

GROUNDING GRID INTEGRITY

REPORT 2017:405



Grounding Grid Integrity

Pre-study

PETER ULRIKSEN

TORLEIF DAHLIN

ISBN 978-91-7673-405-6 | © ENERGIFORSK June 2017

Energiforsk AB | Phone: 08-677 25 30 | E-mail: kontakt@energiforsk.se | www.energiforsk.se

Foreword

A copper grounding grid is placed underneath the entire nuclear power plant, including the substation. The purpose of the grounding grid is to serve the dual purpose of carrying currents into the earth without exceeding the operating tolerances of any protected equipment while assuring that personnel in the vicinity are not exposed to electric shock as would result from excessive step or touch potentials. Similar designs are used in substations in the grid.

The grounding grid was installed upon the construction of the nuclear power plants. Since then, many additional constructions and installations have been performed on the site, and in some cases, it is unclear if the grounding grid has been properly considered in these activities. Also, given that the grid is buried under ground, it is difficult to inspect to verify if there are corrosion attacks. Thereby, it would be beneficial if a non-destructive testing method could be identified, to verify the integrity of the grounding grid.

This pre-study was initiated to map possible non-destructive testing methods to verify the integrity of the grounding grid. It was performed by Professor Torleif Dahlin and Professor Peter Ulriksen at Engineering Geology at Lund University. A parallel project on corrosion in grounding grids has been performed by senior researcher Lena Sjögren, and the results are found in Energiforsk report 2017:397.

Monika Adsten, Energiforsk

Reported here are the results and conclusions from a project in a research program run by Energiforsk. The author / authors are responsible for the content and publication which does not mean that Energiforsk has taken a position.

Sammanfattning

Denna rapport är en förstudie inför utvärdering av metoder för att lokalisera skador i jordlinenät.

Skador kan upptäckas på två nivåer, dels globalt genom impedansmätning i accesspunkter till jordningen och dels lokalt genom att antingen leda ström med känd frekvens genom nätet och mäta signaturer på markytan eller genom att med induktiva metoder alstra virvelströmmar i jordlinorna, vilka kan mätas på ytan. Rapporten beskriver metoder som rekommenderas för lokala undersökningar och presenterar en möjlig försöksplan omfattande laborativa och fältmässiga prov.

Rapporten innehåller korta avsnitt om jordningssystemets syfte och funktion samt en beskrivning av hur man bestämmer markens resistivitet.

Summary

This report is a pre-study before a systematic study of methods suitable to locate damage in grounding grids is made.

Damages can be detected in two levels, globally by impedance measurements in access points to the grounding system and in local scale by either leading a current of known frequency through the grid or by inductive methods whereby eddy currents are created in the wires, generating anomalies that can be measured on the surface. The report describes suggested methods for doing this and presents a possible design for evaluating these methods through laboratory and field tests.

The report includes short chapters regarding the purpose and function of the grounding system in substations.

List of content

1	INTRODUCTION	7
2	GROUNDING GRID PURPOSE	8
3	GROUNDING GRID TERRAIN INVESTIGATION	9
4	GROUNDING GRID FUNCTIONAL CONTROL	12
5	INSTRUMENTS FOR LOCATING DISCONNECTION/CORROSION	17
5.1	VERY LOW FREQUENCY – 3-D VLF	17
5.2	TOTAL MAGNETIC AC FIELD MEASUREMENT	18
5.3	ELECTRIC FIELD MEASUREMENTS	19
5.4	ELECTRIC SURFACE POTENTIAL	20
5.5	INDUCTION INSTRUMENTS	20
5.5.1	GEONICS EM-61	20
5.5.2	SCHIEBEL MINE-SEEKER	23
5.6	PRESENT OR INDUCED FREQUENCY DETECTION	25
5.6.1	LEICA CABLE FINDER	26
5.7	GROUND PENETRATING RADAR - GPR	27
6	RECOMMENDED FIELD TESTS	29
6.1	GENERAL TEST PLAN	29
6.1.1	PURE ANOMALIES (STEP 1)	29
6.1.2	SURFACE LAID GRID (STEP 2)	30
6.1.3	BURIED GRID (STEP 3)	31
7	ESTIMATED COSTS	32
7.1	STEP 1	32
7.2	STEP 2	32
7.3	STEP 3	33
8	DOWN TO EARTH DELIBERATIONS	34
9	ABSTRACTS OF REFERENCED PUBLICATIONS / BIBLIOGRAPHY	37

1 INTRODUCTION

This report is intended to suggest ways of detecting inconsistencies in grounding grids (earthing grids).

It should also suggest field tests suitable for selecting appropriate instruments for detection of those inconsistencies. A further task is to make an estimate of the associated costs of such tests.

We have found it suitable to incorporate, as a background, short chapters about the reason for installing a grounding system and how it operates. Since the authors are geophysicist/civil engineers we have no high voltage background and are therefore citing work of others, chapter 2 and 4.

There is also a chapter regarding how the resistivity of the soil should be determined with modern methods.

2 GROUNDING GRID PURPOSE

A grounding system is laid out in the soil under a substation. According to [1Vaughn]: “The purpose of the grounding system is threefold: conduct faults to earth, limit voltage rise on the station mat and eliminate step and touch potentials.

Normally the grounding system consists of a main grounding bus and the grounded mat. The main bus is a larger copper conductor that rings and crosses the station, usually 4/0. The bus is usually trenched in with leads brought up in critical locations. Rods are installed along the bus anywhere from 5 to 30 m apart according to the calculated conductivity of the earth. They are used to reach more conductive soil layers situated deeper. Woven between the bus conductors is the mat. It is often constructed of smaller copper wires anywhere from #4 to #10, but can be larger. They are cross-connected to form 3 dm to 1 m squares, all depending on the design criteria.

The bus is principally designed to conduct anticipated fault currents to earth, while the mat is principally designed to provide against step potential and as a shield from currents and voltage rise injected into the earth during a fault.

The mat is usually not located as deep as the bus. The mat can be laid on compacted soil, packed and tamped. After the cover soil is tamped, a layer of crushed stone is laid. The stone layer can be from 0.3 to 1 m thick. The crushed stone layer provides an insulating buffer between workers and the mat.”

See chapter 9 for more information, notably reference [1 Vaughn].

3 GROUNDING GRID TERRAIN INVESTIGATION

Proper function of a grounding grid is dependent on sufficient conductance in the soil volume it is installed in, or to express it in the opposite way that the ground resistance is sufficiently low. The resistivity of the ground varies between different soils and rocks, and for the most common geological materials it is mainly dependent on the water content, salinity and clay content of the ground. Metal ores are an exception that can have extremely low resistivity.

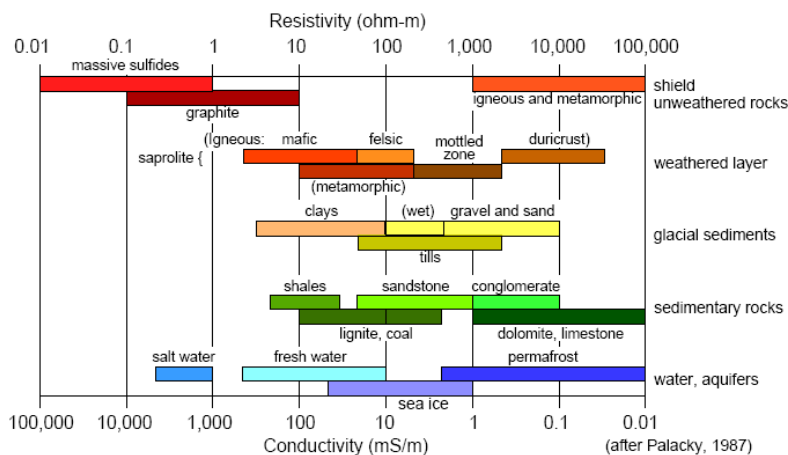


Figure 1. Typical resistivities in geological materials (modified from Palacký 1987)

The resistivity of the ground can be measured using four electrode arrays, where two electrodes are used for transmitting a controlled pulsed direct current and two other electrodes are used for measuring the induced potentials. Pulses of alternating polarities are used to remove electrode polarization effects, and measurements are made so that background drift is filtered away.

One measured value is a weighted mean of the resistivity distribution of the investigated volume, which is only equal to the true resistivity in homogeneous ground. The measured quantity is called apparent resistivity (ρ_a). The depth penetration of the measurement can be varied by varying the separation between the electrodes.

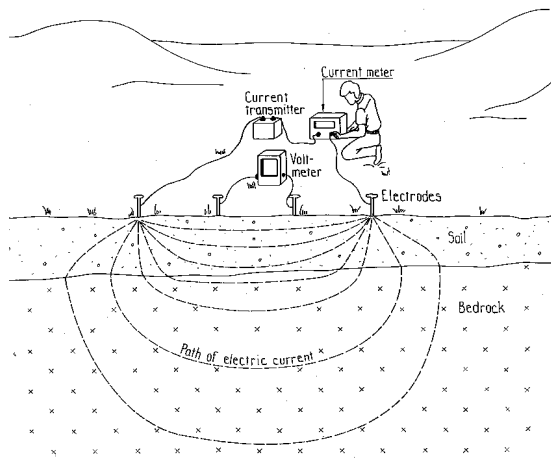


Figure 2. Principle for VES resistivity measurement with 4 electrode configuration (modified from Robinson and Coruh 1988). Depth sensitivity is obtained by increasing electrode separation.

The suitability of the ground is traditionally carried out by vertical electrical sounding (VES) which is done by systematically varying the electrode separation around a common midpoint. The measured variation in apparent resistivity reflects the variation of resistivity with depth, and in order to retrieve an estimate of the true resistivity distribution model interpretation is required. This is normally done by inverse numerical modelling, inversion, in which a discretized model of the resistivity distribution in the ground is adjusted in an iterative process until an acceptable fit between the model response and the measured data is achieved.

