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Condition Assessment of Substation Ground Grids

Phase 2 - Concept Testing

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PRODUCT DESCRIPTION

This report describes the second stage of a research project to develop a simple and inexpensive method and device to assess the integrity of substation grounding grids. The problem has been studied before but a reliable and inexpensive method or device to make a reliable diagnosis of grid condition is still lacking. While the EPRI-developed Ground Grid Evaluator (commercially known as the Smart Ground Multimeter) can be used to provide valuable information, the equipment is expensive and requires extensive high-level training and experience to collect reliable data and interpret the results. The first phase of this project (EPRI report 1013910) determined that low frequency radiation could be used as a viable investigative technique for evaluating the integrity of ground grid structures in substations. This method was further developed and tested in this phase of the project.

Results and Findings

The procedure outlined in this report does function in the predicted manner: currents injected into a subsurface conducting grid can be detected using magnetic pickup coils, thus allowing the current flowing in a conductor to be estimated and the location of a subsurface grid to be determined. Tests using signals in the frequency ranges of 60-200 Hz were successful. The radiated sinusoidal signal was easily obtained with the magnitude of the signal corresponding to proximity to the conduction paths. The measurement equipment was able to acquire signals at vertical offsets of 1-2 meter in both the test grid and substation grids. The ability of this approach to detect signals in deeply buried grids was not investigated.

The ability of this method to assess grid integrity still needs to be determined. However, it is clear that the technique will provide a better assessment of grid integrity where there is previous knowledge of the location and layout of the grid. The absence of a field in an expected region indicates a break. Using this effect requires a knowledgeable user to study the grid field measurements and locate null regions. Disconnected grid conductors and broken welds are more easily analyzed. Assessing corrosion presents the greatest challenge. In particular, the assumption that increasing resistance resulting from corrosion sufficiently reduces the current in multiple paths to allow detection still needs to be verified.

Challenges and Objectives

The safety of personnel and the proper performance of equipment in a high-voltage substation depend on the performance and parameters of the grounding grid. A well-designed grid in good condition should meet industry requirements such as those specified in Institute of Electrical and Electronics Engineers (IEEE) Std 80 "*IEEE Guide for Safety in AC Substation Grounding*." Many large substations are more than 50 years old. During service, corrosion can deteriorate grid components and degrade its integrity. A short circuit or direct lightning strike drives large current through the grid. This current-caused potential increase depends on the grounding grid resistance. Unfortunately, total or partial degradation of grid members increases grid impedance and decreases its ability to carry fault currents. This issue is gaining importance in view of increasing substation age and increasing fault currents in many substations and systems.

Applications, Values, and Use

The researchers will continue to evaluate promising methods for grid assessment from several viewpoints:

- Its ability to detect and locate defects in substation ground grids
- Its feasibility of implementation in actual substations
- The practicality of implementing the assessment method
- The economics of implementation in terms of such factors as equipment cost, crew size, required time to perform the assessment, and equipment power requirements

If successful, the developed method and equipment will be commercialized.

EPRI Perspective

Safety impacts all segments of the electric power industry. Properly designed and maintained substation grounding systems minimize electrical hazards to utility personnel and the public and the possibility of faulty operation of substation equipment. With the help of recognized industry experts, EPRI has led a number of research projects related to substation grounding systems, including development of the Substation Design Workstation and the Ground Grid Evaluator (commercialized under the name Smart Ground Multimeter). The current project addresses the very important issue of assessing the condition of substation ground grids that have seen many years of continual operation and may have suffered unknown degradation. The objective of this research is to develop new reliable and inexpensive method(s) and instrumentation that can be easily deployed in the field and operated by technician-level personnel. No such equipment now exists that would meet all the needs of the electric power industry.

Approach

The project team tested low frequency radiation as an investigative technique for evaluating the integrity of ground grid structures in substations. Testing was undertaken on test grids and an energized substation to verify the method and simulate failure conditions that may be encountered in a substation grid. The purpose of the tests on the substation grid was to verify the data acquisition method and assess the accuracy of the post-processing tools.

Keywords

Condition assessment of substation grounds
Grounding system impedance
Substation equipment grounding
Substation ground corrosion
Substation grounding systems

ABSTRACT

This report describes the second stage of research to develop a simple and inexpensive method and device to assess the integrity of substation grounding grids. The problem has been studied before but there is not, to our knowledge, a reliable and inexpensive method or device to make a reliable diagnosis. While the EPRI-developed Ground Grid Evaluator (commercially known as the Smart Ground Multimeter or SGM) can be used to provide valuable information, the equipment is considered to be expensive and requires extensive high-level training and experience to collect reliable data and interpret the results. Hence, the objective of this research is not to develop a device that reproduces all functions of the SGM, but to develop new reliable and inexpensive method(s) and instrumentation that can be easily deployed in the field and operated by technician-level personnel.

The report is divided into eight sections:

- Section 1 briefly describes the technical problem and situations that are likely to be encountered in substations.
- Section 2 builds on the 2007 *Phase 1 – Proof of Concept EPRI Report 1013910*, that determined low frequency radiation would be a viable investigative technique for evaluating the integrity of ground grid structures in substations. In this section, both the merits and challenges associated with the technique under various conditions are discussed.
- Section 3 describes the principal components of the data acquisition and algorithm development for the inverse problem.
- Section 4 describes the field tests. Two test grids were developed for controlled evaluation of the technique. The tests grids allowed for direct measurement of current in each conducting path and quick connect/disconnect options to simulate grid faults. The EPRI test was implemented outdoors on a grassy surface, with possible ground conduction losses. The RPI grid added some refinements based on previous experience and was a smaller grid designed for travel. A practical application was performed on the substation grid at EPRI Lenox. The initial test on the EPRI grid was performed when the substation was powered down and was intended to verify the proposed technique. The subsequent substation tests were intended to verify the technique at an energized substation and confirm that detection of frequencies away from the 60 [Hz] operating frequency was viable during normal substation operation.
- In section 5, details of the data acquisition and software analysis are evaluated. An initial discussion of the quasi-static approximation of the test grid currents is presented.
- Section 6 continues work started in Phase 1 – *Proof of Concept EPRI Report 1013910.* It describes a review of practices and a literature search of pipeline and other buried infrastructure assets, how they are located and how deterioration is assessed.

- Section 7 briefly looks at other considerations, like using the proposed technique in conjunction with alternative methods.
- Section 8 summarizes the findings of this research to date and outlines general plans for future work.

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1

INTRODUCTION, PROBLEM STATEMENT AND OBJECTIVE

The safety of personnel and proper performance of equipment in a high voltage substation depends on the performance and parameters of the grounding grid. A grid that is well-designed and is in good condition should meet industry requirements such as those specified in IEEE Std 80 "*IEEE Guide for Safety in AC Substation Grounding*".

Many large substations are more than 50 years old. During the long years of service corrosion can deteriorate the grid and degrade its integrity. A short circuit or direct lighting stroke drives large current through the grid. This current-caused potential increase depends on the grounding grid resistance. Unfortunately, total or partial degradation of grid members increases the impedance of the grid and decreases its ability to carry fault currents. This issue is gaining importance in view of increasing age of the substations and increasing fault currents in many substations and systems.

Typically the grounding grid consists of copper or iron conductors buried about 1 to 6 ft (or more) under the substation surface. All substation equipment is connected to the grid. For better performance, addition rods are driven vertically into the ground to provide a low inductance path for lightning currents. These rods are also connected to the grid.

The objective of this research is to develop a method and – if shown to be feasible and practical - develop instrumentation to assess the integrity of the grounding grids in a substation. The problem has been studied before but there is not, to our knowledge, a reliable and inexpensive methods or device to make a reliable diagnosis. While the EPRI-developed Ground Grid Evaluator (commercially known as the "Smart Ground Multimeter" or "SGM") can be used to provide valuable information, the equipment is considered to be expensive and requires extensive high-level training and experience to collect reliable data and interpret the results. Hence, the objective of this research is not to develop a device that reproduces all functions of the SGM, but to develop new reliable and inexpensive method(s) and instrumentation that can be easily deployed in the field and operated by technician-level personnel.

The problem may be divided into three possibly overlapping cases as follows:

- For new constructions, we will be able to accurately specify the material and location of the grid and be assured that all connections are good at the construction stage. We can take measurements to obtain the "as constructed" signature that can be used as a reference for later comparisons. Subsequent measurements that show deviations from this initial signature will indicate that some change has taken place in the grid integrity and we must then determine what that change is and where the problem has occurred.

- In the case of an old substation that has good records from the construction stage, we have a reasonably good picture of what was placed underground. We do not know if the condition of the grid has degraded over time, but at least we know where the grid elements should be found through such methods as magnetic field measurements.
- Finally, if we are dealing with old construction and the construction plans are not available or are not accurate, we face the challenge of not only poor description of the grid, but also lack of information on its design parameters. In this – the most difficult case - our method must be capable of locating unknown underground structures in sufficient detail to locate defects and to suggest remedial action.

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INVESTIGATIVE TECHNIQUE

In the *Phase 1 – Proof of Concept EPRI Report 1013910*, low frequency radiation was determined to be a viable investigative technique for evaluating the integrity of ground grid structures in substations. In this section, both the merits and challenges associated with the technique under various conditions are discussed.

In general, substation conditions can include a complete lack of knowledge regarding the grid location and integrity, which necessitates not only an assessment of the grid but also identifying the location of the conductors. Once the grid layout is known, current can be injected via two surface connections. If a current path or multiple paths exists between the source connections, the currents in each path can be determined by solving the inverse problem with the field measurements. These currents provide an estimate of the resistance between the connections, which can be used to make an assessment of the grid integrity.

Test Facilities

The physical investigation included a test bed facility at RPI, a larger test grid at the EPRI Lenox facility and the substation grid at EPRI Lenox. The purpose of the test beds was to verify the method and simulate failure conditions that may be encountered in a substation grid. The failure conditions included:

- Corrosion simulation by introducing a very small resistance, a high contact resistance indicative of a bad weld.
- Disconnected conductor which corresponds to a physical break in a grid elements continuity path.

The intended purpose of the tests on the substation grid was to verify the data acquisition method and assess the accuracy of the post-processing tools.

