OPTIMIZATION OF AC SUBSTATION GROUND GRID DESIGN AND CALCULATIONS

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Abstract – The most important purpose of a substation ground grid is to ensure personnel safety, hence a proper design is key. Many IEEE standards provide guidance in ground grid design such as IEEE Std 80 [1], IEEE Std 367 [2] and IEEE Std 142 [3]. Computerized software is available to model ground grids and soil layers using IEEE Std 80 as a guide. While software saves designers significant time compared to hand calculations, they may result in unrealistic values. For example, modeling of ground grids in bedrock without applying a compilation of many grounding standards can result in the ground potential rise exceeding the system voltage and an impractically high touch potential. This paper provides guidance in applying an amalgamation of IEEE Grounding Standards, along with engineering judgement, to achieve realistic models. Application of proper soil models, surface layers, Ufer grounds and split factors will achieve realistic results and a calculated ground grid resistivity that will closely reflect the measured value. The paper will also discuss modeling existing ground grids where design drawings are not available. The applicability of this paper would extend to end users, such as the oil & gas industry, and does not apply to the Utility industry.

Index Terms — Ground grid, split factor, Ufer ground, ground potential rise, step potential, touch potential.

I. INTRODUCTION

Industrial AC substation ground grids are often over designed due to limitations of computer software, difficulties in modeling parameters in a realistic manner, and misapplication of the split factor. Overdesigning leads to higher project costs due to the additional materials required, such as copper, additional ground rods, and more real estate. This paper discusses all required steps to achieve the most optimal design and applies a conjunction of three major IEEE grounding standards. It is important for the electrical and civil designers to coordinate with each other to ensure the appropriate soil/backfill is being used and to properly size rebar in Ufer grounds, such as footings and piles. The following section will discuss this and all other design considerations, which will result in the most efficient method of designing. Two calculation methods will be discussed to determine the split factor along with the data that should be requested from the Utility Provider (or powerline owner) to make the best use of the calculations.

Two factors that play a major role in avoiding re-work of ground grids, once installed, are pre-planning and clear direction on the engineering construction drawings (both electrical and civil). Often, the soil is backfilled with a foreign material rather than native soil due to structural integrity, however this may not be communicated to the grounding designer and vice-versa. These issues are only realized after the ground grid resistance test results do not match the value given in the report from the grounding model.

II. GROUND GRID DESIGN CONSIDERATIONS

Ground grid design considerations that should be accounted for prior to beginning any design, calculations, or modeling will be discussed in this section. Pre-analysis and planning play a major factor in optimizing substation grounding, as this allows for the design of a realistic grid and will reduce confusion and errors during construction and commissioning.

A. Initial Details to Gather

Obtaining the latest Utility power supply fault data along with the X/R ratio is the first step. When gathering data from the Utility provider/owner, also obtain the future expected fault levels and discuss if there are any plans for upgrades in the near future. This will help to design for future levels if a numerical value for future predicted fault levels is given, or it will provide the necessary information to apply engineering judgement in determining a future expansion factor. This is simply a percentage applied to the line to ground fault current to take growth into consideration. A ground grid is meant to last the life of the substation, as it is no easy task to modify once installed. Keeping this in mind during the design will ensure the integrity of the analysis results in the future if fault levels increase. Another detail to request from the Utility provider/owner would be the connection of the overhead shield wire to the customer ground grid. This will determine whether a split factor can be utilized, further discussed in Section V.

B. Soil Analysis

Next is to analyze the soil; does the first soil layer have a higher or lower resistivity than the second layer? This will determine the basis of the design. If the second layer has a higher resistivity, there is no point in modeling deep driven ground rods as this will render the ground rods ineffective. In many cases, with a higher resistivity second layer, increasing the number of ground rods will not help much but increasing the ground grid area will; however, this requires more real estate. A shallow grid covering more surface area might be a good option if the area is available. Thinking of these factors prior to beginning modeling and design will save time and frustration so the designer will know which direction to utilize. If the soil characteristics are showing to be bedrock, it may not be practical to drive ground rods into the earth. In this case, a Ufer ground will be more effective, along with the fact that the current will take the paths of least resistance, which will not be the ground grid, but will mainly be taking the path of the overhead shield wire, which will increase the split factor.

C. Type of Facility

Does the ground grid comprise of just a substation or is there a process plant facility, such as a booster pumping station area involved as well? Take into consideration that the pumping station area would not have a high resistivity surface layer such as washed crushed rock and would not be maintained in the same way as substation clean crushed rock. In most cases there is just pit run gravel, which has a much lower resistivity than washed crushed rock. This must be taken into consideration to ensure personnel in the station area have an added safeguard from shock.

