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Testing Grounding Systems

- Why
- How to Specify
- How to Test

Why do we test Grounding Systems?

- We all know that exposure to electrical shock can kill you; is that not enough?
- We have design engineers doing their best to design a safe installation, but is it safe?
- It's safe for humans, but what about the installed equipment?

Why do we test Grounding Systems?

Per IEEE Std 81-2012:

- To verify adequacy of new grounding system
- To determine if there are any changes to an existing grounding system
- To identify hazardous touch and step voltages
- To determine Ground Potential Rise (GPR) for protecting communications circuits.

How to Specify

We see numerous testing specifications come though our office

- Some specify Ohm values for selected items of interest
- 99% of the specifications detail the method of test as Fall of Potential method

So what's the problem?

How to Specify – some examples

3.7 FIELD QUALITY CONTROL

A. Testing Agency: Engage a qualified testing agency to perform tests and inspections.

B. Tests and Inspections:

1. After installing grounding system but before permanent electrical circuits have been energized, test for compliance with requirements.
2. Inspect physical and mechanical condition. Verify tightness of accessible, bolted, electrical connections with a calibrated torque wrench according to manufacturer's written instructions.
3. Test completed grounding system at each location where a maximum ground-resistance level is specified, at each service disconnect enclosure grounding terminal, at ground test wells. Make tests at ground rods before any conductors are connected.
    a. Measure ground resistance no fewer than two full days after last trace of precipitation and without soil being moistened by any means other than natural drainage or seepage and without chemical treatment or other artificial means of reducing natural ground resistance.
    b. Perform tests by fall-of-potential method according to IEEE 81.
    c. If resistance to ground exceeds the following specified values, notify Architect promptly and include recommendations to reduce ground resistance.
        1) Service entrance main ground: 10 ohms.
4. Prepare dimensioned Drawings locating each test well, ground rod and ground-rod assembly, and other grounding electrodes. Identify each by letter in alphabetical order, and key to the record of tests and observations. Include the number of rods driven and their depth at each location, and include observations of weather and other phenomena that may affect test results. Describe measures taken to improve test results.

C. Prepare test and inspection reports.

END OF SECTION

How to Specify – some examples

B. Testing Agency: Engage a qualified testing and inspecting agency to perform the following field tests and inspections and prepare test reports:

1. After installing grounding system but before permanent electrical circuits have been energized, test for compliance with requirements.
2. Test completed grounding system at each location where a maximum ground-resistance level is specified, at service disconnect enclosure grounding terminal, at ground test wells, and at individual ground rods. Make tests at ground rods before any conductors are connected.
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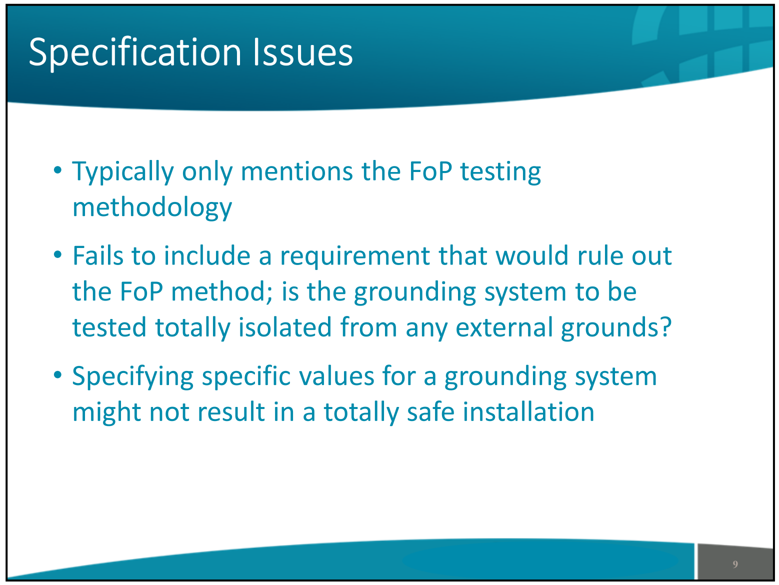
   b. Perform tests by fall-of-potential method according to IEEE 81.
3. Prepare dimensioned drawings locating each test well, ground rod and ground rod assembly, and other grounding electrodes. Identify each by letter in alphabetical order, and key to the record of tests and observations. Include the number of rods driven and their depth at each location, and include observations of weather and other phenomena that may affect test results. Describe measures taken to improve test results.
4. Conduct three separate tests on opposite sides of grounding grid.

How to Test

What are the problems with the existing specifications?

Are there any problems with the tried and tested Fall of Potential (FoP) method?



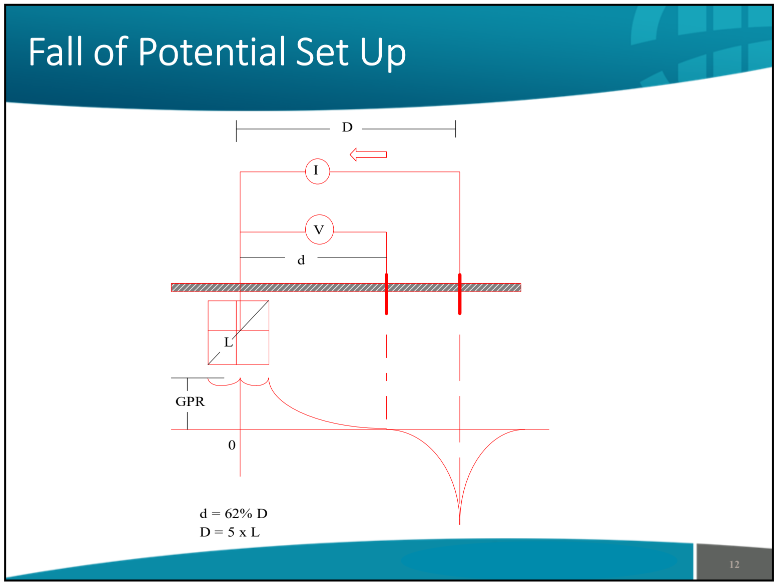
While the specifier may state that the grounding system must be isolated for testing, we can attest to the fact that when we get to the site for testing, the grounding system is already connected and the everything is often already energized

