itself.

Devices that are described above were designed and manufactured by companies which at some level understood the electrical and environmental nature of the electric utility substation. In order to ensure a sustainable business, those suppliers were compelled to continually ruggedize their devices to withstand a wide range of voltage transients, temperature excursions, humidity, and other factors. IEEE Standard 1613 is one example of a standard which was created to provide guidance to equipment manufacturers providing devices with Ethernet ports intended for substation installation to be as reliable as possible.

With the rapid proliferation of microprocessor based Intelligent Electronic Devices (IEDs) came a significantly expanded range of pre-calculated values such as:

- I^2t - enabling Just-In-Time maintenance
- Synchrophasors – enabling system operators and automation programs track system stability and "State" of the grid on a near-real-time basis
- Distance-To-Fault – greatly reducing time needed to determine fault locations and time-to-restore

The very small sample of additional parameters listed above are calculated in the IED and shared with other IEDs that need the data or the energy control center via a protocol-based connection as opposed to discrete hard contacts or analog connection. Today, the delivery methods for leased network operators is now almost exclusively using packet based transportation methods[1]. The relatively rapid shift in delivery method to packet-based technologies typically falls within the responsibility of IT-Telecom professionals on the planning design, and most times for the installation and commissioning activities. A design or installation professional who has been trained and experienced in packet-based equipment installations will likely also have been trained in grounding and bonding techniques that are common in data centers, since the equipment being specified will have at least the following characteristics:

- Common to equipment deployed across the enterprise, thus Information Technology design vs Operations Technology design[2]
- Less IT-Telecom learning curve: the equipment likely exists in data centers across the organization
- Compatibility with Network Operations Center and Trouble Ticket management systems common to IT and Telecom providers and managers
- Spares stocking strategy is made cost effective across the business unit, as the same device(s) are deployed system-wide, no separate devices for substation use…

Ironically enough, in most cases

- The IT-Telecom professional has a solid understanding of proper grounding and bonding design such as available in the Telcordia family of Grounding & Bonding standards, Motorola R56, TIA-942, and others, as common to a data center, but not necessarily to grounding and bonding applications in a substation.
- The protection & controls or substation design professional has a solid understanding of applying IEEE Standards 80, 81, 367, 487, and others which apply to the substation environment but has little understanding of the grounding and bonding standards in which IT-Telecom equipment was specified to operate reliably.

Hence a great divide exists. Grounding and bonding systems in a data center or telecom/microwave site are very specifically designed to create an electrically 'safe' environment for both people **<u>and</u>** equipment.

For the purposes of this discussion, a data center or microwave sites' grounding and bonding systems are engineered in such a manner such as to precisely direct transient energies away from equipment and into earth ground. A substation CEE grounding and bonding system typically represents a 'best effort' by well-intentioned design professionals to create a safe environment for people. After all, our protection & control design engineers have been assured that IEDs typically at least meet IEEE

[1] Some early packet-based delivery methods included Asynchronous Transfer Mode (ATM), Frame Relay, and now Multi-Protocol Label Switched (MPLS) methods. All three methods are commonly available through leased circuit providers or can be developed as private networks.

[2] The terms Information Technology (IT) and Operations Technology (OT) are defined and described by the National Institute of Science and Technology (NIST) as foundational to the deployment of packet-based networks as found in "Smart Grid" applications, including networks as described in IEC-61850 and other industry standards.

C37.94 Surge Withstand Capability requirements and therefore should survive the substation environment. More currently, IEEE Std 1613 provides guidance to manufacturers of products that provide Ethernet connectivity with guidance to provide maximum reliability for those increasingly-critical data connections. However, most IT-Telecom planners or designers which the author has conversed with have never heard of this standard or its application.

From a strict business sense, there's not a financial motivation for IT-Telecom professionals to test and approve a different set of devices for substation use from their standard inventory. From an asset management perspective, using all-familiar devices and manufacturers is most cost effective. Only when failure rates of IT-Telecom devices that have been deployed in substations are high enough' or when an open-minded IT-Telecom professional encounters a protection & control or SCADA peer that presents evidence for selecting at least IEEE-1613 compliant equipment might the decision for non-IT-traditional equipment be specified. Still – certain Cyber appliances or other IT devices will be required for installation where there is no substation-compliant equivalent device.

