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Review of Substation Grounding Practices
Safety and Constructability Enhancements

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SUMMARY

This paper reviews established substation grounding practices in the electric transmission industry, and recommends plausible improvements that enhance safety and constructability of substation grounding applications at AEP transmission and distribution substations. AEP's experience in applying standards and best practices to substation grounding applications has been utilized in the development and implementation of an innovative ground grid design [2] that improves field safety and drives project and construction efficiency.

This paper describes the safe optimal ground grid design methods for transmission and distribution substations, and compares them with design methods described in IEEE 80 – 2013 [1]. Computer software, such as CDEGS [3], designs and models the ground grid by accurately simulating actual site conditions, power system configuration, power system operation, and prevailing or forecasted fault currents with clearing times. Industry standard ASPEN software [4] is used for fault current flow analysis and concepts. Where applicable, fault clearing by segmented clearing time method is used for the ground grid analysis. The methods do not utilize the IEEE 80 - 2013 curves to calculate the distribution of electric current into the grid, and over neutral/shield wire. All fault current values, and clearing times are calculated values specific to the power system configuration and power system operation at the substation location. The methods are theoretically correct, and meet and exceed safety requirements – while enhancing grounding material and construction labor savings. This optimizes the ground grid design for AEP's transmission and distribution substations.

The replacement of exothermic weld connection [5], a primary industry standard for ground grid connections by swage ground connection [6], is an example of a safety evolution in the right direction. This paper questions existing industry grounding practices, details the possible hazards in exothermic welding application, and introduces a safer and cost effective solution utilizing new tools which led to the company wide implementation of swage ground connection in 2016.

In addition, this paper outlines utilizing ground grid integrity testing method to evaluate an existing ground grid. This paper proposes that the ground grid integrity testing method become an AEP standard, along with grounding studies and ground grid installations.

KEYWORDS

Soil Modelling, Fault Analysis, Grounding Study, Swage Ground Connection, Integrity Testing

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AEP GROUNDING STUDY & DESIGN

Review of Industry Practices for Substation Grounding Study:

The IEEE Standard 80 – 2013 serves as an industry reference, and provides practical guidance to achieve two main design goals for all substation ground grids. First, this ensures personnel safety and second, it provides a means to dissipate current into earth – without exceeding an equipment and operating limit. The procedure described in section 16.4 of IEEE 80 - 2013 requires a hand calculation of parameters in the design of a substation ground grid. A notable limitation of the existing guidance is the lack of new tools, such as a computer algorithm in the design of a ground grid. Following the guidance has led to safe ground grid designs. However, it utilizes excessive material and labor – Which does not optimize the cost, especially for substations with large sized yards.

To overcome the limitations of hand calculations, computer algorithm is recommended by IEEE Standard 80 – 2013. In section 16.8, driving factors listed for computer algorithm include modelling the individual components of the grounding system, forming a set of equations describing the interaction of these components, solving the ground fault current flowing from each component into the earth, and computing the potential at any desired surface point, soil model, physical layout reflecting actual site conditions. In addition, reasons listed that justify the use of computer algorithm include uneven grid spacings, presence of buried structures, or objects not connected to the ground grid However, a document detailing substation grounding theory, along with a mechanism to apply for a specific substation with real-time power system parameters, is missing from practicable industry references.

After meticulous design, and reviewing of hundreds of AEP ground grids, AEP has developed innovative methods utilizing new tools for new substation, and existing substation expansion that are practical, enhance time and cost savings, and improve project and construction efficiency.

Fundamentals of Ground Potential Rise and Touch Potential:

During a fault condition, a person inside a station and in contact with structure equipment, or a fence, becomes a part of the parallel circuit. This poses a risk of potential safety hazards of touch or step potential [1]. Because of its greater security, the touch potential is the focus in the content listed below. This section briefly discusses the fundamentals of ground potential rise (GPR), and touch potential risks – based on two different scenarios.

