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THE REVIEW OF THE BRAZILIAN STANDARD NBR-7117

GROUND RESISTIVITY MEASUREMENT AND GEOELECTRIC MODELING

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***Abstract* — This paper is a compliment for the one presented in the conference Ground 2016 [1], with a similar title, which suggested the adoption of the geometric average, instead of the arithmetic average, for obtaining the average apparent resistivity curve from a set of ground resistivity soundings. However, whilst the former paper was dedicated to the proposal of reviewing the averaging method, this one presents the actual modifications which were implemented in the review of standard NBR-7117/2012 [2]. This standard was updated in a much broader scope, and besides the review of the method adopted for averaging the resistivity parameter, it also includes important procedures concerning the resistivity surveys, the processing of the field data and the development of the geoelectric models.**

The ground volume that defines the grounding resistance of installation is a function of its dimensions. The geoelectrical model applicable to a typical substation, with dimension of about tens of meters, cannot be developed in the same way as it is done for a large-scale installation, such as an industrial plant (refinery or petrochemical complex), a big power plant (hydroelectric, eolic [3] and solar), or an HVDC system (converter substations and ground electrodes) [4], with dimensions varying from hundreds of meters to a few kilometers in area or length.

Grounding is a field of electrical engineering that has a strong interface with geosciences (geology, geophysics and geotechnics). The review of NBR-7117 intends to bring to the electric engineering the extensive resources available by the geosciences for mapping the subsurface structure of wide volumes of ground. Therefore, the new standard suggests the use of electromagnetic methods of ground survey, including the TDEM (Time Domain Electromagnetic) and the AMT/MT (audiomagnetotellurics and magnetotelluric) techniques. These methods can probe the near-surface (down to a few hundred meters depth) and the deep ground (down to tens of kilometers depth).

The revision proposed for this standard is a wide one. The first part of the review deals with the ground resistivity surveys. The second part of the standard will deal with the measurement of thermal ground parameters, and the third part will deal with the measurement of electrical permittivity and magnetic permeability. Therefore, it can be said that the future NBR-7117 will be a standard dedicated to the measurement, data processing and modeling of the complete set of ground parameters that are important for the design of parts of the electrical systems that are buried into the ground.

Keywords — ground resistivity surveys; geoelectric modeling; geology; geophysics.

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I. INTRODUCTION

This paper presents the main aspects of the proposed first part of the NBR-7117 standard, for the ground resistivity measurement and geoelectric modeling.

This review incorporates to the electrical engineering knowledge, the geophysics technologies available for surveying the apparent resistivity of different ground layers – electrical methods for the shallow ground (already considered in the standard NBR-7117), and electromagnetic methods for the near-surface (TDEM, down to some hundred meters depth) and for the deep ground layers (AMT/MT, from hundreds of meters depth down to kilometers depth). The combination of these complementary methods allows for the development of deep geoelectric models, compatible with the dimensions of wide-area installations. These methods have already been applied in Brazil and abroad for the development of deep geoelectric models for wide area projects, such as HVDC systems, hydroelectric powerplants and windfarms, whose groundings have dimensions of the order of kilometers.

The development of an average geoelectric model requires the availability of an average apparent resistivity curve, to be inverted. Ground resistivity is a parameter with a wide range of variation, from 10^{-1} Ωm to 10^{5} Ωm, and is compatible with the asymmetrical log-normal statistical distribution, as occurs with most parameters in geology (permeability, porosity, grain sizes etc.). Therefore, the revision suggests that the best averaging method of resistivity data is the geometric mean, instead of the arithmetic mean, which is associated with parameters that have a symmetric Gaussian distribution.

This revision presents considerations on the inversion process, which infers the subsurface structure (which is 3D) from the average apparent resistivities curve, obtained from data measured on the soil surface (which is 2D), resulting in the geoelectric model, which for the object of this standard is stratified into horizontal and parallel layers (1D model).

Considering that the electroresistivity is the sounding technique traditionally used by the electrical community for the electrical grounding design, the review of the NBR-7117 standard dedicates two chapters to this technique, with detailed orientations for the development of the Wenner and Schlumberger surveys, for the determination of the average apparent resistivity curve and for its inversion, in order to achieve the proper geoelectric model.

