Analysis of Transferred Earth Potentials in Grounding Systems: A BEM Numerical Approach

I. Colominas, F. Navarrina, M. Casteleiro

Abstract

In this work we present a numerical formulation for the analysis of a common problem in electrical engineering practice, that is, the existence of transferred earth potentials in a grounding installation [1]. The transfer of potentials between the grounding area to outer points by buried conductors, such as communication or signal circuits, neutral wires, pipes, rails, or metallic fences, may produce serious safety problems [2]. In this paper we summaryze the BE numerical approach and we present a new technique for the transferred potential analysis. Finally, we show some examples by using the geometry of real grounding systems in different cases of transferred potentials.

Keywords: BEM Numerical Methods, Grounding, Transferred Earth Potential

I. Introduction

Main objectives of a grounding system are *a)* to guarantee the integrity of equipment and the continuity of the service under fault conditions (providing means to carry and dissipate electrical currents into the ground), and *b)* to safeguard that persons working or walking in the surroundings of the grounded installation are not exposed to dangerous electrical shocks. To attain these targets, the equivalent electrical resistance of the system must be low enough to assure that fault currents dissipate mainly through the grounding grid into the earth, while maximum potential differences between close points on the earth surface must be kept under certain tolerances (step, touch and mesh voltages) [1], [3].

The operation of grounding systems is a topic which has been extensively studied and analyzed in the last four decades, and several methods for grounding analysis and design have been proposed. Furthermore, several computer programs have been developed to calculate the safety parameters of an earthing installation in order to obtain a reliable model of the grounding system and the hazardous scenarios which could occur. Most of these methods are based on the professional experience, on semi-empirical works, on experimental data obtained from scale model assays and laboratory tests, or on intuitive ideas. Unquestionably, these contributions represented an important improvement in the grounding analysis area, although some problems have been systematically reported, such as the large computational costs required in the analysis of real cases, the unrealistic results obtained when segmentation of conductors is increased, and the uncertainty in the margin of error [1], [3], [4], [5].

The dissipation of the electrical current into the soil is a well-known phenomenon which equations can be stated from Maxwell's Electromagnetic Theory [5]. Nevertheless, their application and resolution for the computing of grounding grids of large installations in practical cases present some difficulties. First, because no analytical solutions can be obtained for most of real problems. On the other hand, the geometry of the grounding grids in main earthing systems (a mesh of interconnected bare conductors with a relatively small ratio diameter-length) makes very difficult the use of standard numerical methods: The use of techniques commonly applied for solving boundary value problems in engineering, such as finite elements or finite differences, is indeed extremely costly since the discretization of the domain (the ground excluding the electrode) is required. Therefore, obtaining sufficiently accurate results should imply unacceptable computing efforts in memory storage and CPU time.

For all these reasons, the authors have proposed in the last years a numerical approach based on the transformation of the differential equations that govern the physical phenomena onto an equivalent boundary integral equation and the subsequent application of the Boundary Element Method [6]. Thus, the statement of a variational form based on a weighted-residual approach of the boundary integral equation and the selection of a Galerkin type weighting lead to a general symmetric formulation, from which it is possible to derive specific numerical algorithms of high accuracy for the analysis of grounding systems embedded in uniform soils models [2]. Furthermore, the development of this BEM approach has allowed to explain from a mathematical point of view the anomalous asymptotic behaviour of the clasical methods proposed for grounding analyis, and to identify rigorously the sources of error [5]. This boundary element approach has been implemented in a Computer Aided Design system for grounding analysis [7] that allows to analyze real earthing installations in real-time using conventional computers. Finally, in recent years we have proposed a generalization of the boundary element formulation for grounding grids embedded in layered soils, which basics, development and application examples can be found in references [8], [9].

Now, we focus our attention on a common and very important engineering problem in the grounding field: potential can be transferred to other grounded conductors in

I. Colominas, F. Navarrina and M. Casteleiro serve at the Dept. of Applied Math., Civil Engrg. School, Univ. of A Coruña, Campus de Elviña. 15071 A Coruña, SPAIN. (e-mail: colominas@iccp.udc.es)

the vicinity of the earthing installation, and subsequently it could reach distant points through communication or signal circuits, neutral wires, pipes, rails, or metallic fences. This effect could produce serious safety problems that should be estimated somehow [1].

In this paper we present a Boundary Element numerical formulation for the analysis of transferred potentials in grounding installations and its implementation in a Computer Aided Design system for grounding analysis. Furthermore, an application example to a practical case by using the geometry of a real earthing system is presented.

