Electrical Engineering 80 (1997) 343–348 © Springer-Verlag 1997

The influence of multi-layer ground on the electromagnetic field of an overhead power transmission line in the presence of buried conductors

K. J. Satsios, D. P. Labridis, P. S. Dokopoulos

Contents The present work investigates the two dimensional, quasi stationary, electromagnetic field of a faulted power transmission line in the presence of a buried pipeline, of mitigation wires and of a multi-layer ground. The related diffusion equation has been numerically solved by using the Finite Element Method (FEM). Using FEM results and Faraday's law, magnetic vector potential, as well as the voltages induced across the buried pipeline and remote earth, are calculated. Parametric analysis has shown that there is a significant influence of the depth and resistivity of the first ground layer, of the resistivities of the different ground layers and of the configuration of mitigation wires on the electromagnetic field and on the voltages induced across the buried pipeline and remote earth.

Der Einfluß der mehrschichtigen Erde auf das elektromagnetische Feld einer Übertragungsleitung in der Anwesenheit von unterirdischen Leitern

Übersicht In der vorliegenden Arbeit wird das zweidimensionale, quasi stationäre, elektromagnetische Feld einer mit einem Fehler behafteten Übertragungsleitung in der Anwesenheit einer unterirdischen Rohrleitung, mehreren Schutzleitungen und einer mehrschichtigen Erde untersucht. Die entsprechende Diffusionsgleichung wird numerisch mit Hilfe der Finiten Elementen Methode (FEM) berechnet. Anschließend werden mit Hilfe der Ergebnisse der FEM und der Faraday schen Gleichung das magnetische Vektorpotential und die zwischen der Rohrleitung und der fernen Erde induzierten Spannungen berechnet. Untersuchungen zeigten, daß für das Feld und die zwischen Rohrleitung und der fernen Erde induzierten Spannungen folgende Parameter von großer Bedeutung sind: Die Dichte der ersten Erdschicht, die spezifischen Widerstände der Erdschichten und die Anordung der Schutzleitungen.

1 Introduction

Analysis of electrical interaction effects between overhead power transmission lines and nearby buried pipelines has been a topic of growing interest, due to the restrictions currently imposed on 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 kilometres. However, electrical interference problems due to conductive and inductive interactions among these systems must be carefully examined, before the sharing of a common right-of-way can be finally decided.

Electrical interference problems have been examined by many scientific organisations and research institutes, leading to various research reports and papers [1–10]. Although the mechanisms by which inductive and conductive interactions arise are well understood, the determination of interaction effects in a typical right-of-way is a complex procedure. This procedure requires not only a good knowledge of conductors layout, power line and pipeline electrical characteristics and electrical system parameters, but also an accurate representation of the ground.

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

In this paper, the influence of a multi-layer ground on the electromagnetic field and on the inductive interaction between an overhead transmission line and a buried pipeline 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. Therefore, a procedure based on FEM has been proposed to solve the two dimensional electromagnetic field problem of a faulted overhead power transmission line, in the presence of buried conductors and multi-layer ground.

2 The electromagnetic field problem

2.1 Finite element formulation

To investigate the influence of multi-layer ground on the electromagnetic field and on the inductive interaction between overhead transmission lines and buried conductors, a typical system shown in Figs. 1–2 has been chosen. This system consists of a long corridor shared between one

Received: 3 December 1996

K. J. Satsios, D. P. Labridis, P. S. Dokopoulos
Power Systems Laboratory, Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, GR-54006, Greece