Methods for Testing

- Fall-Of-Potential Method
- Computer Based Grounding Multimeter Method

Fall of Potential

- Developed in the 1950s when we were less congested
- Does not work well on large ground systems or odd shaped grounding areas
- Ground under test must be isolated – no O/H Statics or Neutrals bonded to ground grid
- No connection from construction supply neutral to site ground
- No error correction for induced voltages and noise
- Small data set
- No statistical analysis



The Fall-of-Potential test is very easy to perform. For maximum accuracy the current return probes (D) should be placed 5 times the diagonal length (L) of the ground grid. The voltage probe is then placed 62% of the current probe distance (d). The resistance read on the meter should be the resistance of the grid to remote earth. From this set up if the voltage probe is moved closer to the grid the resistance should decrease and conversely if it is moved further from the grid the resistance should increase. There should be a distance, for example (60% - 64%) where the resistance appears to be the same. For better assurances several measurements should be taken by moving the voltage probe in equal intervals spaced from the grid.

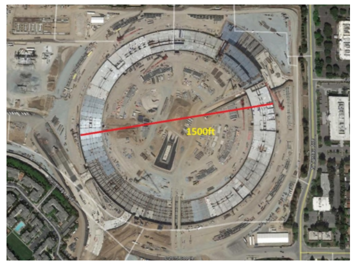
From my experience the 62% rule works very well for small grounding areas of no more than a couple hundred square feet. For large grounding areas this method can be very difficult. It is recommended that two sets of measurements be performed. One as described above and the other where the current probe remains in the same position and the voltage probe is placed 180° from the current probe. Measurements are taken every 100 feet and both sets of data are plotted. Where the two curves intersect is the resistance of the grid.

The problems with these methods are: grid must be isolated from all other grounds, insufficient data collected, no noise correction, and lack of statistical analysis of the results obtained.

Fall of Potential Set Up

Isolate the ground to be tested.

Set up the various probes.



Rule 1: Current at 5 times diagonal of site

Rule 2: Voltage probe varied from 50% to 70% of distance to current probe

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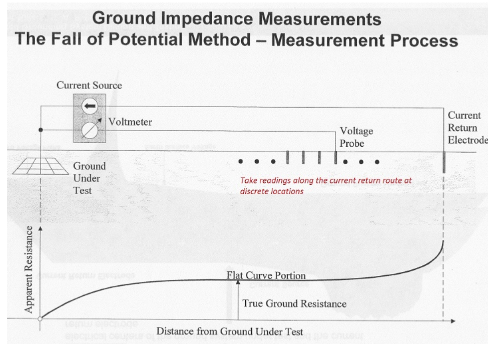
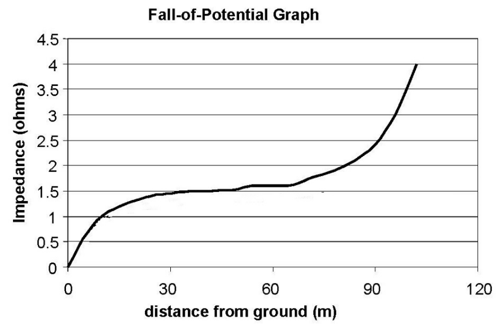
Fall of Potential Results

Ideal results from an isolated ground FoP test



Fall of Potential Results

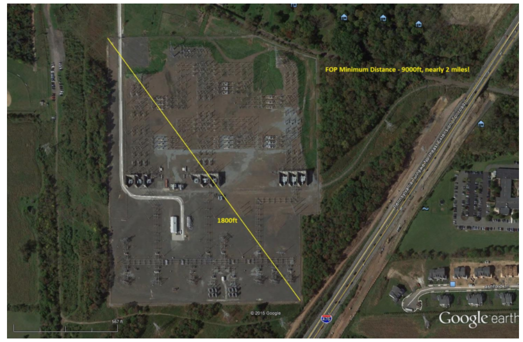
Typical results from an isolated ground FoP test



Performing FoP in this type of congested area for any size grounding system will be extremely difficult if not impossible

FoP Limitations

Large site - already bonded and energized



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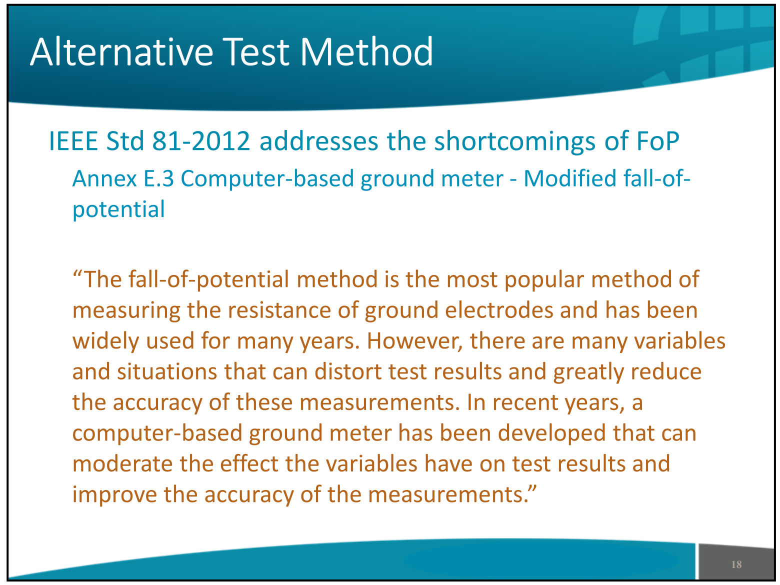


The biggest advantage for me is that the grounding systems to be tested do not have to be isolated from neutrals, OHS, Telcom, water-lines or any other ground sources when using the SGM.

