



White Paper – July 2022

Substation Ground Grid Maintenance & Performance Testing

Ron Proffitt, Project Manager

Table of Contents

Abstract	3
Introduction	3
Safety	3
Problem Statement	3
Review of Step & Touch	5
Problem Causes	5
Testing Strategy	6
Maintenance Testing – Grid Integrity	7
Performance Testing	9
Measurement of Soil Resistivity	10
Ground Mat & System Impedance	11
Conclusion	14
References	14

Abstract

Two of the most crucial substation components related to safety and reliability are the station battery and ground grid. If they do not function correctly, personnel safety and equipment reliability are at risk. With the focus on FERC PRC guidelines, the battery receives plenty of attention, while the ground grid mostly remains ‘out of sight, out of mind.’

Utilities and plants use various grounding strategies and designs, all of which require fundamental testing to ensure the primary objectives of the substation ground grid are being met. Those objectives are to provide low resistance paths for current to flow while maintaining personnel step and touch potentials and equipment bonding are at safe levels. This paper touches on essential ground grid components, common problems, basic maintenance and performance test practices, and examples of identifiable issues.

Introduction

Substation ground grid designs vary greatly as basic electrical components are implemented regardless of the specific design. These components usually include conductive cable runs, grounding rods, and connectors. Components are connected according to the specific design, so all substation power equipment and ancillary components are bonded together. This allows any stray, unbalanced, or fault current to flow through the ground conductors while maintaining step and touch potentials at safe levels, and protecting sensitive digital instrumentation and controls from failure. The ground mat will perform as designed if the ground grid remains intact and the equipment bonded.

Safety

The effectiveness of the substation ground grid is directly related to employee safety. Since the grid condition is unknown until proven, it is imperative to exercise caution when performing ground grid testing, especially in energized stations. For example, standards should require test technicians to wear HV Class II rubber gloves, safety-rated glasses, hard hat, and FR clothing when handling test leads and probes while conducting tests. All testing procedures should adhere to prudent utility safe work practices

Problem Statement: The most frequently incurred problem with a ground grid is that most components are buried underground, remaining ‘out of sight, out of mind’. As a utility or plant owner, understanding the importance of routine testing of ground mat performance is vital. However, testing is rarely performed, and when it is, the data is either unreliable, lost, or unreviewed. Sometimes this occurs because repair orders get created but are relegated to “low-priority” in the budgeting process. The compliance box gets checked, but actual repair work doesn’t happen.

A typical ground mat consists of parallel runs of 4/0 copper, copper clad steel (CCS), or equivalent low resistance electrical conductors bonded underground with either thermal or mechanical connectors in an X and Y grid layout. The grid usually undercovers the entire station and extends several feet outside

the fence line and gate(s) (Fig. 1). If a substation or switchyard is adjacent to an industrial plant or power station, multiple conductor runs may be used to bond the respective yards together. All power

equipment, control houses, and fences are electrically bonded to the ground mat. An insulating layer of gravel may also be an integral component of the substation grounding design.