D. Ufer Grounds

Will there be concrete encased rebar? It's vital to ensure rebar ties are connected securely, continuity confirmed, and pigtails left for connection to the ground grid prior to pouring the concrete. If this step is missed during design prior to pouring, the Ufer ground continuity can be confirmed if construction is still in progress and there is rebar sticking out at multiple ends (for example from rebar points A to B as illustrated in Fig. 1), however corrective measures cannot be taken after the concrete has been poured if there are sections that are not continuous. If possible, consider connecting copper to the rebar in a few areas to provide a better connection and leave copper pigtails out to connect to the rest of the grid/ground rods. Continuity can also be tested by measuring from pigtail points C to D as shown in Fig. 1.

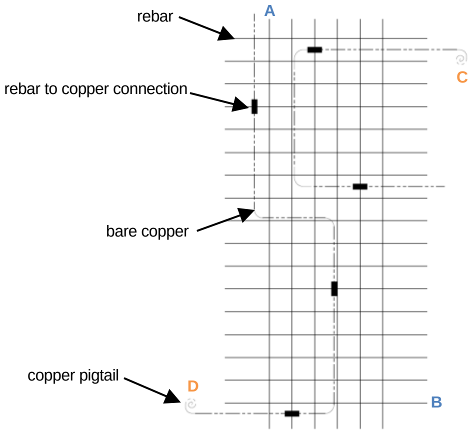

Fig. 1 Ufer Ground – Rebar and Copper Connection

E. Earth Works

The civil/structural designer should be involved when initially planning the design and throughout all design stages thereafter. Often times, the civil or structural designers are not notified of the ground grid design until the last minute which causes inconsistency with earth works, surface materials, and often a ground connection point is not indicated for the piles (which are Ufer grounds).

In areas where the water table is high, concrete foundations/footings may be lined with a vapor barrier. In this case, that portion of the Ufer ground cannot be considered as part of the grid as it is not making direct contact with the earth. Similarly, certain areas will be lined with geotextile liners. If the sides of the footing are making contact with the soil, one can consider this part of the electrode as part of the grid. Rebar can also be coated with non-conductive materials such as epoxy which can affect continuity. The concrete and rebar forming the Ufer ground electrode should be sized adequately to handle the available fault current as required by the Canadian Electrical Code (CEC) [4] and the National Electrical Code (NEC) [5].

III. MEASURING THE SOIL RESISTIVITY

Prior to investing time in creating the design drawings and software model, it is key that the soil characteristics are known as this will dictate the basis of the design and analysis. Utilizing soil resistivity results from previous projects in the area should be avoided as the soil resistivity can change drastically within a geographic region. If possible, the engineer should advise the project to coordinate geotechnical testing and soil resistivity testing so they can be conducted at the same time.

The benefit to this being if any anomalies are seen in the soil resistivity test results, it can be compared with the bore hole soil layer data from the geotechnical report. It can then easily be determined if this aligns with the soil characteristics or if a re-test is required. The bore hole data from the geotechnical report will also give insight into the deeper soil layers along with other soil characteristics such as the water table, moisture content, and what types of sediments make up the soil in the area. This information will be valuable during the design and modeling phase of the ground grid.

In the early stages of design, contingencies can be planned for and it can be determined whether deeper ground rods, deep ground wells using bentonite, Ufer ground, grounding additional piles etc. will be the most effective in reducing the grid resistance. This can help give the project a heads up and save from costly modifications once materials have been installed or even lengthy changes to detail design drawings in the later stages. The designer should also specify that the geotechnical report must indicate the frost depth which is required to create the winter case model. Both winter and summer case models should be taken into consideration when determining the worst-case scenario.

The designer should sketch the desired traverses on either the site layout/plot plan or a satellite map. Ideally this should focus on the location of the substation. A minimum of two traverses should be taken per area, 90 degrees from one another. If the plant facility is a significant distance from the substation, two sets of tests should be completed. The designer should communicate with the personnel conducting the test and ensure measurement pins are inserted to their full depth, if possible, and measure as far out as possible. Test equipment shall be industrial grade and suitable for the application requirements. The designer should review the results while the crew is still on site and determine if a re-test is required immediately. This will save time and avoid multiple trips. If the test area contains a hill, do not go up or down the hill, rather go laterally across the hill, otherwise results will be skewed.

To avoid receiving artificially good results, do not test after heavy rain fall or in times such as early spring where the ground is saturated with water. Conversely, testing during winter when the ground is frozen will lead to very high soil resistivity results. Summer yields for the most accurate results. Designing and modeling the ground grid using soil resistivity results from when the ground is saturated with water will lead to troubles, as the measured ground grid resistivity will be higher than predicted. This leads to modifications after all materials have been installed and commissioned and would now mean dealing with rework.