Current is injected into the grid and returns through the red conductor. Simultaneously, the ground potential differences are measured at the three blue and three yellow probes. The phase angle of those voltages are recorded as well.

Typically, the reactance of a ground grid is small when compared to the reactance of neutrals and OHS. The software calculates the grid impedance based on the amount of current injected, the voltage differences between the probes and the phase angle of those voltages.

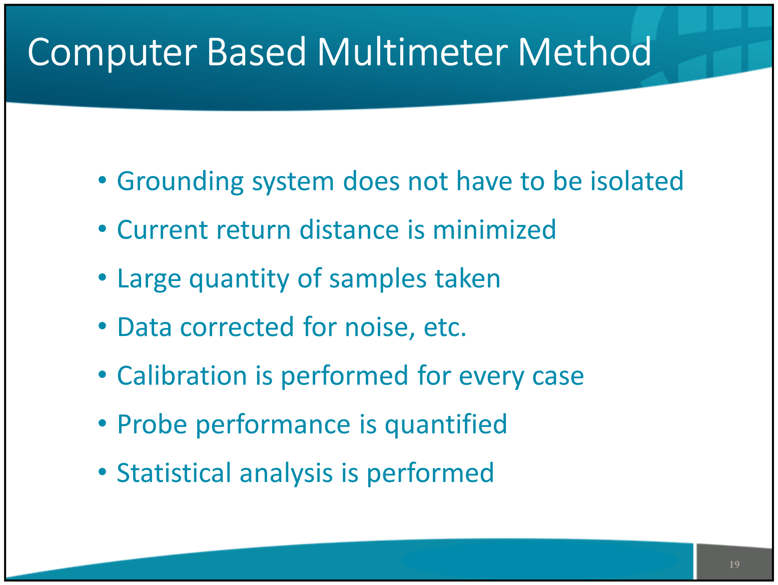
Using the default settings in the software about 125,000 data points are taken per case.

A calibration of the voltage leads is performed for each case. The calibration performs corrections for the voltage lead length and determines the resistance of each Voltage probe to earth.

The data collected and voltage probe performance is qualified.

The current return probe does not have to be positioned as far as it does for the Fall-of-Potential method (minimum of 2 times the diagonal).

A statistical analysis is performed comparing the measured data to the expected data based on the geometry of the grid with respect to the probe locations.



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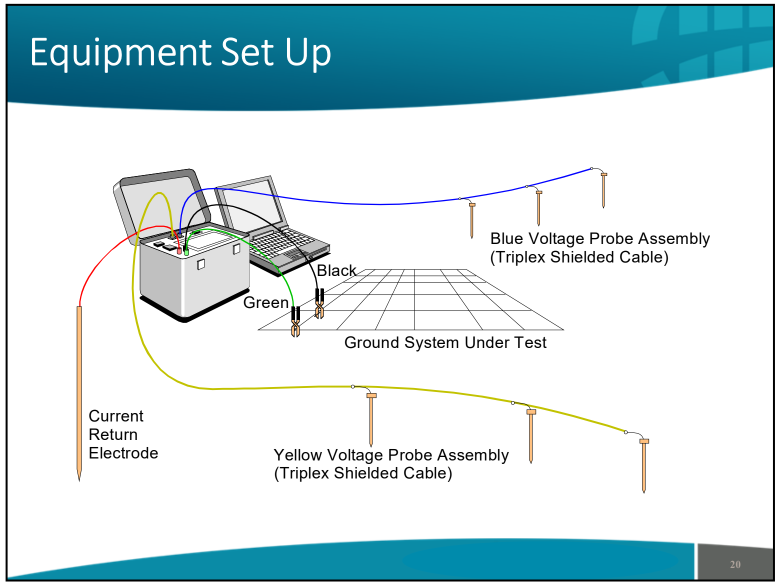
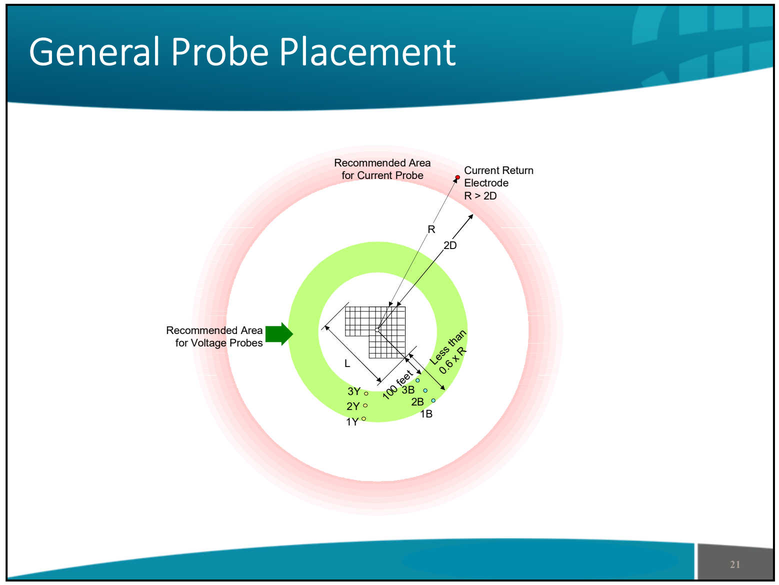


This shows the components that make up the SGM: laptop, current injection unit, the current return electrode, the three blue and three yellow voltage probes, the green reference connection and the black, current injection connection. Ideally the green and black connection should be separated by several feet but it is not necessary.

Defining the set up in the geometry section of the software is quite critical. It is more important to adequately define the outer geometry of the grid shape and size than what is inside the grid. Also, the more accurately the probe placements are defined the better the results will be.

