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Risk in Design, Construction and Testing of Grounding System

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SUMMARY

Grounding system comprise of all interconnected grounding facilities with the primary function of conducting ground current for protective devices and to maintain safe ground potential rise, touch and step values. A number of potential sources of error exist that can result in either overly conservative (in-efficient) ground grid design or result in inadequate ground grid design, unable to provide its intended safety functions.

For example, an inexperienced designer may base the grid design on three-phase short circuit current rather than the single or double line to ground faults, incorrectly assuming that it would result in a conservative design. Contribution of the ground wire is often ignored by designers when information is not known, which can result in conservative design. Due to construction constraints, it is possible that the buried ground conductors or surface stones were not constructed as per specification; this will essentially impact the performance of the ground grid in controlling the voltage gradient and will introduce an error in the grounding parameters. Inductive coupling between parallel leads includes both resistive and reactive component introduces an error on a soil resistivity test with current and potential probes being parallel to each other.

This paper identifies and evaluates the risks in achieving safety when designing, constructing and testing a new grounding system, and provides practical recommendations to mitigate the risks.

KEYWORDS

Grounding, Ground Grid, Soil Resistivity, Risk analysis

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1. INTRODUCTION

Grounding system comprise of all interconnected grounding facilities with the primary function of conducting ground current for protective devices and to maintain safe ground potential rise, touch and step values. A number of potential sources of error exist that can result in either overly conservative (in-efficient) ground grid design or result in inadequate ground grid design, unable to provide its intended safety functions. This paper identifies and evaluates the risks in achieving safety when designing, constructing and testing a new grounding system, and provides practical recommendations to mitigate the risks.

2. UTILITY SURVEY

Electric utility survey was carried out to gather information on common sources of error and potential risks during design, construction or testing of grounding system.

A. Potential Sources of Error and Ranking of Associated Risk

The survey indicates that use of incorrect soil resistivity, inadequate experience of design engineers, use of inappropriate test methods or test equipment and installation of the ground grid does not match the design assumptions, in that order present the highest level of risk in introducing errors.

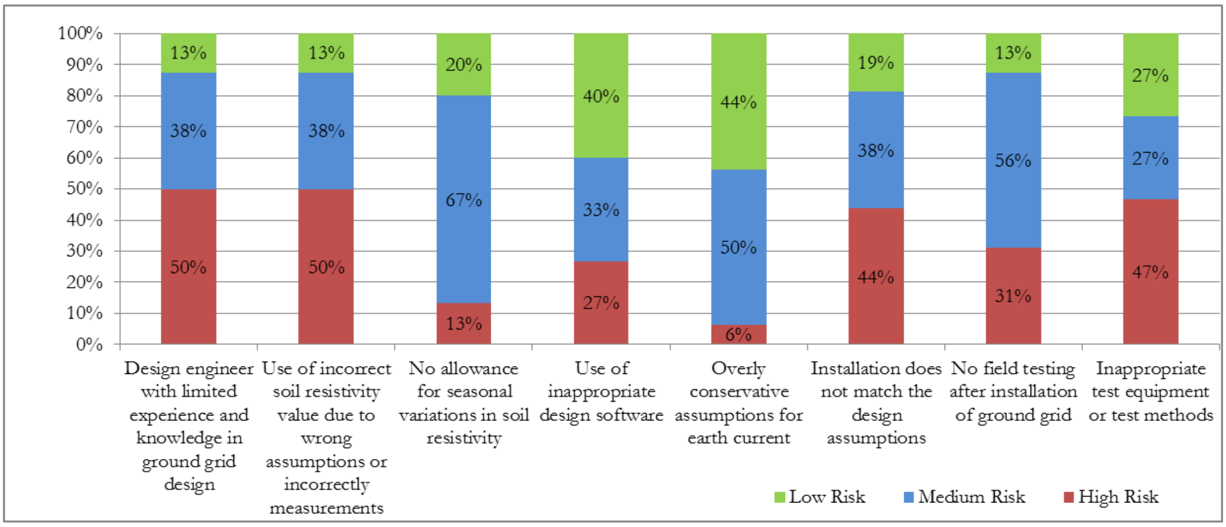

Figure 1- Level of Risk Presented by Various Sources of Error

3. COMMON SOURCES OF ERROR IN GROUND GRID DESIGN

This section describes potential errors during the design stage, which could compromise the functionality of a ground grid in maintaining a safe work environment during normal or abnormal operating conditions. The following categories of ground grid are covered:

(a) Single ground rod with length of 3 m and diameter of 19 mm (b) Small ground grids 25 to 50 m^2, typical small distribution stations. (c) Medium ground grids 100 to 200 m^2, typical large distribution stations or smaller transmission stations and (d) Large ground grids larger than 200m^2, typical larger transmission or terminal stations. Potential sources of errors during the design stage are discussed below:

A. Ground Current Calculation – LG versus LLG

Single line-to-ground fault or double line-to-ground fault will result in ground current. To determine the maximum ground current in an isolated grounding system, zero sequence current of the above mentioned fault types needs to be calculated, and the maximum value shall be used for ground grid design.

An inexperienced designer may base the grid design on three-phase short circuit current rather than the single or double line to ground faults, incorrectly assuming that it would result in a conservative design. However as shown in Table 1 (Scenario 2 and 4), the line to ground faults may exceed the three phase fault level in some cases and the above assumption may result in under sizing of the ground grid conductor. Under Scenario 4, the single phase to ground fault current is higher than the three phase fault by approximately 30 % and the ground current associated with the double phase to ground fault is approximately 46 % higher than the single phase to ground fault. Since there is a linear relationship between the ground current and GPR; ground grid design under the above assumption would lead to unsafe step and touch potential. On the other hand, if the design is based on three phase short circuit levels under scenario 1 and 3; it would result in grossly conservative and costly design.

Table 1- 230 kV Bus Short Circuit Currents under Different System Configurations

Scenario #	1	2	3	4
Voltage Level (kV)	230	230	230	230
Three Phase Fault Current (kA)	10	10	20	20
Single Phase Fault Current (kA)	6	12	12	26
Ground Current: Single Phase-to-Ground Fault (kA)	6	12	12	26
Ground Current: Double Phase-to-Ground Fault (kA)	4.3	15	8.6	3

B. Ground Current Calculation – Overhead Ground wire Consideration

A significant portion of the ground current is carried by transmission line overhead ground wire during system faults and reduced the ground current flowing into the ground grid. Contribution of the ground wire is often ignored by designers when information is not known, which can result in conservative design. The overhead ground wire reduces the ground grid current by inductive and conductive effect.

The inductive effect reduces the fault current due to mutual inductance, resulting from its proximity to the faulty phase conductors. The reduction in fault current is referred to as the Shielding Factor (S) [1]. For the conductive effect, the overhead ground wire provides a parallel path for flow of return current during the fault and reduces the ground current into the grid. As indicated in Table 2, ignoring the beneficial effect of overhead ground wire, can mislead the designer to conclusion of much greater value of expected GPR than its actual value. The omission results in much larger impact on GPR in case of smaller sized station in relation to medium or large sized stations.

Table 2- Effect of Overhead Ground Wire

Description		Ground Grid Size		
		Small	Medium	Large
Ground Grid Resistance (Ω)		7.45	3.71	2.46
Fault Current (kA)		10		
Overhead Ground wire impedance (Ω)		0.5		
Shielding Factor		0.7		
GPR (kV)	Without Considering the effect of ohg wire	74.5	37.1	24.6
	With Considering the effect of the ohg wire	3.3	3.1	2.9

C. Soil Resistivity – Uncertainty on Resistivity Values at Deeper Soil Layer

The resistivity of native soil under a station strongly impacts the size of the grounding electrode required to limit the potential rise at a given fault level. The resistivity also controls the number of conductors required to limit step and touch potentials. Thirdly the resistivity affects the resistance under the foot, which leads to the safe body withstand.