In some manner, a bridge of sorts must be built. Equipment and appliances which an IT-Telecom professional specifies for substation deployment to meet NERC-CIP or other business requirements will be required at substation sites and also survive that environment for a full life span without failure or degradation of performance. The following sections are dedicated to analyzing some typical grounding and bonding practices within a substation CEE. Suitable data-center-like grounding and bonding methods are presented which may help a utility avoid the cost of frequent and usually unexplained IT-Telecom equipment failures. Perhaps more importantly from a financial point of view, reduce the potential of NERC-CIP fines which may result if a security appliance is unavailable to perform its intended functions at a substation site due to a lack of hardening.

III. Gap Analysis – CEE vs Data Center

A Data Center's infrastructure is one of the more tightly controlled and highly engineered environments in the infrastructure sector. A very small segment of grounding and bonding engineers exist in this niche market, perhaps similar to the relatively small niche of protection & control engineers on the electric utility side.

Both utility and non-utility data centers (energy control center rooms typically designed similar to data centers) are designed following generally accepted practices which enable scalability and reliability. Particularly in the broadband communications sector, revenue streams of millions of dollars per day are not uncommon for the traffic that passes into, out of, and through a data center. It is therefore of the utmost importance that the infrastructure supporting IT and telecommunications equipment that become part of the fabric of the World Wide Web and its economy remain online and as isolated from electrical and environmentally toxic conditions as possible to avoid network and circuit down time and stored data corruption.

CyberSecurity appliances are being designed into the substation network typically by IT network and Cyber-engineers in response to deeper levels of NERC-CIP and the need to detect and hopefully prevent hostile actors the ability to penetrate critical operational and controls systems. Quite frequently at this point, those devices have been designed and purchased from known vendors that supply equipment for Enterprise/"IT" networks, not necessarily design to survive the substation environment.

The physical Ethernet layer, as connected by copper wire, operates on +/- 2.5 V DC. Differentiating a logical "1" from a logical "0" is separated by just a few volts at a devices' copper Ethernet port. An unmitigated transient within the CEE may impress itself onto an Ethernet cable in the cable tray by induction, direct connection (less likely), or a momentary difference of potential between the connected Ethernet ports that is larger than the devices' surge withstand capability. This can not only cause momentary packet loss (potentially an interruption of a "TRIP" or "OPEN" command), the surge can also incrementally erode circuit traces within integrated circuits (ICs) located on one of many circuit boards within the device. Eventually that circuit, an IC or even the device itself will fail. The failure will presumably come to light at 5:00 PM on a Friday before a holiday weekend, preceded by a clear sunny sky days or weeks, leaving any frame of correlation to a prior transient event, if in fact a transient event was documented as having occurred, absent.

On the substation design side, a false sense of security can be experienced by an engineer running software which performs analysis to meet IEEE-80. Unless transient analysis is specifically performed, and displaying those transients as waves that effectively 'wash' across a substations', and thus a CEE's grounding plan, a trained engineer may find no reason for concern. Grounding design for substations, after all, is normally performed for personnel safety and the ability of protective devices to sense and respond to system fault condition, not necessarily for equipment reliability, especially inside a CEE.

The reality, however, is that electrons flow slower than the speed of light through different conducting media. Thus streamer activity – the current that's produced prior to a lightning strike as charges flow between earth and the cloud – also washes through the ground grid at many points. And not necessarily just the highest points in a substation. The author has observed failure of many substation GPS antennae and GPS receiver inputs that had apparent damage, where the GPS antenna was installed outside and at a much lower elevation than lighting masts, substation shield wires, and transmission termination structures. Proper grounding and bonding methods must be applied to GPS antennae which are located outside of the CEE. These techniques are readily available for the design engineer in various industry standards such as Motorola R56 and TIA standards.

The GPS antenna which is not properly bonded and grounded can introduce thousands of transient volts and currents into the cable tray systems and adjacent cables (some of which may be copper serial or Ethernet cables) during a typical thunderstorm day. Gradual and progressive melting and 'erosion' of circuit traces within ICs in GPS receivers and other affected nearby equipment will result. The initial symptom may be erratic loss of signal or data and will eventually culminate in device failure. If that device is a Cyber appliance which supports NERC-CIP compliance, penalties and fines may also be presented if it is determined that the initial installation was not performed in accordance with appropriate design methods to promote reliability.