VES is based on the assumption that the ground consists of homogeneous, isotropic plane parallel layers, and if the actual conditions deviate significantly from this it can give misleading results. Developments in data acquisition technology and inversion techniques have been strong in the last decades, and today two dimensional (2D) resistivity surveying, often referred to as earth resistivity tomography (ERT), dominates in practical application. Data acquisition is carried out by setting up spreads of several tens of electrodes, and having the instrument which has a built-in relay matrix switch scan through a predefined measurement sequence. A typical data set often consists of data from more than 1000 different electrode combinations, and lines can be extended by moving part of the electrode spread with so called roll-along. The data are mostly interpreted by inversion in which a 2D finite element model of the ground is created, providing a vertical model section of the resistivity distribution below the electrode spread line. The inversion is highly automated, but data quality control before the inversion is essential in order to receive reliable results.

The measured apparent resistivity depends not only on the resistivity variation with depth, but also changes in the direction perpendicular to the measurement spread affects the data because of the three dimensional (3D) current distribution. Thus so called 3D effects can give misleading results in complex geological environments or if grounded infrastructure is present in the surroundings. By measuring perpendicular or parallel 2D ERT lines the 3D character of the ground can be revealed.

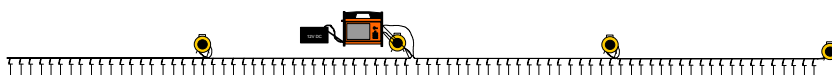


Figure 3. Sketch of electrode spread for 2D ERT. The survey line can be extended with so called roll-along by moving one cable section from one end to the other and shifting the instrument one step.

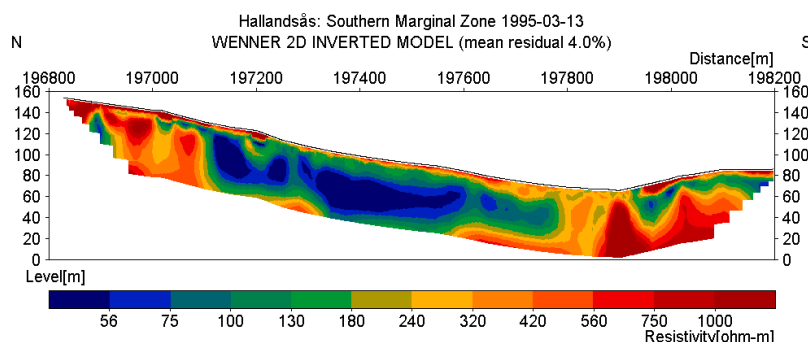


Figure 4. Example of 2D electrical resistivity tomogram.

3D ERT can be achieved by measuring several parallel lines, from which the data is merged and inverted using a 3D finite element model approach. It is also possible to measure on a grid of electrodes, but this obviously requires larger electrode spreads and more complex equipment.

In power grid application it appears that VES using Wenner configuration is still a widespread approach for assessing the electrical grounding properties. The VES is usually carried out according to a laborious manual procedure described in ASTM standard G57. This is a very inefficient way of doing a resistivity survey that gives a small amount of information in relation to the time and cost spent, and the results can be misleading in complex environments. It would be much more appropriate to use modern ERT.

A limitation of the DC resistivity method, such as VES and ERT is that they depend on sufficiently good galvanic contact between the electrodes and the ground, which can be challenging in cases with dry coarse grained sediments or bedrock outcrop. Watering the electrodes and applying conductive gel or bentonite mud usually solves such problems. The method is relatively slow compared to some electromagnetic methods like GPR (Chapter 5) because of the required galvanic contact, but on the other hand it is more robust and works well and provides stable data in most environments. It works in low resistivity soils like clay, where GPR provides no results and GPR does not provide direct resistivity data. It also works well in high resistive environments where inductive electromagnetic methods such as TEM (Chapter 5) have poor resolution of the ground resistivity, and often provides stable results even close to high tension power lines.

4 GROUNDING GRID FUNCTIONAL CONTROL

The functional control of a grounding system can be separated in a global control and a local control. The global control is performed by measuring the impedance at access points to the grounding system. It can only say that the system impedance is too high, it cannot locate the discrepancies.

A good presentation of the global measurements is presented by [2 Jowett]

“Fault clearance and lightning protection can severely damage a grid or mesh. Another agent is corrosion and ironically the best grounding soils are also the most corrosive. Resistance tests performed in the mA current range indicate the overall capability of the grid regarding step or touch potentials, but does not indicate the internal condition of the grid. To test grid integrity the tester must be able to produce high current, in the order of 300A. Rather than calculating and displaying resistance the grid tester evaluates the change in current flow. Test leads are typically welding cables 3 to 30 m long.

1. A reference ground is first established, typically a transformer neutral.
2. The cables are connected to the reference and the test ground.
3. Current is switched on for a period of 3 minutes.
4. A clamp-on ammeter is then used to measure currents around the system A-D.
5. Test lead voltage drop is measured by connecting the ends measuring the voltage
6. An acceptable voltage is 1.5 V per 15 m straight line.
7. For single driven electrodes at least 200 A should return to the source via ground path, *i.e. the circuit should be reasonably closed, the current source almost short-circuited*
8. For mats and grids at least half the current must return via the ground path, *see comment above.*

By isolating the faulty current path the work of excavation and repair is markedly reduced.

For more information see Chapter 9, [2 Jowett]

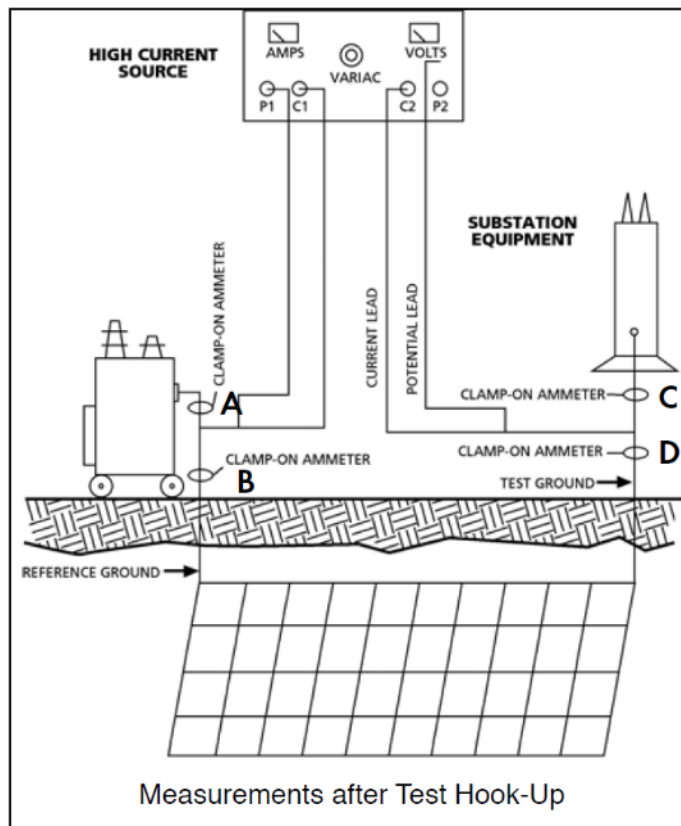


Figure 5. Current based test of grounding system integrity. [2 Jowett]

Local measurements are falling in two categories: electromagnetic field and inductive detection.

Electromagnetic field

Dawalibi [3] presents calculations of the electromagnetic fields around a conductor.

“The problem is to determine the performance of the ground network when it is energized by known currents injected at the source busses. More specifically the objective is to determine:

1. Potentials at all source busses and nodes
2. Longitudinal and leakage currents in every conductor segment
3. Scalar potentials at any observation point in earth
4. Magnetic field at any observation point above earth

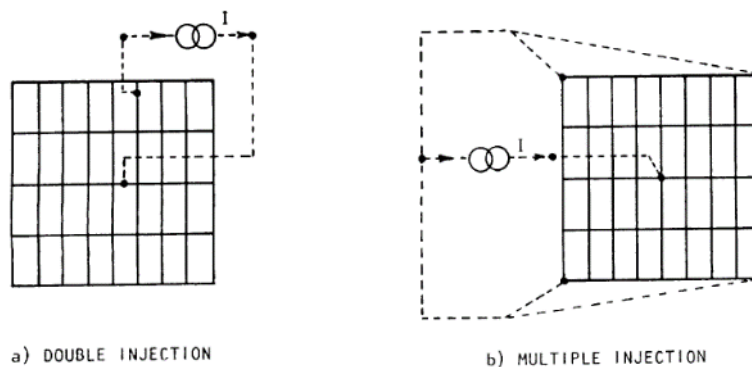


Figure 6. Examples of how current could be injected into a grounding system without the use of a remote electrode. [2 Jowett]

When a DC current of 100 A is injected between the two points of an intact grid, most of the current will flow in the conductors of the grid with only an extremely small portion of the current circulating in the earth. If a grid conductor is broken, then the conductor will experience a significant increase in its earth leakage current in the vicinity of the discontinuity.

The multiple point current injection technique is more practical, in that it provides a global view, but less selective than the double point current injection technique.

Single discontinuities are difficult to detect even with the aid of signature curves (undamaged state), however multiple discontinuities are more easily detected.

More information in Chapter 9, Reference [3 Dawalibi]

Induction – Transient Electromagnetic Method TEM

Yu [4] presents a novel approach using the transient electromagnetic method for fault diagnosis of grounding grids. The induced magnetic intensity is collected by receiver coils in the form of electromotive force. After inversion maps of ground resistivity can be obtained. The faults due to corrosion or breaks can be accurately located from the distribution characteristics of equivalent resistivity maps.

In the introduction are mentioned several previously applied methods for analysis of grounding grid discontinuities as:

1. Point resistance or surface potentials (anomalies are often quite small)
2. Sine wave exciting current
3. Electrochemical potential methods (good for corrosion detection but not for breaks)

The paper advocates the Transient Electromagnetic Method – TEM. A typical TEM is a transmitter –receiver system that records the secondary magnetic field due to the induced eddy currents in the ground. The rapid transmitter current pulse turn-off introduces the primary field impulse that creates eddy currents in the ground. After inversion calculation of the secondary magnetic field recorded by receiver coils, corrosion or break points of grounding grids can be detected from contour maps of the calculated equivalent resistivity.

