Numerical Analysis of the Performance of Ground Grids According to Their Resistance

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***Abstract*—This paper aims to analyze the performance of a ground grid according to their resistance. Grounding is related to two fundamental factors: the performance of the system which the grounding is connected, and safety issues for living beings and equipment protection. In order to ensure its quality, the grounding system must have a high conduction capacity, a configuration that allows the control of the electrical potential gradient and a low impedance or ground resistance value. An efficient ground grid is not only responsible for enabling a path with low impedance to protect the electrical system in surge cases, but also to ensure that the touch and step voltages are within set limits. The resistivity of the soil surrounding the system is the mainly responsible for determining the value of the ground resistance. In this context, a good way of analyzing ground resistance is through numerical modeling. In this work, the resistance of a grounding system is determined by the finite element method (FEM) with the aid of a simulation software. The results obtained through simulations are compared to the fall-of-potential method, analytical methods, and the transmission line method (TLM).**

Keywords—ground grids; ground resistance; grounding systems; numerical simulation.

I. INTRODUCTION

The applications of a grounding system are associated with two fundamental factors: the performance of the system which the grounding is connected, and safety issues for living beings and equipment protection. In both cases, the soil is used as a conductor, where it allows the drainage of loads to the earth. [*1*]

Ground grids are widely used in electric power substations with the purpose of controlling voltage within limits prescribed in standards. However, the grounding system must have a high conduction capacity, a configuration that allows the control of the electric potential gradient and a low impedance value. [*2*] [*3*] [*4*]

The ground impedance is designated as the opposition to the passage of electric charges to earth. In some cases, at low frequencies, the ground impedance can be seen as a ground resistance because of its resistive behavior. [*4*]

In energy substations, the ground resistance is one of the main factors for the analysis of electrical safety. It is not only responsible for establishing a path with low impedance for protection of the electrical system in surge cases, but also to ensure that the touch and step voltages are within set limits. Therefore, it is necessary that a good grounding system does not have a high resistance value. [*5*] [*6*]

The ground resistance is composed of three fundamental components: the resistance of the conductors, the resistance of contact between the conductors and the adjacent soil, and the resistance of the surrounding soil. This latter component is the mainly responsible for determining the value of the ground resistance, since the others usually have a very small or negligible value. [*4*]

In this context, a good way of analyzing the performance of ground grids resistance is through numerical modeling. This work aims to determine the resistance of a grounding system through the finite element method (FEM). For this, the electromagnetic simulation software, ANSYS Maxwell, will be used. The results obtained through the simulations will be compared to the fall-of-potential method, analytical methods, and the transmission line modeling method (TLM).

The resistivity values obtained experimentally, according to the model proposed by [*7*], will be used in the simulation model. The simulations will be performed considering five case studies with different configurations of the grounding system.

II. METHODOLOGY

A. Ground Grids

The ground grids analyzed in case studies from 1 to 4 are located in the Experimental Farm of the Center of Agricultural Sciences - CCA of the Federal University of Santa Catarina (UFSC). Case study 5 does not have its location disclosed for reasons of confidentiality.

In all the case studies, the ground grids are formed only by conductive cables, without rods. All grids are made up of bare copper cables with a cross-section of 95 mm² and a constant spacing of 2.5 m between the cables. All ground grids are buried at a depth of 0.5 m from the soil surface.

The ground grid of the case study 1 has dimensions 10 m x 10 m, totaling an area of 100 m² (Fig. 1). The ground grid of case study 2 has dimension 5 m x 10 m, totaling an area of 50 m² (Fig. 2). The ground grid of the case study 3 has dimension 2.5 m x 10 m, therefore with an area of 25 m² (Fig. 2). The case study 4 has a ground grid size of 5 m x 5 m, with an area of 25 m² (Fig. 3). The case study 5 has similar dimensions to that presented in case 1, but it was carried out in a different location.