A few definitions and important concepts regarding grounding and bonding for equipment reliability…

A. Background

A grounding system is different than a bonding system. Grounding is defined as a method of electrically connecting a facilities' metallic elements to earth. Bonding refers to methods whereby an equipotential plane is developed within a predefined physical area and in a manner which also inhibits circulating currents, or current flowing in an unintended path which may compromise reliability or circuit/device performance.

Bonded elements in a data center, for example are all connected to a single point ground, referred to as an Office Principle Ground Point (OPGP). That ground bus bar is then bonded to other metallic elements within the facility in a very precise and engineered manner, then connected to earth ground.

A partial list of items that are connected to a single point ground bus bar in a data center or Telecom/microwave site includes:

- Legacy metallic water pipes
- Metallic gas lines
- Electric system neutral/ground
- Copper communication cable reference and surge protection
- Antenna (such as GPS antenna) protection
- Rebar in a building's concrete reinforcement
- Connection to outside earth ground and the outside ground grid

The above components are tied together at the OPGP[3], which serves as developing an engineered equipotential plane with very specific connection methods and techniques.

IEEE 80 and IEEE 81 are staples in the electric utility industry and have carved out the benchmark for designing safe and reliable substations. On the IT and Telecom side, Telcordia, EIA/TIA, and Motorola R56 have been drivers for grounding and bonding design that provides both personnel safety and equipment reliability. The National Electric Code also provides some guidance on grounding and bonding with both the electric utility and IT-Telecom industries, but stops short of providing the details of grounding and bonding design that enhances reliability.

For the balance of this text, we will assume that IEEE 80/81/367 have been properly applied and the grounding system at the substation has been well maintained. We will also assume that actual zero sequence faults and their resultant currents have been historically analyzed and corroborated with the utility's system model, with any deviations detected and corrected.

What's left is to analyze typical CEE bonding methods, and practices of how that bonding system is connected to earth ground with the goal of adding device reliability as a characteristic in additional to ensuring personnel safety.

IV. Objectives of Grounding & Bonding

The National Electric Code lists concrete as a conductor. Since IEEE 80 points to step and touch potential needing to be properly managed. A significant goal being that during times of zero sequence fault current flow, a person with a full walking stride that touches a metallic component in a substation won't be subjected to current flows through the body that would result in ventricular fibrillation. What of equipment and connections that can be damaged with as little as a 50 volt transient appearing on a copper communications cable that is attached to a serial or Ethernet port? What if the equipment is a Cyber appliance that is required to be in-service to detect or mitigate an insidious hacking attempt and cannot report back its own health or status?

A. Skin Effects

Prefacing any discussion on grounding and bonding system design for reliability in the CEE, a discussion on skin effect should be understood.

Physics has proven that electron and therefore current flow in a conductor tends to penetrate less into a conductor as the frequency rises. The governing equation[4] is given as:

$$\sigma = \mathrm{sqr}(\rho/\pi f \upsilon)$$

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[3] Refer to Telcordia Grounding and Bonding standard and TIA-942 for a more comprehensive definition design guide.

[4] *Transmission Lines and Networks*, Walter C Johnson, McGraw-Hill Publishing 1963, P 58.

Where

ρ = resistivity of the conductor in [Ohm-m]

F = frequency in [Hertz]

υ = absolute magnetic permeability of the conductor, given by $\upsilon_o \times \upsilon_r$, where $\upsilon_o = 4\pi \times 10^{-7}$ [H/m] and

υ_r = the permeability of the material itself

Several online calculators are available. The table below indicates skin depth at several frequencies for the two dominant conductor types used in control cables and power transmission.

Frequency [MHz]	Skin Depth [in] Conductor Type	
	Copper	Aluminum
0	Infinity	Infinity
0.00005	0.3630	0.4566
0.00006	0.3314	0.4168
0.001	0.0812	0.1021
0.12	0.0074	0.0093
1	0.0026	0.0032
2600	0.0001	0.0001
5000	0.0000	0.0000

Table 1 Conductor Skin Depth vs Frequency

From the above chart, at 60Hz current flow penetration into a copper conductor reaches approximately 1/3" and for aluminum approximately 0.4". At a typical power line carrier frequency of 120kHz, current flow penetration for copper and aluminum are a mere 7 and 9 – thousandths of an inch. Thus a single thicker conductor itself does not guarantee that more power or less voltage drop can be transported for a long run of coaxial or triaxial cable, for example.

