Inductive Interference caused to Telecommunication Cables by Nearby AC Electric Traction Lines. Measurements and FEM Calculations

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Abstract: The present work investigates the inductive interference caused by ac electric traction lines to nearby buried telecommunication cables. Measurements according to the directives of the International Telecommunication Union (ITU) and calculations using the Finite Element Method (FEM) are presented for a real system. This system consists of an ac electric traction line of the Greek Railways Organization and a buried cable of the Greek Telecommunications Organization. Finally, an analysis concerning the most important operational parameters in determining electric traction line influence is presented. Such parameters are the separation distance between the electric traction line and the buried telecommunication cable, the earth resistivity as well as the number and the material of the mitigation wires.

Keywords: electric traction lines, telecommunication cables, inductive interference, finite element method.

I. INTRODUCTION

The proximity of power transmission lines, electric traction lines and telecommunication networks has become more and more frequent, because of the continual increase in energy consumption and communication requirements. 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 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 inductive interference is present, 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.

Using initially the widely known Carson's relation's [1], various formulae have been proposed [2-4] to study the above interference. The introduction of computers has brought a considerable improvement to the procedures for interference calculations, appearing along an influence area, leading to advanced analytical models [5-9]. Recently a Finite Element Method (FEM) approach has been proposed [10], in order to determine the electromagnetic field and the inductive interference generated by power transmission lines to nearby buried conductors. The FEM approach of [10] may also be applied to determine the inductive interference caused by ac electric traction lines to nearby telecommunication cables.

In this paper a real system has been examined, consisting of an ac electric traction line of the Greek Railways Organization (OSE) sharing a common corridor with a shielded buried cable of Greek Telecommunications Organization (OTE). The examined electric traction line has been recently constructed and is still under testing procedures.

In order to study the inductive interference caused to the shielded telecommunication cable, a short circuit test has been carried out in the electric traction line. The location of the short circuit was in a terminal of the electric traction line, far away from the telecommunication cable. Conductive interference is therefore negligible and the inductive interference, due to the magnetic field, prevails. In order to analyze this interference, measurements according to directives [7] of the International Telecommunication Union (ITU) as well as FEM calculations have been performed.

II. SYSTEM ARRANGEMENT

The real system, which has been examined, is shown in Fig.1. This system consists of an ac electric traction line of OSE sharing a common corridor with a buried cable of OTE,

as shown in Fig.1b. The electric traction line connects the city of Thessaloniki with the area of Idomeni at the north borders of the country, while the buried telecommunication cable connects the town of Polikastro with the town of Limnotopos. The telecommunication cable is running parallel and close to the electric traction line for several kilometers, while near the two terminals of the cable, in the areas of Polikastro and Limnotopos, the exposure is oblique.

(a)

(b)

(c)

Fig.1a) Cross-section of the system under investigation
b) Top view of the examined system
c) Detailed telecommunication cable cross-section

The cross-section of the examined telecommunication cable is shown in Fig.1c. 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. After the external sheath there is PVC insulation.

As shown in Fig.1a, 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 the area of Thessaloniki and one in the area of Polikastro.

The examined electric traction line has been recently constructed and is still under testing procedures. In order to study the inductive interference caused to the shielded telecommunication cable, a short circuit test has been carried out in the electric traction line, using a controlled power supply. The location of the short circuit was in Idomeni far away from the telecommunication cable, while the electric traction line has been supplied with a 50 Hz current from the traction power substation of Thessaloniki, as shown in Fig.1b. The duration of the short circuit test was thirty minutes. The steady state rms current I_s in the electric traction line has been measured, during the short circuit test, equal to 420 A. It should be mentioned that this is almost equal to the maximum expected supply current flowing in the electric traction line section which is close to the telecommunication cable, during normal operation of the electric locomotive.

