DESIGNING SAFE AND RELIABLE GROUNDING IN AC SUBSTATIONS WITH POOR SOIL RESISTIVITY: AN INTERPRETATION OF IEEE STD. 80

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Abstract – IEEE Std. 80 "IEEE Guide for Safety in AC Substation Grounding" is most commonly used in the design of substation ground grids and is the basis for today's commercially available software. This paper discusses alternate design approach for substation grounding in areas that have high soil resistivity. It discusses various methods for designing a substation grounding system without changing the characteristics of the soil with additives or adding ground wells to establish a low resistance to remote earth. An interpretation of the equations and a better understanding of the IEEE Std. 80 allows the engineer to provide a cost effective, safe and reliable grounding system design when poor soil conditions exist.

Index Terms — Ground Potential Rise, Split Factor, Grid Resistance, Touch Potential, Step Potential, Resistivity, Ground Rod, Ground Grid Design

I. INTRODUCTION

One of the major contributing factors in the design of grounding in AC substations is the soil resistivity and the effects it has on both the ground potential rise in and around the substation as well as the influence it may have on system protection. In general, the lower the impedance of a substation ground grid with respect to remote earth, the better it is. However in some instances where the soil resistivity is very high, the ability to attain low ground grid resistance may be difficult and costly.

The generally accepted practices to reduce the ground grid resistance include adding soil enhancing materials, using close grid spacing, and installing deep ground wells in an attempt to provide a low impedance path to remote earth. While the benefits of closer grid spacing on the grounding system performance can be calculated with a good degree of accuracy, the effects of ground enhancing material and ground wells on the grounding system are more ambiguous. This may result in a costly design, perhaps with little gain.

This paper focuses on the design of AC substation ground grids with very high soil resistivity. It also explores the fact that it is possible to design a ground grid system that has a relatively high resistance but is also safe for equipment and personnel.

II. ELEMENTS OF GROUND GRID DESIGN

The design of a safe grounding system seeks to make, "the magnitude and duration of the current conducted through the human body…less than the value that can cause ventricular fibrillation of the heart." [1:13] If the effective resistance of a human body is assumed constant, then there are two methods to ensure that the criterion listed above is met:

1. Decrease the touch or step voltage the body can be subjected to. This can be achieved by either limiting the grid current or reducing the grid resistance.
2. Decrease the amount of time to clear a ground fault, which can be used by fast tripping of a protective device.

Understanding these two major criteria, the remainder of this section discusses the various parameters that must be considered for a ground grid design. For illustration and discussion purposes and unless otherwise stated, the following constants are assumed:

$\rho_{soil} = 600\ \Omega \cdot m$	soil resistivity
$\rho_s = 3{,}000\ \Omega \cdot m$	surface material resistivity
$h_s = 4\ in$	surface material depth
$C_s = 0.754$	surface derating
$t_s = 1.00\ s$	fault clearing time
$S_f = 1.0$	split factor

A. Ground Potential Rise

In designing a safe and reliable ground grid in high resistive soil it is necessary to discuss ground potential rise. Ground Potential Rise (GPR) is the maximum electrical potential a grounding grid may attain relative to a distant grounding point assumed to be at the potential of remote earth [1:23]. GPR is proportional to both the current flowing in the ground grid and the equivalent grid impedance as shown in the following equation:

$$GPR = I_f * R_{grid} \tag{1}$$

Where,

I_f	is the total fault current
R_{grid}	is the ground grid resistance to remote earth

Equation (1) assumes that the entire fault current is flowing through the ground grid ($I_f = I_{grid}$) to remote earth (Figure 2). If a substation is supplied from an overhead line with no shield or neutral wire the total ground fault current enters the earth causing an often steep rise in the local ground potential. [1:8] The primary way to limit the GPR in such a case is to create a ground grid that has a very low resistance to remote earth. Limiting the current flowing in the ground grid also lowers the GPR. The use of a shield wire or neutral provides an alternate path for the ground fault current to flow to the source instead of the earth. A split factor is added as shown in equation (2) to indicate the percentage of the ground fault current assumed flowing into the earth (Figure 3).

$$GPR = I_f * S_f * R_{grid} \quad \text{or} \qquad (2)$$
$$GPR = I_f * Z_g$$

Where,

S_f is the split factor

Z_g is the total equivalent ground impedance

The split factor will be discussed later in greater detail and has a significant impact on the allowable step and touch voltages and the grounding system design.

