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Techniques for the Study of Large Industrial Grounding Systems

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Abstract

Studies and designs of large facilities grounding systems, such as industrial complexes, petrochemical, power plants etc., with dimensions on the order of hundreds of meters, are usually developed using the same methodology used for substation grounding grids designs, which have dimensions on the order of tens of meters.
It happens that the assumptions that are valid for the design of a substation grounding grid, do not apply to the grounding system of a large industrial complex. Among the parameters that should be considered for these wide area complexes, it can be noted:
 not equipotential mesh, because of its large size, what results in significant potential differences, even at the commercial frequency (60Hz); and
 need of resistivity soil models that are representative of the soil volume that effectively will be involved in the process of current dissipation into ground, which for large meshes can reach depths of the order of several kilometers.
Among other aspects that shall be considered, it is worth mentioning the contribution of the reinforcement of the foundations of buildings, besides the need to promote the integration of subsystems grounding of a wide range of facilities (high-voltage substations, industrial buildings, process areas etc.), governed by different standards (high, medium and low voltage, lightning protection etc.).
The object of this work is not to present the final results of the application the proposed methodology for grounding studies, but analyze the constraints of the current methodology in use and the resources available to implement a methodology more compatible with large grounding systems, such as:
 geophysical techniques for soil resistivity prospection, considering the modeling of large volumes of soil; and
 software for grounding systems simulation with multiple soil layers and considering the non-equipotentiality of the grounding mesh and alternate current injection.

1. Introduction

The interconnection of different grounding systems that integrate a large industrial complex must be studied considering the premises above mentioned, in order to realistically quantify the interaction of the ground grid of the main high-voltage substation, with the rest of the industrial complex grounding. This interaction interferes with human (step and touch potentials) and equipment (potential transfer) security in the industrial complex, upon the occurrence of a phase-to-earth short circuit in the high-voltage substation.

Large facilities projects, including subsystems with different voltage levels (high, medium and low voltage) has become usual at the current stage of Brazil industrialization. Study and design of grounding systems have been made using soils models, obtained from measurements made by the traditional Wenner technique, with spacing that rarely reach 64m, and the simulations are made usually made with software that considers the ground mat equipotential.

Interference studies of power grids over other systems (pipelines, for example), will also benefit from the application of more sophisticated software and soil models, as above proposed. In Brazil, the use of geophysics techniques that allow more complex soil models, compatible with the large dimensions of these ground mats, is restricted to specific designs (HVDC transmission systems, for example).

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2. Soil Models for Grounding Studies

For the engineer, the term soil identifies all unconsolidated sediments above the bedrock. In the civil engineering, soil mechanics studies the behavior of soil when subjected to loads and efforts, associated with structures in general. For the electrical engineer, soil is the medium through which electrical currents can flow, usually associated with power grids operation, or where it will be buried a grounding electrode system, as well as the entire volume of this medium electrically influenced by this grounding system.

A simple classification, suitable from the engineering viewpoint, divides the earth crust into three layers:

- soil (topsoil) - which contains organic material and can support life;
- subsoil - zone of fragmented and/or partially decomposed rock, and
- bedrock - solid or fissured rock matrix, but not fragmented.

Resistivity is the most important parameter in analyzing the electrical behavior of the soil, determining the performance of grounding electrodes at low frequency. Studies and projects require knowledge of the ground soil resistivity, this essential parameter for the calculation of grounding resistances and potentials at the soil surface.

Soil resistivity measurements allow the development of soil models, which are the best possible representation of the environment in which the grounding electrodes are buried, for the purpose of grounding mat simulation. The model to be obtained is limited by the amount and quality of soil resistivity measurements available, and by the resources to be used for the calculations and simulations.

NBR-7117/1981 is the ABNT code for soil electric resistivity measurement, specific for grounding mats design. The revision of this standard was completed this year (2012), and the new text recommends measurements with electrode spacings ranging up to 64m, that can be expanded depending on the project characteristics. This standard is focused on soil models for not very large installations, typically power substations, telecommunications sites etc.

The grounding system of large industrial complexes usually has been designed based on soil models derived from short spacing measurements, considering the actual dimensions involved, which are extrapolated to deeper layers. It is unclear whether these projects present conservative or pessimistic results, since it is totally unknown the characteristics of the deeper soil layers. Regarding the equipotential premise for large grounding grids, it is known that it results on optimistic calculations, with calculated grounding resistance lower than the actual value.