Scenario 1 (Person is in contact with a metallic object when a ground fault occurs on another metallic object):

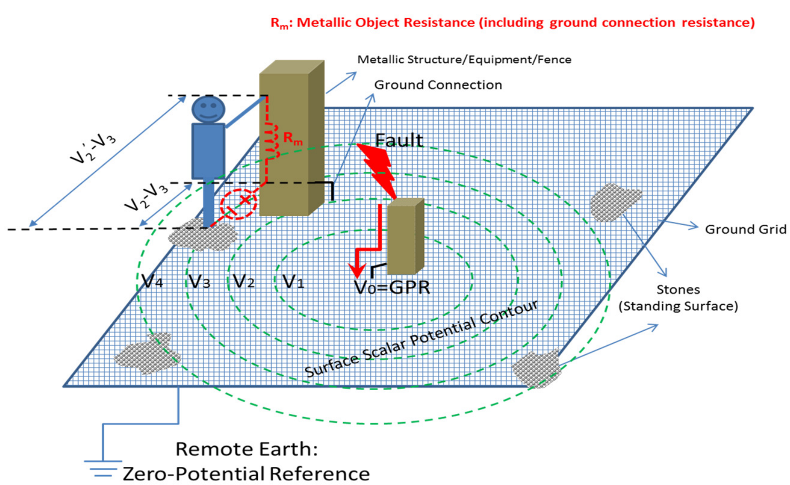

Fig. 1. Touch potential illustration when a ground fault energizes the ground grid

As shown in Fig. 1, a ground fault energizes the ground grid and creates GPR at the fault location comparing to the remote earth. This rise diminishes further from the fault location, and remains at higher values on the top of the ground conductors. A few surface scalar potential contours are shown in Fig. 1. The metallic object (which the person is in contact with) is grounded to the ground grid and at the surface potential of V_2, while the person's standing location surface potential is V_3. The surface potential difference $V_2 - V_3$, is acting as a voltage source, and can result in the body current flowing from the metallic object resistance R_m to human body resistance. Note that the calculated touch potential is $V_2 - V_3$, while the true touch potential is $V_2' - V_3$. This is only one portion of the calculated value (smaller than $V_2 - V_3$). As a result, the larger R_m is, the smaller the true touch potential becomes.

Scenario 2:

(Person is in contact with a metallic object when a ground fault occurs on the same object):

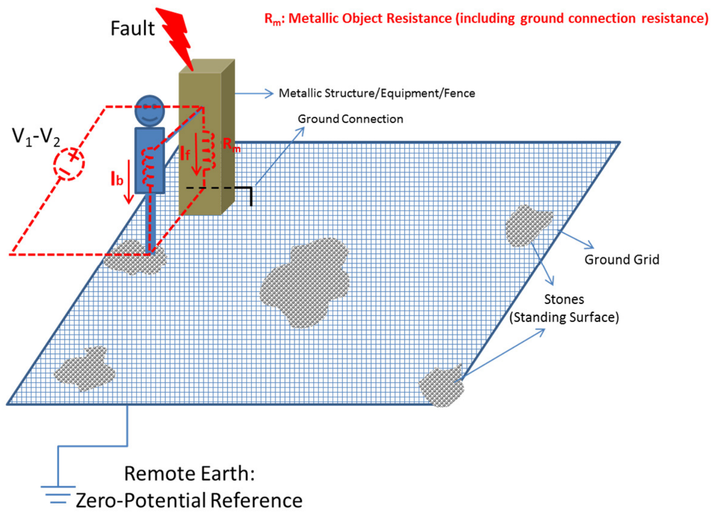

Fig. 2. Touch potential illustration when a ground fault energizes the fence/structure

Scenario 2 explains why utilities always require a good ground connection between the metallic objects and the corresponding ground grid. When a fault occurs when a person is in contact with a metallic object, the body becomes the part of the parallel circuit (as shown in Fig. 2). When there is no connection to ground grid, a bad connection, or a corroded connection, R_m gets larger, resulting in increased current thru the body.

To ensure safety for employees and the public, all metallic objects at AEP substations must be grounded in at least two locations. Fig. 3 shows an example of a metallic structure with two ground rods.

Fig. 3. Two ground connections for one structure

AEP Innovative Grounding Study Methods:

Single line-to-ground fault and double line-to-ground fault categories cause unbalanced fault currents flowing to the ground.. To determine the component of the fault current that flows thru the soil, zero sequence components are used in the fault analysis. The worst case scenario for a ground fault is determined by considering the fault current values, and clearing times at all transmission voltage level bus locations.