The post-processing analysis of the field measurements was applied to the test grid where the physical layout was known and to the substation grid where the location of the current path was unknown. In each case, an interpretation of the results is included sections 4 and 5 of this report. Additionally, a straight-forward DC analysis of the resistive network was applied to the test grid and compared to the current measurements.

Evaluating Method

The evaluation of a substation grid represents an imaging problem, where the conducting material is embedded in an earth with unknown or varied properties. A number of investigative methods are available to locate submerged objects, with advantages and disadvantages and these are discussed in section 6.

The investigating team focused on using signals 60-200 [Hz] to measure field radiation from the line currents. When evaluating the merits of this method with regard to the primary questions:

- Can signal currents injected at the ground connections of a surface framework be used to evaluate the integrity of the grid conductivity?
- Is it possible to utilize the method when no information is available about the location of the subsurface connectors?

The answer is not simple.

Using simulated data for a known geometry, the inverse calculation of the currents from the radiated field accurately determined the current distribution in the grid. When investigating the copper test grid, the determined currents were comparable to calculations made using the field measurements. However, when the conductors' locations of the grid were unknown, a least squares fit method is possible that determines both the current distribution and current location. The greater number of variables in this case indicates greater uncertainty when interpreting the data.

Since the method focuses on determining the current distribution in the grid, it is necessary that the currents provide information about the grid integrity. Interpreting this information is largely dependent on the amount of information available. If the location of the conductors is known, then the method can be easily used to detect a break in a conductor. However, if no information is available about the grid, a break will not be detected since no field will be radiated along the path.

A similar situation is present for evaluating corrosion, though this effect is more difficult to assess. Corrosion can cause a greater resistance in the cable, which would of course result in lowering the current. However, application of a quasi-static estimate of the resistance would require the assumption that the added resistance from a reduction of the cross-sectional area is significant in the circuit.

In general, a worst case scenario would represent initial investigation on an unknown grid layout and a best case scenario is a known grid with a history of measurements for comparison.

Investigations

The following investigations were prioritized:

- Primary: Can signal currents injected at the ground connections of a surface framework be used to evaluate the integrity of the grid conductivity?
- Primary: Is it possible to utilize the method when no information is available about the location of the subsurface connectors?

- Secondary: Is it possible to identify breaks in the current path of the grid?
- Secondary: Is it possible to identify corrosion of the grid that does not result in a break?
- Secondary: Is the developed technique easy to use?
- Secondary: What is the expected time necessary to acquire sufficient data to evaluate the grid integrity?

Simplifications based on the physical assumptions were necessary in the analysis:

- The conducting grid represents the current path for the subsurface current.
- The grid can be considered planar.
- The field detected by the data acquisition equipment is due to injected subsurface currents only.

Detection of a Grid Element Conductor Break

In the grid, a break/disconnect represents removal of a possible current path. In this case, the method proposed will not detect a field in the vicinity of the grid element conductor. The absence of a field in this region represents the diagnostic test to determine a break.

In the field simulations presented in the previous report 1013910, broken conductors were easily recognized by the absence of a field. Similarly, in the field test performed on the substation grid, a conducting path was expected to follow a linear path between two ground connections. This expectation was invalidated by the field measurements which determined a curved path between the two ground connectors. Naturally, repeated measurements on a grid over time offers the best diagnostic tool for determining a disconnected conductor. As with the simulations, if the field in a region disappears between measurements, a break has occurred.

Detection of a Disconnected Weld

In the case of a broken weld, current paths still exist but are isolated with respect to each other. The field will be perturbed by the change in paths. A disconnected weld was applied to the RPI test grid at a four connector square junction. The x and y paths were disconnected. The fields measured at a vertical offset of 1 [ft] are shown in Table 2-1 and the measured currents are shown in Table 2-2. An obvious perturbation exists, with a change in the current path. In this case, the method proposed to evaluate the test grid provides direct information about the status of the grid.

Table 2-1
Fields measured above a four connector square junction for a complete weld and a disconnected weld

Field [mG]	B_x	B_y	B_z
Connected	4.32	11.2	5.89
Disconnected	4.24	11.6	6.8

Table 2-2
Currents measured in the connectors at a square junction for a complete weld and a disconnected weld

Current [A]	I_{x1}	I_{x2}	I_{y1}	I_{y2}
Connected	0.77	0.83	0.37	0.41
Disconnected	0.82	0.82	0.39	0.39

Detection of Corrosion

Determining the corrosion of a conductor that still offers a continuous current path is the most challenging of the failure situations considered. Two assumptions are necessary:

- First, the corrosion affects the resistance of the conductor which in turn will act as an impedance source for the current.
- Second, a parallel path must exist such that resistance effects can be compared.

Considering the quasi-static current, the resistance in a conductor depends on the conductivity, length and cross-sectional area.

$$R = \frac{L}{\sigma A}$$

The cross-sectional area and the conductivity provide the information necessary to determine effects caused by corrosion. We assume that corrosion results in a measurable physical change where both terms in the denominator will become smaller, increasing the effective resistance. However, to determine this effect, it is absolutely necessary that multiple current paths exist since the resistance of the grid is nominal compared to the internal impedance of a voltage source. Impedance measurements of the test grid and substation grid revealed resistances on the order of milliohms. A simple model is given Figure 2-1, where the resistors RL and RS are much larger than the resistance of two possible conduction paths. In a case where only one path exists, it is clear that the resistance contribution to the circuit is nominal and resistive effects caused by corrosion cannot be evaluated. The investigations into this effect are uncertain. Addition of resistance to the circuit does demonstrate effects of the current on the test grid. However, it is still necessary to determine if the corrosion does noticeably cause a change in resistance.

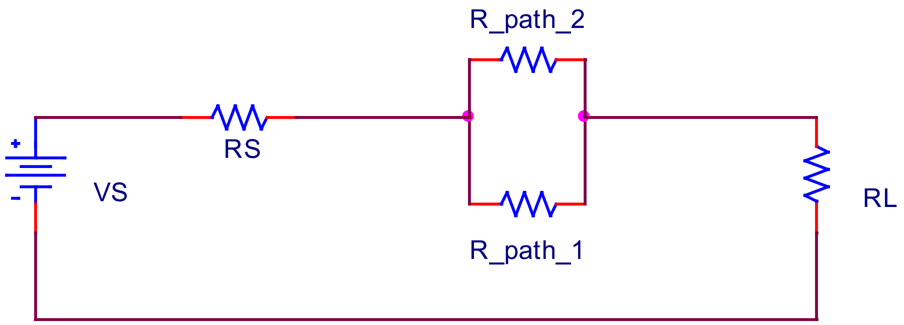


Figure 2-1
Simple Model of test circuit for two current paths between the source leads

3

DATA ACQUISTION, POST PROCESSING OF LOW FREQUENCY SIGNALS

The principal components of the data acquisition system are the coils to detect field, the gaussmeter that performs the voltage amplification and the oscilloscope used for the signal processing.

Hardware

In the Figure 3-1 the surge coils used for detecting the magnetic field are shown. The coils are configured in a perpendicular geometry so that all three field components can be determined. Each coil had the same surface area and number of windings. The surface area of the coil was approximately 3.5x 5.5 [cm] with a thickness of about 1.5 [cm]. A Faraday's Law approximation is utilized, where the voltage is determined by

$$\mathrm{V_{EMF}} = -\frac{d}{dt}\oint \vec{B} \bullet d\vec{S}$$

Since the surface position of the coil is constant, only the time varying magnetic field contributes to the EMF voltage. An approximation that the field is linear over of the surface of the coil leads to

$$\mathrm{V_{EMF}} = -\omega B_o A$$

where *Bo* is the assumed field at the center of the coil and *A* is the surface area of the coil. When considering the inverse problem to evaluate the currents in the grid, we assume the field is measured at specific points in space. This assumption introduces some error area since the field is not linear over the surface of the coil and more closely obeys the r-1 inverse rule for a line current. The thickness of the coil also affects the measurement since the field lines may not pass through all the current loops. Future designs would need to minimize the surface area of the coil to reduce these effects and improve the accuracy.

Figure 3-1
Perpendicular surge coils used to detect the magnetic field

The Gaussmeter used for low frequency magnetic field detection is shown in Figure 3-2. The surge coil is connected to the inputs and an output signal is available for data storage. The Gaussmeter implements a low pass filter with constant gain over the frequencies of interest. Multiple input devices are possible, with settings to indicate the expected total flux coupled to a detection coil. Calibration is still recommended with a known measurement and was performed using a handheld Gaussmeter that was tuned for 60 [Hz] signals.

Figure 3-2
Gaussmeter used for detection of the voltage induced in the pickup coil

The Tektronix Oscilloscope shown in Figure 3-3 was used for data storage and verification of the detected signal. In the Figure, the 100 [Hz] signal is clearly displayed. Real time frequency sampling and amplitude detection was available for visual verification of expected results. The number of wavelengths stored was easily set, with a greater number allowing for more accurate detection of the wave magnitude. Sample images are shown in the Results section of the report.

