

Application of Electromagnetic Field Theory to Measure Correct Grounding System Impedance: A Parametric Analysis

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Abstract

Measurement of the grounding system impedance of a substation or power plant is often required immediately after construction, in order to verify that the design calculations correctly predict the performance of the system. Years later, new measurements are sometimes required to check that the performance of the grounding system has not deteriorated. This type of measurement, however, which is typically carried out using the fall-of-potential method, is plagued by a number of potential problems: conductive coupling between the grid under test and the remote current return electrode, especially for soil structures with low resistivity over high; inductive coupling between current and voltage test leads; inductive coupling between test leads and grounding grid conductors; inductive coupling between test leads and power line static or neutral wires; additional grounding provided by power line static and neutral wires, which lowers the apparent impedance of the grounding grid. This paper presents a methodology for measuring ground impedances that minimizes the effects of inductive coupling, conductive coupling, and power line grounding. A parametric analysis is carried out to illustrate how measurement error changes as a function of grid dimensions, soil structure, test electrode locations, test lead separation distance, locations of test lead connections to the grounding grid, and test signal frequency used. It is found that accurate ground impedances can be obtained by interpreting the test data using electromagnetic field models that determine the expected error as a function of test signal frequency.

Keywords

Fall-of-Potential, 3-Pin, Earthing, Test

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1. Introduction

Upon construction of an electrical substation or power plant grounding system, its ground impedance is usually measured, in order to validate the design calculations [1]. The fall-of-potential method, also known as the “3-pin” method, is typically used [2]. The test method consists in essence of causing a test current to flow through the soil, from the grounding system under test to a remote current return electrode, while the resulting potential rise of the grounding system is measured with respect to a sufficiently distant potential reference electrode (see Figure 1). Typically, several potential rise values are measured for increasingly distant reference electrode positions, in order to confirm that the full potential rise has been measured. The potential rise divided by the test current yields the ground impedance. For small grounding systems that are isolated from any other ground electrodes and have sufficient clearance from nearby grounded structures, this test is usually as simple as it sounds.

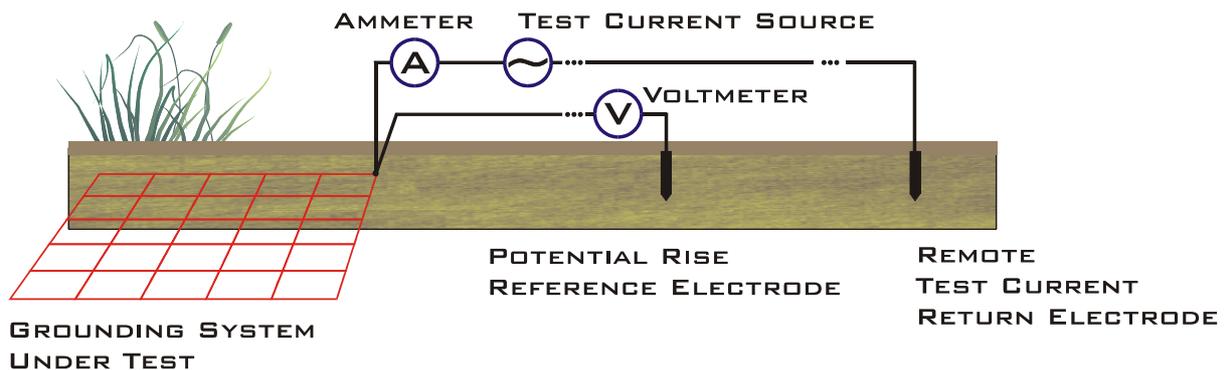


Figure 1 Fall-of-Potential Method

On the other hand, for larger grounding systems or those that are not electrically isolated from other ground electrodes, a plethora of problems can occur, which is why a distinct IEEE standard was written to address the testing of such large systems [3]. The following points must therefore be considered:

1. The ground impedance of a large grounding system tends to be low. As a result, the measured grid potential rise is small and undesirable effects, such as induced voltages, that would otherwise go unnoticed, can become large enough to alter the measured signal considerably. Stray noise also becomes a greater issue, but can usually be handled by frequency-selective test gear.
2. Since the potential rise of the grounding system is small, it is more susceptible to earth potentials transferred from the remote current return electrode, so this latter must be placed further away than for a small grounding system. Indeed, IEEE Standard 81.2 [3] indicates that a separation distance of 6.5 times the maximum diagonal of a rectangular grounding system is required to achieve 95% accuracy. As this paper will show, the actual required separation distance is a function of soil structure.
3. As a result of this large separation distance, long test leads are required.
4. A long lead carrying an ac test current is apt to induce significant voltages in the test lead used to measure the potential rise of the grounding system, if the two leads are run parallel to one another or at an acute angle to one another. Induced voltages do not decrease rapidly as a function of separation distance between leads [4], so increasing the spacing between them is of limited effectiveness.
5. The current-carrying test lead can also induce voltages in long grounding grid conductors, if there is any parallelism or an acute angle between them, thus altering the distribution of test current in the grounding system and its measured impedance.
6. Test current injected into a long grounding grid can induce significant voltages in the test lead that measures the potential rise, if this test lead is run parallel or at an acute angle to the grounding grid.
7. The above concerns would be eliminated by the use of a very low frequency test signal. However, for large grounding grids or even smaller ones in low resistivity soils (the size of concern is strongly related to soil resistivity), the 50 or 60 Hz reactance of the grounding grid conductors make a major contribution to the total grid impedance. A very low frequency test signal would not reproduce the inductive choke effect that these conductors exhibit at power frequency and therefore provide false results, underestimating the grounding system impedance. It is important that the test signal be carefully chosen to avoid this pitfall. Guidance in the selection of the appropriate test frequency is one important part of this paper's contribution.
8. When a grounding system is connected to other ground electrodes, as is the case for an operating station, whose grounding grid is typically connected to lightning shield wires (or other types of ground return conductors), the effective size of the grounding system is increased and all of the above problems are compounded, with the lightning shield wires introducing additional inductive coupling problems. Furthermore, since the objective of the test is to measure the ground impedance of the station, it is desirable to somehow exclude the supplemental grounding provided by the exterior electrodes.

By means of a parametric analysis carried out with software [5,6] that represents aboveground and buried conductors simultaneously, accounting for conductive coupling, magnetic field inductive coupling, and capacitive coupling, this paper illustrates to what degree the accuracy of ground impedance measurements can be influenced by the following factors:

1. Size of grounding system,
2. Distance from the grounding system of the remote test current return electrode and the potential reference electrode,
3. Soil resistivity and layering,
4. Test signal frequency,
5. Angle and separation distance between test leads,
6. Type of lightning shield wire,
7. Separation between test leads and power lines,
8. Separation between test current injection point and potential rise measurement point on grounding system.

With this information, it is hoped the reader will be able to choose an adequate separation distance between the grounding system and the test electrodes, suitable routing and grid connection points for the test leads, and optimal test frequencies.

2. Computer Model

Figure 2 shows a plan view of the system modeled. It consists of the following elements:

1. The grounding system under test, which consists of a grounding grid made up of 4/0 AWG copper cables buried 0.5 m deep. Different computer simulations model grounding grids chosen from among the following three:

- a. 400 m x 400 m, with 21 meshes x 21 meshes
 - b. 200 m x 200 m, with 10 meshes x 10 meshes (this is the one illustrated in Figure 2)
 - c. 100 m x 100 m, with 10 meshes x 10 meshes
2. Two pairs of transmission lines extending a distance of 4 km on each of two sides of the grounding system, each with 2 lightning shield conductors spaced 16.6 m apart, at an average height of 28 m, and connected to the grounding system perimeter and to each supporting structure. These latter are grounded by means of four 97 cm x 6.1 m vertical footings per structure, with the footings located at the corners of a 6.25 m x 9.36 m rectangle. The span length of the transmission lines is 200 m and the parallel transmission lines are spaced 25 m apart, center-to-center, with transmission lines TL-1 and TL-3 located midway along their corresponding sides of the substation. In different simulations, two different types of shield wire pairs have been studied:
 - a. Two 3/8" EHS galvanized steel wires, with a 60 Hz ac resistance of 5.9 ohm/km.
 - b. One 64mm²/528 ALCOA (13.4 mm diameter) optical ground wire (OPGW), with a 60 Hz ac resistance of 0.54 ohm/km, and one 3/8" EHS steel wire.

