Grounding System Analysis Using CAD Assisted Software

Pande Popovski[1], Nikolche Acevski[2], Mitko Kostov[3]

Abstract – **Regardless of it being a practice that hasn't noticeably changed throughout the years, there is still extensive research in the area of design and analysis of grounding systems. Studies such as finding the optimal design of a ground grid in different geological conditions, optimizing mesh grid using intelligent software and algorithms are still common. This is because of the individuality of each case when it comes to grounding systems. Although there are a number of computer applications available on the market that allow engineers to analyse grounding systems in great detail, taking into account that analyses may be conducted primarily for research purposes, it would be a financially costly decision to get a licensed software for this particular purpose only. This paper presents an application, developed using open-source software that can be used to analyse the main characteristics of a ground grid, such as grounding resistance, ground potential rise, touch and step voltages and current dissipation. The application allows modelling of the ground grid using an open-source CAD application.**

Keywords – **Ground Systems, Grounding Analysis, CAD Modelling, Python, Open-Source Software.**

I. INTRODUCTION

Grounding, by definition, encompasses a set of methods aimed at establishing normal operating conditions of the power system, as well as ensuring a safe working environment, and protecting individuals and animals near structures and installations that may pose a potential hazard under both normal and emergency circumstances [1].

Even though the fundamental principles of grounding have remained relatively unchanged over time, a lot of research has been conducted in modelling and analysing grounding systems (GS). The adoption of various commercially available software solutions for grounding design and analysis has notably advanced this field, enabling engineers to simulate and optimize ground grid (GG) models under diverse conditions. An example would be the versatile ETAP software that allows for analysis of GS aside from power system analysis [2]. Moreover, the rapid progress in Artificial Intelligence has further refined methodologies for designing grounding systems, leveraging techniques such as Genetic Algorithms (GA) and Pattern Search (PS) to achieve optimal ground grid designs. Such is the case in [3], where a two-step optimization method is developed in MATLAB, which works iteratively to produce the GG layout that would give the

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optimal results. The two-step method utilizes GA and PS separately and then compares the two. The results are also compared to ones obtained by the software package WinIGS [4]. In [5], a concise review of different GG optimization techniques is given. In the paper, the Simulated Annealing (SA) method is proposed in the case of increased problem complexity.

Regardless of which method they are based on, the presence of commercial software packages such as WinIGS, EMTP [6], CYMGRD [7], ETAP [8], SafeGrid [9] offer a wide variety of tools for GS design, analysis, optimization and reinforcement. They can be however, quite costly.

This paper presents an application, developed using open-source software that can be used to analyse the main characteristics of a GS for high voltage / medium voltage (HV/MV) as well as medium voltage / low voltage (MV/LV) substations (SS). It analyses characteristics such as grounding resistance (GR), ground potential rise (GPR), touch and step voltages and current dissipation. The application allows modelling of the GS using an open-source CAD application.

The paper is organized as follows. Section II covers the methodology for the calculations on which the application is based upon. Section III covers, in short, the features of the application. Section IV shows examples analysed using the application, one of which is a real-life example of a HV SS. The results from the application are compared with ones obtained from commercial software. The conclusion of the paper is presented in Section V.

II. METHODOLOGY

In this section, the theory upon which the application is built is presented, called the potential method. A much more detailed explanation on the subject can be found in [1], the main source for this section.

If a GS were to be imagined as a group of rectilinear electrodes, its main characteristics could be explained with the help of the electric field manifested as a result of current flow in each of the straight electrodes. For example, if a given GS consists of n elements, according to the principle of superposition, the potential of the k-th electrode would be the sum of the partial potentials created at the k-th electrode, from each electrode in the GS:

$$\varphi_k = r_{k1}I_1 + r_{k2}I_2 + \cdots + r_{kk}I_k + \cdots + r_{kn}I_n = \sum_{j=1}^{n} r_{kj}I_j \qquad (1)$$

where φ_k is the potential of the k-th electrode, r_{kj} is the resistance between the k-th and j-th electrode (electrode's own resistance in the case of $k=j$), and I_j is the current flowing through the j-th electrode.

