Finite Element Computation of Field and Eddy Currents of a System Consisting of a Power Transmission Line Above Conductors Buried in Nonhomogeneous Earth

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Abstract: The present work investigates the electromagnetic field and the eddy currents of a system consisting of a faulted power transmission line above parallel conductors buried in nonhomogeneous earth. The electromagnetic field diffusion equation has been numerically solved, using finite element method (FEM). Using FEM results, magnetic vector potential distribution in the cross-section of the parallel exposure, as well as eddy currents induced in all conductive parts, are calculated for various nonhomogeneous earth models. An analysis concerning the most important operational parameters in determining power transmission line influence is presented. Such parameters are the depth of the first earth layer, the resistivities of the different earth layers and the number of the mitigation wires.

Keywords: power transmission lines, eddy currents, finite element methods, nonhomogeneous earth.

I. INTRODUCTION

World-wide tendency is to use a common band of land, which is usually a straight narrow corridor, for utilities such as power transmission lines, pipelines, railroads and communication lines. This policy minimizes the amount of land used. An energized power transmission line in such a corridor causes significant interferences to nearby parallel buried conductors, especially in cases of single-phase faults. These interferences were first studied using the widely-known Carson's relations [1]. Various other approximating formulae have also been proposed, leading to technical recommendations [2-3].

Progress in computing power led to advanced analytical models [4-9]. Recently, two extensive research projects of Electrical Power Research Institute (EPRI) and American Gas Association (AGA) introduced:

i) practical analytical expressions, which could be programmed on hand-held calculators [10-12], and
ii) computerized techniques [13],

for the analysis of power transmission line inductive interference to gas pipelines.

More recently, EPRI and AGA in a joint research developed the ECCAPP program [10-16]. Equivalent circuits with concentrated or distributed elements are used in ECCAPP and the self and mutual impedances are calculated using formulae from Carson [1], Pollaczeck [17] and Sunde [4]. The program combines an input data preprocessor with a computation algorithm, which evaluate effects, defined there as *conductive* and *inductive* interference, for arbitrarily positioned conductors. Combinations of parallel and non-parallel constructions, power line discontinuities, as well as grouping pipeline sections according to their electrical length proposed by [10-12] are also included.

Although the mechanisms by which inductive and conductive interferences arise are well understood, the determination of these effects is a complex procedure. This procedure requires not only a good knowledge of conductors layout, power transmission line and pipeline electrical and geometrical properties, but also an accurate representation of the earth.

The earth model is of particular importance for the determination of interference levels and of the performance of mitigation systems. Without an adequate modeling of the earth structure, the mitigation systems have to be conservatively estimated, in order to ensure a sufficient protection. When the earth structure is accurately modeled, effective and low-cost mitigation designs may be evaluated.

Therefore, this paper addresses the influence of nonhomogeneous earth on the electromagnetic field and on the eddy currents induced in all conductive parts, i.e. in overhead ground wires, mitigation wires, buried pipeline and earth layers. The use of finite elements method (FEM) for the solution of Maxwell's equations leads always to useful conclusions, even in the case of complex electromagnetic field problems. Therefore, a procedure based on FEM has been proposed to solve the two dimensional electromagnetic field problem of a faulted power transmission line, in the presence of buried conductors and nonhomogeneous earth.

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II. THE ELECTROMAGNETIC FIELD PROBLEM

A. System arrangement and assumptions justification

To investigate the influence of nonhomogeneous earth on the electromagnetic field of a power transmission line, a typical system shown in Fig.1 has been chosen. This system consists of a power transmission line running parallel for some kilometers to a buried pipeline, as shown in Fig.1c. The assumption that the power line is parallel to the buried pipeline for some kilometers is valid for many practical applications, when both are located in straight narrow corridors.

The power transmission line consists of an ACSR (HAWK) two conductors bundle per phase. The buried pipeline, the cross section of which is shown in Fig.1b, is wrapped in an electrically insulating coating and has been dimensioned according to characteristics given in Appendix of [16].The separation distance d between the power transmission line and the parallel buried pipeline is shown in Fig.1a.