II. Mathematical Model of the Problem of the Electrical Current Dissipation into a Soil

It is common knowledge that Maxwell's Electromagnetic Theory is the general framework to derive the equations that govern the dissipation of electrical currents into a soil [1]. Thus, restricting the analysis to the electrokinetic steady-state response and neglecting the inner resistivity of the earthing conductors (potential can be assumed constant at every point of the grounding electrode surface), the 3D problem can be written as

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

where E is the earth, $\boldsymbol{\gamma}$ is its conductivity tensor, Γ_E is the earth surface, $\boldsymbol{n}_E$ is its normal exterior unit field and Γ is the electrode surface [2]. Therefore, the solution to (1) gives potential V and current density $\boldsymbol{\sigma}$ at an arbitrary point $\boldsymbol{x}$ when the electrode attains a voltage V_Γ (Ground Potential Rise, or GPR) with respect to remote earth. Next, for known values of V on Γ_E and $\boldsymbol{\sigma}$ on Γ, it is straightforward to obtain the design and safety parameters of the grounding system [2].

Different approaches can be stated depending on the soil model that one considers. Since the objective of this paper is to analyze the problem of the transferred potentials in grounding systems, we will consider the simplest soil model, that is, the homogeneous and isotropic soil model [1], [2]. Consequently, the conductivity tensor $\boldsymbol{\gamma}$ will be substituted by an apparent scalar conductivity γ that must be experimentally obtained [1]. Furthermore, if one takes into account that the surroundings of the substations site are levelled and regularized during its construction (then the earth surface can be assumed horizontal), the application of the "method of images" and Green's Identity yields the following integral expression for the potential V at an arbitrary point $\boldsymbol{x} \in E$:

$$V(\boldsymbol{x}) = \frac{1}{4\pi\gamma} \int\!\!\int_{\boldsymbol{\xi}\in\Gamma} k(\boldsymbol{x},\boldsymbol{\xi})\,\sigma(\boldsymbol{\xi})\,d\Gamma \tag{2}$$

being $\sigma(\boldsymbol{\xi})$ the unknown leakage current density at any point $\boldsymbol{\xi}$ of the electrode surface $\Gamma \subset E$ ($\sigma = \boldsymbol{\sigma}^t\boldsymbol{n}$ being $\boldsymbol{n}$ the normal exterior unit field to Γ) [2].

The integral kernel $k(\boldsymbol{x},\boldsymbol{\xi})$ is given by

$$k(\boldsymbol{x},\boldsymbol{\xi}) = \frac{1}{|\boldsymbol{x}-\boldsymbol{\xi}|} + \frac{1}{|\boldsymbol{x}-\boldsymbol{\xi}'|} \tag{3}$$

where $\boldsymbol{\xi}'$ is the symmetric of $\boldsymbol{\xi}$ with respect to the earth surface [2].

Now, since integral expression (2) also holds on Γ, where the potential is given by the essential boundary condition ($V(\boldsymbol{\chi}) = V_\Gamma$, $\forall\boldsymbol{\chi} \in \Gamma$), the leakage current density σ must satisfy a Fredholm Integral Equation of the First Kind on Γ, which variational form is given by the integral equation

$$\int\!\!\int_{\boldsymbol{\chi}\in\Gamma} w(\boldsymbol{\chi}) \left[V_\Gamma - \frac{1}{4\pi\gamma}\int\!\!\int_{\boldsymbol{\xi}\in\Gamma} k(\boldsymbol{\chi},\boldsymbol{\xi})\,\sigma(\boldsymbol{\xi})\,d\Gamma \right] d\Gamma = 0, \tag{4}$$

which must hold for all members $w(\cdot)$ of a class of functions defined on Γ [2].

Obtaining the leakage current density σ from (3) is the key of the problem, because the potential at any point (and, of course, on the earth surface) can be straightforwardly computed by means of (2). And if the potential values are known, then the safety design parameters of the grounding system (touch, step and mesh voltages, for example) can also be immediately obtained [2]. At this point, since the unknown function σ is defined on the boundary of the domain, it should be obvious that a numerical aproach based on the Boundary Element Method [6] seems to be the right choice to solve integral equation (3) [2]. In the next section we briefly summarize this numerical approach. The complete development and discussion, including several application examples, can be found in references [2], [5], [7], [8], [9], [10].