If the voltage drop through each electrode were to be neglected, then the potential of each electrode would be the same. This potential, would in fact be the GS voltage U_g:

$$U_g = r_{11}I_1 + r_{12}I_2 + \cdots + r_{1n}I_n$$
$$U_g = r_{21}I_1 + r_{22}I_2 + \cdots + r_{2n}I_n$$
$$\vdots$$
$$U_g = r_{n1}I_1 + r_{n2}I_2 + \cdots + r_{nn}I_n$$
(2)

or in matrix form:

$$\mathbf{E} \cdot U_g = \mathbf{r} \cdot \mathbf{I}$$
(3)

where $\mathbf{E}$ is a n x 1 column vector consisting of 1s, $\mathbf{r}$ is a n x n matrix consisting of electrodes' own and mutual resistances, and $\mathbf{I}$ is a n x 1 column vector consisting of the currents flowing through each electrode.

The GS resistance (or GR) R_g and voltage U_g can be calculated using Eqs. (4) and (5) respectively:

$$R_g = \frac{1}{\mathbf{r}^{-1}} = \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{n} \mathbf{y}_{ij}}$$
(4)

$$U_g = R_g \cdot I_g$$
(5)

where $\mathbf{y}$ is the admittance matrix of the GG, and I_g is the total current injected into the GG.

The electric potential at an arbitrary point M in space, caused by the current flow in an electrode in its vicinity, can be calculated in the following way:

$$\varphi_M = \frac{\rho \cdot I}{4\pi l} \cdot \ln \frac{r_1 + r_2 + l}{r_1 + r_2 - l}$$
(6)

where ρ is the specific soil resistivity, I is the current flow in the electrode, l is the length of the electrode, r_1 and r_2 are the distances from each end of the electrode to the point M as shown in Fig.1.
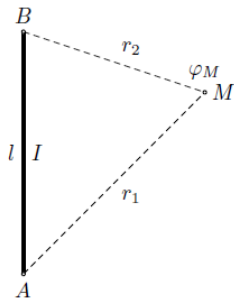

Fig. 1. Electric potential at arbitrary point [1]

An electrode's own resistance α_s can be calculated using Eq. (7):

$$\alpha_s = \frac{\rho}{2\pi l} \cdot \ln \frac{2l}{d}$$
(7)

where d is the equivalent diameter of the electrode.

The mutual resistance between two electrodes i and k in a GG can be calculated using the method of mean potentials [10]:

$$\alpha_{ik} = \frac{\rho}{4\pi \cdot l_i \cdot l_k} \cdot \int_{l_i}\int_{l_k} \frac{dl_i \cdot dl_k}{r}$$
(8)

where l_i and l_k are the lengths of the electrodes i and k respectively.
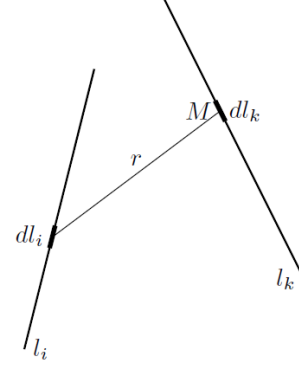

Fig. 2. Mutual resistance calculation [1]

The integrand in Eq. (8) is also known as Neumann's integral.

Considering that in reality, a GS is placed in an environment that is not infinite, but is buried at a certain depth underground, the ground surface can be viewed as a plane which separates the soil and the area above ground as two different homogenous environments. Having this in mind, the physical limits of the environment in which the GS is buried have to be considered. This is done using the method of images, where a replica of the GS is imagined, symmetric to the ground surface, when doing any type of calculation.

III. APPLICATION FEATURES

In this section, a short description of the features of the developed application is given.

The application allows modeling of the geometry of the GG via a CAD software. More specifically, it is used alongside the open-source FreeCAD software. The GS can be modeled in a 3D space, and the application is built to be able to read the file containing the model of the GS, using the dimensions and coordinates of each electrode for the calculations.

The user can input the specific soil resistance, the fault current injected in the GS, as well as the equivalent diameter of the electrodes. All of the calculations are made with the assumption that the soil is homogenous.