Correspondence to: K. J. Satsios

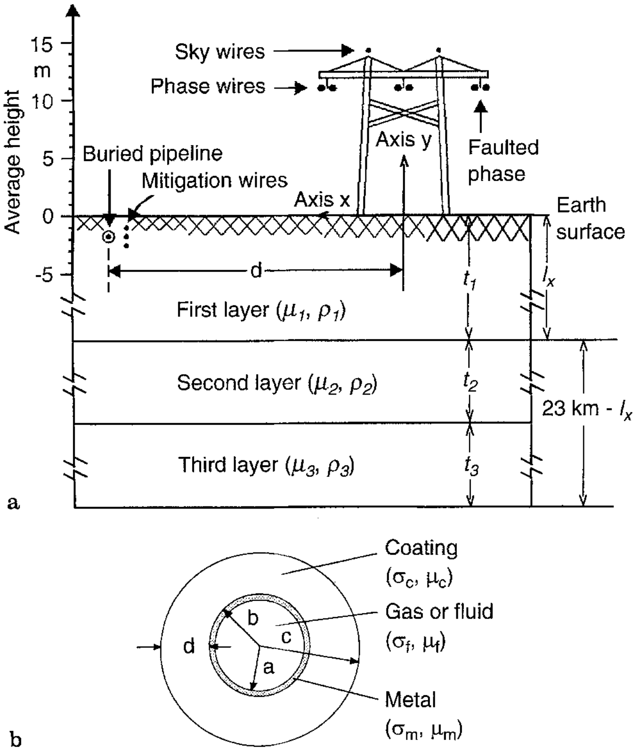

Fig. 1. **a** Cross-section of the system under investigation, **b** Detailed pipeline cross-section

pipeline and one transmission line. The geometry of the transmission line consists of a pair of conductors. Pipeline metal and skywires have a conductivity $\sigma_m = \sigma_s = 7.0E + 06$ S/m and relative permeability $\mu_{rm} = \mu_{rs} = 250$ respectively. Pipeline's coating is assumed to be perfect ($\sigma_c \cong 0.0$), which is reasonable for nowadays synthetic coatings [9]. Aluminium mitigation wires shown in Fig. 1a are bare and the ground is subdivided in layers with different properties μ, ρ. A standard power frequency of 50.0 Hz has been used to simulate a phase to ground fault I_F at point B of Fig. 2, which is outside of the parallel exposure. Therefore, conductive interference is negligible and only the inductive interference, occurred by the magnetic field, exists. Due to this inductive interaction, currents are induced in mitigation wires, skywires and ground layers by the current of the faulted conductor, and voltages appear across pipeline's surface and ground. For the inductive interaction calculations, end effects neglect leads to very small errors and to a two dimensional problem. Therefore, if the cross-section of the system shown in Fig. 1a lies on the x-y plane, the 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 is described by the system of equations [11–12]

