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Inductive interference calculation on imperfect coated pipelines due to nearby faulted parallel transmission lines

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Abstract

The interference of power transmission lines to nearby pipelines and other metallic structures has been a research subject over the past 20 years. Especially during fault conditions, large currents and voltages are induced on the pipelines. Several methods have been proposed over the years and more recently one utilizing finite element calculations. The last method has the disadvantage that if it considers the pipeline to have a perfect coating, which is rarely the case as defects appear on the coating soon after the pipeline is buried in the ground. In this work a hybrid method employing finite element calculations along with Faraday's law and standard circuit analysis is discussed. The method is used in order to calculate the induced voltages and currents on a pipeline with defects, running in parallel to a faulted line and remote earth. Non-parallel exposures are converted to parallel ones and dealt with similarly. The defects are modeled as resistances, called leakage resistances. The fault is assumed to be a single earth-ground one and outside the exposure so that conductive interference is negligible. A sample case is analyzed and discussed. The results show that although the pipeline defects act in a way as to reduce the levels of induced voltages and currents, large currents can flow to earth through the defects that may damage the pipeline.

Keywords: Finite element method; Gas pipelines; Inductive interference; Power line faults

1. Introduction

The electrical interference effects of power transmission lines upon closely located metal pipelines have been a major concern since the early 1960s. Recently the problem has become even more acute, due to the restrictions imposed on various utilities to use common courses, called right-of-ways, by various environmental regulations aiming to protect nature and wildlife. There exist situations where power lines and pipelines have to be laid in close distances for several km. The interference is present both during normal conditions and faults. Especially during earth faults this interference can endanger people or working personnel touching the pipeline or other metallic structures connected to it, even if the fault occurs far away from them. Moreover, the possibility of damage to the pipeline coating, insulating flanges or rectifiers is increased and the corrosion of the metal is accelerated.

Many scientific organizations and research institutes have examined the problem and produced various reports and papers. The first to study these interferences was Carson using his wide known formulae [1], while various other approximating formulae were introduced later [2–6]. With the advances in computer technology and the increase in computational power, more advanced and sophisticated analytical models were adopted. As a result, a technical recommendation was developed [7], based also on experimental results. During the late 1970s and early 1980s, two research projects of the Electrical Power Research Institute (EPRI) and the American Gas Association (AGA) targeted the analysis of power line inductive coupling to gas pipelines using practical analytical expressions which could be programmed on hand held calculators [8] and computerized techniques [9].

In the following years a joint program of EPRI and AGA led to the development of a computer program

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[10–12]. This program utilizes equivalent circuits with concentrated or distributed elements, with the self and mutual inductances being calculated using classic formulae from Carson [1], Pollaczek [13] and Sunde [4]. Furthermore, CIGRE's Study Committee 36 produced a report detailing the different regulations existing in different countries [14] and some years later published a general guide on the subject [15].

More recently, a new method employing the Finite-Element Method (FEM) was proposed [16,17] that aims to provide an alternative calculation method of the induced voltages on the pipelines. However, this method limits itself to dealing with pipelines with perfect coatings, a situation that is rarely encountered in reality. Defects on pipeline coating are a common fact, especially in old pipelines, and can range from a few millimeters to several decimeters. Glow discharges may occur at defects or pores when the induced voltage on the pipeline exceeds 1 kV [18]. Therefore, the presence of defects or pores needs to be taken into consideration when calculating the coupling between a transmission line and a pipeline.

Generally, AC interference consists of an inductive and a conductive component. The proposed paper deals with the inductive interference caused by the magnetic field generated by the transmission line and, specifically, when the pipeline coating has defects. In the circuit analysis, these defects are represented with resistances, called leakage resistances. The method utilizes finite-element calculations for the determination of the Magnetic Vector Potential (MVP) on the surface of the faulted transmission line and the pipeline. Using a combination of Faraday's law and the results obtained from the FEM calculations, the self and mutual inductances of the power line and the pipeline are computed. Finally, a circuit model of the specific problem is constructed and solved using standard methods [19].