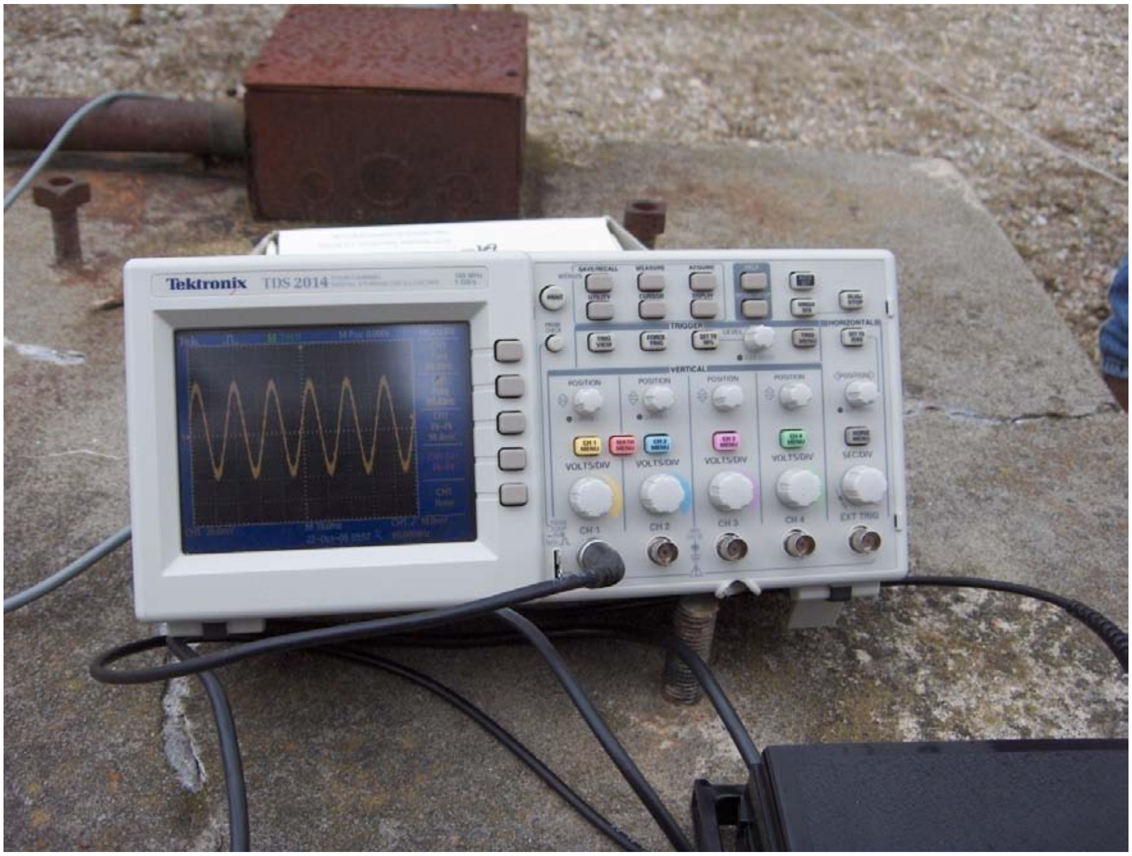


Figure 3-3
The amplified signal is verified using the Oscilloscope display and stored in memory

Algorithm Development for the Inverse Problem

At the frequencies proposed for the investigation, the wavelengths are much greater than the grid dimensions. Therefore, a quasi-static estimate of the radiation from the grid lines provides a reasonable estimate of the measured field above the surface. For a finite current length, the ideal field radiation is given by

$$B_\phi = \frac{\mu_o I}{4\pi r}\,[\cos(\alpha) - \cos(\beta)]$$

where the angles and current direction are shown in Figure 3-4. Coordinate transformations are used to determine the field for an arbitrary orientation of the line segment and relative position of the observation point. For an arbitrary orientation in the *yz* plane, the field in Cartesian coordinates is given by

$$\begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} = \frac{\mu_o I}{4\pi r}\,[\cos(\alpha) - \cos(\beta)]\begin{bmatrix} \cos\phi \\ \sin\phi\sin\theta \\ \sin\phi\cos\theta \end{bmatrix}$$

where φ is the angle of elevation and θ is the angle of the current segment relative to the *z*-axis. For a multiple connected grid or a discretization of line segments, superposition gives the following summation

$$\begin{bmatrix} B_{x_o} \\ B_{y_o} \\ B_{z_o} \end{bmatrix} = \sum_{n=1}^{N}\left(\frac{\mu_o I_n}{4\pi r_n}\,[\cos(\alpha_n) - \cos(\beta_n)]\begin{bmatrix} \cos\phi_n \\ \sin\phi_n\sin\theta_n \\ \sin\phi_n\cos\theta_n \end{bmatrix}\right)$$

where $B_{xo,yo,zo}$ is the field at the observation point in Cartesian coordinates due to the N finite line currents. This equation represents the forward problem, where both the current path and current magnitude are known. In the measurement system, the fields are known and the inverse problem is considered. If the grid layout is known, only the currents are unknown. If the grid layout is unknown, both the geometry variables and currents then become the unknowns. An iterative calculation to determine a least squares fit of the variables minimizes

$$\frac{\partial}{\partial x_i}\left(\begin{bmatrix} B_{x_o} \\ B_{y_o} \\ B_{z_o} \end{bmatrix} - \sum_{n=1}^{N}\left(\frac{\mu_o I_n}{4\pi r_n}\,[\cos(\alpha_n) - \cos(\beta_n)]\begin{bmatrix} \cos\phi_n \\ \sin\phi_n\sin\theta_n \\ \sin\phi_n\cos\theta_n \end{bmatrix}\right)\right)^2$$

where the minimization is performed over the variables in each line segment, current or angle.

$$x_i \in [I_n, \theta_n]$$

Based on path fitting, the length of the line segment will also be dependent on forming a continuous path of discrete segments with given angles of orientation in the *yz* plane.

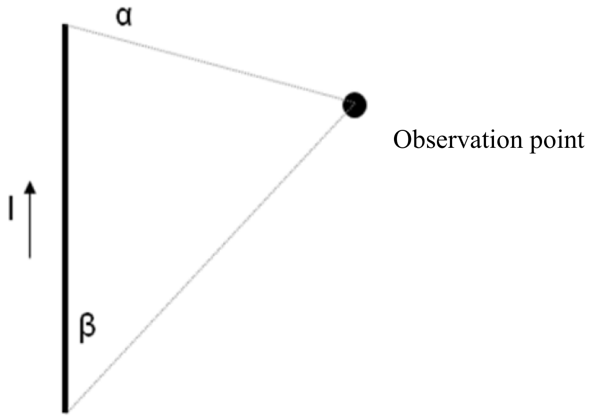


Figure 3-4
Geometry of finite line segment of current source with an observation point

4

FIELD TESTS

Two test grids were developed for controlled evaluation of the technique. The tests grids allowed for direct measurement of current in each conducting path and quick connect/disconnect options to simulate grid faults. The EPRI test was implemented outdoors on a grassy surface, with possible ground conduction losses. The RPI grid added some refinements based on previous experience and was a smaller grid designed for travel.

A practical application was performed on the substation grid at EPRI Lenox. The initial test on the EPRI grid was performed when the substation was powered down and was intended to verify the proposed technique. The subsequent substation tests were intended to verify the technique at an energized substation and confirm that detection of frequencies away from the 60 [Hz] operating frequency was viable during normal substation operation.

EPRI Lenox Test Grid

The initial test grid developed at EPRI consisted of a 3 x 3 square layout, as shown in Figure 4-1. The straight segments were copper, with alligator clip connections at each node. The alligator clips allowed for easy connect/disconnect to provide variable current paths. The source current was injected at the nodes, as shown in the Figure 4-1. An external load in the 1-3 [Ω] range was connected in series to maintain safe operations. A Variac transformer was used to generate the currents.

For testing purposes, both current and field measurements were made on the grid using an Ammeter and a Gaussmeter. Both devices were tuned using a bandpass filter centered at the 60 [Hz] source frequency. The current measurements were performed on the current path segments to verify that a conduction path existed and to compare to the inverse results. Field measurements were performed at both the grid surface and at various heights above ground level. For this investigation, a handheld Gaussmeter was utilized which measured all three field components with perpendicular coils. One consideration with regard to the Gaussmeter is that the offset of the coils is important when considering an accurate data fit for the inverse problem, especially for measurements that are closer to the grid. The coils inside the Gaussmeter were located approximately 5 [cm] apart. If the device were located in the immediate vicinity of the current path, this separation distance complicates the point measurement assumption, as with the surge coils used in the latter tests.

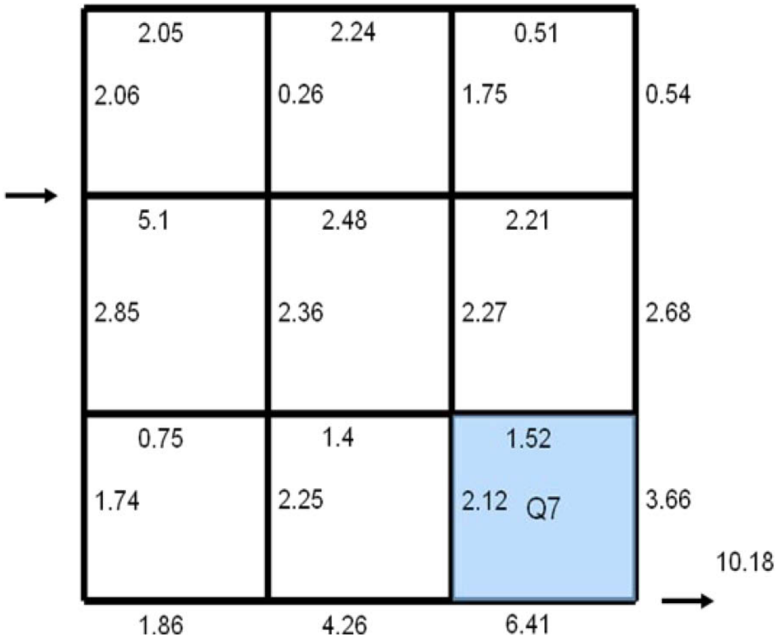


Figure 4-1
Square test grid

Square test grid array Figure 4-1 was constructed at EPRI Lenox. Each segment was approximately 10 [ft] in length. Current was injected at the arrows shown, with measured currents indicated.

RPI Test Grid

The grid developed at RPI was similar to the EPRI grid, on a smaller scale with 4 [ft] square sections. The smaller size allowed easier packaging for demonstration purposes in an indoor setting. To minimize the effect of the contact resistance of the alligator clips, copper clips were used with solder welds. Similar measurements performed on the EPRI grid were also performed on the RPI grid. The RPI grid did offer greater flexibility in adjusting test situations due to the resources available. The second round of tests was initially performed on this grid. These tests involved using the function generators for producing frequencies away for the 60 [Hz] power frequency, isolation power amplifiers to inject currents in the 1-10 [A] range and new coils for field measurements.

EPRI Lenox Substation Test Grid

The substation grid field test at EPRI in Lenox, MA was intended to evaluate the proposed method in a setting similar to what would be expected for grid evaluation. The purpose was twofold;

- First, to establish that the equipment worked as intended when the substation was live with 60 [Hz] voltages on the line.
- Second, to verify that the data acquired was useful for determining a subsurface current between two ground connections of the surface structure.