III. Basics of the BEM Numerical Approach for Grounding Analysis

The starting point in the development of the numerical model for solving the integral equation (3) is the discretization of the leakage current density σ and of the electrode surface Γ, for given sets of N trial functions $\{N_i(\boldsymbol{\xi})\}$ defined on Γ, and M boundary elements $\{\Gamma^\alpha\}$:

$$\sigma(\boldsymbol{\xi}) \approx \sigma^h(\boldsymbol{\xi}) = \sum_{i=1}^{N} N_i(\boldsymbol{\xi})\,\sigma_i^h, \qquad \Gamma = \bigcup_{\alpha=1}^{M} \Gamma^\alpha. \tag{5}$$

Now, expression (2) for potential $V(\boldsymbol{x})$ can also be discretized as

$$V(\boldsymbol{x}) = \sum_{i=1}^{N} \sigma_i^h V_i(\boldsymbol{x}), \qquad V_i(\boldsymbol{x}) = \sum_{\alpha=1}^{M} V_i^\alpha(\boldsymbol{x}), \tag{6}$$

where $V_i^\alpha(\boldsymbol{x})$ depends on the integral on Γ^α of the integral kernel $k(\boldsymbol{x},\boldsymbol{\xi})$ (given in (2)) times the trial function $N_i(\boldsymbol{\xi})$ [2].

On the other hand, for a given set of N test functions $\{w_j(\boldsymbol{\chi})\}$ defined on Γ, the variational form (3) can be written in terms of the following linear system of equations, as it is usual in boundary elements and finite elements:

$$\sum_{i=1}^{N} R_{ji}\sigma_i^h = \nu_j \quad j = 1,\ldots,N; \tag{7}$$

being

$$R_{ji} = \sum_{\beta=1}^{M} \sum_{\alpha=1}^{M} R_{ji}^{\beta\alpha}; \quad \nu_j = \sum_{\beta=1}^{M} \nu_j^{\beta} \tag{8}$$

where $R_{ji}^{\beta\alpha}$ depends on the integrals on Γ^α and on Γ^β of the integral kernel $k(\boldsymbol{\chi}, \boldsymbol{\xi})$ (given in (2)) times the trial function $N_i(\boldsymbol{\xi})$ and times the test function $w_j(\boldsymbol{\chi})$, and ν_j^β depends on the integrals on Γ^β of the test function $w_j(\boldsymbol{\chi})$ [2].

As we can observe, the solution of system (6) provides the values of the unknowns σ_i^h $(i = 1, \ldots, N)$ that are necessary to compute the potential V at any point $\boldsymbol{x}$ by means of (5). Besides, the other safety parameters can be easily obtained from the potential distribution and the leakage current density σ [2].

In the present work, we focus our attention on the analysis of the transferred earth potentials in grounding systems. The starting point for this study is the numerical approach based on the BEM which main highlights have been presented above. This numerical formulation for grounding analysis in uniform and layered soil models is completely developed in references [2], [9]. In them, it also can be found the derivation of a 1D approximated numerical approach (taking into account the real geometry of grounding systems in practical cases), and the highly efficient analytical integration techniques developed by the authors for computing terms $V_i^\alpha(\boldsymbol{x})$ of (5) and $R_{ji}^{\beta\alpha}$ of (7) which are finally computed by means of explicit formulae. Moreover, in [2], [5] a fully explicit discussion about the main numerical aspects of the BEM numerical approaches (such as the asymptotic convergence, the overall computational efficiency, and the complete explanation of the sources of error of the widespread intuitive methods) can be found.

This numerical approach (mathematically and numerically well-founded) is highly efficient from a computational point of view, and it has been implemented in a Computer Aided Design system for grounding analysis in uniform and layered soil models [2], [5], [7], [9].

IV. The Problem of Transferred Earth Potentials

Transferred earth potentials refer to the phenomenon of the earth potential of one location appearing at another location where there is a contrasting earth potential [11]. Thus, the grounding grid of an electrical substation attains a voltage (the Ground Potential Rise, or GPR) during a fault condition which can be on the order of thousands of volts. This voltage (or a fraction of it) may be transferred out to a non-fault site by a ground conductor (such as metal pipes, rails, metallic fences, etc.) leaving the substation area. Obviously, this event could produce serious hazards and must be avoided to ensure the protection of people, the equipment and even the animals at the non-faulted end [12].

The importance of the problem results from the very high difference of potential that can be produced in unexpected areas. Main danger uses to be of the "touch type". That is, when a person standing at a remote location, far away from the substation site, touches a conductor connected to the grounding grid, or touches a conductor not directly connected to the grounding grid but with a high voltage level (a fraction of the GPR) produced by a transferred potential.