A 3D representation of the GS can be drawn using the application, as well as a 3D plot of the GPR, alongside equipotential lines. The user can also set arbitrary points, at which the application then calculates the GPR, thus enabling calculation of touch and step voltages.
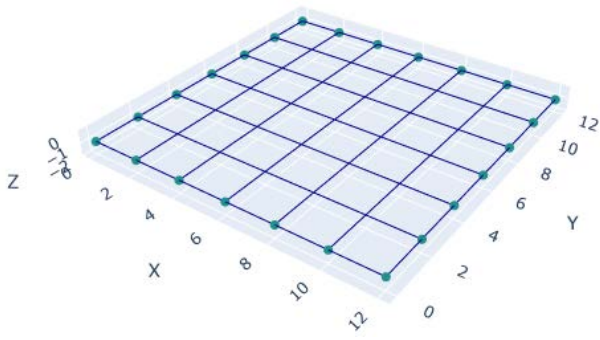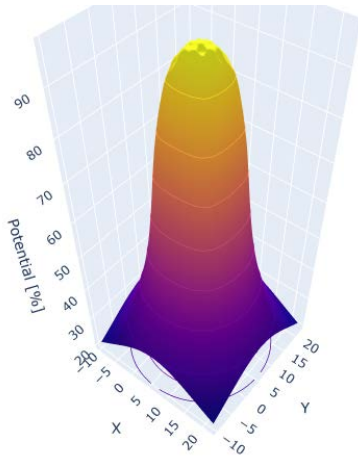
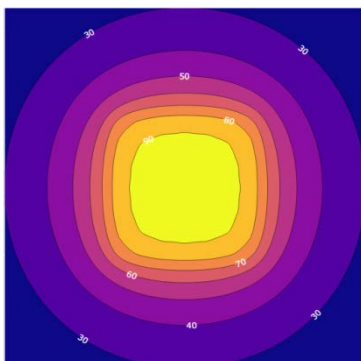Fig. 3. 3D representation of GG

Fig. 4. 3D GPR plot

Fig. 5. GPR Equipotential lines

Figs. 3-5 show the aforementioned graphic results obtained from the application, for an example 12x12m GG.

The GS resistance and voltage are also calculated, along with the entire resistance matrix of the GS and the current drain from each electrode separately. These results, along with the GPR calculations at any arbitrary points are saved to an Excel file upon running a calculation.

The application is developed in the Python programming language, which features a wide plethora of libraries for plotting data, matrix calculations, integral calculations and so on. The Pyside6 package for Python, used in the application, enables the development of a graphical user interface (GUI), and the PyInstaller package makes it possible to compile the application into a standalone executable.

IV. CASE STUDY

Five different GS examples are used in this study in order to test the application. The results from it are compared to ones obtained from empirical equations commonly used in design practice, ones obtained from Aspix - software for simulation of GS of any shape [11], as well as ETAP, software used for power system modeling analysis, which also has a toolset for designing and analyzing GS based on the finite element method.

The five observed examples are typical grounding solutions for MV/LV and HV/MV SS. Examples 1-3 are taken from [1], noting that in none of the GS solutions vertical rods have been taken into consideration, even though Figs. and 8 display vertical rods.

The first example "Type 1" is a GS of a MV/LV house SS with dimensions 10x10m. All of the electrodes in this type of GS are placed at the same depth of 1 meter. The GS design is as shown on Fig. 6.

The second example, called "Type 2", is shown in Fig. 7. Here, the electrode contours around the SS are at different depths: 0,5m, 0,7m and 1m respectively. The grounding of the house foundation is also considered. The dimensions of the house are 4,8x5,8m.
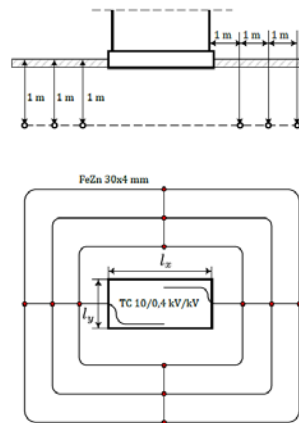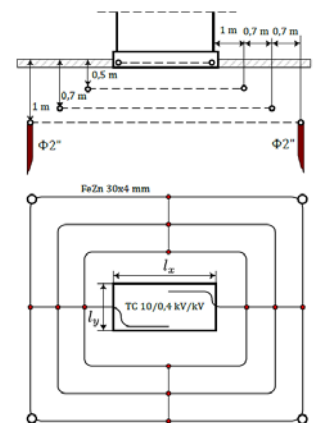

Fig. 6. Type 1 GS [1]   Fig. 7. Type 2 GS [1]

The third example "Type 3" shown in Fig. 8 is used in pole mounted SS. As with the second example, the electrode contours are placed at different depths. The grounding of the foundation is also considered. The pole foundation has dimensions 1,8x1,8m.