Geophysics has a wide range of technologies for exploring subsoil, ranging from surface measurements to wells logging - seismic, gravimetric, magnetic, electrical, electromagnetic and radiometric. The electrical and electromagnetic methods includes various measurement techniques (Wenner, Schlumberger, TDEM, Magneto-telluric etc.), which together allow the development of complex resistivity soil models, layered stratified or showing lateral variations, ranging down to several tens of kilometers deep, reaching the crust-mantle interface (typically with the order of 30-40 km).

In Brazil, consulting companies and academic institutions with research activities in geophysics, have being using some of these techniques for the exploration of mineral resources and for geology research. INPE – Instituto Nacional de Pesquisas Espaciais – applies these techniques for research on tectonics (geological processes involving the earth's crust), and have done measurements to Furnas, in view of the electromagnetic soil modeling for transmission lines studies and for monitoring telluric currents on transformers neutrals.

3. Electric Currents Circulation in Earth Lithosphere (crust and rigid mantle upper layer)

Earth is subject to several processes that, among other effects, result in electrical manifestations, which give rise to electric/magnetic fields and to current circulation (and therefore to potential differences), in the various layers of the Earth’s atmosphere, oceans, solid crust, mantle and core.

Exosphere, the outermost layer of the atmosphere (also known as the magnetosphere), houses the Van Allen belts, huge ionized layer contained by the Earth's magnetic field. Toward the sun these belts extend over 80,000 km, and in the opposite direction they go much further, dragged by the solar wind. The inside limit of Van Allen belts has variable distance with respect to earth surface, being nearest over Miami and the Rio de Janeiro, what may be associated with the high lightning incidence in these cities.

The rotation of the globe inside the magnetosphere magnetic fields gives rise to a dynamo effect, resulting in potential differences between sunrise and sunset regions and between equator and poles, and also to electric current flow between these regions in the upper atmosphere, with the order of up to hundreds of thousands of amps, causing disturbances in Earth's magnetic field and inducing the flow of electric currents in the lithosphere.

Geomagnetic storms, originated from disturbances in sun's magnetic fields, results in the emission of energetic particles (solar wind) that interact with the magnetosphere and ionosphere (which is the plasma region that begins at about 100 km altitude and extends far into space), separated from Earth's surface by the atmosphere. As Earth is conductive, electrical currents known as telluric currents are induced on its surface, circulating with pulses in the ultralow frequency range (ULF) of 1-0.001 Hz, which generates secondary electromagnetic fields that can be measured on soil surface. These EM waves are only weakly attenuated in the Earth's crust, what means they have a high penetration depth, from surface to kilometers below, deeply penetrating in the lithosphere.

Besides the telluric currents, for the purpose of this work, it shall be highlighted two other types of electric currents on Earth's crust, associated with the operation of power grids:

- continuous currents – originated by HVDC – high-voltage direct current transmission systems;
- low frequency alternating currents - associated with power transmission and distribution systems.

A single-phase AC line or, more typically, a three-phase transmission line with a phase to ground short-circuit at one of its ends, has the phase circuit closed by the ground return circulation, with the current flowing through the soil from the short-circuited end to the transformer grounding, at the power system end, following the path of the line. Figure 3.1 shows this current will circulate below the line, through the ground section depicted by area A1, being this section area inversely proportional to the frequency of the current.

The soil section involved in this current circulation can be associated to two parameters, associated with current penetration in the soil - the penetration depth (δ) and the equivalent return depth (*De*), which can be calculated with expressions given in Table 3.1. These concepts are essential for the calculation of longitudinal transmission line parameter (resistance and inductance), which are influenced by the equivalent soil resistivity in the region through which the line passes.

The penetration depth (δ) characterizes the "skin effect", which represents the depth (in meters) at which the current density per unit of soil section is reduced by the factor 1/*e* (1/2,718 = 0.3679). The exponential decay of the current density is also manifested laterally, limiting the width of the current strip below the LT. The current density in the ground surface can be considered negligible at a distance greater than 3δ, at each side of the row axis.

The equivalent return depth (*De*) represents the depth of a virtual conductor carrying the return current (I), whose electromagnetic interaction with the transmission line conductor is identical to that produced by the same amount of current flowing through the cross section of soil below the line (area A1), as shown in Figure 3.1. This parameter has its origin in the Carson formulation, for the transmission line parameter correction for a not ideal soil (non-zero resistivity).

The application of these expressions for continuous currents (zero frequency) results in infinite values for these two parameters, what can be interpreted as the decoupling between the electrodes located at both ends of the HVDC line.