Finally, it should be remarked that earth resistivity measurements have been carried out in various points across the telecommunication cable route. The earth resistivity has been found equal to 50 Ωm in all the measurement points. This result is justified, because the ground in the area is rural and does not present variations.
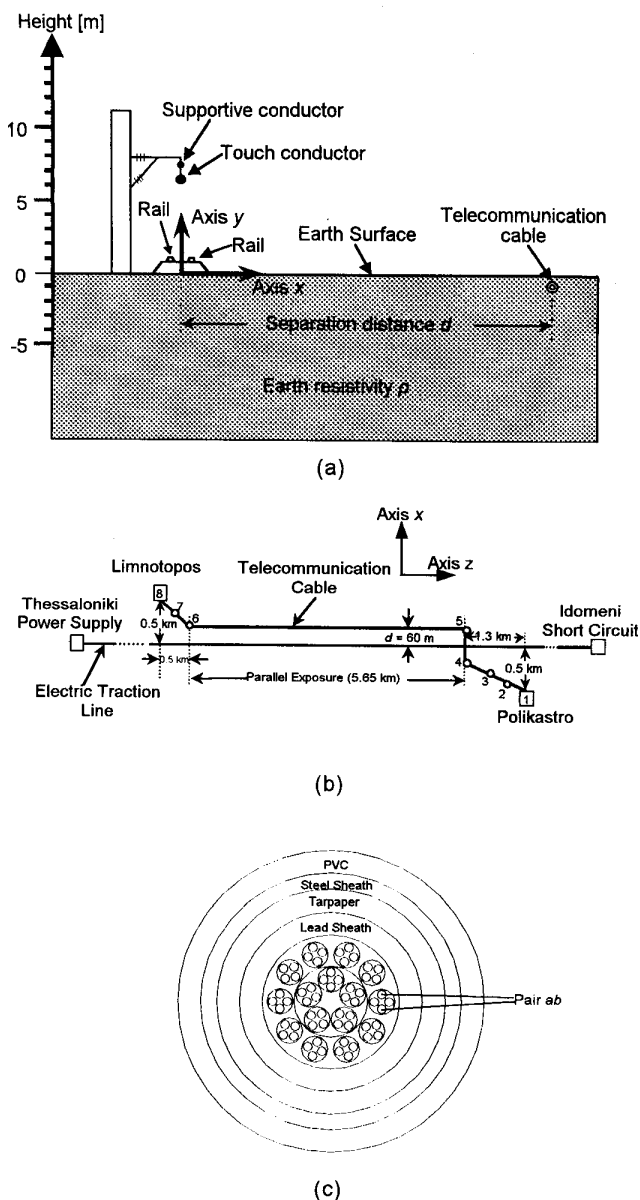
III. INDUCTIVE INTERFERENCE MEASUREMENTS

In order to estimate the inductive interference caused by the ac electric traction line to the nearby telecommunication cable measurements have been carried out, according to ITU directives [7]. The measurements took place on September 19, 1997, in the center of OTE at Polikastro, during the above described short circuit test.

In particular, the voltage across a pair ab of the telecommunication cable and its grounded sheath has been measured as shown in Fig.2, using a measurement device, connected to a Laptop Personal Computer equipped with a data acquisition card. The sampling frequency was 64 kHz. The pair ab has been connected with the grounded sheath of the cable in the center of OTE at Limnotopos. The measured voltage is the longitudinal electromotive force e.m.f. induced

in the circuit formed by the conductors of the telecommunication cable pair *ab* and earth, by the current flowing in the electric traction line. According to [7], this e.m.f. is dangerous for workers and equipments when the circuit formed with earth is closed. This happens in the examined system, for example, if a leakage current flows from the pair *ab* to the ground at the telecommunication center in Limnotopos and concurrently a workman touches the pair *ab* in Polikastro.
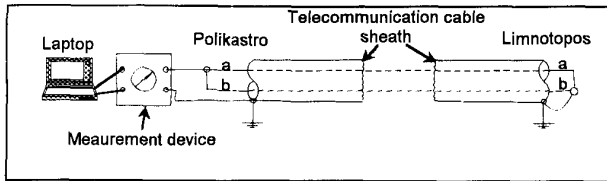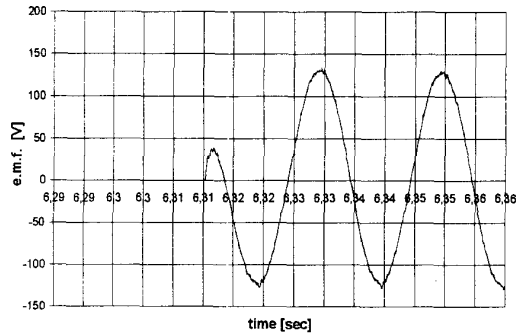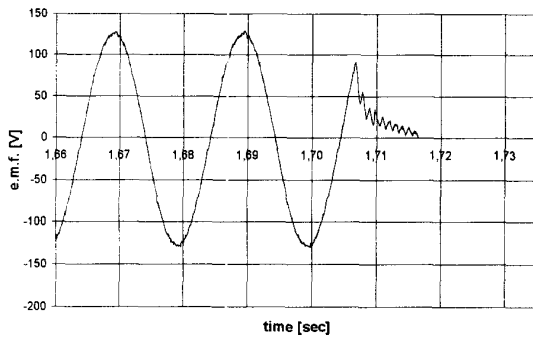