II. Soils – General Concepts

The ground is the superficial layer of the crust, composed of sediments and altered or fragmented rocks, clay minerals, iron oxides and several other unconsolidated materials, formed by the weathering action and the chemical alteration of the minerals of the original matrix rock, as well as by the organic matter produced by living organisms. The soil, *strictu-sensu*, is the product of physical and chemical alteration of the rocks, with depth limited to two meters and that can sustain vegetable and animal life. Its basic constitution involves different proportions of a mixture of gravel with three types of sediments - sand, silt and clay (listed in descending order of grain size).

The concept of soil from the point of view of electrical engineering, better expressed in English by the word ground, is the medium in which an electrode is buried and includes the entire ground volume that dissipates an injected current and is electrically influenced by this current dissipation.

A simple classification from the point of view of electrical engineering subdivides the soil into a basic three-layer structure:

- surface layer - dry or with low water content (unsaturated), with organic matter and presenting medium resistivity;
- saturated soil - constituted by fractured or altered rocks, where the saturation of the pores and fissures of the rocks with water and dissolved salts (which act as a weak electrolyte), results in lower resistivities; and
- bedrock - a layer of very compacted sediments or non-fragmented rocks; with intermediate resistivity, in the case of porous or cracked rocks saturated with water; or with high resistivity, in the case of non-fissured igneous rocks (granites, gneisses or basalts).

The soil has a heterogeneous structure, with resistivity that varies in time and space. The variation in time derives from climatic seasonality, and may also be associated with human interference, such as land movements and contamination. The variation in space, horizontally and vertically, occurs as a function of mineral composition, moisture level, temperature, salinity, degree of compaction and the geological processes that gave rise to the formation of subsurface structures.

III. Geoelectric Modeling

The development of a geoelectric model, based on the results of a resistivity survey, is the first activity for the designing of a grounding system and for the calculation of its electrical performance. The electrical performance of a grounding system can be measured or calculated based on specific parameters such as ground resistance and the soil surface potential profile, from which can be calculated the step and touch potentials.

The potential gradients on the soil surface, within or adjacent to the area where the electrode is buried, are mainly a function of the geoelectric structure of the shallow ground layers. On the other hand, the resistance of the electrode depends not only on the ground surface layers but also on the regional deep geoelectric structure, the relevant depth being a function of the size of the grounding electrode.

The simplest geoelectric model is the one-dimensional (1D), which consists of parallel horizontal layers, each layer characterized by its thickness (*e*, in m) and resistivity value (ρ, in Ωm), as shown in Figure 2. This kind of model is associated with grounds originated from sedimentary geological processes, despite it is applied to a broader range of tectonic settings.

Vertical Electrical Surveys (VES) are geophysical techniques for the investigation of the vertical distribution of the resistivity parameter, as seen from a point on the soil surface, which is expressed by the apparent resistivities curve. This curve does not characterize a physical parameter of the medium, but a profile of resistivities as viewed from the soil surface, that is dependent of the subsurface structure and a function of the sounding method applied.

A mathematical process called inversion infers the subsurface structure (which is 3D) from the apparent resistivities curve, measured on the soil surface (which is 2D), resulting in the geoelectric model, which for the object of this standard is stratified into horizontal and parallel layers (1D).

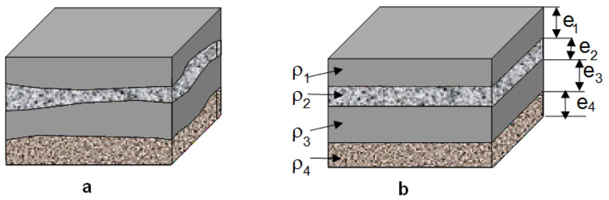

Fig. 1. Real ground structure (a) and the corresponding 1D model (b), characterized by horizontal and parallel layers, each one with width e_i and resistivity ρ_i.

IV. Geoelectric Sounding

All the techniques for the ground resistivity survey produce apparent resistivities curves and can be divided into two groups - electrical and electromagnetic.