Three situations are considered: the grounding grid at a depth of 0.8 m has no faults, a single break point at the middle of a conductor and a single break cut at the cross node of conductors. Also the presence of a 0.5 m diameter pipeline at different depths above and under the grid was calculated, Figure 7. The simulations were carried out using a 3-D transient simulator, a FEM package from Ansoft. The simulated transmitter loop has a radius of 0.302 m and is excited by a 16 A current pulse of trapezoidal shape. In Chinese grounding grids iron bars 5x0.5 cm are used instead of copper wires.

A broken wire is expected to reduce the electromagnetic coupling between transmitter loop and the grid mesh.

The simulation results clearly indicates the presence of wire breaks with the break at the cross point E being of largest magnitude.

The presence of the pipeline made serious disturbances in the case it was above the grid, but had no significant influence when it was buried below the grid, Figure 8.

A weaker magnetic intensity is interpreted as a higher equivalent resistivity in the inversion process.

Consequently there is no advantage in calculating the equivalent resistivity. In fact there is no need to display the entire magnetic intensity history either, it suffices to present the value of one recorded time sample. The authors have chosen the 3 ms sample for that purpose, Figure 9.

Grounding materials of higher conductivity results in stronger magnetic intensity. Thus copper wires give a stronger intensity than iron wires. The soil material appears to have little influence as long as the conductivity of the soil is much below that of copper.

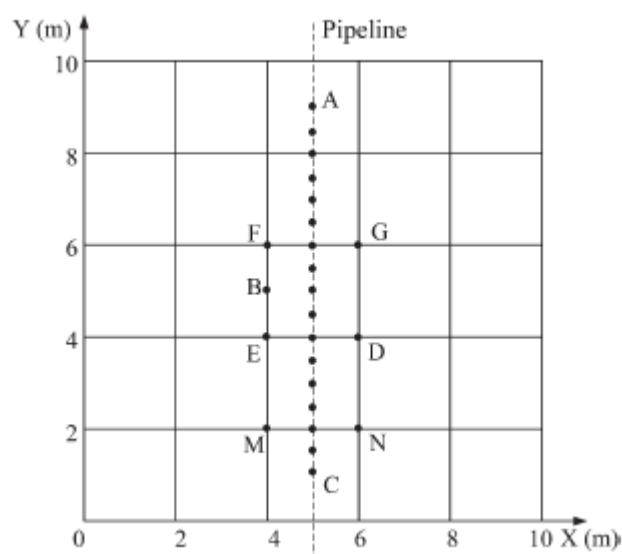


Figure 7. Layout of experimental plan with assumed break points B and E. [4 Yu et al]

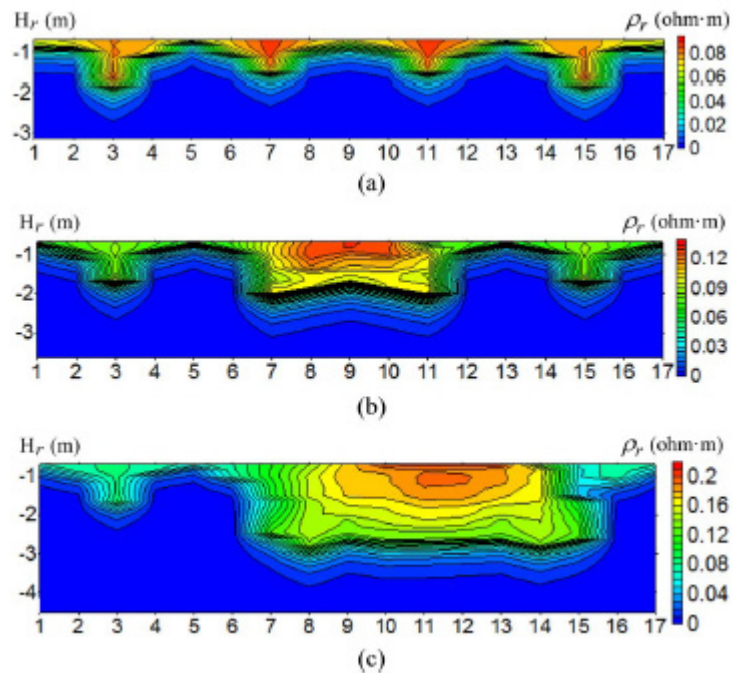


Figure 8. Contour map of equivalent resistivity with 17 measuring points along A(#1)-C(#17) when the grounding grid has a) no faults, b) a break cut on conductor at B (close to point #9) and c) a break cut at cross point E (close to point #11). No pipeline was present in this simulation. A weaker magnetic intensity is interpreted as a higher equivalent resistivity in the inversion process. [4 Yu *et al*]

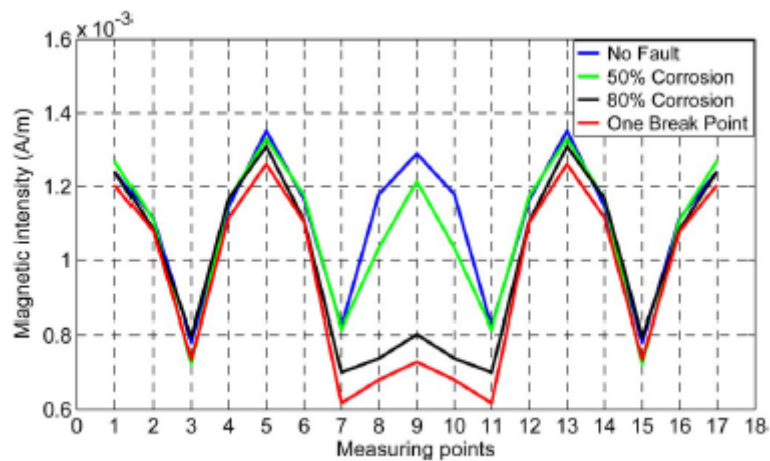


Figure 9. The influence of different degrees of damage to a copper wire between point #7 and #11 (green, black) and a break at point B (#9) on the magnetic intensity at the 3 ms sample. [4 Yu *et al*]

5 INSTRUMENTS FOR LOCATING DISCONNECTION/CORROSION

5.1 VERY LOW FREQUENCY – 3-D VLF

Electromagnetic fields in the frequency range 10-30 kHz are referred to as very low frequency (VLF). VLF fields transmitted by distant radio transmitters can be regarded as essentially parallel to the ground, Figure 10. When they penetrate the ground they give rise to induced eddy currents. The eddy currents in turn give rise to secondary electromagnetic fields, which vary in direction and phase in relation to the transmitted fields. By measuring variations in direction and phase of the resultant total field around a buried conductive structure it's presence can be revealed.

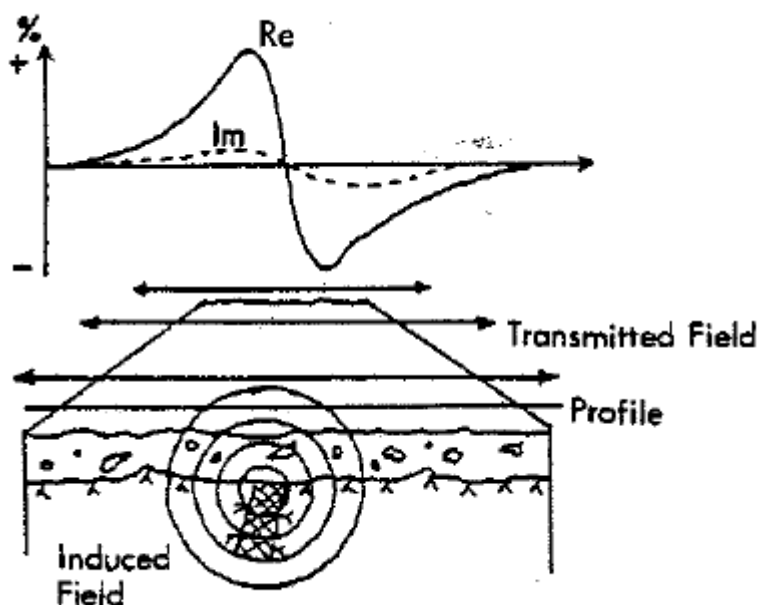


Figure 10. Sketch of VLF field from remote transmitter and induced secondary field from conductive zone in bedrock, with typical measured principle response above. The measured response is often presented after applying a digital filter that transforms the inflection points to peaks, which is easier to interpret and plot in map format.

Induction will take place in conductive structures that are aligned with the direction of the transmitter, so that the magnetic component of the electromagnetic field is more or less perpendicular to the conductive structure. In order to capture all possible structure directions it is therefore essential to measure with more than one transmitter direction. Ideally an instrument, Figure 11, should measure in a rather wide frequency band with three perpendicular receiver coils, with automatic recording of direction of the coils and positioning with sufficiently high resolution. In this way all possible directions could be detected in one round of scanning over a grid in an area of investigation.



Figure 11. Equipment for VLF measurements

An advantage of the VLF technique is that it uses remote transmitters, which means that the equipment can consist of small and easily portable receiver units. A major disadvantage is that it depends on these remote transmitters, and it may happen that transmitters in suitable directions are not operating when a survey is planned to take place. Another limitation of the method is that man-made conductive structures such as power lines and wire net fences give rise to strong responses that will mask more subtle responses in their vicinity.

5.2 TOTAL MAGNETIC AC FIELD MEASUREMENT

In the LTH inventory there is a total field magnetic AC instrument. The probe, Figure 12, consists of three orthogonal coils, Figure 13, and an electronics box for calculating what is the total field. It is possible to measure the three orthogonal field components separately, using external equipment, to calculate also the direction of the magnetic field. The *instrument* is limited to fields below 2 kHz. This part of the magnetic spectrum is labeled Extremely Low Frequency - ELF. The sensor does not react to the static magnetic field of the earth when the sensor is held in a fixed position.



Figure 12. The sensor head of the total magnetic field instrument. Thin lines indicate the orientation of the coils inside the sensor head.



Figure 13. Top of sensor head removed to show the arrangement of the three orthogonal coils.

5.3 ELECTRIC FIELD MEASUREMENTS

This is referring to measurements of the electric field in the air above the ground where the grounding grid is buried. The sensor would be a dipole antenna, possibly with metal spheres at the ends, increasing the sensitivity.

