Improving the Reliability of Power Systems With More Accurate Grounding System Resistance Estimates

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***Abstract*-- While there are standards and papers which specify in detail how to make soil resistivity measurements using the Wenner 4-pin method, nowhere is there any published reference indicating what range of pin spacings is required in order to obtain sufficient data for an adequate substation or power plant grounding grid design. This paper quantifies the degree of error that can occur in the computed grid resistance, touch voltages and step voltages as a function of maximum pin spacing, as the soil structure is varied through a wide range of values.**

***Index Terms*-- Substation Grounding Design, Earthing, Soil Resistivity Measurements, Wenner 4-Pin Method**

I. Introduction

For the design of a substation or power plant grounding system, the resistivity of the soil is one of the most important factors. Indeed, the construction cost of the grounding system can vary over one or more orders of magnitude, as a function of this resistivity.

It should be noted, however, that the soil is a three-dimensional medium, typically characterized by horizontal layers of different materials, each with their own resistivities. While the layer or layers in which the grounding grid and its associated ground rods are located are important, they represent only part of the picture. In fact, the resistivities of the soil layers at depths significantly greater than the grounding grid and its rods have a great influence on the performance of the grounding grid, as we shall see. By performance, we are primarily concerned in this paper with the ground resistance of the grid (i.e., the resistance through earth between the grid and remote earth or infinity), touch voltages (i.e., the potential difference between the grounding grid and earth surface points when the grid is energized), and step voltages (i.e., the potential difference between earth surface points 1 m apart when the grid is energized).

To gain an intuitive understanding of why deep soil layers might be important, consider the following simplified description of what happens when current is injected into a grounding grid. When current flows into the earth from a large grounding grid, buried near the surface (a typical depth is 0.5 m), it spreads out in all directions in such a way as to minimize the voltage drop between the grid and a remote point (at infinity). Close to the grid, this means a primarily downward direction, perpendicular to the face of the grid; at greater distances from the grid, the current spreads to form roughly hemispherical equipotential lines. In both cases, the current has a downward component, which is greatest while the current is still shaping itself from an almost purely downward direction, near the grid, to more of a hemispherical shape, further from the grid. For a small grounding grid, the hemisphere can form at a relatively short distance from the grid, whereas for a large grounding grid, the hemisphere forms at a considerably greater distance. Simplifying, for the purpose of presenting the concept, one can say that while the current is moving downward, the contribution of each soil layer to the resistance of the grid is equal to the resistivity of the layer, times the thickness of the layer, divided by the area of the grid. The contribution of each layer is therefore roughly proportional to its thickness: for a large grid, fairly deep soil layers contribute in this way, almost as much as shallow layers.

To measure the resistivity of the soil as a function of depth, the Wenner 4-pin method is typically used by power engineers [1-3]. A current is forced to circulate between a pair of outer electrodes, while the resulting voltage is measured between a pair of inner electrodes. The 4 electrodes are all equally spaced and co-linear. A series of readings are taken with the electrodes or “pins” at progressively increasing spacings. When the electrodes are close together, resistivities near the surface of the earth are detected, since most of the current flow remains near the surface of the earth; as the electrodes are spaced further and further apart, resistivities corresponding to soil layers at greater and greater depths are detected, since the current can spread further downward on its way from one outer electrode to the other. The so-called apparent resistivity, in Ω-m, at each pin spacing is equal to $2\pi\mathbf{a}\mathbf{V}/\mathbf{I}$, where **a** is the electrode spacing in meters, **V** is the measured voltage in volts, and **I** is the injected current in amperes. In a uniform soil, this is the actual resistivity of the soil and is measured at all electrode spacings. Unfortunately, for non-uniform soils, there is no simple relationship between the so-called apparent resistivity measured at a

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given electrode spacing and a corresponding depth: the resistivity measured at each pin spacing is a weighted sum of the resistivities of a range of soil depths, with the weight of deeper layers increasing with pin spacing. As a result, interpretation of the measured data typically requires the use of curves [4-5], for simple cases, or, as suggested in IEEE Std. 80 [2], computer software [6-8], when multiple layers are involved. As will be seen, it is certainly not easy to say what maximum pin spacing is required to determine the soil resistivity at a given depth, unless one has prior knowledge of how the actual soil resistivities vary with depth! Furthermore, although the necessary computer modeling tools are available, there appears to be little published work describing to what degree a grounding system will be influenced by soils beyond a given depth.

