Numerical simulation of multilayer grounding grids in a user-friendly open-source CAD interface

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***Abstract*—In this paper we present TOTBEM: a freeware application for the in-house computer aided design and analysis of grounding grids. The actual version of the software is available for testing purposes (and also use) at no cost and can be run on any basic personal computer (as of 2011) with no special requirements. The distribution kit consists in a single ISO bootable image file that can be freely downloaded from the Internet and copied into a DVD or a USB flash memory drive. The application runs on the Ubuntu 10.04 (Lucid Lynx) LTS release of Linux and can be easily started by just booting the system from the live DVD/USB that contains the downloaded file. This operation does not modify the native operative system nor installs any software in the computer, but the application is still fully operational while the live DVD/USB is taking control. The pre- and post-processing engines of the application have been built on top of the open source SALOME platform toolkit. On the other hand, the analysis part of the code is based on the Boundary Element Method (BEM). The implemented BEM formulation (that has been presented by the authors in previous publications) is suitable for computing the equivalent resistance and the step and touch voltage in most large electrical overground substations with a grounding grid embedded in a single- or multi-layer stratified soil.**

***Keywords*-Grounding; Computer Aided Design; Numerical analysis; SALOME; BEM;**

I. INTRODUCTION

The computation of the distribution of potential levels of earthing systems is one of the most important challenges in electrical engineering since the beginning of the generalized use of electricity in modern societies. These systems are devoted to the dissipation into the soil of the electrical currents generated when a fault condition occurs. An adequate dissipation of these electric currents allows to guarantee the safety of persons, to avoid malfunction or damages to equipment and to guarantee the power supply. Most relevant parameters of grounding grids design are the equivalent resistance of the entire dissipation system, which is mainly related to the protection of the equipment and the continuity of the power supply, and the distribution of electric potential on the ground surface, which it is directly related to the safety of persons and animals. The goal is to minimize the equivalent resistance in order to adequately dissipate the electrical currents while the potential distribution on the earth surface satisfies the safety conditions established in actual norms [1], [2].

The electric dissipation problem is usually treated by using grounding grids which can be analyzed from a mathematical point of view by considering the Maxwell's Electromagnetic Theory. The equations that govern the physics of this problem are perfectly known since a long time ago. However, the analysis of these systems present some important difficulties due to the particular characteristics of the domain geometry (3D and semi-infinite) and the geometry of the dissipation elements: a grid of very thin and large conductors. In practice, the length of the conductors is usually about three order of magnitude larger than the diameter (meters versus millimeters).

These specific properties mean that common and widely used numerical methods like FEM or FDM become not affordable in practice to accurately solve the dissipation problem. The discretization of the semi-infinite domain both together with the level of refinement required to consider the small diameter of the conductors becomes a challenging problem nowadays that will require very large computing resources.

First methods for grounding analysis were based on the professional practice, on empirical studies and on experimental data. These methods drove to great progress in this field, although they presented important drawbacks in real projects. Some of these limitations have been more recently studied and explained in detail. Thus, unfeasible solutions when the discretization of conductors is refined have been rigorously analyzed in [3] by using a numerical model based on the BEM proposed by the authors in the 90's [4].

The numerical formulation proposed in [3], [4] is the main reference for all the subsequent developments that allow to define high-accurate and efficient numerical methods for grounding analysis in uniform and layered soil models [4]–[6]. In addition, other specific problems like transferred potentials phenomena were also analyzed by using this numerical formulation in both uniform [7] and two-layer soils [8].

In this paper the authors present TOTBEM: a numerical simulation tool for grounding analysis based on the BEM numerical formulation developed by the authors [3]–[6] and on the open-source graphical interface Salome [9].

The software package integrates the numerical formulation developed by the authors in the user-friendly interface of SALOME. TOTBEM has been specifically designed to perform the preprocess (geometry, mesh, soil layers, soil properties, etc.), the current dissipation analysis (by BEM) and the postprocessing (earth surface potential distributions, equivalent resistance, etc.) with adequate tools to facilitate the analysis of real grounding grid installations under real conditions.

The outline of the paper is divided into four main sections. After this introductory section, the fundamentals of the mathematical and numerical model for grounding analysis are analyzed. Then, the authors present and describe the TOTBEM software. Finally, main conclusions are summarized.