If a current is forced through a wire with a locally reduced cross section the electric field surrounding the wire would increase due to the increased voltage drop over the damaged part.

5.4 ELECTRIC SURFACE POTENTIAL

The electric fields produced by the wires and irregularities could also be measured using a distant reference electrode and a surface probe electrode.

5.5 INDUCTION INSTRUMENTS

The inductive instruments work on the principle of establishing a magnetic field in a coil and the abruptly turning this field off, creating an induced current in the ground, Figure 14. The measured parameter is the fall-off rate of the induced current. The instruments come with different size coils and the larger the coils are, the deeper is the surveyed layer of the ground. Some instruments have separate transmit and receive coils.

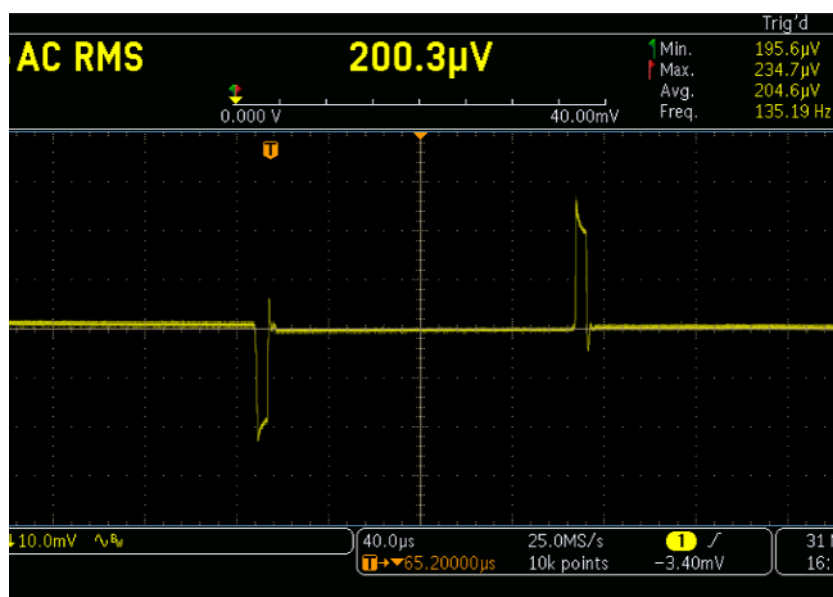


Figure 14. Pulses used in the Schiebel mine seeker of the inductive type. As can be seen pulses of about 8 us are transmitted at about 150 us intervals, with every other of opposite polarity.

Here we will describe two induction instruments, the Geonics EM-61, which is made for geophysical measurements of ground properties and the Schiebel mine-seeker, which is a military instrument. The EM-61 has a data recorder while the Schiebel in standard option only has an audible output in headphones.

5.5.1 GEONICS EM-61

The metal detector Geonics EM61 is based on the time domain electromagnetics principle. It includes a transmitter coil and a receiver coil, in the EM61-Mk2 edition it comprises two different receiver coils for enhanced detection of small targets, Figure 15. Other version of the system are EM61-HH and EM63, which are

optimized for different targets and modes of operation. It is suitable for detection of ferrous as well as non-ferrous metal.

The transmitter coil generates a primary magnetic field which induces eddy currents in conductive objects such as metal. The eddy currents decay with time, at rates that depend on the characteristics of the object. The eddy currents produce secondary magnetic fields that decay accordingly, and these fields are detected by the receiver coil(s). Measurements are made in several time windows after the transmitted pulse has been turned off.

The instrument comprises the coils, a control unit with data storage, Figure 16 and a backpack with batteries and the power electronics, Figure 17.



Figure 15. Geonics EM-61 TEM sensor with two different coils. The black cable is the LTH test square.



Figure 16. Geonics EM-61 control unit



Figure 17. Geonics EM-61 back pack (batteries, power electronics)

Figures 18 and 19 illustrates the single square grid simulator put together at LTH. It is modular and permits total breaks to be opened and segments to be replaced with partly damaged (corroded) wires.



Figure 18. LTH 3 x 3 m grid with a break point connection in one segment and all corners.



Figure 19. Close-up of grid break point in one segment

5.5.2 SCHIEBEL MINE-SEEKER

The Schiebel mine-seeker, Figure 20-23, is delivered with headphones for audible indication of anomalies, this signal can be digitized by additional equipment and used for scientific measurements. The signal varies in strength and pitch. Presently it is unclear if this represents two variables or if it is two representations of the same variable.



Figure 20. The Schiebel AN-19 military mine seeker (courtesy of FOI)



Figure 21. Schiebel AN-19 mine-seeker coils



Figure 22. Schiebel AN-19 control unit. Dials for sensitivity and headphone loudness.



Figure 23. Schiebel AN-19 Headphones

5.6 PRESENT OR INDUCED FREQUENCY DETECTION

These instruments operate on detection of a magnetic field created by a current floating in a cable. They appear unable to detect a cable with no current flowing. Several manufacturers produce these instruments.

5.6.1 LEICA CABLE FINDER

The Leica cable finder, Figure 24, has two operating modes. The first mode is used to locate cables carrying an electric current at the normal 50 Hz frequency. This requires a magnetic field, which in turn requires a certain level of the current. If no current is flowing in the cable it can be created by means of a portable current source, Figure 25-26. This can be laid on the ground just above a location where the cable is known to be and will then induce a current in the cable by induction. It can also be connected directly to the cable and to a grounding post. There are several varieties of this instrument. The source demonstrated has two frequencies 8 kHz and 33 kHz.



Figure 24. Leica Digicat 550i Cable-finder. Magnetic field detector. Requires current in the cable to be detected.



Figure 25. Leica cable-finder system. Near: Digitex transmitter (induction or connection) and Distant: Digicat receiver.



Figure 26. Leica Digitex inductive/connective transmitter for frequencies 8 kHz or 33 kHz.

5.7 GROUND PENETRATING RADAR - GPR

The ground penetrating radar provides truly continuous cross sections of soil profiles by reflected electromagnetic waves in shape of short bursts of energy – impulses. Due to the much larger conductivity of copper wires than of soil, such wires are formidable reflectors. Due to the wide beam-width of GPR antennas, echoes from wires are seen before the antenna is just above the wire. This generates

a hyperbolic shape of the echo signals, which clearly identifies the position along-track the profile, Figure 27. It is unclear if GPR is capable of detecting damages in wire. This is because the pulse lengths of the GPR are larger than the damages and that a GPR profile should typically be oriented perpendicular to the wire to provide best positioning.

Modern GPR systems may have many antennas providing a swath of parallel profiles. LTH pioneered GPR in Sweden.

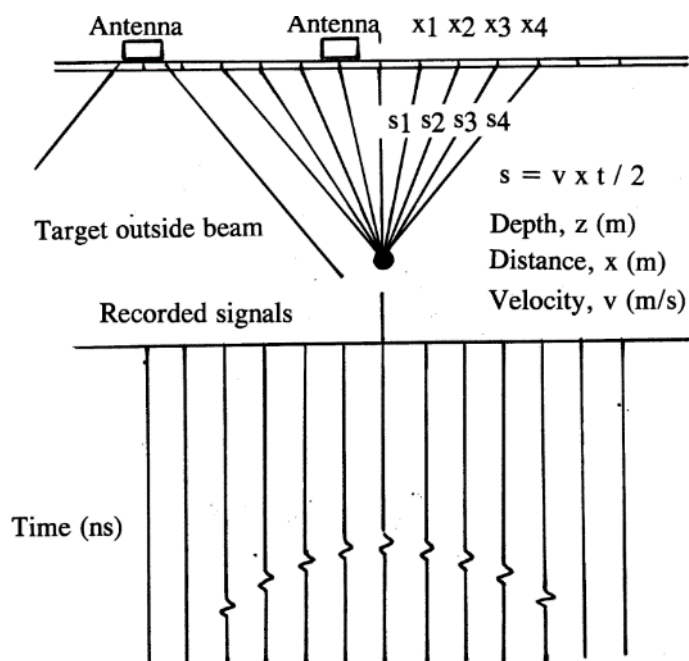


Figure 27. Typical radar echo from a metallic conductor (black).

6 RECOMMENDED FIELD TESTS

6.1 GENERAL TEST PLAN

The test plan is designed in three steps. The first step is to record pure anomalies of different damages. The second step is to make the operators acquainted with the damage type signatures for the different instruments. Using terminology from geophysics the *anomalies* that can be expected are established in the first and second steps. The third step is to evaluate the capacity of operators to find and evaluate grid wires of unknown position and discontinuities using the knowledge about expected anomalies.

It seems to be a good idea to perform step 1 before any decision on step 2 and 3 is made. This is for two reasons. Step 1 will demonstrate if selected physical principles can detect created damages and it will do that at a relatively low cost. If the instruments are not succeeding, there is no reason to perform steps 2 and 3.

6.1.1 PURE ANOMALIES (STEP 1)

Any measurement taken of wire anomalies along the wire will also have a component from the natural terrain, which varies along the measured path. In order to circumvent that the sensor must be kept in a fixed position. This can be obtained by leading the wire along the periphery of a large diameter “wheel” and keeping the sensor stationary, Figure 28. This would have to be done where the electric and magnetic fields are constant, i.e. outdoors.

This kind of anomalies could be labeled as *in vitro* anomalies. Since the cable is heavy and the diameter of the wheel would be large the arrangement would have a quite high inertial moment. Thus it would suffice to manually start the rotation and measure the rotational period to have high quality data regarding distance. This would be an advantage since an electric motor would produce disturbing magnetic and electric fields.

It would be necessary to construct an arrangement whereby a current could be led through the wire during rotation.