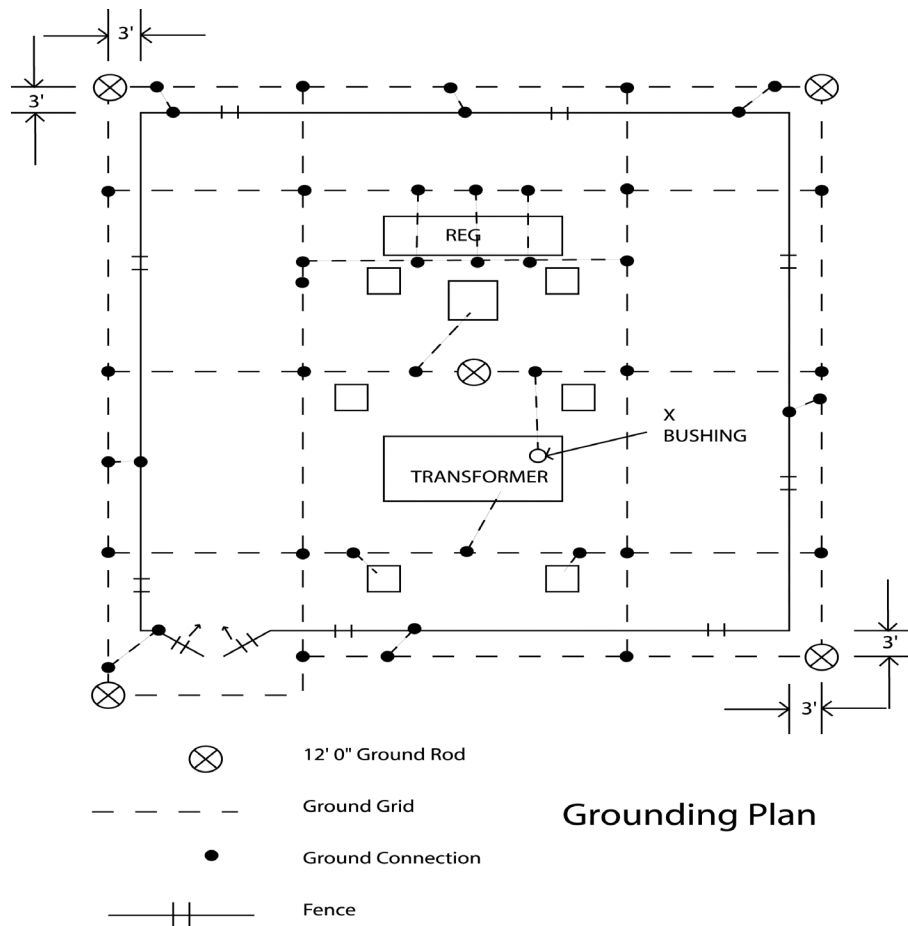


FIG. 1 – Example of Typical Ground Grid Design from Client

Again, most grid components are buried and not visually accessible for inspection, making it challenging to know the actual condition of your ground grid system. Important details such as knowing if it was installed and connected as shown on the station prints or if it has remained intact and functional throughout revisions/construction projects, are often uncertain.

Review of Step and Touch

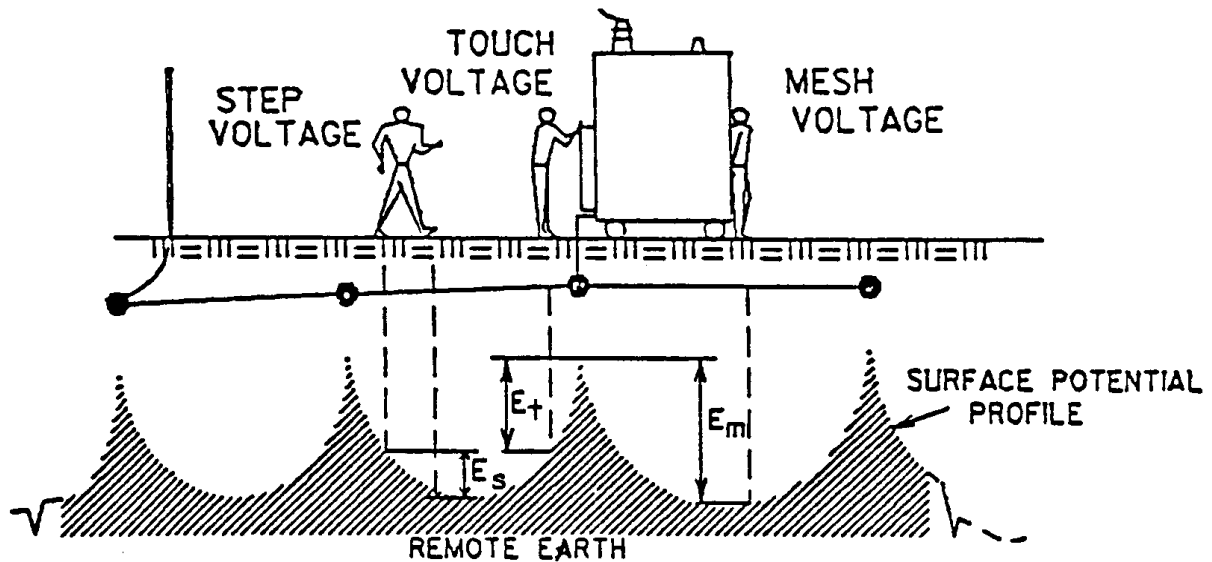


FIG. 2 – STEP AND TOUCH POTENTIAL
IEEE Standard 80 (2013 Edition), “IEEE Guide for Safety in AC Substation Grounding”

Step potential (Fig. 2) is the voltage difference between the feet of a person standing or walking through a substation or near an object. If a fault should occur, the ground mat must be effective enough to keep the step voltage at safe levels for employees.

Touch voltage (Fig. 2) is the voltage difference measured when a person contacts a metallic conductive object in reference to the ground mat. Mesh voltage is when a more significant portion of a person’s body is in contact with the metallic object referenced to the ground mat. Again, if a fault should occur, the ground mat must be effective enough to flow current while maintaining voltage differences at a safe level.

Problem Causes

A ground grid consists primarily of conductors and connectors. When the ground grid fails to perform there are generally two reasons why:

- 1) Current cannot adequately flow if conductors are either open-circuit or connectors are deteriorating, causing open or high resistance connections.
- 2) The design or installation is inadequate to safely mitigate available fault current.

Conductors and connections get compromised for a variety of reasons:

- Ground conductors shown on prints were not installed properly or may not exist.
- Grading or construction in and around the substation can damage the ground grid.
- Grounds get cut or damaged when replacing failed equipment (Fig. 3).
- When equipment failures occur, fault currents can be of a high enough magnitude to damage ground connections and/or melt conductors. The actual condition is unknown unless verified.
- Copper theft. Thieves steal copper ground risers (Fig. 4).
- Connectors deteriorate with age. Older style mechanical connectors are especially prone to deterioration. Even thermal connectors can deteriorate over time if not applied correctly.