Fig.2. Measurement of the longitudinal electromotive force e.m.f. in the telecommunication cable, according to ITU directives

(a)

(b)

Fig.3. Measured longitudinal electromotive force e.m.f. induced in the telecommunication cable as a function of the time during (a) the connection and (b) the disconnection of the electric traction line respectively.

Fig.3a and Fig.3b show the e.m.f. versus time, during the connection and the disconnection of the electric traction line respectively. Using the maximum values of this voltage in the steady state, i.e. after the connection or before the disconnection of the electric traction line, the rms value of the e.m.f. is found to be equal to 90.6 Volts.

IV. FEM CALCULATIONS

A. Assumptions

In order to solve the examined problem using the FEM the following assumptions have been made:

1. The electric traction line is assumed parallel to the nearby telecommunication cable. This is valid for the examined case, because the telecommunication cable is running parallel to the electric traction line for several kilometers. The small sections of the cable, which are not parallel to the electric traction line, are converted to equivalent parallel sections, according to the ITU directives [7].

2. For the ferromagnetic metal components of the system, i.e. the steel used in the rails and in the telecommunication cable sheath, the permeabilities are treated in the steady state [8-9] as constant. Only in transient studies [9] the nonlinearlity in these materials must be taken into account. Therefore, in the examined steady state case the non-linear effects are neglected.

3. The earth is assumed to be homogeneous, having a resistivity equal to 50 Ωm, although this not a necessity for FEM. This is valid for the examined system, due to the results of the earth resistivity measurements.

4. End effects are neglected, leading to a two dimensional problem. The assumption concerning the ignorance of the end effects is reasonable, because the location of the short circuit was in Idomeni, i.e. in a location 22 km north of the Polikastro. Therefore, conductive interference is negligible and the inductive interference, due to the magnetic field, prevails.

B. Field equations and FEM formulation

The previous assumptions lead to a steady state 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 [10] by the system of equations

$$\frac{1}{\mu_0\mu_r}\left[\frac{\partial^2 A_z}{\partial x^2}+\frac{\partial^2 A_z}{\partial y^2}\right]-j\omega\sigma A_z +J_{sz} = 0 \tag{1a}$$

$$-j\omega\sigma A_z + J_{sz} = J_z \tag{1b}$$

$$\iint_{S_i} J_z ds = I_i \tag{1c}$$

where σ is the conductivity, ω is the angular frequency, μ_0 and μ_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 [11] 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^e_{ez} of element e is obtained from relation [10]

$$J^e_{ez}(x,y) = -j\omega\sigma A^e_z(x,y) \qquad (2a)$$

and the total element current density J^e_z will be the sum of the conductor-i source current density J_{szi} and of the element eddy current density J^e_{ez} given by (2a), i.e.

$$J^e_z(x,y) = J^e_{ez}(x,y) + J_{szi} \qquad (2b)$$

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

The solution domain of the 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 [12] adaptive mesh generation algorithm has been developed for the original discretization. The continuity requirement of the flux density B on the interface between neighboring elements has been chosen [13] as the criterion for an iteratively adaptive mesh refinement. The original discretization of appr. 2000 elements, using the above criterion, led in almost all cases tested to a mesh of 18000-21000 elements. Relative element distribution in the meshes reveals the good behavior of the criterion chosen. A subsequent refinement is not necessary because, although it rises the number of triangles up to 50%, MVP results are hardly influenced.