The goals can be summarized as:

- Verify the new data acquisition equipment
- Collect data from a live substation.
- Investigate a section of the grid where no *a priori* information is provided

The testing procedure used may be summarized as:

1. Signal generation using a function generator, 60-200 [Hz]
2. Source signal input to a power amplifier to produce a 5 [A] injected current
3. Source current lines positioned far from the region of interest
4. Magnetic field detection with surge coils with an approximate surface area of 18 [cm^2]
5. Perpendicular components, (B_x, B_y, B_z) acquired over a periodic grid
6. Data acquisition and storage using a gaussmeter output feed into an oscilloscope
7. Post processing to determine subsurface current and location

Procedure steps 1 and 2 provide a variable source frequency with isolation of the electronics for safe operation. Step 3 minimizes the effect of radiation from the source current lines when taking magnetic field measurements in the region of interest. As discussed, the surface area of the coil will affect the accuracy of the point measurement assumption. A periodic grid in Step 5 offers computational and measurement simplicity. The data acquisition in step 6 requires detection of multiple periods of the measured wave for greater accuracy. As the time interval of measurement is increased, the effects of signal noise are removed. The post processing is presented in the software description.

The test was performed on a subsection with multiple connections to the grounding grid. The ground connections and surface structures are shown in Figure 4-2 and Figure 4-3. Multiple current paths were determined for various ground connections, including an overhead path through the surface framework. The surface path was sufficiently distant that it did not interfere with the field measurements on the surface. In practice, it is recommended that the pair of ground connections chosen for current injection do not have a low resistance path in the surface structures. In Figure 4-2, three square foundation structures are shown in the left center. The source current is injected at the near and far foundation structures. The three foundation structures on the right side of the image also had ground connections, as can be seen in Figure 4-3.

Figure 4-2
Surface structures for the substation test grid

The source feed lines are shown in Figure 4-2 located at the near and far square cement blocks.

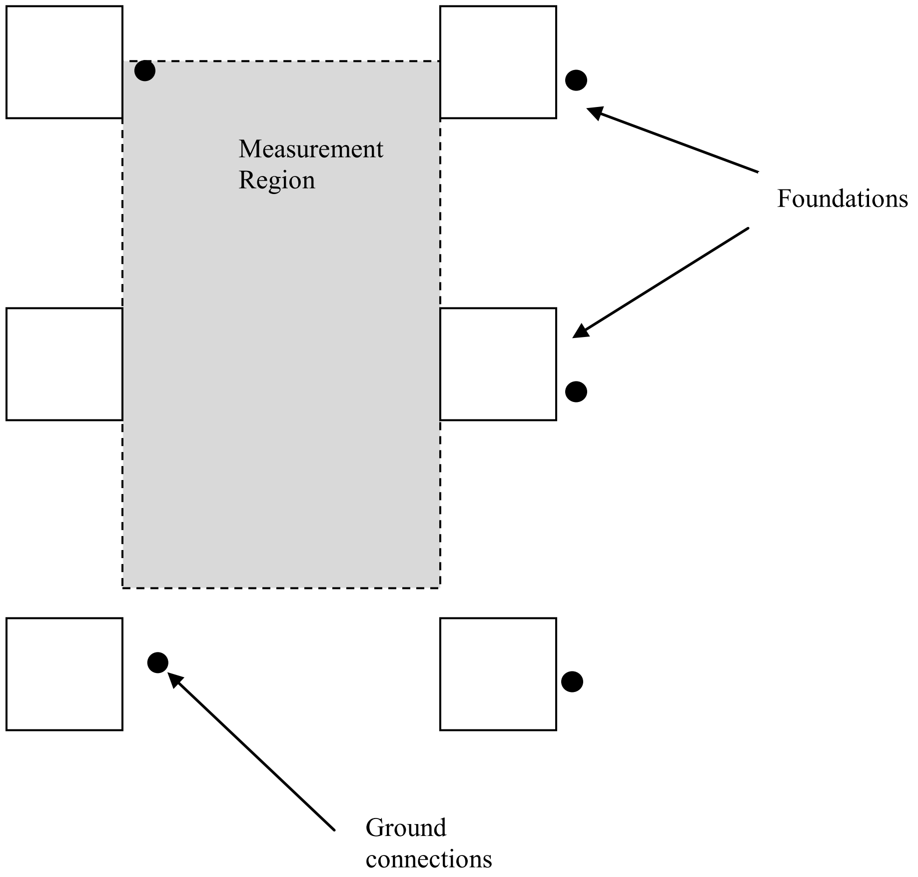


Figure 4-3
Overhead view of the grid region for field measurements on the Lenox substation grid

5

RESULTS AND DISCUSSION

In this section, details of the data acquisition and software analysis are evaluated. An initial discussion of the quasi-static approximation of the test grid currents is presented.

DC Analysis

In the test frequency ranges, the electromagnetic analysis is quasi-static. Therefore, DC current simulations maybe used to assess the measured results. In Figure 5-1, the 3x3 grid is shown, with a 10 [A] current source injected at the points shown. In the test grid, a voltage source was used with the voltage set at a level that corresponded to the 10 [A] source current in the feed wires. Since each grid segment was approximately the same length and came from the same spool of wire, each segment should have the same resistance. The measured currents are shown in the Figure 5-1. In the simulation, 100 [mΩ] resistors were implemented. Since a current source is used in the simulation, it is not necessary that the resistors exactly reflect the physical resistance of each path. The external 1 [Ω] (R25 Figure 5-2) is also included in the simulation. The circuit, Figure 5-2, was evaluated in PSpice (simulation software) and the results are shown in Figure 5-3 for the fully connected grid.

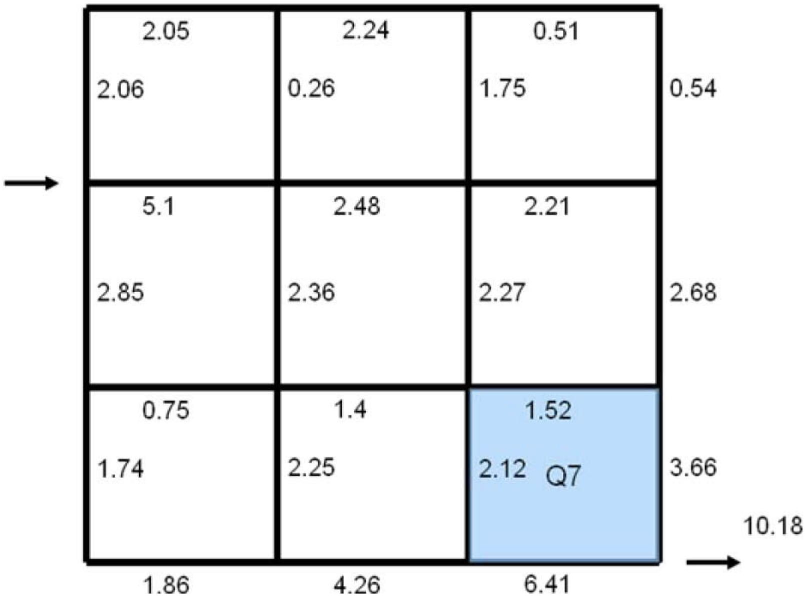


Figure 5-1
Square test grid array constructed at EPRI Lenox

Each segment shown in Figure 5-1 was approximately 10 [ft] in length. Current was injected at the arrows shown. The measured currents are indicated. Quadrant 7 is highlighted.

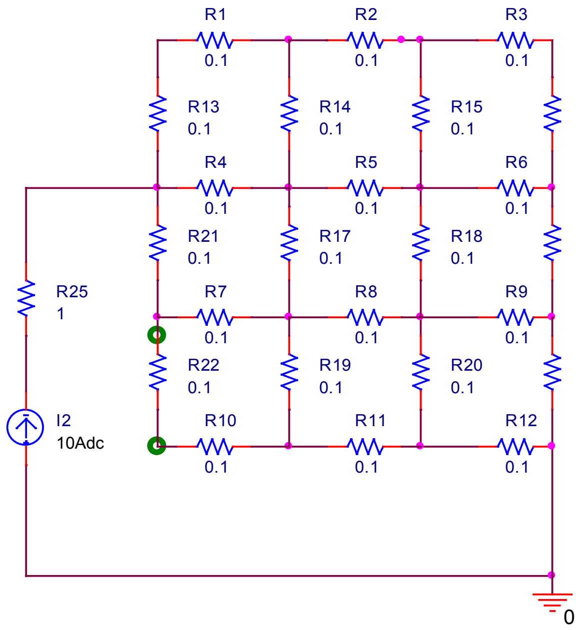


Figure 5-2
Resistive network with a current source connected at the networks

The resistive network in Figure 5-2 shows the grid is fully connected with each line segment having an equal resistance.

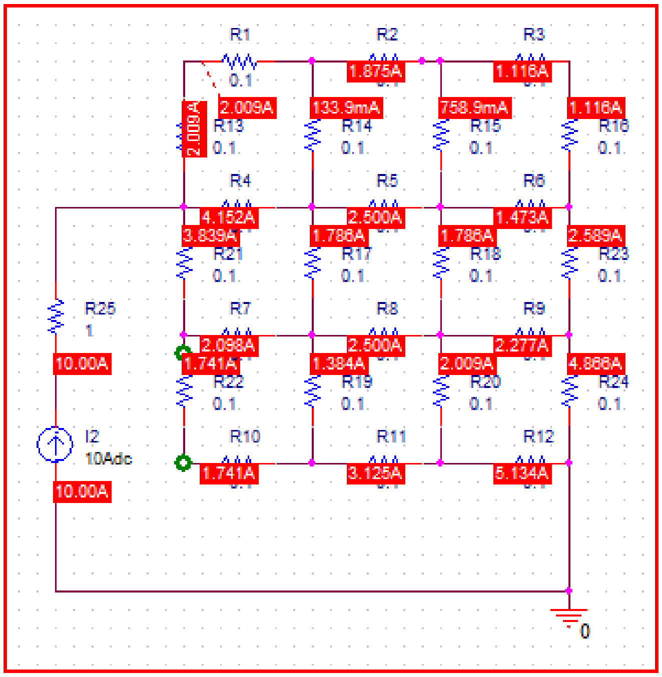


Figure 5-3
DC currents in fully connected resistive network

As can be seen in the Figures, the measured currents and simulated currents have similar relationships, but different values. For example, the currents in the R10, R11 and R12 demonstrate comparable ratios but have different absolute values. These differences are not unexpected since the test grid consisted of exposed copper. Additionally, the alligator connections at the nodes introduced a noticeable contact resistance. In Table 5-1, two repeated current measurements of R1, R2, and R3 are shown. The variation in resistance measurements was due to physical manipulation of the alligator contacts. Oxidation of the contacts can result in variations of the current as indicated. The magnetic fields measured for the two different measurements demonstrated a similar perturbation. While this effect is not surprising with the exposed grid and the contacts used, it does have a correlation effect on the substation grid. If a larger time scale is configured, perturbations in the currents will occur as the grid degrades, resulting in a similar variation of the measurements. It is then possible to consider the time evolution of the grid integrity.