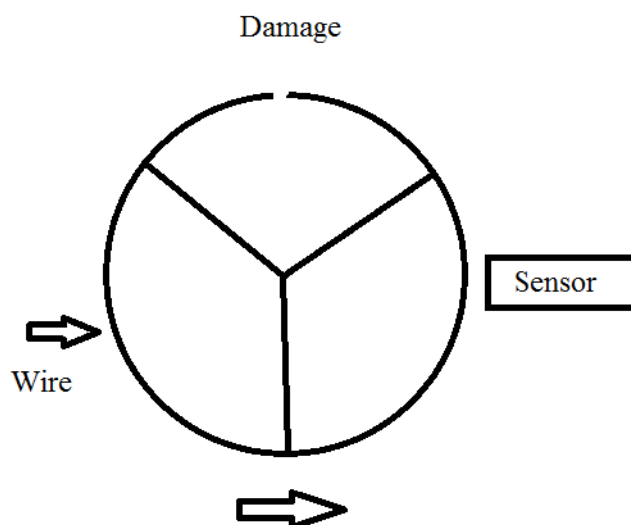


Figure 28. Wheel-method to record “pure” anomalies with a fixed sensor. The grid wire is formed around the periphery of a large wheel of non-conductive material. The wire could be laid in a plastic tube. Due to its’ inertia the wheel (cable + spokes) does not need any motor. It will keep rotating at a given rpm for a while after being manually spun. Diameter 2-3 m.

6.1.2 SURFACE LAID GRID (STEP 2)

Anomalies in the ground without any surface grid laid out

Before measurements are started the *in situ* anomalies for each candidate instrument must be established. This is done by exactly marking the intended position of the surface laid grid before it is laid out.

Learning anomalies over known intact grid wires

In this step primarily the Leica cable finder or similar is applied in passive and active mode to check its’ capacity to correctly locate the surface laid wires. The passive mode of the cable finder requires the wires to be carrying an AC current emanating from an external source, e.g. the 50 Hz. The active mode of the instrument is using an associated current source to generate a frequency of 8 or 33 kHz which is connected to the grid wires.

Learning anomalies over known corrosion in known grid wires

Corrosion has the effect of reducing the cross section of the grid wires. This means that the resistivity locally increases. Since the same current must flow through the damaged part as in the adjacent parts of the wire due to Kirchhoff’s law for a simple circuit, the potential fall will have to be larger over the corroded part. This may result in a stronger electric field over the corroded part making a case for electric field measurements. Corrosion will reduce the induced current from a TEM instrument (induction) making a case for such measurements.

A combination of exact point measurements and line measurements repeated for all candidate instruments will be adequate.

Learning anomalies over known breaks in known grid wires

A break in a wire will produce larger currents in the soil (Dawalibi [3]) which may be detected by surface potential measurements, electromagnetic or inductive methods.

6.1.3 BURIED GRID (STEP 3)

An explosive cap can be tied to a buried cable and change its state to broken without unearthing the cable.

In this experiment the grid is buried at a representative depth. There must be several grounding posts located in such a manner as to not reveal the structure of the buried net, i.e. e.g. not in the corners of the grid.

The surface of the ground must be such that it does not reveal where the grid wires have been buried.

Anomalies in the ground without any buried grid

It is not without problems the background anomalies could be established because it would reveal the planned location of the buried grid. Ideal would be a large soil surface without any reference points. Or the soil surface could be covered with crushed stone as in a real substation.

Locating unknown grid wires

In this step primarily the Leica cable finder is applied in passive and active mode. The passive mode requires the wires to be carrying a current emanating from an external process, e.g. 50 Hz AC. The active mode of the instrument use an instrument associated current source to generate a frequency of 8 or 13 kHz which is connected to the grid wires. When the location is completed the wires' positions should be marked on the surface with spray paint.

Locating unknown corrosion in grid wires

All available instruments are tested along the previously located grid segments. Possibly the inductive methods like the EM-61 is powerful enough to sense anomalies even if the sensor coils are not just above the inconsistencies of the wires.

Locating unknown breaks in grid wires

All available instruments are tested along the previously located grid segments. Possibly the inductive methods like the EM-61 is powerful enough to sense anomalies even if the sensor coils are not just above the inconsistencies of the wires.

7 ESTIMATED COSTS

7.1 STEP 1

This is the most significant test suggested, although it is not a realistic simulation of the conditions for a wire buried in soil. What is not possible to simulate is surface potentials around a break in a wire. But a break and many levels of corrosion can be simulated. The instruments would be positioned at different distances from the cable, to map their area of influence.

These measurements would be compared to theoretical calculations and numerical modelling, which is an activity intended to take place at KTH

The wheel method is not suitable for evaluating cable seekers, since these are locating the cable by moving the seeker in a line perpendicular to the cable direction. For the cable seeker a test-rig with a horizontally moving vertical cable carrying current is envisaged. It could be like a vertical rectangle rotating around a center post passing the stationary cable finder instrument that would be positioned at different distances from the cable, to map its' area of influence. In natural terrain the fields would be attenuated in accordance with the conductivity of the soil. This attenuation is possible to calculate theoretically from resistivity values.

The costs arise from building the intended wheel and performing the tests. The task is potentially suitable for a M. Sc. project, since it can be launched with quite short instructions. This approach depends on the availability of such students.

The procedure would be to have a fixture for the sensors that would allow for different distances between the sensor and the rotating cable. For the electromagnetic instruments it would also be of interest to vary the current in the wire.

The construction of the test rigs would probably cost around 50 kSEK. For each tested instrument it is estimated that the cost would be 35 kSEK including report. Rental costs are not included in this estimate. It is standard that geophysical equipment is rented at 5% of the instrument cost per week. Since we have all instruments and some others like GPR (Ground Penetrating Radar) it may be an alternative to buy a GEONICS EM-61. It would then be an upgrade compared to the one illustrating the figures in this report. The cost of a modern GEONICS EM-61 MkII is 37.000 USD. The daily rental cost is 144 Euro/day

7.2 STEP 2

This is the easiest test to perform. But it would be separated in time from the step 1 measurements, because of the necessary evaluation period after step 1. It is suggested that several frames of mechanically connected wire segments, like the one shown in the EM-61 pictures, is used. Segments with different standardized damages are constructed. This segment could be covered by plastic tubes in a second test on the surface laid grid. The exercise would accustom operators to quantify the outputs of their instruments. For silent sensors that would be pointless.

Building wire frames is estimated at 25 kkr and reporting for each instrument at 35 kkr.

7.3 STEP 3

This is the most expensive test to perform. Since it requires the engagement of construction companies it lies beyond our capacity to estimate the costs. A complication requiring afterthought is the availability of a suitable site. Ideally this site should be possible to establish as a permanent test site also for other problems that may require evaluation of methods and training of personnel.

However the measurement and evaluation costs would be comparable to those in step 2.

8 DOWN TO EARTH DELIBERATIONS

This part is only speculation by the authors and not based on the scientific literature.

Remembering that:

“The bus is principally designed to conduct anticipated fault currents to earth, while the mat is principally designed to provide against step potential and as a shield from currents and voltage rise injected into the earth during a fault.

The stone is not there for architectural reasons. The crushed stone bed provides an insulating buffer between workers and the mat. The stone layers resistance is sometimes 3000 Ohms/m or more between the worker and the mat. Voltage without current, even at high levels, is not usually deadly. The stations ground grid is practically of zero resistance while you are more than 4000 ohms across your body and the stone layer to the mat.” [1 Vaughn].

There is thus always a resistance between a person’s hand and the ground under the mat of at least 4000 Ohms. That resistance will reduce the current to unlethal levels also in single hand contact with high voltages. Hand to hand currents should be taken care of through the installation’s grounding bars in contact with the bus. For this reason a fault in the mat (grounding grid) will not compromise the function of the mat unless the fault has a considerable extension.

In our opinion there is thus no reason to proceed to an extensive grounding grid survey unless measurements at the available grounding posts show that something may be wrong, see e.g. [2 Jowett] for how this is done.

Apart from the standard impedance measurements we suggest the following:

It has not escaped our notice that the mat is like a plate in a condenser stretched by the bus. The other plate would be the first conductive soil layer or the groundwater table. Between these “plates” there should be a measurable capacitance. The capacitance C of a plate condenser with area A and distance between plates d is

$$C = \epsilon A / d$$

if the material between plates has a dielectric constant ϵ . *Thus any significant reduction in the area A should result in a reduction in the capacitance C . A complication is of course that the original capacitance is unknown.*

The contact with the other plate, a conducting soil layer or the groundwater table, could be made by inserting an isolated rod, with a tip electrode, to the desired depth. This kind of measurement is labeled *mis a la masse* in geophysics. This expression is French and means approximately “brought to protective ground”.

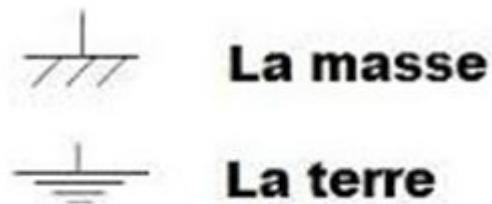


Figure 29. Mise a la masse symbols. Approximate meaning is protective ground (skyddsjord).

Then, by using a technique similar to the induction methods previously discussed regarding the Schiebel metal detector and the Geonics EM-61 a high power pulse is injected over a grounding post and the isolated rod. The fall-off voltage as the current is switched off can be used to measure the capacitance of the circuit.

This is routinely made in the geophysical method Induced Polarization – IP, which LTH happens to have a great deal of knowledge in (e.g. Dahlin and Leroux 2012).

An extension of this technique would be to measure in the frequency domain instead of the time domain. The pure capacitive impedance is a complex number depending on the frequency according to

$$Z = 1 / j\omega C$$

It makes the voltage lag the current by 90 degrees. If there is also a resistive component (in phase with the current), the resultant impedance will be according to Figure 30.

Frequency domain measurements result in a complex number for each frequency, which can be recalculated into phase and amplitude.

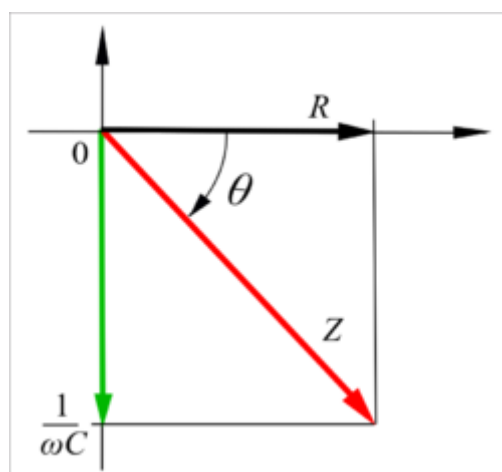


Figure 30. The impedance Z resulting from combined resistive and capacitive impedances. [Wikipedia].