IV. Ground Potential Rise (GPR)

Per Rule 36-304 (1) of CEC [4], the maximum allowable GPR is 5,000 V however this may differ in each province, territory or state. The Utility or local authority having jurisdiction may have an allowable limit that is either lower or higher than 5,000 V. This is because GPR does not affect personnel safety but does damage communication and sensitive equipment. Touch and step potentials are the values calculated to ensure personnel safety. In areas where all copper cables have been converted to fiber optic, the allowable limit of GPR will be much higher or may be eliminated altogether. Where ground grids are being installed in very difficult conditions, such as bedrock or sand, it is important to discuss communication equipment details with the Utility, local authority having jurisdiction and communication provider. If all cables have been converted to fiber optic or the insulation levels of the communication equipment allow for a higher limit, a deviation can be granted due to unrealistic design conditions. This is also noted in CEC Rule 36-304 (1) “however in special circumstances where this level cannot be reasonably achieved, a higher voltage up to the maximum insulation level of the communication equipment shall be permitted where a deviation has been allowed in accordance with Rule 2-030.” [4].

Two factors affect the GPR, the available fault current and the grid resistance. To optimize the use of ground electrodes, rather than first focusing on reducing the grid resistance, first determine what the available fault current would realistically be by applying the split factor, as discussed in Section V. Particularly in difficult design conditions, the grounding software may present a GPR value that exceeds the system line to ground, or even phase to phase voltage which is not possible. In fact, as discussed in IEEE 367 [2], under unusual circumstances a GPR of 25 kV is possible however, most values are less than 10 kV. If the ground grid resistivity has been tested accurately and is confirmed to be very close to the analysis results, there is only one variable remaining which is the grid current (as we know the grid resistance and soil resistivity are accurate). The spilt factor needs to be calculated in further detail, as discussed in Section V.

V. CALCULATING THE SPLIT FACTOR

A. Data to Request

The split factor will be one of the important factors in determining a realistic GPR, specifically when dealing with installation in bedrock or sandy/silty soil. This will also impact the step and touch potentials as the split factor determines the amount of current that will pass through the grid and how much will pass through alternate paths such as the overhead shield wire. If confirmation has been received from the Utility provider/owner that the overhead shield wire is to be connected to the ground grid, request the following information from the Utility provider/owner. If there are two lines coming into the customer substation (redundant feed), request the same information for each.

Note: for the purpose of this paper, overhead shield wire and neutral are used interchangeably.

1. Size of the overhead shield wire (AWG or circular mils).
2. How many distribution line or transmission line structures exist between the customer substation and source (Utility) substation?
3. The applicable Utility grounding standard which specifies the intervals in which the neutral is grounded and what the typical design is, such as a square grid with 4 ground rods, or just one ground rod. A reference from IEEE 367 [2] for these intervals is “majority of distribution lines have neutral conductors, typically grounded four times per kilometer,”.
4. If the distribution or transmission lines were built recently or are in progress, ask the Utility provider/owner to share their soil resistivity test results for the area of the transmission or power line structure grounding. Additionally, if the transmission or distribution ground grid resistance test results are available, these should also be obtained from the Utility provider/owner. On the other hand, the designer can request additional soil resistivity testing be done in this area if accessible.

If the above noted information cannot be reasonably obtained, assumptions can be made based on recommended practices which will be discussed in the following subsections.

B. First Calculation Method

The split factor is simply a ratio of the substation ground grid resistance to the equivalent system impedance, determining how much fault current will go through the customer substation ground grid vs. through the overhead shield wire back to the source and through the equivalent multi grounded neutral system, as depicted in Fig. 2.

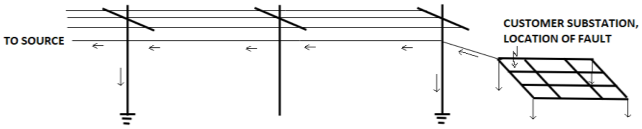

Fig. 2 Path of Fault Current with Overhead Shield Wire Connected

In this section it will become clear that several assumptions have been made to simplify the process for typical industrial substations. The simplification is justified as this provides a realistic split factor using practical engineering judgment. More detailed parameters can be used to produce custom calculations, however this involves a more detailed analysis and requires more time to gather the applicable data.

Safety factors are applied in several parameters, such as the fault clearing time and maximum grid current, hence the design of the substation ground grid is already conservative. The equation for computing the split factor from IEEE 80, Section 15.9 [1] is shown below:

$$S_f = \left|\frac{Z_{eq}}{Z_{eq}+R_g}\right| \qquad (1)$$

S_f	fault current division factor;
Z_{eq}	equivalent impedance of the Utility transmission and/or distribution ground;
R_g	substation ground resistance in Ω.