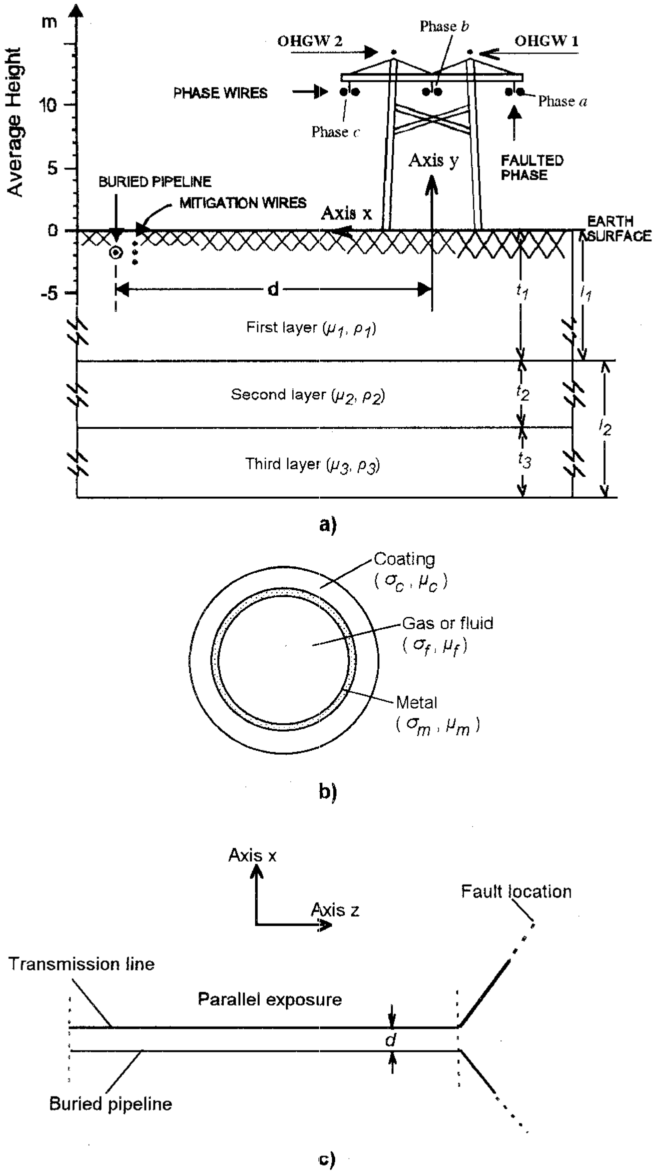


Fig.1. a) Cross-section of the system under investigation
b) Detailed pipeline cross-section
c) Top view of the parallel exposure

Pipeline's metal and overhead ground wires (OHGW) have conductivities σ_m=σ_g=7.0E+06 S/m and relative permeabilities $\mu_{rm} = \mu_{rg} = 250$ respectively. For these ferromagnetic metal components of the system, i.e. the steel used in the ground wires and in the pipeline, the non-linear effects are not considered. This may be easily justified, because the maximum occurring magnetic field values are low and therefore cannot force these materials into saturation. For example, the magnetic flux density on OHGW #1 under the fault conditions examined in chapter III of this paper is lower than 0.45 T, while the corresponding magnetic flux density on the pipeline cannot exceed 0.052 T. Both are obtained from the most pessimistic case examined, i.e. when d = 25 m and ρ_1=ρ_2=ρ_3=1000 Ωm.

Pipeline's coating has a conductivity σ_c=1E-13 S/m, which is a common accepted value for synthetic coatings, and a relative permeability $\mu_{rc} = 1$. Aluminum mitigation wires shown in Fig.1a are bare. In order to avoid possible corrosion problems, a system to protect these bare mitigation wires against corrosion may be required. The earth finally is subdivided in layers with different resistivities, while their relative permeabilities are $\mu_{r1} = \mu_{r2} = \mu_{r3} = 1$. These layers, shown in Fig.1a, are assumed to be homogeneous across the x-dimension, although this is not a necessity for the method developed.

A standard power frequency of 60.0 Hz has been used to simulate a single-phase fault. This fault is happening outside of the parallel exposure, as shown in Fig.1c. Therefore, conductive interference is negligible and only the inductive interference, due to the magnetic field, exists. Consequently eddy currents are induced in buried pipeline, mitigation wires, OHGW and earth layers. 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.

