



## Ground Impedance Tests

### Fall-of-Potential Method vs. Smart Ground® Meter Method

The following discussion will describe the test methods for measuring the ground impedance of a substation ground grid; The Fall-of-Potential (FOP) method and the Smart Ground® Meter (SGM). The FOP method has been used for years while the SGM method is the relatively “new kid on the block.”

### Fall-of-Potential Method

The FOP method is the most popular method of measuring the ground impedance of a substation ground grid. The test equipment is typically very portable and either battery powered or hand-cranked. The test frequency on the battery powered units is normally fixed at a value that is different from the power system fundamental frequency of either 50 or 60 hertz. The fixed test set frequency can range from 20 hertz to 418 hertz depending on the manufacturer. The battery powered units are typically digital units. On the older, analog hand crank units, the test frequency varies with the speed at which the unit is cranked. Crank slowly for a lower frequency, crank faster for a higher frequency.

The FOP test method and probe arrangement is fully described in the IEEE Std. 81-1983 and Std. 81.2-1991. Please note in Std. 81-1983, page 10, Section 6.1 - **Complexities**

1. With the development and industrial growth adjacent to power substation, it becomes difficult to choose a suitable direction or locations for test probes to make a resistance test. Moreover, the connection of overhead ground wires, buried water pipes, cable sheaths, etc. all have the effect of physically distorting and enlarging the ground grid (par. 3).
2. Ground impedance measurements should be made immediately after the ground grid has been installed to insure that there are no major omissions of the grounded components normally connected to the grid. Future installations of water pipes, rail, etc. will alter the readings (par. 4).

Also, per the standard's definitions, a Ground Grid is a system of grounding electrodes consisting of interconnected bare cables buried in the earth to provide a common ground for electrical devices and metallic structures while the Grounding System consists of all interconnected grounding connections in a specific area.

The FOP test procedure is based on the fact that the earth voltage potentials, with respect to *remote earth* decrease the further one gets from the ground grid. If one gets far enough from the ground grid, theoretically the voltage is zero which is, for all practical purposes, referred to as *remote earth*. For the FOP test to work correctly the current return probe must be positioned some distance beyond this zero voltage point, actually about 40% further, or else the voltage gradients around the current probe interacts with the ground grid voltage gradients. On small, isolated ground grids, practical experience





has shown us that a properly placed current return probe location will return accurate test results. However, this same practical experience has also shown that as the ground grids get larger or are interconnected to other grounding sources the ability to accurately measure the ground grid or system impedance becomes more complex.

The Std. 81.2-1991 “IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems” lists many variables and situations that introduce complications and impose constraints on the measurement techniques (Section 5, pages 12 and 13). As this guide discusses many different types of measurement techniques, for the sake of our discussion, we will only discuss those limitations pertaining to the FOP method. Note that Std. 81 was written with its emphasis on testing the Ground Grid impedance while Std. 81.2 was written with its emphasis on testing the Grounding System impedance.

1. Distance to current and potential electrodes – To achieve 95% accurate readings, the current return probe must be located 6.5 times the grids maximum diagonal distance **if the grid is isolated**. If not isolated then the maximum diagonal distance of the grid increases based on the amount of additional conductors, both buried and aerial, connected to the grid (See Appendix C). Current return and voltage measuring probes should not be placed in the vicinity of any other ground source.
2. Selection of test probe locations and test conductor routing (to minimize AC mutual coupling), the voltage probes should be located at 90° to the current probe.
3. Test current sources – Typically, low-impedance grounding systems will require a higher test current than the 5 – 40 mA sources provided by most portable ground testers. The required test current may range from 0.1 – 100A.
4. The addition of other interconnected grounding sources has a huge impact on the effective ground grid size and shape. Overhead, interconnected ground conductors, neutrals and shielding, significantly increase the reactive component of the grid impedance.