All transmission lines have the same shield wire pair in a given simulation.

3. A test current return electrode, which receives all the test current injected into the grounding grid. Unless specified otherwise, the distance of the return electrode from the grounding grid perimeter is 6 times the length of the grid.
4. A test current injection lead, which runs at ground level, in a straight line, from the grounding grid to the remote test current return electrode, and which is assumed to include a sinusoidal signal source (not illustrated) and a frequency-selective ammeter. The test current injection lead has been modeled at various locations and in various orientations: these are labeled C1 through C4.
5. A potential rise measurement lead, which runs at ground level, in a straight line, from the grounding grid to the potential rise reference electrode and contains a short gap, which represents the frequency-selective voltmeter that is normally used. This lead has also been modeled at various locations and in various orientations: these are labeled P1 through P7. The angle between the potential rise measurement lead and the test current injection lead varies from 0 to 90 degrees. The length of this lead (and therefore the distance of the reference electrode from the perimeter of the grounding grid) is 6 grid lengths, when the angle between it and the current injection lead is non-zero; when the angle is zero, its length is 62% of the distance between the current injection point and the current return electrode. For cases when the two leads are parallel, separation distances of 1 m, 5 m, 10 m, 20 m and 40 m have been studied.

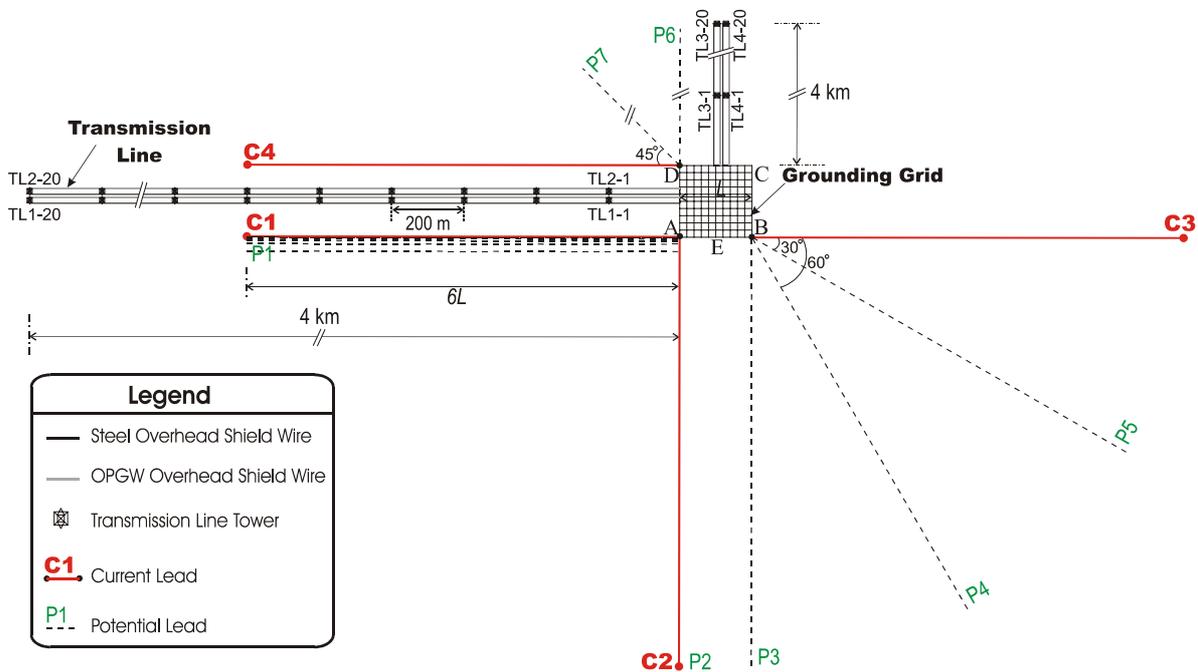


Figure 2 Plan View of System Studied. Note that grounding grid dimensions and number of meshes vary throughout study.