Despite the importance of the deeper soil layers (which this paper will quantify for some selected scenarios) and the corresponding need to measure soil resistivities at large pin spacings, none of the pertinent standards [1-2] so much as make passing reference to the maximum pin spacings required for a satisfactory design, nor are there any published papers on the subject, to the authors' knowledge. As is to be expected, this lack of guidelines has resulted in a wide range of measurement practices, many of which are based more on minimizing the time spent making the measurements than on science. Ironically, cost saved during the measurements may be expended manyfold on construction of the grid resulting from these incomplete measurements or on corrective measures after construction, when tests show that the grid is not performing according to predictions.

The contribution of this paper is to provide such guidelines, based on computer modeling of both the soil resistivity measurement interpretation process and of the resulting grounding grid performance, as a function of electrode spacings used for the soil resistivity measurements and as a function of soil structure.

II. METHODOLOGY

This study is based on computer simulations of both the soil resistivity measurement interpretation or "inversion" process and the grounding grid analysis process. The soil resistivity interpretation is made based on a steepest-descent algorithm, in which the apparent resistivities from a series of soil structure candidates are compared with those actually measured and the soil structure is selected for which the root mean square error between computed and measured resistivities is the smallest [7-10]. The grounding grid analysis is based on a moment method, in which the grounding grid conductors are fragmented into small segments and the influence of each conductor's leakage current on each conductor's potential (and on earth surface potentials) is computed by a method of images; the conductor potentials are then all set equal to one another and the total of the leakage currents set equal to the total injection current [11-13]. Only two-layer soils are considered in the present study, as they are sufficient to prove the point being made and represent a good starting point for future research in this vein.

This study focuses on a standard 152 m x 152 m (500 ft x 500 ft) grounding grid, with a total of 64 (i.e., 8 x 8) square meshes. The grid is 0.46 m (18 inches) deep and made up of 4/0 conductors. Conductors are segmented for the computations at all conductor intersections, resulting in 19 m segments and, throughout one corner mesh where touch and step voltages are highest (and therefore of interest), into 0.95 m segments. Effects of variations on this grid are discussed in the last section of this paper: i.e., grid dimension, aspect ratio, ground rods (none are present in the base model), and mesh size.

After having demonstrated the sensitivity of grounding grid performance to the soil's electrical structure and the detectability of the soil's structure from measurements made with the 4-pin Wenner method, this paper proceeds to quantify the error that can occur under extreme conditions, when incomplete soil resistivity measurements are made. In this part of the study, a 2-layer soil structure is selected and its apparent resistivity profile computed up to sufficiently large pin spacings to indicate the bottom layer resistivity. This profile is then truncated, as would occur when measurements are made to limited pin spacings. This truncated profile is then submitted to a soil resistivity interpretation algorithm (described above) to obtain an equivalent two-layer soil. The grounding grid performance is then computed in this soil and compared with the performance in the two-layer soil that was used to generate the apparent resistivity profile.

One important point is what assumptions the soil resistivity interpretation algorithm makes regarding the missing soil resistivity data at larger spacings. The bottom layer resistivity selected by the algorithm is as close as possible to the apparent soil resistivity value provided at the largest pin spacing, while still allowing all the apparent resistivity values to be correctly fit by the computed apparent resistivities resulting from the soil model selected by the algorithm. The root mean square error is less than 2% in all cases. Fig. 1 provides an example of typical fits for a 100 ohm-m, 30.5 m (100 ft) thick soil layer, underlain by 5000 ohm-m soil. Each curve represents apparent resistivities computed for the soil model determined by the software to best fit the data from a measurement traverse whose maximum electrode spacing is as indicated. As can be seen, the fit is excellent, up to the maximum electrode spacing for each curve, so the software is providing a good equivalent soil model in each case, for the data available. It is clear, however, that because of the limited electrode spacings, the true bottom layer resistivity is not obtained. The soil model obtained for each measurement traverse is indicated in the figure.

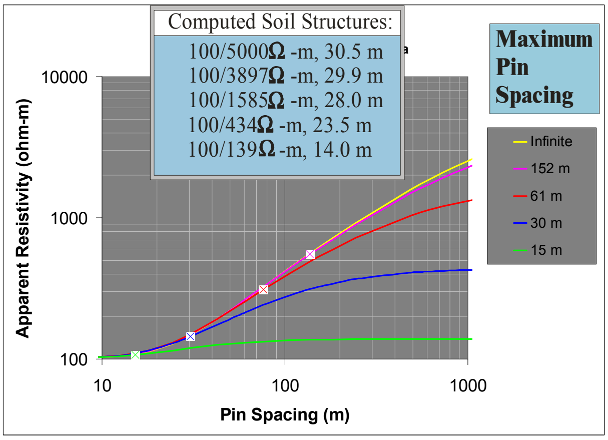

Fig. 1. Progressive Loss of Accuracy in Computed Soil Structure as the Maximum Pin Spacing is Decreased. The true soil has a 30.5 m thick, 100 ohm-m top layer overlying a 5000 ohm-m soil. Note that despite the overall loss of accuracy, the computed curves closely match the measurement data up to the maximum pin spacing (marked by an "X").