The calculation examples 1 and 2 in Figure 3.1, shows that for the 400Ω.m equivalent soil resistivity under a transmission line operating at 60 Hz frequency, the penetration depth (δ) and the equivalent return depth (*De*) will be, respectively, 1300m and 1700m. If by hypothesis the line operates at a frequency of 6000Hz, then both parameters will be reduced to 10% of the above calculated values (respectively, 130m and 170m).

In practice, the analysis is more complex, because subsoil never presents uniform resistivity, having layers and volumes of different resistivities, as a function of geological structure of the region through which the transmission line passes by.

As it happens for large installations grounding designs, also for transmission lines design, the soil resistivity measurements are usually made by means of Wenner technique, with maximum spacing of 64m, what means that these soil models do not represent even a small fraction of the effective soil volume involved in the process of current circulation.

$\delta = \sqrt{\frac{\rho}{\pi\mu_0 f}} = 503\sqrt{\frac{\rho}{f}}$	$De = 658\sqrt{\frac{\rho}{f}}$

Table 3.1: penetration depth (δ) and the equivalent return depth (*De*), in meters, as a function of soil resistivity (ρ) and frequency (f).

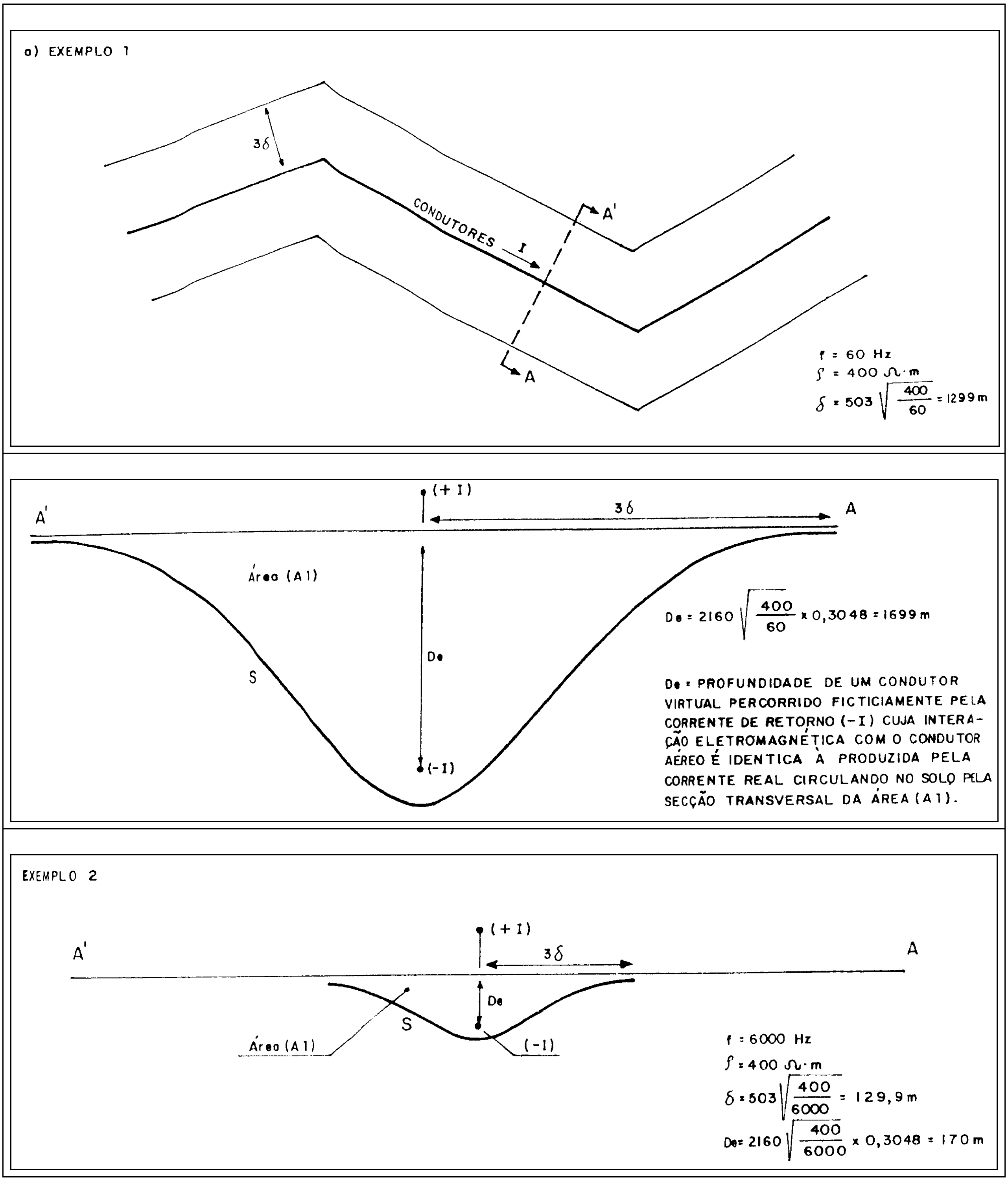


Figure 3.1: circulating pattern of transmission line ground return current.