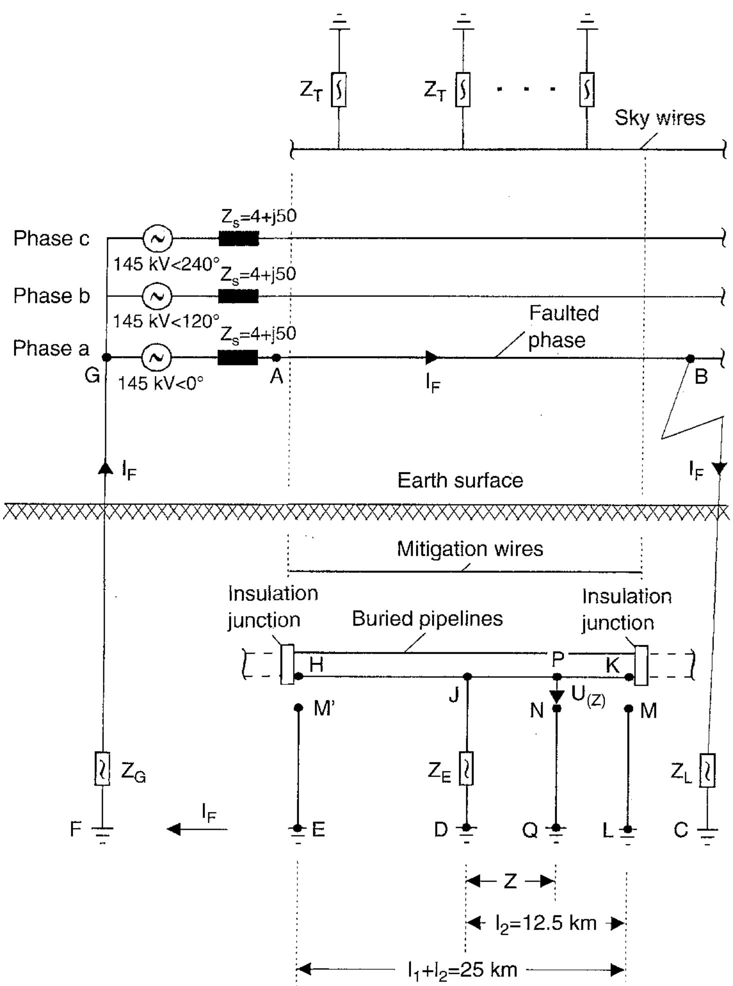

Fig. 2. Circuit diagram of the system under investigation

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

$$-\mathrm{j}\omega\sigma A_z+J_{sz}=J_z \quad (1b)$$

$$\iint_{S_i} J_z \mathrm{d}_s = I_i \quad (1c)$$

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 [13] in the z-direction and I_i is the rms value of the current flowing through conductor i of cross section S_i.

The matrix equation obtained [13] from the finite element formulation of equations (1a–c) 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 can be computed [11] and the total element current J^e_{ez} will be the sum of the conductor-i source current density J_{szi} and of the element eddy current density J^e_{ez}, i.e.

$$J^e_z(x,y)=J^e_{ez}(x,y)+J_{szi}=-\mathrm{j}\omega\sigma A^e_z(x,y)+J_{szi} \quad (2)$$

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

When applying FEM for the electromagnetic field calculation of a multi-conductor system, a zero Dirichlet boundary far away from the system is generally assumed, enclosing all the currents flowing in the system. If a current flows in one conductor (i.e. the faulted phase a) of a transmission line and returns through the earth, the boundary inside the earth has been estimated in the order of 10δ away from the current-carrying conductor, in order to approximate accurately the earth current. The penetration depth δ is defined as $\delta=\sqrt{2\rho/(\omega\mu)}$. With maximum values $\rho_{\mathrm{earth}}=1000\,\Omega$m and $\mu r_{\mathrm{earth}}=1$ for the earth, the corresponding δ_{earth} is 2250 m at 50 Hz. Therefore, the Dirichlet boundary inside the earth should be greater than $10\delta=22500$ m.

The total solution domain for our problem is therefore a square with 46 km side as shown in Fig. 3. This solution domain is subdivided in first order triangular finite elements. The complicated geometry of the examined interaction 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 [14] adaptive mesh generation algorithm has been developed for the original discretization. The continuity requirement of the flux density B on the interface between neighbouring elements has been chosen [15] as the criterion for an iteratively adaptive mesh refinement. The Delaunay based original mesh of appr. 5000 elements, using the above criterion, led in almost all cases tested to a mesh of 25000–27000 elements. Relative element distribution in this mesh reveals the good behaviour of the criterion chosen. A subsequent refinement is not necessary because, although it rises the number of triangles up to 50%, hardly influences MVP results.

2.2 Faraday's law application for pipeline's voltage calculation

Consider now the pipeline HK of Fig. 2 running parallel to the faulted phase a. The pipeline is grounded with a resistance Z_E at the middle point J, while junctions isolate the pipeline at both end-points H and K for cathodic protection purposes. If reference earth CLDEF is supposed to be a conducting plane of infinite conductivity, then the voltage V_{PN} across a point P of the pipeline and remote earth N may be determined by combining FEM calculations and Faraday's law applied in the closed path PNQDJP

$$\oint \vec{E}\mathrm{d}\vec{l}+\frac{\partial\phi}{\partial t}=0 \quad (3)$$

where ϕ is the flux of the magnetic field through the closed path PNQDJP. In a two-dimensional field, this flux in the plane (x,y) is given by

$$\phi = A\cdot z \quad (4)$$

where A is the z-component of the MVP and z is the distance of P from grounded point J. Using phasors instead of time functions (3) may be written in the form

$$V_{PN}+V_{NQ}+V_{QD}+V_{DJ}+V_{JP}+\mathrm{j}\omega\phi=0 \quad (5)$$

Finally the voltage V_{PN} across the point P and remote earth N is easily obtained as a function of its distance z from grounded point J

$$V_{PN}(z)=\mathrm{j}A\omega z \quad (6)$$

The maximum value of this voltage is occurred across point K and remote earth M as

$$V_{KM}=\mathrm{j}A\omega l_2 \quad (7)$$

Due to the symmetry of pipeline HK across grounding point J, the same conclusions hold for both sections KJ and HJ.