The fourth example is a GG with dimensions 12x12m. The spacing between each electrode both along the x and y axis is 2m. The GG is buried at a depth of 1m. A visual representation of the GG is shown in Fig. 3, mentioned in the previous section.

The fifth example is a real life example, a GG design of a HV/MV SS. A representation is shown in Fig. 8. The entire GG is placed at a depth of 1 meter [12].

Regarding the analysis results of the five examples, the calculated GR is used for comparison. The analysis for each GS is done for a specific soil resistance of 100Ωm. Results for GR obtained from empirical equations for examples 1-3 are taken from [1]. For examples 4 and 5, the Thapar & Gerez

formula from [13] is used for calculating the GR. The results are shown in Table I.
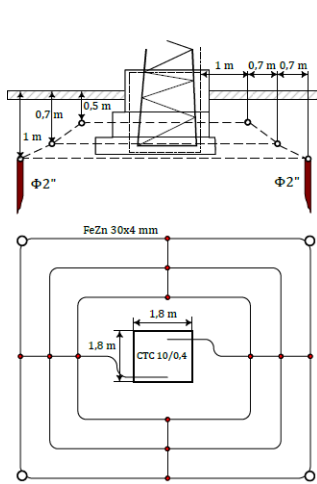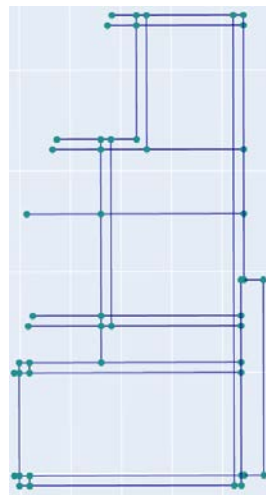

Fig. 8. Type 3 GS [1]

Fig. 9. Example 5 GG [12]

TABLE I
GROUNDING RESISTANCE RESULTS

Example	Grounding Resistance [Ω]			
	Empyrical	Aspix	ETAP	Application
1	2,690	2,696	2,713	2,694
2	3,990	4,034	4,055	4,092
3	5,770	5,817	5,858	5,893
4	3,575	3,390	3,450	3,401
5	1,556	1,474	1,484	1,481

From Table I it can be noted that the developed application deviates very little from the results obtained from commercial software, as well as results from empirical equations. The percent by which the results of the application deviate from the empirical results, Aspix and ETAP are shown in Table II.

TABLE II
RELATIVE ERROR COMPARED TO OTHER APPROACHES

Example	Relative Error [%]		
	Empyrical	Aspix	ETAP
1	0,15	0,07	0,70
2	2,56	1,44	0,91
3	2,13	1,31	0,60
4	4,87	0,32	1,42
5	4,82	0,48	0,20

Observing the data from Table II, it can be seen that the application deviates no more than maximum 1,44% from the results obtained with commercial software. On average, the relative error compared to commercial software is 0,75%.

The relative errors compared to empirical calculations are higher than the errors compared to commercial software. Taking into consideration that ETAP conducts analysis based on the finite element method, it can be assumed that those results are close to the real GR value, and with that can be used as a reference point for accuracy.

It is worth noting that a comparison was done for the maximum touch voltages for each example as well. Close results were obtained for the touch voltages too; however ETAP does not allow computation of GPR at arbitrary points which is a problem for examples 1, 2 and 3. Presumably ETAP searches for the maximum touch voltage one meter around the edges of the GG, which is not the case for examples 1, 2 and 3, where the maximum touch voltage appears 1 meter diagonally from the SS housing.

V. CONCLUSION

An application developed using open-source software was presented in this paper, with the goal of demonstrating its practical use in the case of GS analysis.

The theory upon which the application was built was briefly explained, along with its features such as modeling the GS with the use of a free CAD alternative named FreeCAD, visual representation of the GG, a 3D representation of the GPR, and GPR equipotential lines.

Five different examples of GS were analyzed using the application, and the results were compared to ones obtained from empirical equations as well as commercial software. The results shown in the paper confirm that the application produces results very close to the ones from commercial software an empirical formulas, thus confirming its practicality.

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