R_g is the grid resistance value that is obtained from the software model (or through hand calculations or a measured value). Z_{eq} is obtained from Table C.1 of IEEE 80 [1]. It is the impedance seen by the current passing through the overhead shield wire and through the transmission or distribution ground. A proportional amount of the current will flow back to the source and a portion through each transmission or distribution ground. The equivalent impedance neglects incidental impedances in the system, such as metallic pipes and railways etc. as explained in IEEE 367 [2]. Z_{eq} changes based on two factors; the number of distribution or transmission lines and the soil resistivity. Here is how Z_{eq} will be selected:

Step 1: Determine the number of transmission lines or distributed neutrals feeding the customer substation. In a typical industrial substation, there will only be one, or in cases where there is a redundant feed, there will be two. Select the appropriate row in Table C.1. It can be noticed that there is no row in Table C.1 with zero transmission lines and one distribution neutral. The previous version, IEEE 80-2000 [6], contained this case and can still be used as a reference. A second option is to apply a safety factor to the case where there is one transmission line and one distributed neutral. If enough data is available, the exact impedance can be calculated using the formulas provided in Section C.4 of IEEE 80 [1] or use the guidelines provided in Table 2 of IEEE 367 [2].

Step 2: Determine the transmission or distribution ground resistance. This can be done by modeling the ground grid (the typical grounding installation should be available from the Utility's standards). This may consist of one ground rod or several ground rods connected with a copper loop. Model this grid in the appropriate soil resistivity. If the results are $R_{tg} \leq 15$ or $R_{dg} \leq 25$ use column three of Table C.1. If the results are $15 < R_{tg} \leq 100$ or $25 < R_{dg} \leq 200$ use column four of Table C.1. If the structure ground grid resistance is significantly exceeding the values shown in column four, a reasonable safety factor can be applied using engineering judgement or can be hand calculated as discussed in Step 1.

If sufficient data is not available regarding the distribution system, IEEE 367 [2] Sections 5.6.1, 5.6.2, 5.6.3, and 5.7 provide details regarding the configuration and neutral impedance (in North America) for a typical Utility distribution line, which would be applicable to the locations in which most industrial substations are installed. In Section 5.7 of IEEE 367 [2] the following is noted, "the grounding of a pole would be defaulted to 25 Ω, since most power utilities are required to drive in as many ground rods to ensure the grounding at the distribution poles are 25 Ω".

The first method is applicable to many installations and is also practical, such that it does not require an extraneous amount of data or calculations. If the resultant GPR is exceeding the system voltage using the calculated spilt factor, a second method of calculation can be utilized. This method will require more effort but is still realistic to calculate.

C. Second Calculation Method

The second calculation method is discussed in IEEE 367 [2]. All the equations will not be re-iterated here from the standard as this section will discuss how to apply the standard to calculate the split factor. The method utilized in IEEE 367 [2] revolves around the application of a multigrounded neutral network in distribution (or transmission) systems, where the same neutral conductor is grounded multiple times at varying intervals [2]. The neutral conductor will be grounded at several distribution poles throughout the lines, as well as at other customers' ground grids. Other customer ground grids however will not be taken into consideration in these calculations. In order to apply this calculation method, it is crucial to first determine that the line is sufficiently long [2]. This is determined by satisfying the following inequality from IEEE 367 [2]:

$$\ell\sqrt{Z_s/Z_p} > 2 \qquad (2)$$

ℓ	total length of line in mi or km;
Z_s	the per-span self-impedance of the overhead ground wires in Ω;
Z_p	the per-span tower (pole) footing impedance in Ω.

As previously mentioned, Z_p will typically be 25 Ω for most power utilities. However, if there is knowledge of the specific network and it is known that the line is connected to many other customer ground grids and the line is grounded a minimum of three ground electrodes per kilometer [2], Section 5.6.2 of IEEE 367 [2] can be used to calculate the new Z_p, the parallel impedance of the combined contribution of ground rods and customers' ground per span.

For a sufficiently long line, the ground grid current split is calculated using the following equation from IEEE 367 [2]:

$$I_e = \frac{I_c}{Z_{sg} \cdot Y_p} \qquad (3)$$

$$Y_p = \left(\frac{1}{Z_1} + \frac{1}{Z_{sg}}\right) \qquad (4)$$

$$Z_1 = Z_\infty$$

I_e	ground grid current split;

I_c	the conductive component of fault current;
Z_{sg}	ground grid impedance in Ω;
Y_p	admittance matrix Ω;
Z_1	equal to Z∞ assuming there is only one sky wire;
Z_∞	sky wire impedance;

There are many intermediate equations associated with the above, throughout Section 5 of IEEE 367 [2], which the user must understand prior to applying this method. These may seem very complicated and intimidating at first, however IEEE 367 [2] provides an example calculation in Annex H which makes it very simple to understand. In addition, if information is not available through the Utility, IEEE 367 [2] provides very clear guidelines on which value(s) can be used for each parameter based on a typical system in North America.

The major difference in this calculation method is that the actual line length, line specific span, exact footing impedance and overhead shield wire size/impedance are taken into consideration. This provides a more accurate calculation specific to the substation and line configuration. If the line is very long and consists of low impedance tower footings, the split factor calculation will reflect this in the sense that more current will flow through the multigrounded network.