The electrical techniques, grouped under the general name of electroresistivity, are based on the injection of electric currents in the ground by means of two current electrodes, with the use of two potential electrodes for the measurement of the potentials produced on the soil surface by the circulation of the injected current in the ground. The VES – Vertical Electrical Sounding, uses the Wenner and Schlumberger arrangements, with electrodes aligned and symmetrical with respect to the central position of the measuring equipment. Electrical techniques are suitable for sounding the shallow ground layers, reaching with depths down to a few tens of meters.

Electromagnetic techniques use electromagnetic fields, either natural or produced by the measuring equipment, to probe deeper ground layers. The technique known as Time Domain Electromagnetic (TDEM) uses current pulses injected in a coil laid on the soil surface, which induces a magnetic field in the ground. The induced field gives rise to a secondary field, which is a response of the ground to the initial excitation, that is measured by another coil. It is a very sophisticated and complex technique that allows the sounding of the ground down to depths of the order of hundreds of meters.

The magnetotelluric technique (AMT and MT) involves the measurement on the soil surface of natural electric and magnetic fields, induced in the earth's crust by atmospheric and ionospheric phenomena. After very complex processing, it is obtained two sets of curves in orthogonal directions, apparent resistivity and phases, which characterize a two-dimensional model (2D). MT soundings are able to probe the entire Earth's crust (about 40 km thick) and part of the mantle, penetrating from tens of meters down to tens of kilometers deep.

Finally, there is the well profiling technique, which uses probes that are lowered into a drilled well, down to the depth of interest, which measures the resistivity of the wells' walls, using an electrical or electromagnetic technique. The well profiling has the advantage of directly measuring the resistivity of the drilled ground column, rather than the apparent resistivity. Therefore, it serves to calibrate the shallow geoelectric model obtained from the VES (Vertical Electrical Sounding), which is an inferred model. The well profiling is also suitable for the sounding of built-up areas, where there is no free space for the application of other ground resistivity survey techniques.

It is important to note that the above-mentioned techniques of measurement of the electrical resistivity parameter (except well profiling) are volumetric measurements, which cover large volumes of the ground and measure an average of the resistivity within this volume, in principle the same volume seen by the grounding electrodes to be dimensioned. Other techniques, which measure the resistivity of ground samples or the resistance of an auxiliary electrode, do not lend themselves to the modeling of the wide areas compatible with the typical groundings, which occupy areas with dimensions from tens to thousands of meters.

The sounding technique traditionally used by the electrical community for the electrical grounding design is the electroresistivity. The electromagnetic sounding techniques can be used in special ground designs that require differentiated resources due to very high resistivity grounds or to aspects associated with large size or specific applications.

For example, the design of the ground electrodes of HVDC transmission systems requires deep geoelectric models, which depending on regional tectonics may cover the entire Earth's crust (about 40 km deep). Windfarm grounding designs have used intermediate geoelectric models, down to hundreds of meters deep, obtained from the combination of electroresitivity and AMT or TDEM electromagnetic techniques.

V. Electroresistivity Soundings

A. Principles of the Method

The electroresistivity method infers the ground geoelectric structure from the set of data that includes the geometry of the current and potential electrodes arrangement, a set of injected currents and the measured potentials at the soil surface.

The VES using the electroresistivity technique employs a voltage source, and an array of four symmetric and aligned electrodes, shortly inserted into the soil surface. By means of the two current electrodes, a current I is injected into the ground, and the two potential electrodes measure a ΔV in the soil surface, by means of a potentiometer or a high impedance voltmeter.

It can be demonstrated that the resistivity of the ground is proportional to V/I, being the proportionality factor a function of the sounding arrangement. The so-called apparent resistivity (ρa) is calculated from the relationship between the measured voltage and the injected current and considering the proportionality factor k, which depends only on the configuration of the sounding electrodes.

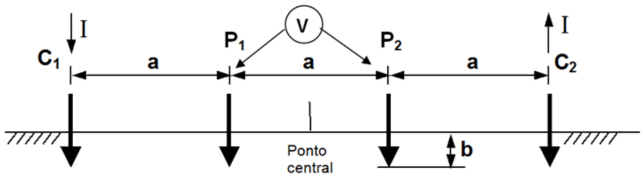

Fig. 2. Wenner arrangement and associated configuration parameters, where a is the spacing between electrodes, I is the current injected by the external electrodes (C_1 and C_2) and V is the potential difference measured between the internal electrodes (P_1 and P_2).