4. Geophysics Surveys Methods

Geophysics can be defined as "the science that deals with the study of structures inside the Earth, and with the localization of bodies, bounded by contrasts of its physical properties and with the surrounding environment, using measurements taken on the surface, wells and aerial surveys". It is a science based on geology and physics, using physics concepts to solve geology problems.

The physical phenomena associated with Earth’s processes are: magnetic field, geothermal flows, seismic waves propagation, gravity, electrical and electromagnetic fields, electrical telluric currents and radioactivity. Depending on the physical parameter used, geophysics uses various methods, with emphasis on gravity, seismic, and geoelectric/magnetoelectric. The subsoil electrical processes can be used for a wide range of geologic studies – basic and applied (mineral reserves exploration, environmental, hydrogeology, geotechnical etc.).

The next sub-items deal with geophysical methods that measure soil electrical resistivity, which is the parameter required for obtaining soil models for large grounding studies, such as industrial grounding mats and HVDC grounding electrodes. Although soil resistivity measuring methods such as electroresistivity and magnetotelluric, are the ones of most direct application, because they already present electrical resistivity as output parameter, other methods can supplement by helping the subsurface mapping and soil model calibrating (thickness of soil strata, fault location etc.). The various geophysical features can be complemented with the following investigations:

- survey of the region geological history and structure;
- surface geological mapping, for the evaluation of site lithology; and
- well drilling and its electric logging, to verifying the geological model obtained.

4.1 Electroresistivity Methods (ER)

This method infers the subsurface structure, by means of the geometric aspect of the current and voltage electrodes array, and from a set of values of injected currents and measured potentials. The Wenner and Schlumberger techniques fall into this category of geophysical survey.

ER methods employs an artificial source of continuous or very low frequency current (few Hz or fraction of Hz), and four electrodes, two for current injection and two for potential measuring, with various arrangements, resulting in different mapping capabilities of soil resistivity. Among the different survey techniques, it can be pointed:

- vertical electrical sounding (VES) - one-dimensional (1D) – the vertical variation (in depth) of soil resistivity at a point on soil surface (a series of VES can be processed to result in two dimensional subsoil cross section profile);
- electrical resistivity soil tomography- pole-dipole or dipole-dipole acquisition for two-dimensional (2D) or three-dimensional (3D) subsoil resistivity mapping; and
- well profiling - when the resistivity measurements are performed in wells.

The resolution and depth of the survey depend on the frequency of the injected current and on the electrodes arrangement and spacing adopted. Among the possible surface arrangements of four electrodes, it can be pointed:

- Wenner and Schlumberger - more suitable for vertical electrical sounding - where the electrodes are aligned and displaced in pairs, symmetrically with respect to the center of the array; and
- dipole-dipole - more suitable for soil tomography - with the current and voltage electrodes grouped in pairs, the current electrodes remaining fixed, with voltage electrodes being displaced regularly.

Electrical engineers are used to soil resistivity measurements by means of the Wenner technique, for developing substation grounding studies. The spacing used for these measurements seldom reaches 64m, what means a maximum distance of 192m between the external (current) electrodes. For this spacing, it can be said broadly (as the current penetration depth will depend on the soil resistivity and on the operating frequency of the measuring equipment) that it is being prospected a soil layer of a maximum 64m depth.

Geophysics professionals usually prefer the Schlumberger technique, especially when larger spacings are involved (reaching up to 2000m between current electrodes). This technique moves, every measurement, only the two external electrodes. The internal electrodes have the spacing increased only when the ground potential signal becomes too small, due to the large spacing between the current electrodes.