II. Mathematical foundations for the analysis of the current dissipation problem

The equations that govern the dissipation phenomena of electric current through a grounded conductor are given by

$$\begin{array}{l} \mathrm{div}(\boldsymbol{\sigma}) = 0, \quad \boldsymbol{\sigma} = -\boldsymbol{\gamma}\,\mathbf{grad}(V) \text{ in } E; \\ \boldsymbol{\sigma}^t \boldsymbol{n}_E = 0 \text{ in } \Gamma_E;\ V = V_\Gamma \text{ in } \Gamma;\ V \to 0,\ \text{if } |\boldsymbol{x}| \to \infty \end{array} \tag{1}$$

where E denotes the earth, γ its conductivity, Γ_E its surface, $\boldsymbol{n}_E$ its normal exterior unit field and Γ the surface of the electrodes of the grounding grid [4].

The goal of the formulation proposed in (1) is to obtain the steady-state solution. The potential on the conductors surface is assumed as constant (neglecting the effect of the internal resistivity of the electrodes). This formulation allows to obtain the current density $\boldsymbol{\sigma}$ and the potential V at any point $\boldsymbol{x}$ when the electrodes are connected to a Ground Potential Rise V_Γ (GPR) relative to the remote earth potential. In practice, the most interesting variables that define safety parameters are the current density ($\boldsymbol{\sigma}$) on Γ and the potential (V) on Γ_E [4], [6].

Soil properties are usually stated, in practice, by using simplified soil models. The simplest model corresponds to an isotropic and homogeneous approach, i.e. a "uniform soil model" defined by an scalar conductivity tensor γ that replaces the conductivity tensor proposed in (1) [1], [4]. More sophisticated models usually correspond to stratified soils with uniform properties of conductivity for each layer. Thus, each layer is stated by defining its scalar conductivity tensor and its thickness [1]. In practice, two or three-layer models are considered as adequate to obtain accurate results in real cases.

The formulation proposed in (1) can be rewritten for soils stratified in C layers with different scalar conductivities as:

$$\begin{array}{l} \mathrm{div}(\boldsymbol{\sigma}_c) = 0,\ \boldsymbol{\sigma}_c = -\gamma_c\,\mathbf{grad}(V_c) \text{ in } E_c,\ 1 \le c \le C; \\ \boldsymbol{\sigma}_1^t \boldsymbol{n}_E = 0 \text{ in } \Gamma_E,\ V_b = V_\Gamma \text{ in } \Gamma; \\ V_c \to 0 \text{ if } |\boldsymbol{x}| \to \infty,\ 1 \le c \le C; \\ \boldsymbol{\sigma}_c^t \boldsymbol{n}_c = \boldsymbol{\sigma}_{c+1}^t \boldsymbol{n}_c \text{ in } \Gamma_c,\ 1 \le c \le C-1; \end{array} \tag{2}$$

where b is the layer that contains the conductors, E_c is the domain of layer c, γ_c is its conductivity, V_c is the potential at a point in E_c, $\boldsymbol{\sigma}_c$ is its current density, Γ_c is the interface between E_c and E_{c+1}, and $\boldsymbol{n}_c$ is the normal unit field to Γ_c [6].

Potential $V_c(\boldsymbol{x}_c)$ at an arbitrary point $\boldsymbol{x}_c \in E_c$ can be expressed, by application of Green's Identity and the "Method of Images", in an integral form [6] in terms of the leakage current density $\sigma(\boldsymbol{\xi})$ at any point $\boldsymbol{\xi}$ on the surface of the conductors $\Gamma \subset E_b$ as:

$$V_c(\boldsymbol{x}_c) = \frac{1}{4\pi\gamma_b} \int\int_{\boldsymbol{\xi}\in\Gamma} k_{bc}(\boldsymbol{x}_c, \boldsymbol{\xi})\,\sigma(\boldsymbol{\xi})d\Gamma,\ \forall \boldsymbol{x}_c \in E_c, \tag{3}$$

where the leakage current density σ is computed as $\boldsymbol{\sigma}^t\boldsymbol{n}$, being $\boldsymbol{n}$ the normal exterior unit field to Γ. In practical applications $c = 1$ since the parameters that characterize an earthing system (*e.g.* mesh, touch, and contact voltages) need to be computed on the earth surface. Thus,

$$V_1(\boldsymbol{x}_1) = \frac{1}{4\pi\gamma_b} \int\int_{\boldsymbol{\xi}\in\Gamma} k_{b1}(\boldsymbol{x}_1, \boldsymbol{\xi})\,\sigma(\boldsymbol{\xi})d\Gamma,\ \forall \boldsymbol{x}_1 \in \Gamma_E. \tag{4}$$