Other pertinent system parameters are as follows:

1. Throughout most of the analysis, uniform soils with the following three resistivities have been studied:
 - a. 10 ohm-m (this results in a tower ground resistance of 0.29 ohm)
 - b. 100 ohm-m (this results in a tower ground resistance of 2.84 ohms)
 - c. 1000 ohm-m (this results in a tower ground resistance of 28.3 ohms)

2. In studying the proximity effect of the test current return electrode on the measured grid impedance, the following two-layer structures have also been examined in addition to uniform soil:
 - a. 5000 ohm-m over 100 ohm-m
 - b. 100 ohm-m over 5000 ohm-m

with the top layer thickness varying from 0.5 to 4 times the length of the grounding grid. In this part of the study, the separation distance from the center of the grid to the test current return electrode was varied from 2 to 40 times the diagonal length of the grid.

3. Test frequencies in the range of 60 Hz to 10,000 Hz

The software used for the computer modeling (i.e., the HIFREQ™ module of the CDEGS™ software package, by Safe Engineering Services & technologies ltd.) is highly accurate, as it solves Maxwell’s equations directly, without simplifying assumptions of any importance made for test frequency calculations, other than the usual conductor segmentation used by all numerical methods. The field theory approach used in this paper is an extension to low frequencies of the moment method used in antenna theory. By solving Maxwell’s electromagnetic field equations, the method allows the computation of the current distribution (as well as the charge or leakage current distribution) in a network consisting of both aboveground and buried conductors with arbitrary orientations. The scalar potentials and electromagnetic fields are thus obtained. The effect of a uniform or layered earth of arbitrary resistivity, permittivity and permeability is completely taken into account by the use of the full Sommerfeld integrals for the computation of the electromagnetic fields. The details of the methods are described in [5] and [6] and their references.

3. Results

3.1 Distance of Test Electrodes from Grounding System

Before even considering test lead routing or test current frequency and the resulting accuracy, it is instructive to consider how much accuracy can be obtained under even the most favorable conditions, as a function of soil structure and distance of the test current return electrode from the grounding system under test. For this analysis, therefore, a grounding system is modeled under the following favorable conditions:

1. No lightning shield conductors or other such alternate ground paths are connected to the grounding system;
2. No inductive coupling occurs between the test current injection lead and the potential rise test lead (they are assumed to be perpendicular);
3. No significant inductive coupling occurs between the test leads and the grounding grid;
4. The ground potential rise of the grounding system is measured with respect to a remote (zero-volt) reference point.

The 100 m x 100 m grounding grid described in the previous section is modeled in two extreme types of two-layer soils, with varying top layer thicknesses:

1. The first soil type consists of a low resistivity layer (100 ohm-m) over a high resistivity layer (5000 ohm-m);
2. The second type consists of a high resistivity layer (5000 ohm-m) over a low resistivity layer (100 ohm-m).

Figure 3 presents the results of this analysis: it shows the percent error of the measured grid impedance as a function of the distance of the return electrode from the grounding system. In the graphs, this distance is expressed in multiples of the grid diagonal distance of 141 m. Each curve represents a different top layer thickness, as indicated in the legend, with the uniform soil representing an infinite top layer thickness.