The concept of ground fault analysis is the total ground fault current ($3I_0$) that returns to a remote source (or multiple remote sources) through the earth and neutral/shield wire connections. The auto-transformer (when installed) acts as a local source, where the neutral current circulates through the ground grid returns to the auto-transformer from the fault location. The interconnection of incoming lines, buses, and transformers enables a metallic path through which multiple sources contribute to the fault current at a central station (a term used to describe a station where the ground grid is being analysed?.

AEP standard recommends two methods of designing a ground grid.

1. Single Injection (SI) method
2. Multiple Injection (MI) method

The SI method is applicable when a distribution substation has a transformer connected in delta configuration on the high side, and a wye- grounded configuration on the low side. The total fault current ($3I_0$) distributes while returning to the remote sources as I_g and I_n. The ground grid current returning to remote sources via earth is represented as I_g, and the neutral/shield wire current returning to remote sources is represented as I_n. At the fault location, a single injection of ($3I_0$ - I_n = I_g) is injected into the ground grid in a computer simulation. The ground grid design is completed when calculated touch and step potentials are below the allowable thresholds.

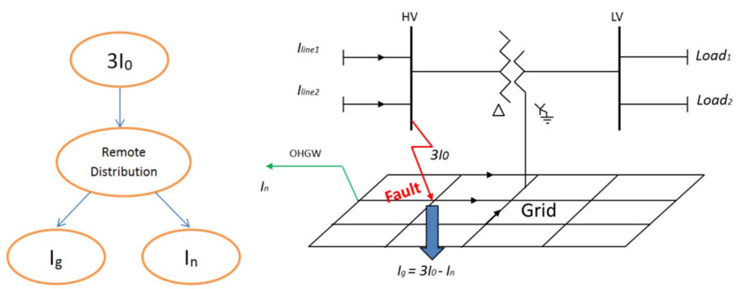

Fig. 4. SI method fault current distribution

Note that the low side fault current returns to the transformer neutral through the ground grid, due to the wye-grounded connection on the low side. This enables most of the current to return through the metallic path – with a negligable leakage current through the soil. It is for this reason that low side faults in a distribution substation are typically not considered.

The MI method is applicable to transmission and distribution substations with autotransformer banks, the total fault current is sourced from both sides of the auto-transformer, as shown in Fig. 5. As a result, there are three components for the total fault current ($3I_0$) which are I_g, I_n, and I_{cir} – the current that returns to the neutral of the autotransformer from the fault location. In addition, I_g and I_n constitute the remote distribution components, and I_{cir} is the local distribution, as the autotransformer is a local source to the fault. Each of the components ($3I_0$), I_n, and I_{cir} are injected separately at the physical locations of bus, neutral/shield, and autotransformer on the ground grid that constitute the MI method. The ground grid design is completed when calculated touch and step potentials are below the allowable thresholds.

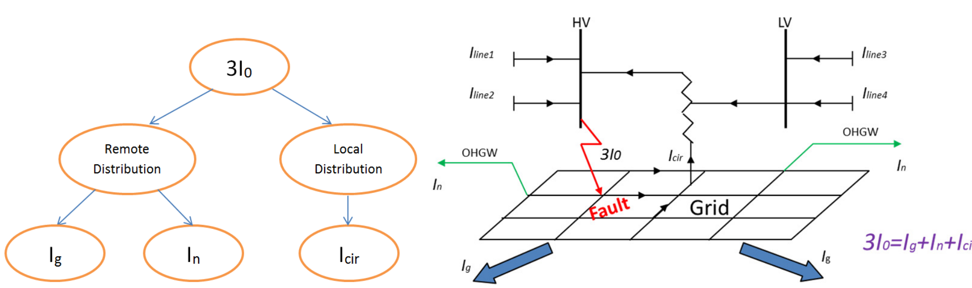

Fig. 5. MI method fault current distribution

Fault Analysis Tool & Application:

AEP uses ASPEN OneLiner for fault analysis. For a grounding study, ground faults on each high side bus is simulated at the bus location in ASPEN. Information such as $3I_0$, I_{cir}, and X/R ratio are directly obtained from ASPEN, and simulated as a scenario in CDEGS. The ASPEN value from each incoming transmission line is used as an input to calculate the split factor in the FCDIST module of CDEGS – to determine the neutral/shield wire currents and grid current. Further, the grid current is injected into the ground grid at the fault location, as in the SI method. For the MI method, the total fault current, neutral/shield wire current, and neutral current returning to the auto-transformer are injected at the respective physical locations of the high side bus, neutral/shield wires, and auto-transformer. After completing the injection(s), the actual step and touch potentials are calculated. The grounding study is considered complete when the calculated actual step and touch potentials on the ground grid are below the threshold limits for all fault current scenarios.