Kernel $k_{b1}(\boldsymbol{x}_1, \boldsymbol{\xi})$ is a series which terms correspond to the images introduced in the transformation of problem (2) to the integral form (3) [4], [6]. The number of terms of the series is finite in homogeneous and isotropic soil models ($C = 1$), but infinite in, for example, two-layer soil models ($C = 2$) [8].

The resulting integral kernels are weakly singular and they depend on the distances from $\boldsymbol{x}_1$ to $\boldsymbol{\xi}$ and on the distances from $\boldsymbol{x}_1$ to all its images with respect to Γ_E and with respect to Γ_c [1], [10]. The kernels also depend on the thickness and the conductivity of the layers according to a ratio. In two-layer soil models, for instance, the ratio κ is defined as $\kappa = (\gamma_1 - \gamma_2)/(\gamma_1 + \gamma_2)$ and the kernels can be expressed as

$$k_{b1}(\boldsymbol{x}_1, \boldsymbol{\xi}) = \sum_{n=0}^{\infty} k_{b1}^{[n]}(\boldsymbol{x}_1, \boldsymbol{\xi}), \quad k_{b1}^{[n]}(\boldsymbol{x}_1, \boldsymbol{\xi}) = \frac{\psi_n(\kappa)}{r(\boldsymbol{x}_1, \boldsymbol{\xi}_n)}, \tag{5}$$

where $r(\boldsymbol{x}_1, \boldsymbol{\xi}_n)$ represents the distance from $\boldsymbol{x}_1$ to images $\boldsymbol{\xi}_n$. The weighting coefficient $\psi_n(\kappa)$ only depends on the ratio κ and the thickness of the layer [6].

The substitution of the general form for the inner kernel (5) in (4) drives to the computation of the potential at an arbitrary point $\boldsymbol{x}_1 \in \Gamma_E$ as a sum of the contribution of the images as:

$$V_1(\boldsymbol{x}_1) = \sum_{n=0}^{\infty} V_1^{[n]}(\boldsymbol{x}_1), \tag{6}$$

where the contribution $V_1^{[n]}(\boldsymbol{x}_1)$ of image n is:

$$V_1^{[n]}(\boldsymbol{x}_1) = \frac{1}{4\pi\gamma_b} \int\int_{\boldsymbol{\xi}\in\Gamma} k_{b1}^{[n]}(\boldsymbol{x}_1, \boldsymbol{\xi})\,\sigma(\boldsymbol{\xi})d\Gamma. \tag{7}$$

The potential contribution of each image given by (7) can be obtained by multiple numerical methods proposed in the bibliography [1], [2]. The authors have developed a numerical formulation based on a BEM analysis for the computation of real earthing designs in multi-layer soil models and other related problems of great interest in industry [3]–[8], [11].

On the other hand, the rate of convergence of the series that appear when the method of images is used in stratified soil models (e.g., two-layer soil model) can be very low depending on the ratio between the layer conductivities (κ). In practical applications, the conductivities of the layers are quite different (e.g. concrete or gravel versus soil). Thus, $|\kappa| \approx 1$ and the series involved present very low convergence rates. Consequently, the computation of the potential distribution on the ground surface by using the method of images is the most CPU time consuming process since the potential in a very large number of points needs to be computed with very low rate convergence series. In real installations, thousands of potentials on the earth surface need to be computed. Thus, it is necessary to obtain accurate and low-cost techniques to compute potentials on the ground surface when $|\kappa| \approx 1$. The authors have also developed a method based on the Aitken δ^2-extrapolation process to increase the rate of convergence of the series involved [12] which has been also implemented in TOTBEM. This algorithm allows to obtain potential distributions on the earth surface for actual grounding installations in real time with a modern conventional computer.