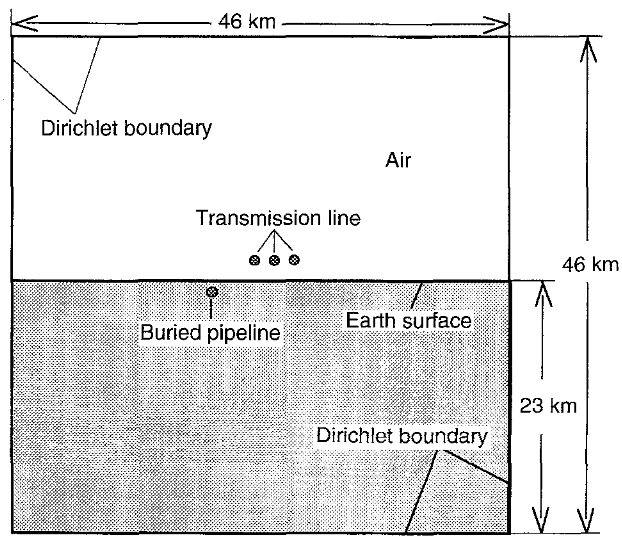

Fig. 3. FEM solution domain of the examined problem

3
Investigation of multi-layer ground influence

The transmission line system shown in Fig. 1–2 has been investigated for several different configuration cases. The system of equations (1a–c) has been solved and MVP distribution is calculated for various multi-layer ground models.

3.1
Two ground layers without mitigation wires

Suppose that in the system of Fig. 1a the second ground layer has the same properties μ, ρ as the third ground layer, i.e. a two ground layer model is initially considered. First ground layer depth is equal to l_x, while second ground layer thickness is equal to 23km $-l_x$. Initially it is assumed that no mitigation wires are present. The influence of each ground layer resistivity on the electromagnetic field and on the inductive interaction between the overhead transmission line and the buried pipeline depends on the depth of the first ground layer. It may be interesting to investigate the depth l_x from which the first ground layer resistivity determines almost exclusively the electromagnetic field and the inductive interaction.

Initially, the first and second ground layers are assumed to have resistivities $\rho_1 = 100\,\Omega$m (dry ground) and $\rho_2 = 1000\,\Omega$m (rocky ground) respectively. The parametric analysis for the first ground layer depth, concerning the pipeline inductive voltage V_{PN}, is shown in Fig. 4. V_{PN} is here defined as the voltage across a point P on the pipeline and remote earth N, when this point P lies at a distance $z = 1000$ m from J. The application of the proposed method for the same separation distances of Fig. 4 but for homogeneous ground (i.e. when the resistivities of the ground layers of Fig. 1a are $\rho = \rho_1 = \rho_2 = \rho_3$) having resistivity $\rho = 100\,\Omega$m or $\rho = 1000\,\Omega$m has given the results shown in Table 1. Comparing Table 1 calculation voltages V_{PN} with Fig. 4 curves it is evident that

- when the first ground layer depth varies between $l_x = 10$ m and $l_x = 50$ m, the electromagnetic field and the inductive interaction between the overhead transmission line and the buried pipeline is determined properly from the second ground layer resistivity.
- for $l_x = 400$ m and deeper the first ground layer resistivity plays the dominant role in the electromagnetic field and inductive interaction influence.