The base case considered first layer soil resistivity of 50 Ωm, depth for the first layer of 2m and second layer soil resistivity of 500 Ωm. As shown in Figure 2, an error in accurately capturing the resistivity of the first layer (top layer) of the soil introduced a significant error in calculation of the ground rod resistance. However in case of larger ground grids, the top layer soil resistivity does not have a dominant effect on resistance of the grid. A 200% error in accurately defining the first layer soil resistivity results in an error of 132% in calculation of the resistance of a single ground rod, whereas this error is only 59% for the large ground grid. On the other hand, second layer soil resistivity value plays a much more important role in calculation of the resistance of a large ground grid, while it does not affect resistance of a single ground rod, by the same ratio. A 200% error in defining the second layer soil resistivity creates an error of 65% in calculation of the large ground grid resistance, while this error is only 17% in case of a single ground rod.

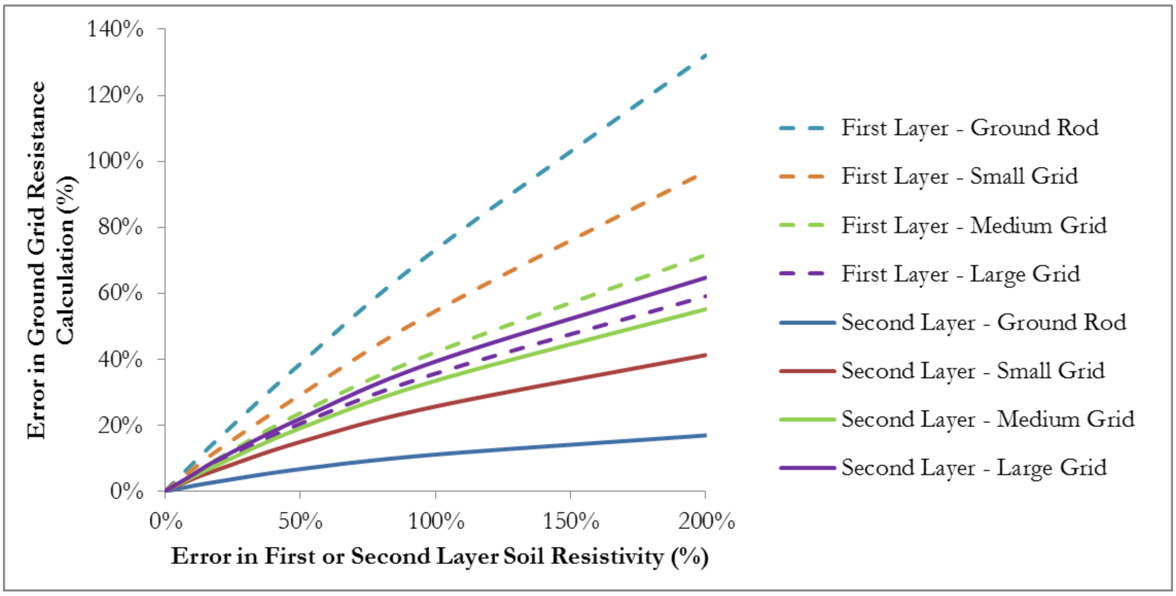

Figure 2- Error in Ground Grid Resistance (Unreliable First or Second Layer Soil Resistivity)

4. Common Sources of Error in Ground Grid Construction

At the construction stage, because of construction constraints, it is possible that the buried ground conductors or surface stones were not constructed as per specification. This will essentially impact the performance of the ground grid in controlling the voltage gradient and will introduce an error in the grounding parameters.

A. Conductor Depth

The ground grid is typically buried at the depth of 300 to 600 mm below the grade level. At the design stage, the grounding software calculates resistance of the ground grid based on the burial depth proposed by the designer. Because of construction constraints, it is quite common for the burial depth to be different from that specified during the design. Resistance of the ground grid does not considerably change with the burial depth of the conductors. For example, a 100% change in burial depth of the ground conductors in our large grid model will change the resistance of the grid by only 1%. On the other hand, the percentage error in resistance of a single ground rod for the same change in burial depth of the rod is about 10%.