VI. MODELING

A. Soil Layers & Surface Material

To correctly model the two soil layers, identify at which depth the soil resistivity has a significant change. The first layer will be an average of the soil resistivities up to and including this depth, the second will be an average of the depth below this. Often times, we are limited to software that only has a two-layer soil model. In some cases, the soil resistivity results may have a second drastic change within the soil layers. This would indicate there is a third layer of significantly lower resistivity. Options that explore if deeper ground rods or deep ground wells are effective, should be analyzed. In this case, set up three models. These three models will provide a preliminary analysis which will allow the designer to recommend if deep ground wells will be an economically feasible solution. The recommendation should include that the final model and deep ground well design be analyzed using a software that allows for more than two soil layers.

1. The first model should utilize the first and second soil layers which will provide a comparison of what the step and touch potential, and GPR would look like with standard length ground rods. The first model will also be used to report the tolerable step and touch potential values, as this provides the interaction profile between the surface layer and first layer. As can be seen in the following equations from IEEE 80 [1], the tolerable step and touch potentials only change based on the first soil layer resistivity, the fault duration, and the thickness of the surface layer. The tolerable values will not change with the use of a more complex software or with the ground grid design.

$$E_{step50} = (1000 + 6C_s \times \rho_s)\frac{0.116}{\sqrt{t_s}} \quad (5)$$

$$E_{touch50} = (1000 + 1.5C_s \times \rho_s)\frac{0.116}{\sqrt{t_s}} \quad (6)$$

E_{step}	the tolerable step voltage in V;
E_{touch}	the tolerable touch voltage in V;
C_s	the surface layer derating factor;
ρ_s	the surface material resistivity in Ω-m;
t_s	the thickness of the surface material in m.

$$C_s = 1 - \frac{0.09\left(1-\frac{\rho}{\rho_s}\right)}{2h_s+0.09} \quad (7)$$

ρ	the resistivity of the earth beneath the surface material in Ω-m;
h_s	the duration of the shock current in seconds.

2. The second model should utilize the first soil layer and third layer to provide a good idea of what the step and touch potentials and GPR would be with deeper ground rods or deep ground wells. The second model provides a good understanding in how the electrodes interact with the higher resistivity layer to lower.
3. The third model will model the grid buried in the second soil layer and the third layer being modeled as the "second layer" in the model. The purpose of the third model is to ensure there is a significant enough change between the second and third soil layers, such that the current does not resonate in the second layer and rather is re-directed through the electrodes deeper into the ground away from the surface. The third model will also provide a realistic value of the grid resistance, as the ground rods will be mostly in contact with the second and third layers (dependent on the soil layer and rod depth).

By comparing these three models, a recommendation can be made regarding the effectiveness of deep ground wells or increasing the rod length. Often times, the first question asked by the client would be "how much would the results improve if we move forward with this recommendation and what additional materials and construction will be required?". This allows the designer to quantify the recommendation and ensure it will be effective prior to investing further into the design. Simply averaging the second and third layers would not portray whether the ground rods would re-direct a significant portion of the current away from the more shallow layers into the deeper layers.

Care should be taken where there are extended concrete pads, which personnel can step on, between washed crushed rock and concrete. Concrete can be quite conductive and when reinforced with rebar, even more so. Ensure the concrete pad either does not protrude enough to use as a step between the two surfaces, or such that a person can have both feet on the concrete pad simultaneously while performing any type of maintenance etc., since a potential difference can be created between the two materials creating a step potential hazard. The two different scenarios can be modeled, one with concrete as the surface layer and another with crushed rock; then assess if the tolerable step potential is sufficient against the calculated step potential. When modeling the concrete pad, concrete's resistivity should be entered as the surface layer as well as the first layer (equal to the total thickness of the pad), then conductors should be placed close together near the surface to represent the rebar, this will create an equipotential surface, which will mitigate the step potential providing a more realistic value.

In summary, it is important to assess each scenario and take a realistic approach to illustrate that many of these items that may at first seem like a hazard, will not pose a real danger if modeled correctly.

B. Ground Grid

1) *Optimizing Use of Copper & Modeling Ufer Grounds*

To optimize the use of copper, the designer should take advantage of all ground electrodes available. In the application of industrial substations and plant facility station area, heavy equipment requires the use of structural piles. Buildings require concrete rebar enforced footings and structural steel. These should be taken advantage of as they function as great ground electrodes. An advantage of utilizing piles (both concrete and steel piles) is that they often have a depth greater than a standard ground rod and hence act as deep ground rods. Per IEEE 142 [3], each footing's electrode has a resistance equal to, or lower than, that of a driven rod of equal depth. When using structural members as ground electrodes, the designer should ensure that grounding of any piles or footings is communicated to the structural engineer to ensure the rebar is sized for the available fault current, which will prevent the concrete from getting damaged or exploding. The current carrying capacity of building rebar is given in Table 4.7 of IEEE 142 [3].