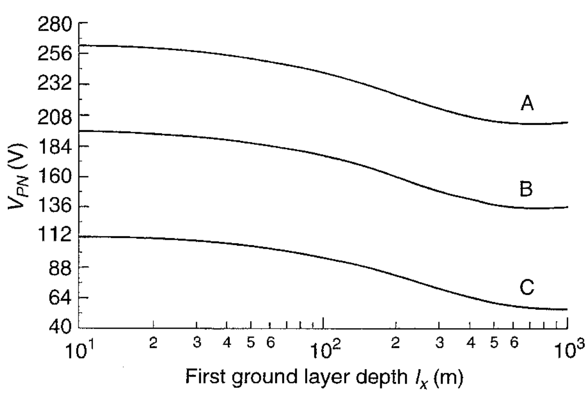

Fig. 4. Voltage V_{PN} as a function of the depth of the first ground layer of Fig. 1a, for a two ground layer model with resistivities $\rho_1 = 100\,\Omega$m and $\rho_2 = 1000\,\Omega$m. Curve A corresponds to separation distance $d = 25$ m, curve B to $d = 100$ m and curve C to $d = 500$ m respectively

Table 1. Pipeline inductive voltage V_{PN} for a homogeneous ground (i.e. when resistivities of the three layers shown in Fig. 1a are $\rho_1 = \rho_2 = \rho_3 = \rho$) and for various separation distances d.

Separation distance d [m]	$\rho = 100\,\Omega$m	$\rho = 1000\,\Omega$m
	V_{PN} [V]	V_{PN} [V]
25	202.1	266.4
100	136.1	200.5
500	55.2	116.2

The influence of the depth of the first ground layer may be easily understood from Fig. 5–6, in which flux lines are shown for two first ground layer depths, $l_x = 50$ m and $l_x = 400$ m respectively. From the MVP distribution of Fig. 5, which is valid for a first ground layer depth $l_x = 50$, it is clear that the influence of the resistivity of the first ground layer on the electromagnetic field is negligible. In this case, the field is almost exclusively influenced by the resistivity of the second ground layer. On the other hand, from the MVP distribution of Fig. 6, which is valid for a first ground layer depth $l_x = 400$ m, the influence on the electromagnetic field due to the resistivity of the first ground layer is evident, since the field lines are now compressed in that layer.

Finally, the first and second ground layers are assumed to have $\rho_1 = 1000\,\Omega$m and $\rho_2 = 100\,\Omega$m respectively. The corresponding parametric analysis for the depth of the first ground layer, concerning the pipeline inductive voltage V_{PN}, is now shown in Fig. 7. Comparing the results shown in Fig. 7 and in Table 1, it can be concluded that when the depth of the first ground layer is greater than

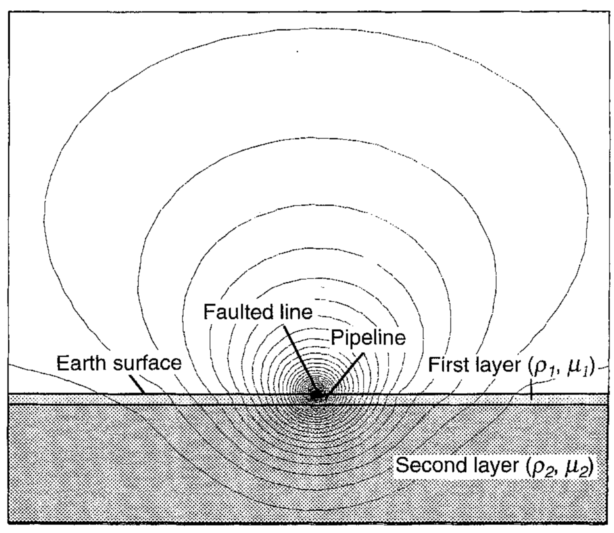

Fig. 5. Flux lines ($A =$ const) of the electromagnetic field, for a two ground layer model with resistivities $\rho_1 = 100\,\Omega$m and $\rho_2 = 1000\,\Omega$m. The depth of the first ground layer is $l_x = 50$ m, while overhead transmission line – pipeline separation distance is $d = 100$ m