B. Allowable Step and Touch Voltage

To evaluate the allowable step and touch voltages the equations for a person weighing 50kg are used to offer a more conservative value. The calculation for step voltage is given by the following equation (3): [1:27]

$$E_{step50} = (1{,}000 + 6C_s * \rho_s)\frac{0.116}{\sqrt{t_s}} \qquad (3)$$

Where,

C_s is a function of ρ_s and h_s. It is a correction factor for computing the effective foot resistance in the presence of a finite thickness of surface material

ρ_s is the resistivity of the surface layer in ohm-meter

t_s is the duration of the shock current in seconds

The correction factor C_s is dependent upon the depth and resistivity of the surface material and the resistivity of the soil layer beneath the surface material. C_s provides a correction to the estimated resistance of a human foot in contact with the surface material and is used in both the calculations for allowable step and touch voltages. C_s increases as the surface material thickness increases. However, the effect of the surface material thickness diminishes greatly after approximately 12in (or 0.3m).

The higher this value of C_s, the greater is the allowable step potential before the body will absorb a critical amount of shock energy. [1:27]

Based on the above equation (3) the greater the resistivity of the surface layer, and the shorter the fault duration, the greater the step voltage must be to have an effect on the human body. Faults can be cleared in very short time periods depending on protective devices and relaying schemes. A fault clearing time of one second (a common design practice) is assumed to be on the conservative side. If the time is held constant at one second, the greater the surface soil resistivity is, the greater the allowable step voltage can be without causing a hazardous shock.

Allowable touch voltage uses a very similar equation to step voltage and is shown in equation (4): [1:27]

$$E_{touch50} = (1{,}000 + 1.5C_s * \rho_s)\frac{0.116}{\sqrt{t_s}} \qquad (4)$$

Again, if the fault duration time is held constant and the surface material resistivity is increased, then a greater potential rise may be present in the substation without causing a hazardous shock. Figure 1 shows the effects surface material resistivity on the allowable step and touch voltages for a fault duration of 1 second.

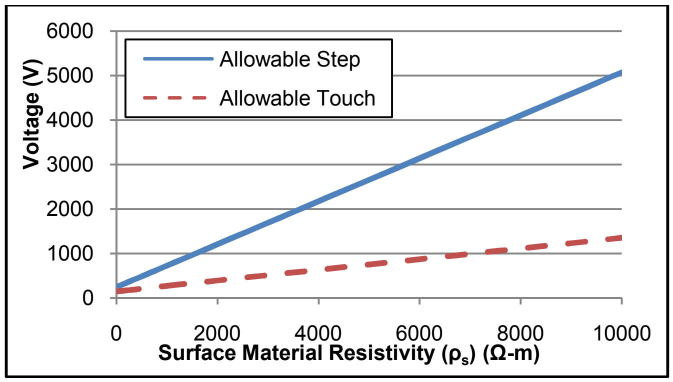

Figure 1 Effects of surface material resistivity on allowable touch and step voltages

C. Split Factor

The generally accepted practice, and in some instances a requirement of a ground grid, is to have a low impedance to remote earth (less than 1 to 5Ω). [2] However, as stated in IEEE Std. 80, "a low substation ground resistance is not, in itself, a guarantee for safety. There is no simple relation between the resistance of the ground system as a whole and the maximum shock current to which a person may be exposed." [1:8] Even though IEEE Std. 80 states that a low ground resistance is not in itself a guarantee of a safe ground grid, somehow it has become a standard practice in determining the acceptability of a ground grid.

In cases where a ground resistivity is high yielding a high ground grid resistance, the use of overhead neutral or ground wires can help alleviate the amount of fault current flowing through the ground grid. This is defined by the split factor (S_f).