B. 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 [18] by the system of equations

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

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

$$\iint_{S_i} J_z ds = I_i \qquad (1c)$$

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 [19] 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 the relation [18]

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

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 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 [20] 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 [21] as the criterion for an iteratively adaptive mesh refinement. The original discretization of appr. 5000 elements, using the above criterion, led in almost all cases tested to a mesh of 22000-24000 elements. Relative element distribution in this mesh 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.

III. INVESTIGATION OF NONHOMOGENEOUS EARTH INFLUENCE

The power transmission line system shown in Fig.1 has been investigated for several different configuration cases. The system of equations (1a-c) has been solved and MVP distribution is calculated for various nonhomogeneous earth models.

A. Two earth layers without mitigation wires

Suppose that in the system of Fig.1a 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 km - l_1. The layers extend across x-axis up to 2 km from the power transmission 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 ρ_1 = 100 Ωm (dry earth) and ρ_2 = 1000 Ωm (rocky earth) respectively. The parametric analysis for l_1, concerning the pipeline eddy current I_p, 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 the resistivities of the earth layers of Fig.1a are $\rho = \rho_1 = \rho_2 = \rho_3$) having resistivity ρ = 100 Ωm or ρ = 1000 Ωm has given the results shown in Table 1. Comparing eddy current values of Table 1 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 = 400 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, since when l_1 is equal to 50 m, the eddy current I_{SEL} induced in the second earth layer is three times bigger than the eddy current I_{FEL} induced in the first earth layer. The contrary condition holds when l_1 is equal to 400 m.

The influence of the depth of the first earth layer may be easily understood from Fig.4-5, in which flux lines are shown for two cases with l_1 = 50 m and l_1 = 400 m respectively. From the MVP distribution of Fig.4, which is valid for a first earth layer depth l_1 = 50, 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 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.

Finally, the first and second earth layers are assumed to have ρ_1 = 1000 Ωm and ρ_2 = 100 Ωm respectively. The corresponding parametric analysis for the depth of the first earth layer, concerning the pipeline eddy current I_p, is now shown in Fig.6. Comparing the results shown in Fig.6 and in Table 1, it can be concluded that when the depth of the first earth layer is greater than $l_1 = 900$ m, the electromagnetic field and the inductive interference are determined solely from the first earth layer.

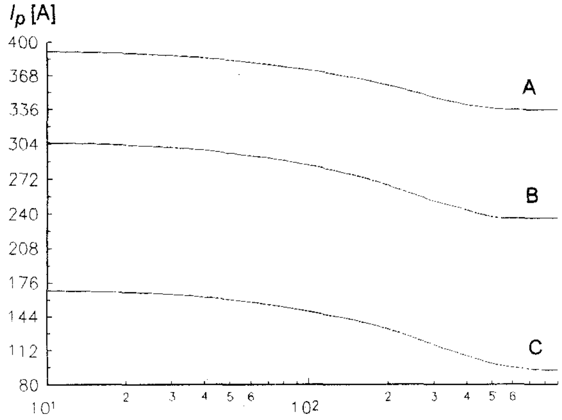


Fig.2. Pipeline eddy current I_p as a function of the depth of the first earth layer of Fig.1a, for a two earth layer model with resistivities $\rho_1 = 100\ \Omega$ and $\rho_2 = 1000\ \Omega$. Curve A corresponds to separation distance 25 m, curve B to 100 m and curve C to 500 m.

B. Two earth layers with mitigation wires

The previous examined model is further extended to include mitigation wires near the pipeline, as shown in Fig.1a. The reduction of pipeline eddy current I_p obtained by installing progressively more bare mitigation wires, made of a low resistivity and permeability material such as aluminum, is shown in Table 2. From this Table it is clear that buried mitigation wires are very effective. This Table also shows that if the depth of the first earth layer is equal to 250 m, the resistivities of the two earth layers have almost the same influence on the electromagnetic field and on the inductive interference.

Table 3 shows the eddy currents induced in OHGW, earth layers, buried pipeline and mitigation wires by a current $I_F = 1000$ A of the faulted phase *a*. These currents are shown for both cases, i.e. with and without the three aluminum mitigation wires shown in Fig.1a. It can be observed that in the absence of mitigation wires, the eddy currents induced in the pipeline and in the two earth layers are bigger compared to the corresponding values obtained when the three aluminum mitigation wires have been installed.