I always sketch the set up prior to inputting the data into the program. This sketch is very valuable when your back in the office trying to remember just what you did out in the field.

I usually try to set up in a corner and run the voltage probes so that they are 90 degrees apart or I place the voltage probes directly in line with the current return electrode.

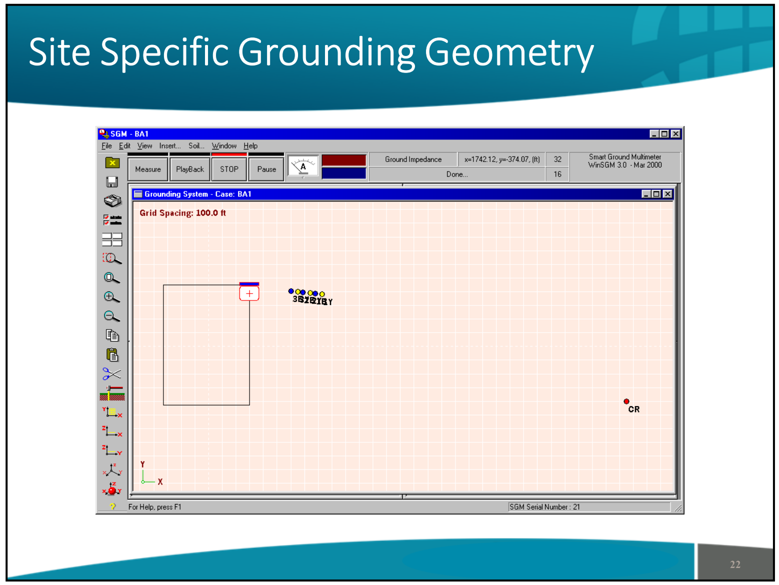


This depicts the general physical limitations regarding the current and voltage probe placements with respect to the ground grid.

The current return electrode should be placed no closer than 2 times the longest diagonal distance of the grid. If the current probe is not placed far enough from the station a warning message will be displayed.

The voltage probes should be placed no closer than 100 feet from the station and no closer than 1.2 times the longest diagonal distance of the grid. If the voltage probes are placed to close to the current probe a warning message will be displayed telling the user which probe is to close to either the grid or current return electrode.

It is best to keep all probes away from distribution and transmission lines, water lines and Telco lines if possible.



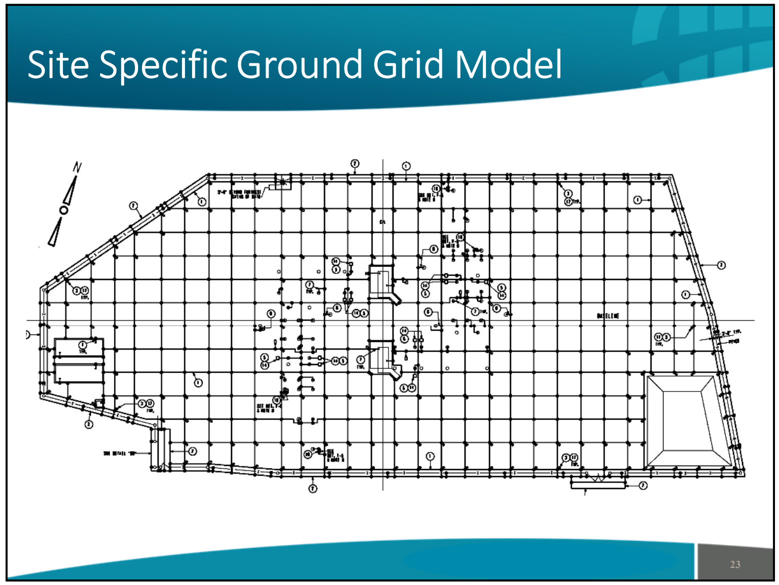
This is the Probe and Grounding editor window. In this window the ground grid geometry is defined including the locations of the voltage and current probes. The numbering of the voltage probes is 1 through 3 with 1 being the first voltage connection coming off of the reel and 3 being the last or closest probe to the station.

All items defined in the Grounding Editor have unique Group numbers. Group number 1 is the ground grid, 2 through 8 are used for the voltage probes and current return probe respectively, 9 and greater can be used to define other grounded items that are not tied to the grid.

Please note that the Interstate highway symbol represents where the SGM unit is with respect to the grid. The default position is in the center of the grid. Always move the SGM unit to the area where it is connected to the grid.

All voltage and current probe distances should be entered as if from the 0,0 coordinates of the grid. The repositioning of the SGM unit will correct those distance in the program.

Details of using the ground grid editor and building the ground grid model will be discussed later in this presentation.



SGM Ground Grid editor model showing fence, ground rods and buried ground conductors.

Site Test View

24

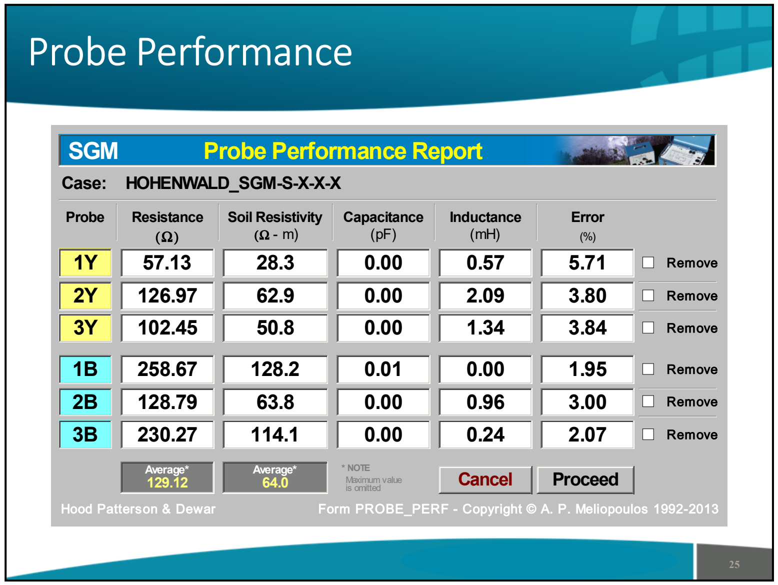
Using Google Earth to gain an overview of the site to be tested.