FIG. 3 – Broken 4/0 Copper Conductor at Client Site



FIG. 4- Copper Theft (Cut Ground on Regulator Neutral)

The testing process injects current to measure voltage drops at specific reference points to identify open conductors and poor connections.

Testing Strategy

Testing can vary widely due to some utility operators using handheld impedance meters to spot-check the ground risers. The best practice is by far more complex but still begins with the basics. Once a job is initiated, prints should be reviewed to understand the specific ground mat installation. Often through the life of a substation, the grid has been modified/added to or ‘overlaid’ to meet present-day requirements. Therefore, when developing a test plan to satisfy requirements, it is crucial to understand what should be in the ground and how it is connected.

From this information a test plan is developed. For the first step, it is important to tag and label all test points. For example, Fig. 5 shows ground risers and reference points labeled with durable brass tags or an equivalent, allowing for concise documentation and reference for future maintenance testing.



FIG. 5 – Example of Labeling Ground Risers from Client Site

Maintenance Testing – Grid Integrity

Basic testing (Fig. 6) of the ground mat employs a high current DC power supply (300A continuous rating), calibrated digital voltmeter, and a DC clamp-on ammeter to perform Integrity (Point-to-Point) measurements (Fig. 7). Testing can be performed while the substation is energized; since measured voltage drop is sensitive, clean connections are imperative and every ground riser must be tested. Voltage drops are recorded from the riser test point to a preselected reference point. The magnitude of current flow is recorded in both directions registering the magnitude of current flow supplied by the 300A source. It is recorded up the riser into the steel and down the riser into the ground mat. Depending on adequate equipment grounding, the current split should make sense. Additionally, the voltage drop must meet specific guidelines depending on the size and type of grounding conductors used.

All riser current and voltage values are entered into a spreadsheet for evaluation, and localized mat issues are identified during this time, allowing for simple repairs to be made on-site if desired. However, more systemic problems often become apparent, requiring budgeting for more significant repairs or perhaps even an entire station ‘overlay’ or redesign project (Fig. 8).

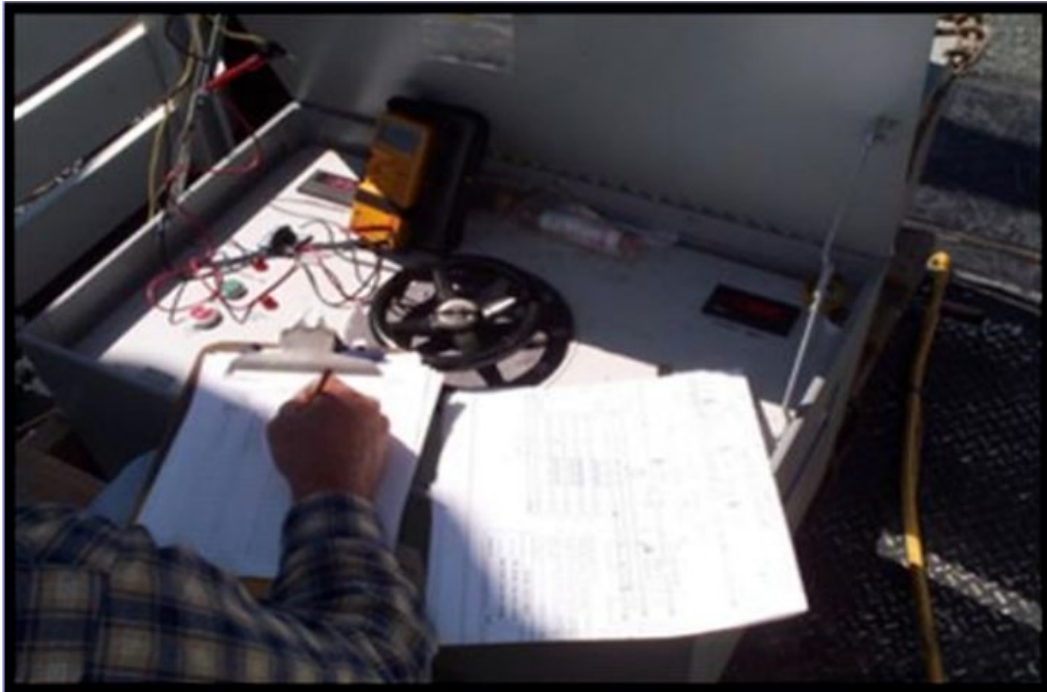
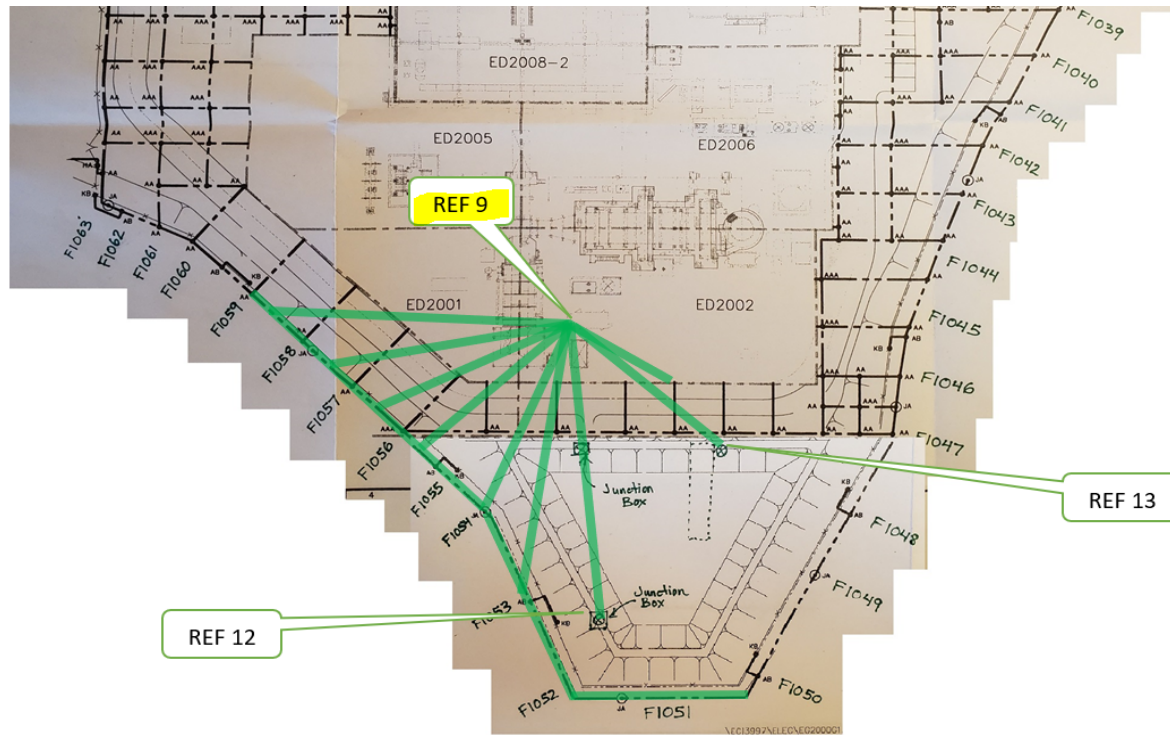


