The Influence of Nonhomogeneous Earth on the Inductive Interference Caused to Telecommunication Cables by Nearby AC Electric Traction Lines

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Abstract—This work investigates the inductive interference caused by ac electric traction lines to nearby buried telecommunication cables, in the presence of a nonhomogeneous earth. The two dimensional, quasi stationary electromagnetic field diffusion equation has been numerically solved by using the Finite Element Method (FEM), in a system involving an ac electric traction line of the Greek Railways Organization and a buried cable of the Greek Telecommunications Organization. Using FEM results, magnetic vector potential in the cross-section of the examined system, as well as the longitudinal electromagnetic force induced in the circuit formed by the telecommunication cable and earth, are calculated. A rigorous parametric analysis concerning various nonhomogeneous earth models has shown a significant influence of the depth and resistivity of the first earth layer, as well as of the resistivities of the different earth layers, on the electromagnetic field and on the inductive interference caused to the buried telecommunication cable.

Index Terms—Electric traction lines, finite element methods, nonhomogeneous earth, telecommunication cables.

I. INTRODUCTION

A NALYSIS of electrical interaction effects between electric traction lines, power transmission lines and nearby telecommunication networks has been a topic of growing interest, due to the restrictions currently imposed to public utilities in the use of right-of-ways. These restrictions have resulted in situations in which power lines, pipelines, railroads, telecommunication lines etc. have to be laid in close distance for several kilometers. However, electrical interference problems among these systems must be carefully examined, before the sharing of a common right-of-way may be finally decided.

A telecommunication cable, even below ground, following an ac power transmission line or an ac electric traction line over a certain distance, is subjected to a significant interference. This interference consists of an inductive, a conductive and a capacitive component. Inductive interference, generated by the magnetic field, is present during both normal operating conditions and fault conditions. Conductive interference arises when a power transmission line or an electric traction line injects a large current into the earth during a fault and the telecommunication cable is located near this fault. Capacitive interference, which is generated by the electric field, influences only cables above ground, having no earth-connected sheath.

The inductive interference caused by an energized ac power transmission line is significant in cases of single-phase faults. In normal operating conditions, the balance of the three-phase currents causes no substantial effect. In this case only a small electromagnetic force is induced, due to the geometrical asymmetry of the electromagnetic field. On the other hand the inductive interference generated by ac electric traction lines is significant even in normal operating conditions, since these lines are by definition asymmetrical.

Electrical interference problems have been examined by many scientific organizations and research institutes, leading to various research reports, papers and books [1]–[10]. Although the mechanisms by which inductive, conductive and capacitive interferences arise are well understood, the determination of interaction effects in a typical right-of-way is a complex procedure. This procedure requires a good knowledge of electrical and geometrical properties as well as an accurate earth representation.

The earth model is particularly important for the determination of interaction levels and of the performance of mitigation systems. Without an adequate modeling, the mitigation designs have to be conservative in order to ensure a sufficient protection. When the earth structure is accurately modeled, effective and cost-efficient mitigation designs may be evaluated.

In this paper the influence of the nonhomogeneous earth on the inductive interference caused by an ac electric traction line to a nearby telecommunication cable has been examined. The use of finite elements method (FEM) for the solution of Maxwell’s equations which describe complex electromagnetic field problems leads always to useful conclusions [11]. Therefore, a procedure based on finite element method (FEM) has been proposed to solve the electromagnetic field problem of an ac electric traction line, in the presence of a buried telecommunication cable and a nonhomogeneous earth.

II. SYSTEM ARRANGEMENT AND ASSUMPTIONS JUSTIFICATION

To investigate the influence of nonhomogeneous earth on the inductive interference caused to telecommunication cables by nearby ac electric traction lines, a typical system shown in Fig. 1 has been chosen. This system consists of a typical ac electric traction line of the Greek Railways Organization,
running parallel to a typical shielded buried cable of the Greek Telecommunications Organization, as shown in Fig. 1(c). The parallel exposure is equal to 1 km. The assumption that the traction line is parallel to the buried telecommunication cable is valid for many practical applications, when both are located in straight narrow corridors.

As shown in Fig. 1(a), the electric traction line consists of a copper touch conductor, which supplies the electric locomotive with alternating current at 50 Hz. The touch conductor is connected with the electric traction line through a supportive bronze conductor. The current of the touch conductor returns to the traction power substation partially through the rails and partially through the earth. There are two traction power substations, one in point A and one in point D.