Finally, flux lines of the electromagnetic field near the power transmission line are shown in Fig.7, when the three aluminum wires are located near to the pipeline. 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 faulted power line. In the absence of mitigation wires, the magnetic field would have a y-axis symmetry and flux lines in the pipeline region would be similar to those of the left part of y-axis of Fig.7.

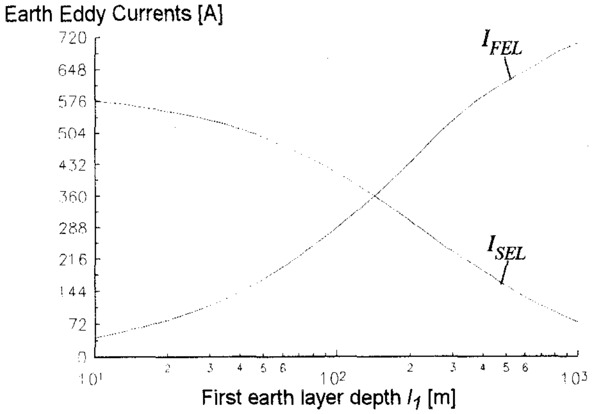


Fig.3. Eddy currents induced in the earth layers as a function of the depth of the first earth layer, for a two earth layer model with resistivities $\rho_1 = 100\ \Omega$ and $\rho_2 = 1000\ \Omega$. The separation distance *d* is equal to 100 m. I_{FEL} is the eddy current induced in the first earth layer and I_{SEL} the eddy current induced in the second earth layer.

C. Three earth layers

Consider now a model with three earth layers, as shown in Fig.1a, having layer thicknesses $t_1 = 10$ m, $t_2 = 190$ m and $t_3 = 1800$ m respectively. The separation distance *d* between the power transmission line and the buried pipeline is equal to 100 m and no mitigation wires are present. A parametric analysis for various resistivities of the three earth layers, concerning pipeline eddy current I_p, is presented in Table 4. This Table, in the case of $\rho_1 = \rho_2 = \rho_3 = 100\ \Omega$m shows pipeline eddy current equal to 234.77 A, while in the case of $\rho_1 = \rho_2 = \rho_3 = 1000\ \Omega$m equal to 307.7 A. These two cases lead to the minimum and maximum pipeline eddy current values and correspond to the minimum and maximum inductive interference levels respectively. From the other

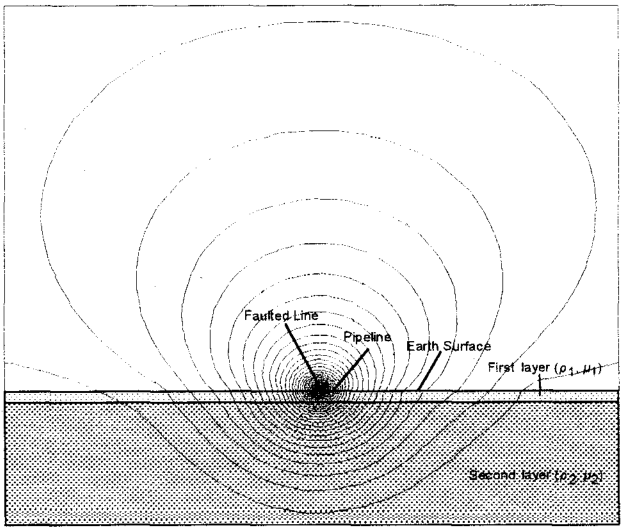


Fig.4. Flux lines (A = const) of the electromagnetic field, for a two earth layer model with resistivities $\rho_1 = 100\ \Omega$ and $\rho_2 = 1000\ \Omega$. The depth of the first earth layer is $l_1 = 50$ m while separation distance is $d = 100$ m.