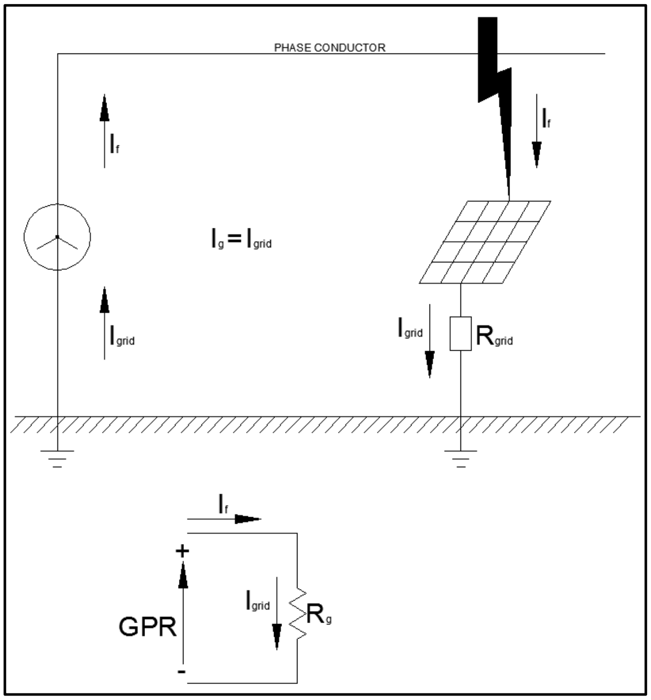

Figure 2 The grid current equals the fault current when no shields or neutrals are present. [1:9]

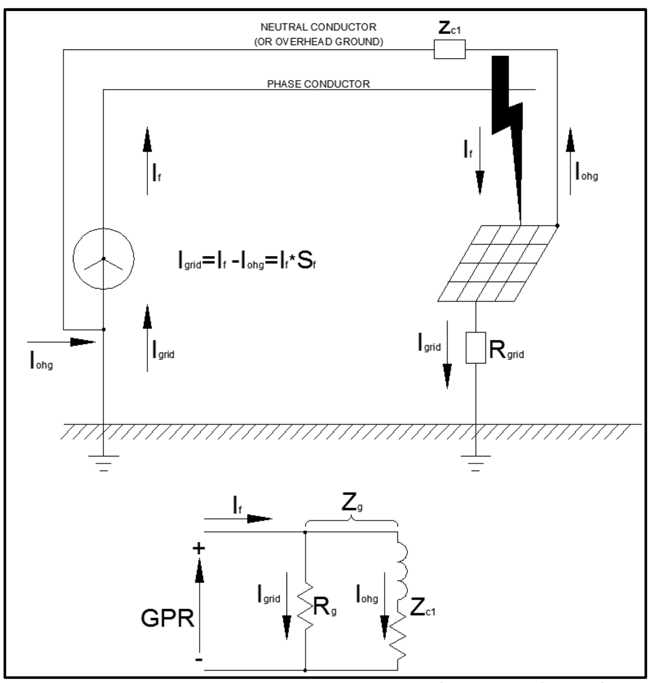

Figure 3 The grid current is only a fraction of the fault current when a shield or neutral is present. [1:9]

As depicted in Figure 3, part of the fault current (I_E) flows back over the overhead ground wire to the source, thereby reducing the grid current (I_{grid}) which will limit the step and touch potentials. It should be noted that the Ground Potential Gradient may be higher requiring additional equipment to isolate communication circuits and other devices that are not rated for the higher voltage levels. Applying the split factor should be used with caution, since it is very difficult to calculate the exact value. Various factors including shield wire resistance, number of shield wires, remote substation ground resistance, and pole footing resistance will all influence the amount of current flowing to remote earth and to remote grounding systems.

D. Single Layer, Two Layer, and Multi-Layer Soil Models

Many of the commercially available software utilizes multi-layer soil model. Single Layer soil model assumes a generally uniform and homogeneous soil resistivity and is calculated by using the arithmetic average of the measured soil resistivity data. The equation for this model is: [1:56]

$$\frac{\rho_{a(1)}+\rho_{a(2)}+\rho_{a(3)}+\cdots+\rho_{a(n)}}{n} \tag{5}$$

The single layer model does not provide good accuracy with large variations in soil resistivity measurements.