4.1 Magnetotelluric Method (MT)

Developed in the 1930s, this is a of natural field method, being thus subject to interference from anthropogenic electromagnetic fields, demanding a great distance (minimum one kilometer) from noise sources (energy installations, urban and industrial facilities), what limits its applicability. This method is based on Maxwell's equations, which relate the electric and magnetic fields. The vectorial nature of these fields allows the determination of the soil resistivity tensor structure, by measuring the following five parameters over a time period:

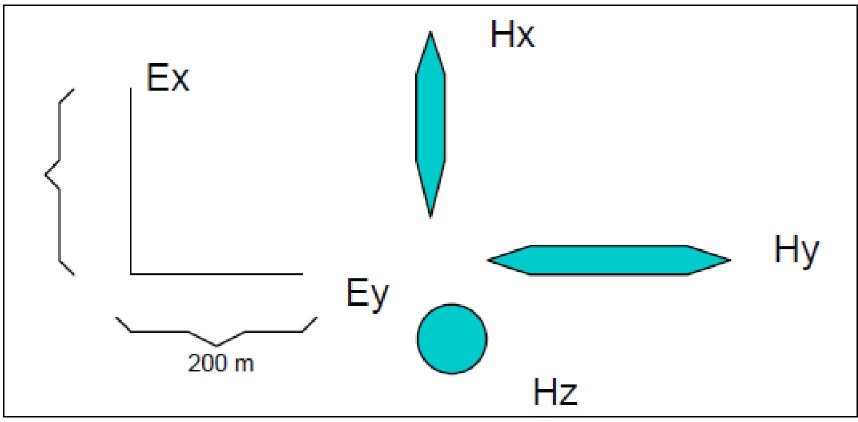
- magnetic field in three axes - Hx, Hy and Hz, and
- surface electric field in two axes - Ex and Ey.

MT method measures the horizontal components of naturally occurring electric and magnetic fields, by means of coils (Hx, Hy and Hz) and probes in the soil surface (Ex and Ey), as depicted in Figure 4.1. The soil resistivity can be calculated by means of the ratio of orthogonal components of the electric and magnetic fields, and the electromagnetic plane wave depth of penetration, by means of the same equation presented in Table 3.1.a.

As the magneto-telluric fields are the result of many astrophysical phenomena, they vary all the time, both in direction and in magnitude. The method limitation is then the measuring difficulty introduced by these fast magnetic field fluctuations. Natural electromagnetic fields contain a wide spectrum of frequencies. As the electromagnetic field depth of penetration is dependent on the field frequency and soil resistivity, the latter can be calculated as a function of frequency, by the transformation of the recorded electric and magnetic fields to the frequency domain.

Whereas the soil depth of penetration is inversely proportional to the signal frequency, it is needed to measure data for extended time periods. Measurements at low frequencies (long periods) will yield information from large depths and vice versa. In soils of moderate to low resistivity, one day measurements may be sufficient for modeling of down to 10km soil deep. For depths of about 50 km it may be required measurements for about one week.

The phase between the electric and magnetic fields for different frequencies is also calculated. The phase difference will be 45° for a homogeneous ground. Larger phase values than 45° indicates a decreasing resistivity with depth and vice versa.



$$\delta = 503 \times \sqrt{\frac{\rho}{f}} \text{ (m)}$$

$$\rho = \frac{1}{\omega\mu} \times \left|\frac{E}{H}\right|^2 \ (\Omega.\text{m})$$

Figure 4.1: MT coils and probes arrangement, for measuring magnetic and electric fields on soil surface, and expressions for the calculation of soil resistivity (ρ) and depth of penetration (δ).

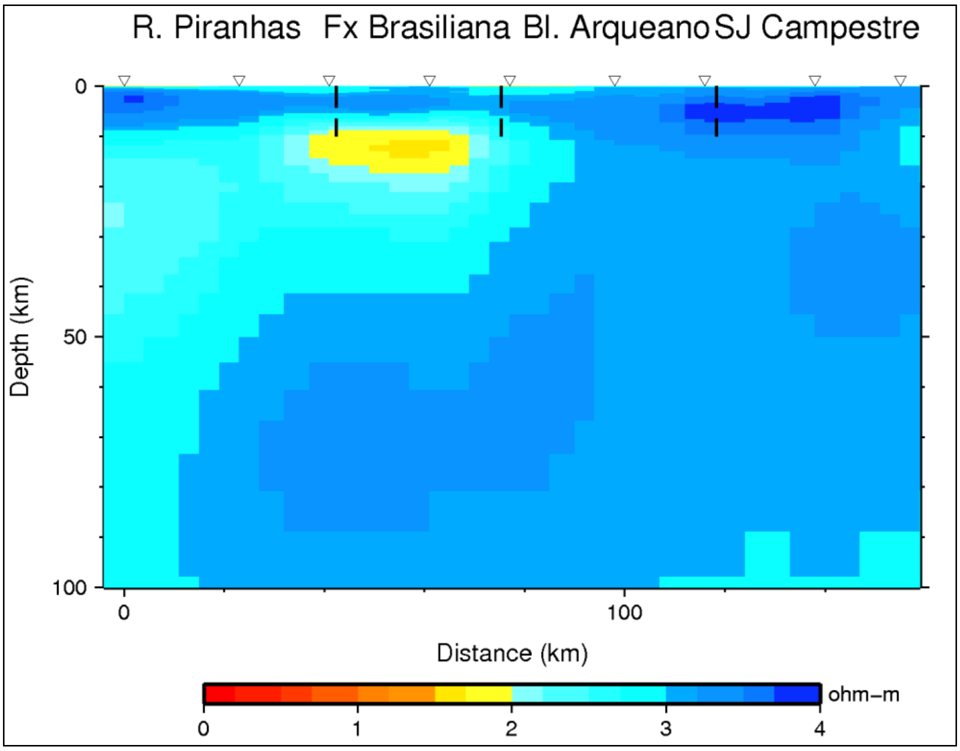
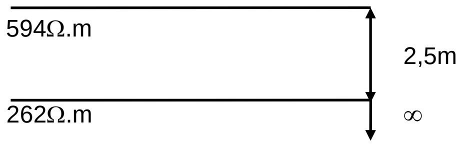