B. Measuring Equipment

For the measurement of the ground resistivities, it is used equipment composed basically of a voltage source (DC or low-frequency AC), an ammeter and a voltmeter (more properly, a galvanometer). Usually, the equipment display is calibrated to provide the relationship between voltage and current, which becomes an apparent resistance. The equipment has 4 terminals which are connected to the four measuring probes on the soil surface by means of two current electrodes (C1 and C2) and two potential electrodes (P1 and P2).

There are two types of ground resistivity sounding equipment - the ground meter and the resistivimeter. The ground meter with the Wenner arrangement is the more commonly setup used by electrical professionals for resistivity surveys. It operates with AC frequency and has low power, for the safety of the operator, presenting for these reasons smaller volume and weight than the resistivimeter (and thus lower price). The counterpart of these advantages is that the applicability of this equipment is restricted to grounds with lower resistivity (less than 10,000 Ωm) and smaller areas (limited to a maximum diagonal of 200 m). In general, the ground meter shows a significant increase of measurement errors for openings higher than 100 m between the current electrodes, due to the reduction of the signal-to-noise ratio, which increases for the larger sounding spacings. This error generally results in higher apparent resistivity readings than the actual values.

Geophysics professionals generally prefer to use the resistivimeter with the Schlumberger array. The resistivimeter has the following advantages with respect to the ground meter:

- operates with DC, which penetrates deeper into the ground than AC currents (avoiding the skin effect), allowing for the sounding of deeper ground layers;
- has a higher power (of about 20 times), allowing for the injection of higher measuring currents, which result in higher values of ΔV and thus on better signal-to-noise ratios;
- the best signal-to-noise ratio enables better soundings, mainly for the larger openings of the current electrodes.

C. General Considerations

Considering the seasonal variation of the resistivity of the shallow ground layers, it is desirable that the resistivity survey shall be carried out in the dry period. However, the project management usually requires that ground resistivity survey to be performed at the time determined by the project schedule, which eventually does not coincide with the dry period.

It is observed that the ground resistivity varies only in the shallow layers affected by the water table oscillation. Below the minimum groundwater level, the ground resistivity is stable throughout the year and is not influenced by weather seasonality.

Predominantly sandy soils will drain rainwater more quickly than grounds with clay content. This means that the composition of the ground interferes with its capacity of water retention and, therefore, with the effect that recent rains can have on the resistivity of the shallower ground layers.

It shall be avoided resistivity soundings close to existing groundings, transmission lines (which may have counterpoises) and any other buried conducting elements, including building and structures' foundations, which have steel reinforcements. In this case, the measuring line should be moved to a distance where the interference is reduced to avoid or attenuate the effects of proximity with buried metallic masses. It is suggested a distance of at least 1/3 of the largest opening of the current electrodes of the measurement line.

For transmission line and windfarm projects, two measurements in orthogonal directions should be made at the location of towers (not necessarily in all towers, to be determined by the project), preferably one aligned with the transmission line axis and another perpendicular to it.

For the Wenner arrangement, each measurement line shall cover different distances between electrodes, extending at least up to the largest (diagonal) dimension of the prospective area. The measuring line shall be prospected from a distance between electrodes of 1 m and proceed, if possible, to a power of 2, namely: 1, 2, 4, 8, 16, 32, 64 m etc. If necessary, intermediate distances between electrodes may be used.

For measurements with Schlumberger arrangement, the reading of the measured potentials should be monitored and, if these are reduced to levels below the sensitivity of the equipment, the spacing between the potential electrodes should be increased with the repetition of the measurement without the displacement of the electrodes due. This procedure results in the segmentation of the apparent resistivity curve, which will show small vertical displacements associated with the static deviation of each opening of the potential electrodes.

If the area exceeds 20,000 m² or if its diagonal exceeds 200 m, it may be necessary the subdivision of the area into smaller areas. In this case, the complementation with an electromagnetic survey may be necessary, with the combination of different techniques of ground resistivity survey, in order to produce a ground model with depth compatible with the size of the grounding to be designed.

The electrodes shall be firm and with good adhesion to the soil. Sandy or rocky soils may require the addition of water at the placement of the electrodes for better electrical contact.