When dealing with ground grid installations in bedrock, concrete encased electrodes should be the first option considered. As discussed in IEEE 142 [3], concrete encased steel rods have been found to be greatly superior than other electrodes in very rocky soil or in bedrock. This is essentially a concrete pile or footing.

While modeling a pile within a grounding software is quite straight forward, as a ground rod of equivalent depth, what is the most effective way to model concrete footings? Modeling the footing as a single ground rod in the software may not reflect the true step and touch potential profiles. Instead, model the rebar strands as #2/0 AWG copper wire, along the depth and width of the footing. Fig. 3 below shows a sketch of how this would look in the model. Concrete encased rebar often portrays an equipotential plane (depending on the gap between each rebar strand).

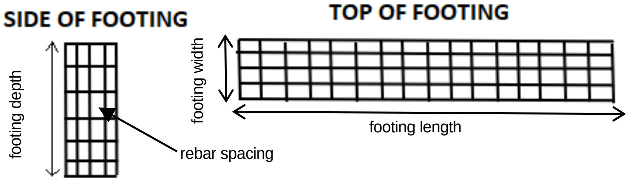

Fig. 3 Modeling of a Concrete Footing

This will result in a much lower step potential and may also somewhat lower the touch potential. This allows the user to model the full surface area of the concrete reinforced rebar and will achieve much more realistic step and touch potential profiles along with a modeled grid resistance that will be very accurate against the measured, especially when dealing with installations in bedrock. In reality, using 4/0 AWG copper vs. 2/0 AWG copper will make a difference, however in the software world these parameters often will not make a huge difference. Prior to modeling, the user should experiment changing parameters to see how much the result is affected. It is important to ask the software Vendor about these parameters and to understand limitations of the software. Engineering judgement must be used when creating grounding models as it is nearly impossible to model all real-world characteristics.

2) *Realistic Approach to Modeling Interconnected Grids*

a) *Interconnected Substation Grids*

When modeling interconnected substation ground grids, first check with the software Vendor to determine the distance at which the grids are automatically considered to be connected. For instance, when modeling an insulated copper cable connection between the substations, the software may just consider the grids to be connected if they are less than a certain distance apart.

In some cases, the step or touch potential may be showing as exceeding in the areas between the grids because the software is not seeing the cable as insulated. In these cases, where the step and touch potential is showing to be high between the grids, use the contour plot view to check where the step and touch potentials are high within the vicinity of the grids rather than in between. Check which areas they are high in, then export numerical data of the step and touch potentials. From the contour plot one may immediately see that the step and touch potentials in the grid areas are acceptable. If it is borderline, or there are some areas exceeding, export a detailed report/table of step and touch potentials for all coordinates of the model. This is required as with most software, the standard analysis results just state the maximum step and touch potentials within the overall model. Determine between which coordinates the grid lies within and check the maximum step and touch within that area.

When modeling interconnected grids over a vast area, if the touch potential is showing to be high in an area outside the grid, question if there are any metallic objects to touch and if there are any real hazards. If there is nothing to physically touch, again revert to the contour plot to analyze the step and touch potentials that affect personnel.

b) *Interconnected Substation & Station Grid*

Where there is a substation and station plant facility area present, it is nearly impossible to isolate the two ground grids. Even if a direct connection is not made, they will be interconnected through equipment such as cable sheaths and shields.

The station plant area often does not utilize washed crushed rock as a surface layer. Stations often simply utilize pit run gravel. Furthermore, much of the native soil in the station area will be backfilled with pit run gravel. In this case, details need to be gathered regarding to what depth will be back filled. Pit run gavel will then become the surface layer and may also become the first soil layer if this is the material in which the ground grid is buried.

A duplicate model should be created for the station area, with the above noted surface layer (pit run) and first soil layer changes. The maximum tolerable step and touch potential levels will be different than in the substation due to the change in surface layer from washed crushed rock to pit run gavel. Most software do not allow multiple surface layers to be modeled, hence this must be analyzed through two models. Contour plots can again be utilized along with exporting a detailed report to determine the maximum step and touch potentials in the substation and plant facility station area separately.

Utilizing equipment piles as ground electrodes within the station will be extremely beneficial, as the deep piles will be able to penetrate to the deeper lower resistivity soil layers since quite a bit of native soil has been replaced with pit run gravel. Burying copper in pit run gravel will not be very effective for lowering the ground grid resistance. Hence, if an insulated copper conductor is already installed within a cable tray around/near equipment, consider using this as the ground grid which forms a loop around equipment to be grounded. This will optimize copper use as the bare copper which would have been buried in pit run gravel around the equipment will minimally affect the grid resistance. Cable tray can be used as the bonding conductor to interconnect the copper pig tails from the piles to the copper conductor installed within the tray. However, care must be taken in the design to ensure the grounding installation meets CEC [4] or NEC [5] requirements as applicable. The main ground electrode will be the piles, along with the perimeter conductor and ground rods around the boundaries of the station area where required. If touch potentials are showing to be very high along the perimeter fence of the station area, consider introducing a small amount of washed crushed rock on either side of the fence or substituting that specific portion of the fence with nonconductive fence material. This may be more effective than the addition of ground rods in pit run gravel.