Two possible options for the current probe placement:-

Discuss at class session

By following the transmission right of way, there will be more electrical noise induced into the current leads.

For the second option, actual site inspection will determine if this route is viable.

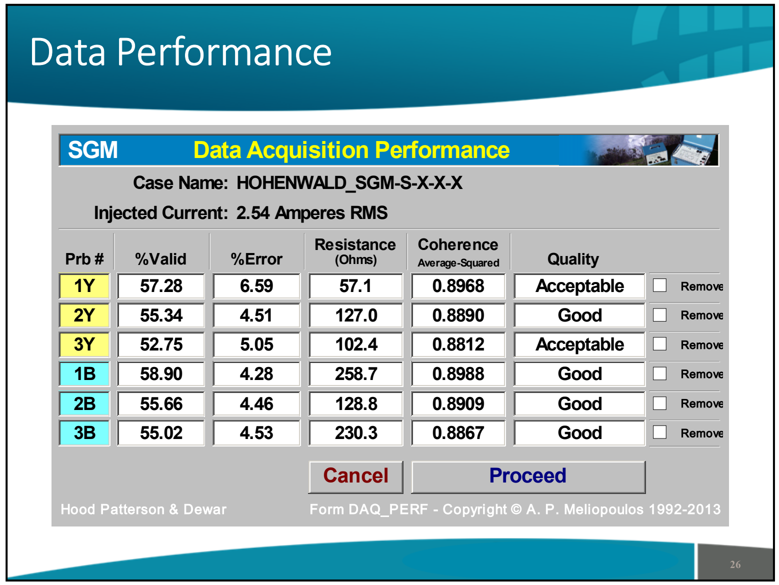


Probe Performance Report shows the first set of results presented by the SGM. For every test, the first thing the SGM does is to determine the performance of the voltage measurement probes. After all, the voltage probe measurements are the source of the measurements made by the instrument. During the setup for any test, the number of probe calibration tests and number of measurements made can be selected.

During this portion of the test, the SGM injects current into one voltage probe and measures the resistance and error for the other voltage probe. Each pair of probes is calibrated at a time and after the user selected number of calibrations, the probe performance report is presented.

Voltage probes should have resistances less than 1.0-k Ohm. If at the end of the calibration tests the results are unacceptable, the test can be terminated and the probes improved.

Improving the voltage probes by the addition of salt water and the addition of a second probe (placed 2 feet apart) usually improves the situation.



Prb #	%Valid	%Error	Resistance (Ohms)	Coherence Average-Squared	Quality	
1Y	57.28	6.59	57.1	0.8968	Acceptable	Remove
2Y	55.34	4.51	127.0	0.8890	Good	Remove
3Y	52.75	5.05	102.4	0.8812	Acceptable	Remove
1B	58.90	4.28	258.7	0.8988	Good	Remove
2B	55.66	4.46	128.8	0.8909	Good	Remove
3B	55.02	4.53	230.3	0.8867	Good	Remove

The Data Performance window displays in laymen's terms what the spectrum analysis windows displayed for each voltage probe. This information makes the SGM unit much easier to use.

The RMS injected current is listed. The % Valid column displays the amount of data that will be used in the upcoming calculations. In this case it is somewhat low due to the large amount of harmonics in the ground. The % Error column is the amount of error in the used data. For a distribution station the % Error is normally around +/- 2.0%. The Resistance column tells us what each probe resistance is. As long as the value is under 1.0kΩ the software wont display an error message!

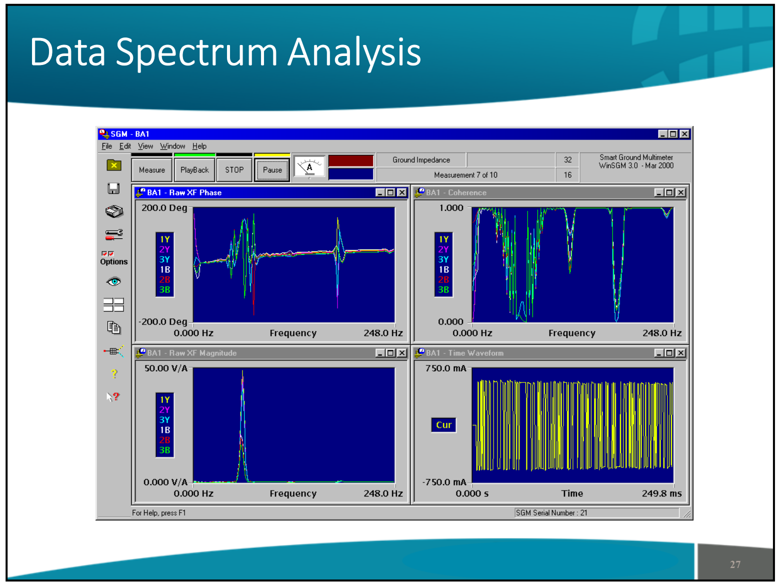
Low probe resistance is required due to the use of high impedance voltage measurement circuit. High probe resistance increases the probability of measuring noise in the circuit.

Typically the injected current should be as high as possible, but anything over 2.0 Amps is adequate. For testing I prefer to have current in the 3.0 to 5.0 Amp range as a high signal (current) to noise ratio improves the test results.

The Quality column is a qualitative evaluation of all three previous columns into the following descriptions: Excellent, Good, Marginal, Poor, and Unacceptable.

The Remove column allows the user to remove a particular probe data set from the calculations by checking the appropriate Remove box.

