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# GROUNDMESH: A FREEWARE TOOLBOX FOR GROUNDING SYSTEM DESIGN

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**Abstract - The design of a grounding grid aims to protect the human life when exposed to high operating voltages on power systems derived from short circuits or lightning. The same is done through a standardized procedure for design aiming a project that meets the safety limits with a low implementation cost. Due to the limited tools found in the market that help the designer, this work seeks to develop a free software for the design of electrical grounding systems. The performance of the developed software was validated with a well-known example found in the literature and with real projects of electrical grounding systems.**

## 1 – INTRODUCTION

An acceptable design of a grounding grid depends on the soil resistivity field measurements and the model adopted [14]. The soil model is an approximation of the same by horizontal stratified layers in order to facilitate the development of analytical solutions.

Figure 1 – First step for the construction of a particular grounding grid in the sand dunes of the state of Ceará in Brazil (Landfill with red sand over the dune). Source: Private project.

The step and touch voltages limits are substantially dependent on the value of the apparent resistivity seen by the designed mesh, if this value or the soil model are calculated wrongly the reliability of the design is compromised and fatal accidents can occur to the operators of the substation.

This work aims to use open source alternatives as development tools of an electrical grounding design software. For the code development was used libraries and functions written in the Python programming language [8], the libraries of mathematical treatment used were Numpy [12] and Scipy [11].

## 2 - OPEN SOURCE TOOLS

For the solution of the basic equations for a ground mesh design was chosen the Python programming language, which is considered the future successor of the FORTRAN language. Python was originally developed by Guido van Rossum in the 80's aiming to be simple and out of the paradigms of the compiled languages like FORTRAN and C, the dominant languages in market and academy.

Figure 2 – The Python programming language logo. Source: [10]

Python has as main features: Object Orientation, be interpreted via bytecode, dynamic typing, be modular, multiplatform (Windows, Linux, Mac, FreeBSD) and integration with C and FORTRAN. To increase the language numerical computational power, it must to be included in project the Scipy (Scientific Python) and Numpy (Numerical Python) libraries that are also used in order to have a ready solution for optimization problems. Scipy and Numpy require BLAS, LAPACK and ATLAS libraries for vectors and matrices manipulation on single or multicore computers [9].

## 2 – GROUNDING MESH DESIGN

A grounding mesh design must be able to reach the safety limits defined in [3] in case of any failure of insulation, short and lightning also providing a resistance value below the standardized.

For the sizing of mesh conductor of diameter $d$ , it must support the short circuit current and also the mechanical stresses from the mesh assembly. According to [2] the fault current flowing through the mesh cables is around 50% of the maximum short circuit, but for the conductor sizing is taken into account an increase of 10% as a safety margin.

Briefly a design of ground grid must have the following input variables: soil stratification, surface layer resistivity $\rho_s$, maximum single-phase short-circuit current $I_{\max}$, the percentage of the maximum short circuit current that will flow through the ground grid $I_{mesh}$, the protection acting time $t_{fault}$, the area devoted to grounding grid $A_{mesh}$ and the substation voltage class. One practical advice given by [2] is that the mesh depth $h$ should be between 0.25 and 2.5 meters being the spacing between conductors greater than or equal to 2.5 m.

## 2.1 – SOIL MODEL

The soil model can be done by graphical methods such as Yokogawa or by optimization methods [2]. The graphical methods are subject to human error due to the table's interpolation, graphical analysis and assignment of the first layer resistivity value [14].

This paper will use the optimization based method for a two layer soil model that uses the equation (1) where the theoretical apparent resistivity curve $\rho(a)$ is a function of the height $h$ of the first layer, the spacing $a$ between the auxiliary electrodes and the electrical resistivity of the first $\rho_1$ and second layer $\rho_2$ of the soil

$$\frac{\rho(a)}{\rho_1} = 1 + 4\sum_{n=1}^{\infty}\left(\frac{K^n}{\sqrt{1+\gamma^2}} - \frac{K^n}{\sqrt{4+\gamma^2}}\right) \tag{1}$$

where the reflection index $K$ is defined by

$$K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \tag{2}$$

and $\gamma$ is given by equation (3).

$$\gamma = 2n\frac{h}{a} \tag{3}$$

The optimal stratification method consists in minimizing the error between the resistivity field readings and the theoretical curve given by equation (1). The objective function $f_{\min}$ to be minimized is given by

$$f_{\min} = \sum_{i=0}^{q}\left(\rho(a_i)_{field} - \rho_1(1+4\psi_i)\right)^2 \tag{4}$$

where

$$\psi_i = \sum_{n=1}^{\infty}\left(\frac{K^n}{\sqrt{1+\gamma_i^2}} - \frac{K^n}{\sqrt{4+\gamma_i^2}}\right) \tag{5}$$

To minimize the equation (4) several optimization methods can be applied such as Conjugated Gradient, Quasi-Newton methods and the Hooke and Jeeves method [2]. To implement the optimization method was used the SLSQP function (*Sequential Least Squares Programming*) found in the Scypy library, this function was initially developed and implemented by [13] in FORTRAN which is still widely used in high performance numerical computing.