C. Parallel and oblique exposures

The FEM may be applied directly to compute the inductive interference caused to the large section 5-6 of the telecommunication cable, shown in Fig.1b, which is parallel to the electric traction line. All the other small sections of the cable, which are not parallel to the electric traction line, are converted to equivalent parallel sections according to the ITU directives [7]. An oblique exposure, as for example the section 6-8 of the examined telecommunication cable, is considered in [7] as a parallel section having a distance d from the electric traction line equal to

$$d = \sqrt{d_1 \cdot d_2} \qquad (3)$$

provided that $\dfrac{1}{3} \le \dfrac{d_1}{d_2} \le 3$.

If $\dfrac{d_1}{d_2}$ is outside these two limits, the section 6-8 is divided into sections 6-7 and 7-8 so that $\dfrac{d_1}{d_3}$ and $\dfrac{d_3}{d_2}$ lie between $\dfrac{1}{3}$ and 3 (see Fig.4). The section 6-7 is converted to

a parallel section, having a distance from the electric traction line $d = \sqrt{d_1 \cdot d_3}$, while the section 7-8 is converted to a parallel section, having a distance from the electric traction line $d = \sqrt{d_3 \cdot d_2}$. The lengths of these equivalent parallel sections are equal to the projections l_1 and l_2 of the sections 6-7 and 7-8 to the electric traction line respectively.
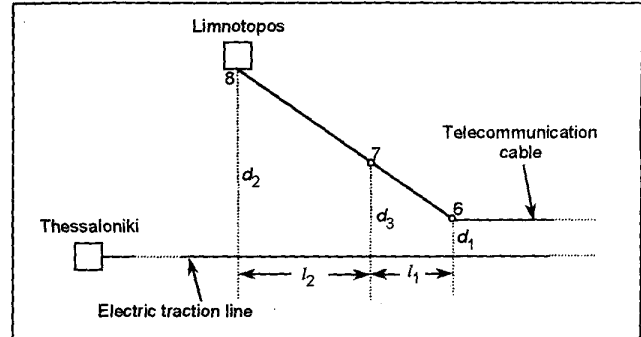

Fig.4. Conversion of the section 6-8 of the examined telecommunication cable to equivalent parallel sections, according to ITU directives [7]

According to the previous analysis, the section 1-4 of the examined telecommunication cable of Fig.1b is also converted to equivalent parallel sections. Finally, it should be pointed out that the inductive interference on the telecommunication cable section 4-5 (shown in Fig.1b) is negligible, because this section is perpendicular to the electric traction line.

D. Calculation of the longitudinal electromotive force e.m.f.

The longitudinal electromotive force e.m.f. induced in the telecommunication cable is calculated from the following equation

$$e.m.f. = -j\,2\,\pi\,f\sum_{i=1}^{n}\Phi_i \qquad (4)$$

where :

f is the frequency of the inducing current in Hz (in the examined case $f = 50$ Hz);

n is the number of the equivalent parallel sections in which the cable is converted;

Φ_i is the flux of the electromagnetic field through the parallel section i of the telecommunication cable and the ground.

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

$$\Phi_i = A_{zi}\,l_i \qquad (5)$$

where A_{zi} is the MVP, derived from FEM calculations, in the parallel section i of the telecommunication cable and l_i is the length of this parallel section.

Table 1 summarizes the conversion of the sections of the examined telecommunication cable to parallel sections. Furthermore, Table 1 presents FEM calculation results for all these parallel sections. All the FEM calculations have been made for the measured steady state rms current in the electric traction line I_s = 420 A and for the measured earth resistivity ρ = 50 Ωm. Using Table 1 results and equations (4)-(5), the amplitude of the e.m.f. induced in the examined telecommunication cable is calculated equal to 95.1 Volts. Comparing this result with the measured value of 90.6 Volts it is evident that the FEM is in good agreement with the measurements and on the safe side.