The other side of the discussion relates to how effectively a conductor can drain transients due to lightning, switching surges, power supply failures, etc. to earth ground and away from the balance of equipment. Many studies have been performed regarding switching surge analysis. The following chart illustrates lightning radiation spectrum, Electric Field strength to frequency range. Actual current flow during a lightning stroke would have similar frequency components.

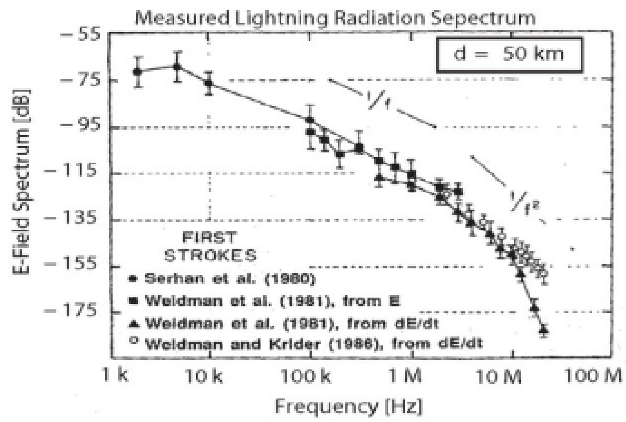

Figure 1 – Measured Lightning Radiation Spectrum [1]

Analyzing one model of the complex frequency content of lightning against the skin depth chart in Table 1. With a reliability need to keep lighting energy content away from equipment inside the CEE, it becomes apparent that finely stranded grounding conductors should be applied, since the skin depth of lightning energy is but handfuls of thousandths of an inch of penetration on either a copper or aluminum wire. In the IT-Telecom industry, finely stranded 'welding cable' is typically used as an effective means for diverting transients effectively toward earth ground.

B. On Sharp 90-degree Bends in Grounding Conductors

Reiterating a point made elsewhere in this document, sharp 90-degree bends have been favored or perhaps instilled in electric utility electricians and wiremen for neatness purposes and cable grooming practices. These practices run contrary to keeping energies that essentially travel on the surface of a conductor actually contained on the conductor.

A simple analogy might be drawn as a fully loaded 100 car freight train running down a steep incline with no or limited brakes. At some given speed, the train will derail and not run along its prescribed path. In quite a similar manner, higher frequency lightning energies which travel mostly on conductor surfaces will 'derail' from the surface of a conductor if the conductor bends which attempt to direct the energies toward earth ground, are too sharp. The energy will essentially attempt to find a lower-impedance path to earth ground. The lower-impedance path may well be an ionized-air jump off point near a foundation bolt or a panel's ground bus bar. That derailing of energy from a desired path will either serve to crumble and weaken a structures' foundation, or destroy devices and components in a CEE as those energies are now seeking lower-impedance paths to ground rather than 'along the rails' of an engineered path to ground.

C. Grounding and Bonding for the CEE

From the TIA-942 and Telcordia Grounding and Bonding standards, five requirements can be drawn from in order to provide a solid foundational framework for a CEE grounding and bonding philosophy which include both personnel safety and equipment reliability:

1. *The grounding system shall be intentional.*

A substation or protection and design engineer can determine the ultimate layout of the substation transformers, buss, transmission line terminations, distribution feeder breakers and other components installed in the yard with corollary protection control, metering, and SCADA equipment required inside the CEE to meet operational requirements. It is therefore possible to design a grounding and bonding system which can provide a safe equipotential plane within the CEE to which all equipment can be connected.

Development of an equipotential plane within a CEE is not an insurmountable task, but does require thoughtful planning of the manner in which cable tray systems, panels, grounding conductors, inter-panel communication cables et al are installed. Once panel and cable management layouts are known, engineered grounding and bonding methods can be developed, and the OPGP connection point defined, providing an opportunity to achieve both a safe and reliable foundation for people and equipment.