In most cases, the potential difference will be too low to cause a shock hazard to persons or livestock. However, the difference of voltage between close points on the earth surface could be enough to produce some discomforts to sensitive persons (like children), or to affect the livestock (i.e., problems with milk production could occur [13]). On the other hand, the presence of these transferred potentials due to buried conductors may also produce the anomalous operation of some electrical equipment or the distorsion in the measurement instruments or electronic devices [12], [14]. In references [1], [12], it can be found a discussion on the means that can be taken to protect communications circuits, rails, low-voltage neutral wires, portable equipment and tools supplied from substation, piping, auxiliary building and fences.

Generally, we consider two main cases of transferred potentials: **a)** the trasference of the Ground Potential Rise to distant points of the grounding site by means of a conductor directly linked to the earthing system; and **b)**, the transference of a fraction of the Ground Potential Rise to distant points of the grounding site by the existence of conductors close to the earthing grid but not directly connected to it (these conductors are energized to a fraction of the GPR when an eddy current is derived to the grounding grid during a fault condition). It is important to remark the difference between both situations: in one case, all conductors attain the GPR, and in the second situation, the conductors not connected to the grounding grid attain a fraction of the GPR. In both cases, the potential distribution on the earth surface will be significantly modified. And this could imply a serious safety problem when it affects to non-protected areas [11].

Evidently, the best way to deal with these problems is to avoid transferred potentials. However, this is not always possible. For example, in large electrical substations it is often routed a railway spur to facilitate the installation of high-power transformers or other large equipment. These railroad tracks frequently extend beyond the substation site, and they can transfer dangerous potentials during a fault condition in the grounding system [15].

The practices generally used to prevent these hazardous voltages (e.g., the use of isolation joints or the removal of several rail sections) are based on the combination of a good engineering expertise, some very crude calculations and, in a few cases, field measurements [1], [12], [14], [15], [16].

Nowadays, with the development of new computer methods for grounding analysis, one should seek for a more accurate determination of the dangerous transferred earth potentials. In the next section, we propose the analysis of transferred earth potentials in grounding systems by using a numerical approach based on the Boundary Element Method. The starting point of this approach will be the

BEM formulation that was briefly presented in the previous section.

V. Analysis of Transferred Earth Potentials

When the extra-conductors and the grounding grid are both electrically connected, the analysis of transferred earth potentials does not imply a significant change in the numerical approach. As it has been previously exposed, the potential can be assumed constant at every point of the surfaces of all conductors, since their inner resistivity is neglected. Therefore, during fault conditions all conductors are energized to the Ground Potential Rise and the bare extra-conductors also work as "grounded electrodes" leaking electrical current into the ground. That is, the extra-conductors become part of the grounding grid, and they should be included in the earthing analysis as part of the grounding grid [10].

When the extra-conductors and the grounding grid are not interconnected, the analysis of transferred earth potentials is more difficult to deal with. The main problem is that the extra-conductors attain an unknown voltage (i.e., a fraction of the GPR) due to their closeness to the grounding grid when a fault condition occurs. Our objective is to obtain this voltage, and the rest of the safety parameters of the grounding system: the potential distribution on the earth surface, the step and touch voltages, the equivalent resistance, etc.

The key idea to solve this problem is that the set of electrodes which form the grounding grid (energized to the GPR) is an "active grid" (which is leaking into the soil an unknown total current I_G), while the extra-conductors (energized to an unknown fraction of the GPR) make up a "passive grid" (which is leaking no current into the soil). The importance of these transferred potentials will obviously decrease if the "passive grid" is far from the "active grid", and their effects will be local; however it may produce non-negligible differences of potential on the earth surface in unexpected areas, even outside of the substation site.

The analysis of the transferred potential from the "active grid" to the "passive grid" can be performed by means of a superposition of elementary states, given the linear condition of the state equations. We consider two elementary states: **state 1)** the "active grid" is energized to 1 V and the "passive grid" is energized to 0 V; and **state 2)** the "active grid" is energized to 0 V and the "passive grid" is energized to 1 V. With these values of unitary Ground Potential Rise, we can apply the BEM numerical approach presented in section 3 to each elementary state in order to compute the total electrical currents by unit of voltage which flow from each "grid": $i_{\mathrm{A}1}$, $i_{\mathrm{A}2}$, $i_{\mathrm{P}1}$ and $i_{\mathrm{P}2}$ ("A" refers to the "active grid", "P" refers to the "passive grid", and the numbers refer to each elementary state).