Fig. 6- Technician conducting a routine maintenance test at client site



Fig. 7- DC clamp-on ammeter



Test Reference 9 (TAG 1219 on the NOX WATER SKID BUILDING) was used as the primary reference for testing the ground grid in CT CONTROL CAB 2CT2A BUILDING.

1. Test performed on the 2CT2A BUILDING itself were overall very good: between the two exterior grounds (Tags 1221 & 1222), between REF 9 and the steps on both ends, between REF 9 and the hand rails on south end, between REF 9 and the metal floor of the 2CT2A building. Note: test to the magnetic bracket on the top of the door to REF 9 showed no current path... so probably paint preventing contact of metal surfaces.
2. Test results were VERY bad for the following:
 - a. REF 9 to Tag 1221 showed no current down... so only 1 ground on the 2CT2A building is connected to grid.
 - b. REF 9 to Junction box in parking area near bollard by road
 - c. REF 9 to Junction box WWPB1 by road
 - d. REF 9 to Junction box by metal walkway at pond near the FENCE
 - e. REF 9 to Junction box by metal walkway at pond near the ROAD
 - f. REF 9 to any of the perimeter fence grounds

FIG. 8 -Shows Typical Integrity Test Report from Client

Performance Testing

Basic testing (Fig. 6) of the ground mat employs a high current DC power supply (300A continuous rating), calibrated digital voltmeter, and a DC clamp-on ammeter to perform Integrity (Point-to-Point) measurements (Fig. 7). Testing can be performed while the substation is energized; since measured voltage drop is sensitive, clean connections are imperative and every ground riser must be tested. Voltage drops are recorded from the riser test point to a preselected reference point. The magnitude of current flow is recorded in both directions registering the magnitude of current flow supplied by the

300A source. It is recorded up the riser into the steel and down the riser into the ground mat. Depending on adequate equipment grounding, the current split should make sense. Additionally, the voltage drop must meet specific guidelines depending on the size and type of grounding conductors used.

Measurement of Soil Resistivity

Soil resistivity can vary widely from region to region across the continent. Therefore, knowing accurate soil resistivity values at a specific substation location is essential in determining that safe step and touch potentials are met, and grid design is optimal. Using the SGM, simultaneous measurements are made on nine probes located along a line on the soil surface, as illustrated in Fig. 9. The measurements obtained from the nine pins (several tests are run at varying pin spacings) are processed by error correction and estimation algorithms to construct a two or three-layer soil model (Fig. 10).