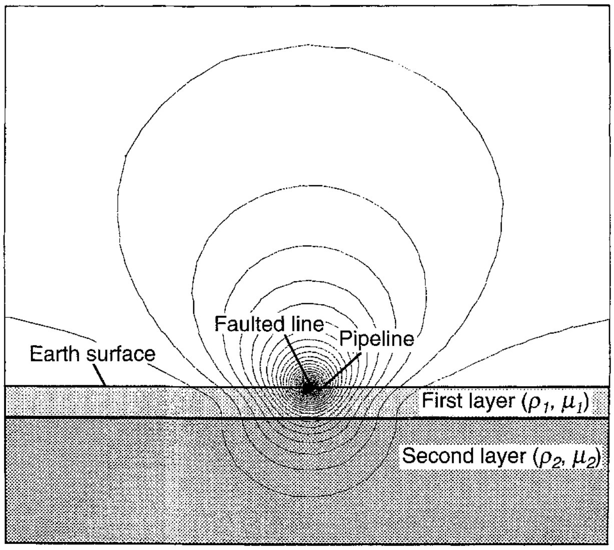

Fig. 6. Flux lines ($A =$ const) of the electromagnetic field, for a two ground layer model with resistivities $\rho_1 = 100\,\Omega$m and $\rho_2 = 1000\,\Omega$m. The depth of the first ground layer is $l_x = 400$ m, while overhead transmission line – pipeline separation distance is $d = 100$ m

$l_x = 900$ m, the electromagnetic field and the inductive interaction are determined solely from the first ground layer.

3.2 Two ground layers with mitigation wires

The previous examined two ground layer model is further extended to include mitigation wires near the pipeline, as shown in Fig. 1a. The reduction of voltage obtained by installing progressively more bare mitigation wires, made of a low resistivity and permeability material such as aluminium, 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 ground layer is equal to 250 m, the resistivities of the two ground layers have the same influence on the electromagnetic field.

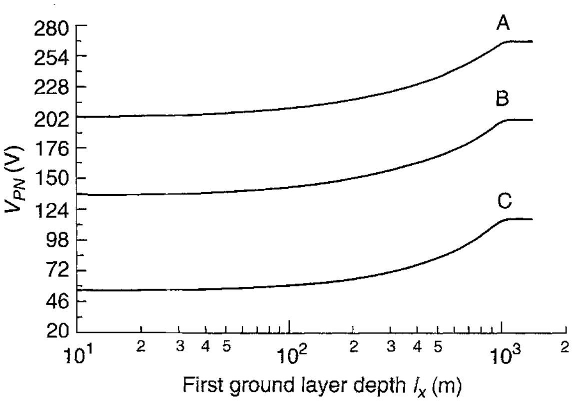

Fig. 7. Voltage V_{PN} as a function of the depth of the first ground layer of Fig. 1a, for a two ground layer model with resistivities $\rho_1 = 1000\,\Omega$m and $\rho_2 = 100\,\Omega$m. Curve A corresponds to separation distance $d = 25$ m, curve B to $d = 100$ m and curve C to $d = 500$ m respectively

Table 2. Effect of the buried mitigation wires of Fig. 1a on the magnetically induced pipeline voltage V_{PN}, for a two ground layer model. The depth of the first ground layer is $l_x = 250$ m, the overhead transmission line-pipeline separation distance is $d = 200$ 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 centre

Number of Aluminium Mitigation Wires	$\rho_1 = 100$, $\rho_2 = 1000$ [Ωm]	$\rho_1 = 1000$, $\rho_2 = 100$ [Ωm]
	Pipeline inductive Voltage V_{PN} [V]	
none	114.72	111.28
1	62.86	58.33
2	41.08	38.20
3	31.81	30.15

Finally, flux lines of the electromagnetic field near the transmission line are shown in Fig. 8, when three aluminium wires are located near to the pipeline. The effect of voltage mitigation due to the aluminium wires is here easily understood, since the electromagnetic field is compressed towards the faulted line. If no mitigation wires were present, 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. 8.