In the final state the "active grid" is energized to the GPR and the "passive grid" is energized to an unknown (but constant) potential, (that is, the fraction λ of the GPR). Consequently, this final state can be obtained by superposition of the previous two elementary states: the state **1)** weighted by the GPR of the "active grid" (V_Γ); and the state **2)** weighted by a fraction λ of the GPR (V_Γ). Finally, the coefficient λ and the total fault current being leaked into the soil I_G can be computed by imposing that the fault condition is produced only in the "active grid" and by imposing that no current is leaked by the "passive grid" [10]; that is, by solving the linear system of equations,

$$\begin{aligned} I_G &= V_\Gamma\, i_{\mathrm{A}1} + \lambda V_\Gamma\, i_{\mathrm{A}2} \\ 0 &= V_\Gamma\, i_{\mathrm{P}1} + \lambda V_\Gamma\, i_{\mathrm{P}2}. \end{aligned} \tag{9}$$

Once the total fault current I_G and the fraction λ of the GPR are known, it is possible to obtain the equivalent resistance of the grounding system and to compute the potential distribution on the earth surface (and consequently, one can obtain the touch and step voltages at any point of the substation site and of its surroundings). Of course, the extension of this technique to cases with more than one "passive grid" is straightforward.

TABLE I
Grounding System: Characteristics

Data	
Number of electrodes:	534
Diameter of electrodes:	11.28 mm
Depth of the grid:	0.75 m
Number of ground rods:	24
Diameter of ground rods:	15.00 mm
Length of ground rods:	4 m
Max. dimensions of grid:	230×195 m^2
Soil Resistivity:	60 Ωm
GPR:	10 kV

TABLE II
Railway Tracks: Characteristics

Data	
Number of tracks:	2
Length of the tracks:	260 m
Distance between the tracks:	1668 mm
Diameter of the tracks:	94 mm
Depth:	100 mm

VI. Example of Transferred Potential Analysis and Discussion

The above methodology has been applied to the analysis of the transferred earth potentials by railway tracks close to the grounding system of an electrical substation. In order to show the feasibility of this approach in a practical case, we have chosen the geometry of a real grounding grid, which plan is shown in Figure 1. The earthing grid is formed by a mesh of 534 cylindrical conductors buried to a depth of 75 cm, supplemented with 24 ground rods of 4 m length (see Table I).

In all examples presented in this paper, we have considered the soil homogeneous and isotropic with an apparent scalar resistivity of 60 Ωm, and the GPR of 10 kV.

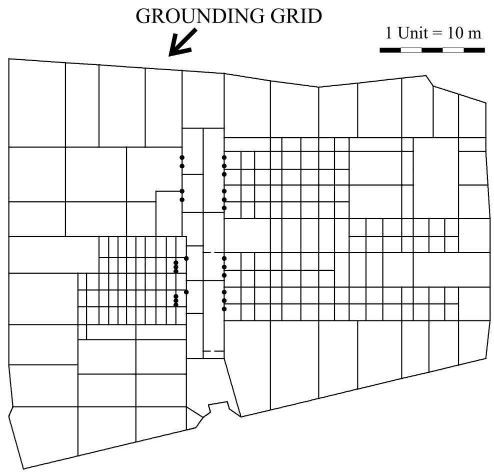

Fig. 1. Plan of the grounding grid of the electrical substation (the ground rods are marked with black points).

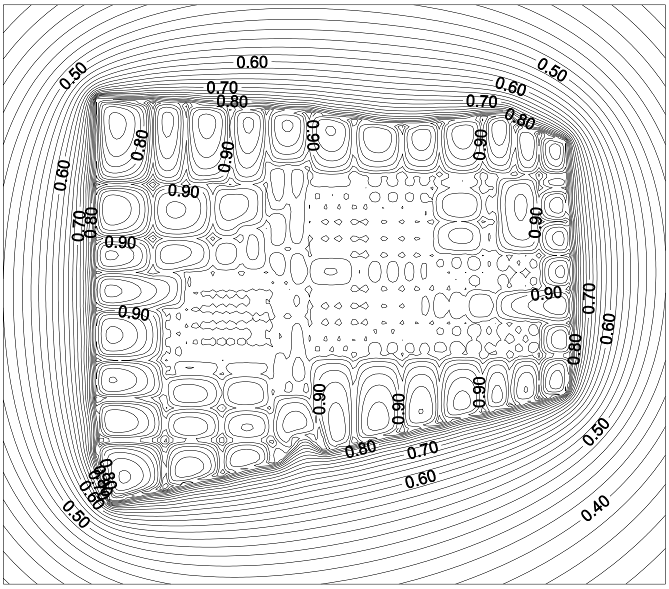

Fig. 2. Case 1: Potential distribution (×10 kV) on the ground surface obtained with a homogeneous and isotropic soil model.