III. Grid Performance as a Function of Soil Structure

Let us start with a look at how deep soil resistivities can influence primary attributes of a grounding grid: i.e., its ground resistance, the maximum touch voltage and the maximum step voltage. Note that it is assumed that the substation fence is located 1 m inside the perimeter of the grid, so touch voltages are computed up to earth surface points extending as far outward as the perimeter grid conductor.

Figs. 2 and 3 show how the grid performance varies as a function of top layer thickness for two 2-layer soil types: first a soil with a top layer resistivity of 100 ohm-m, a typical value for soil, and a bottom layer resistivity of 5000 ohm-m, a moderately high value for bedrock. The second soil type consists of a high resistivity layer, 5000 ohm-m, over a low resistivity layer, 100 ohm-m. The computed ground resistance is expressed in ohms. The touch voltage is expressed both as a percentage of the potential rise of the grid and as a percentage (in V) of the current (in A) injected into the earth by the grid; the same has been done for the step voltage. The top layer thickness is expressed as a percentage of the length of the grounding grid.

The following observations can be made from these graphs:

1. For the soil with the 100 ohm-m upper layer, even bedrock beginning at a depth of 50% of the length of the grid, i.e.,76 m (250 ft) for the case studied, can increase the ground resistance of the grid by a factor of 3 compared with a uniform 100 ohm-m soil extending to infinite depth (see Fig. 2). Bedrock occurring at shallower depths naturally has an even more marked effect.

2. On the other hand, the soil with the 5000 ohm-m top layer as thick as 50% of the length of the grid results in a ground resistance underestimated by a factor of 1.57 compared with a uniform 5000 ohm-m soil. Unanticipated low resistivity material at a great depth clearly has a lesser effect than high resistivity material.

3. As far as touch and step voltages are concerned, once the earth injection current is known, the behavior of the grounding grid is quite stable for both soil types, once the top layer thickness is 50% of the grid length or greater, with the maximum variation being 11% as the top layer thickness is increased from 50% of the grid length to infinity.

4. On the other hand, when the ground potential rise (GPR) of the grid is used as a reference, touch and step voltages vary with top layer thickness in a similar way to ground resistance for large top layer thicknesses: this is no accident, since GPR is the product of earth injection current (with respect to which touch and step voltages are relatively constant at large top layer thicknesses) and ground resistance.

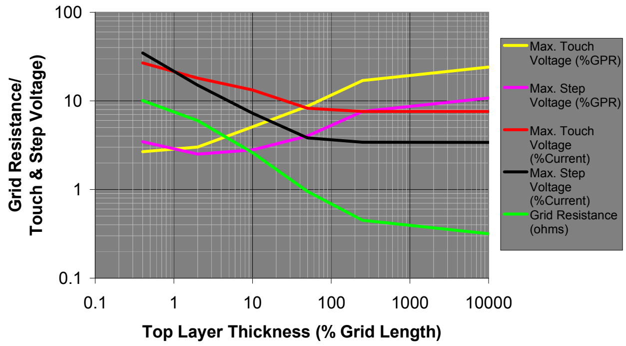

Fig. 2. Grid Performance as a Function of Top Layer Thickness: 100 ohm-m layer over 5000 ohm-m layer.

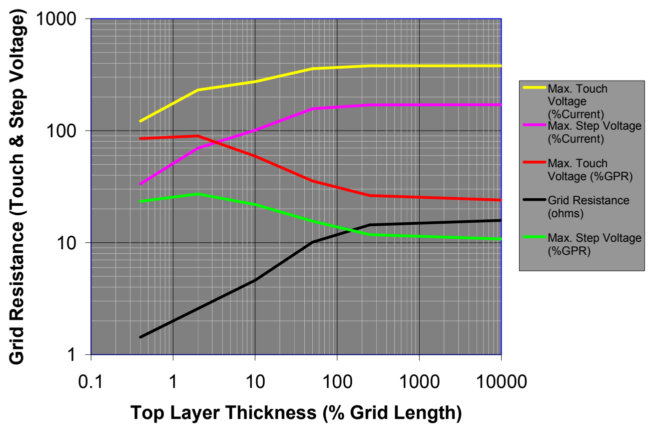

Fig. 3. Grid Performance as a Function of Top Layer Thickness: 5000 ohm-m layer over 100 ohm-m layer.