You can remove up to 3 individual sets of probe data and the software will calculate an answer. However, confidence and error will typically increase.

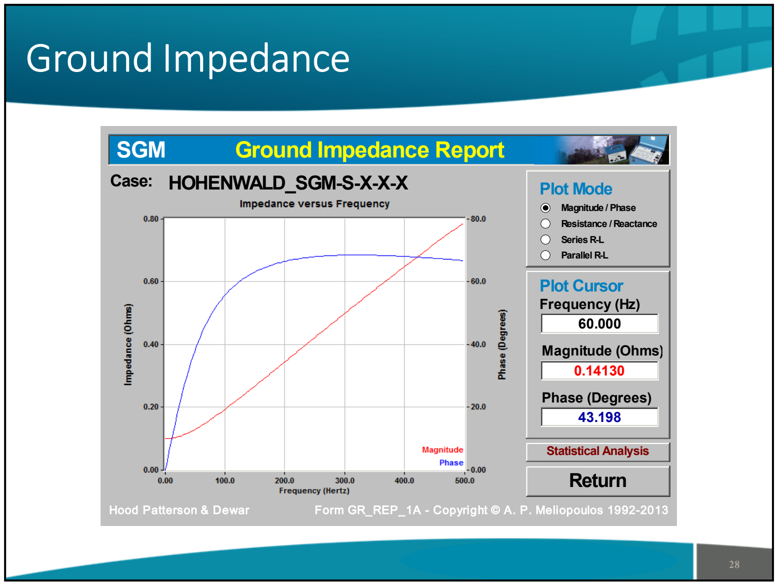


The Data Spectrum Analysis window has a multitude of analysis windows for the user to view. These are the default windows that I typically never change. The graphs are dynamically linked to the downloaded data. I'm asked this question every time so here's the definition: Transfer Function is "that function of frequency which is the ratio of a phasor output to a phasor input in a linear system". Good now that's out of the way!

Generally speaking if all of the lines are grouped close together in Windows 1, 2, & 3 (Left-Right, Top-Bottom) things are going good. If one line is far removed from the others the Probe Performance for that line will not be as good as the others and you may need to check on that probe.

Window 2, Coherence, vividly displays the harmonic interference in the ground voltages. Please note the huge amount of distortion at the 60, 120 and 180 hertz levels. Notice the large separation at 60 hertz. This is caused by the soil modulating this frequency and indicates a large amount of 60 hertz ground current. No data is used within this 30 - 90 hertz range. How accurate of a ground impedance result would you expect if you were using a device that injected current at 92 hertz?

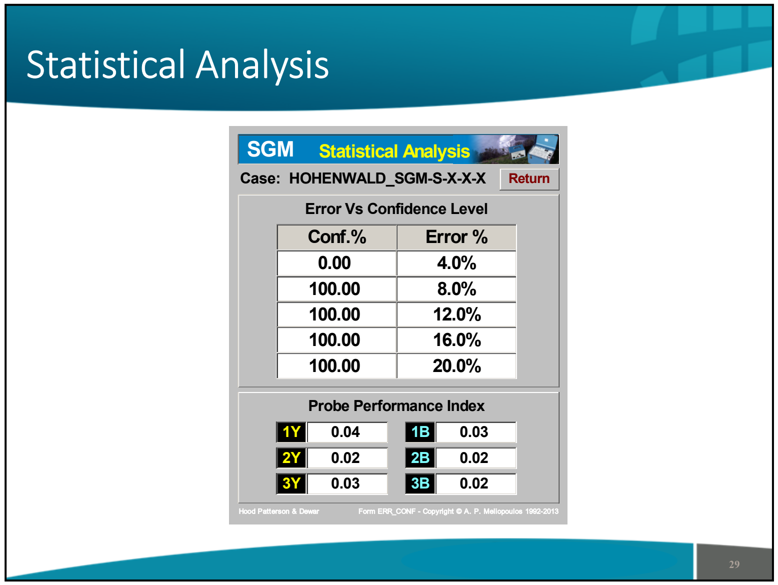
Window 4 displays the peak RMS current that is randomly injected over time.



The Ground Impedance Test is the measurement of the total grounding system impedance of everything connected to the ground grid with respect to remote earth. This is the ground impedance for that TN ground grid. The Red line is the impedance versus frequency with impedance on the left Y axis. The Blue line is the phase angle versus frequency with the phase angle on the right Y axis. Frequency is the X axis.

You can’t tell from this picture but when the program is running one uses the mouse to pick a point on the graph and the frequency, ohms, and phase values are displayed in the boxes under the Plot Cursor.

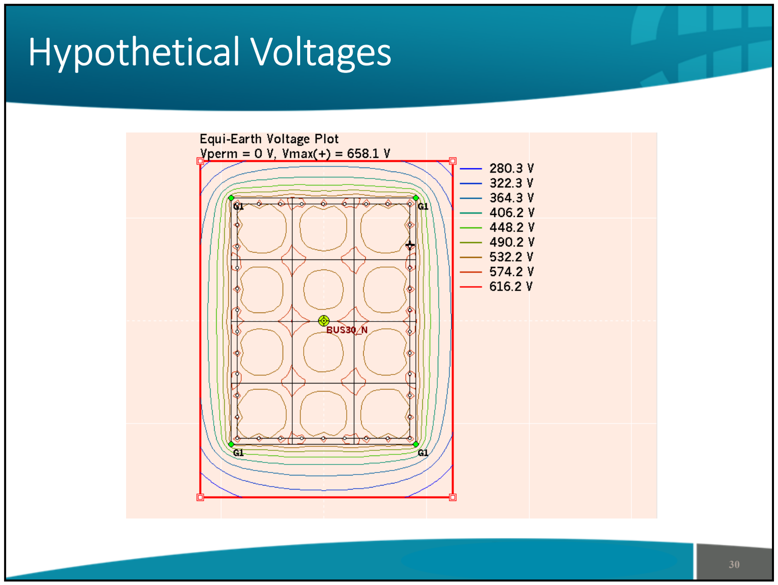
Clicking on the box labeled Statistical Analysis reveals the following screen.



