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Modelling and simulation of the grounding system of a class of power transmission line towers involving inhomogeneous conductive media

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ABSTRACT

The grounding system of a class of power transmission line towers involving inhomogeneous conductive media is modelled in order to simulate its behaviour in case that a current earth fault takes place. The simulation includes structural elements of the tower and provides an estimate of the grounding resistance of the tower, assuming that a standard grounding electrode is buried as the main part of the grounding installation. The effect of structural elements on grounding resistance is discussed and a quantitative estimate of this effect is evaluated.

1. Introduction

Certain types of towers for power transmission lines are installed in the ground with a foundation that is introduced into the soil to a significant depth, containing a part of the metallic tower structure, all forming a compact cubic block of concrete in contact with the conductive surrounding soil. Standard grounding electrodes are used as the main part of the grounding system, adapting their type and form to the operating range of the power line [1]. Finally, to avoid high potential gradients that would occur near the tower in case of current fault, an “equipotential platform” is usually added around the tower, which consists of a platform made of concrete, inside which a metallic grid is placed. This grid is usually connected to the metallic structure of the tower itself, the latter being electrically connected to the grounding electrode buried into the soil. The result is a flattening of the contact potential profile on the platform in case of fault. However, the grounding system of the tower has become complex because it consists of a set of three interconnected conductors, which are immersed in conductive media of different nature and properties, namely, on the one hand, the metallic grid of the platform and the metallic structure of the tower, that are forming a regular concrete block sunk into the ground, and on the other hand, the grounding electrode buried into the soil. The objective is to simulate in a suitable manner a system consisting of three electrodes, two of which are immersed in a finite volume of material which has low electrical conductivity such as concrete, which in turn is surrounded by a semi-infinite volume of material with higher conductivity, where the third electrode is placed, that is, the soil. The three electrodes are interconnected so as to have the same electric potential. Thus, the effect of the platform and the tower foundations on the grounding resistance of the tower can be appropriately studied.

The analysis of grounding systems buried in soils composed of finite volumes of different conductivities such as the system of electrodes placed in different electric media appearing in this paper, falls into the problems studied by electromagnetism in inhomogeneous media [2,3]. When the semi-infinite medium is composed of horizontal or vertical layers of infinite extension, the image theory and similar approaches can be applied to find an approximate solution [4–6]. In this case, it is not possible to do so, because the interface between the two existing electrical media, though fairly regular, is not layered, but instead is composed of finite volumes of different conductivities.

In this paper, we will address the problem through the so-called equivalent surface charge distributions (ESCD) [7,8], which proposes to replace the influence of the interface between the different electrical media for surface current distributions to the surrounding medium, so that the boundary condition is satisfied at the interface, namely, the conservation of the normal component to the interface surface of the current density $J_{1n} = J_{2n}$, $\vec{n}$ being the unitary

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normal vector to the interface when crossing from medium 1 to medium 2.

Although the ESCD was originally applied to calculate capacitances [9–11], the method, with some modifications, will be used in this paper to calculate the current delivered by each electrode and the common potential to all of them, being able to eventually estimate the grounding resistance of the tower composed by the three electrodes previously described. The dependency on the tower grounding resistance with the ratio between the conductivities of the two involved media will be also investigated. As an application, the resistivity changes associated spatial and temporal variability [12] of soil and structural elements on the grounding resistance can be evaluated through the aforementioned ratio.

With this general approach, the paper is organized as follows: After the introduction to the problem in this section, the theoretical foundation and calculation scheme that has been used is developed in Section 2. In Section 3, the complete modelling of the tower grounding system and the numerical procedure used to find an approximate solution to the problem is presented. Results and recommendations for a better design adapted to the actual conditions of such towers are addressed in Section 4. Finally, the conclusions of this work are summarized in Section 5.

2. Theoretical background

The problem of finding the potential profile, step, touch and mesh voltages created by a system of conductors in mutual interaction, immersed in an electrically inhomogeneous medium can essentially be solved by finding a solution of

$$\vec{\nabla} \bullet (\sigma(\vec{r}) \cdot \vec{\nabla}\phi(\vec{r})) = 0 \tag{1}$$

where, $\sigma(\vec{r})$ is the conductivity function and $\phi(\vec{r})$ the potential that satisfies a set of boundary conditions which define univocally the configuration of the conductors, their electrical state and the properties of the inhomogeneous medium.

We assume that there exist N_C conductors of surfaces S_{C_i}, located in a semi-infinite medium horizontally bounded by the ground surface G. It is assumed that the whole semi-infinite medium is globally inhomogeneous, but consists of N_R finite size volumes of constant conductivity and surface S_{I_j}, immersed in a homogeneous semi-infinite medium of different conductivity, as is schematically illustrated in Fig. 1.