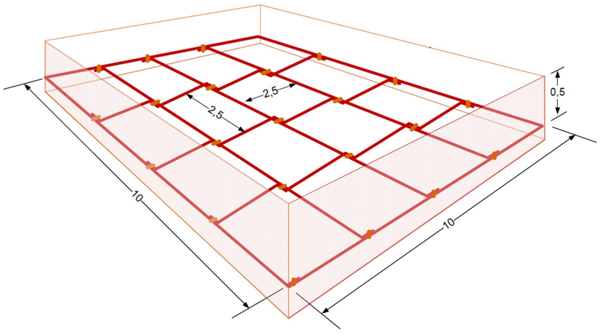

Fig. 1. Ground grids of case study 1 and 5
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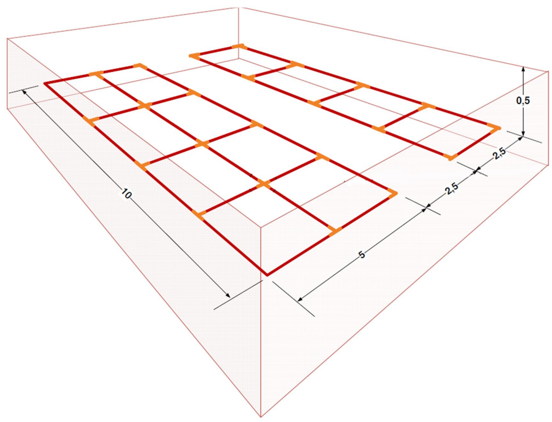

Fig. 2. Ground grids of case study 2 and 3
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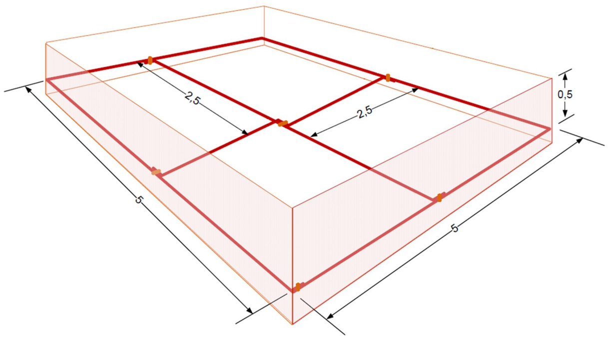

Fig. 3. Ground grid of case study 4
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B. *Soil Characterization*

Generally , the soil is not homogeneous, being formed by several layers that have different resistivities. These layers can vary in shape and layout, but in most cases, they have a horizontal profile, parallel to the surface.

One way to characterize the soil is through its stratification. Several formulations have been proposed to represent it, and the usual models consist of dividing the soil into layers, with different resistivities and depths. Several methods are provided in [7] for soil stratification. In this work, the Wenner Method was used.

With this method, and through the stratification process, the soil was characterized in two layers with the flat profile, defining the depth of the upper layer.

TABLE I. SOIL STRATIFICATION

Case study	Grid dimensions	ρ1 (Ωm)	ρ2 (Ωm)	a1 (m)	ρa (Ωm)
1	10 m x 10 m	845	144	3	592
2	5 m x10 m	1069	207	4	855
3	2.5 m x 10 m	1069	207	4	855
4	5 m x 5 m	1069	207	4	855
5	10 m x 10 m	750	295	9	675

C. *Ground Resistance Measured And Calculated*

There are several measurement methods to obtain ground resistance, The fall-of-potential method will be used in this work .

This method consists in circulating a current over the ground grid through an auxiliary current electrode. After that, it is measured the voltage between the ground grid and the reference electrode by means of a probe or auxiliary voltage electrode.

In the cases under study, the methodology of the collinear voltage and current auxiliary electrodes was adopted, that is, with coincident direction. From the ratio of voltage and current, the ground resistance curve is determined. The horizontal section of the curve represents the value of the ground resistance of the system under test. For the verification of the horizontal section of the curve, the current auxiliary electrode must be at least three times the largest dimension of the system, given by the diagonal of the ground grid. [*2*]

The NBR 15751:2013, by ABNT, provides a calculation method for an approximate ground resistance value. This method is given as a function of the soil resistivity and the area occupied by the ground grid. [*6*]

Another known calculation method is the Sverak Method. This method consists of expanding the equation of the previous method taking into account the depth of the ground grid. [*9*]

The following values were obtained through the fall-of-potential method and the values calculated with the approximate method of ABNT and the Sverak Method.