5. The touch and step voltage behavior of a grounding grid varies in a substantially different pattern as a function of top layer thickness, depending on whether the GPR or the injection current of the grid is held constant. Thus, a small distribution substation in moderate to high resistivity soil, connected to a multigrounded neutral, is more apt to exhibit the behavior associated with a constant GPR, whereas a larger transmission substation, in low to moderate resistivity soil, with poor or non-existent earth return conductors, is more likely to reproduce the constant current curve. All substations can be considered to lie somewhere between these two extremes.

IV. Detectability of Soil Structure

Now that we have seen the influence of soil layering on key grounding grid parameters, let us look at the detectability of the soil structure as a function of the maximum pin spacing used in the measurements.

Let us first look at how the structure of the soil is reflected by measurements made at the earth surface when the Wenner 4-pin method is applied. Figs. 4 and 5 show apparent resistivities as a function of pin spacing for 2-layer soils studied in Figs. 2 and 3, respectively. Fig. 4 shows two-layer soils whose bottom layer is 5000 ohm-m and whose top layer is 100 ohm-m. Fig. 5 shows the inverse: 100 ohm-m on the bottom and 5000 ohm-m on the top.

Fig. 4 shows that the presence of a bottom layer becomes just slightly apparent when the pin spacing reaches about half the thickness of the top layer. When the pin spacing is equal to the top layer thickness, the apparent resistivity indicates a soil resistivity of about 150 ohm-m, a far cry from the 5000 ohm-m of the actual bottom layer! Only when the pin spacing reaches 10 times the top layer thickness does the apparent resistivity curve begin to plateau ever so slightly, and here the measured resistivity is still only 20% of the bottom layer resistivity. The pin spacing must reach 100 times the top layer thickness in order to measure 80% of the bottom layer resistivity! The bottom layer resistivity is measured with less than 10% error at a pin spacing which is approximately 150 times the top layer thickness! This graph illustrates the shielding effect of a low resistivity layer, which has important ramifications in grounding system design.

As can be seen in Fig. 5, the presence of a lower layer, with a lower resistivity, becomes slightly detectable when the pin spacing reaches about half the thickness of the top layer: at this point the apparent resistivity slowly begins to drop. When the pin spacing becomes equal to the top layer thickness, the apparent resistivity is still equal to about 70% of the top layer resistivity. Only when the pin spacing becomes about six times larger than the top layer thickness, does the apparent resistivity curve begin to level off, within 10% of the bottom layer resistivity. Clearly, a low resistivity layer is much easier to detect than a high resistivity layer.

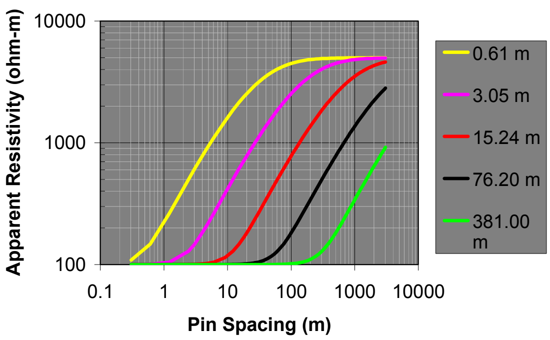

Fig. 4. Measured Apparent Resistivities for Different Top Layer Thicknesses: 100 ohm-m layer over 5000 ohm-m layer. Thickness of top layer shown in legend.

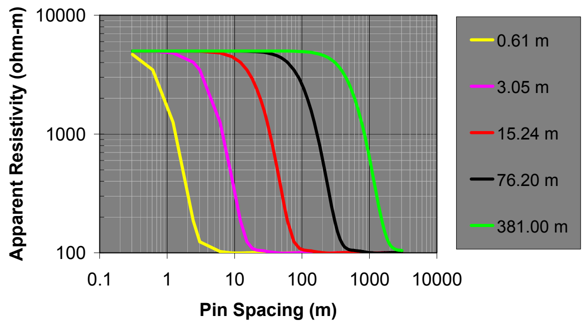

Fig. 5. Apparent Resistivities for Different Top Layer Thicknesses: 5000 ohm-m layer over 100 ohm-m layer. Thickness of top layer shown in legend.