TABLE 1

Conversions of sections of the examined telecommunication cable to equivalent parallel sections and MVP A_z values as obtained by FEM for all these parallel sections. d_1 is the distance of the first terminal of a section from the electric traction line, d_2 is the distance of the second terminal of a section from the electric traction line, d is the separation distance between the equivalent parallel section and the electric traction line and l is the projection of a section to the electric traction line.

Sections	d_1 [m]	d_2 [m]	$d = \sqrt{d_1 d_2}$ [m]	l [m]	A_z [Wb / m $\angle$ °]
1 – 2	500	300	387.3	750	1.64E-05 $\angle$ -118.0
2 – 3	300	100	173.21	400	2.78E-05 $\angle$ -102.0
3 – 4	100	60	77.45	150	4.17E-05 $\angle$ -94.6
5 – 6	60	60	60.0	5650	4.65E-05 $\angle$ -93.0
6 – 7	60	170	101.0	100	3.77E-05 $\angle$ -97.4
7 – 8	170	500	291.5	400	2.08E-05 $\angle$ -111.6

V. Operational Parameters Influence

Using the FEM approach, an investigation concerning the most important operational parameters in determining ac electric traction line influence is performed. Such parameters are the separation distance between the electric traction line and the buried telecommunication cable, the earth resistivity as well as the number and the material of the mitagion wires.

Fig.5 presents the induced longitudinal electromotive force e.m.f. as a function of the separation distance d between the electric traction line and the buried telecommunication cable for various earth resistivities ρ. The calculations have been made using FEM and equations (4)-(5), for a steady state current I_s in the electric traction line equal to 420 A at a frequency 50 Hz. The length l of parallel exposure between the electric traction line and the telecommunication cable is equal to 1km. However, the electromagnetic field flux Φ and hence the induced e.m.f. are proportional to the steady state current and to the length of parallel exposure, so the presented curves in Fig.5 may be easily used for any given steady state current I_s and length l of parallel exposure.
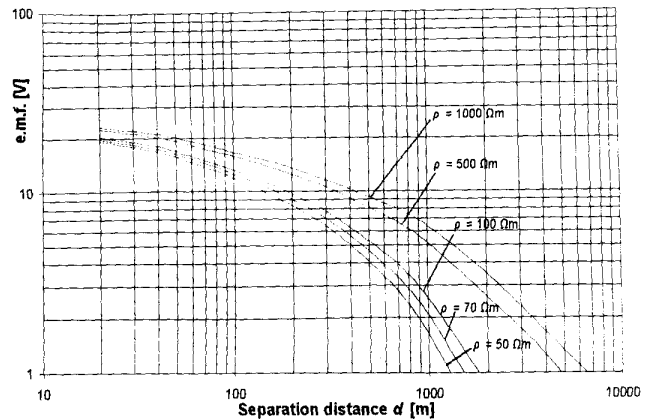

Fig.5. Induced longitudinal electromotive force e.m.f. as a function of the separation distance d between the electric traction line and the buried telecommunication cable, for various earth resistivities ρ.

Consider now that mitigation wires are installed near the telecommunication cable of Fig.1a, 1 m to the left from this cable axis. The reduction of e.m.f. obtained by installing progressively more bare mitigation wires, is shown in Table 2. These wires are made of a low resistivity and permeability material such as aluminum or copper. The calculations have also been made for I_s = 420 A and for l = 1 km. From Table 2 it is clear that buried mitigation wires may be very effective.

TABLE 2

Effect of aluminum and copper mitigation wires on e.m.f. The earth resistivity ρ is equal to 50 Ωm and the separation distance d is equal to 60 m. The bare mitigation wires have a radius equal to 5 mm and they are located at a distance equal to 1 m to the left from the telecommunication cable axis.