Figure 4.2: 2D soil resistivity profile measured by INPE at Brazil Northeast, along a path 160km long, down to 100km deep (resistivity scale is logarithmic base 10, what means it goes from 1 to 10.000 Ω.m).

5. Application to an Industrial Ground Mat

Figure 5.1 presents two simulations of a grounding grid, with size of about 60 x 360 m. In the first case the simulation was made with a constant potential software (considering ideal conductors and continuous current injection). In the second case it was used a more sophisticated software (MALZ, developed by SES – Safe Engineering and technologies, www.sestech.com), considering a ground mat made of 4/0 AWG cooper conductors, and a 60 Hz current injection, made at a specific point of the ground mat. It can be seen that the potential profiles on soil surface are quite different.

Figure 5.2 shows the geometry of an industrial complex grounding grid, with size of about 1km². This mesh was simulated with software that considers the grid conductors longitudinal impedance, with the below double layer soil model (obtained from soil resistivity measurements made by Wenner technique, with spacings of up to 32m).



This simulation revealed a grounding resistance of 0.35Ω, with potential differences along the grid up to one third of the total ground potential rise (GPR), which occurs at substation (place of the short-circuit application).

The calculated grid resistance resulted in a very optimistic value, being the true resistance probably higher, because the calculation did not consider the deeper soil layers influence, especially the bedrock, unknown with the available soil resistivity measurements, due to the electrodes spacing limited to 32m. The effect of the grid non-equipotentiality results in the occurrence of potential steps higher in the substation vicinity, decreasing with the distance from substation.

The soil volume involved in the dissipation process of currents injected into a grounding grid is a direct function of the grid size, of the soil resistivity and of the magnitude of injected current. With respect to grid size, the influence area (to reach remote earth), is equivalent to an area with radius typically 3 to 7 times the equivalent radius of the area occupied by grid (depending on the soil resistivity). Just as discussed for the case of transmission lines, this large volume of soil never presents uniform resistivity, showing usually layers and volumes of different resistivities, depending on the region geologic structure/history.

For the Figure 5.1 grid, with dimension of approximately 1 km, it can be expected the amount of soil that participates in the process of the ground current dissipation of the order of several thousand meters. If we consider the equivalent depth of return as a reference depth for large grid designs, considering the calculated resistivity of the 2nd soil layer (262 Ω.m), it will be obtained the value of 1376m. It is evident that the soil does not present a 262 Ω.m uniform resistivity from surface to more than 1000 m depth. Before this depth is reached there will be other soil layers and, to some depth, bedrock basement will appear, what will certainly result in different values for the calculated grid parameters.

6. Conclusions

The analysis here presented reveals that the knowledge of the deep soil resistivity layers is important for the calculation of transmission lines parameters and is essential for modeling large grounding grids, such as those associated to modern industrial complexes, especially petrochemical and refinery complexes.

For these large meshes, the equipotential consideration no longer applies, since potential differences of about 30% occur in the grid itself.

Obtaining models that include deep soil layers is perfectly possible with the use of geophysical techniques, what is already being applied in specific grounding projects, such as for the grounding electrodes of HVDC systems. More complicated is the development of appropriate models for large soil volumes, which usually will present several volumes of different resistivities and sometimes very complex geometry.