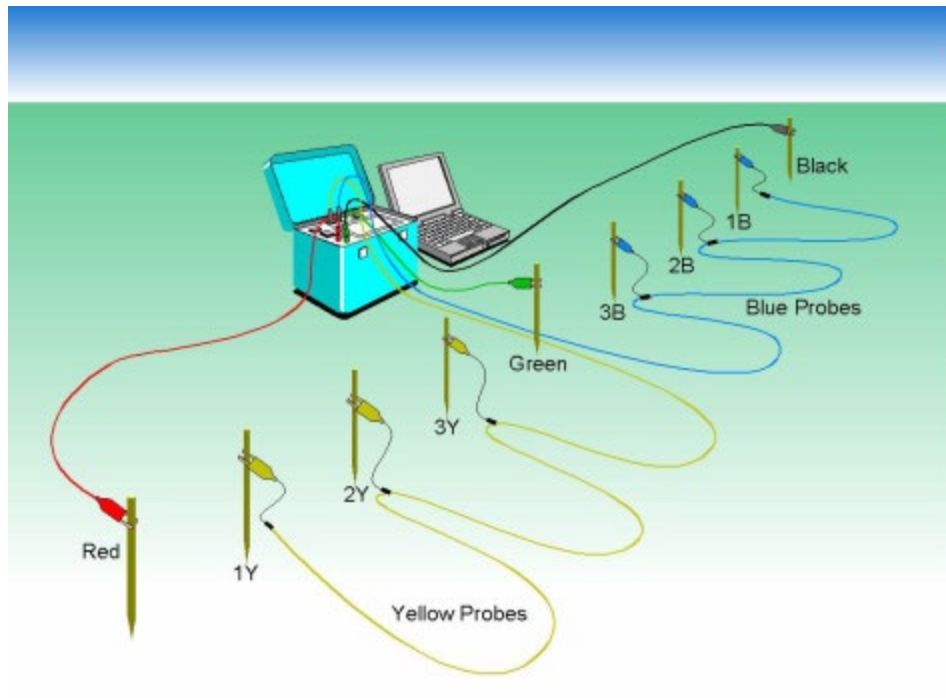


FIG.9 – Typical Soil Resistivity Connection
 Meliopoulos, A. P. (Sakis), February 2020, “*Smart Ground Multimeter (SGM) Operating Manual*”

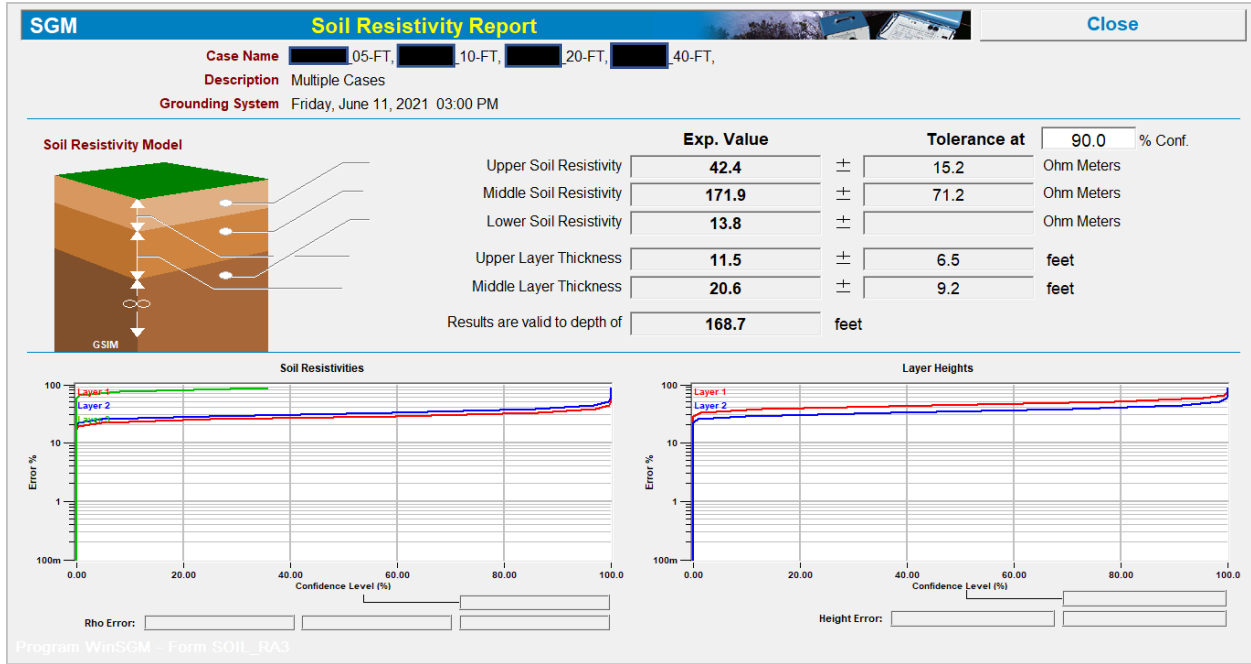


FIG. 10 – Ex. of Typical Three Layer Soil Resistivity Report with 90% Confidence Interval

Ground Mat & System Impedance Test Method

The overall substation ground mat impedance is measured to 'remote earth.' A source current is injected into the ground mat referenced to the return electrode some distance away (in some instances, as far as one mile) while the voltage drop is measured at prescribed probe distances. A typical measurement arrangement is depicted in Fig. 11 below, along with examples of reports (Fig. 12-17).