V. Error in Grid Performance Predictions as a Function of Maximum Pin Spacing

Now that we have seen independently the influence of the deeper soil's resistivity on grid performance and the detectability of the deeper soil's resistivity as a function of pin spacing, let us combine the two together and see what is the direct influence of maximum pin spacing on the accuracy of grid performance predictions for the grid that we have been studying so far and three sample soil models.

Figs. 6-8 show the error resulting in predicted ground resistance, touch voltages and step voltages, when soil resistivity measurements are made to limited maximum pin spacings. Figs. 6 and 7 correspond to soil structures with a low resistivity layer overlying a high resistivity layer, the first figure for a soil whose top layer thickness is 30 m (100 ft), the second figure for a soil with a top layer thickness of 152 m (500 ft). Fig. 8 corresponds to the converse: a high resistivity layer over low resistivity material, with a top layer thickness of 30 m (100 ft).

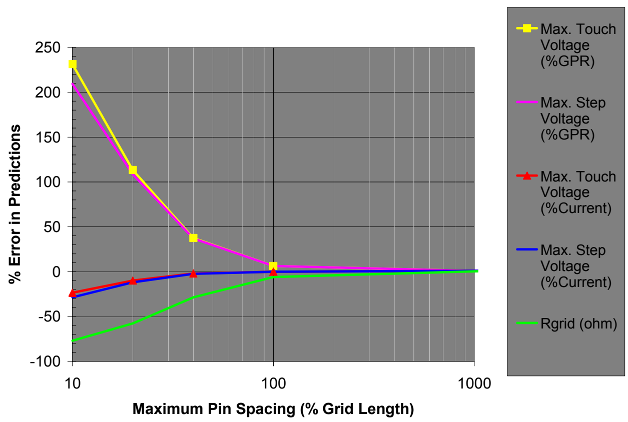

Fig. 6. Error in Grid Performance Predictions Versus Maximum Pin Spacing: 100 ohm-m soil layer, 30 m (100 ft) thick, over 5000 ohm-m soil.

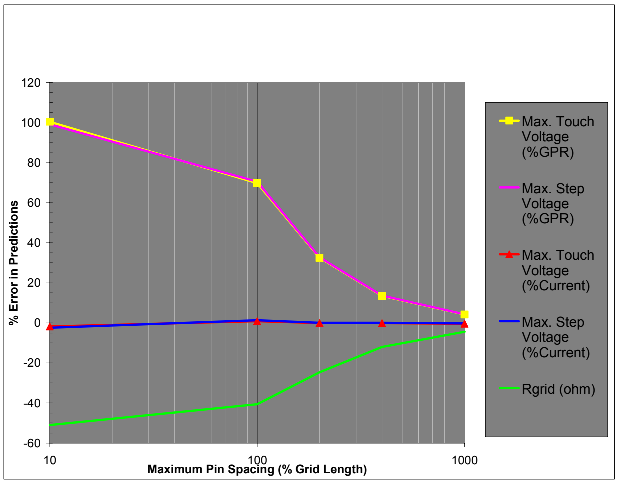

Fig. 7. Error in Grid Performance Predictions Versus Maximum Pin Spacing: 100 ohm-m soil layer, 152 m (500 ft) thick, over 5000 ohm-m soil.

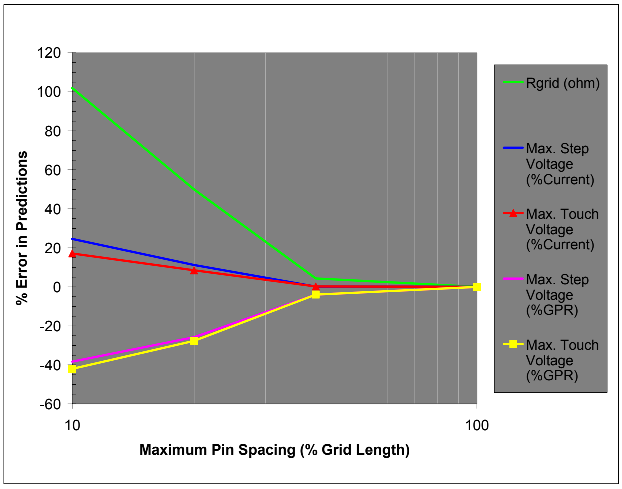

Fig. 8. Error in Grid Performance Predictions Versus Maximum Pin Spacing: 5000 ohm-m soil layer, 30 m (100 ft) thick, over 100 ohm-m soil.