Table 5-1
Current measurements of R1, R2, R3

Resistor	Measurement 1 [A]	Measurement 2 [A]
R1	2.05	1.76
R2	2.24	2.06
R3	0.51	0.72

In Figures 5-4 and 5-5 a simulation of a disconnected grid is shown. The disconnected resistors have been removed from the PSpice simulations. As expected, the currents in the grid are affected by the disconnect. In Table 5-2, the measured currents and simulated currents are compared, again demonstrating similar relationships with different absolute values.

These two cases represent an initial technique to evaluate the efficacy of the field measurements.

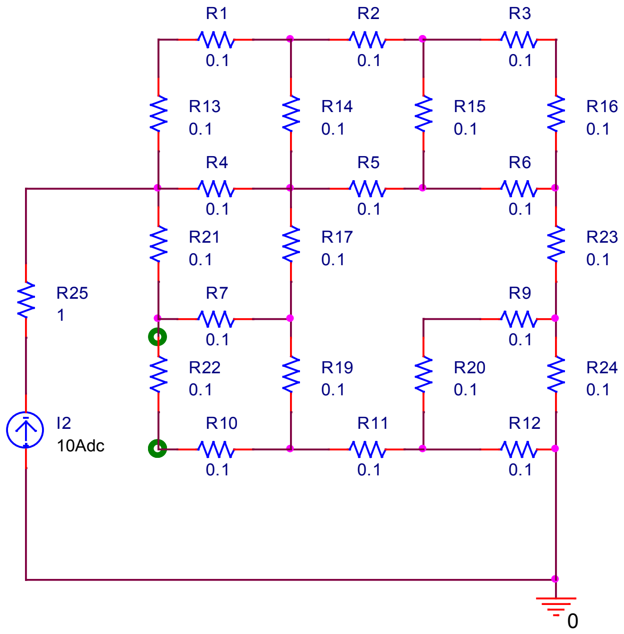


Figure 5-4
Resistive network with a current source connected at the inputs.

The disconnected grid connections are shown in Figure 5-4. Each line segment has equal resistance.

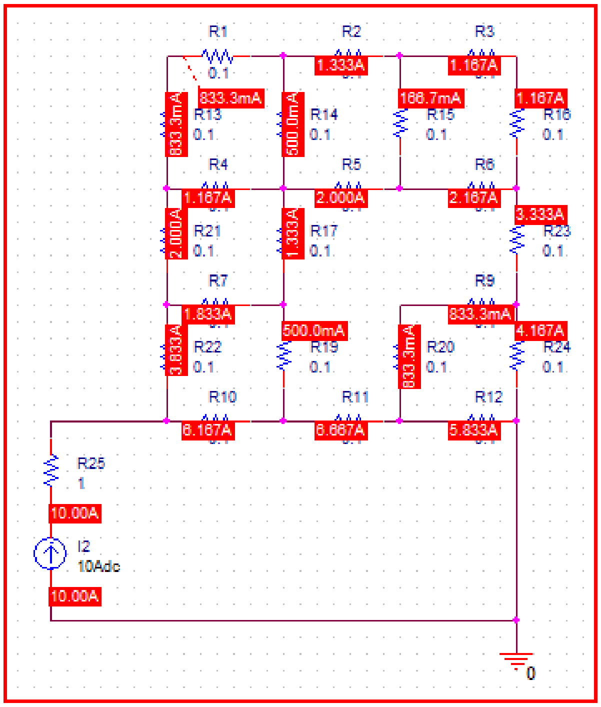


Figure 5-5
DC currents in a resistor network with disconnect line segments

Table 5-2
Comparison of measured and simulated currents in the line segment connected to Q7.

Resistor	Measured current [A]	Simulated current [A]
R9	0.38	0.833
R12	6.8	5.833
R20	0.37	0.833
R24	3.53	4.167

Field measurements on the Test Grid

In Figures 5-6, 5-7, 5-8, the measured field in quadrant 7 of the test grid is shown at various heights. In the figures, the field magnitude is strongest at the edges, which corresponds to the locations of the conductors. The field does demonstrate an approximate r^{-1} inverse relationship as the measurement distance is increased.

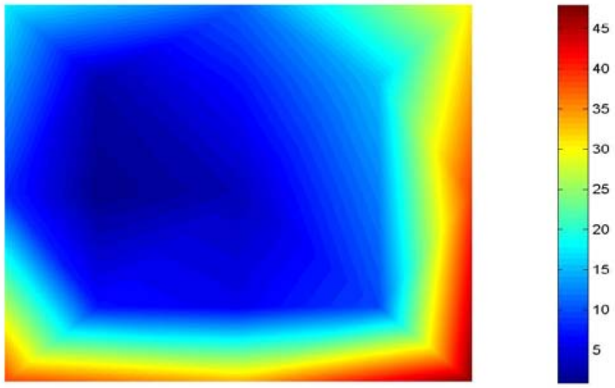


Figure 5-6
Field distribution in quadrant 7 at height of 1 [ft]

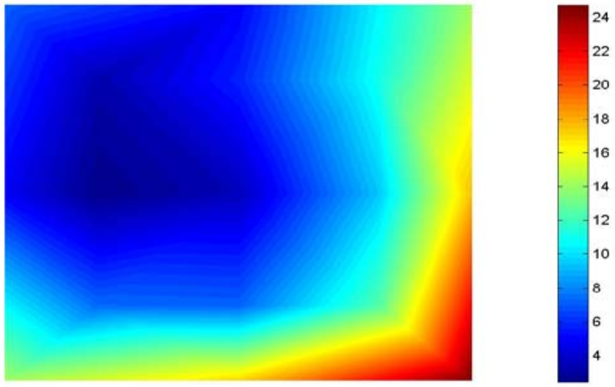


Figure 5-7
Field distribution in quadrant 7 at height of 2 [ft]

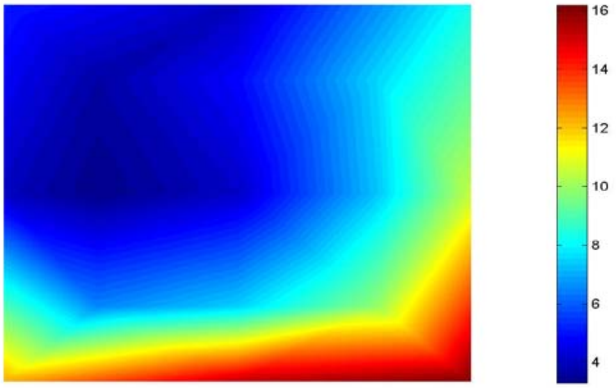


Figure 5-8
Field distribution in quadrant 7 at height of 3 [ft]

Field Measurements on the Substation Grid

Sample voltage measurements, and the fourier transforms at select grid locations, are shown in Figures 5-9, 5-10, 5-11. The examples demonstrate the utility of the surge coils for acquiring signals from the frequency range of interest.

The investigation frequency of 100 [Hz] was easily detected, with an associated strong magnitude for the correct orientation of the coil and distance from the subsurface current, as seen in Figure 5-9.

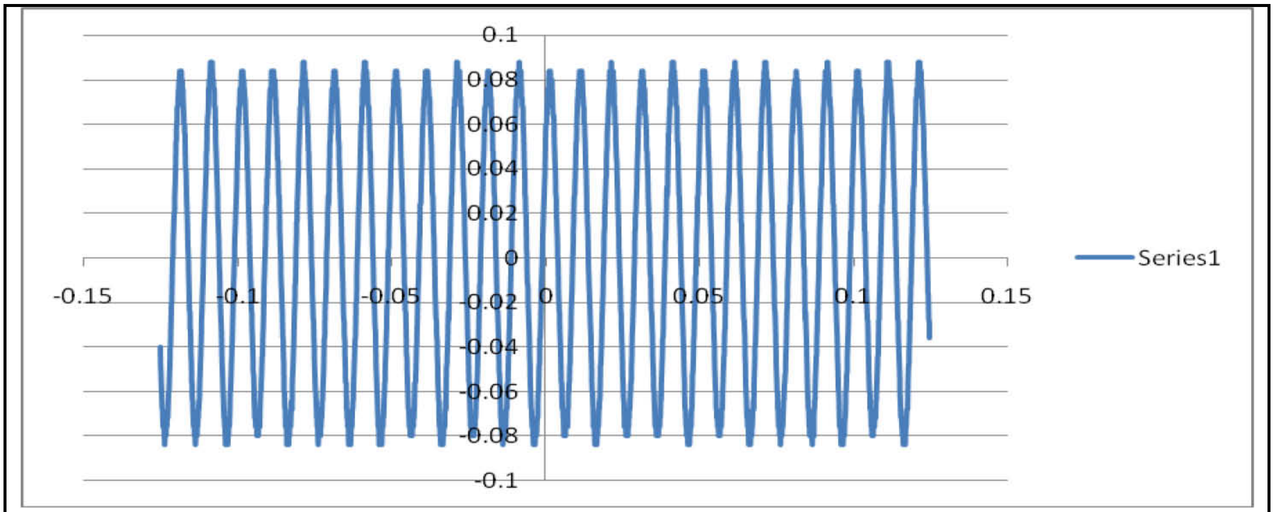
When the orientation of the coil was set such that the field lines were more parallel than perpendicular to the coil surface, the superposition of both the 60 [Hz] power signal and 100 [Hz] test signal is shown in Figure 5.10. A Fourier transform clearly picks up both frequencies.