In the first case (Case 1) we have studied the grounding analysis of the earthing system of Figure 1, that is, the grounding grid without considering the railway tracks. Figure 2 shows the potential distribution on the earth surface when a fault condition occurs.

On the other hand, we have studied the same earthing system but now considering the existence of two railway tracks in its vicinity. As it was previously exposed, this is a common situation in electrical substations and generating plants where a railway spur is used for the installation of large equipment during the construction phase of the electrical installation, fuel supplying, etc. [15]. The characteristics of the tracks and the plan are given in Table II and Figure 2. We have analyzed two situations: In Case 2, the grounding grid and the tracks are not directly connected, whereas in Case 3 both systems (the grounding grid and the tracks) are electrically linked.

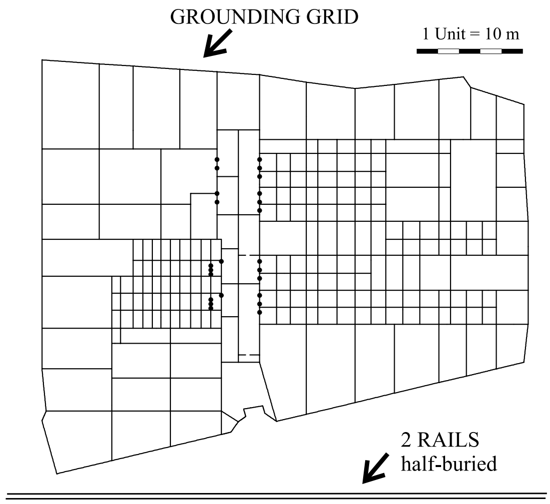

Fig. 3. Plan of the grounding grid of the electrical substation and the two railway tracks (ground rods are marked with black points).

As we have explained in previous sections, in Case 2 when the grounding grid of the substation is energized to the GPR (that is, it is the "active grid"), the tracks are energized to a fraction of this GPR (i.e., the tracks are a "passive grid") producing the transference of potentials in their vicinity. However, in Case 3 since the grounding grid and the tracks are connected, both are energized to the GPR. Table III summarizes the three cases studied and the main results obtained for each one (Equivalent Resistance and Total Fault Current leaked to the ground). Figure 4 shows the potential distribution on the earth surface obtained in Case 2, and Figure 5 the potential distribution in Case 3.

The analysis of transferred earth potentials in Case 2 has been performed by using the proposed BEM approach and the superposition of unit elementary states presented previously. The fraction of the GPR of the "passive grid" turns out to be of $\lambda = 0.516$.

The analysis of transferred potentials in Case 3 has been performed by using the BEM numerical approach since the tracks can be formally considered part of the earthing system.

As expected, it is obvious that for the three cases there are no significant differences in the potential distribution on the earth surface (neither in the touch and step voltages) in the area covered by the grounding grid of the electrical substation. Related to the equivalent resistance of the earthing system, there are only slight differences between cases 1 and 2 (in one case, the tracks are not considered, and in the second one, they are not connected to the grounding grid), while in case 3 the resistance changes since the tracks also work as grounded electrodes.

However, the most important differences can be noticed in the potential distribution on the earth surface, specially in the surroundings of the railway tracks. The comparison between figures 2, 4 and 5 shows that in some areas close to the rail tracks, important potential gradients are produced.

TABLE III
Grounding Analysis: Numerical Model and Results

Case 1	
Railway tracks:	No considered
Type of numerical approach:	Galerkin
Type of 1D BEM element:	Parabolic
Number of elements:	558
Degrees of freedom:	920
Fault current:	67.36 kA
Equivalent Resistance:	0.1484 Ω
Case 2	
Railway tracks:	Considered
Connection Tracks—Grounding Grid:	No
Type of numerical approach:	Galerkin
Type of 1D BEM element:	Parabolic
Number of elements:	560
Degrees of freedom:	1002
Fault current:	67.47 kA
Equivalent Resistance:	0.1482 Ω
Case 3	
Railway tracks:	Considered
Connection Tracks—Grounding Grid:	Yes
Type of numerical approach:	Galerkin
Type of 1D BEM element:	Parabolic
Number of elements:	560
Degrees of freedom:	1002
Fault current:	73.27 kA
Equivalent Resistance:	0.1365 Ω