For all incoming lines, neutral/shield wire currents I_n values are calculated utilizing the FCDIST module of CDEGS software. For a distribution substation, the sum of all neutral/shield wire currents from FCDIST can be injected from the grid at one location. For a transmission station, each neutral/shield wire current calculated from FCDIST may need to be injected at the respective structure locations of the shield wires. This is due to the large distance between incoming line structures, which is typical to a transmission station.

The FCDIST output file provides the values of I_n – from the central station where the ground grid is being designed – to each specific remote terminal station that is a source for the fault at the central station.

Soil Resistivity Testing:

The 4-point Wenner method is used to determine the soil resistivity at the substation site. Specific traverses for the tests are chosen where there is least interference from nearby power lines, or from buried objects. A minimum of two sets of readings are obtained in most cases, and the values obtained are used in RESAP module of CDEGS software to determine the soil model. Some of the quality measures used to ascertain the quality of the soil model, and used to design the ground grid, include the difference between measured and computed values of resistivity, calibration of the test equipment, and probe spacings up to the diagonal distance of the station from fence corner to fence corner..

AEP Standard Recommendations:

This paper describes the methods to design a safe optimal ground grid for a transmission station or a distribution substation. Hand calculations to determine the grid spacing, conservative approaches such as not calculating the fault current division factor (also known as split factor), or sizing the ground grid to the same kA as the equipment rating can lead to the excessive use of copper, and labor for trenching and installation. By utilizing the optimization process described in this paper, a safe ground grid has been designed using less copper.. In addition, the constructability of the project is enhanced, as the trenching is also optimal with the optimal design.

In addition to increasing costs, an overdesigned grid can create excess trenching – which increases site safety hazards from open trenches, and complicates the logistics of moving construction equipment and material at sites. Thus, the AEP standard methods utilize these new tools to enhance safety and constructability.

A comparison table between IEEE 80 – 2013 and AEP design methods is shown in Table 1. IEEE 80 - 2013 safety requirements are satisfied in AEP design methods, with the additional advantage of correctly simulating actual site conditions, and optimizing materials and labor in the design and installation of the ground grid.

Table 1 Comparison Table**Category Description**	**IEEE 80 - 2013**	**AEP DESIGN METHODS**

Calculation Method	Uses hand calculation, utilizing equations to calculate an actual value of a touch potential and a step potential at one point on top of the surface (not the entire surface area). The threshold values for the touch and step potentials are also hand-calculated for comparison.	Use computer algorithms to accurately simulate the site conditions, power system configurations, power system operations, and prevailing or forecasted fault currents with clearing times – and determine the actual potentials throughout the surface, then compares them to threshold.
Soil Model, Resistivity and Thickness	Uses uniform soil model with one resistivity value.	Uses multi-layer soil model. Accounts for the prevailing resistivity and thickness of each soil layer.
Fault Clearing time	A single fault clearing time is considered in the hand calculation.	Segmented clearing times for multiple fault current magnitudes can be analysed.
Split factor calculation	Utilizes pre-determined split factor curves (that may not be applicable to a specific station) to determine the grid current and shield/neutral wire currents.	Calculates the split factor with the prevalent and pertinent conditions to a specific station site (where the ground grid is being designed).
Grid shape and spacing	Analysis is limited to a square or rectangular grid shape, and equal grid spacing.	Can analyse all grid shapes and sizes, with no limitation on grid spacing.
Buried objects	GPR impact on buried objects cannot be analysed.	Can analyse buried objects, such as pipelines, above ground hydrants, or telecom interface boxes.
Transfer Potential	Provides minimum guidance on transfer potential impact on a neighbor's fence, and recommends the insulation of a fence extending outside the substation area.	Can determine transfer potential impact on a neighbor's fence, along with mitigation that identifies a non-metallic fence location and length that would mitigate the transfer potential from the substation fence.

Table 1. Comparison Table

Note: The above comparison indicates some of the differences between industry and AEP standards, and is not meant to undermine either or both standards.