Figure 5-11 illustrates the physical effect of moving the coil while making measurements. The physical motion of the coil is slow relative to the 1/60 [s] period, however, is sufficiently fast to introduce a low frequency signal that causes a voltage offset. The test signal is easily determined using signal processing. Motionless data acquisition is still recommended to minimize electromagnetic noise.

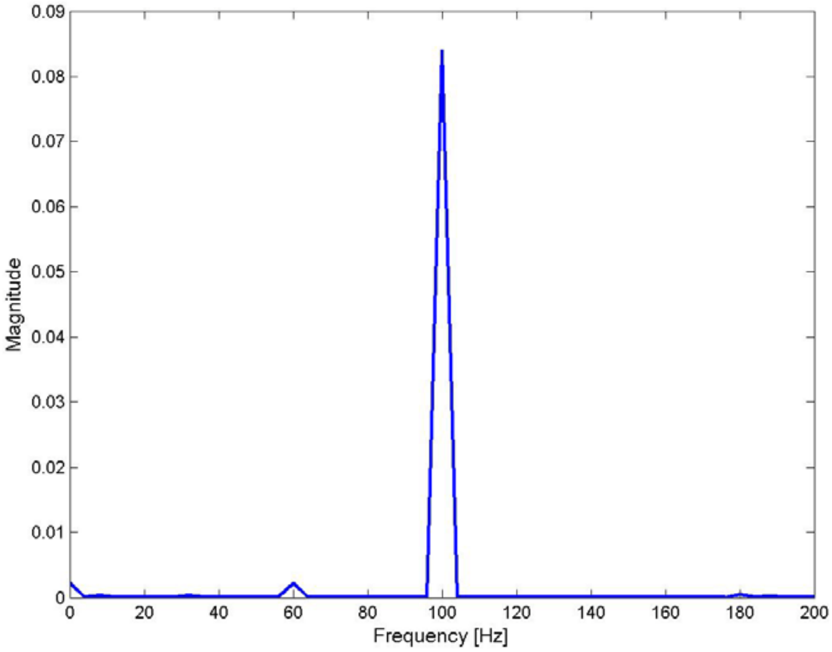
In Figure 5.12, the interpolated field distribution is shown over the region of interest. The color plots indicate strength of the field. The results of the 100 [Hz] test were consistent with measurements made at 60 [Hz] when the substation was powered off. The 60 [Hz] test was made with a Gaussmeter tuned to that frequency, for optimal signal detection.

Figure 5-13 plots the iterative calculation of the current path for the field test. An assumed linear path is used to initialize the calculation, along with the current that minimizes the error between measurement data and calculated field due the subsurface current.

Success iterations to determine the path, are performed based on segmenting the path into eight linear sections and perturbing the position and angle of each segment. The error of each iteration is shown in Table 5-3, where an error of 23% exists after 15 iterations.