The recommended procedure for performing the FOP test on a large grounding system is to establish the current return probe location (at a distance of 6.5 times the maximum diagonal) and to perform a series of voltage measurements, each measurement progressively further from the grid than the last, until the difference between several of the voltage readings are negligible. The voltage probe should be placed 90° to the current probe location to minimize mutual inductance. If this can't be accomplished, then the phase angles of both the injected current and measured voltages must be measured and accounted for. Next, the current return probe distance should be increased significantly and the potential measuring procedures repeated. It should be noted that even under homogeneous soil conditions with a grid having no extended ground connections and a current probe spacing 50 times the maximum grounding system dimensions the expected measurement error could be 1.5%.



There are many factors that affect the ability to accurately measure the ground impedance of a large ground grid or system:

1. Background noise and voltage resulting from conductive coupling
  - a. Neutral current flow through earth
  - b. Harmonic current flow through earth
  - c. Circulating current through extended interconnected conductors
  - d. Impulse-type noise induced into the grounding system
  - e. Telluric stray current
2. Electromagnetic interference resulting from mutual coupling
  - a. Induced voltages from magnetic coupling in the test circuit from nearby current carrying lines or bus
  - b. Induced voltages from capacitive coupling in the test circuit from energized lines or bus

Therefore, it should be concluded from all of the above listed conditions, warnings and problems noted in both Std. 81 and Std. 81.2 that the typical FOP test method utilizing the typical portable test equipment is not suitable for the measurement of ground impedance of large ground grids, and it is definitely not acceptable for interconnected grounding systems. The Std. 81.2 lists several other measurement techniques that are more suitable such as tunable voltmeter method, dual-channel network analyzer method, beat frequency method, magnitude phase nuller method, and others that more accurately measure the ground impedance while correcting and adjusting for all of the problems that were listed above. Each of these methods has their own strengths and weaknesses. Common to all of these other methods is that they are cumbersome, lack data storage, lack voltage lead and probe resistance correction, and do not provide statistical analysis. They also require a greater knowledge of signal processing rules, procedures and processes.

Due to the increased complexities of using the FOP method, inadequate test units, the new improved Std. 81.2, and the difficulties of trying to use alternative test equipment, it is obvious that most testing procedures have been inadequate. While it is not empirically stated, a thorough review of the Standards reveals that the FOP method utilizing simplified, low powered, testing equipment was intended for small, isolated ground grids; typically ground grids smaller than 900 m<sup>2</sup> in size. The test procedures that worked 30 to 40 years ago on smaller, remote, isolated ground grids won't work in today's congested geography. This has resulted in ground tests that are being performed incorrectly per the present standards.



## SGM Method

The development of the SGM test method centered on all of the known inherent impedance measurement problems and test equipment limitations that have been mentioned above. The SGM test equipment has two primary components, a laptop computer running Windows OS and the test unit itself. The test unit is a combined variable frequency current source and a six channel data acquisition platform. The SGM software, which is installed on the laptop, interfaces with the test unit via a USB cable. The software allows the operator to select the function or test that is to be performed, change various test parameters, and define, through a grounding editor, the basic geometry of the grid under test and the position of the voltage and current probes with respect to the ground grid.

The SGM method is an enhancement on the dual-channel network analysis method that is discussed in Std. 81.2-1991, pages 23, 24. The SGM uses seven channels, one for the injected current and the other six are for the measured voltage. The use of six voltage channels allows more data to be collected during the current injection period. This increases the overall accuracy of the impedance value and provides better statistical analysis of the collected data. One key component in these measurements is the magnitude of the phase angles of the voltages and current. The SGM measures the phase angle to a resolution of  $10^{-3}$  and typically collects more than 140,000 samples of data. While the SGM follows the fundamental principles of the FOP method, it differs in that the SGM method emphasizes the potential differences between the six voltage probes, along with their unique voltage value with respect to the ground grid. By concentrating on the voltages differences, the current return probe need only be placed about 2 times the maximum diagonal distance of the grid. This reduction of distance coupled with the one time placement of the voltage probes, significantly reduces the testing time when compared to the correct procedures for performing the FOP method. The many advanced features that the SGM offers over the typical Fall-of-Potential (FOP) test devices are listed below:

- Ground grid does not need to be isolated from other grounding sources
- Current is injected over a user selected frequency spectrum (example: 0 – 250 Hz, 0-500 Hz or up to 1,000 Hz)
- Selectable voltage source (150, 250 or 500 volts)
- Injected current magnitude (2 to 15 amps) is typically 100 times greater than most FOP test devices
- Ground potentials and their phase angles are measured at 6 discrete locations
- Typically 10 current injections are performed for each individual test
- Typically 140,000 data samples are collected
- Voltage conductors and probes are calibrated prior to each test
- Lead induced voltage is removed
- The collected data and voltage probe performance is qualified
- The data is corrected for noise and harmonics
- The current return electrode does not have to be positioned as far from the ground under test (minimum of 2 times the grid diagonal)



Through a Ground CAD Editor, the operator draws the ground grid under test and positions the six voltage probes and one current probe in relationship to the grid. There are many ground grid options available such as conductor type, size, depth, and number of ground rods. The most important aspect of the modeled ground grid is accurately depicting its geometric shape. Misrepresenting the shape of the grid can cause more error in the statistical analysis which will be discussed later. Once the test parameters have been selected and the grid modeled, the test begins with first performing a series of voltage lead calibration tests. The voltage lead calibration tests gather data pertaining to the capacitance and inductance of the leads and the voltage probe to earth resistance. The results of these tests are displayed prior to the current injection tests, so if there are problems identified, the operator can adjust the voltage probes prior to the final tests. Knowing the voltage probe resistance early in the test procedure saves time. The voltage probe resistance must be less than 2,000 Ohms for meaningful data collection. No other test equipment provides this information or data. Probe resistance can be lowered by adding salt water, additional probes, or relocating the probe. Once these calibration tests have been completed, the current injection tests occur. The test unit injects current into the subject grid through the earth to the current return electrode. The program performs 10 separate current injections across the selected frequency spectrum (i.e. 0-250 Hz) while simultaneously recording the earth potentials and their phase angles. At the conclusion of the current injection tests the data is summarized in a Data Acquisition Performance table. This table quantifies and qualifies the data for each voltage channel in the following format:

- Percent Valid – this is the percentage of the collected data that will be used
- Percent Error – this is the percentage of error in the used data
- Resistance – probe resistance
- Quality – this is a generalized quality assessment based on the values of percent valid, percent error, and probe resistance

The data is then filtered for noise, smoothed for digital analysis and compared to a model of the grounding system under test. The data is fitted to the modeled ground grid. The best fit follows with the measured ground impedance graph which is plotted impedance vs. frequency. In addition, a statistical analysis is performed on the result of the best fit analysis. There is typically a fair amount of error calculated by the statistical analysis. Due to our life in the “digital” world this error may seem unacceptable. However, the program is comparing the measured voltage gradients to the *modeled voltage gradients*. The *modeled voltage gradients* exist in a perfect computer model; that is, the soil resistivity is homogeneous, the ground conductors are perfect conductors with no resistance, there is zero interference or noise, and there are no other grounding variances in the model. Whereas in the real world where the measured data is collected, very seldom is the soil resistance homogeneous, ground conductors are not perfect conductors and there is always additional grounding variances in the vicinity of the tests (i.e. water pipes; Telco and power lines; concrete structures; roads; etc.). All of these factors have a severe impact when trying to compare perfect modeled data to real world measured data. Accurately depicting the geometric shape of the grid is the only variable available to the operator. For example, if the grid is modeled incorrectly as a square when it is actually a rectangle the modeled voltage gradients will be significantly altered.



In summary, the SGM method embraces many of the recommendations that are discussed in IEEE Std. 81.2-1991 and combines them into a convenient package that simplifies set up time, provides data assessment, statistical analysis, and data storage. The SGM provides additional test functions for performing touch and step voltage, soil resistivity, transfer voltage, and continuity tests. The SGM method adheres to the proper methods as outlined in the Standards. Conversely, what is typically being performed by utilities and testing companies is a convenient shortcut that yields a number that is not corrected for all of the conditions that one normally encounters with large, complex, energized grounding systems.