AEP GROUNDING APPLICATION & INSTALLATION

Exothermically welded Connection – A Primary Industry Standard

The exothermic connection is a welded connection. It has an inherent requirement of cleaning the conductors; is moisture intolerant; and emits flames, fumes, high temperature while welding. This could expose an installation crew to an un-safe mold explosion (Fig. 6 & 7). It is a challenge to install an exothermic connection on rainy days. Water logged trenches can create project inefficiency (Fig. 6 & 7). The lessons learned from near-miss incidents provide us an opportunity to improve both the safety and efficiency of installing an above-grade or below-grade connection.

Fig. 6. Exothermic weld ignition (left) Challenging site condition (right)

Fig. 7. Exothermic weld near miss (left) Challenging site installation (right)

The swage connection provides an alternative that enhances both safety and project efficiency, in addition to increasing the quality of the connection.

Swage Connection - A Safer Practice

Swage is the generic term used for a cold forging process when the dimensions of the conductor and connector are altered in the tool die. This creates equal compressive forces while making the connection.

AEP's grounding standard since 2016 is all above-grade neutrals, and below-grade ground connector installations are made by swage connection. The swage connection is achieved by electric pump, with a recommended 10 ft. hose, power unit, head assembly, and quality check gauge. The necessary on-site training for swage connector installation is being provided for the crew so they develop an understanding of the new technology, and familiarity with swage process. A finished ground connection is checked with an inspection gauge provided by the manufacturer.

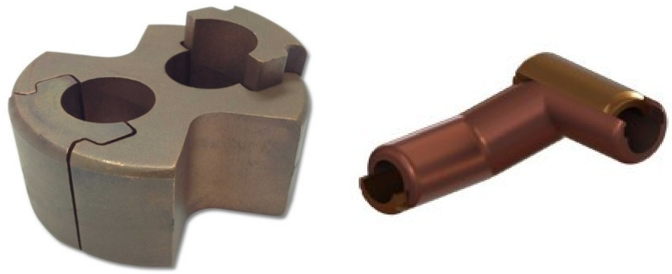

Fig. 8. Typical swage connector for 4/0 (left)   Typical swage connector for ground rod (right)

Fig. 9. Head Assembly (left) Gauge (right)

The quality of swage is consistent, and not dependent on the skill of the person installing the connection. A standard process utilizes a custom head assembly suitable for a specific type of swage connector, along with portable equipment and a quality check gauge (Fig. 9). Applying equal compressive forces simultaneously – 360 degrees around the connector assembly – creates a quality swage which is more controllable than an exothermic connection (Fig. 10).

Fig. 10. Inconsistently welded connection (left) Swage connector cross-section (right)

AEP GROUND GRID INTEGRITY TESTING

After designing a ground grid in CDEGS by using more accurate analysis methodologies and design strategies, it is issued for construction. AEP construction representative will work with contractors to ensure that the installed ground grid follows the design requirements, by visually checking before backfilling the soil. In addition, a ground grid integrity testing is strongly recommended after the installation, to check the installation quality and provide the baseline for monitoring the ground grid aging or corrosion situations.

Recently, AEP found severe ground conductor corrosion at one station near a retired coal-fired power plant. As shown in Fig. 11, the solid 4/0 conductor had corroded significantly. This is problematic if it can handle high fault current, and could result in an increase in the surrounding touch/step potentials.

Fig. 11. Corroded ground conductor

As a result, it is necessary to find a way to conveniently and routinely detect grounding system installation quality and future health issues. Based on current industry practices, grounding system integrity testing is the only way to detect the quality of ground grid continuity – especially the ground connections to the above-grade equipment/structure/fence. This method is very useful to identify the bad connection between the main ground grid and the above-grade objects. It can also detect any degradation that occurs at an old ground grid, by comparing the historically measured ground conductor impedances with the present. However, it cannot identify any bad connections or corroded conductors at specific locations below grade. This is especially true for large or dense ground grids, as there are multiple current paths between the above-grade testing points and the reference point.

The tool kit has fours probes: two voltage probes and two current probes. One pair of current and voltage probes are clamped to a reference point (e.g. transformer neutral), while another pair of current and voltage probes are used to touch any testing point. The theoretical diagram is shown in Fig. 12.