The difficulty of this method is of course that a baseline value is needed before you can make any statement on the measured value of the capacitance. This could however be obtained by making regular measurements or even better, making continuous measurements. That would also take care of seasonal effects due to variations in ground moisture and ground water level. The latter could be automatically measured in the isolated rod, if this is made like a tube.

The transient method measurements, we assume, would have to disconnect the mat from the grounding system, which is obviously not desirable or even impossible. Then the frequency domain method would be a better alternative, since the measurements could be made in other frequency domains than the network's 50 Hz, e.g. with extremely narrow-band detectors like a lock-in amplifier.

We have been informed, by Ringhals operatives, that touch potentials at selected points can also be measured when performing tests by injecting current at available grounding posts.

9 ABSTRACTS OF REFERENCED PUBLICATIONS / BIBLIOGRAPHY

The number of * indicates the estimated significance of the paper as judged by the authors of this report. Most significant papers are provided with an extensive abstract for those readers that have no access to scientific databases.

[1] ** Vaughn, Jim, CUSP, January-February 2009, "What you need to know about Substations",

<http://incident-prevention.com/ip-articles/what-you-need-to-know-about-substations>

The ground system has three purposes all of equal importance: conduct faults to earth, limit voltage rise on the station mat and eliminate step and touch potentials. There are two components to the stations grounding system made up of the main grounding bus and the grounded mat. The main bus is a larger copper conductor, usually 4/0, that rings and crosses the station. The bus is usually trenched in with leads brought up in critical locations. Rods are installed along the bus anywhere from 5 to 30 m apart according to the calculated conductivity of the earth. Woven between the bus is the mat. They are often constructed of smaller copper wires anywhere from #4 to #10, but can be larger. They are cross connected to form 3 dm to 1 m squares, all depending on the design criteria. Mats and buss are usually exothermically welded. If wires are brazed heat development in prolonged faults can melt the connections.

The buss is principally designed to conduct anticipated fault currents to earth, while the mat is principally designed to provide against step potential and as a shield from currents and voltage rise injected into the earth during a fault. The mat is usually not located as deep as the buss. The mat can be laid on compacted soil and the covered with good clay soil, packed and tamped. After the cover soil is tamped, a layer of crushed stone is laid. The stone layer can be from 03 to 1 m thick. The stone is not there for architectural reasons. The crushed stone bed provides an insulating buffer between workers and the mat. The stone layers resistance is sometimes 3000 Ohms/m or more between the worker and the mat.

Voltage without current, even at high levels, is not usually deadly. The stations ground grid is practically of zero resistance while you are more than 4000 ohms across your body and the stone layer to the mat. Just like overhead EPZ, the mat and resistance of your body took the voltage but minimized the current to a survivable level. Still rubber gloves are recommended.

Ground buss and mat resistance is usually monitored by substation departments. Test wells are often installed so that fall of potential tests can be compared to the original installation test data to monitor for degrading conditions. These tests don't always turn up damage that might affect you in the station. It's not an exhaustive list, but here are some things to watch for:

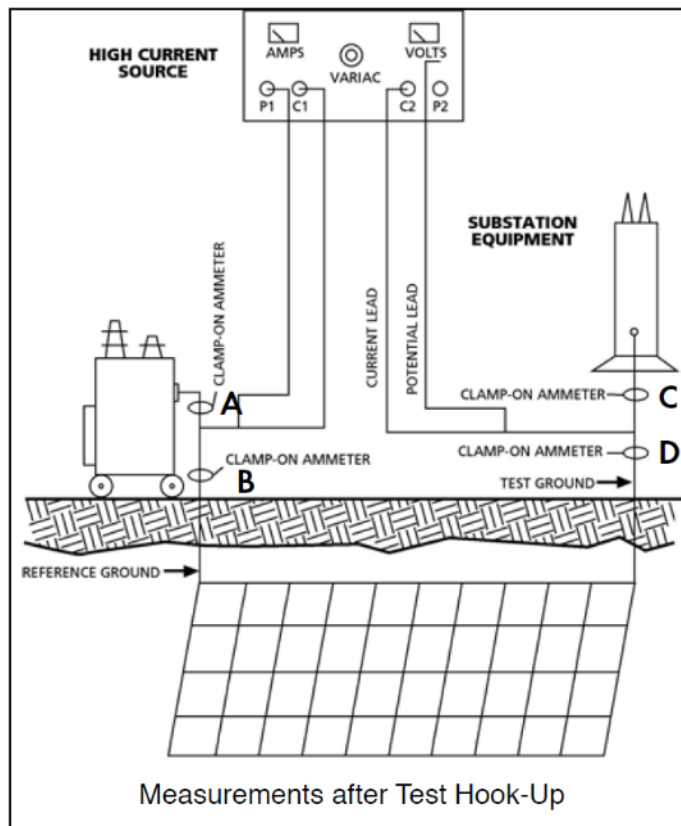
1. Deep wheel tracks (may damage the mat)
2. Dead grass (could be due to electric heating)
3. Rust (could be some form of cathodic activity)
4. Burn Marks
5. Missing ground straps (empty holes, missing paint are clues)
6. Cracked concrete (may be due to steam generated from current in re-bars)

[2] * Jowett, Jeff, "Ground Grid Integrity", MEGGER, NETA WORLD Fall 2008, www.netaworld.org**

Fault clearance and lightning protection can severely damage a grid or mesh. Another agent is corrosion and ironically the best grounding soils are also the most corrosive. Resistance tests performed in the mA current range indicate the overall capability of the grid regarding step or touch potentials, but does not indicate the internal condition of the grid. To test grid integrity the tester must be able to produce high current, in the order of 300 A. Rather than calculating and displaying resistance the grid tester evaluates the change in current flow. Test leads are typically welding cable in 3 to 30 m lengths.

1. A reference ground is first established, typically a transformer neutral.
2. The cables are connected to the reference and the test ground.
3. Current is switched on for a period of 3 minutes.
4. A clamp on ammeter is then used to measure currents around the system A-D.
5. Test lead voltage drop is measured by connecting the ends measuring the voltage
6. An acceptable voltage is 1.5 V per 15 m straight line.
7. For single driven electrodes at least 200 A should return to the source via ground path
8. For mats and grids at least half the current must return via the ground path

By isolating the faulty current path the work of excavation and repair is markedly reduced.



Current based test of grounding grid integrity [2 Jowett]

[3] *** DAWALIBI, F., "Electromagnetic fields generated by overhead and buried short conductors Part 2 – Ground Networks, IEEE Transactions on power Delivery, Vol PWRD-1, No.4, October 1986.

The self-impedance of a conductor has been traditionally expressed as the sum of two components, namely the internal and external impedances. The internal impedance of a perfect conductor is zero by definition. Real conductors have a nonzero internal impedance, representing energy in the conductor, which is frequency dependent. At very low and zero frequencies the internal impedance reduces to the DC resistance. The external impedance of a wire represents the energy in the surrounding medium.

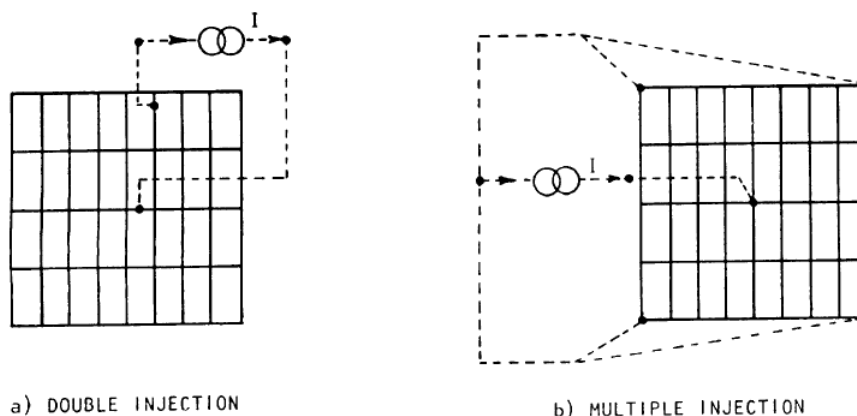
The classical definition of the mutual impedance between two conductors is the ratio of the voltage in one conductor to the current flowing in the other conductor, but this definition assumes the current to be constant, which is unlikely for buried bare conductors.

The problem is to determine the performance of the ground network when it is energized by known currents injected at the source busses. More specifically the objective is to determine:

1. Potentials at all source busses and nodes
2. Longitudinal and leakage currents in every conductor segment
3. Scalar potentials at any observation point in earth
4. Magnetic field at any observation point above earth

Two methods to solve this problem are discussed: one method based exclusively on electromagnetic field theory and secondly a hybrid method based both on electromagnetic field theory and electric circuit concepts. The first method results in computational difficulties caused by a $2n \times 2n$ matrix to be solved. The hybrid method introduces mutual impedances between conductor segments, but by neglecting inductive components the matrix size is reduced to $n \times n$.

This model was applied to a grounding grid with and without imperfections and different effects on the *ground potentials* and the *magnetic field* were studied. It appears reasonable to expect that by a judicious choice of the current magnitude and the injection nodes used, the damaged conductor detection capability can be enhanced.