Table 4-2 of IEEE 142 [3] and Table 7 of IEEE 80 [1] can be used to determine the typical resistivity of pit run gravel. Use engineering judgement by assessing how much soil/silt/sand is mixed with gravel and how large the gravel size is, such as #2, #3, #4, #57 etc. Typically, values of 800-1500 Ω-m are seen, however this can vary vastly depending on the material composition.

VII. GROUND GRID INTEGRITY

Installation and testing of the ground grid would ideally be a multi-phase process. Ground grid connections should be inspected and a point to point test should be conducted to confirm the continuity of the ground grid prior to backfilling. Situations where the grid is lacking continuity, or poor connections are seen, can easily be corrected as the grid has not yet been buried. The depth of the ground grid conductors should also be confirmed at this time to ensure the depth is as specified on the engineering construction drawings.

If time and project coordination allow, the ground grid resistivity should be tested once all the ground rods and copper conductor have been installed but not yet backfilled. This will provide a good idea as to what the final grid resistivity will be. If the grid resistance is much higher than what is forecasted, solutions such as the addition of ground rods or addition of more copper can be implemented at this stage, which is much easier than when rough grading and final grading are complete. The grid resistance should then again be tested once the grid has been buried.

Construction notes on the engineering construction drawings must specify that the grid area is required to be backfilled with native soil (both on the civil and electrical drawings). The note should mention if this cannot be achieved, work must be halted and engineering must be contacted for further direction. The engineering drawings must also specify what the tested grid resistance shall be and the required resistance of the surface material. Note also that the test results are required to be sent to the engineering department so the designer can verify the integrity of the installation and hence ensuring personnel safety.

When performing testing of the grid resistance, if the fall of potential test method is being utilized, ensure an instrument is selected that allows for a sufficient test distance. As industrial substations are large in size, it is crucial the testing be performed to the proper distance otherwise results will be skewed and inaccurate. If there are metallic underground pipes, this can also skew test results. Underground infrastructure should be confirmed prior to testing if possible. When testing in a highly congested area or an area with underground metallic infrastructure, the right test method should be selected. This can be discussed with the manufacturer of test equipment to determine which method will suit the specific locations needs. Testing in winter should be avoided as the grid resistance may not be accurately portrayed and the test results will indicate a grid resistance much higher than what it actually is.

VIII. STEP AND TOUCH POTENTIALS

When addressing high step and touch potentials, one of the simplest methods is to increase the surface layer depth or change to a higher resistivity material to increase the tolerable step and touch limits. The professional engineer must indicate the required washed crush rock resistivity in both the report and engineering construction drawings and indicate that it must be tested to confirm the value meets or exceeds, prior to installation.

Changing the depth of the ground grid changes the calculated values considerably. When faced with high step and touch potential levels, try setting the ground grid to a shallower depth. In fact, Rule 36-302 of the Canadian Electrical Code [4] limits the depth of the ground grid to ensure a dangerous potential difference is not created. Bare copper shall be buried to a maximum depth of 600 mm below rough grade (the first soil layer) and a minimum of 150 mm below finished grade (the surface layer). It is crucial that the exact burial depth used in the study be specified in the engineering construction drawing otherwise the calculated step and touch potentials would be invalid.

For small substations, such as a unit substation, in a geographic location where the substation is situated in bedrock, even if the GPR is acceptable with effective use of a split factor, the step and touch potentials may be exceeding. This is due to the soil profile, where the soil layers (bedrock) have a higher resistivity than the surface material of washed crushed rock. Two options may be deployed. First would be to utilize an extremely high resistivity surface material such as larger diameter rock or asphalt, however asphalt should only be used where it is known that the area beneath will not have to be accessed in the near future as it is not easy to excavate. The second is to decrease the grid spacing between conductors to simulate an equipotential plane. This option is only economically feasible for small substations, as more copper is required.

The industry standard for an industrial substation ground grid resistance is still commonly known to be less than 1 Ω or between 1 Ω to 5 Ω, even though this recommendation has been removed in the latest revision of IEEE 80 [1]. A low grid resistance should be achieved where possible to provide the fault current with a low resistance path to ground, however this may not be practical in sandy areas or where there is bedrock. The focus should not be on decreasing the grid resistance, but rather on personnel safety, by ensuring the step and touch potentials are within tolerable limits.

The actual fault duration should be determined by assessing the protective device time current curve against the available fault current, rather than using the industry standard of 0.5 seconds. The actual clearing time may be significantly lower or higher than 0.5 seconds, which will affect the tolerable step and touch potential limits. The upstream protective device settings should be requested from the Utility provider/owner to determine this. The application of a safety factor to the clearing time should be assessed by the designer based on the guidance provided in IEEE 80 [1].