## 2.2 – APPARENT RESISTIVITY

The apparent resistivity is the uniform soil resistivity seen by a grounding system for a specific soil [2]. To obtain the equivalent uniform soil it can be used the methodology of [1] where divergence and penetration coefficients are calculated for a specific geometry.

## 2.3 – EQUATIONING

The mesh design is done repetitively from an initial guess until the specified limits for the project are met. In many situations changes in the spacing $e$ between the conductors are made in order to correct some project failure, the number of mesh conductors will be defined by equation (6) where $x$ represents the current calculation axis.

$$N_x = \frac{x}{e_x} + 1 \tag{6}$$

The cable length is then defined by the equation (7) where $a$ and $b$ are the mesh dimensions.

$$L_{cables} = aN_b + bN_a \tag{7}$$

If ground rods are inserted in the mesh in order to reduce the step voltage at the edges of the same, the equation (8) is used where $L_{rods}$ is the total length of grounding rods adopted.

$$L_{total} = L_{cables} + L_{rods} \tag{8}$$

In [15] is formulated an equation for mesh resistance calculating, this equation is a correction of the Laurent equation[7]. The equation adopted in this paper is the Sverak formula given by

$$R = \rho_a\left(\frac{1}{L_{total}} + \frac{\delta}{\sqrt{20A_{mesh}}}\right) \tag{9}$$

where

$$\delta = 1 + \frac{1}{1 + h\sqrt{\frac{20}{A_{mesh}}}} \tag{10}$$

The maximum mesh voltage $V_{mesh}$ found in the mesh periphery is defined by the equation (11) where $K_m$ is a correction factor defined for a variety of mesh geometries.

$$V_{mesh} = \frac{\rho_a K_m K_i I_{mesh}}{L_{total}} \tag{11}$$

being

$$K_m = \frac{1}{2\pi}\left(\ln\left(T_{km}\right) + \frac{K_{ii}}{K_h}\ln\left(\frac{8}{\pi(2\mathrm{N}-1)}\right)\right) \tag{12}$$

and

$$T_{km} = \frac{e^2}{16hd} + \frac{(\mathrm{e}+2h)^2}{8ed} - \frac{h}{4d} \tag{13}$$

Where $N=\sqrt{N_a^{\,2}}$ for a square mesh, $K_{ii}=1$ if there are ground rods at the periphery of the mesh or $K_{ii}=1\Big/(2N)^{2/N}$ otherwise, $K_h=\sqrt{1+h}$ is the depth correction factor and $K_i$ is the irregularity factor related to the non-uniform effects of the electric current distribution through given by equation (14).

$$K_i=0.656+0.172N \tag{14}$$

The insertion of grounding rods at the edges of the mesh facilitates the electric current flow, for this cause Kindermann in [2] takes into account an additional 15% of the total length of the grounding rods as shown in equation (14).

$$L_{total}=L_{cables}+1.15L_{rods} \tag{15}$$

The step potential $V_{step}$ is defined by the larger potential difference between two points one meter spaced and is given by the equation (16)

$$V_{step}=\frac{\rho_a K_p K_i I_{mesh}}{L_{total}} \tag{16}$$

where

$$K_p=\frac{1}{\pi}\left(\frac{1}{2h}+\frac{1}{e+h}+\frac{1}{e}\left(1-0.5^{N-2}\right)\right) \tag{17}$$

and being $N$ the greater value of $N_a$ and $N_b$.

## 3 – CASES STUDIES

In this paper in order to validate the GROUNDMESH three case studies were made. The first one presents the design of a grounding grid proposed by Kindermann in the reference [2], the second case study presents a comparison of the apparent resistivity for a 15 thousand square meters mesh with the measured field data found in [6] and concluding the case studies a stratification of a particular wind generation park substation soil in the sand dunes executed in the state of Ceará is performed.

### 3.1 – CASE STUDY 1

The first design for the software validation is a grounding grid found in [2] using the same constructive data and soil model. The constructive parameters of the original design that adopts a 20 centimeters layer of crushed stone and 73 ground rods of 3 meters length are shown in table 1.

| VARIABLE | VALUE | VARIABLE | VALUE |
|---|---|---|---|
| $I_{\max}(A)$ | 3000 | $h_1(m)$ | 12 |
| $I_{mesh}(A)$ | 1200 | $h_s(m)$ | 0.6 |
| $\rho_1(\Omega\cdot m)$ | 580 | $A(m^2)$ | 2000 |
| $\rho_2(\Omega\cdot m)$ | 80 | $e_a(m)=e_b(m)$ | 3 |