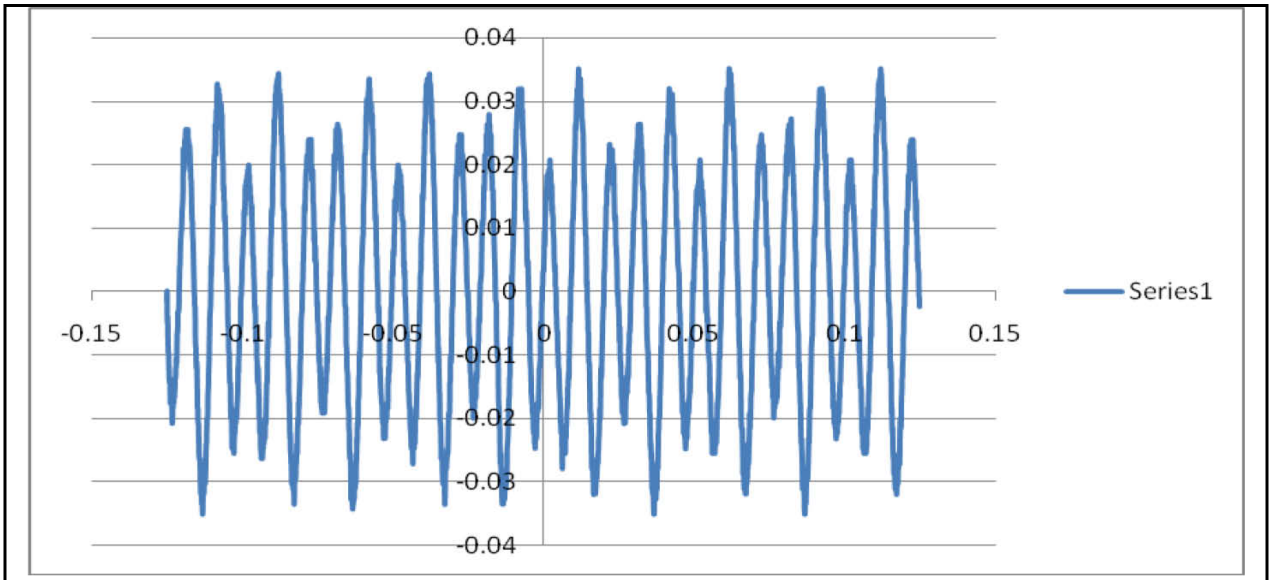
Measured voltage



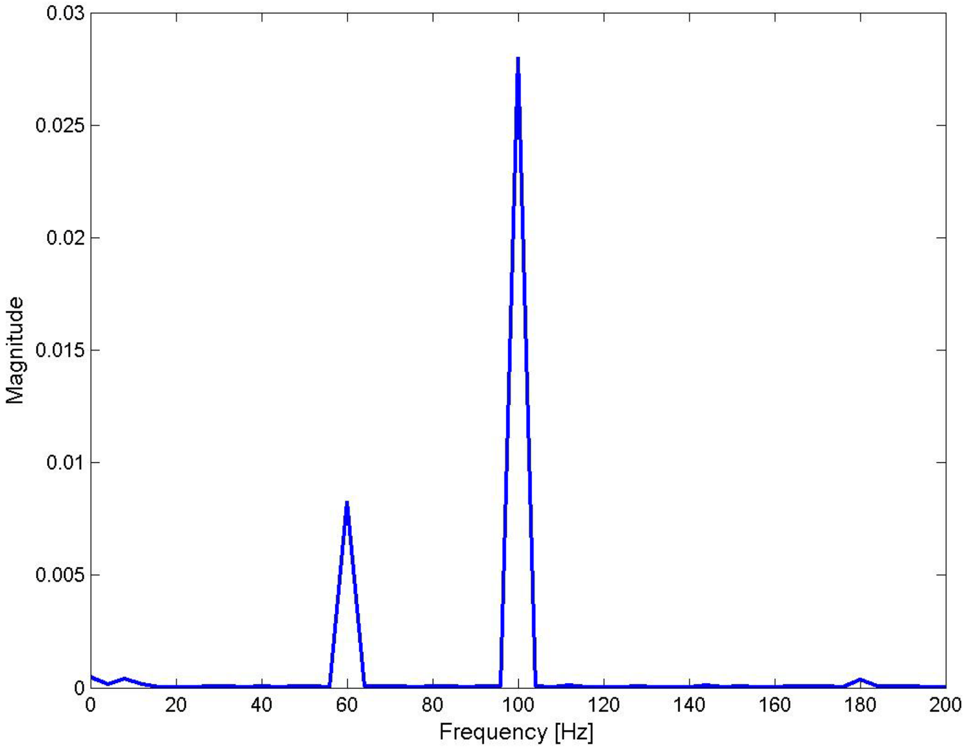
Fourier transform

Strongly dominant 100 [Hz] signal

Figure 5-9
Magnetic field measurements – Strong signal at the test frequency



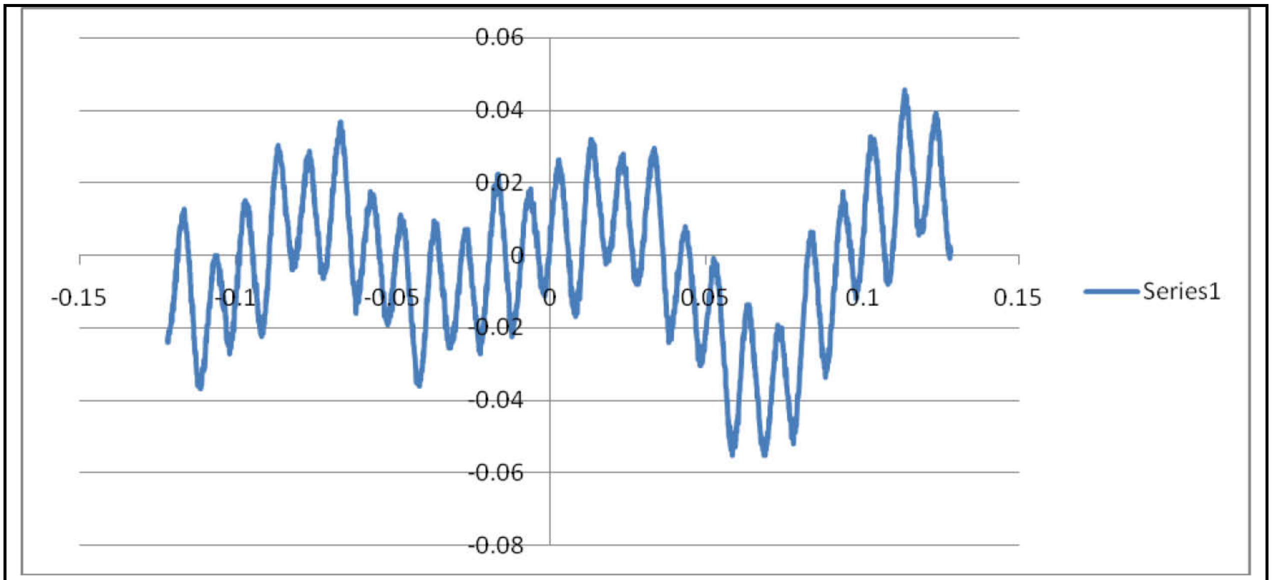
Measured voltage



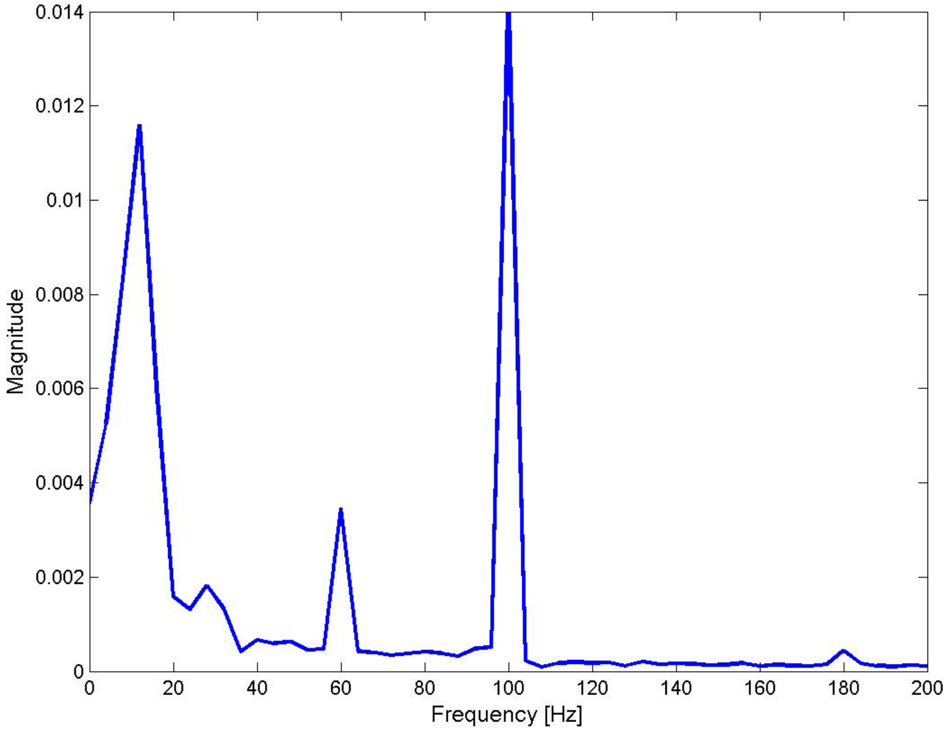
Fourier transform

Mixed signal, 60 and 100 [Hz]

Figure 5-10
Magnetic field measurements – Mixed signal, test frequency and power frequency



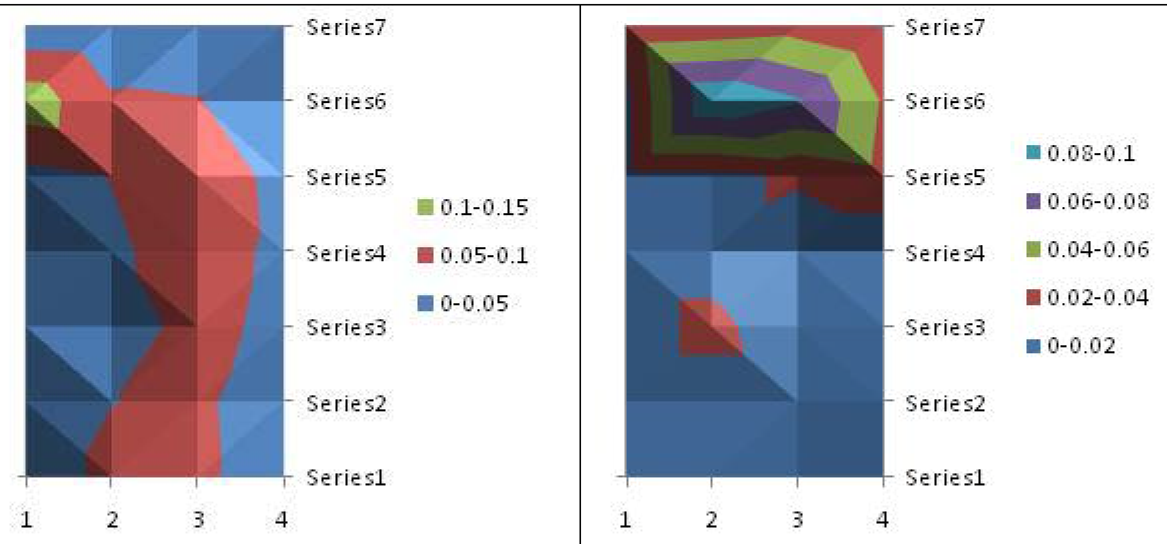
Measured Voltage



Fourier transform

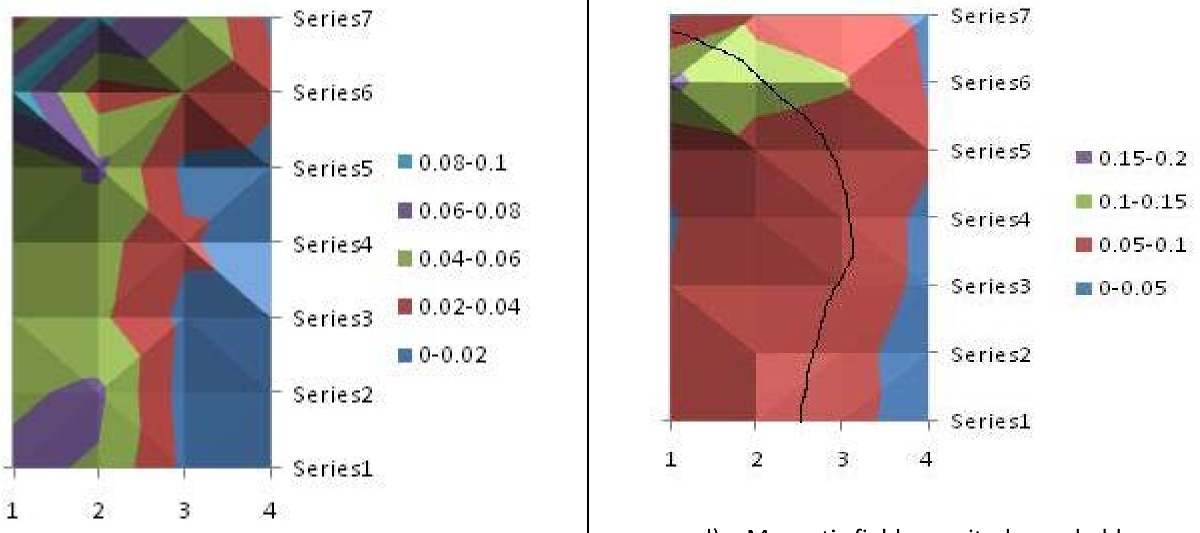
The effects of external vibrations on the measured signal

Figure 5-11
Magnetic field measurements – Mechanical noise effects from moving coil



a) Magnetic field – x component

b) Magnetic field – y component



c) Magnetic field – z component

d) Magnetic field magnitude, probable current path

Figure 5-12
Magnetic field distribution over the testing region

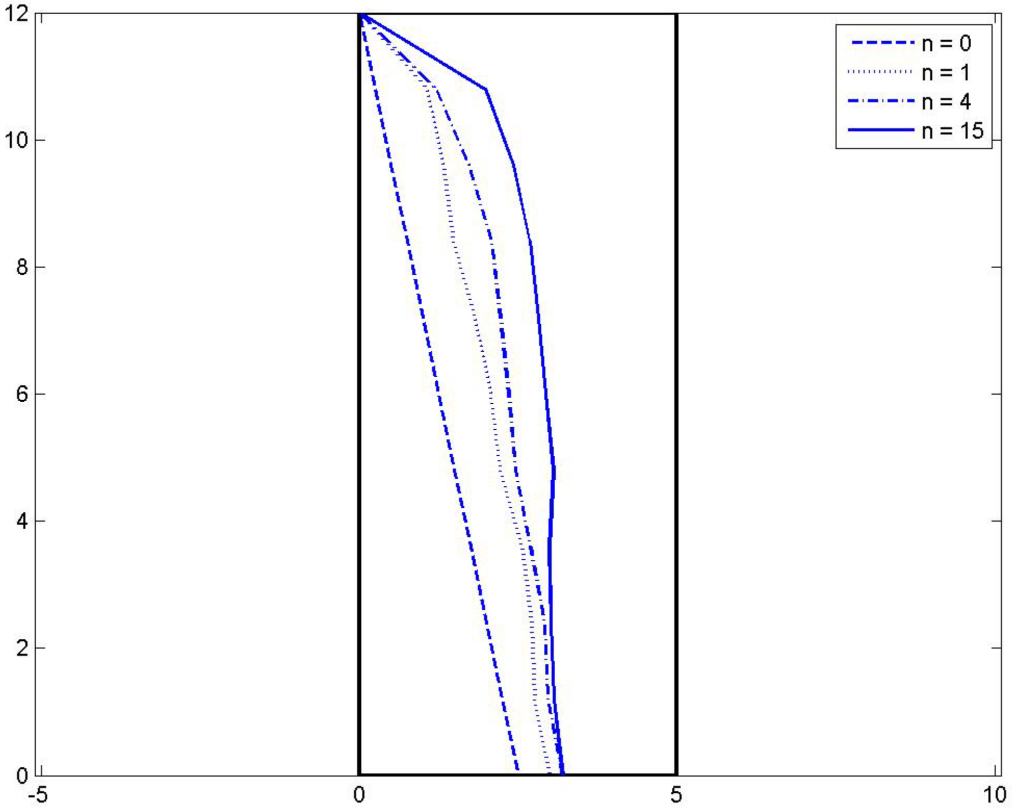


Figure 5-13
Current path estimate for an unknown substation grid layout

The current path estimate in Figure 5-13 for an unknown substation grid layout demonstrates iterative curve fitting to determine likely path when a depth of 18 inches is considered.