Some consideration needs to be given to training for design and installation professionals. Attention to details such as

- Specifying and installing insulated grounding conductors to avoid unintentional parallel grounding current paths
- specifying and installing finely stranded grounding conductors to offer maximum surface area for transients to travel
- installation techniques to ensure proper grounding and bonding conductor bend radius requirements are adhered to
- use of double-hole lugs where possible for a more reliable connection
- use of anti-oxidant grease to facilitate a corrosion-free connection

Simply specifying the proper components from a design perspective and assuming legacy substation electricians and wiremen will install the components properly (with respect to equipment reliability) can compromise the best intentions. For example, in a substation yard, each metallic structure will normally be connected to earth ground. It's not uncommon for an electrician to tightly follow the contour of the squared-off foundation for physical personnel safety, this to avoid a tripping hazard by having the grounding conductor too far away from the foundations' edge. Installing grounding and bonding conductors with a tight bend radius, however can produce unwanted voltage building at higher transient frequencies, to the point of rapid and potentially catastrophic energy jump-off points at those points of tight radius bends.

2. *The grounding system shall be visually verifiable.*

When implemented properly, a visual inspection of every component of the grounding system will be possible. This includes discrete rack-mounted equipment connection points to their rack or cabinet ground bus bar connections, rack or cabinet ground bus bar connections to the insulated grounding conductor, insulated grounding conductors to the OPGP, and so on. Such a system can be inspected for degradation such as corrosion or loose terminations, ensuring long-term system reliability. In addition, the outside connection to the station ground grid should be made in a manner such that the grounding conductor from the OPGP to the station grid can be easily inspected.

3. *The grounding system shall be adequately sized.*

TIA-942 provides guidelines for sizing each component of the grounding system. Improper use of the guidelines can reduce network availability and cause premature equipment failure that contributes to increased operating costs. Sizing is based on the grounding systems' ability to divert power system fault current (60Hz AC or transients) inside the CEE away to earth ground efficiently and safely, as well as enable high-frequency transient energy to be diverted to earth ground in a low impedance manner, and without producing weak points, or 'jump-off' points along the way to earth ground.

A protection & control or substation design engineer can calculate available fault current from station service as well as a DC fault (which normally wouldn't flow through ground). More complex is a calculation involving non-60Hz transient current and potential flow, which can be generated from static discharges whether person-to-equipment in dry conditions, cloud-to-ground or ground-to-cloud streamer discharges including the worst-case direct lightning strike, switching transients, system faults, etc.

4. *The grounding system shall direct damaging currents away from equipment.*

From the point of equipment reliability, a grounding system that complies with TIA-942 requires each rack to bond directly to the OPGP, thereby directing current away from sensitive electronics. At most CEE relay racks or cabinets, the cabinets and racks are directly bolted to the floor without isolation, they are also typically directly bolted to each other and to the cable tray system for strength and support. All of these paths are 'unengineered' paths for transient currents to travel. An 'engineered' path to earth ground ideally only provides one low impedance path to earth ground. During a surge event, such a power supply failure in a piece of rack-mounted element, the entire row of daisy-chained racks becomes energized with stray current, potentially resulting in additional damaged equipment[5].

Another fairly common CEE grounding practice is to design two (or more) points of entry for grounding conductors to the substation grid. The rationale is primarily for safety and redundancy of grounding connections. Creating an equipotential plane across the CEE interior space becomes virtually impossible at sites where multiple grounding conductors enter the building, since near-continuous current (hence a voltage difference) will flow through the CEE's metallic infrastructure.

The ground grid in a substation is a dynamic system. It is continuously carrying zero sequence/system imbalance currents, harmonic frequency content. During quiescent conditions, up to several amps of current have been measured in multiple conductors at several sampled CEEs. It is not unlikely that several tens or perhaps hundreds of amps of 'through-CEE' current could be measured for a static discharge event or lightning strike, or certain system faults. Where a utility has an established practice of requiring two or more entry points of grounding connections, it is still possible to create an equipotential plane within a CEE, but the engineer must be more creative in establishing physical and electrical connectivity boundaries.

5. *All metallic components in the data center (CEE in our case) shall be bonded to the grounding system.*

The goal is to have all conductive materials at the same electrical potential to minimize undesirable 'stray' or 'circulating' current flow. Current flows when there is a difference in potential between components. If the current flows across a piece of equipment, damage to devices may occur. Equipment, racks, cabinets, ladder racks, enclosures, and cable trays must be bonded to the grounding system[6].