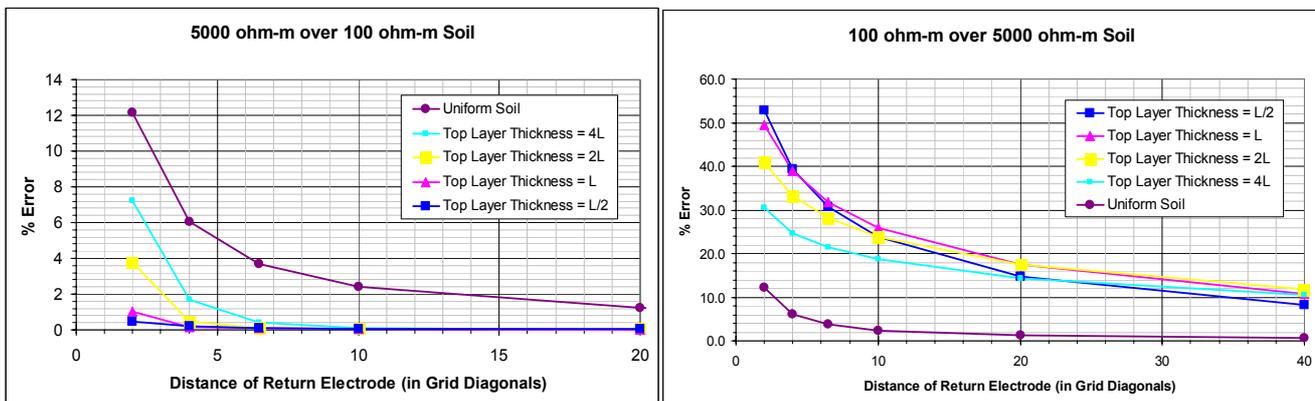
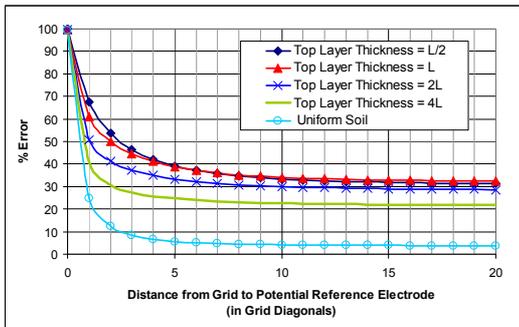


Figure 3 Best Case Error in Measured Grid Impedance as a Function of Remote Test Current Return Electrode Position

The following observations can be made from the graphs in Figure 3:

1. Measurement error is considerably higher for low resistivity over high resistivity soils than for high resistivity over low. The low resistivity top layer acts like a shield, concentrating an undesirably large proportion of the test current in the conductive top layer, such that the contribution of the high resistivity bottom layer to the grid impedance is under-represented. Note that the ground impedance is underestimated in all soil types.
2. Measurement error decreases with increasing return current electrode distance from the grounding grid. This decrease occurs the most rapidly for the high-over-low resistivity soil, for which accuracy is already good at relatively short electrode distances; it occurs considerably more slowly for the low-over-high resistivity soil. Indeed, even at a distance of 20 grid diagonals, the measurement error is still approximately 18% for the worst case soil.
3. For the uniform soil, the error for the current return electrode located 6.5 grid diagonals away from the center of the grid is 4%. For the worst case low-over-high resistivity soil studied, however, the error at this distance is 32%. For the worst case high-over-low resistivity soil studied, this error is less than 1%.
4. Taking measurements with two substantially different return electrode positions makes it possible to determine whether further increases in separation distance will result in substantial improvement in measurement accuracy.

Note that the above results are derived with the potential rise reference electrode located at infinity. If it is not, then the measurement error is compounded by coupling with this electrode. Figure 4 shows the error which results when the potential rise reference electrode is placed at varying distances from the center of the grounding grid for the troublesome low-over-high resistivity soils, with the current return electrode located 6.5 grid diagonals away from the center of the grounding grid. The two electrodes are placed such that their corresponding test leads would be perpendicular to one another.