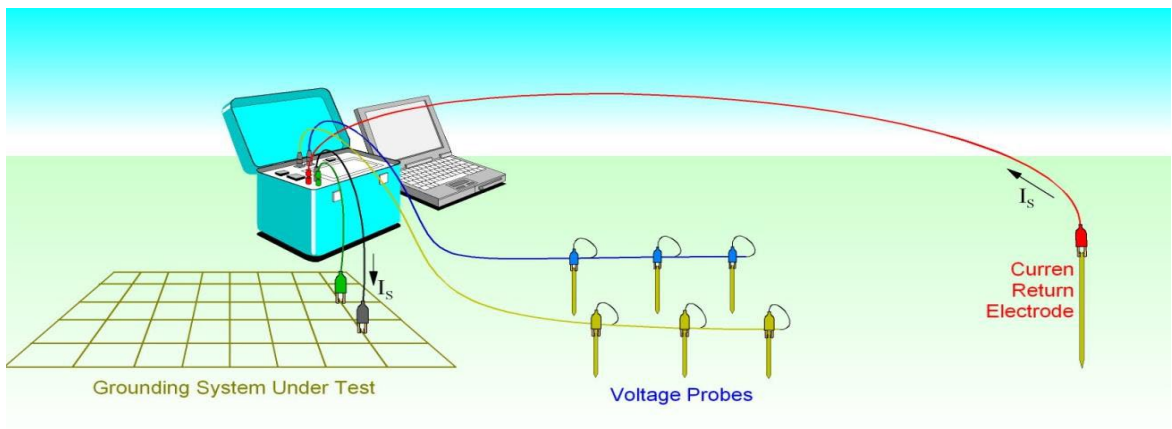


FIG. 11 – Ex. of Ground Mat Impedance Test Connections
 Meliopoulos, A. P. (Sakis), February 2020, 'Smart Ground Multimeter (SGM) Operating Manual'

SGM Probe Performance Report

Case: ██████-SGM-GROUND-MAT-IMPEDANCE-██████-2020

Probe	Resistance (Ω)	Soil Resistivity (Ω - m)	Capacitance (pF)	Inductance (mH)	Error (%)	
1Y	105.49	52.3	0.00	0.80	1.41	<input type="checkbox"/> Remove
2Y	165.87	82.2	0.00	1.37	2.01	<input type="checkbox"/> Remove
3Y	63.45	31.5	0.00	1.73	4.23	<input type="checkbox"/> Remove
1B	58.45	29.0	0.00	1.61	2.94	<input type="checkbox"/> Remove
2B	53.11	26.3	0.00	1.13	1.63	<input type="checkbox"/> Remove
3B	58.13	28.8	0.00	1.54	4.34	<input type="checkbox"/> Remove

Average* 67.72 Average* 33.6 *NOTE: Maximum value is limited

Cancel Proceed

Hood Patterson & Dewar Form PROBE_PERF - Copyright © A. P. Meliopoulos 1992-2017

Fig. 12- Ex. of Probe Performance from client site

SGM Data Acquisition Performance

Case Name: ██████-SGM-GROUND-MAT-IMPEDANCE-WITHOUT-2020

Injected Current: 2.78 Amperes RMS

Prb #	%Valid	%Error	Resistance (Ohms)	Coherence Average-squared	Quality	
1Y	73.08	1.49	105.5	0.9785	Excellent	<input type="checkbox"/> Remove
2Y	73.08	1.84	165.9	0.9738	Very Good	<input type="checkbox"/> Remove
3Y	71.79	1.87	63.5	0.9750	Very Good	<input type="checkbox"/> Remove
1B	71.79	1.98	58.4	0.9685	Very Good	<input type="checkbox"/> Remove
2B	71.79	2.05	53.1	0.9678	Very Good	<input type="checkbox"/> Remove
3B	71.79	2.08	58.1	0.9705	Very Good	<input type="checkbox"/> Remove