Two-layer soil model is represented by an upper layer uniform soil of a finite depth and a lower layer of uniform soil of infinite depth. As a compromise the two-layer soil model is often used for designing of grounding systems. These calculations are often sufficient, while a more accurate multi-layer soil model is rarely justifiable or technically feasible. [1:58]

A Multi-layer soil model is used when highly non-uniform soil conditions are encountered and requires complex computer programs or graphical methods and seldom used in the design. [1:64]

E. Surface Material

Surface material becomes very important when designing a substation ground grid in high resistive soil. A layer of crushed rock or other material has become the design standard to provide a high resistance between the ground grid and personnel. If the underlying soil has a lower resistivity than the surface layer then only a small amount of grid current will flow into the surface layer resulting in smaller potential rise in the surface material. Additionally, the resistance between personnel and the ground is increased, reducing the amount of current that may flow through the person to ground. [3]

Figure 1 shows the effects of surface material resistivity on allowable step and touch voltages. Figure 4 shows the effects of varying surface material depth on allowable step and touch potentials. As the figure shows, five inches of surface material provides the most cost effective benefit.

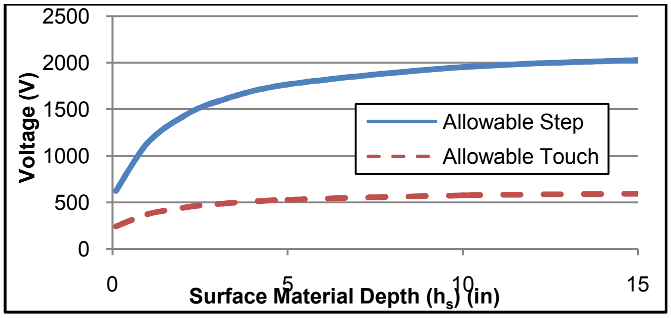

Figure 4 Effects of surface material depth on allowable step and touch voltages

III. TECHNIQUES FOR INCREASING GROUND GRID SAFETY

A. Traditional Methods

Traditionally, as it is mentioned before, the aim of ground grid engineers has been to lower the grid resistance, and thus minimize step and touch voltages during a ground fault. This is accomplished by one or more of the following methods:

1. Decreasing ground grid spacing
2. Installing additional ground rods
3. Using longer ground rods
4. Digging/drilling ground wells
5. Encasing the ground grid in concrete
6. Treating the soil with less resistive materials
7. Bonding the ground grid to foundation rebar

Except for the last option, these are all expensive solutions. Bonding to the rebar, however, potentially creates new issues such as corrosion of the rebar, damage to foundations during fault conditions, or the need for cathodic protection.

B. Current Division

While traditional methods seek to lower the grid resistance, an alternate solution, as discussed earlier, would be to decrease the amount of current flowing into the ground grid. Figure 3 shows that by having alternate paths, the amount of current flowing into the ground grid can be reduced. [4]

Most substations typically have incoming (or outgoing) lines with shield wires installed. It would be appropriate for the design engineer to investigate the properties of these shield wires and how they could affect current division as discussed in Annex C of IEEE Std. 80. [1]

In some instances, the calculated split factor may not be substantial enough to limit the grid current to a safer level. Some possible solutions to alleviate this include:

1. Upsize the transmission/distribution shield/neutral wires
2. Utilize aluminum shields instead of steel
3. Install shields on unshielded lines
4. Consider connecting to a satellite ground grid

Each of these methods must be carefully scrutinized and evaluated as they may result in hazardous voltage conditions at remote locations during a ground fault.

C. Surface Layer

From Figure 1 and Figure 4 above, it can be concluded that:

1. A minimum of 5 inches of surface material should be used.
2. Increasing the surface material resistivity linearly increases the safely allowable step and touch voltages.

A subset of IEEE Std. 80 [Table 7] is displayed in Table 1 below. It is apparent that by carefully selecting the surface material, the engineer can have a larger effect on the allowable step and touch voltages, even when wet.