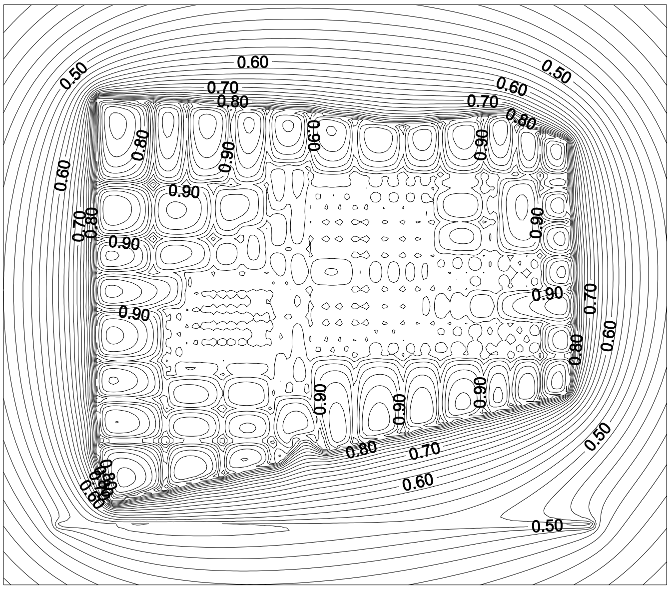

Fig. 4. Case 2: Potential distribution (×10 kV) on ground surface obtained with a homogeneous and isotropic soil model. In this case, the grounding grid and the railway tracks are not interconnected.

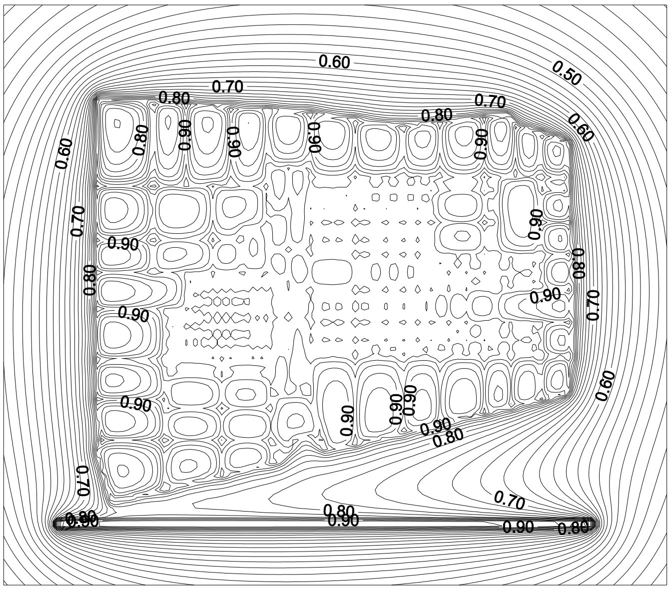

Fig. 5. Case 3: Potential distribution (×10 kV) on ground surface obtained with a homogeneous and isotropic soil model. In this case, the grounding grid and the railway tracks are interconnected.

In Case 2, the danger is not due to the magnitude of the transferred potentials, but to the difference of potential values: in some points in the vicinity of the tracks, we compute step voltages that are ten times higher than the step voltages computed without considering the transferred potentials by the tracks. Obviously, this situation is dangerous because one does not expect to find such potential gradients on the ground surface far away from the substation site, specially in non-protected areas.

Case 3 is much more dangerous since the touch voltages in the vicinity of the railway tracks are very high, as we can observe in Figure 5. However, this situation of connection between grounded conductors can be prevented by using an efficient insulation.

VII. Conclusions

In this paper, we have revised the mathematical model of the physical phenomenon of the electrical current dissipation into the soil through a grounding grid. We have summarized the main highlights of the numerical approach based on the BEM proposed for the authors for grounding analysis in uniform soil models.

Furthermore a numerical approach for the computational analysis of transferred earth potentials by electrical conductors buried in the surroundings of a grounding system has been presented for the first time. Two main cases of transferred potentials have been analyzed: the analysis if the grounding grid of the substation is electrically linked to other buried conductors, and the analysis if there is no connection between both systems.

The numerical formulation has been implemented in a Computer Aided Design system for earthing analysis, which allows to design grounding grids in real-time taking into account the effects of the transference of potential to distant points of the substation site.