Cancel Proceed

Hood Patterson & Dewar Form DATA_PERF - Copyright © A. P. Meliopoulos 1992-2017

Fig. 13- Ex. of Data Acquisition Performance from client site

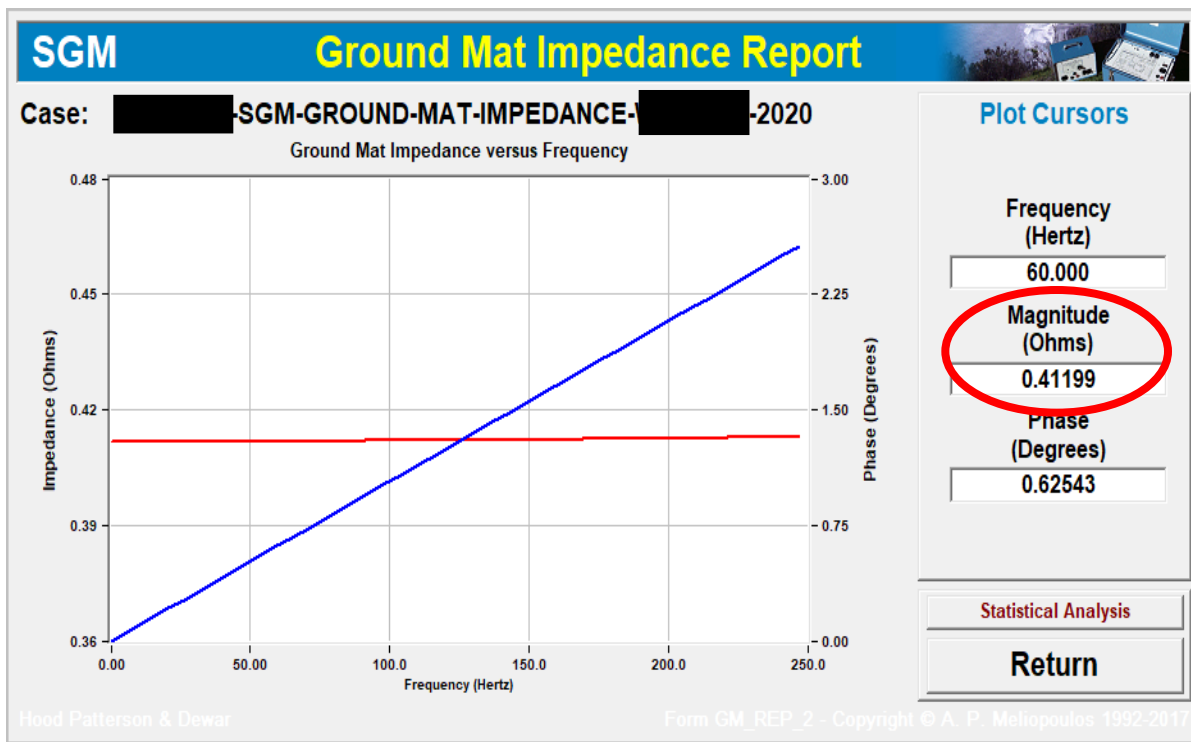


FIG. 14 – Example of Ground Mat Impedance from Client Report

When performing a system study, obtaining an accurate ground mat impedance value is a vital input component for the SGM intelligence to model step and touch potentials. Switching modes on the SGM and using the same test connections can also measure a ‘system’ impedance. The ground impedance measurement function can be applied to any existing grounding system of an energized or de-energized facility. From this data, the impedance of the grounding system under test is extracted using SGM program intelligence. The measured impedance of the grounding system is obtained as a function of frequency. The estimated impedance is reported in a plot of impedance magnitude and phase versus frequency. Note the measured ground impedance is the combination of the impedance of the grounding system under test, in parallel with the impedance to ground of all the shield wires, neutral

wires, and other grounded metallic structures connected to the grounding system under test. An estimation algorithm ‘fits’ the measurements to the model of the grounding system, shield wires, neutrals, etc. No knowledge of the type and number of shield wires, neutrals, etc., is required.

SGM Probe Performance Report						
Case: ██████████ SGM-GROUND-IMPEDANCE-WITHOUT-2020						
Probe	Resistance (Ω)	Soil Resistivity (Ω - m)	Capacitance (pF)	Inductance (mH)	Error (%)	
1Y	107.02	53.0	0.00	0.59	5.56	<input type="checkbox"/> Remove
2Y	166.70	82.6	0.00	1.11	3.18	<input type="checkbox"/> Remove
3Y	62.77	31.1	0.00	1.54	2.26	<input type="checkbox"/> Remove
1B	59.89	29.7	0.00	1.41	10.53	<input type="checkbox"/> Remove
2B	53.69	26.6	0.00	0.92	3.32	<input type="checkbox"/> Remove
3B	57.64	28.6	0.00	1.40	2.23	<input type="checkbox"/> Remove

Average* 68.20 Average* 33.8 *NOTE Maximum value is omitted

Cancel Proceed

Hood Patterson & Dewar Form PROBE_PERF - Copyright © A. P. Melliopoulos 1992-2017

Fig. 15- Ex. from client site

SGM Data Acquisition Performance						
Case Name: ██████████ SGM-GROUND-IMPEDANCE-WITHOUT-2020						
Injected Current: 2.79 Amperes RMS						
Prb #	%Valid	%Error	Resistance (Ohms)	Coherence Average-Squared	Quality	
1Y	73.08	1.91	107.0	0.9728	Very Good	<input type="checkbox"/> Remove
2Y	71.79	2.35	166.7	0.9653	Very Good	<input type="checkbox"/> Remove
3Y	71.79	2.54	62.8	0.9650	Very Good	<input type="checkbox"/> Remove
1B	71.79	2.68	59.9	0.9589	Very Good	<input type="checkbox"/> Remove
2B	71.79	2.80	53.7	0.9567	Very Good	<input type="checkbox"/> Remove
3B	71.79	2.86	57.6	0.9581	Very Good	<input type="checkbox"/> Remove