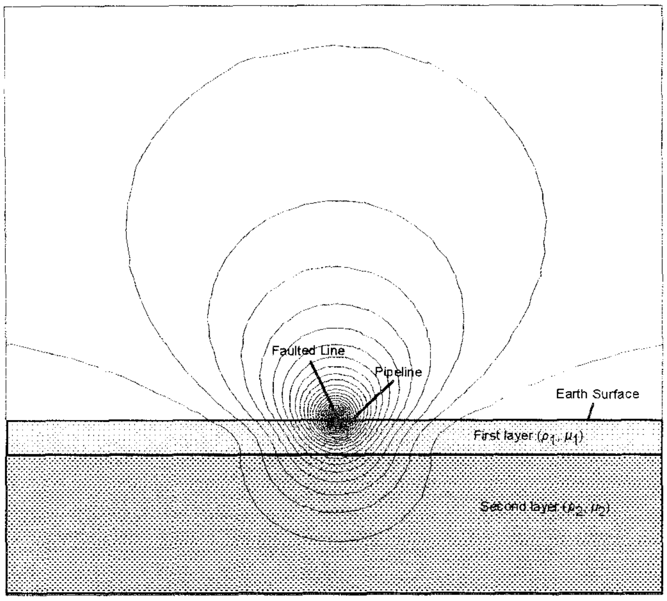


Fig.5. Flux lines (A = const) of the electromagnetic field, for a two earth layer model with resistivities ρ_1 = 100 Ω and ρ_2 = 1000 Ω. The depth of the first earth layer is l_1 = 400 m while separation distance is d = 100 m.

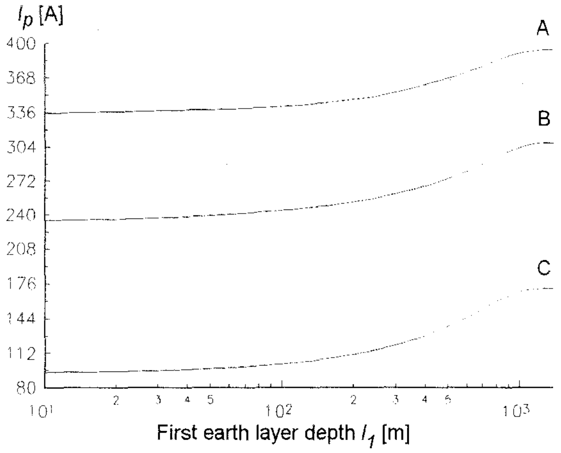


Fig.6. Pipeline eddy current I_p as a function of the depth of the first earth layer of Fig.1a, for a two earth layer model with resistivities ρ_1 = 1000 Ω and ρ_2 = 100 Ω. Curve A corresponds to separation distance 25 m, curve B to 100 m and curve C to 500 m.

TABLE 1

Pipeline eddy current I_p for homogeneous earth (i.e. when resistivities of the three layers shown in Fig.1a are $\rho_1 = \rho_2 = \rho_3 = \rho$) for various separation distances d.

	ρ = 100 Ωm	ρ = 1000 Ωm
Separation distance d [m]	I_p [A]	I_p [A]
25	333.48	393.60
100	234.77	307.70
500	93.44	171.71

TABLE 2

Effect of the buried mitigation wires of Fig.1a on pipeline eddy current I_p, for a two earth layer model. The depth of the first earth layer l_1 is equal to 250 m, the separation distance d is equal to 200 m, the bare mitigation wires have a radius equal to 5 mm and they are located at a distance equal to 1 m right to the pipeline axis.

	ρ_1=100, ρ_2=1000 [Ωm]	ρ_1=1000, ρ_2=100 [Ωm]
Number of Aluminum Mitigation Wires	I_p [A]	I_p [A]
none	216.02	210.35
1	173.10	168.07
2	142.80	138.21
3	121.58	117.09

results of Table 4 it can be concluded that I_p 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 10 m.

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

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.

TABLE 3

Eddy currents induced in OHGW, earth layers, buried pipeline and mitigation wires by the current I_F = 1000 A of the faulted conductor for a two earth layer model with resistivities ρ_1 = 100 Ω and ρ_2 = 1000 Ω. The depth of the first earth layer l_1 is equal to 250 m, the separation distance d is equal to 200 m, the bare mitigation wires have a radius equal to 5 mm and they are located at a distance equal to 1 m right to the pipeline center.