A comparison of the three figures suggests the following:

1. For the same top layer thickness, the high over low resistivity soil structure results in more rapid convergence to a small level of error than the low over high resistivity soil structure (compare Figs. 6 and 8). Indeed, for the soils with a 30 m thick top layer, the error in ground resistance, maximum touch voltage in %GPR, and maximum step voltages in %GPR, is less than 10% once the maximum pin spacing reaches 40% of the grid length for the high over low resistivity structure, whereas the error is on the order of 30-40% for the low over high resistivity soil, for the same maximum pin spacing.

2. When the thickness of the top layer increases from 30 m (i.e., 20% of the length of the grid) to 152 m (i.e., 100% of the length of the grid), the error in all calculated quantities decreases signficantly for small maximum pin spacings, but remains high (compare Figs. 6 and 7); furthermore, the maximum pin spacing required to reduce the error to small values becomes considerably larger. For example, for a maximum pin spacing equal to 10% of the grid length, the error in maximum touch voltage as a percentage of the grid GPR decreases from 230% to 100%, as the top layer thickness is increased from 30 m to 152 m. On the other hand, for a maximum pin spacing equal to 100% of the grid length, the error in this touch voltage actually increases from 6% to 70%.

3. It is relatively easy to achieve a small error in touch and step voltages as a percentage of the grid current, with maximum pin spacings of 40% of the grid length or less. The problem is ascertaining the ground resistance of the grid, which has a direct bearing on touch and step voltages as a percentage of the grid potential rise.

We have seen, now, that if we know the soil structure, we can predict the error as a function of maximum pin spacing and thus determine what maximum pin spacing is required. Of course, in reality, we do not know the soil structure (otherwise, why measure?). So let us look at the problem from another perspective. For a given maximum pin spacing, what is the maximum possible error as a function of soil structure?

VI. Adequacy of Maximum Pin Spacing Versus Soil Structure

We have demonstrated that the predicted grid performance criteria can depend greatly on the maximum pin spacing employed for certain given soils. The most important question now arises: for a given maximum pin spacing, what maximum error can be expected for a large range of soils? Let us continue to assume fairly extreme ratios of 100:5000 and 5000:100 for the top and bottom layer resistivities, with widely varying top layer thicknesses and study grid performance prediction error for three different maximum pin spacings.

Figs. 9-13 summarize the results of this part of the study, with each graph showing the error in predicted grid performance as a function of the top layer thickness. Figs. 9-11 show the behavior of soils with a 100 ohm-m top layer and 5000 ohm-m beneath; in Fig. 9 the maximum pin spacing is 40% of the grid length, in Fig. 10 it is 100% of the grid length, and in Fig. 11 it is 300%. Figs. 12-13 correspond to soils with 5000 ohm-m on top and 100 ohm-m beneath, with Fig. 12 corresponding to a maximum pin spacing of 40% of the grid length and Fig. 13 to 100% of the grid length.

As Fig. 9 shows, when the maximum pin spacing is 40% of the grid length and the top layer is very low in resistivity compared to the bottom layer, the maximum error occurs for a top layer thickness of about 50% of the grid length (which also happens to be just a bit larger than the maximum pin spacing). For this soil structure, the ground resistance is underestimated by about 50%; touch and step voltages are overestimated by almost 110% in a situation where the GPR of the grid is relatively insensitive to the ground resistance of the grid (this could very well be the case for a distribution substation) and can be accurately established based on a known (low) ground impedance of the power system to which the substation is connected. On the other hand, touch and step voltages are fairly accurate (within about 5%) if the current injected into the grid is relatively insensitive to the ground resistance of the grid (this is likely to be the case for a substation whose ground resistance is very low compared to other earth return paths) and can be accurately established based on known available fault current levels from a system with a relatively high equivalent ground impedance.

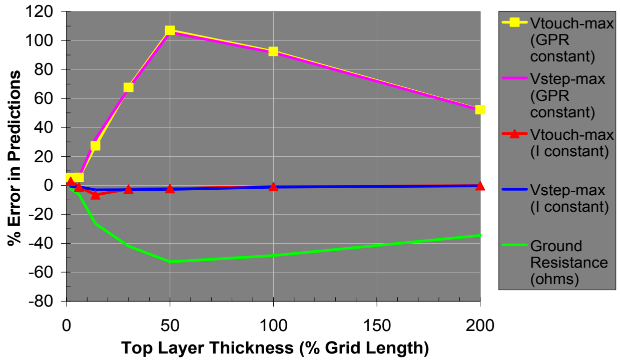

Fig. 9. Error in grounding performance predictions is worst for low resistivity soil (100 ohm-m) over high resistivity soil (5000 ohm-m), with pin spacings that are limited in extent (here, 40% of the grid length).