The error between the field due to a calculated current in the path and the measured field, for several iterations of the current path approximation, is shown in Table 5-3

Table 5-3
Error of each iteration

Iteration	Error [%]
0	79
1	52
2	47
3	41
5	36
8	30
10	26
15	23

6

COMPARISONS OF DIAGNOSTIC METHODS

This section builds on work started in Phase 1 – *Proof of Concept EPRI Report 1013910.* The effort includes a review of practices and a literature search of pipeline and other buried infrastructure assets, how they are located and how deterioration is assessed.

Discussions with the service providers of buried infrastructure assets reveled ground penetrating radar (GPR) is typically used to locate and monitor pipes and rebar in roads and bridges. It was concluded that GPR would not be very useful in the application of determining degradation in ground grid size cable. The GPR effectiveness decreases with depth. As a rule of thumb the resolution decreases about one inch per foot of depth. The resolution is best in dry sandy soil. Lowering the frequency improves depth of exploration but results in a loss of resolution. An exponential increase in transmitter power will increase the depth of exploration, however, if the GRP transmitter signal becomes too large interference with other instruments (cell phones, TV, radios) may occur. Typically ground grid wires have a diameter less than one inch, therefore it was concluded GPR will not be effective location method at depths much below a foot or two. Also, the GPR can not assess the corrosion of pipes or other underground metallic objects. There are some indirect inferences which can be made based on the strength of the reflected signals, corrosion means that some material disappeared and this will reduce the scattered signal.

The literature search found a lot of literature on pipeline diagnostics, especially in the water and sewer area. Many techniques are now being used but most are not applicable to our problem. For example, the GPR can be used to locate pipes but also to locate water leaks since the dielectric constant of water is much higher than the surrounding soil.

Many of the larger water and sewer utilities are using Digital Scanning and Evaluation Technology (DSET) and Closed Circuit Television (CCTV) Systems to perform an evaluation on a pipes inner wall.

Sonar systems use a very high frequency to measure geometrical changes in the sewer interior wall. The high-frequency wave travels to the object and reflects whenever there is a change in the density of the material. An advantage is that this system can detect corrosion pits, voids and perpendicularly oriented cracks on the pipe's inner wall. Sonar can detect defects as small as 5 mm in size.

Laser scanning systems, like sonar, also measure geometric images. Laser scanning utilizes a laser as a light source to scan the geometric shape of a pipes interior wall and can detect cracks as small as 0.3 mm

The conclusions to date are that none of the above methods are applicable to the problem of locating and assessing the condition of the substation ground grids. They all involve large diameter pipes and the most useful require optical scanning.

Methods have been developed which measures the chemical potential produced by corrosion products. There is a measurable chemical cell potential that depends on the material and percentage of the pipe which is coated. Both the value and the decay rate when the source is turned off is an indication of the corrosion. The test is known as "the polarization potential decay". The rate of deterioration is based on the principle that the transmission of an AC through some metal oxides produces unique harmonic frequencies; for example, iron oxide and copper oxide produce 3f and 2f harmonics, respectively. The electrical properties of copper oxide appear very nonlinear and very dependent on polarity. For this review it was concluded that the possibility of using this relationship, didn't not at present, allow for any simple way to excite the grid with current through the oxide.

The review of practices in other industries found that the magnetic field measurement technique was a promising way of assessing the damage to the grid.

When considering diagnostic approaches, RPI reviewed some existing methods present in published literature and used in industry. The results of the review were mixed and the interpretation is open for discussion. The following tables indicate perceived advantages and disadvantages of various approaches. Separate tables exist for both identifying the grid location and assessing the quality. As mentioned, the two problems are strongly related, but they may be approached differently. An imaging method to locate the grid may have a distinct advantage over other methods while an alternate technique can be useful for identifying grid characteristics. In general, an application of multiple investigative methods is often extremely useful, though certainly more costly.

Table 6-1
Performance characteristics of common techniques for subsurface imaging

	Low frequency injected currents	**Ultrasonic**	**GPR**
Ease of use[1]	fair	good	good
Equipment availability[2]	medium	very good	very good
Rate of data acquisition[3]	poor	medium	medium
Data analysis[4]	good	good	good
Sensitivity to environment[5]	good	poor	poor

[1] Most subsurface detection systems are self-contained, compact and designed to be used by an individual. Given the number of surface structures in a substation, motorized systems capable of sweeping a larger path are impractical. GPR and ultrasonic systems have an advantage in that the source and receiver are contained in the same unit. Injecting the currents requires that multiple source locations are used, corresponding to the grounding cables of the surface structures.

[2] The prevalent use of ultrasonic and GPR equipment for non-destructive testing has readily available industrial equipment. The equipment necessary to perform magnetic field measurements is also fairly common, though implementation for this application would require a small effort.

[3] Ultransonic and GPR systems are self-contained and require a single pass to identify subsurface objects. The detection of the magnetic field on the surface requires multiples passes in regions where the current is supplied.

[4] The data analysis of most imaging systems is well understood by experienced users.

[5] The grounding grid typically represents a high conductivity path. In the absence of perturbing magnetic material, the field from the currents is easily acquired. A GPR data acquisition depends on conductivity of the soil and ultrasonic measurements depend on the porosity of the soil.

Table 6-2
Performance characteristics of some techniques proposed for assessing the integrity of ground grids

	Low frequency injected currents	Connectivity tests	High frequencies
Grid location[1]	very good	very poor	poor-good
Sensitivity to weather[2]	very good	very good	poor
Sensitivity to ground conditions[3]	very good	very good	medium
Data analysis[4]	medium	good	medium

[1] Determining the grid location may be intrinsic to assessing the quality. The proposed technique has been discussed previously. Connectivity tests provide no information about the physical location of the grid. As mentioned, GPR is an established imaging technique, though its utility depends on the depth of penetration.

[2,3] As discussed, the proposed method is robust and produces detectable signals in multiple environments. A connectivity test is likewise viable. High frequency measurements are not reliable in the presence of ground water or inclement weather, where strong signal attenuation occurs.

[3] Ultransonic and GPR systems are self-contained and require a single pass to identify subsurface objects. The detection of the magnetic field on the surface requires multiple passes in regions where the current is supplied.

[4] The data analysis and interpretation of the field measurements does require an experienced individual who has an understanding of field behavior. Similarly, high frequency tests require knowledge of field propagation through media. Connectivity tests are straightforward to interpret.

7

FUTURE CONSIDERATIONS

The question of making a definitive statement about ground grid integrity can only be answered with measurements on a grid where the physical characteristics are known. The most informative scenario would be a substation grid with known faults that were confirmed by visual inspection. Field tests on this type of grid are essential to verify the assumptions regarding resistance characteristics and current.

When considering the hardware system, the next refinement would be the development of a functioning prototype. This would comprise a unit that can be managed by a single user. The design needs to include changes in a number of techniques to improve the efficiency and accuracy. Initially, the detection coils for field measurement need to be reduced in size so a point estimate is more valid. A higher gauge magnet wire and reduction in surface area will satisfy this requirement. Laboratory tests on the test grid did confirm that the dimensions of the coil are a contributing factor to error. A rigid structure for mounting the three perpendicular coils with an exactly measured offset is also necessary to reduce measurement error.

Signal sampling also is an area where the system can be readily improved. A larger number of wave signals yields greater accuracy in the Fourier Transform to determine the magnitude of the source test frequency. With frequencies in the 100 [Hz] range, a pulse sample of 1 [s] would yield 100 cycles of the test frequency. Simple experiments in the data acquisition did demonstrate that longer sampling times enabled better resolution at the frequencies of interest, as would be expected. The prototype system should simply and easily enable a fixed sampling rate with minimal interaction from the user.

During a measurement pulse length of ~1 [s] mechanical vibrations can be apparent as seen in Section 5. This factor needs to be considered in the design of a system, such that the coils are stable during a sample interval. Fourier Transforms will filter a significant part of the noise however; reducing the noise is more desirable. A prototype would benefit from a stable carriage with mechanical damping.

When considering an investigation of a full sized ground grid, the initial investigation should include a connectivity test, which is an established technique. Performing this test initially allows mapping of the ground connections and identifies the most useful connections for the source. Injection of the current at physically distance nodes offers the largest number of conduction paths between the feed lines. A larger number of paths provides the most useful scenario for data acquisition. Using feed points on the ‘edges’ of the grid would prevent noise from the source signals during measurement and likely reduce the number of measurement sweeps necessary.

Another consideration would be using the proposed technique in conjunction with alternative methods. There is no question that the multiple techniques are useful. A number of methods for locating subsurface conductors exist, each with advantages and disadvantages. As has been discussed, the low frequency test benefits when the grid conducting paths are known. If the location of the grid is unknown, using an alternative method to determine the presence of conductors would provide a useful initial layout for the proposed method.

8
CONCLUSION

The procedure outlined in this report does function in the manner predicted; injected currents into a subsurface conducting grid can be detected using magnetic pickup coils. Therefore, the current flowing in a conductor can be estimated. The method satisfies one of the primary questions as to whether the location of a subsurface grid can be determined.

As mentioned previously, if greater knowledge of the grid location is present, the technique will provide a better assessment of the grid integrity. With specific knowledge of the conductor paths available, the inverse calculation of the currents from the measured field is more precise, resulting in greater confidence in the analysis.

In consideration of specific investigations, the low frequency test was successfully performed using signals in the frequency ranges of 60-200 [Hz]. In this range, the radiated sinusoidal signal was easily obtained. As would be expected, the magnitude of the signal corresponded to proximity to the conduction paths. The measurement equipment was able to acquire signals at vertical offsets of 1-2 [m] in both the test grid and substation grids. This aspect sets aside concerns detecting signals in deeply buried grids.

The three components of the field were measured and consistent with a likely subsurface current path. The error between the forward calculation of the field due to the current source and the field measurements is sufficiently small to have confidence in the inverse calculation.

The ability of this method to assess the grid integrity still needs to be determined. The detection of a break is determined by the absence of a field in an expected region. This effect requires a knowledgeable user to study the grid field measurements and locate null regions. Broken welds are more easily analyzed in the postprocessor, with the inverse problem indicating the current paths that do not connect. The issue with regard to corrosion presents the most challenging assessment. The assumption that the resistance sufficiently reduces the current in multiple paths still needs to be verified.

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