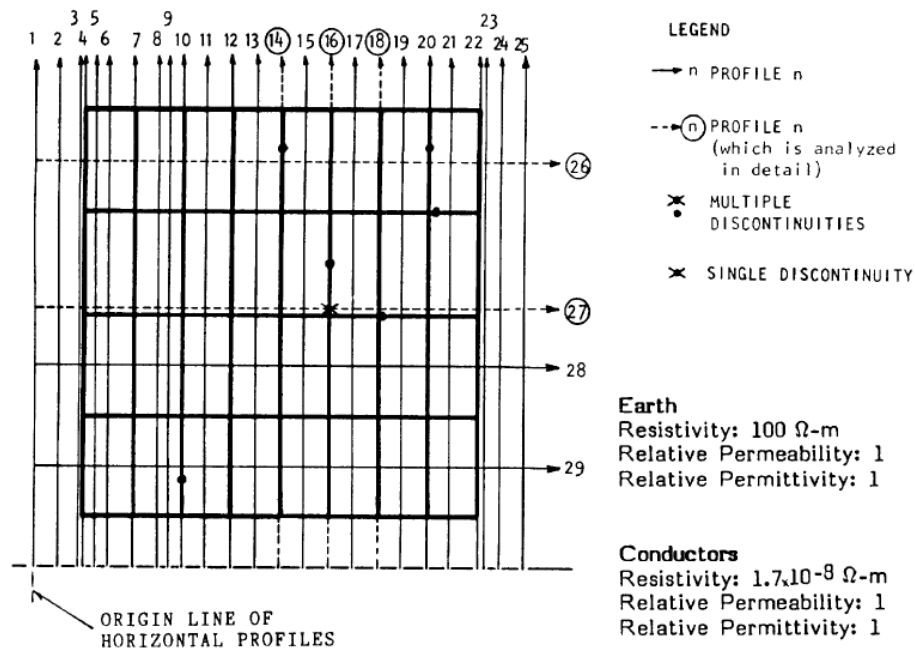


Examples of how current could be injected into a grounding grid without a remote electrode. [3 Dawalibi]

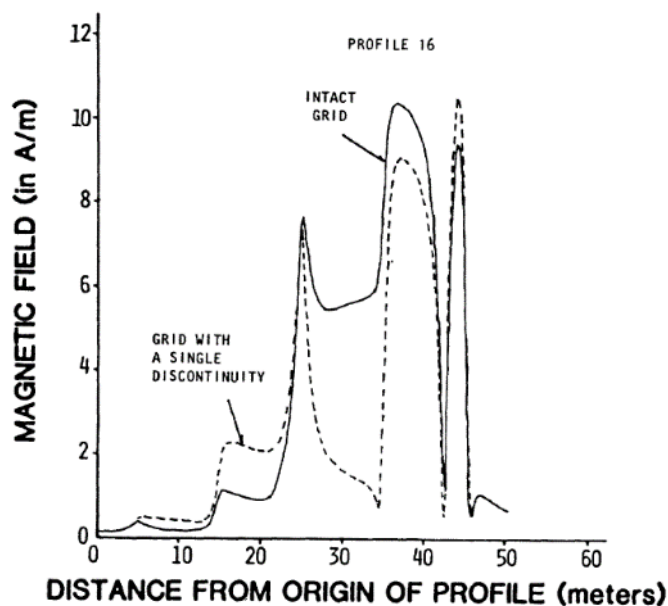
When a DC current of 100 A is injected between the two points of an intact grid, most of the current will flow in the conductors of the grid with only an extremely small portion of the current circulating in the earth. If a grid conductor is broken, then the conductor will experience a significant increase in its earth leakage current in the vicinity of the discontinuity.

The multiple point current injection technique is more practical, in that it provides a global view, but less selective than the double point current injection technique.

Single discontinuities are difficult to detect even with the aid of signature curves (undamaged state), however multiple discontinuities are more easily detected.



Test grid and damages [3 Dawalibi]



Magnetic profile over single discontinuity located at 27 m in the upper figure. Double injection. [3 Dawalibi]

[4] ***Yu, C., Fu, Z., Wang, Q., Tai, H., M., Qin, S., "A Novel Method for Fault Diagnosis of Grounding Grids", IEEE Transactions on Industry Applications, Vol. 51, NO. 6, November/December 2015.

This paper presents a novel approach using the transient electromagnetic method for fault diagnosis of grounding grids. The induced magnetic intensity is collected by receiver coils in the form of electromotive force. After inversion maps of ground

resistivity can be obtained. The faults due to corrosion or breaks can be accurately located from the distribution characteristics of equivalent resistivity maps.

In the introduction are mentioned several previously applied methods for analysis of grounding grid discontinuities as:

1. Point resistance or surface potentials (anomalies are often quite small)
2. Sine wave exciting current
3. Electrochemical potential methods (good for corrosion detection but not for breaks)

The paper advocates the Transient Electromagnetic Method – TEM. A typical TEM is a transmitter –receiver system that records the secondary magnetic field due to the induced eddy currents in the ground. The rapid transmitter current pulse turn-off introduces the primary field impulse that creates eddy currents in the ground. After inversion calculation of the secondary magnetic field recorded by receiver coils, corrosion or break points of grounding grids can be detected from contour maps of the calculated equivalent resistivity.

Three situations are considered: the grounding grid at a depth of 0.8 m has no faults, a single break point at the middle of a conductor and a single break cut at the cross node of conductors. Also the presence of a 0.5 m diameter pipeline at different depths above and under the grid was calculated. The simulations were carried out using a 3-D transient simulator, a FEM package from Ansoft. The simulated transmitter loop has a radius of 0.302 m and is excited by a 16 A current pulse of trapezoidal shape. In Chinese grounding grids iron bars 5x0.5 cm are used instead of copper wires.

A broken wire is expected to reduce the electromagnetic coupling between transmitter loop and the grid mesh.

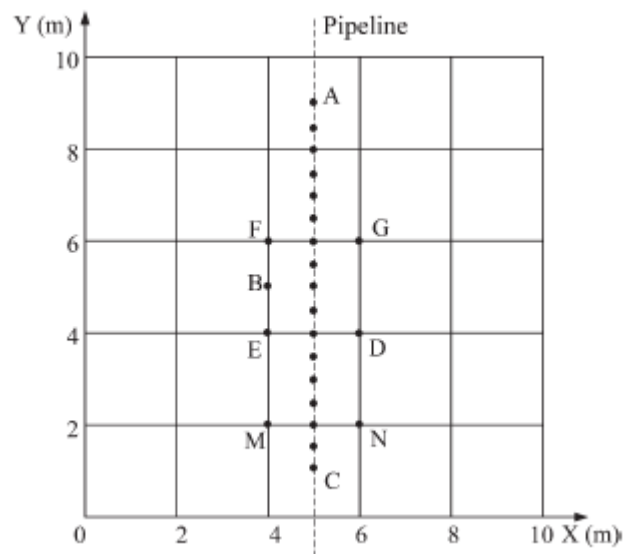
The simulation results clearly indicates the presence of wire breaks with the break at the cross point E being of largest magnitude.

The presence of the pipeline made serious disturbances in the case it was above the grid, but had no significant influence when it was buried below the grid.

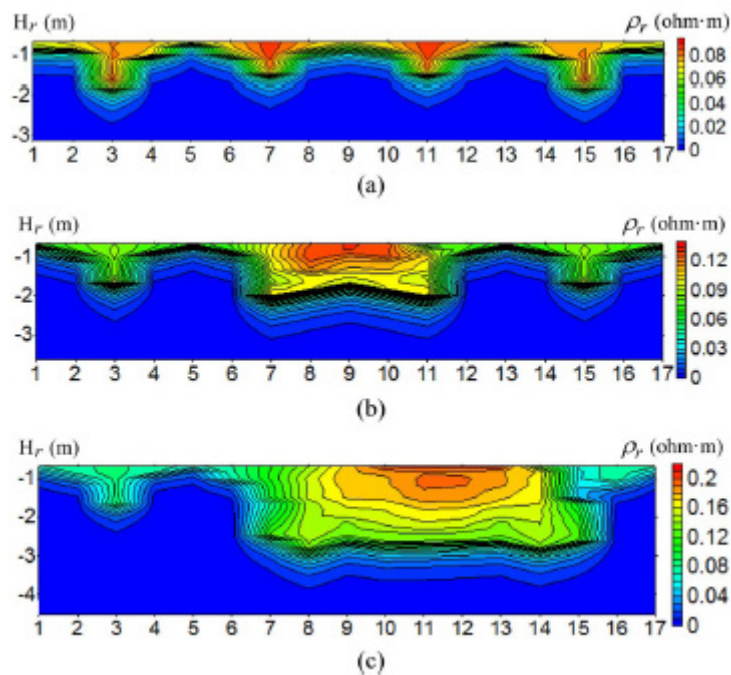
A weaker magnetic intensity is interpreted as a higher equivalent resistivity in the inversion process.

Consequently there is no advantage in calculating the equivalent resistivity. In fact there is no need to display the entire magnetic intensity history either, it suffices to present the value of one recorded time sample. The authors have chosen the 3 ms sample for that purpose.

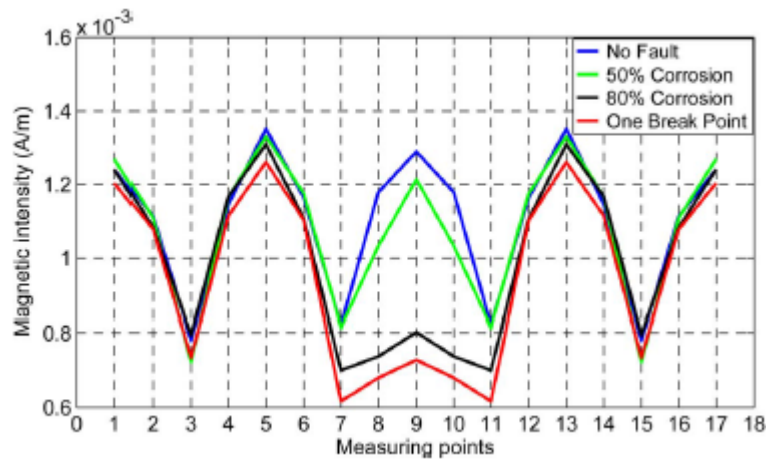
Grounding materials of higher conductivity results in stronger magnetic intensity. Thus copper wires give a stronger intensity than iron wires. The soil material appears to have little influence as long as the conductivity of the soil is much below that of copper.



Layout of experimental plan with assumed break points B and E. [4 Yu *et al*]



Contour map of equivalent resistivity with 17 measuring points along A(1)-C(17) when the grounding grid has a) no faults, b) a break cut on conductor at B (close to point 9) and c) a break cut at cross point E (close to point 11). No pipeline was present in this simulation. A weaker magnetic intensity is interpreted as a higher equivalent resistivity in the inversion process. [4 Yu *et al*]



The influence of different degrees of damage to a copper wire between point 7 and 11 (green, black) and a break at point B (9) on the magnetic intensity at the 3 ms sample. [4 Yu *et al*]

[5] **Zhang, B., Zhao, Z., Cui, X. and Li, L., "Diagnosis of breaks in Substations Grounding Grid by Using the Electromagnetic Method", IEEE Transactions on Magnetism, Vol 38, NO. 2, March 2002.