At present, we are working in the generalization of the transferred earth potential analysis to non-uniform soil models.

Acknowledgments

This work has been partially supported by the "Ministerio de Ciencia y Tecnología (project #DPI2001-0556)" of the Spanish Government cofinanced with FEDER funds.

References

[1] IEEE Std.80, *IEEE Guide for safety in AC substation grounding.* New York, (2000).

[2] Colominas I., Navarrina F., Casteleiro M., *A boundary element numerical approach for grounding grid computation*, Computer Methods in Applied Mechanics and Engineering, **174**, 73-90, (1999).

[3] Sverak J.G., *Progress in step and touch voltage equations of ANSI/IEEE Std.80*, IEEE Transactions on Power Delivery,**13**, 762–767, (1999).

[4] Garrett D.L., Pruitt J.G., *Problems encountered with the APM of analyzing substation grounding systems*, IEEE Transactions on Power Apparatus Systems **104**, 3586-3596, (1985).

[5] Navarrina F., Colominas I., Casteleiro M. *Why do computer methods for grounding produce anomalous results?*, IEEE Transactions on Power Delivery, (2002) [In Press].

[6] Wrobel L., Aliabadi F., *The Boundary Element Method (Vols. 1 & 2)*, John Wiley & Sons, Chichester, UK (2002).

[7] Casteleiro M., Hernández L.A., Colominas I., Navarrina F., *Memory and User guide of system TOTBEM for CAD of grounding grids in electrical installations*, (in spanish), Civil Engineering School, Universidad de La Coruña, (1994).

[8] Colominas I., Gómez-Calviño J.,Navarrina F., Casteleiro M., *Computer analysis of earthing systems in horizontally and vertically layered soils*, Electric Power Systems Research, **59**, 149-156, (2001).

[9] Colominas I., Navarrina F., Casteleiro M. *A numerical formulation for grounding analysis in stratified soils*, IEEE Transactions on Power Delivery, **17**, 587-595, (2002).

[10] Colominas I., *A CAD system of grounding grids for electrical installations: A numerical approach based on the Boundary Element integral method*, (in spanish), Ph.D. Thesis, Civil Engineering School, Universidad de La Coruña, (1995).

[11] Shipp D.D., Nichols N., *Designing to avoid hazardous transferred earth potentials*, IEEE Transactions on Industry Applications, **1A-18**, no. 4, (1982).

[12] IEEE Std. 142-1991, *IEEE Recommended practice for grounding of industrial and commercial power systems.* New York, (1996).

[13] Dick W.K., Winter D.F., *Computation, measurement and mitigation of neutral-to-earth potentials on electrical distribution systems*, IEEE Transactions on Power Delivery, **2**, no. 2, (1987).

[14] IEEE Std. 81-1983, *IEEE Guide for measuring earth resistivity, ground impedance and earth surface potentials of a ground system.* New York, (1983).

[15] Garrett D.L., Wallace K.A., *A critical analysis of grounding practices for railroad tracks in electric utility stations*, IEEE Transactions on Power Delivery, **8**, 90-96, (1993).

[16] IEEE Std. 665-1987, *IEEE Guide for generating station grounding.* New York, (1987).

Ignasi Colominas Industrial Engineer, M.Sc. (Univ. Autònoma de Barcelona, 1990), Ph.D. (Univ. de A Coruña, 1995). Associate Professor of Applied Math at the Civil Engineering School of the Univ. of A Coruña. His main research areas are those related with computational mechanics in engineering applications. He currently leads a R&D project of the Spanish Government with european funds for the computational design of grounding systems of electrical substations. He is member of IEEE.

Fermín Navarrina Civil Engineer, M.Sc. (Univ. Politécnica de Madrid, 1983), Ph.D. (Univ. Politècnica de Catalunya, 1987). Professor of Applied Math at the Civil Engineering School of the Univ. of A Coruña. His research fields are related to the development of numerical methods for analysis and design optimization in engineering. He has directed and/or collaborated in a number of R&D projects and is the author of more than 50 papers published in scientific journals and books.

Manuel Casteleiro Civil Engineer (Univ. Politécnica de Madrid, 1971), M.Sc. (Northwestern Univ., 1972), Ph.D. (Northwestern Univ., 1974). Professor of Applied Math at the Civil Engineering School of the Univ. of A Coruña. His research fields are large-scale simulation techniques, computational mechanics, and statistical and risk analysis in engineering science. He has directed many R&D projects and has published a large number of scientific and technical papers and books.