3.3 Three ground layers

Consider now the three ground layer model of Fig. 1a having layer thicknesses $t_1 = 10$ m, $t_2 = 190$ m and $t_3 = 22.8$ km respectively. The separation distance between the overhead transmission line and the buried pipeline is equal to $d = 100$ m and no mitigation wires are present. A parametric analysis for various resistivities of the three

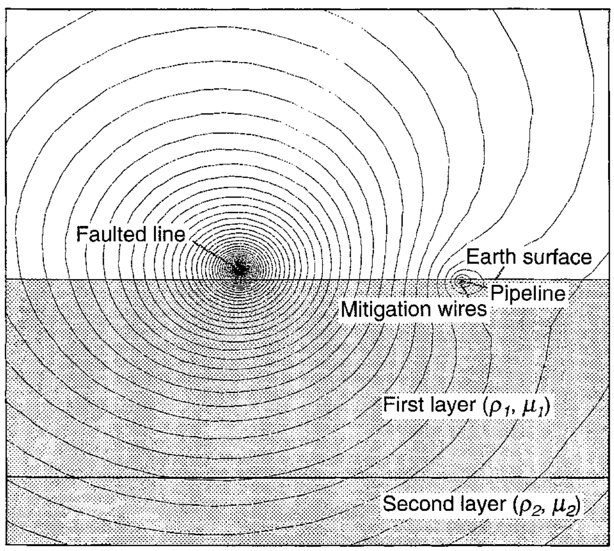

Fig. 8. Flux lines ($A =$ const) of the electromagnetic field near the transmission line, for a two ground layer model with resistivities $\rho_1 = 100\,\Omega$m and $\rho_2 = 1000\,\Omega$m. The depth of the first layer is $l_x = 250$ m, overhead transmission line – pipeline separation distance is $d = 200$ m and three aluminium mitigation wires exist near the pipeline

ground layers, concerning pipeline's surface MVP values and inductive voltages V_{PN}, is presented in Table 3.

Table 3 in the case of $\rho_1 = \rho_2 = \rho_3 = 100\,\Omega$m shows pipeline inductive voltage V_{PN} equal to 136.1 V, and in the case of $\rho_1 = \rho_2 = \rho_3 = 1000\,\Omega$m equal to 200.5 V. These two cases lead to the minimum and maximum induced voltage values respectively. From the other results of Table 3 it can be concluded that MVP values and pipeline inductive voltages are influenced only by the resistivities of the second and the third ground layers. The corresponding influence of the resistivity of the first ground layer is negligible, because t_1 is only 10 m.

All the above calculations have been made for a phase a to ground fault current equal to 1000 A. However, MVP values and therefore pipeline induced voltage are proportional to the fault current, so the presented results may be easily used to predict the inductive voltage for any fault current I_F.

From all the previous results it is evident that resistivity measurements in relative small depths, in order to simulate the inductive interaction problem using a homogeneous ground, may lead to an erroneous ground model and to an inaccurate determination of the induced voltages on the buried pipeline.

4 Conclusions

In this paper, a numerical method employing the finite element technique has been developed for the computation of the electromagnetic field caused by an overhead power transmission line above a multi-layer ground having buried conductors. The method is able to compute the distribution of the magnetic vector potential in the cross-section of the parallel exposure, the eddy currents in all conductive parts, as well as the voltages induced on the buried pipelines.

Results concerning various ground models have been tabulated. Conclusions referring to the influence of the ground structure on the induced voltage levels are presented. The performance of bare mitigation wires is also investigated. It is concluded that a multi-layer ground model is essential for an accurate computation of the inductive interaction and for the effective design of mitigation systems.

Table 3. Pipeline's surface MVP values and inductive voltages V_{PN}, for various resistivities of the three ground layer model of Fig. 1a having layer thickness $t_1 = 10$ m, $t_2 = 190$ m and $t_3 = 22.8$ km. The separation distance in all cases is $d = 100$ m.