The cross-section of the examined telecommunication cable is shown in Fig. 1(b). The cable consists of thirty copper paper insulated pairs. The diameter of the conductor of each pair is equal to 0.8 mm. An internal lead sheath encloses the pairs, which are isolated with tarpaper from an external steel sheath. The external sheath has a PVC insulation.

Aluminum mitigation wires shown in Fig. 1(a) are bare. In order to avoid possible corrosion problems, a system to protect these bare mitigation wires against corrosion may be required. The earth is subdivided in layers with different resistivities, while their relative permeabilities are \( \mu_{r1} = \mu_{r2} = \mu_{r3} = 1 \). These layers, shown in Fig. 1(a), are assumed to be homogeneous across the \( x \)-dimension, although this is not a necessity for the method developed.

The maximum expected supply current \( I_s \) flowing in the electric traction line section BC of Fig. 1(c), which is parallel to the telecommunication cable, is assumed equal to 1 kA. In this case conductive and capacitive interference are negligible and the inductive interference, due to the magnetic field, prevails. End effects are neglected for the inductive interference calculations, leading to a two dimensional problem. The assumption concerning the ignorance of the end effects is valid for the inductive interference calculations and for the lengths of parallel exposures encountered in practical applications.

### III. FEM Calculations

#### A. Field Equations and FEM Formulation

The previous assumption lead to a linear two-dimensional electromagnetic diffusion problem for the \( z \)-direction components of the magnetic vector potential (MVP) \( A_z \) and of the total current density vector \( J_z \). This problem is described [11] by the system of equations

\[
\begin{align*}
\frac{1}{\mu_0 \mu_r} \left[ \frac{\partial^2 A_z}{\partial x^2} + \frac{\partial^2 A_z}{\partial y^2} \right] - j \omega \sigma A_z + J_{sz} = 0 \\
-j \omega \sigma A_z + J_{sz} = J_z \\
\int_{S_i} J_z ds = I_i
\end{align*}
\]  

where

- \( \sigma \) is the conductivity,
- \( \omega \) is the angular frequency,
- \( \mu_0 \) and \( \mu_r \) are the vacuum and relative permeabilities respectively,
- \( J_{sz} \) is the source current density in the \( z \)-direction and
- \( I_i \) is the current flowing through conductor \( i \) of cross section \( S_i \).

The matrix equation obtained [12] from the finite element formulation of equations (1a)–(1c) is solved using the Crout variation of Gauss elimination. MVP values in every node of the discretization domain as well as the unknown source current densities are calculated using the matrix equation solution. Consequently, the eddy current density \( J_{ez}^c \) of element \( e \) is obtained from the relation [11]

\[
J_{ez}^c(x, y) = -j \omega \sigma A_z^c(x, y)
\]
and the total element current density \( J_{cz}^\text{e} \) will be the sum of the conductor-\( i \) source current density \( J_{czi}^\text{e} \) and of the element eddy current density \( J_{cz}^\text{ed} \) given by (2a), i.e.

\[
J_{cz}^\text{e}(x, y) = J_{czi}^\text{e}(x, y) + J_{cz}^\text{ed}
\]  

(2b)

Integration of (2b) over a conductor cross-section will give the total current flowing through this conductor.

The solution domain of our problem is subdivided in first order triangular finite elements. The complicated geometry of the examined problem requires an optimal grid generator which provides triangular finite elements, each of which contribute very nearly the same error to the overall solution. Therefore a Delaunay based [13] adaptive mesh generation algorithm has been developed for the original discretization. The continuity requirement of the flux density on the interface between neighboring elements has been chosen as the criterion for an iteratively adaptive mesh refinement.

B. Calculation of the Longitudinal Electromotive Force E.M.F.

A measure of the inductive interference caused to the telecommunication cable by the ac electric traction line is the longitudinal electromotive force (e.m.f.) induced in the circuit formed by a pair of the cable and the earth. This e.m.f. is calculated from the following equation

\[
\text{e.m.f.} = -j2\pi f\phi
\]  

(3)

where:

- \( f \) is the frequency of the inducing current in Hz (in the examined case \( f = 50 \) Hz);
- \( \phi \) is the flux of the electromagnetic field through the parallel section of the telecommunication cable and the ground.

In a two-dimensional problem, the flux of the electromagnetic field through the parallel section of the telecommunication cable and the ground is given by

\[
\phi = A_e l
\]  

(4)

where \( A_e \) is the MVP, derived from FEM calculations, in the telecommunication cable and \( l \) is the length of this cable.