TABLE II. MEASURED AND CALCULATED GROUND RESISTANCE

Case study	Grid dimensions	$R_{Measured}$ (Ω)	R_{ABNT} (Ω)	R_{Sverak} (Ω)
1	10 m x 10 m	14	26.21	29.95
2	5 m x10 m	38	53.59	66.59
3	2.5 m x 10 m	55	75.79	90.98
4	5 m x 5 m	74	75.79	93.18
5	10 m x 10 m	23.3	29.91	34.18

III. System Modeling Through The Finite Element Method (FEM)

A. Finite Element Method (FEM)

Finite element method is one of the most applied techniques for calculating the dispersion of electromagnetic fields in engineering problems. In general, this method consists of dividing the geometry of a problem into small elements, where each element represents a continuous domain of the problem. This technique allows solving a complex problem, subdividing it into simpler problems. [*10*]

According to [*8*], the software ANSYS Maxwell 3D can be used for the analysis of electromagnetic phenomena at low frequencies in grounding systems obtaining satisfactory results.

ANSYS Maxwell 3D software uses the FEM in its calculations, and when it is compared to other simulation methods, this method presents an adequate estimate. When compared to analytical methods, it has a better approximation because analytical methods are not capable of capturing the effect of mutual coupling of the electrodes in the ground grid. [*8*]

B. Simulation Model

The implemented system model was based on the works of [*8*] and [*11*] seeking to replicate the fall-of-potential method.

In this work a semi-spherical model was used to represent the soil. Ground grids are allocated in the center of the semi-sphere according to their depth.

The soil was represented according to the presented stratification model given by the Wenner Method. For each case study, the data of Table 1 were used, for the resistivities of the first and second layers (ρ1 and ρ2), and for the depth of the first layer (a1). In addition, a soil with relative permissivity εr = 36 was considered.

The radius of each semi-sphere was considered to be four times greater than the diagonal of the ground grid. This size is sufficient to have no interference in the calculation procedure of the ground resistance.

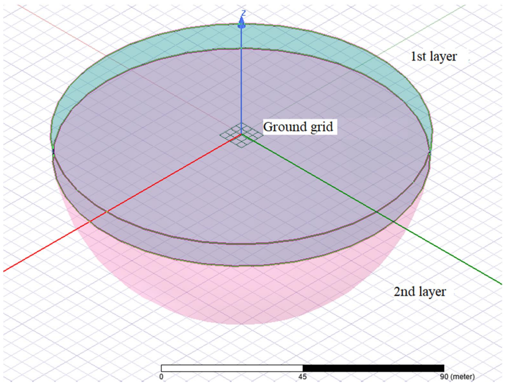

Fig. 4. Implemented model of soil stratification

The ground grids were configured according to their actual dimensions, conform to the models presented.

In the ANSYS Maxwell 3D software, the material used for the characterization of the ground grids is copper, from the software library. This material has a relative permittivity equal to εr = 1 and an electrical conductivity $\sigma = 5{,}80 \times 10^{7}$ S/m.

In all case studies, the ground grid was excited at its center with a sinusoidal alternating voltage with a peak value of 311 V. The voltage value was chosen arbitrarily, because it does not interfere in the calculation of the ground resistance.

To reproduce the measurements of the fall-of-potential method, a frequency of 1470 Hz was used, which is commonly used by terrometers.

The excitation source can be described by (1):

$$V(t) = 311\sin(2\pi \times 1470 \times t) \tag{1}$$

Where:
V – Source voltage, in volt (V);
t – Discrete time, in second (s).

The external surfaces of the semi-spheres are defined by the sink contour condition. This condition is used in order to guarantee a single solution for the FEM matrix system and avoid truncation errors. This condition can be seen as a “drop” of current, allowing all current flow to be drawn to the surface, exiting normal to it. Therefore, the sum of currents flowing through the surface and that injected by the source must be equal to zero.