B. Conductor Location

The charts presented in Figure 3 shows the fence touch potential variation as a factor of ground potential rise when the outer loop of the ground grid is dislocated. Dislocation of “0” means that the outer loop is positioned at the location defined by the designer. By the same token, dislocation of “-1” means that the outer loop is located inward by a distance of 1 m and dislocation of “+1” means that the outer loop is dislocated outward by a distance of 1 m. Small ground grid are more sensitive when the outer loop dislocated inward compare to medium and large grid. Ground grid has less impact on the touch voltage when the outer loop is dislocated outward.

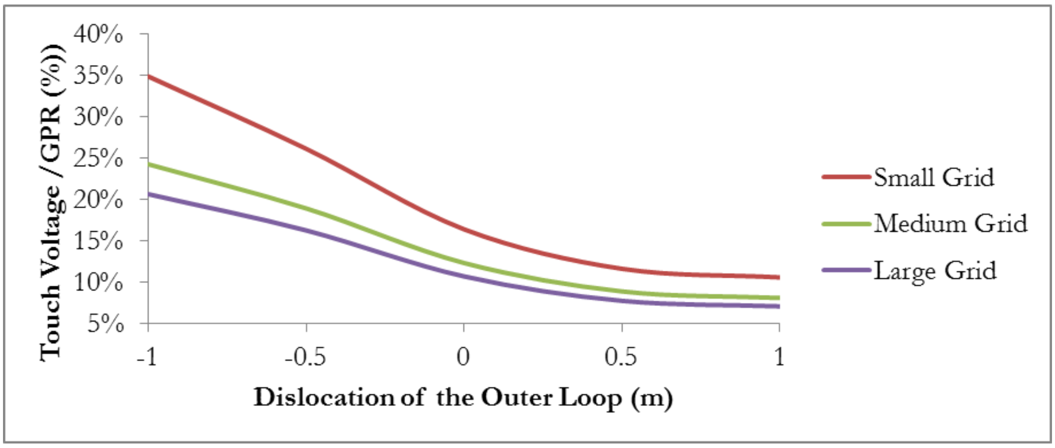

Figure 3- Touch Voltage as a factor of GPR vs. Ground Grid Outer Loop Dislocation

C. Surface Stone Depth and Resistivity

High resistivity material such as gravel with 3000 Ωm is spread on the surface above the ground grid with thickness of 80 to 150 mm to increase tolerable step or touch voltage. Tolerable step or touch voltage is a function of the thickness and resistivity of the surface material [2]. Figure 4 shows the relationship between the tolerable touch potential to the thickness of the surface material for underlying soil resistivity values of 50, 100, 200, 400 and 1600 Ωm. Resistivity of the surface stone is considered to be 3000 Ωm in this analysis. The percentage error is the highest when the underlying soil below the surface stone has the lowest resistivity.