IV. INVESTIGATION OF NONHOMOGENEOUS EARTH INFLUENCE

A. Two Earth Layers Without Mitigation Wires

Suppose that in the system of Fig. 1(a) the second earth layer has the same resistivity as that of the third earth layer, leading to a model with two earth layers. The depth of the first earth layer is equal to \( l_1 \), while second earth layer thickness is equal to \( l_2 = 2 \text{ km} - l_1 \). The layers extend across \( z \)-axis up to \( 2 \text{ km} \) from the electric traction line axis of symmetry, in both directions. Initially it is assumed that no mitigation wires are present. The influence of each earth layer resistivity on the electromagnetic field and on the inductive interference depends on the depth of the first earth layer. It may be interesting to estimate the depth \( l_1 \) from which the first earth layer resistivity determines almost exclusively the electromagnetic field and the inductive interference.

First and second earth layers are initially assumed to have resistivities \( \rho_1 = 100 \Omega \text{m} \) (dry earth) and \( \rho_2 = 1000 \Omega \text{m} \) (rocky earth) respectively. The parametric analysis for \( l_1 \), concerning the e.m.f. induced in the telecommunication cable, is shown in Fig. 2. The application of the proposed method for the same separation distances of Fig. 2 but for homogeneous earth (i.e. when resistivities of the three layers shown in Fig. 1(a) are \( \rho_1 = \rho_2 = \rho_3 = \rho \) for various separation distances \( d \)

**TABLE I**

<table>
<thead>
<tr>
<th>Separation distance ( d ) [m]</th>
<th>e.m.f. ([\text{V}])</th>
<th>e.m.f. ([\text{V}])</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \rho = 100 \Omega \text{m} )</td>
<td>( \rho = 1000 \Omega \text{m} )</td>
</tr>
<tr>
<td>60</td>
<td>37.754</td>
<td>45.774</td>
</tr>
<tr>
<td>100</td>
<td>31.165</td>
<td>39.555</td>
</tr>
<tr>
<td>500</td>
<td>12.505</td>
<td>22.145</td>
</tr>
<tr>
<td>1000</td>
<td>6.083</td>
<td>15.229</td>
</tr>
</tbody>
</table>

Fig. 2. Longitudinal electromotive force e.m.f. induced in the telecommunication cable as a function of the depth of the first earth layer of Fig. 1(a), for a two earth layer model with resistivities \( \rho_1 = 100 \Omega \text{m} \) and \( \rho_2 = 1000 \Omega \text{m} \). Curve A corresponds to separation distance 60 m, curve B to 100 m, curve C to 500 m and curve D to 1000 m.

Comparing e.m.f. values of Table I with the corresponding values obtained from Fig. 2 it is evident that:

- when the depth \( l_1 \) of the first earth layer varies between 10 m and 50 m, the electromagnetic field and the inductive interference is determined properly from the resistivity of the second earth layer.
- for depth \( l_1 = 600 \text{ m} \) and greater, the resistivity of the first earth layer plays the dominant role in the electromagnetic field and inductive interference influence.

The above conclusions may be also explained with the help of Fig. 3. From this figure it is evident that when \( l_1 \) is equal to 600 m, the induced e.m.f. derived for the earth model with
resistivities \( \rho_1 = 100 \, \Omega \cdot \text{m}, \rho_2 = 1000 \, \Omega \cdot \text{m} \) is equal to the induced e.m.f. calculated for the earth model with resistivities \( \rho = 100 \, \Omega \cdot \text{m}, \rho_2 = 500 \, \Omega \cdot \text{m} \).

The influence of the depth of the first earth layer may be easily understood from Figs. 4 and 5, in which flux lines are shown for two cases with \( l_1 = 50 \, \text{m} \) and \( l_1 = 400 \, \text{m} \) respectively. From the MVP distribution of Fig. 4, which is valid for a first earth layer depth \( l_1 = 50 \, \text{m} \), it is clear that the influence of the resistivity of the first earth layer on the electromagnetic field is negligible. In this case, the field is almost exclusively influenced by the resistivity of the second earth layer. On the other hand, from the MVP distribution of Fig. 5, which is valid for a first earth layer depth \( l_1 = 400 \, \text{m} \), the influence on the electromagnetic field due to the resistivity of the first earth layer is evident, since the field lines are now compressed in that layer.