Cancel Proceed

Hood Patterson & Dewar Form DAQ_PERF - Copyright © A. P. Melliopoulos 1992-2017

Fig. 16- Ex. from client site

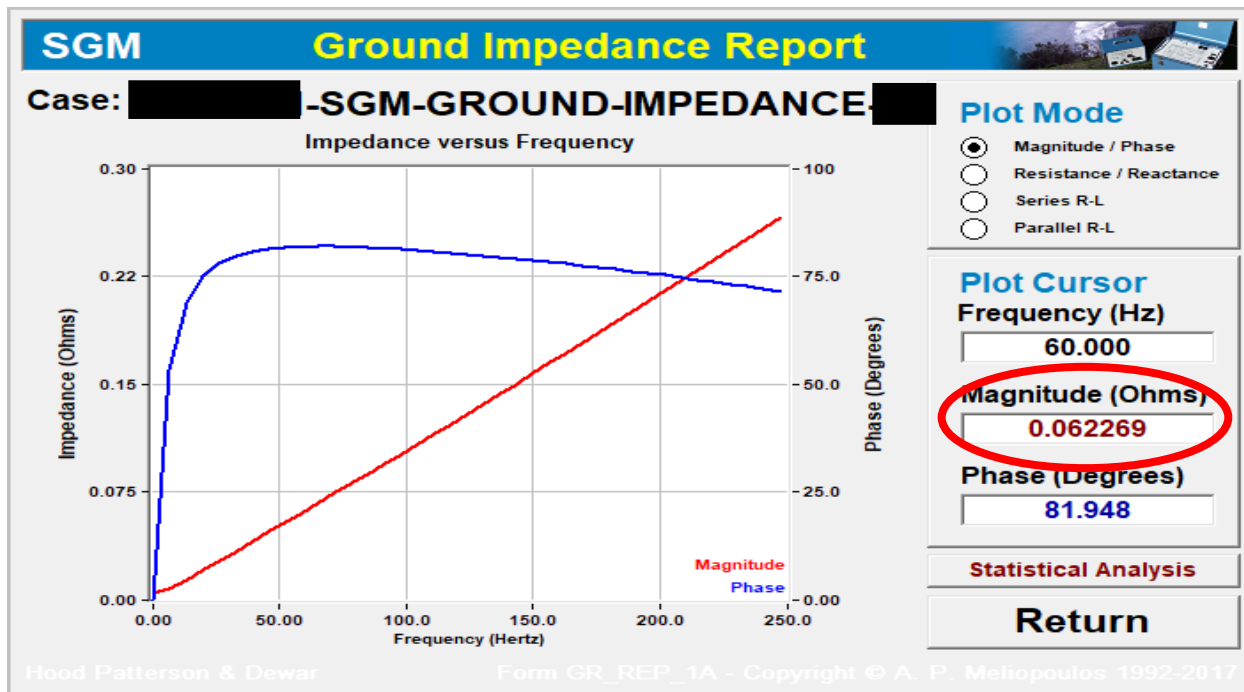


FIG. 17 – Example of System Impedance from Client Report

Once soil resistivity, substation ground mat impedance, and ‘system’ impedance are known, those values will be entered into the program model, along with other factors provided by the utility, such as maximum available fault current and IEEE Std.80 reduction factors and safety parameters. Ground Potential Rise (GPR) and Equipotential Plots can then be projected and displayed.

Conclusion

Ground grid integrity is one of the most critical factors in the safe and reliable operation of the substation. However, it is often overlooked because many of its components are underground. Unfortunately, the station ground grid gets attention when sensitive digital controls or equipment continuously fail during switching events and storms or when a safety incident occurs. As explained in this paper, the grid components are rather basic, and integrity testing can be performed with a high current source and handheld instruments. However, it is difficult for untrained personnel to take measurements, collect data in an organized format, and review it to make informed decisions.

Using specifically trained and experienced crews to routinely perform ground grid testing is a prudent practice to maintain the ground grid integrity. Also, using the SGM or equivalent to conduct the more elaborate soil resistivity, ground mat, and system impedance testing and modeling to determine adequate design and substation grid performance is best accomplished with trained personnel. A detailed final report will help the utility client justify cost-effective repair options to maintain the safety and reliability of their ground grid.

References

Meliopoulos, A. P. (Sakis), February 2020, *“Smart Ground Multimeter (SGM) Operating Manual”*

¹Figure 11 - *“Ground Mat Impedance Test Connections”*

IEEE Standard 80 (2013 Edition), *“IEEE Guide for Safety in AC Substation Grounding”*

¹Figure 2 - *“Step and Touch Potential”*

²Figure 9 - *“Typical Soil Resistivity Connection”*