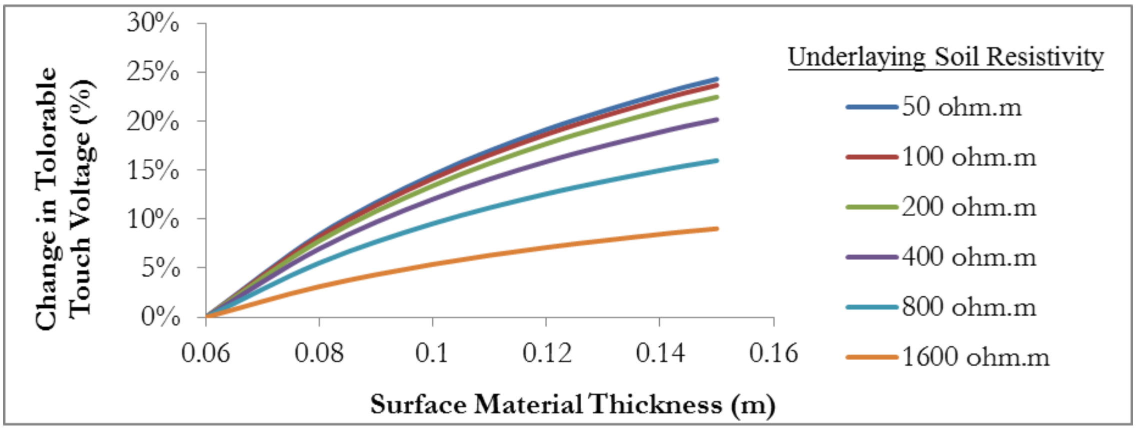

Figure 4- Tolerable Touch Voltage vs. Surface Material Thickness

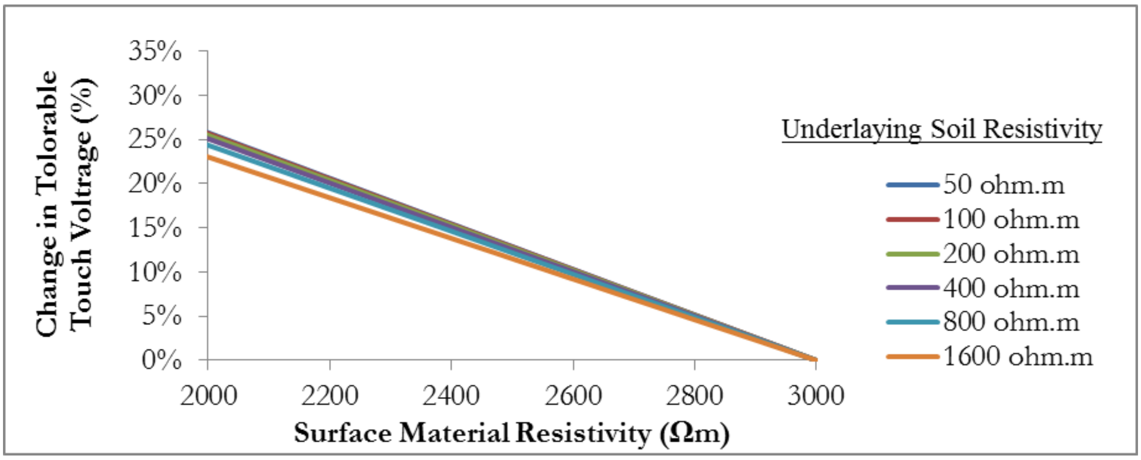

Figure 5- Tolerable Touch Voltage vs. Surface Material Resistivity

5. Common Sources of Error in Ground Grid Testing

The ground grid testing at substations, typically involves three types of tests:

(1) Soil resistivity measurements to be used as an input for ground grid design and construction. (2) Integrity tests on visible and non-visible grounding conductors. (3) Ground grid impedance measurement and reviewing of the coordination of step and touch potentials against the safe body withstand.

A. Error Due to External Interconnections of Ground Electrode

Most station ground grids have external interconnections, i.e. through transmission line overhead ground wires and through multi-grounded neutral conductors installed on distribution lines. It is often difficult to disconnect these connections to perform ground grid resistance measurements of the isolated station resistance.

The station grounding impedance Zg with interconnected overhead ground wires or distribution neutrals cannot be accurately measured using the classical Fall-of-Potential method because the correct placement for remote potential probe P2 is unknown. Here the Proximity Correction method may be considered [3]. It uses arbitrary placement of current probe (C2) and potential probe (P2), preferably in opposite directions, at distances several times the electrode diameter, and away from other buried conductors and lines over a sector of at least 60 degrees wide to either side. Impedance measuring instrumentation system that resolves magnitude and phase angles is used for the measurements. Current splits in overhead ground wires, distribution neutrals and other remote electrodes can be measured using a split-core current transformer, local shunt and twisted pair test lead to return the current signal to the measuring instrument. In this test both the magnitude and phase angle of each current split should be measured and compared to the modeled values. These splits should be subtracted from the current injected into probe C2 as vector quantities (magnitude and phase angle) to allow resolving the current injected to remote earth by the local station grid.

