Electrical Power and Energy Systems 45 (2013) 353–361

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

A numerical simulation tool for multilayer grounding analysis integrated in an open-source CAD interface

I. Colominas *, J. París, D. Fernández, F. Navarrina, M. Casteleiro

Group of Numerical Methods in Engineering, Department of Applied Mathematics, Civil Engineering School, University of La Coruña, Campus de Elviña, 15071 La Coruña, Spain

ARTICLE INFO

Article history:
Received 26 April 2011
Received in revised form 18 August 2012
Accepted 29 August 2012
Available online 29 October 2012

Keywords:
Grounding
Numerical analysis
Convergence of numerical methods
Computer aided analysis
Computer graphics software
Open-source platform

ABSTRACT

In this paper we present TOTBEM: a simulation tool for grounding systems based on the open-source platform SALOME. The package TOTBEM includes all the preprocessing, computing and postprocessing stages necessary to perform a complete earthing analysis. The kernel of TOTBEM is a numerical formulation based on the Boundary Element Method for uniform and stratified soil models proposed by the authors in the last years. Furthermore, in this work we show the main highlights of an efficient technique based on the Aitken δ^2-process in order to improve the rate of convergence of the involved series expansions in multilayer soil models.

1. Introduction

Obtaining the distribution of potential levels of an earthing system has been one of the challenges of the electrical engineers and designers since the beginning of the large-scale harnessing of electricity. Thus, the grounded electrode dissipates the electrical currents generated during a fault condition in order to guarantee the safety of persons, to maintain the integrity and proper functioning of equipment and to assure the continuity of the electrical supply. Main parameters commonly used to characterize a grounding grid are the equivalent resistance of the system and the potential distribution on the earth surface. As general rules, the resistance should be low enough in order to produce the dissipation of the electrical current into the ground through the earthing electrode, while certain values of potential differences on the earth surface should be under some well-established safety limits [1,2].

Maxwell's Electromagnetic Theory is the general framework for the statement of the mathematical model for the phenomenon of the electrical current dissipation into the ground. Notwithstanding the equations that govern this problem are known for a long time, the analysis of large earthing systems in practice presents some important complications: on the one hand, due to its specific tridimensional geometry (a grid of bare conductors with a large "length/diameter" ratio), and on the other hand for the uncertainty in the electrical properties of the ground. These facts mean that the use of common and widespread numerical methods in engineering (FEM or FDM) is very costly (in computing time and memory storage) since it is required the discretization of the domain, i.e., the whole ground excluding the part occupied by the electrodes.

Over recent decades a large number of methods to calculate and design these grounding systems has been proposed, generally based on the professional practice, on empirical work and on experimental data. Some of these techniques have resulted in computer methods for grounding analysis which have led to significant progress in this area [1,2].

However, some problems with the application of these methods in the analysis of real cases have been documented, for example, unrealistic results when the discretization level of the electrodes is risen, uncertainties in the margin of error, or high computational costs [3]. These topics were fully analyzed in the reference [4] where the authors explained from a rigorous point of view the anomalous asymptotic behavior of the classical grounding methods (identifying also the sources of error), taking as a starting point the numerical formulation for grounding analysis based on the Boundary Element Method proposed by the authors in the nineties [5].

This numerical approach is the framework from it is possible to develop high-accurate computer methods for grounding analysis in uniform and layered soil models [5–7]. Furthermore, in 2005, we propose a methodology also based in this BEM numerical formulation for the analysis of transferred earth potentials in earthing

* Corresponding author.
E-mail address: icolominas@udc.es (I. Colominas).
URLs: http://www.caminos.udc.es/gmni/ (J. París), http://www.caminos.udc.es/gmni/ (D. Fernández), http://www.caminos.udc.es/gmni/ (F. Navarrina), http://www.caminos.udc.es/gmni/ (M. Casteleiro).

0142-0615/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijepes.2012.08.079

systems (the appearance of dangerous potential levels in metallic elements, structures or other conductors as a result of the energization of the grounding electrode during a fault condition [8]). The methodology was published in the reference [9] for uniform soil models, and in the reference [10] its extension to layered soil models.

In this paper we present TOTBEM: a power system numerical simulation tool for grounding analysis. TOTBEM is based on the open-source software SALOME [11], and it allows to perform the preprocess of the model (geometry data of the grounding mesh, soil properties, etc.), the earthing grid analysis by using the Boundary Element approach developed by the authors, and the postprocess and visualization of results. The outline of the paper is as follows: after the introductory section, it is presented a summary of the fundamentals of the mathematical and numerical model for grounding analysis based on the BEM; Section 3 is devoted to present a technique to accelerate the convergence of the calculations recently developed by the authors [12] which has been implemented in TOTBEM; and next, we present and describe the TOTBEM platform and its functionality. Finally, main conclusions are stated.