IX. REVERSE MODELING OF EXISTING GRIDS

Where there is an existing ground grid with no existing engineering drawings, no existing soil resistivity results, and no grid resistance test results, some reverse engineering will be required to assess the grid. Assessment of an existing ground grid may be required as part of a maintenance program or due to substation expansions.

A. Data Gathering

Prior to beginning any modeling, a point to point test needs to be conducted throughout the substation ground grid to confirm that the grid is still continuous. Older ground grids, especially those situated in corrosive soils or near saltwater, may experience erosion over time. Next would be to measure the soil resistivity and ground grid resistivity. Photos of the surface material should be gathered so the designer can use engineering judgment to assess what the resistivity is, based on the size and condition (for example if the crushed rock is kept free of snow, weeds, dirt etc.). A measurement of the substation perimeter should also be taken to determine the dimensions of the ground grid. Inspect whether the Utility overhead shield wire is connected to the customer ground grid to assess if a split factor can be used.

B. Modeling & Analysis

Using the information collected, model a ground grid based on industry standards. Begin with a grid spacing of 3m – 4m (9.8ft – 13.2ft) and place 3m x 19mm (9.8 ft x 0.75 in) ground rods around the perimeter 6m apart, and a few throughout the inside of the grid, focusing on where the major equipment such as the transformer and breakers are placed. Continue to increase/decrease the grid spacing and number of ground rods until the modeled grid resistance matches the measured.

To assess the step and touch potentials, the grid burial depth should be varied, for example between 100mm to 600mm (3.9 in to 23.6 in), to determine the worst-case scenario. If any step or touch potential hazards exist, consider increasing the thickness of the surface material which can be less invasive than expanding the ground grid or adding ground rods. If step and touch potential concerns exist at a certain depth, but not at more shallow depths, consider uncovering a small portion of the grid to confirm the existing burial depth, if practical. Another option would be to install a remote ground grid and connect it to the existing ground grid using insulated copper conductor to ensure no step or touch potentials are created in the area between the grids. This option avoids extensive rework, hydrovacing, and minimizes disruption to the substation. This can also help reduce the GPR if required. If the area required for the remote grid is not available, the design should focus on adding rods along the perimeter of the grid (and vary the length of the rods to improve results if required) as this minimizes disruption around major equipment in the substation and hence reduces the risk of damage.

If the step and touch potentials are within the tolerable limits, but the GPR is exceeding the acceptable limit per CEC [4] or as specified by the local standards, consider first speaking with the local authority having jurisdiction to check if a deviation can be approved as this is an existing installation and considerable re-work would be required.

X. CONCLUSIONS

In summary, with the application of sound engineering judgement along with IEEE 80 [1], IEEE 367 [2], and IEEE 142 [3], a practical and efficient design can be achieved that focuses on personnel safety. Calculation of the split factor will ensure a realistic GPR value and will optimize the use of ground electrodes, specifically in rocky/sandy soil. Copper can be optimized by utilizing available Ufer grounds such as piles and footings. The soil characteristics should be well understood prior to beginning the design, as this will dictate the basis of the ground grid design.

Limitations of software should be well understood prior to beginning any modeling. Several models may have to be simulated to obtain the equivalent conditions to those on site, such as modeling separate surface layers within the substation and plant facility area.

Clear direction on engineering construction drawings and performing inspections during construction will ensure the integrity of the ground grid and will avoid costly re-work once the grid has been buried and the surface material is installed. In summary, pre-analysis, planning, and understanding real world conditions are the key to optimizing ground grids.

XI. REFERENCES

[1] IEEE 80-2013, *IEEE Guide for Safety in AC Substation Grounding*, New York, NY: IEEE.

[2] IEEE 367-2012, *IEEE Recommended Practice for Determining the Electric Power Station Ground Potential Rise and Induced Voltage from a Power Fault*, New York, NY: IEEE.

[3] IEEE 142-2007, *IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems*, New York, NY: IEEE.

[4] CSA C22.1-18, *Canadian Electrical Code, Part I*, Toronto, ON: CSA.

[5] NFPA 70, *2020 National Electrical Code (NEC)*, Quincy, MA: NFPA.

[6] IEEE 80-2000, *IEEE Guide for Safety in AC Substation Grounding*, New York, NY: IEEE.

XII. VITA

Amnit Dhindsa graduated from the University of Alberta in 2014 with a Bachelor of Science in Electrical Engineering degree. She currently works for BC Hydro and previously comes from a background of consulting and operations. At the time of authoring this paper, she was with the Liquid Pipelines Operations Engineering team at Enbridge. She has also previously co-authored another paper on the topic of potential ignition sources in electric rotating machines operating in explosive gas atmospheres for IEEE PCIC. She is a registered professional engineer in the provinces of Alberta and British Columbia.