An estimate of the isolated station ground resistance is made from measurement of the interconnected impedance, through measurement of the current splits between local electrode and external ground connections, as illustrated in Figure 6.

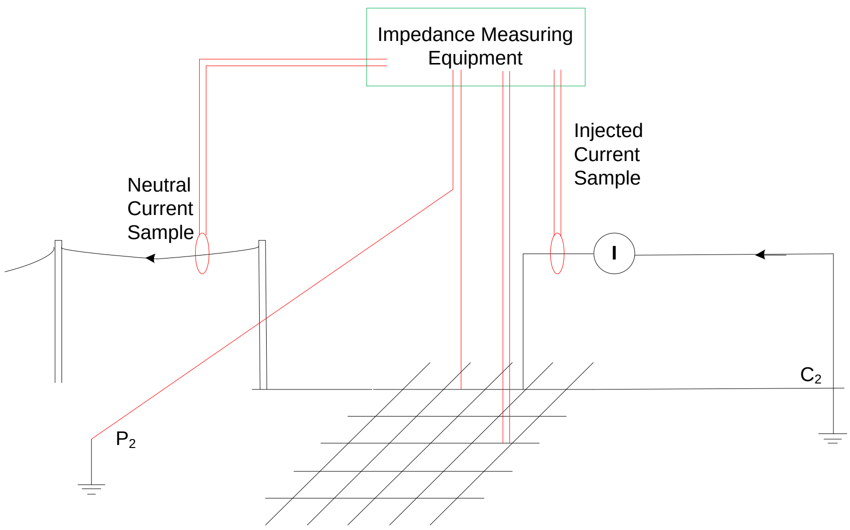

Figure 6- Modified Fall-of-Potential Test Method [4]

B. Error due to Inductive Coupling between the Leads

Inductive coupling between parallel leads includes both resistive and reactive components. This introduces an error on a resistivity test with current and potential probes being parallel to each other. Some resistivity meters measure only the resistance component so the reactive part of the inductive coupling does not affect the measurement. The chart in Figure 7 shows the error in apparent resistance measurement with respect to the offset between the current and voltage test leads. In this study we considered probe separation of 200 m and soil resistivity of 100 Ωm. As shown, separating the test leads to 50 m does not reduce the error.