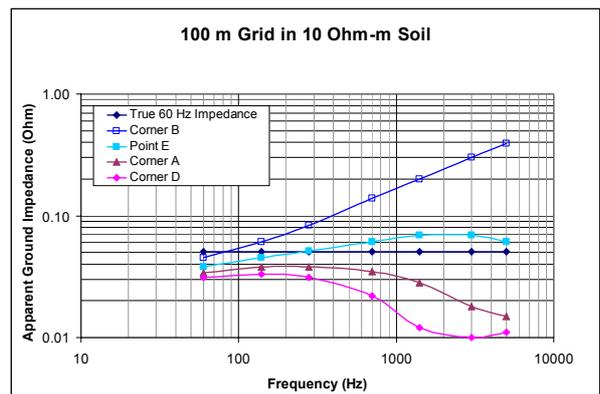
As Figure 4 shows, the measurement error decreases as a function of distance, dropping much faster for the uniform soil than for the low-over-high resistivity soil. For the uniform soil, the error drops to 5 % when the potential reference electrode is 6 grid diagonals from the center of the grid. The error for high-over-low resistivity soils would be even smaller. On the other hand, for the worst low-over-high soil, however, the error is still 37 % when the potential reference electrode is 6 grid diagonals from the center of the grid. This error can be decreased to 34 % by locating the potential reference electrode 10 grid diagonals away and to 32.4% with 20 grid diagonals.

Figure 4 Error in Measured Grid Impedance as a Function of Potential Rise Reference Electrode Position, With Current Return Electrode Located 6.5 Grid Diagonal Lengths from the Center of the Grid

3.2 Test Frequency and Potential Test Lead Connection Location

So far, testing of a grounding grid isolated from any other grounding has been studied. Furthermore, the grounding grid has been relatively small and the soil resistivity moderate, so voltage drops of grid conductors have not been a concern. Often enough, however, the grid to be tested is connected to lightning shield wires or other such ground paths: choosing a suitably high test frequency can increase the reactance of these conductors to the point where they effectively isolate the grounding grid under test from other grounding, making it possible to measure the impedance of the grid alone. On the other hand, increasing the test frequency also increases the reactance of the grid conductors themselves: depending upon the dimensions of the grid and the soil resistivity, the frequency required to isolate the grid from the external grounding may significantly increase the grid impedance as seen at the test current injection point. One way to compensate for a large voltage drop in the vicinity of the current injection point is to measure the potential rise of the grid at a point more representative of the electrical center of the grid. For a current injection at Corner B (see Figure 2) of the grid, for example, a better potential test point might be Point E.

The graphs in Figure 5 show how the measured ground impedance varies as a function of test frequency. Each graph represents one of three different grid sizes and one of three different soil resistivities, as indicated by the title of the graph. Each curve represents a different potential test point (refer to Figure 2 for the test points, which are indicated in the legend of each graph). In each case, the current is injected by a test lead in the C3 position indicated in Figure 2, with the current return electrode located 6 grid lengths from the perimeter of the grid. The potential rise of the grid at each test location is measured with respect to a remote point and with no induced voltages in the potential test lead. The transmission lines shown in Figure 2 are present, with the OPGW type of shield wire, which represents the worst case.