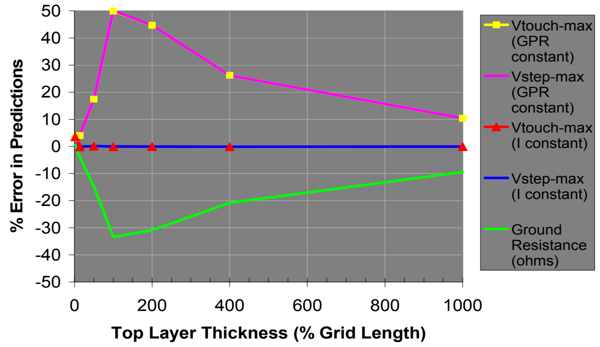

Fig. 10. Grounding performance predictions improve with maximum pin spacings reaching 100% of the length of the grid: 100 ohm-m over 5000 ohm-m soil.

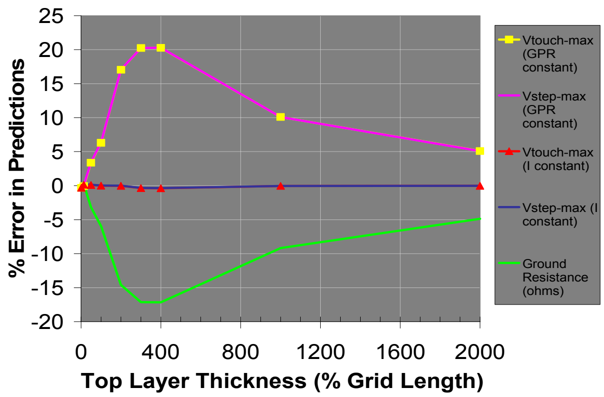

Fig. 11. Minimizing the error in grounding performance predictions comes at a cost: with pin spacings reaching 300% of the grid length, the total measurement traverse length is 9 times the grid length. Soil is 100 ohm-m over 5000 ohm-m.

As Fig. 10 shows, increasing the maximum pin spacing to 100% of the grid length reduces the maximum error in the grid resistance to approximately -33% and that of the touch and step voltages (in % GPR) to approximately +50%. The error in touch and step voltages as a percentage of the grid injection current is negligible. Again, these peak errors occur for a top layer thickness that is similar to the maximum pin spacing.

To reduce the error further, the maximum pin spacing can be increased to 300% of the grid length (this means that the outer current pins are now separated by a distance equal to 900% of the grid length!), resulting in a maximum ground resistance error of –17% and a maximum touch and step voltage error of 20%, as can be seen in Fig. 11. Again, the maximum error occurs for a top layer thickness which is approximately equal to the maximum pin spacing.

From Fig. 12, it can be seen that the maximum error resulting from a high over low resistivity soil is considerably lower than that seen for the low over high resistivity soils represented by Fig. 9. Indeed, for the 5000 ohm-m over 100 ohm-m soils, the maximum ground resistance error is approximately +30% for a maximum pin spacing equal to 40% of the grid length, occurring for the soil with a top layer thickness approximately double the maximum pin spacing. The maximum touch and step voltage error is approximately –20% when the GPR of the grounding grid is relatively insensitive to the ground resistance of the grid; this error is negligible when the current injected into the grounding grid is insensitive to the ground resistance.

Fig. 13 shows that increasing the maximum pin spacing to 100% of the grounding grid length, in such soils, decreases the maximum computed error to +9% for the ground resistance, -7% to –8% for touch and step voltages as a percentage of the grid GPR, and a negligible value for touch and step voltages as a percentage of the grid earth injection current.

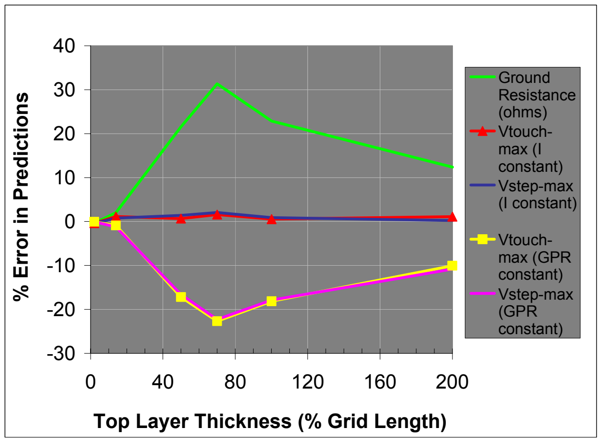

Fig. 12. Error in grounding performance predictions is lower when the top layer is higher in resistivity (5000 ohm-m) than the bottom layer (100 ohm-m): compare with Fig. 9.