Table 1 Typical surface material resistivities (A subset of IEEE Std.-80 Table 7) [1:52]

Surface Material (State where found)	**Resistivity (ohm-meter)**	
	Dry	Wet
#3 washed granite (GA)	2.6×10^6 to 3×10^6	10,000
Washed granite (0.75”)	2.6×10^6	10,000
#57 washed granite (NC)	190×10^6	8,000
Asphalt	2×10^6 to 30×10^6	10,000 to 6×10^6

D. Fault Clearing Time

Limiting the duration of a ground fault on the system also reduces the hazardous touch and step voltages. Figure 5 shows the benefit derived from decreasing fault clearing times below 0.1 second. The recommended practice, however, is to design a substation ground grid using the backup relaying clearing time of 1s. This is a conservative estimate that will not falsely elevate safe step and touch voltages. Installing high speed primary and backup relaying schemes will allow the engineer to lower this backup protection tripping time, thus having a significant, and relatively low cost, impact on designing a safe grounding grid.

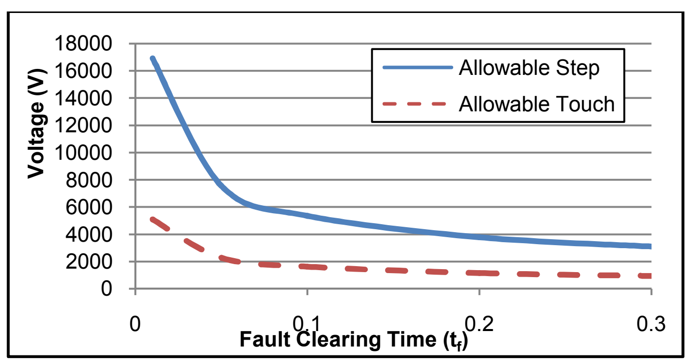

Figure 5 The effect of fault clearing time on allowable step and touch voltages

IV. AN EXAMPLE

A. Background

Consider an example of a ground grid design for a substation that was built on backfill from mine tailings consisting of large rocks and fines. The backfilled area utilized a retaining wall on two sides and was approximately 20 feet deep on average. The site itself was located in a mountainous region with a high concentration of granite near the surface. Due to the inconsistent backfilling, resistivity readings at the site were high and inconclusive. Using the data from the geotechnical report and reference material on standard soil resistivity it was estimated the soil had a resistivity of approximately 600 ohm-meters and the reported available ground fault current was 4020A. Following the calculations suggested in the IEEE Std. 80 the initial grid spacing and ground conductor sizes were determined. It was apparent that the design would require further investigation and perhaps, non-standard design principles.

Because of the poor soil resistivity, the basic design required a grid spacing of 6 feet and it would be very costly and difficult to install. Alternatives were investigated including tying all of the foundation steel reinforcement to the ground grid in hope that they would act as ground wells and reduce the grid resistance. However, the results of this approach were hard to quantify due to the inability to collect usable soil resistivity readings and may or may not have had the expected result. Because the results could not be verified until the grid was complete, and any rework would be costly as well as time consuming, the design was approached from another angle.

B. Higher Resistance, Safer Ground Grid

There have been several papers written by the mining industry to indicate that an acceptable design of a ground grid to be safe must have a resistance of less than 5 ohms.[2] [5] This recommended industry practice, along with the conditions described earlier required further investigation into the IEEE Std. 80 and the interpretation of what constitutes a safe and reliable ground grid.

Once the basic ground grid is designed it is possible to analyze the influence the grid resistance would have on the step and touch potential values. Table 2 was created using the estimated ground resistance values, R_g. Since measuring the grounding resistance of the shield wires leaving the substation was not reasonable, IEEE reference tables in conjunction with conservative estimates were used. The shield wire equivalent ground impedance ($\overrightarrow{Zc1}$=1.09+0.208i) from IEEE Std.80 Table C.1 [1] was used to calculate the equivalent total ground impedance (Z_g) using the equation:

$$\left|\overrightarrow{Z_g}\right| = \left|\frac{\overrightarrow{R_g}*\overrightarrow{Z_{c1}}}{\overrightarrow{R_g}+\overrightarrow{Z_{c1}}}\right| \qquad (6)$$

Once Z_g is calculated the GPR is found by using equation (2). The split factor (S_f) for the table is calculated using the equation:

$$S_f = \left|\frac{\overrightarrow{Z_{c1}}}{\overrightarrow{R_g}+\overrightarrow{Z_{c1}}}\right| \qquad (7)$$

I_{grid} for the table is calculated by dividing the GPR by the grid resistance R_g.