The Statistical Analysis shows, in percentages, the confidence versus error in the presented result. The results for this substation are quite good. Actually, one of the best runs I've seen. This is due to the substation location which was out in a desolate area, there was no distribution system to deal with, the soil structure was fairly homogeneous, and while it was a large station it was not huge. Many times the analysis will indicate low confidence and high error but it does not mean that the impedance value is wrong. When high error occurs it is typically due to unknown grounded objects in the area that aren't and can't be modeled.

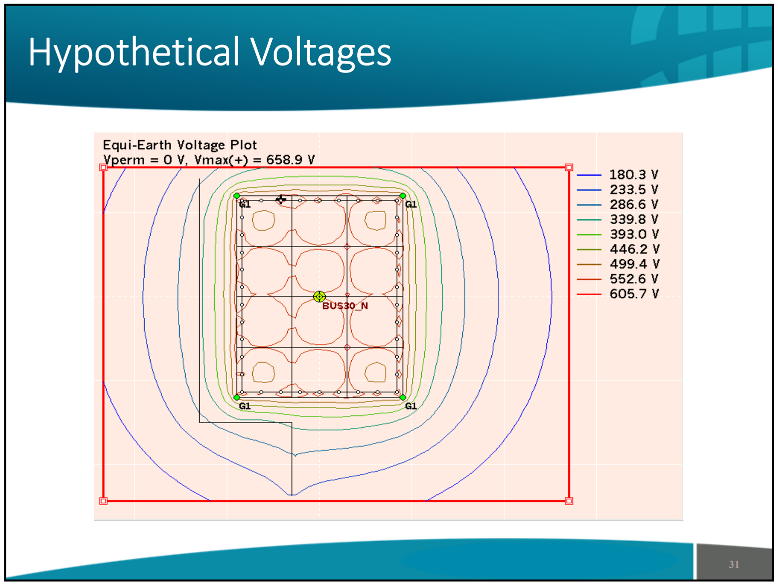
The Probe Performance Index data is very good. This number can range from 0.01 to 1.0. The higher the number, the more inadequate and inaccurate the data is from that probe. The lower the index the better. If a particular probe has an extremely high index, or it goes negative (-1.0) , it was probably placed over a grounded and or bonded object and it needs to be moved. A disconnected voltage lead will yield a negative index also.

Now, with that being said, the statistical analysis is based on the comparison of the measured data to modeled data derived from the geometry of the grounding system that the user defined. The key items in this comparison are the exterior grid geometry, probe placements, and soil structure. Usually, as mentioned above, there are many grounded items in the surrounding area that can't be modeled. This will skew the comparison made between the modeled (expected) voltages and what is actually measured.

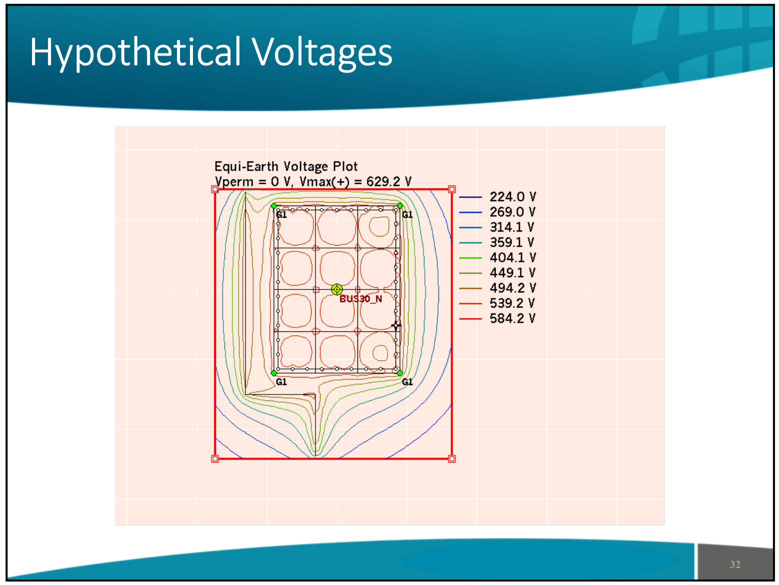


The next few examples are ground grids that I modeled in a grounding design program to display how voltage gradients occur in the soil and how those gradients can be affected by other grounded objects in the area.

If a voltage probe was set along the negative Y axis about 50 feet outside the station one would expect to read 280 volts to remote earth. You can see that the voltage gradients are fairly smooth and attempting to form a circle the further one gets from the station.



Same station but I've added a ground conductor that is not tied to the station. If the voltage probe is located in the same location as in the previous picture one would expect to read about 233 volts to remote earth. That's 50 volts less than the other slide and would represent an -18% error if the conductor is really located there but not shown in the model.



Same station with the added conductor but I've modeled this conductor in the same group as the ground grid which means they are electrically bonded together in the program as a 0% impedance connection. Same probe as before would measure about 350 volts. This represents about a +20% error in the measured data to the modeled data.

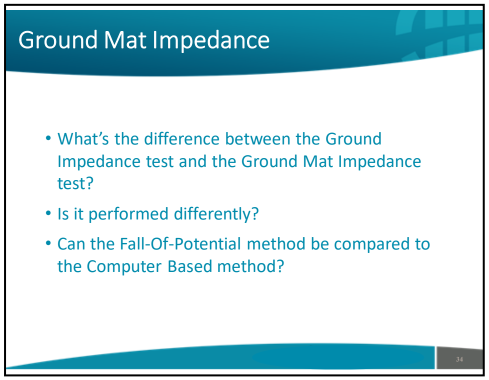
This is a complexity that we have very little control of. If known grounded objects are in the area the best thing to do is stay away from them. If the geography does not allow that, then those objects can be added to the model but add them cautiously. The problem is this. When a ground is added as a Group 1 it is a 0 impedance connection to the grid. Presently, the software doesn't calculate an impedance for any Group 1 connection therefore, no voltage drop is considered along the ground conductor.