Table 1 – input data for the grounding design in the case study 1

The comparison of the output values found by the GROUNDMESH design in comparison with the original one is shown in accordance with table 2.

| VARIABLE | KINDERMANN [2] | GROUNDMESH |
|---|---|---|
| $\rho_a(\Omega\cdot m)$ | 411.800 | 444.800 |
| $R(\Omega)$ | 4.291 | 4.640 |
| $V_{step}(V)$ | 513.910 | 496.840 |
| $V_{mesh}(V)$ | 557.020 | 714.730 |

Table 2 – Output data for the case study 1

Because of the touch and step potentials values are directly related to the apparent resistivity, as Kindermann design was developed by analyzing the apparent resistivity curve, which is a graphical method, it is quite subject to errors due to approximations. The method used in this paper is based on the work of [1] which shows the equationing that generates the apparent resistivity curve, this explains the discrepancy between the values obtained by GROUNDMESH and the one found at the original design.

### 3.2 – CASE STUDY 2

In the reference [6] many case studies for resistivity field measurements for grounding grids designs are found. A 138 kV / 13.8 kV substation with rectangular geometry and constructive data as shown in Table 3 was selected to this case study.

| VARIABLE | VALUE | VARIABLE | VALUE |
|---|---|---|---|
| $\rho_1(\Omega\cdot m)$ | 341.00 | $A(m^2)$ | 15000 |
| $\rho_2(\Omega\cdot m)$ | 1130.00 | $e_a(m)$ | 4.50 |
| $h_1(m)$ | 15.85 | $e_b(m)$ | 4.50 |

Table 3 – input data for the grounding design in the case study 2

As the adopted single-phase short circuit level was not reported the for this mesh in reference [6], the same was estimated in an iterative manner assuming that the mesh was designed for the maximum safety limit supported in accordance with [3]. It was assumed the mesh depth of 0.6m and it was used 44 ground rods of 3m length on the mesh periphery, the values found by the software are shown in Table 4.

| VARIABLE | $R(\Omega)$ | $V_{step}(V)$ | $V_{mesh}(V)$ | $I_{mesh}(A)$ |
|---|---|---|---|---|
| VALUE | 1.90 | 415.60 | 704.01 | 2663.00 |

Table 4 – Output data for the case study 2

The value of grounding resistance measurement for this mesh was 2.63 Ω, which is quite consistent with the estimated in this paper.

3.3 – CASE STUDY 3

The case study 4 performs a soil stratification through resistivity measurements of an already bulldozed soil for the installation of a wind generation park substation as shown in Figure 1. The measurements were performed on a red sand landfill over a sand dune obtaining resistivity values according to table 5.

| **SPACING** $(m)$ | 2 | 4 | 8 | 16 |
|---|---|---|---|---|
| **RESISTIVITY** $(\Omega \cdot m)$ | 284.0 | 458.7 | 951.3 | 1576.0 |

Table 5 – Field measurements for case study 3

The stratification was performed using the SLSQP optimization function from the Scypy library for a range of values from 1 to 10 thousand $\Omega \cdot m$ for the layers resistivity and from 1 to 10 m for the first layer thickness. The values obtained were 173.7911 $\Omega \cdot m$ for the first layer resistivity, 5333.0721 $\Omega \cdot m$ for the second layer resistivity and 1.7627 m for the first layer thickness.

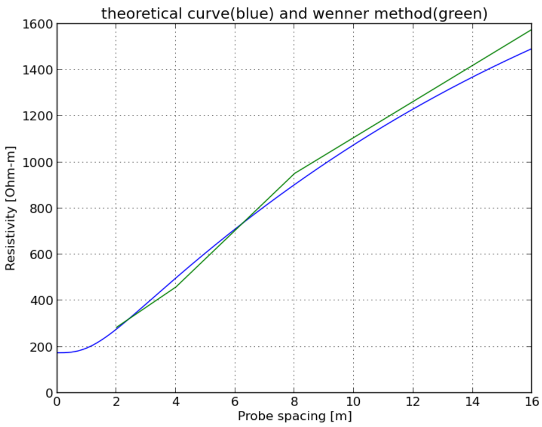


Figure 3 – apparent resistivity curve with the performed stratification values in comparison with the field readings

4 – CONCLUSION

This paper shows an open source computational tool for automatic grounding meshes design through the methodology shown in [2] in order to assist the engineer in projects of electrical grounding systems. The software performs the soil stratification in two layers by optimization techniques and also performs the calculation of the soil apparent resistivity, which greatly increases the accuracy in the required calculations for the project as compared to the traditional methods.

The case studies showed satisfactory values for grounding grids designs when compared with the original ones, especially with regard to the soil stratification, thus validating the developed software.

As a future development the GUI (*Graphical User Interface*) will be completed to make GROUNDMESH more users friendly and intuitive to the designer engineer as well as a future work a design environment based on the Finite Element Method (FEM) can be created using open source Python FEM tools as an alternative to the conventional design.

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