The calculated touch (sometimes referred to as mesh) and step voltages are recalculated using IEEE Std. 80 equations (8) and (9) below:

$$E_m = \frac{\rho * K_m * K_i * I_g}{L_m} \qquad \text{(Touch V)} \qquad (8)$$

$$E_s = \frac{\rho * K_s * K_i * I_g}{L_s} \qquad \text{(Step V)} \qquad (9)$$

Where,

ρ is the substation soil resistivity (assumed constant)

$K_{...}$ and $L_{...}$ are based on physical grid parameters (assumed constant). In our case, $K_s = 0.416, K_i = 3.21, L_m = 2646.0, L_s = 1995.8$

These step and touch voltages were then compared with the allowable values calculated by equations (2) and (3). It can be seen from Table 2 that as R_g increases, the step and touch voltages both decrease. This is a result of more current flowing back along the overhead ground wire rather than to remote earth or by the decreasing split factor, S_f.

Table 2 Calculated step and touch voltages as a function of grid resistance [assuming ρ_s = 600 ohm-meter]. Equations used for each column are referenced in the header.

R_g	GPR (V) (2)(6)	I_{grid}(A) (2)(6)(7)	S_f (7)	Step V (9)	Touch V (8)	
0.5	1384.02	2768.0	0.69	1111.23	1079.94	
1	2113.33	2113.3	0.53	848.40	824.50	ACCEPTABLE STEP AND TOUCH VOLTAGE RANGE
2	2866.44	1433.2	0.36	575.37	559.16	
3	3251.55	1083.8	0.27	435.11	422.86	
4	3485.24	871.3	0.22	349.79	339.94	
5	3642.11	728.4	0.18	292.43	284.19	
6	3754.67	625.8	0.16	251.22	244.14	
7	3839.36	548.5	0.14	220.19	213.99	
8	3905.40	488.2	0.12	195.98	190.46	
9	3958.33	439.8	0.11	176.56	171.59	
10	4001.71	400.2	0.10	160.65	156.12	
11	4037.90	367.1	0.09	147.37	143.22	
12	4068.55	339.0	0.08	136.11	132.28	
13	4094.85	315.0	0.08	126.45	122.89	
14	4117.66	294.1	0.07	118.07	114.75	
15	4137.63	275.8	0.07	110.74	107.62	
16	4155.27	259.7	0.06	104.26	101.32	
17	4170.95	245.3	0.06	98.50	95.72	
18	4184.99	232.5	0.06	93.34	90.71	
19	4197.62	220.9	0.06	88.69	86.19	
20	4209.06	210.5	0.05	84.49	82.11	
30	4282.96	142.8	0.04	57.31	55.70	

Note: Allowable step and touch voltages were previously calculated to be 3,116V and 902V, respectively

To further demonstrate the soil resistivity is increased to 2,200 ohm-meter. It becomes apparent that the higher the R_g the lower the step and touch voltages become.

Table 3 Calculated step and touch voltages as a function of grid resistance [assuming ρ_s = 2,200 ohm-meter]. Equations used for each column are referenced in the header.

Rg	GPR (V)	Ig (A)	Sf	Step V	Touch V	
0.5	1384.02	2768.0	0.69	4074.52	3959.76	
1	2113.33	2113.3	0.53	3110.80	3023.18	
2	2866.44	1433.2	0.36	2109.69	2050.27	
3	3251.55	1083.8	0.27	1595.42	1550.48	
4	3485.24	871.3	0.22	1282.56	1246.44	
5	3642.11	728.4	0.18	1072.23	1042.03	
6	3754.67	625.8	0.16	921.14	895.20	ACCEPTABLE STEP AND TOUCH VOLTAGE RANGE
7	3839.36	548.5	0.14	807.36	784.62	
8	3905.40	488.2	0.12	718.59	698.35	
9	3958.33	439.8	0.11	647.40	629.17	
10	4001.71	400.2	0.10	589.05	572.46	
11	4037.90	367.1	0.09	540.34	525.12	
12	4068.55	339.0	0.08	499.07	485.02	
13	4094.85	315.0	0.08	463.66	450.60	
14	4117.66	294.1	0.07	432.94	420.75	
15	4137.63	275.8	0.07	406.04	394.60	
16	4155.27	259.7	0.06	382.28	371.52	
17	4170.95	245.3	0.06	361.15	350.98	
18	4184.99	232.5	0.06	342.24	332.60	
19	4197.62	220.9	0.06	325.20	316.04	
20	4209.06	210.5	0.05	309.78	301.06	
30	4282.96	142.8	0.04	210.15	204.23	