It is probably better to add them as a different Group number such as 9 or greater. Play back the data and see if the statistical analysis and probe performance improves. If not, change that added object to Group 1, the same Group as the ground grid, and replay the data.

If a particular probe has an extremely high index, or it goes negative, it is probably been placed over a grounded or bonded object, or a highly resistive area in the soil. As in the soil resistivity tests, salt water will reduce the probe resistance and lower the probe index number.

Ground Impedance Problems

- High probe index (poor probe performance)
- High error/low confidence
- Insufficient injected current
- High earth voltage harmonics

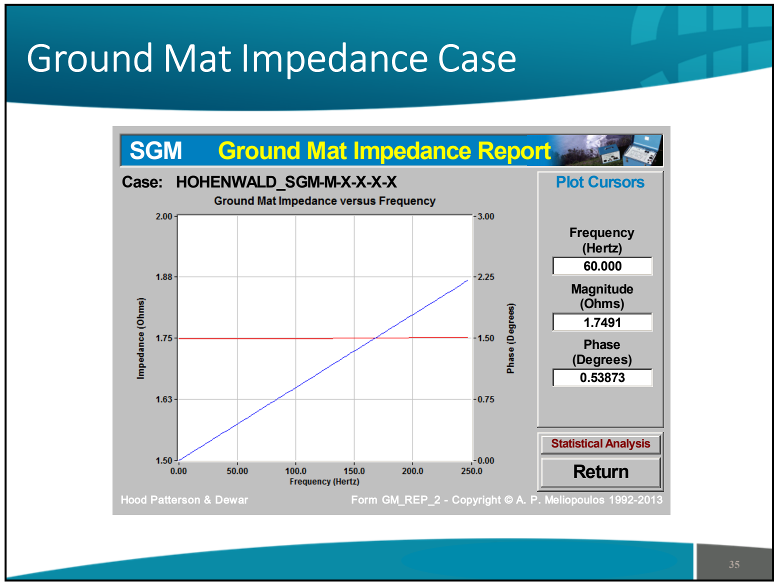


The Ground Mat Impedance Test is the measurement of the ground mat impedance to remote earth.

The same setup is used for both tests. Therefore, the same data can be used. You can go through the motions of injecting current and measuring voltages or you can save the Ground Impedance case using the "save as" Windows function and save it as a Ground Mat Impedance case. Then open that case and do a "Playback". The data will be recalculated and the results will be displayed in much the same fashion as the Ground Impedance test.

The ratio of the Ground Mat Impedance to the Ground Impedance is the "Split Factor" for that substation. The "Split Factor" is that amount of current that will return through the grid to the source versus the amount of current that will return to the source through the other paths, i.e. neutrals, OHS, Telco, water and sewer lines. The "Split Factor" is extremely important in determining the Touch and Step voltages for the substation.

The Fall-of-Potential can be directly compared to the SGM as long as the current return and voltage probes are placed along the same axis, and one of the voltage probes is placed close to the 62% area. Open the SGM case as normal then open the Study Case Parameters window and change the Lead Induction from "Remove" to "Ignore" and hit "Playback". The result should compare quite closely to the value obtained from the Fall-of-Potential test.



This is the Ground Mat Impedance for a station in TN. The grid impedance is 1.75 Ω with a slight phase angle which is indicative of a small amount of reactance due to the area of the grid. The impedance of a smaller grid is normally shown as a flat line across the frequency spectrum.

The “Split Factor” for this station is about 50%. This results in a fairly even split of the fault current. If the line to ground fault current for this station is 35,000 amps then only 17,500 amps would flow from the grid through earth to its source. So, basically the grid could be designed with half as much conductor.

Obviously, for a new station there is no grid to test; however, if the “Split Factor”, that can be approximately determined from IEEE guidelines, was used in the design then it can be verified after the grid is installed. This is especially important in designs where the engineer is forced to rely on a less conservative “Split Factor” due to high soil resistivity, small grid area, and high fault currents to make the station safe.

“Split Factor” curves can be found in the IEEE Std 80-2000 Guide for Safety in AC Substation Grounding.

Summary

TESTING CHALLENGE	FOP	SGM
Isolated ground grid	Yes	No
Distance for current probes	5-10 times ground grid diagonal	2 times ground grid diagonal
Current electrodes – need sufficient current	Typical test equipment = 5-40mA	2-15A
Voltage electrodes – need low resistance	Probe resistance unknown	Probe resistance quantified & qualified by software
Stray currents	Can influence result - unquantified	Influence removed by software
Reactive component of impedance of large ground grid	Can influence result - unquantified	Influence documented by software
Ground grid shape	Large and/or complex shaped grids require knowledge of "electrical center" for accuracy	Shape is modeled in software
Coupling between test leads	Can influence result - unquantified	Influence documented by software - Probe placement can be corrected
Buried metallic objects	Can influence result – unquantified, presence unknown	Influence documented - Modeling/set up can be corrected
Phase angle measurements – needed for impedance results	Unknown	Measured at 6 locations
Quantity of Data	Minimal	140,000 data samples per test
Frequency spectrum	Fixed or variable to 400Hz	User selected 0-1,000Hz
Statistical Analysis	None	Based on site model
Resulting measured ground grid impedance value	Unquantified	Quantified & Qualified

What to Specify?

Replace

	natural drainage or seepage and without chemical treatment or other artificial means of reducing natural ground resistance.
b.	Perform tests by fall-of-potential method according to IEEE 81.

with

Perform tests by method as described in IEEE 81-2012.

Questions?

Thank you