For the calculation of the ground resistance, it was tried to replicate the calculation used in the fall-of-potential method, applied in the field measurements.

According to [*4*], the value of the ground resistance can be quantified by the relation between the voltage drop between the applied voltage in the ground grid and the potential electrode (dV) by the current flow between the ground grid and the current electrode (dA).

In order to obtain the ground resistance curves, the following method was applied, maintaining dA fixed at 4 times the diagonal of the ground grid and varying dV in fractions of dA.

For the representation of dV, a semi-spherical shell of negligible thickness and without defined material was used. This semi-spherical shell will have its radius varied according to the fractions of dA.

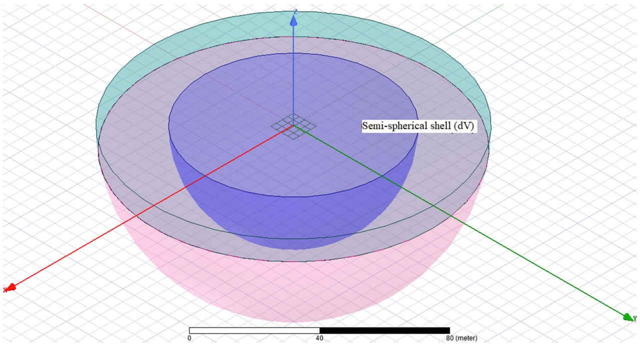

Fig. 5. Semi-spherical shell (dV)

With the excitation applied to the center of the ground grid, the average voltage is calculated on the entire surface occupied by it. The voltage in dV is also calculated by the average voltage in your area. The potential difference between the ground grid and dV is given by (2):

$$\Delta V = V_{grid} - V_{dV} \tag{2}$$

Where:
ΔV – Potential difference between the ground grid and dV, in volt (V);
V_{grid} – Average voltage in the ground grid, in volt (V);
V_{dV} – Average voltage in dV, in volt (V).

According to Ohm's Law, the relation between the electric field (**E**) and the surface current density vector (**J**) given by (3):

$$\mathbf{J} = \sigma \mathbf{E} \tag{3}$$

Where:
J – Current Surface Density, in ampère / meter² (A/m²);
σ – Electric conductivity, in siemens / meter (S/m);
E – Electric Field, in volt / meter (V/m).

From the surface current density, it is possible to calculate the current flowing from the ground grid to dA. As the current flow obeys the contour conditions imposed by the sink, from a surface integral it is feasible to obtain its value. For this, it was chosen to perform the integration in the same semi-spherical shell where dV is calculated.

$$\mathrm{I} = \int_S \boldsymbol{J} \cdot ds \tag{4}$$

Where:
I – Current that flows between the ground grid and dA, in ampère (A);
J – Current Surface Density, in ampère / meter² (A/m²);
ds – Infinitesimal portion of the semi-spherical shell surface, in meter² (m²);
S - Semi-spherical shell surface, in meter² (m²).

According to [*4*], at low frequencies, it is achievable use the relation given by (5) for calculate the ground resistance.

$$\mathrm{R} = \frac{\Delta \mathrm{V}}{\mathrm{I}} \tag{5}$$

Where:
R – Ground resistance, in ohm (Ω);
ΔV – Potential difference between the ground grid and dV, in volt (V);
I – Current that flows between the ground grid and dA, in ampère (A);

The ground grid was defined with elements of a maximum size of 50 mm. The first layer of soil was defined with elements of 2 m and the second layer with elements of 5 m.

The semi-spherical shell, because there is no thickness, has a finite triangular element mesh, being specified by a special "surface approximation" function. In this function, the resolution of the finite element mesh for curved surfaces is defined, where a fine mesh is chosen, that is, with a greater amount of elements, hence a mesh denser than the one regularly used by the software (Fig. 6).