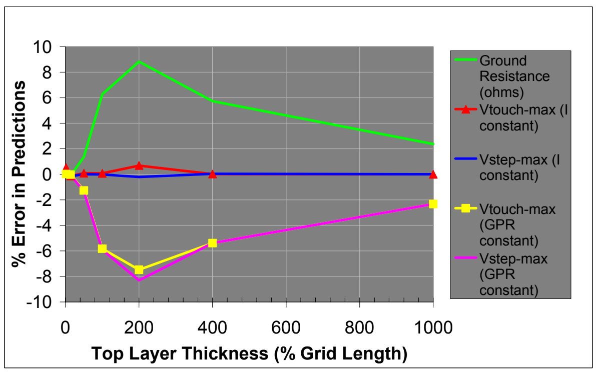

Fig. 13. Error in grounding performance predictions is quite acceptable for a high (5000 ohm-m) over low (100 ohm-m) resistivity soil, when the pin spacing (between adjacent pins) is equal to the grid length.

VII. Influence of Other Parameters: Grid Size, Grid Shape, Mesh Density, Ground Rods

As has been seen in the preceding section, deep soil resistivities can have a significant effect on the ground resistance of a grid; error in this ground resistance is the primary source of error in touch and step voltages. Accordingly, it is not anticipated that factors that have only a small impact on the grid resistance will have any significant impact on the level of error in touch and step voltages.

Such factors are the mesh density, once a certain threshold has been reached, and the presence of ground rods, if the dimensions of the grounding grid are large compared with the ground rods and the soil resistivity at rod depth is not very much lower than it is at grid depth. Of course, small grounding grids with disproportionately long ground rods or wells will be influenced even more by deep soil layers than the example grid discussed in this paper. On the other hand, extremely sparse grids (i.e., grids with significantly fewer meshes per side than the example here) will be less influenced by deep soil layers.

All other factors being equal, the size of the grounding grid is expected to have only a small influence on the percent error in ground resistance and touch and step voltages, for measurements made to maximum pin spacings equal to a given percentage of the grid's length.

The aspect ratio of the grounding grid is expected to have a more significant effect: square grids should be influenced by deeper soil layers to a greater extent than rectangular grids with the same maximum length. The error for a rectangular grid should therefore be lesser if soil resistivity measurements are made to maximum pin spacings equal to a given percentage of the length of the longer side of the grid.

VIII. Conclusions

The conclusions of this study are as follows:

1. Soil resistivities at depths on the order of half the grid length can have a significant influence on grounding performance: a factor of three difference in ground resistance, touch voltages and step voltages is possible in extreme cases. It is therefore important to measure soil resistivities to sufficiently large electrode spacings when carrying out a grounding analysis.

2. In order to determine the soil resistivity at a given depth, it is necessary to extend a soil resistivity measurement traverse such that the maximum pin spacing is several times that depth. The required pin spacing can become extremely large when low resistivity soil overlies high resistivity soil.

3. Fortunately, it is not necessary to know deep layer soil resistivities with precision, in order to predict grounding grid performance with reasonable accuracy.

4. Computer simulations have shown that for two-layer soils, with resistivity ratios varying from 1:50 to 50:1 between the two soil layers and with the top layer thickness varying throughout the worst case range, the maximum error is expected to be on the following order, as a function of the maximum Wenner pin spacing employed:

Max. Adjacent Pin Spacing (% Grid Length)	Maximum Error Range (%):	
	Grid Resistance	Touch & Step Voltage (in % of Grid GPR)
40%	-50% to +30%	-20% to +110%
100%	-33% to +9%	-8% to +50%
300%	-17% to +(<9%)	-(<8%) to +20%

5. In situations in which the grid current is little affected by the grid resistance, due, for example, to a lack of significant additional grounding provided by the power system, a maximum pin spacing of 40% of the grid length limits the error in predicted touch and step voltages to less than about 7% in all situations studied.

This paper provides the reader with useful information in planning the extent of traverses along which soil resistivity measurements are to be carried out for a given grounding analysis and in determining what safety factor to incorporate into the study as a function of the extent chosen for the measurement traverses.

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