The use of a pair of $Cu/CuSO_4$ non-polarizing half-cells contributes to significantly improve the signal-to-noise ratio of potential measurements made with the internal electrodes. The reading of the measured value shall wait for a few seconds so that the potentials stabilize on the internal electrodes. The soil surface where the semi-cells are placed for the measurement shall be previously cleared of weeds, rock fragments etc.

The measuring worksheets should be organized in such a way to allow for a complete record of the field work, including - date, name of the equipment operator, identification and location of the project, coordinates of the line center and VES alignment, soil characteristics (type, humidity, compaction conditions etc.) and environmental (temperature, moisture etc.), and the measurements' results (spacings and measured parameters).

If it is not possible to comply with the recommendations of the standard, technical justifications shall be submitted to the stakeholders of the project.

VI. Geoelectric Modeling

The geoelectric modeling here proposed considers the construction of a 1D model, stratified into horizontal and parallel ground layers, each one with a width and a resistivity. It can be summarized into two activities – the construction of an average apparent resistivities curve and the inversion of this curve.

A. Construction of an Average Apparent Resistivity Curve

The first activity for the processing of the ground resistivity values consists of obtaining an average apparent resistivities curve, which is representative of the geoelectric structure of the average soil in the prospected area. Considering that the ground resistivity parameter has a statistical distribution that approaches the log-normal (in which the logarithms of the measured values have a Gaussian distribution), the average apparent resistivities curve can be obtained from the geometric mean of the values of apparent resistivity measured for each sounding spacing.

The use of the geometric average, besides complying with the recommendation of the technical literature in the area of geophysics, has the advantage of reducing the weight of extreme measures (the so-called outliers), the ones that are out of the range of most of the measured values. This leveling of the data occurs because the geometric mean corresponds to the inverse log of the arithmetic average of the logarithms of the measured values. The conversion of the measured values to the corresponding logarithms decreases the weight of the outliers.

The geometric average presents a second advantage. All surveys of ground resistivity based on the measurement of electric fields at the soil surface (both electroresistivity and magnetotelluric techniques) are affected by the phenomena known as static-shift. This static deviation is caused by non-homogeneities of the soil around the potential measuring rods and results in the vertical displacement of the apparent resistivities curve.

The geometric average of a statistically representative set of soundings (at least 10 lines) results in the reduction of this deviation, considering that the errors associated with this deviation have a Gaussian statistical distribution.

Exemplifying, considering only two values - 1 Ωm and 100 Ωm, each representing half of the area surveyed; the arithmetic average will result in 50 Ωm, and the geometric average will result in 10 Ωm. This last value is the most representative of the average ground, because the currents will not be equally divided between the two areas, but rather will be concentrated in the area of lower resistivity.

Under a practical point of view, it is suggested the elimination of apparent resistivity values that lie in decades that are outside the range of most of the measured values. For example, if most of the curves is within 100 Ωm and 20,000 Ωm, the few measurements that are less than 100 Ωm and higher than 20,000 Ωm can be eliminated. This assessment is facilitated if all the apparent resistivities curves measured in the area are plotted on a log-log graph. The analysis of the set of curves allows for the identification of the values that extrapolate the range of the resistivities in the area, allowing for the elimination of outliers.

It is observed that the most reliable segment of the average apparent resistivities curve is the intermediate section. The initial segment is affected by under-sampling, because for small spacings (up to 25 m between current electrodes), the number of soundings usually performed is not enough to have a statistical significance, especially when dealing with the modeling of a large area. The final segment (from 32 m of spacing) is typically affected by an increasing loss of precision, due to the decrease in the signal-to-noise ratio for the soundings with wider spacing.

B. Inversion of the Average Apparent Resistivity Curve

The previous versions of this standard suggested the use of homogeneous or double-layer ground models, which were constructed with the help of families of pre-plotted curves on a transparent log-log paper.

Nowadays, there is a wide availability of software for the inversion of apparent resistivities curves, which can be purchased or even downloaded free on the internet, designed for the calculation of multi-layer geoelectric models. It should be noted, however, that the inversion process of an apparent resistivity curve infers the subsurface structure (which is 3D) from soundings done at the soil surface (which is 2D). Due to the unbalance between the number of equations and the number of variables, as well as to the errors associated to the measurements, the mathematical inversion process has the characteristic of admitting multiple solutions in terms of geoelectric models, for the same curve of apparent resistivities.