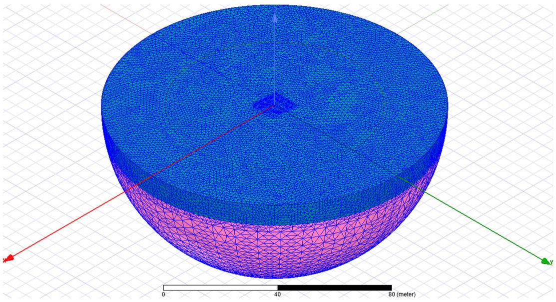

Fig. 6. Finite element mesh

IV. Results

In the following figures, Fig. 7 and Fig. 8, the results for the electric field, **E**, the current density, **J**, are presented at the instant of 2 ms in the simulation, for the case study 1. The sink contour condition, applied to the model, can be verified in this figure, where **J** is normal to the surface. The other cases in study behave in a similar form.

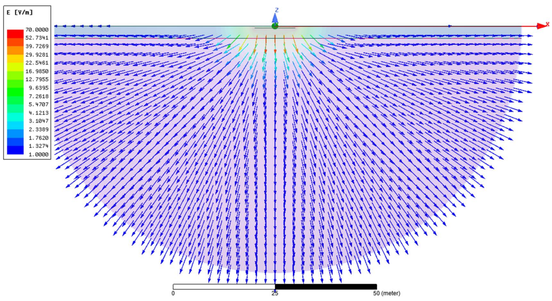

Fig. 7. Electrical field in the case study 1: Ground grid 10 m x 10 m

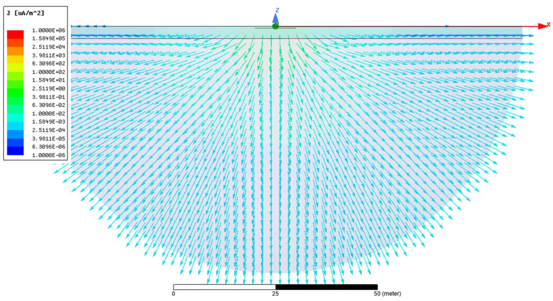

Fig. 8. Current density in case study 1: Ground grid 10 m x 10 m

The ground resistance curves obtained by the variation of dV in the percentages of dA, for all the case studies, can be observed in Fig 8, Fig 9, Fig 10, Fig 11, and Fig 12. As it was done in fall-of-potential method, the ground resistance of the curves presented, according to the horizontal section, was obtained as shown in Table 3.

TABLE III. Simulated Ground Resistance by FEM

Case study	Grid dimensions	R_{FEM} (Ω)
1	10 m x 10 m	19.54
2	5 m x10 m	43.77
3	2.5 m x 10 m	63.53
4	5 m x 5 m	70.20
5	10 m x 10 m	28.64