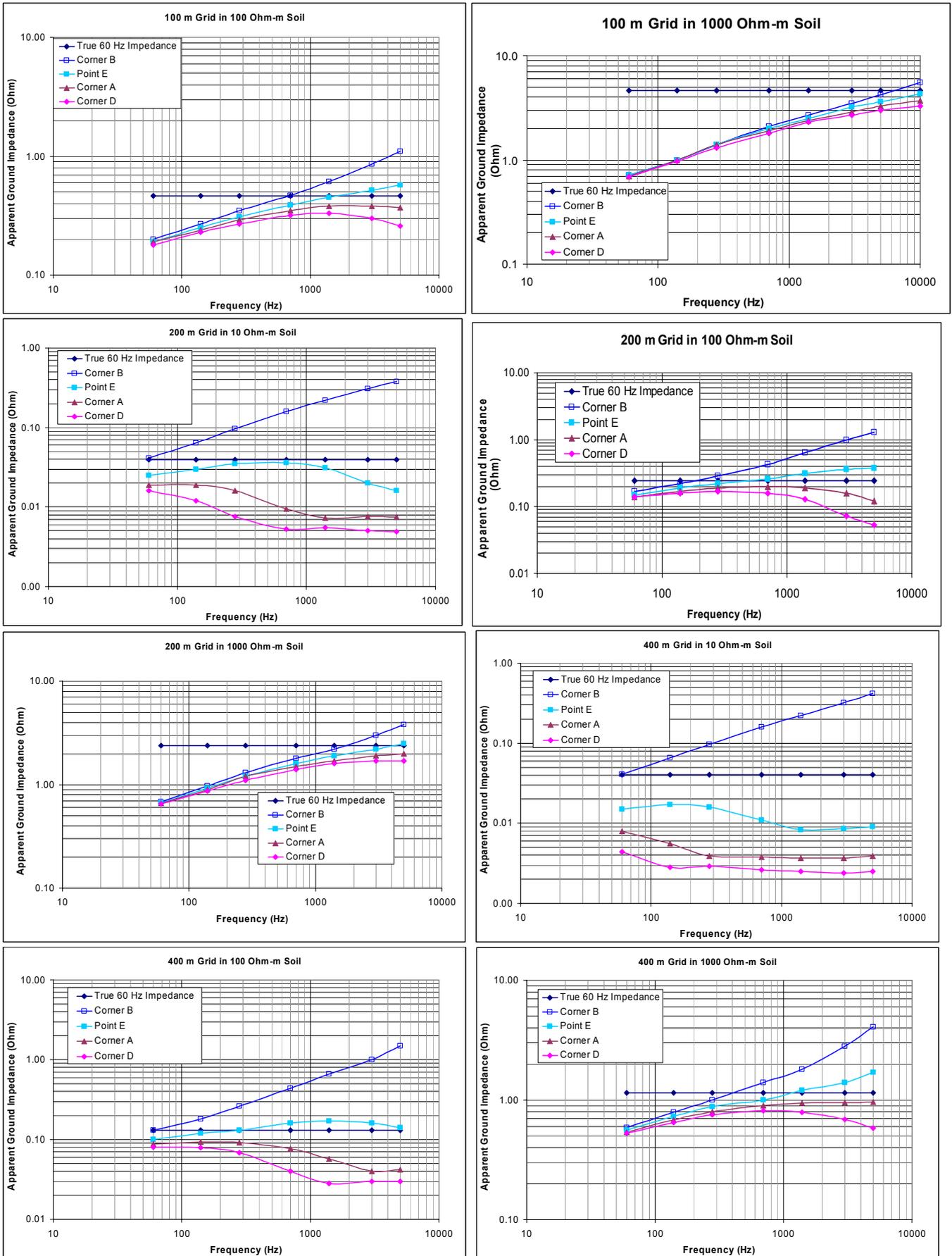


Figure 5 Measured Grid Impedance as a Function of Frequency and Potential Lead Connection Point

The following observations can be made from Figure 5:

1. For very low resistivity soils (in this case, 10 ohm-m), good test results are obtained using a test current on the order of 60 Hz and connection of the potential test lead to corner B. Note that the “true” grid impedance is considered to be the impedance measured with a 60 Hz (or so) test current injection at corner B, with a remote current return electrode, no inductive coupling from test leads, and with no external grounding connected to the grid. Other definitions are possible, since the grid impedance varies as a function of the current injection point.
2. On the other hand, for high resistivity soils (in this case 1000 ohm-m), low test signal frequencies result in severe underestimation of the true grid impedance, because the grid impedance is comparatively larger with respect to the impedance of the transmission line shield wires, which therefore allow the grounding effect of the towers to be more pronounced.
3. Measured voltages and therefore impedances at corner B, where the current is injected, tend to rise sharply with frequency, making it necessary to choose the test current frequency with high precision if good measurement accuracy is desired. This makes this test point less attractive for moderate to high resistivity soils.
4. Test point E, on the other hand, not only rises less sharply than corner B as a function of frequency, but also, as a result, approaches the true grid impedance over a significantly wider range of frequencies for moderate to high resistivity soils. That makes this connection point for the potential rise reference test lead more useful, particularly for such soils.
5. Clearly, computer modeling of the grounding system, external grounding connections, and soil structure make it possible to choose an optimal frequency range and grid connection point. If measurements are made in the field for a range of frequencies, then the optimal one can subsequently be chosen during interpretation of the field data.