Note: Allowable step and touch voltages were previously calculated to be 3,116V and 902V, respectively

C. Surface Material Considerations

As noted earlier, the depth and the resistivity of the surface material have a big effect in the design and the allowable step and touch voltages. Effects of different materials that could be used in a substation were investigated and it was found that asphalt has a very high resistivity (approximately 10,000 ohm-meters when wet [1:52]) which would greatly increase the allowable step and touch voltages. Asphalt would be much more expensive to install than crushed rock, however when compared to the cost of adding additional ground wells, trenching and burying more copper, or bringing in ground enhancing materials, asphalt becomes a viable option to improving substation grounding safety.

V. SYSTEM PROTECTION AND MAINTENANCE

A. Protection

As a part of the design of a substation ground grid in high resistive soil the protection scheme and the relay settings at the source should be studied and considered. With the addition of the overhead shield wire, a return path for ground fault current flow remains. However, the loss of the overhead shield wire will isolate the substation ground grid from the source and will either cause additional current to flow to the earth (which will occur under normal conditions) or the system could become effectively ungrounded.

The doubling of the overhead shield wire may be considered based on economics of additional shield wire, additional transmission structure cost, and installation cost. This would provide redundancy in the event one of the shields should fail. If a single shield wire is employed and the grid resistance to remote earth is high it may be necessary to install protective equipment at the source to be able to detect a ground fault on an ungrounded system. Auxiliary wye-grounded – broken-delta transformers can be used with line or bus PT's to alarm or trip for a ground fault if the overhead shield fails.

B. Maintenance

Although there are varying opinions on the topic of ground grid maintenance, one thing is clear: for a grid to properly protect personnel and equipment it must be designed to operate over the length of the installation. In order to ensure safe operation, integrity tests can be performed to verify that the conductor hasn't degraded. Two main reasons that conductors can degrade underground are acidic soil and dissimilar metals.

The first of such tests is a routine ground grid resistance measurement. This test is most accurate if using relatively high AC current (around 300A) injection in conjunction with a voltmeter. Simply, current is injected at a desired piece of equipment back to a known ground reference, usually a transformer neutral. The voltage measured divided by the current injected yields an effective grid resistance. Although it is beyond the scope of this paper, a thorough description of conditions and acceptable results is given in "Electrical Power Equipment Maintenance and Testing" [6].

Another method of verifying the safety of a ground grid is to periodically unearth a portion to spot check the integrity of the grounding conductor and joints. Although this more subjective method is not common and requires substantial work, it can be indicative of the grid's health as a whole. However, in the event that a material like asphalt is used to create a highly resistive surface, then the prospects of unearthing portions of the grid to inspect it are unlikely.

When considering maintenance on a ground grid installed in highly resistive soil, one must consider that a low grid resistance is not always required for safe operation. As discussed earlier, grids with higher resistance can be safe so long as an adequate split factor is present to minimize grid current. Therefore, grid resistance measurements should be compared to baseline measurements taken during installation and expected values derived from mathematical modeling. Grid resistance measurements should not necessarily be compared to industry standards such as outlined in "Electrical Power Equipment Maintenance and Testing" [6].

VI. CONCLUSIONS

It is possible to design an AC substation ground grid system that has a relatively high resistance to remote earth but is safe and reliable for system protection. The paper has discussed several alternatives to the generally accepted practice of attempting to lower the ground grid resistance. It provides guidance for designing a safe and reliable substation ground grid in situations where achieving very low grid resistance is both physically and economically challenging.

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VIII. VITA

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