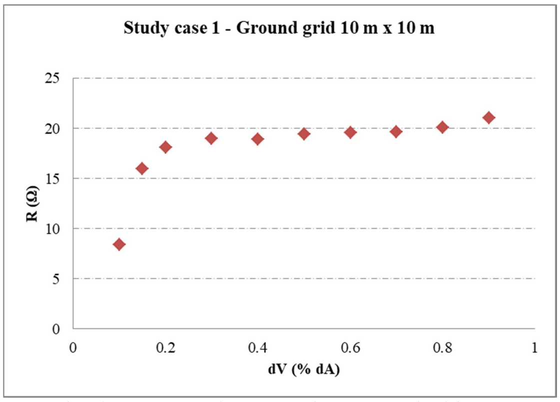

Fig. 9. Ground resistance curve in case study 1: Ground grid 10 m x 10 m

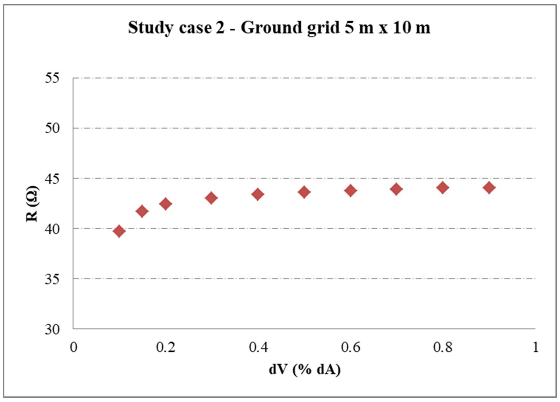

Fig. 10. Ground resistance curve in case study 2: Ground grid 5 m x 10 m

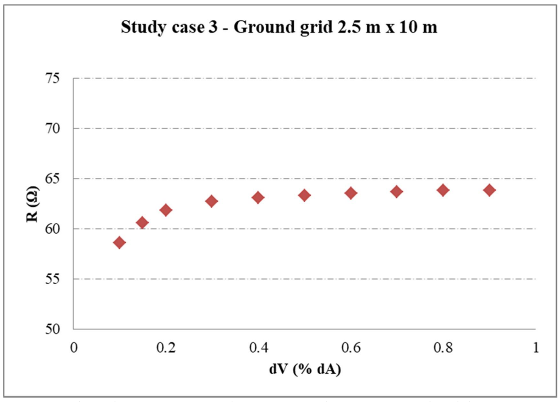

Fig. 11. Ground resistance curve in case study 3: Ground grid 2.5 m x 10 m

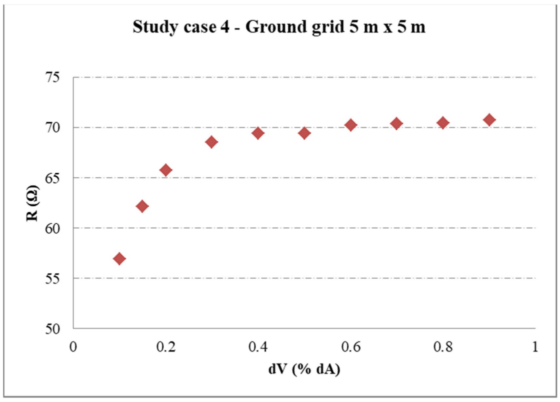

Fig. 12. Ground resistance curve in case study 4: Ground grid 5 m x 5 m

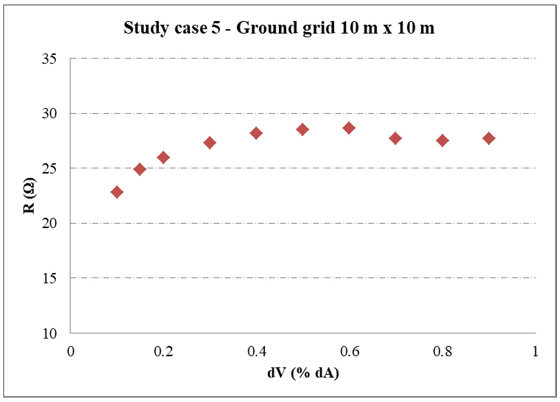

Fig. 13. Ground resistance curve in case study 5: Ground grid 10 m x 10 m

V. COMPARISONS AND DISCUSSIONS

This section will present and discuss the comparisons between the analyzed methods. The obtained results will also be compared to the TLM numerical method. However, the configurations of this method are not discussed in this work because they are out of scope.

TLM is a differential method, which it is necessary to discretize time and dimensions of the space under study. It consists of the modeling of electromagnetic fields by electrical circuits, more specifically by transmission line circuits. TLM is based in the Huygens principle for the propagation of waves, making a discrete implementation of this principle. The cases of studies from 1 to 4 were modeled by this method with the same stratified soil used by FEM, according to the models presented by [*12*] and [*13*].

Table 4 presents the results obtained between the different methods presented in this work, for each case in the study. The percentage relative error between FEM and the other methods can be observed in Table 5.