The expected impedances are calculated by a numeric method. These values are compared to measured values and large differences are an indication of deficiencies in the grounding grid.

Earth resistivity tests with values under 10000 Ocm generally indicate that corrosion is in process. Current-to-ground in line anchors in excess of 5 mA indicate failure will occur. Grid to soil voltages of less than -0.75 V referred to a copper-copper sulfate half-cell represents destruction of tin and zinc coatings from the buried ground bus and line anchors.

[6] **Mi, Z., Jianguo, W., Yang, L., Nianwen, X., Zhen, S., Junjie, C., Chunhua, F., "Causes, Forms and Remedies of Substation Grounding Grid Corrosion", 2008 International Conference on High Voltage Engineering and Application, Chongqing, China, November 9-13, 2008

Paper describes the basic corrosion theory and discusses factors affecting the corrosion rate such as soil resistivity, pH value, water content, soluble salts content. The most common methods for protection are metallic coating, cathodic protection and corrosion allowance in conductor cross section area.

[7] **Lawson, V., "Problems and Detection of Line Anchor and Substation Ground Grid Corrosion", IEEE Transactions on Industry Applications, Vol. 24, NO. 1, January/February

To estimate the rate of grounding grid corrosion four tests are suggested 1) earth resistivity, 2) guy current, 3) grid-to-earth potential and 4) polarizing current.

Earth resistivity tests with values under 10000 Ocm generally indicate that corrosion is in process. Current-to-ground in line anchors in excess of 5 mA indicate failure will occur. Grid to soil voltages of less than -0.75 V referred to a

copper-copper sulfate half-cell represents destruction of tin and zinc coatings from the buried ground bus and line anchors.

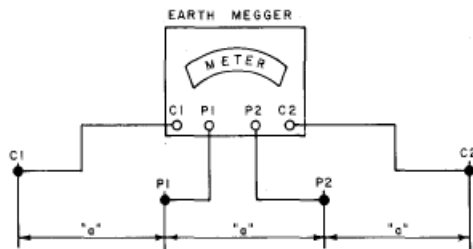


Fig. 1. Test no. 1.

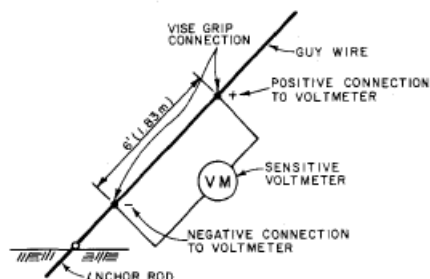


Fig. 2. Test no. 2.

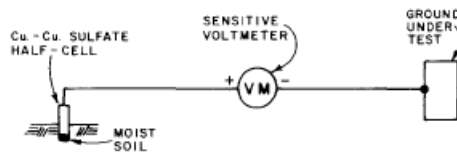


Fig. 3. Test no. 3.

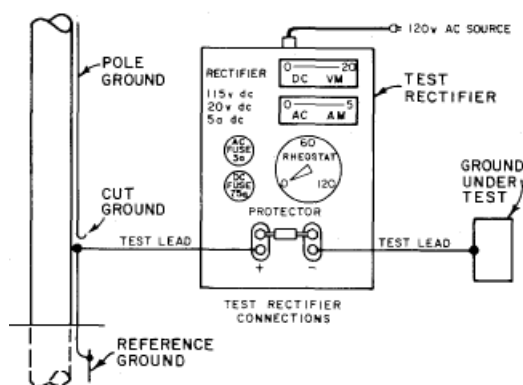


Fig. 4. Test no. 4.

Figure 1 Ground resistivity test with Wenner 4 electrode arrangement

Figure 2 Voltage drop on guy wire indicating currents

Figure 3 Ground to soil potential drops

Figure 4 Polarizing tests using 0-20V 0-5A test rectifier

Corrosion measurements [7 Lawson]

Papers 8-11 below describes procedures to verify that the grounding grid works as intended. The control parameter is the impedance at the grounding point. This is measured with a remote current electrode and a remote potential electrode.

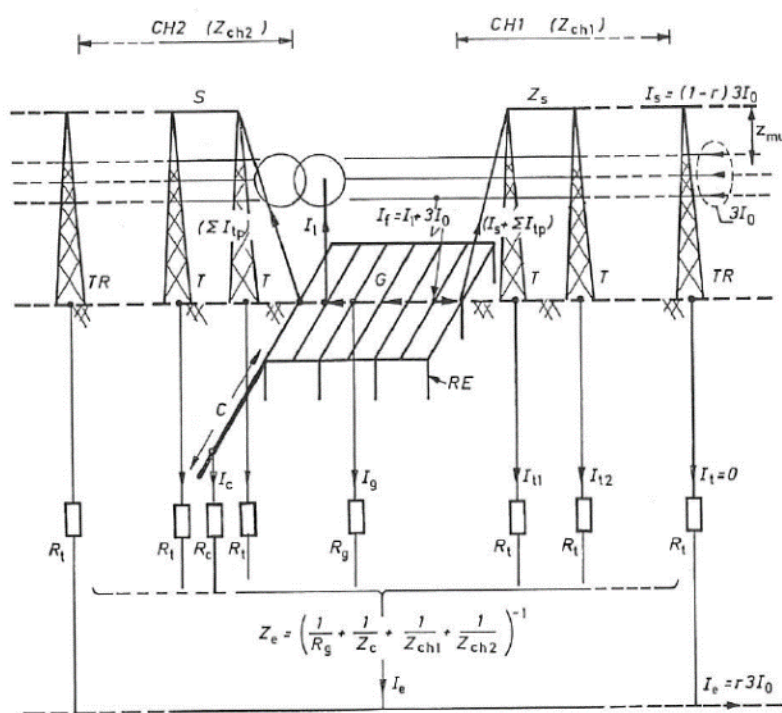
In the ELEKTRA-paper it is also described how to measure the soil resistivity before theoretical calculations of how the grounding grid will work. It is important to determine the soil resistivity as a function of depth, since there may be large vertical differences. It may also be necessary to measure at different times of the year, because the moisture content in the soil may vary.

[8] M Kuusaa[ri, A J Pesonen, Cigré 36-02, "Earthing Impedance Measurement of Substations", 1978 Session, August 30 – September 7, 1978

[9] T Bertling, J Dischner, G Heim, H U Paul, Cigré 36-02, "Corrosion Behaviour of Earthing Materials", 1984 Session, 29th August – 6th September, 1984

[10] J Valjus, R Särämäntö, Cigré 36-04, "Practical Earthing Measurements of Large Rural and Urban Substations, 1984 Session 29th August – 6th September, 1984

[11] ELECTRA, "Station Earthing. Safety and Interference Aspects", Final report of task force 36.04.01



Schematic example of a substation earthing system.

G station earthing grid, RE earthing rod electrode, C external horizontal electrode, T line tower near the station, TR line tower remote from the station, S overhead shield wire, CH1 and CH2 shield wire tower-footing chains. [11 Electra]

[12] ELEKTRA Working group 36/03, "Corrosion and Cathodic Protection", No 29, p 45"

Då man av säkerhetsskäl förbinder olika metalledar i en anläggning elektriskt uppstår det korrosionsceller. Korrosion kan förväntas uppstå om små anodiska ytor är kopplade till stora katodiska ytor.

[12] Xuan Wu, Vinod Simha, Ronald J. Wellman, "Optimal Ground Grid Design for Large EHV Substations with Auto-Transformer, IEEE 2015.

[13] M F B R Concalves, E G da Costa, R C S Freire, M S de Castro, J R L Filho, "Experimental evaluation of Impulsive Impedance in Grounding Grids Subjected to Current Impulses", 19th Int Symp on High Voltage Engineering, Pilsen, Czech Republic, August 23-28, 2015.

[14] S Castro, E G Costa, R C S Freire, M F B R Goncalves, and J R Lima Fo, "Experimental Evaluation of Grounding Grids", 19th Int Symp on High Voltage Engineering, Pilsen, Czech Republic, August 23-28, 2015.

[15] Watson J., D. and Crick, F., H., C., "Molecular Structure of Nucleic Acids", Nature, April 25, pp737-738, 1953

Textbooks on Geophysics

Palacky, G. J. 1987. Resistivity characteristics of geologic targets. In: Nabighian, M. N. (ed.) Electromagnetic Methods in Applied Geophysics. Society of Exploration Geophysicists, Tulsa, 53–130.

Robinson, E.S. and Coruh, C. (1988) Basic Exploration Geophysics, Wiley, New York, 562p.

Reynolds J.M. (2011) An Introduction to Applied and Environmental Geophysics, 2nd Edition, Wiley, ISBN: 978-0-471-48535-3, 710p.

An Introduction to Applied and Environmental Geophysics describes the rapidly developing field of near-surface geophysics. The book covers a range of applications including mineral, hydrocarbon and groundwater exploration, and emphasises the use of geophysics in civil engineering and in environmental investigations. The book contains descriptions of commonly used geophysical techniques and case histories.

Dahlin T. and Leroux V. (2012) Improvement in time-domain induced polarisation data quality with multi-electrode systems by separating current and potential cables, Near Surface Geophysics, 10, 545-565.

GROUNDING GRID INTEGRITY

This report is a pre-study before a systematic study of methods suitable to locate damage in grounding grids is made.

Damages can be detected at two levels, globally by impedance measurements in access points to the grounding system and in local scale by either leading a current of known frequency through the grid or by inductive methods whereby eddy currents are created in the wires, generating anomalies that can be measured on the surface. The report describes suggested methods for doing this and presents a possible design for evaluating these methods through laboratory and field tests.

The report includes short chapters regarding the purpose and function of the grounding system in substations and how to evaluate the resistivity of the ground layers.

Energiforsk is the Swedish Energy Research Centre – an industrially owned body dedicated to meeting the common energy challenges faced by industries, authorities and society. Our vision is to be hub of Swedish energy research and our mission is to make the world of energy smarter!