The combination of soil models with depths compatible with the dimensions of industrial complexes, and software able to simulate complex soil models, with several layers of different resistivities and not equipotential grids, will allow the development of safer grounding studies. One of the main objects of these studies shall be the definition of the interconnection, or not, of the industrial and main substation grounding grids, being the latter usually with a rated voltage of 69kV up to 500kV, and possibly high value of short circuit current at the high-voltage bus bar.

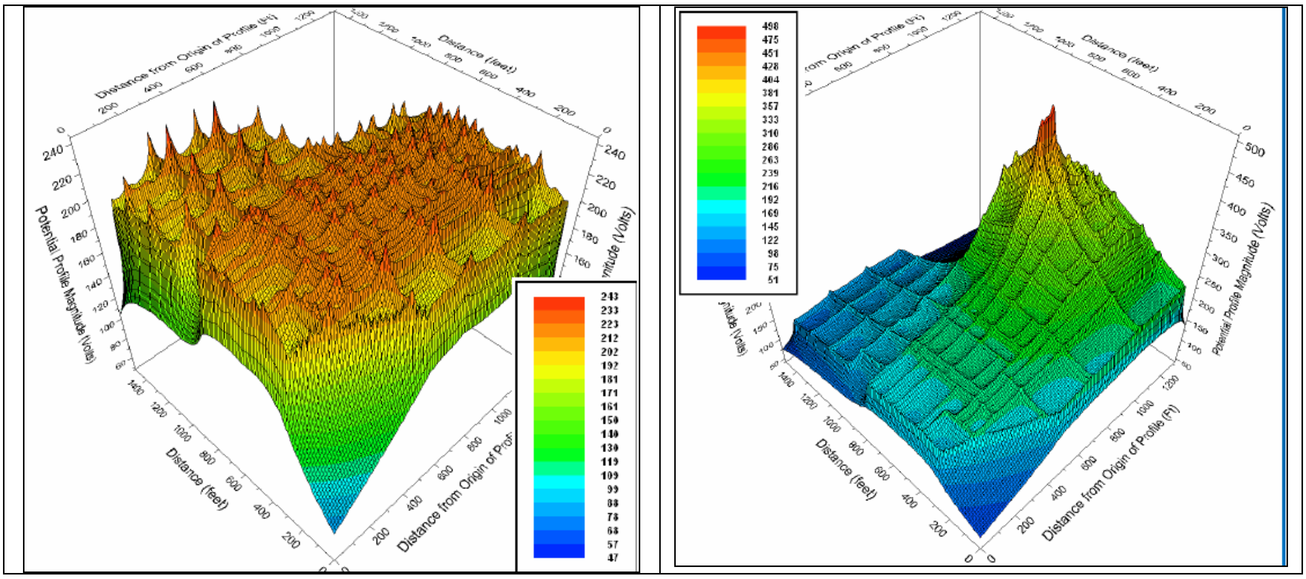


Figure 5.1: soil surface potential profile above a ground mat (360 x 60 m) with two different simulation conditions:

- 1st – ground mat with ideal conductors and continuous current injection;
- 2nd – 4/0 AWG ground mat conductors and 60 Hz current injection (using SES MALZ Software).