Number of Mitigation Wires	Material : Al e.m.f. [V]	Material : Al Reduction %	Material : Cu e.m.f. [V]	Material : Cu Reduction %
0	14.60		14.6	
1	8.90	39.0	7.96	45.5
2	6.66	54.4	5.80	60.3
3	5.27	63.9	4.38	70.0

Finally, equipotential lines (A_z = ct) of the electromagnetic field in the region between the electric traction line and the telecommunication cable are shown in Fig.6, when the three 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 towards the electric traction line. In the absence of mitigation wires, only the rails and the telecommunication cable influence the electromagnetic field and the equipotential lines have almost complete y-axis symmetry, as shown in Fig.7-8.
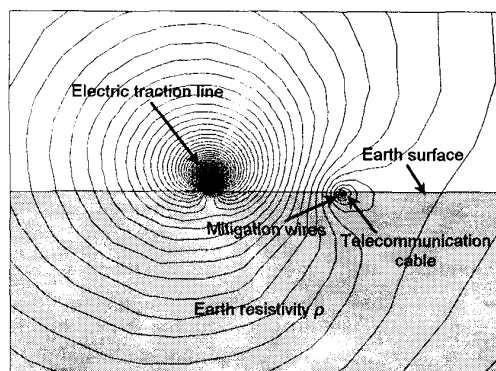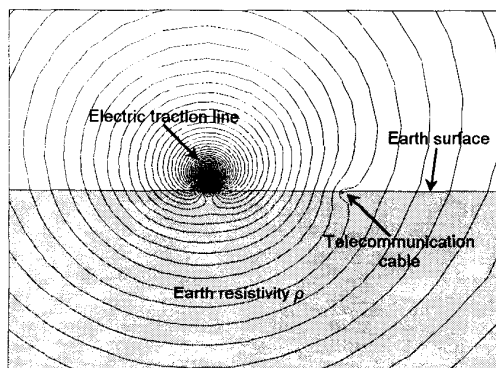
Fig.6. Equipotential lines (A_z = ct) of the electromagnetic field in the region between the electric traction line and the telecommunication cable, when the three aluminum wires are located near to the telecommunication cable. The earth resistivitiy ρ is equal to 50 Ωm and the separation distance is d = 60 m.

Fig.7. Equipotential lines (A_z = ct) of the electromagnetic field in the region between the electric traction line and the telecommunication cable in the absence of mitigation wires. The earth resistivity ρ is equal to 50 Ωm and the separation distance is d = 60 m.
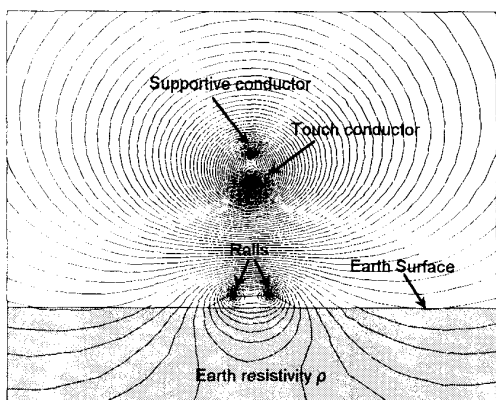

Fig.8. Equipotential lines (A_z = ct) of the electromagnetic near the electric traction line in the absence of mitigation wires. The earth resistivity ρ is equal to 50 Ωm and the separation distance is d = 60 m.

VI. CONCLUSIONS

The inductive interference caused by ac electric traction lines to nearby telecommunication cables has been investigated. In order to analyze this interference, a real system consisting of an ac electric traction line of the Greek Railways Organization and a nearby cable of the Greek Telecommunications Organization has been considered. Measurements according to International Telecommunication Union (ITU) directives [7] as well as Finite Element Method (FEM) calculations have been performed. The results show that the FEM is in good agreement with the corresponding measurements and on the safe side.

Finally, useful conclusions concerning the influence of the separation distance between the electric traction line and the telecommunication cable, of the earth resistivity and of the mitigation wires on the inductive interference levels have been obtained, by using a FEM parametric study.

VII. ACKNOWLEDGEMENTS

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IX. BIOGRAPHIES

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Dimitris P. Labridis (S' 87-M' 90) was born in Thessaloniki, Greece, on July 26, 1958. He received the Dipl.-Eng. degree and the Ph.D. degree from the Department of Electrical Engineering at the Aristotle University of Thessaloniki, in 1981 and 1989 respectively.

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Petros S. Dokopoulos (M' 77) was born in Athens, Greece, in September 1939. He received the Dipl. Eng. degree from the Technical University of Athens in 1962 and the Ph.D. degree from the University of Brunswick, Germany, in 1967.

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