III. Highlights of the TOTBEM software package

In the previous section, the fundamentals of the numerical model developed for grounding analysis based on BEM have been introduced. In this section the authors present its implementation in a user-friendly graphical interface: TOTBEM.

TOTBEM is an integrated software package which essentially contains a set of modules that facilitate the preprocessing, the grounding grid analysis and the postprocessing of real grounding installations. TOTBEM has been developed on the SALOME platform [9]. SALOME is an open-source software for numerical simulation which incorporates a graphic interface for preprocessing and includes postprocessing tools based on visualization libraries (VTK). In addition, it allows to include external applications (analysis tools, add-ons) and problem specific functions for the pre and postprocessing stages.

A version of the TOTBEM system can be downloaded from the webpage http://caminos.udc.es/gmni/ (Research Activity).

A. Data input and preprocessing functions

The TOTBEM software has been developed and adapted to facilitate the input of data using a graphic interface (Fig. 1). The geometry of the grounded electrodes can be manually introduced in graphical windows or by using the "Orthogonal mesh" option, which automatically generates a rectangular structured mesh of electrodes at a given depth. Different options to add or erase electrodes, or to modify their geometric characteristics have been specifically included (Fig. 2). Obviously the user can also define all visualization variables (point of view, perspective, zoom, colors, etc.), in a user-friendly interface (Fig. 1 and 2).

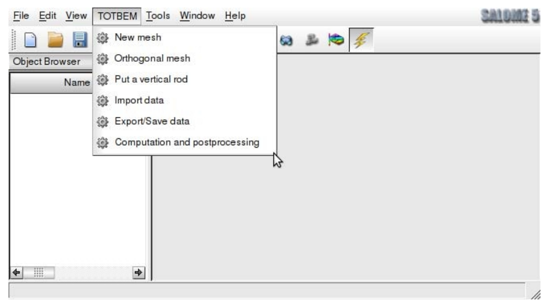

Figure 1. TOTBEM: Toolbox for preprocessing and input data.

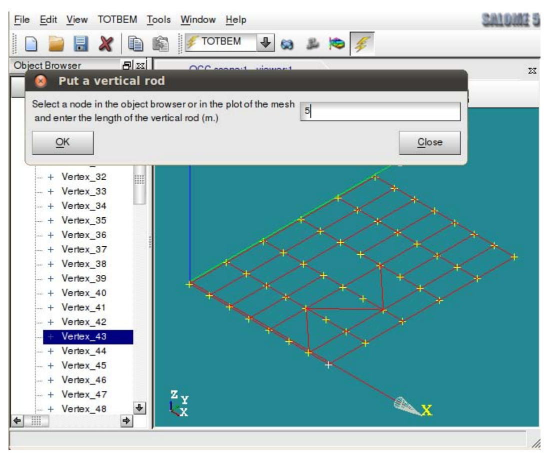

Figure 2. TOTBEM: Example of the input data for vertical rods.

In addition, all the input data can be also loaded from two external files containing the geometry of the grounding grid and the properties of the soil and electrodes (among other parameters). This function is essential if the mesh has been previously planned and design with other CAD applications or in the case of recovering previous projects already analyzed with TOTBEM.

B. Computing module

The computing module is the kernel of TOTBEM. It has been originally programmed in FORTRAN and included in the SALOME platform as an external application. This module is an efficient implementation of the numerical approach based on the BEM developed for the grounding analysis in layered soil models developed by the authors [3]–[8], [12]. In addition, it also includes the convergence acceleration techniques proposed in [12]. The grounding analysis module also creates the required files to facilitate the postprocessing and the visualization of results. The evolution of the analysis process can be observed in an execution console, where the main parameters of the grounding analysis are shown (Fig. 3).

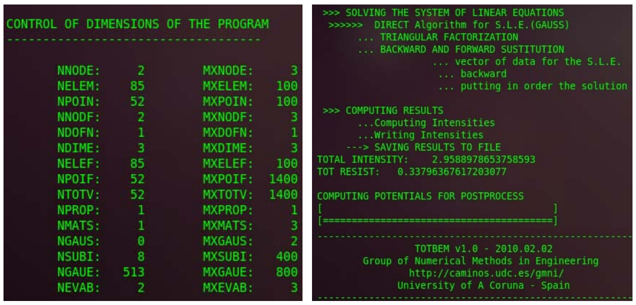

Figure 3. TOTBEM: Execution console window during a grounding analysis.