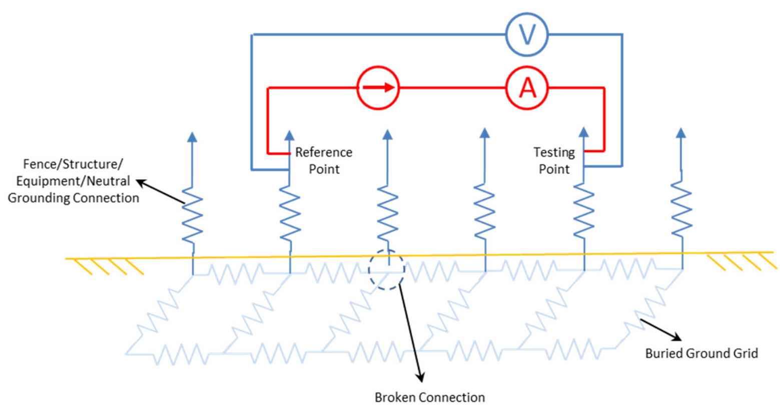

Fig. 12. Grounding integrity testing

An AEP test set-up is shown in Fig. 13.

Fig. 13. Ground grid integrity testing set-up

In this AEP test, some test results are shown in Table 3. All the impedance (real and reactive parts) readings are smaller than 100 mΩ, except two of them. These are between the main gate and Far East fence, and between the main gate and north eastern fence (highlighted in Table 3). The findings do match the grounding plan drawing in Fig. 14 (highlighted in the red box with very little ground conductors). Note that there is no universal measurement threshold indicating if the ground grid is sufficient or healthy. Comparisons and experiences should be used to make any judgment. As a result, the testing example shown in Fig. 13 and 14 does not mean this ground grid is insufficient. Instead, it is used to verify the old ground grid drawing, and make a record for future comparisons.

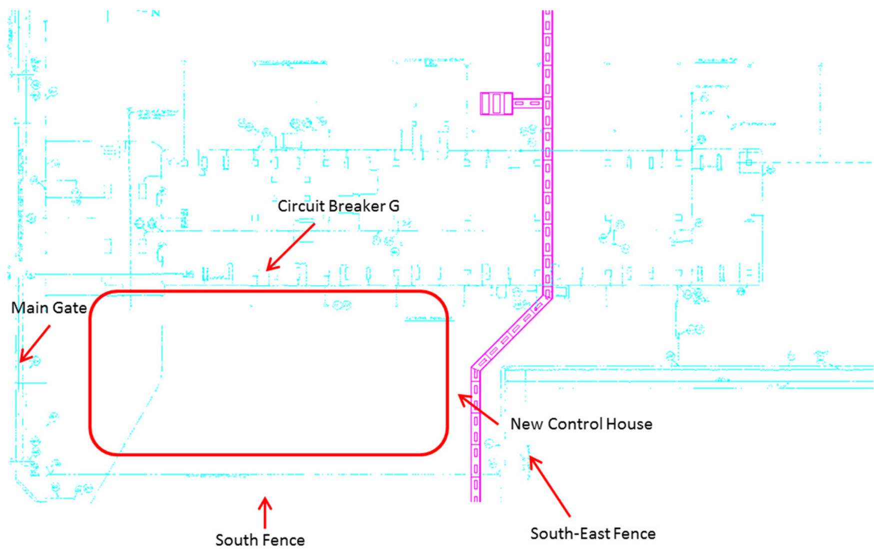

Fig. 14. Grounding plan drawing

Table 3 Ground Grid Integrity Test Data

Test Lead Red	Test Lead Black	Test Current Amps	Resistance mΩ	Reactance mΩ
Main Gate	CB-G	50	6.93	48.7
Main Gate	South Fence	50	215.1	104
Main Gate	New Control House	50	15.18	68.6
Main Gate	Southeast Fence	50	280	200

CONCLUSIONS & FUTURE VISION

This paper reviews ground grid design and installation practices, and recommends an innovative ground grid design and installation methods that enhance safety and project efficiency. This optimally-designed ground grid provides material and labor savings – while meeting all IEEE 80 safety requirements. The use of a swage ground connection facilitates a better quality installation, and improves construction efficiency and project schedule in all-weather site conditions. This paper also details a ground grid integrity testing method that can be deployed to track the health of the ground grid conductors over the service lifetime. The authors of this paper will continue to explore new innovative designs and products that enhance safer design, efficient installation, and monitor the health of the ground grid.

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