Enter the Equipotential Ground Plane…

D. Equipotential Plane Concepts

Perhaps one of the more difficult aspects of implementing an equipotential plane in a legacy CEE is that in the great majority of utility substations the author has visited, a 'more is better' concept has been dominant. To the point where multiple and diverse entry points of grounding conductors[7] are attached to cable trays, cable termination racks, Unistrut, or directly to the closest rack in the closest bay as the grounding conductor now turns into a bonding conductor by function and provides a bonding point for each subsequent panel or cabinet beneath or above its' path. At some point the grounding conductors may meet at a predefined location in the CEE so as to electrically complete a transit across the CEE inside. More often than not, cable trays, panels or cabinets, and the concrete to which the panels or cabinets are attached make up the physically missing connection point between all the grounding conductors.

What's the problem with the 'more is better' concept, the inquiring reader may ask? The paradigm and mindset of most utility engineers centers around 60Hz. CTs and PTs detect the presence of 60Hz voltage and current, and convert primary values into secondary values which IEDs in the CEE use. The ground grid is observed as a passive safety asset, and not necessarily as a component which is associated with data and communications equipment reliability.

With no earth faults present, zero sequence currents can be readily modeled and measured within a station ground grid. Practically speaking, with diverse entry points of grounding conductors, conductive materials (cable trays, racks, cabinets, etc.) now become an above-ground-level part of the circulating current network within the substation. Recall that where current flows, potential differences exist. Theoretically, an equipotential plane is difficult to establish within a physical area that is electrically carrying through-currents/

Also recall that as part of engineered safeguards, the grounding system, as designed using IEEE 80 as the guiding document, a utility worker is relatively well assured that no personal harm will attach itself during the course of a days' work if proper Personal Protective Equipment is used, Situational Awareness techniques are followed, and thoughtful following of accepted processes and procedures are followed. The same ground grid that enables 60Hz current to flow also enables higher-frequency transients to enter and pass through the CEE.

High frequency transient conditions due to switching surges and lightning have been fairly well studied. However, these switching surges can quite readily flow through the CEE grounding and bonding system with virtually no restraint, unless proper restraints are designed and properly installed.

'Our relays, meters, and RTUs have not been failing. Why should I be concerned now?' The good news about the question is that the question was asked. IEDs installed to protect, control, meter, and monitor the grid are commonly designed to meet IEEE C37.94 for Surge Withstand Capabilities for electrical conditions experienced in a substation. All IED connection points are typically designed to operate reliably in the transient-rich substation environment. Further, most IED manufacturers have also adopted IEEE 1613 to provide

[5] Good industry practice also requires racks to be electrically isolated from each other and from electrical connection to a concrete floor.

[6] Additional information is available in the white paper, Facility Considerations for the Data Center, authored by American Power Conversion, Cisco Systems, and Panduit Corp.

[7] Conductors, typical AWG # 4/0 in size, that are connected to one or more electrical points in the CEE and then to the stations' ground grid.

additional hardening of Ethernet communication ports. Unfortunately, suppliers of Cyber- and some families of IT networking equipment that are deployed at substations were not designed for the substation environment in the truest sense, and have not been designed to meet IEEE-1613 requirements at even the most basic level.

Since it's difficult to encourage an industry that sells equipment the utility industry as a side-job to change its design to accommodate our industry, the protection & control or substation design engineer can take a few steps to modify CEE grounding and equipment layout designs to accommodate equipment that is more susceptible to damage than 'substation-class' IEDs.

What must be properly managed at a minimum are the following conditions:

- Transient through-current flow through a substation CEE
  - externally induced – lightning, including pre-strike streamer discharge currents
  - internally induced – switching surges, zero sequence ground fault currents with high harmonic content

Ideally, the grounding and bonding system inside the CEE should be designed to create an equipotential voltage profile throughout the CEE and its racks, cabinets, and individual devices during any or all of the above described transient conditions.