ρ_1[Ωm]	ρ_2[Ωm]	ρ_3[Ωm]	MVP [Wb/m]	V_{PN}[V]
100	100	100	4.332E-04	136.10
100	100	500	4.909E-04	154.22
100	100	1000	5.089E-04	159.88
100	500	100	4.706E-04	147.85
100	500	500	5.697E-04	178.98
100	500	1000	6.110E-04	191.97
100	1000	100	4.756E-04	149.42
100	1000	500	5.906E-04	185.55
100	1000	1000	6.229E-04	195.71
500	100	100	4.348E-04	136.61
500	100	500	4.944E-04	155.35
500	100	1000	5.144E-04	161.63
500	500	100	4.728E-04	148.55
500	500	500	5.760E-04	180.98
500	500	1000	6.190E-04	194.49
500	1000	100	4.778E-04	150.12
500	1000	500	5.863E-04	184.21
500	1000	1000	6.351E-04	199.55
1000	100	100	4.355E-04	136.81
1000	100	500	4.950E-04	155.52
1000	100	1000	5.150E-04	161.8
1000	500	100	4.734E-04	148.72
1000	500	500	5.755E-04	180.80
1000	500	1000	6.196E-04	194.67
1000	1000	100	4.781E-04	150.21
1000	1000	500	5.872E-04	184.47
1000	1000	1000	6.382E-04	200.50

References

1. **Carson, J.** (1926) Wave Propagation in Overhead Wires with Ground Return. Bell System Technical Journal, Vol.5: 539–554
2. **Pollaczeck, J.** (1966) Beeinflussung von umhüllten Rohrleitungen durch Hochspannungsfreileitungen. CIGRE-Conference Bericht Nr. 326
3. **Böcker, H.; Oeding, D.** (1966) Induckionsspannung an Pipelines in Trassen von Hochspannungsleitungen. Elektrizitätswirtschaft 65, Heft 5
4. **Kaiser, G** .(1966) Die elektrischen Konstanten von Rohrleitungen und ihre Messung, ETZ-A 87: 792–796
5. **Sunde, E.** (1968) Earth Conduction Effects in Transmission Systems. Dover Publications, New York
6. **Technical Recommendation No 7** (1968) 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 Elektrizitätswerke mbH – VWEW
7. (1987) Power Line Fault Current Coupling to Nearby Natural Gas Pipelines. EPRI/A.G.A. Project 742, EL-5472/PR176-510
8. **Kouteynikoff, P.** (1987) Résultats d' une enquete internationale sur les régles limitant les perturbations créées sur les canalisations par les ouvrages électriques. ELECTRA, No 110
9. **Jacquet, B.; Kouteynikoff, P.** (1990) Influence of High Voltage Lines and Installations on Metal Pipelines. Paper 36-203 presented in the name of Study Committee 36. CIGRE
10. **CIGRE** (1992) Guide Concerning Influence of High Voltage AC Power Systems on Metallic Pipelines. CIGRE Working Group 36.02 Preliminary Guide 36-92 (WG02)17
11. **Hatziathanassiou, V.; Labridis, D.** (1993) Coupled magneto-thermal field computation in three-phase gas insulated cables. Archiv für Elektrotechnik, Vol. 76, No 4: 285–292
12. **Labridis D,; Dokopoulos, P.** (1988) Finite element computation of field, losses and forces in a three-phase gas cable with non-symmetrical conductor arrangement. IEEE Trans. Power Delivery, Vol. PWDR-3, No 4: 1326–1333
13. **Weiss, J.; Cendes, Z.** (1982) A one-step finite element method for multiconductor skin effect problems. IEEE Trans. Power App. Syst., Vol. PAS-101, No 10: 3796–3803
14. **Cendes, Z.; Shenton, D.; Shahnasser, H.** (1983) Magnetic field computation using Delanuary triangulation and complementary finite element methods. IEEE Transactions on Magnetics, Vol. MAG-19: 2551–2554
15. **Labridis D.** Comparative presentation of criteria used for adaptive finite element mesh generation in multiconductor eddy current problems. Submitted for publication in IEEE Transactions on Magnetics