$I_F = I_a = 1000$ A $< 0^\circ$, $I_b = I_c = 0$ A		
Eddy Currents	No mitigation wires	Three mitigation wires
I_{g1} (1st OHGW)	60.53 A < -142°	60.10 A < -141°
I_{g2} (2nd OHGW)	50.93 A < -144°	50.48 A < -143°
I_{FEL} (1st Earth Layer)	501.03 A < -160°	467.98 A < -157°
I_{SEL} (2nd Earth Layer)	274.09 A < 147°	256.18 A < 150°
I_p (Pipeline)	216.02 A < 159°	121.58 A < 139°
I_{m1} (1st mitigation wire)		55.21 A < 167°
I_{m2} (2nd mitigation wire)		52.51 A < 160°
I_{m3} (3rd mitigation wire)		56.75 A < 173°
I_R (Total return current)	991.7 A < -179.3°	992.27 A < -179.4°

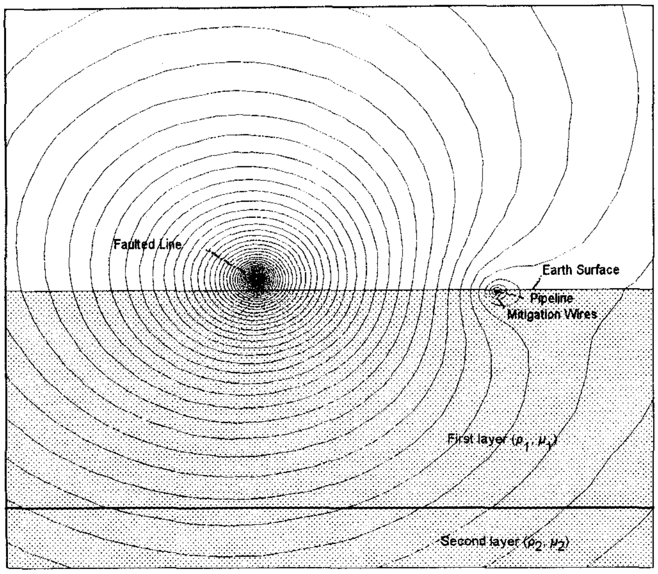


Fig.7. Flux lines (A = const) of the electromagnetic field near the transmission line, for a two earth layer model with resistivities $\rho_1 = 100\ \Omega$ and $\rho_2 = 1000\ \Omega$. The depth of the first earth layer is $l_1 = 250$ m, the separation distance is $d = 200$ m and three aluminum mitigation wires are located near the pipeline.

TABLE 4

Pipeline eddy current I_p, for various resistivities of the three earth layer model of Fig.1a having layer thickness $t_1 = 10$ m, $t_2 = 190$ m and $t_3 = 1800$ m. The separation distance in all cases is $d = 100$ m.

ρ_1 [Ωm]	ρ_2 [Ωm]	ρ_3 [Ωm]	I_p [A]
100	100	100	234.77
100	100	500	258.35
100	100	1000	265.25
100	500	100	255.63
100	500	500	283.96
100	500	1000	301.52
100	1000	100	257.30
100	1000	500	289.54
100	1000	1000	304.80
500	100	100	235.03
500	100	500	259.69
500	100	1000	265.89
500	500	100	256.43
500	500	500	286.84
500	500	1000	303.85
500	1000	100	258.09
500	1000	500	291.29
500	1000	1000	307.11
1000	100	100	235.70
1000	100	500	259.86
1000	100	1000	266.10
1000	500	100	256.53
1000	500	500	287.75
1000	500	1000	304.18
1000	1000	100	258.87
1000	1000	500	291.51
1000	1000	1000	307.70

IV. CONCLUSIONS

The electromagnetic field problem of a power transmission line in the presence of nonhomogeneous earth and buried conductors has been numerically solved, using finite element method. Magnetic vector potential distribution in the cross-section of the parallel exposure and eddy currents induced in OHGW, earth layers, pipeline and mitigation wires 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.

V. REFERENCES

[1] J. R. Carson "Wave Propagation in Overhead Wires with Ground Return", Bell System Technical Journal, Volume 5, October 1926, pp.539-554.

[2] Technical Recommendation No 7: " Arbitration Agency for Problems of Interference Between Installations of the German Federal Railways, the German Federal Post Office and the Association of German Power Utilities", Verlags und Wirtschaftsgesellschaft der Elektrizitatswerke mbH - VWEW, May 1982.

[3] Pohl, J., : Beeinflussung von umhullten Rohrleitungen durch Hochspannungsfreileitungen, CIGRE-Conference 1966, Bericht Nr. 326.

[4] E. D. Sunde, "Earth Conduction Effects in Transmission Systems", Dover Publications, New York, 1968.