3.3 Test Lead Routing

The influence of test lead routing on the accuracy of measured impedances was studied by varying the current injection point on the 200 m x 200 m grounding grid described in Section 2, the test lead separation angle, and, when parallel, the separation distance between the two. The test current frequency, type of transmission line shield wires and soil resistivity were varied as well. The following table summarizes the results of this parametric analysis:

Current Injection Point (Fig. 2)	Test Lead Positions (Fig. 2)	Lead Separation Angle	Test Lead Separation (m)	Frequency (Hz)	% Error in Measured Impedance			
					Steel Shield Wires Only			Steel + OPGW Shield Wires
					10 Ω-m soil	100 Ω-m soil	1000 Ω-m soil	100 Ω-m soil
B	C3 – P3	90°	-	60	+ 11	- 17	- 57	- 30
				140	+ 68	- 3	- 5	
				700		+ 96	- 24	+ 79
				1400		+ 191	- 4	+ 193
				5000		+ 527		+ 527
	C3 – P5	30°	-	60		- 10	- 62	
				140		+ 21		
				700			- 16	
				1400			+ 12	
	C3 – P4	60°	-	60		- 14	- 58	
				140		+ 3		
				700			- 25	
1400						- 6		
A	C1 – P1	0°	1	60	+ 745	+ 75		+ 65
				140	+ 1715	+ 262		+ 260
				700		+ 1478		
			5	60		+ 40		
				140		+ 177		
				700		+ 1067		
			10	60		+ 26		+ 14
				140		+ 140		+ 137
			20	60		+ 11		
				140		+ 104		
			40	60		0		
				140		+ 72		
	C1 – P2	90°	-	60		- 26	- 62	- 44
				140		- 11		- 24
				700			- 34	
1400						- 23		
C2 – P1	90°	-	140		- 10		- 20	

D	C4 – P6	90°	-	60		- 30	- 68	- 58
				140		- 20		- 43
				280		+ 3		+ 3
				700			- 47	
				1400			- 36	
	C4 – P7	45°	-	140		- 10		

The following observations can be made from this table:

1. At low test frequencies, the conductive OPGW shield wires result in greater error, as they depress the measured impedance of the grid further below the grid's true impedance than the more resistive steel shield wires do; at higher test frequencies, both types of shield wire yield similar results.
2. Running the test leads parallel to one another easily leads to excessive error, particularly when the soil resistivity is low or when the test frequency is even moderately high. Increasing the lead separation distance reduces the error substantially, but it remains high for all but the lowest frequency.
3. Running the test leads at angles of 30 to 60 degrees with respect to one another results in little increased error, compared with the 90 degree angle, up to fairly high frequencies (i.e., 1400 Hz) when the soil resistivity is high; however, for the 100 ohm-m soil, the 30 degree angle results in appreciably higher error for a test frequency as low as 140 Hz.
4. Choice of the corner of the grounding system used for the current injection has a significant impact on the error in the measured impedance; this is particularly true when conductive (OPGW) transmission line shield wires are connected to the grounding system. For example, moving the test point from corner B (see Figure 2), which is completely devoid of nearby transmission lines, to corner A, which has transmission lines entering one adjacent side, to corner D, which has transmission lines entering both adjacent sides, increases the percent error for the 140 Hz test frequency by approximately 10% from one corner to the next with steel overhead ground wires; the increase is about 20% for each change of corner when optical ground wires are present.

4. Conclusions

This paper has demonstrated that the accuracy of a ground impedance test is highly dependent upon a number of variables, the most important of which can be controlled. The parametric analysis conducted in this study provides those planning field tests with reference data allowing them to estimate the accuracy of test results, as a function of grounding system size, soil resistivity and layering, test electrode positioning, test signal frequency, and proximity to connection points of external grounds to the grid. It is shown that computer modeling of the grounding system and associated connecting conductors to external grounds can be indispensable for the determination of suitable test signal frequency ranges and grid connection points for test electrode leads.

Acknowledgements

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