6. Proposed Design Basis

For green field sites, an area should be made available in the CEE in which IT-Telecom equipment will be installed[8]. A utility's CEE design practices may require 4/0 grounding cables to enter opposite ends of the building, and thus bringing the ground grid and its' host of circulating currents and transients through the CEE. Even if that is the case, a dedicated row or sets of rows, preferably in an offset part of a new CEE should be designated for IT-Telecom equipment installation. Such an area should contain the following critical design elements and characteristics:

- A single OPGP point, installed on insulated stand-offs. The OPGP will have one insulated grounding conductor which will serve to tie the OPGP to earth ground.
- The grounding conductor connected to the substation ground grid will be exothermically connected to the OPGP and directly to a ground rod and the substations' ground grid in the shortest distance possible, maintaining a minimum bend radius of 12" and insulated from any contact with metallic or concrete/conductive elements. This implies that the grounding conductor be installed within a PVC conduit to prevent incidental contact with the CEE's concrete/stucco or other metallic elements. Once again, a reinforcement of an engineered path for grounding and bonding.
- Grounding conductors to individual racks or cabinets shall be no smaller than finely stranded AWG #6, and insulated from electrical contact with any other device or component along its path from device being bonded to the grounding bus bar or grounding conductor.
- Each rack or cabinet into which IT-Telecom equipment will be installed will be electrically isolated from the floor and from adjacent cabinets or racks.
- Each rack or cabinet will have its own ground bus bar to which all rack or cabinet-mounted equipment will be connected via insulated conductor. Additionally, the rack or cabinet will be connected to its own ground bus bar.
- Each grounding connection shall be made with a metal-to-metal connection, using appropriate anti-oxidation compound (no painted surface "connection" attempts shall be made)
- Cables which serve to bond equipment to a ground bus bar should have a two-hole lug connection as a first preference. A single-hole lug may be used in cases where a two-hole lug is impractical to install.
- Each cable tray section shall be intentionally bonded, one section to another, and then one main insulated connection to the OPGP
- Each cable tray section shall carry one insulated finely stranded AWG #1/0 (or larger) conductor. Connections to each rack or cabinet shall be made to the grounding conductor, parting sufficient insulation in the grounding conductor so as to make a solid and facilitate ease of visual inspection and testing
- All bonding connections shall be made with large-radius bends, and pointing toward the OPGP

Brown field sites may be more difficult or virtually impossible to properly isolate and treat in a data-center-like manner with respect to grounding and bonding methods. Some CEEs are a part of an all-metal switchgear assembly, with through- or circulating currents impossible to isolate and manage in an engineered fashion. Some utilities may choose to intersperse IT-Telecom equipment with protection & control equipment or where space might simply be available with the CEE. Each case will certainly deserve an evaluation to determine what steps, if any, toward a more reliable grounding-bonding design is possible.

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[8] Note – while the most holistic approach to equipment reliably would be to treat the entire CEE as a data center in terms of grounding and bonding connections, most IED manufacturers have already invested into device hardening. Thus, a utility may choose to only apply data-center-like grounding and bonding practices to the portion of a CEE which has been dedicated for IT-Telecom equipment.

7. Closing Comments

A certain degree of skepticism is healthy and to be encouraged in debating the merits of any new approach or method. The content of this document was intended to share practical understanding and experiences the author has gained through a career that has been balanced between practical field and design experience in protection & control, SCADA, IT- Telecom, and in a manufacturing environment. There is a gap waiting to be bridged to ensure reliable deployment of current-state and soon-to-be-deployed technologies in the electric utility industry, including technologies not originally intended to be installed or applied in a substation environment. Hopefully enough content has been presented so as to benefit both the IT-Telecom and protection & control/substation engineer or designer arrive to a solution which will be practical and cost effective for their utility.

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I would personally like to thank the late John Lazarra, formerly of Florida Power Corporation (and Progress Energy – FL and Duke – FL) for giving me a nudge toward bridging the gap between protection & controls engineering, SCADA, and the IT-Telecom disciplines in the mid-1990's. To Nelson Barbeito of Florida Power Corporation who served as my initial and foundational grounding and bonding mentor, and who also actively served on IEEE grounding and bonding standards development, working closely with Dr Sakis Meliopoulos. I have had many other mentors and fine teachers along the way, and simply desire to keep passing on the knowledge and understanding which I have gained. The hope is to inspire others to reach new levels of understanding, develop new industry-changing methods, techniques, and standards, and continuing the practice of engineering by applying scientific principles for the betterment of humanity in a cost effective manner.

Thanks to Power Grid Engineering executives who continue to place their precious trust in me to make a difference both within our team and in our industry. Thanks to my lovely wife and my daughter who have provided plenty of love and patience along my continuing life's path. And finally to God, Who provides understanding, patience and love in all things and has been an ever-present influencer.

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