[5] A. Taflove, J. Dabkowski, "Mitigation of Buried Pipeline Voltages Due to 60 Hz AC Inductive Coupling - Part I, Design of Joint Rights-Of-Way", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-98, No. 5 Sept/Oct 1979

[6] J. Dabkowski, A. Taflove, "Mitigation of Buried Pipeline Voltages Due to 60 Hz AC Inductive Coupling - Part II, Pipeline Grounding Methods", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-98, No. 5 Sept/Oct 1979

[7] F. Dawalibi, D. Mukhedkar, "Optimum Design of Substation Grounding in Two-Layer Earth Structure - Part I, Analytical Study", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-94, No. 2, March/April 1975, pp. 252-261.

[8] F. Dawalibi, D. Mukhedkar, "Optimum Design of Substation Grounding in Two-Layer Earth Structure - Part II, Comparison Between Theoretical and Experimental Results", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-94, No. 2, March/April 1975, pp. 262-266.

[9] F. Dawalibi, D. Mukhedkar, "Optimum Design of Substation Grounding in Two-Layer Earth Structure - Part III, Study of Grounding Grids Performance and New Electrode Configurations", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-94, No. 2, March/April 1975, pp. 267-272.

[10]J. Dabkowski, A. Taflove, Mutual Design Considerations for Overhead AC Transmission Lines and Gas Transmission Pipelines - Volume 1: Engineering Analysis. EPRI Report EL - 904, September 1978, Chapter 3.

[11]A. Taflove, J. Dabkowski, "Prediction Method for Buried Pipeline Voltages Due to 60 Hz AC Inductive Coupling - Part I, Analysis", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-98, No. 3 May/June 1979.

[12]J. Dabkowski, A. Taflove, "Prediction Method for Buried Pipeline Voltages Due to 60 Hz AC Inductive Coupling - Part II, Field Test Verification", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-98, No. 3 May/June 1979.

[13]Fraiser et autrs "Power Line-Induced AC Potential on Natural Gas Pipelines for Complex Rights-of-Way Configurations", EPRI/A.G.A. Project 742-2, EL-3106/PR-151-127, May/November, 1983.

[14]"Power Line Fault Current Coupling to Nearby Natural Gas Pipelines", EPRI/A.G.A. Project 742. EL-5472/PR176-510, November 1987.

[15]F. Dawalibi, R. D. Southey, "Analysis of Electrical Interference from Power Lines to Gas Pipelines Part I: Computation Methods," *IEEE Transactions on Power Delivery*, Vol. 4, No. 3, July 1989, pp. 1840-1846.

[16]F. Dawalibi, R. D. Southey, "Analysis of Electrical Interference from Power Lines to Gas Pipelines Part II: Parametric Analysis," *IEEE Transactions on Power Delivery*, Vol. 5, No. 1, January 1990, pp. 415-421.

[17]F. Pollaczeck, "On the Field Produced by an Infinitely Long Wire Carrying Alternating Current", Electrische Nachricten Technik, Volume III, 1029, No. 9, pp. 339-359 (in German). French translation also available in Revue Generale de l' Electricite, Volume 29, 1931, No. 22, pp. 851-867.

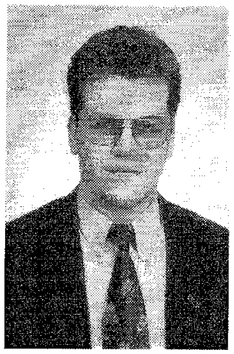
[18]D. Labridis and P. Dokopoulos, "Finite element computation of field, losses and forces in a three-phase gas cable with non-symmetrical conductor arrangement," *IEEE Transactions on Power Delivery*, vol. PWDR-3, October 1988, pp. 1326-1333.

[19]J. Weiss and Z. Csendes, "A one-step finite element method for multiconductor skin effect problems," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-101, October 1982, pp. 3796-3803.

[20]Z.J. Cendes D. Shenton and H. Shahnasser, "Magnetic field computation using Delaunay triangulation and complementary finite element methods," *IEEE Transactions on Magnetics*, vol. MAG-19, November 1983, pp. 2551-2554.

[21]D.P. Labridis, "Comparative presentation of criteria used for adaptive finite element mesh generation in multiconductor eddy current problems", submitted for publication in *IEEE Transactions on Magnetics.*

VI. BIOGRAPHIES



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