The conductors may be independent or electrically interconnected. For each region R where, conductivity is a constant, the equations that needs to be solved are

$$\begin{aligned}
\Delta\phi_R &= 0\\
\phi_R(\vec{r})\big|_{\vec{r}\in S_{C_i}} &= V_i\\
\vec{n}\bullet\vec{\nabla}\phi_R\big|_G &= 0\\
\phi_R(\vec{r})\big|_{S_I} &= \phi_{R'}(\vec{r})\big|_{S_I}\\
\sigma_R\vec{\nabla}\phi_R(\vec{r})\bullet\vec{n}\big|_{S_I} &= \sigma_{R'}\vec{\nabla}\phi_{R'}(\vec{r})\bullet\vec{n}\Big|_{S_I}
\end{aligned} \tag{2}$$

The last two equations in Eq. (2) express the continuity of both the electric potential and the current density flow through the interface S_I, separating the R and R′ regions of constant conductivities σ_R and $\sigma_{R'}$. The vector $\vec{n}(\vec{r})$ is a unitary vector normal to S_I along R–R′.

Using the second Green identity, Eq. (2) can be converted to an integral form where the sources of the potential ϕ_R are surface current distributions on all the conductors of the system λ_{C_i}, and surface current distributions λ_{I_j} on all the interfaces I_j, separating regions of different conductivity, the core of the ESCD approach

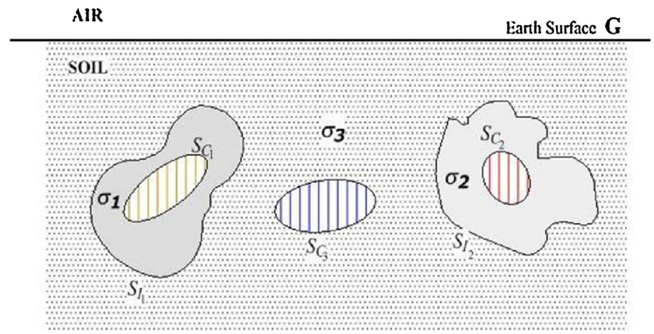

Fig. 1. Pictorical representation of a complex system of interacting electrodes in an inhomogeneous piece-wise medium.

[7–11],

$$\phi(\vec{r}) = \sum_i \int_{C_i} \frac{\lambda_{C_i}(\vec{r}_i)\mathrm{d}S_i}{4\pi\sigma_i\left|\vec{r}-\vec{r}_i\right|} + \sum_j \int_{I_j} \frac{\lambda_{I_j}(\vec{r}_j)\mathrm{d}S_j}{4\pi k_j\left|\vec{r}-\vec{r}_j\right|} \quad i = 1,\ldots,N_C;\quad j = 1,\ldots,N_I \tag{3}$$

where, N_C is the number of conductors in the system and N_I is the number of different interfaces separating the different conductive media.

Eq. (3) is valid for all the regions R where, the conductivity σ_i is a constant and k_j is given by $k_j = \sigma_-\sigma_+/\sigma_- - \sigma_+$, where, σ_- and σ_+ account for conductivities at both sides of the interface I_j.

The surface current distributions λ_{C_i} and λ_{I_j} can be calculated by imposing the boundary conditions on all the conductor surfaces S_{C_i} and density current fluxes continuity along all the interfaces S_{I_j}

$$\begin{aligned}
\phi(\vec{r})\big|_{S_{C_i}} &= V_i \quad i = 1,\ldots,N_C\\
\sigma_-(\vec{r})\vec{\nabla}\phi_-(\vec{r})\bullet\vec{n}\big|_{S_I} &= \sigma_+(\vec{r})\vec{\nabla}\phi_+(\vec{r})\bullet\vec{n}\big|_{S_I}
\end{aligned} \tag{4}$$

where, symbols subscripted with + and – denote the values on either side of the interface and the unitary normal vector $\vec{n}$ pointing from region – to region +. The continuity of current density flux through the interface surface separating the two media, as expressed by the last Eq. (4), means that although the potential is continuous in the interface, the normal component of the potential gradient at the interface surface is discontinuous. The discontinuity can be expressed by the following equation [7–11],

$$\frac{\lambda_{I_j}(\vec{r})}{k_j} + 2K\left[\begin{aligned}&\sum_i \int_{C_i}\frac{\lambda_{C_i}(\vec{r}_i)}{4\pi\sigma_i}\vec{\nabla}\Big(\frac{1}{\left|\vec{r}-\vec{r}_i\right|}\Big)\bullet\vec{n}\,\mathrm{d}S_i\\ &+\sum_j \int_{I_j}\frac{\lambda_{I_j}(\vec{r}_j)}{4\pi k_j}\vec{\nabla}\Big(\frac{1}{\left|\vec{r}-\vec{r}_j\right|}\Big)\bullet\vec{n}\,\mathrm{d}S_j\end{aligned}\right] = 0 \quad i = 1,\ldots,N_C;\quad j = 1,\ldots,N_I \tag{5}$$

where, point $\vec{r}$ belongs to the I_j interface and point $\vec{r}_j = \vec{r}$ is excluded in the integrand of the second integral term of Eq. (5). The prefactor K is defined by $K = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$, where, as before, σ_- and σ_+ account for conductivities at both sides of the interface I_j. Note that for convenience, in this theoretical framework the variables $\frac{\lambda_{C_i}}{\sigma_i}$ and $\frac{\lambda_{I_j}}{k_j}$ $(\mathrm{A}\,\Omega\,\mathrm{m}^{-1})$ are chosen as unknowns to be computed, but the really important variables are the densities λ_{C_i} and λ_{I_j} $(\mathrm{A\,m}^{-2})$.