2. Foundations of the mathematical model for the current dissipation problem through a grounding electrode

Equations that govern the dissipation of the electrical current into a media through a grounded electrode are given by

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

As it can be seen, this model restricts the analysis to obtain the steady-state response; furthermore the potential is assumed constant on the conductors surface (so the internal resistivity of the electrodes is neglected). In (1), E denotes the earth, $\boldsymbol{\gamma}$ 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 [5]. Solving this problem provides the current density $\boldsymbol{\sigma}$ and the potential V at any point $\boldsymbol{x}$ when the grounded electrode is energized to a Ground Potential Rise (or GPR) V_Γ with respect to remote earth. On the other hand, most safety parameters that characterize an earthing system should be obtained straight from V computed on Γ_E and $\boldsymbol{\sigma}$ on Γ [5,7].

An important point on the definition of the mathematical model for grounding analysis is the selection of the more appropriate soil model: Obviously, it is not possible to take into account all variations of the soil conductivity since it is not feasible or from an engineering point of view neither economic nor practical. The simplest model that has been proposed is the isotropic and homogeneous one, i.e., a "uniform soil model" (so an scalar conductivity γ is introduced instead of conductivity tensor $\boldsymbol{\gamma}$ [1,5]); the "layered models" represent the soil in a number of strata, each one defined by means of a scalar conductivity and thickness [1] (in practical grounding analysis, it should be enough to consider models with *two* or *three* strata to achieve accurate results).

The set of Eq. (1) can be rewritten in terms of the next exterior problem if the soil is modeled by C layers with different scalar conductivities:

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

where b is the layer that contains the buried conductor, E_c is each stratum, γ_c is its conductivity, V_c is the potential at a point in layer 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 [7]. In the following section of this paper we will present the improvement in the convergence for the case of two layered soil models ($C = 2$), although it is direct the extension of the analysis to other stratified models.

On the other hand, by application of Green's Identity and the "Method of Images" potential $V_c(\boldsymbol{x}_c)$ at an arbitrary point $\boldsymbol{x}_c \in E_c$ can be expressed in an integral form [7] in terms of the leakage current density $\sigma(\xi)$ at any point ξ on the surface of the conductors $\Gamma \subset E_b$ ($\sigma = \boldsymbol{\sigma}^t\boldsymbol{n}$, being $\boldsymbol{n}$ the normal exterior unit field to Γ):

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

Furthermore, since most parameters that characterize an earthing system (mesh, touch, and contact voltages, for example) are obtained from the potential distribution computed on the earth surface Γ_E, from now on we will consider $c = 1$ in the grounding analysis:

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

Generally, kernel $k_{b1}(\boldsymbol{x}_1,\xi)$ is a series which terms correspond to the images introduced in the transformation of problem (2) to the integral form (3) [5,7,13]. The number of terms of these series can be finite, for example in the case of homogeneous and isotropic soil models ($C = 1$), or infinite, for example in two-layer soil models ($C = 2$). In the appendix section of the reference [10] can be found the explicit formulae of these integral kernels.

It is well known the integral kernels are weakly singular and they depend on the distances from $\boldsymbol{x}_1$ to ξ and depend on the distances from $\boldsymbol{x}_1$ to all its images with respect to Γ_E and with respect to Γ_c [1,14]. The kernels are also function of the thickness of the layer and the layer conductivities according to a ratio. In a two-layer soil model, this ratio κ is:

$$\kappa = \frac{\gamma_1 - \gamma_2}{\gamma_1 + \gamma_2} \tag{5}$$

so the kernels should be expressed in the general form

$$k_{b1}(\boldsymbol{x}_1, \xi) = \sum_{n=0}^{\infty} k_{b1}^{[n]}(\boldsymbol{x}_1, \xi), \quad k_{b1}^{[n]}(\boldsymbol{x}_1, \xi) = \frac{\psi_n(\kappa)}{r(\boldsymbol{x}_1, \xi_n)}, \tag{6}$$

$r(\boldsymbol{x}_1,\xi_n)$ represents the distance from $\boldsymbol{x}_1$ to images ξ_n while the weighting coefficient $\psi_n(\kappa)$ is a function that only depends on the ratio κ and the thickness of the layer [7].

The substitution of the general form for the inner kernel (6) in (4) allows to express the computation of the potential at an arbitrary point $\boldsymbol{x}_1 \in \Gamma_E$ in terms of the contribution of each image as follows:

$$V_1(\boldsymbol{x}_1) = \sum_{n=0}^{\infty} V_1^{[n]}(\boldsymbol{x}_1) \tag{7}$$

and $V_1^{[n]}(\boldsymbol{x}_1)$ is the contribution in the potential computing due to the image n:

$$V_1^{[n]}(\boldsymbol{x}_1) = \frac{1}{4\pi\gamma_b} \int\!\!\int_{\xi\in\Gamma} k_{b1}^{[n]}(\boldsymbol{x}_1, \xi)\sigma(\xi)\,d\Gamma. \tag{8}$$

In the bibliography can be found some different computer methods for obtaining the potential contribution of each image given by (8) [1,2]. Specifically, the authors proposed a methodology based on the Boundary Element Method for the computational design of real earthing systems in layered soil models, which can be analyzed other related problems of industrial interest like the transferred earth potentials [4–7,9,10].

The rate of convergence of the different series that appear when the method of images is applied in the case of stratified soil models