TABLE IV. COMPARISON BETWEEN METHODS

Case study	Grid dimensions	R_{ABNT} (Ω)	R_{Sverak} (Ω)	$R_{Measured}$ (Ω)	R_{TLM} (Ω)	R_{FEM} (Ω)
1	10 m x 10 m	26.21	29.95	14.00	20.00	19.54
2	5 m x 10 m	53.59	66.59	38.00	38.00	43.77
3	2.5 m x 10 m	75.79	90.98	55.00	58.00	63.53
4	5 m x 5 m	75.79	93.18	74.00	76.00	70.20
5	10 m x 10 m	29.91	34.18	23.30	-	28.64

TABLE V. PERCENTUAL RELATIVE ERROR BETWEEN THE FEM AND THE OTHER METHODS

Case study	Grid dimensions	Error $_{ABNT}$ (%)	Error $_{Sverak}$ (%)	Error $_{Measured}$ (%)	Error $_{TLM}$ (%)
1	10 m x 10 m	25.45	34.76	39.57	2.30
2	5 m x 10 m	18.32	34.27	15.18	15.18
3	2.5 m x 10 m	16.18	30.17	15.51	9.53
4	5 m x 5 m	7.38	24.66	5.14	7.63
5	10 m x 10 m	4.25	16.21	22.92	-

Analytical methods are extremely important for the calculation of ground resistance. They are easy to apply, do not rely on computational performance and allow an adequate estimation of the ground resistance value. Nevertheless, they are more susceptible to error when compared to numerical methods. This can be seen in Table 4, where the values of the analytical methods differ more from the measured value than the numerical methods.

Case studies 3 and 4 present two distinct ground grids, but with the same area and soil stratification. In the approximate method of NBR 15751: 2013 [*6*], they present the same resistance value for both configurations, considering only the area of the ground grid. The Sverak Method, even taking into account the length of the conductors, that constitute the ground grid and its depth, also presents very close values. However, the measured values differ markedly, and this effect can be captured by the numerical methods of TLM and FEM.

Different from the analytical methods, which consider the soil formed only by a layer with an apparent resistivity (ρa), the numerical methods use the two-layer soil stratification (ρ1 and ρ2), which is a better approximation. Moreover, through the numerical methods, it is possible to capture the effect of the mutual coupling of the electromagnetic fields.

The main factor that alters ground resistance is soil stratification. The resistivity values of the first and second layers have a significant influence on their value. One of the problems encountered during this work was the application of the Wenner Method.

The Wenner Method for soil stratification is subject to interference, so it is necessary to identify that the measured values correspond to actual values. That is, that the measures carried out are free from external interference.

The simulation model implemented, which uses the finite element method, was adequate for the calculation of ground resistance. Through the resistance curves, it is possible to note the expected behavior, according to the profile obtained in the measurement processes using the fall-off-potential method. Another important aspect is the proximity of the values with the TLM method, where the percentage error was below 16 % for all the cases in the study. When compared to measured values, this method is also suitable. Case study 1 has a greater percentage error, 39.57 %, but presents a variation between measurement and simulated of less than 6 Ω. It should be noted that the propagation of the equipment error and the measurement uncertainties were not taken into account for the calculation.

VI. CONCLUSION

According to the analyzed in the course of this work, the simulation model implemented, using FEM, presents satisfactory results, consistent with the values calculated and measured. When it compared to the simulation model that uses the TLM method, its percentage relative error was below 16%. When it compared to measured values, neglecting the uncertainties of measurement and propagation of errors, it presents a value less than 6 Ω for the largest relative percentage error calculated. Therefore, as shown by the obtained results, the presented model is coherent for the determination of the ground resistance.

The resistivity of the soil surrounding the system is the mainly responsible for determining the value of the ground resistance. As previously mentioned, the main factor that alters ground resistance is soil stratification. The results obtained with MEF have a direct relation with the soil resistivity measurement performed by Wenner Method. The resistivity values of the first and second layers have a significant influence on ground resistance value.

Through more reliable soil resistivity values, it is possible to obtain more accurate data in the simulations with FEM. During this work, one of the problems encountered was the uncertainty if the data obtained with the soil stratification represented its actual value. In this way, in the Wenner Method is necessary to identify that the measured values correspond to actual values because is subject to interference. Therefore, for future work, it is suggested the development or analysis of a different method to obtain soil stratification that is less susceptible to external interference.

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