Therefore, the geoelectric model calculated by the software, despite being a solution that mathematically solves the inversion problem, may not correspond to the average geophysical structure that exists in the ground of the prospected area. An inversion without any additional information on the ground structure to be modeled is called a blind inversion. Whenever possible, additional information on the geology of the prospected area should be sought, to allow for a constrained inversion, which ads complementary data to the apparent resistivity curve and results in a more reliable geoelectric model.

It should be noted that most of the inversion software allows for one or more variables to be imposed on the solution, either in terms of thickness (or depth) of a layer or a specific value of ground resistivity, for example:

- the depth of the water table, which marks the interface between a dry and high resistivity surface layer and a deeper water-saturated layer with a lower resistivity;
- the impenetrable, measured by one or more SPT (Standard Penetration Test) soundings, which identifies the compact ground layer, where it is expected that the resistivity will increase due to the reduction in volume and communicability of the rocks' pores, which may contain water.

In order to obtain an inversion that is more representative of the local geology, direct information on the ground structure shall be used. Three sources of complementary information can be considered:

- drilling and profiling one or more wells (depending on the size of the area to be modeled), which will provide information that effectively will contribute to better modeling of the shallow ground layers of the surveyed area;
- SPT surveys, information that is often available by the civil engineers in charge of the foundations' design, but rarely considered - these surveys usually cover the depths and materials of the different shallow ground layers, the depth of the water table (when it is reached before the impenetrable) and the depth of the impenetrable (when the survey is interrupted);
- information on the local stratigraphy (layers of the geological formations in the area), which can be obtained from geologists who have local knowledge or found in the available technical literature on the geology of the area.

The availability of these complementary information allows for the inversion of the average apparent resistivities curve to be made under the restriction of data considered to be known, which are informed to the software and will result in a better geoelectric model.

VII. Conclusion

The proposed NBR-7117 standard review is ambitious and intends to include the determination of the complete set of ground parameters that are used for electrical design, including the electrical parameters (electrical resistivity, electrical permittivity and magnetic permeability) and the thermal parameters (thermal capacity, the thermal conductivity and the thermal diffusivity).

This first part of the standard, described in this paper, considers only the electrical resistivity, and incorporates to the electrical engineering the knowledge of geophysics for the geoelectric modeling of the ground, considering the electrical and electromagnetic methods for sounding the shallow, near-surface and deep ground.

The thermal parameters are important data for the design of electrical systems whose operation results on a continuous dissipation of heat into the ground, such as buried energy lines and HVDC ground electrodes. The growing of HVDC transmission systems and of windfarms and solar power plants, the latter with medium-voltage energy lines buried within wide areas, highlights the importance of the definition of these thermal parameters. The procedures for the measurement and processing of the thermal parameters shall be established by the second part of the standard, which is yet under development.

The third part of the standard will deal with the determination of electrical permittivity and magnetic permeability, which are important parameters for the calculation of the ground performance under the injection of impulsive or high-frequency currents, such as the ones associated to lightning discharges or to the operation of surge protection devices.

REFERENCES

[1] Freire PEF. Silva JM. Pereira SY. Borin PFO. Jardini JF. Brazilian Standard NBR-7117/2012 - A Review Proposal. Ground 2016 - International Conference on Grounding and Earthing & 7th International Conference on Lightning Physics and Effects. Porto de Galinhas, Brazil. June 2016.

[2] ABNT NBR-7117/2012. Medição da resistividade e determinação da estratificação do solo.

[3] PEF. Freire & SY. Pereira. Windfarm Grounding. 2016 CIGRE C4 International Colloquium on EMC, Lightning and Power Quality Considerations for Renewable Energy Systems. Brazil. 2016.

[4] PEF. Freire. Grounding electrode of Rio Madeira – Bipole 1: geoelectric modeling of Earth's upper crust for the electrode design. Ph.D. Thesis, University of Campinas, Brazil. July 2018.

[5] PEF. Freire. & SY. Pereira. Ground Geoelectric Modelling for the Study of Large Grounding Systems. ERIAC XVI. Foz do Iguaçu. Argentina. 2015.