C. *Postprocessing and results visualization module*

Once the computing stage has finished, the postprocess module uploads the results files and creates postprocess files in standard VTK and MED formats. Both formats are widespread and open-source, so the visualization of results can also be exported to other postprocessing platforms like Paraview [13], among others. TOTBEM also includes specific options for the visualization of output data for grounding analysis: 3-d views of the potential distribution on the earth surface, isopotential lines, equivalent resistance of the grounding system, total intensity derived through the grounding grid, etc. Fig. 4, 5 and 6 show some of the tools available in SALOME for results postprocessing.

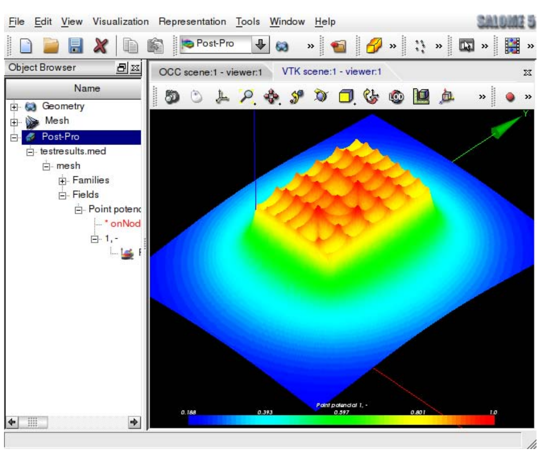

Figure 4. TOTBEM: 3D view of computed potentials on the ground surface.

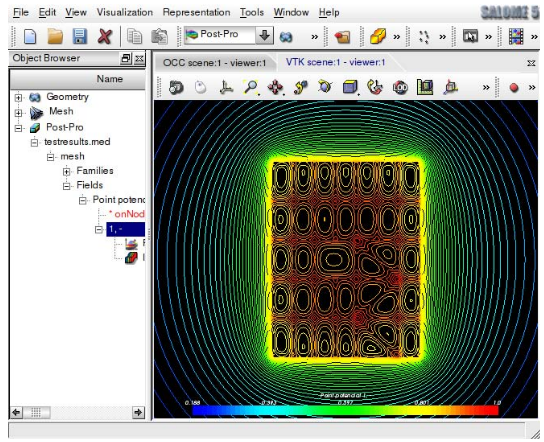

Figure 5. TOTBEM: Visualization of isopotential lines on the ground surface.

IV. Conclusions

In this paper, the authors have revised the foundations of the mathematical model for the analysis of electrical current dissipation through earthing electrodes to the ground. More specifically, the main highlights of the numerical formulation for grounding analysis in uniform and two-layer soil models have been also pointed out.

Furthermore, the authors present TOTBEM: a user-friendly simulation tool for grounding analysis based on the open-source software SALOME and on the BEM numerical formulation developed by the authors. TOTBEM is a CAD system that allows to analyze grounding systems in a friendly interface that facilitates the preprocessing, analysis and postprocessing. The kernel of the system is a powerful and efficient grounding analysis module which implements a complete and well-founded BEM numerical approach developed by the authors.

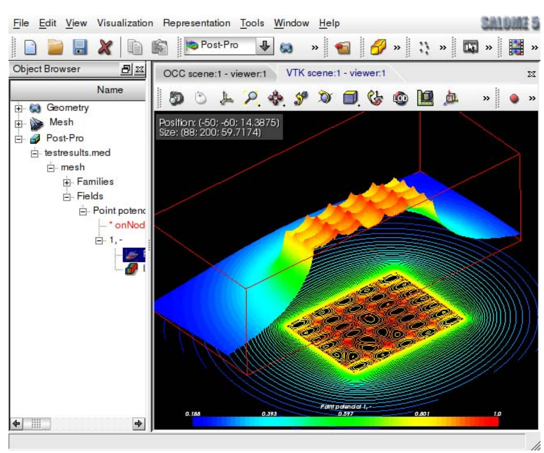

Figure 6. TOTBEM: 3D view of potential and isopotential lines.

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