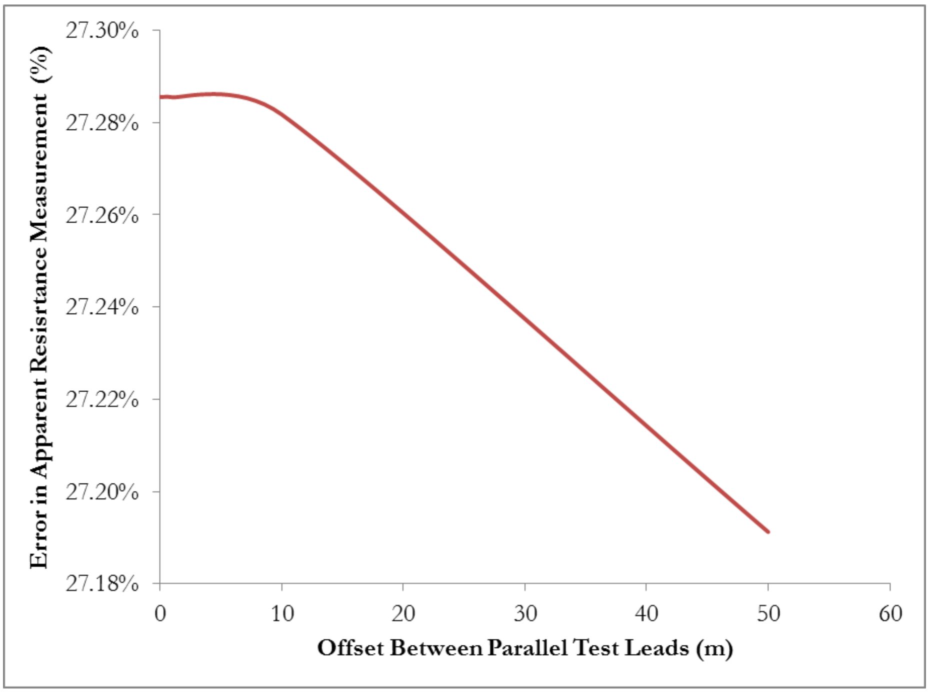

Figure 7- Error in Resistance Measurement Due to Proximity between the Test Leads

6. Conclusion and Recommendation

A number of potential sources of error exist that can result in either overly conservative (in-efficient) ground grid design or result in inadequate ground grid design, unable to provide its intended safety functions. Common sources of error in ground grid design, construction and testing are summarized below, along with practical recommendations to mitigate the risks.

A. Use of Incorrect Value of Ground Current

GPR are directly proportional to ground current, using the incorrect ground current value will result in either inefficient or inadequate ground grid design. It is recommended short circuit analysis be performed to accurately determine ground current during Line-to-ground (LG) and Double-line-to-ground (LLG) faults and the higher of the two values be used in ground grid design.

B. Contribution of Transmission Ground Conductors and Distribution Neutrals

Transmission line ground conductors (sky wires) and distribution system neutrals make significantly large contributions in reducing the ground current to be carried by local ground electrode and lowering the GPR. Not including the beneficial effect of transmission line ground wires and distribution neutrals would lead to inefficient and costly designs. It is recommended that the effect of transmission line grounds and distribution neutrals be considered during design of the ground grids.

C. Incorrect use of Resistivity Values

Soil resistivity largely impacts the size of electrodes required to limit the potential rise. The number of conductors required to limit step and touch potentials are also greatly affected by the resistivity values of the soil. Inaccurate resistivity values for the top layer of soil can introduce significant error in ground resistance calculation of small electrodes, i.e. a single rod or a few rods. Errors in soil resistivity values for the secondary underlying layer of soil have a more profound impact on ground grid resistance of larger grids. It is recommended that the soil resistivity be accurately measured and the top layer resistance appropriately adjusted for frost conditions for use in ground grid design.

D. Conductor Depth and Location of Buried Mesh Conductor

Significant impact on step and touch potentials result from deviation in ground grid location, particularly in areas in areas outside of the station fence and in close proximity to the fence. It is recommended that extra caution be exercised during the construction stage in accurately locating the buried mesh conductors near the external fence, per design specifications.

E. Surface Stone Depth

Safety limit for tolerable touch and step voltage depends on the thickness and depth of the surface stone. Presence of fines or growth of weeds in surface stone can decrease the resistivity value below safe limits. Similarly driving of heavy vehicles on top of gravel can compact it, reducing the thickness of surface stone layer to an unsafe level.

F. Error due to External Interconnection of Ground Electrode

Most stations ground grids have external interconnections which are difficult to disconnect in order to perform ground grid resistance measurements of the isolated station resistance. To mitigate this problem, it is recommended to use the average of multiple iterations of the proximity correction method. The method uses arbitrary placement of the current probe and potential probe at distances several times the electrode diameter and away from other buried conductors and lines. Instrumentation which resolves magnitude and phase angles is used to make measurements. Furthermore, it is recommended to conduct a separate soil resistivity measurement to account for the transfer resistance between the station, current probe, and potential probe, along with the fraction of test current injected into the local station grid.

G. Error due to Inductive Coupling between the Leads

Inductive coupling between parallel leads introduces resistive and reactive components. This creates an error on a resistivity test in the case that current and potential probes are parallel to each other. Some resistivity meters measure only the resistance component so the reactive component does affect the measurement. It is recommended to include appropriate offest so that the error is in an acceptable range.

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