\[ \text{Fig. 3. Longitudinal electromotive force e.m.f. induced in the telecommunication cable as a function of the depth of the first earth layer, for a two earth layer model and a separation distance } d = 60 \, \text{m}. \text{ Curve A corresponds to resistivities } \rho_1 = 200 \, \Omega \text{ and } \rho_2 = 1000 \, \Omega \text{, curve B to } \rho_1 = 100 \, \Omega \text{ and } \rho_2 = 1000 \, \Omega \text{ and curve C to } \rho_1 = 100 \, \Omega \text{ and } \rho_2 = 500 \, \Omega. \]

\[ \text{Fig. 4. Flux lines } (A = \text{ const}) \text{ of the electromagnetic field, for a two earth layer model with resistivities } \rho_1 = 100 \, \Omega \text{ and } \rho_2 = 1000 \, \Omega \text{. The depth of the first earth layer is } l_1 = 50 \, \text{m} \text{ while separation distance is } d = 100 \, \text{m}. \]

Finally, the first and second earth layers are assumed to have \( \rho_1 = 1000 \, \Omega \cdot \text{m} \) and \( \rho_2 = 100 \, \Omega \cdot \text{m} \) respectively. The corresponding parametric analysis for the depth of the first earth layer, concerning the e.m.f. induced in the telecommunication cable, is now shown in Fig. 6. Comparing the results shown in Fig. 6 and in Table I, it can be concluded that when the depth of the first earth layer is greater than \( l_1 = 900 \, \text{m} \), the electromagnetic field and the inductive interference are determined solely from the first earth layer.

\[ \text{B. Two Earth Layers with Mitigation Wires} \]

The previous examined model is further extended to include mitigation wires near the buried telecommunication cable, as shown in Fig. 1(a). The reduction of induced e.m.f. obtained by installing progressively more bare mitigation wires, made of a low resistivity and permeability material such as aluminum, is shown in Table II. From this Table it is clear that buried mitigation wires are very effective.

\[ \text{Finally, flux lines of the electromagnetic field near the } \text{electric traction line are shown in Fig. 7, when the three } \text{aluminum wires are located near to the telecommunication cable. The effect of mitigation of inductive interference level due to the aluminum wires is here easily understood, since the electromagnetic field is compressed toward the electric traction line. In the absence of mitigation wires, the magnetic field would have a } y\text{-axis symmetry and flux lines in the telecommunication cable region would be similar to those of the left part of } y\text{-axis of Fig. 7.} \]

\[ \text{C. Three Earth Layers} \]

Consider now a model with three earth layers, as shown in Fig. 1(a), having layer thicknesses \( t_1 = 100 \, \text{m}, t_2 = 300 \, \text{m} \) and \( t_3 = 1600 \, \text{m} \) respectively. The separation distance \( d \) between the electric traction line and the telecommunication cable
is equal to 60 m and no mitigation wires are present. A parametric analysis for various resistivities of the three earth layers, concerning the e.m.f. induced in the telecommunication cable, is presented in Table III. This table, in the case of $\rho_1 = \rho_2 = \rho_3 = 100 \, \Omega \cdot m$ shows induced e.m.f. equal to 37.754 V, while in the case of $\rho_1 = \rho_2 = \rho_3 = 1000 \, \Omega \cdot m$ equal to 45.774 V. These two cases lead to the minimum and maximum e.m.f. values and correspond to the minimum and maximum inductive interference levels respectively. From the other results of Table III it can be concluded that e.m.f. is mainly influenced by the resistivities of the second and the third earth layer. The corresponding influence of the resistivity of the first earth layer is negligible, because $t_1$ is only 100 m.

All the above calculations have been made for a supply current $I_s$ equal to 1000 A. However, MVP distribution and therefore eddy current values are proportional to the supply current, so the presented results may be easily used for any given supply current $I_s$.

From all the previous results it is evident that resistivity measurements in relative small depths, in an attempt to simulate the...
inductive interference problem using a homogeneous earth, may lead to an erroneous earth model. This model may lead to an inaccurate determination of the inductive interference problem.

V. CONCLUSIONS

The electromagnetic field problem of an ac electric traction line in the presence of nonhomogeneous earth and a telecommunication cable has been numerically solved, using the finite element method. Magnetic vector potential distribution in the cross-section of the parallel exposure and the longitudinal electromotive force induced in the telecommunication cable may be easily computed with the proposed method, for any nonhomogeneous earth model. Many different earth models have been examined. Useful conclusions concerning the influence of the earth structure on the inductive interference levels are presented.

Mitigation wires performance has also been investigated. It is concluded that a nonhomogeneous earth model is essential for the accurate computation of the inductive interference levels and for the effective design of mitigation systems.

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REFERENCES


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