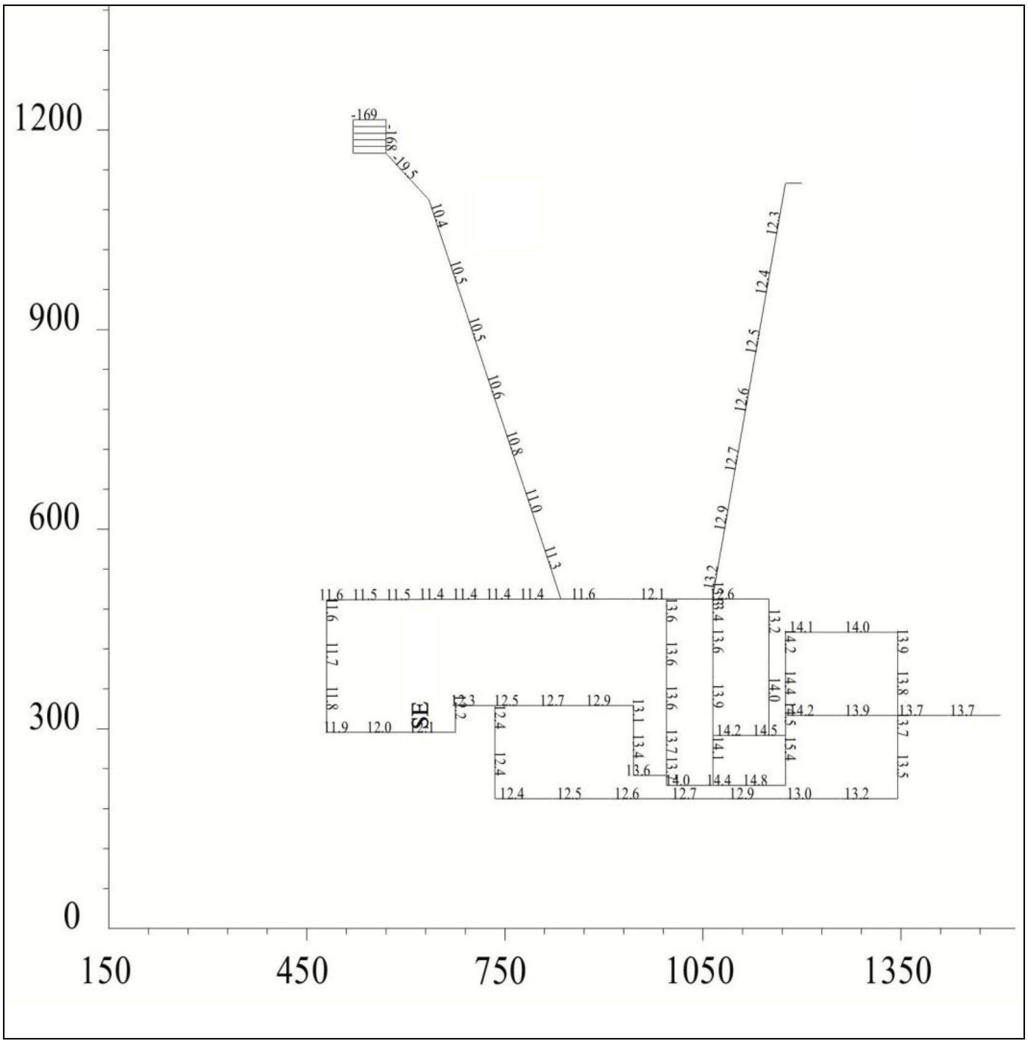


Figure 5.2: industrial grounding grid.

7. References

Reinhold Rudenberg, Fundamental Considerations on Ground Currents, ANSI/IEEE Std. 80-1986 – Appendix H.

VITORELLO, Í. ; PÁDUA, M. B. ; FONTES, S.; FUCK, R. A. ; PADILHA, A. L. ; BOLOGNA, M. S. ; MEDEIROS, W. E. ; SANTOS, A.C.L. ; FURLAN, M. . 2011-INCTET Progress Report on Magnetotelluric and Geomagnetic Depth Soundings in the Borborema Province and Adjacent Terrains, NE Brazil. In: International Congress of the Brazilian Geophysical Society, 2011, Rio de Janeiro.

BOLOGNA, M. S. ; VITORELLO, Í. ; PÁDUA, M. B. ; PADILHA, A. L. . Geoelectrical structures retrieved from a Magnetotelluric Transect in the northwestern Borborema Province, NE Brazil. In: International Congress of the Brazilian Geophysical Society, 2011, Rio de Janeiro.

BRAGA, Prof. Dr. Antonio Celso de Oliveira. *Métodos Geoelétricos Aplicados:* Modulo:Hidrogeologia. Universidade Paulista Estadual – UNESP/Campus de Rio Claro. Instituto de Geociências e Ciências Exatas – IGCE. Departamento de Geologia Aplicada – DGA.

BRAGA, Prof. Dr. Antonio Celso de Oliveira. *Métodos Geoelétricos Aplicados:* Métodos Geoelétricos Aplicados nos Estudos de Captação e Contaminação das Águas Subterrâneas: . Universidade Paulista Estadual – UNESP/Campus de Rio Claro. Instituto de Geociências e Ciências Exatas – IGCE. Departamento de Geologia Aplicada – DGA.

DÍAS, Luiz Alberto Alonso. *Estúdio de Prospección Geofísica e Geotécnica para El Emplazamiento Del Embalsede San Esteban de Andagoya (Álava).* Escuela Técnica de Superior de Ingenieros de Minas. Proyecto Fin de Carrera. Departamento de Ingeniería Geológica. Novembro, 2001.

ABREU, Paulo Marques. *Estudos Geofísicos (Magnetotelúrico e Eletromagnético) da Porção Leste da Bacia do Parnaíba:* Contribuição ao conhecimento Hidrogeológico. Ministério da Ciência e Tecnologia. Observatório Nacional. Pós-Graduação em Geofísica. Dissertação de Mestrado. Orientador: FONTES, Prof. Sérgio L. M., 2002.