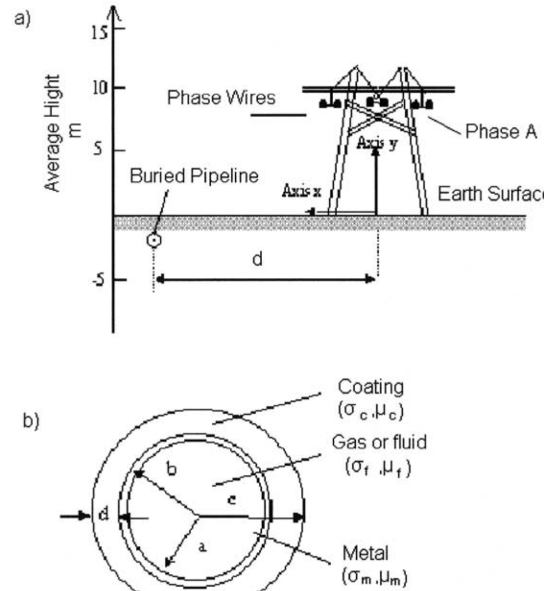

Fig. 1. System under investigation. (a) Cross-section of the system. (b) Detailed pipeline cross-section.

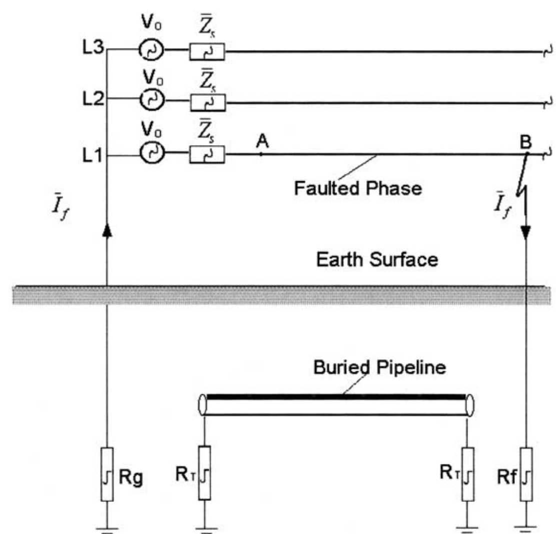

Fig. 2. Circuit diagram of the system under investigation.

2. Problem description

In order to demonstrate the proposed method, the system shown in Figs. 1 and 2 was chosen. In this configuration, an $l_P = 25$ km long right-of-way is shared between a pipeline and a power transmission line. At point B of phase A, which is $l = 30$ km away from the source, a phase-to-earth fault is assumed. The fault is assumed to be in steady state condition, with 50 Hz standard frequency. As this point is outside of the parallel exposure, the conductive interference can be neglected. Therefore, we focus the analysis solely on the inductive coupling between the overhead transmission line and the neighboring conductor or the gas pipeline particularly. In this study we assume that the pipeline and the power line are parallel. However, Section 4 discusses how non-parallel exposures may be converted to parallel ones, so that the proposed method is applicable to them also. Due to this inductive interaction, currents are induced in the pipeline and earth, while voltages appear across pipeline's surface and ground. By neglecting end effects, a two-dimensional problem is considered consisting of infinite length conductors, without significant errors.

The transmission line consists of a pair of HAWK ACSR conductors and the source phase voltage of the terminal is 145.22 kV behind a source impedance of $\bar{Z}_s = 4 + j50\ \Omega$. The neutral of the source is grounded with a resistance $R_g = 0.2\ \Omega$, while the tower's ground resistances are negligible. The earth is assumed to be homogeneous with a resistivity ranging from $\rho = 30$ to 1000 Ωm. In spite of that, the proposed method may deal with situations with non-homogeneous earth also. The pipeline has an inner radius of 0.195 m, while its outer radius is 0.2 m and its coating thickness is $s = 0.1$ m. The conductivity and relative permeability of the pipeline's metal are $\sigma_m = 3.522 \times 10^6$ S/m and $\mu_{r,m} = 250$ respectively.

The fault impedance is considered all resistance (R_f). In the case of an arc phase-to-ground fault, the fault resistance is not linear having a typical value of 1 or 2 Ω for about 0.5 s, with peaks of 25–50 Ω later. Since we consider steady state condition, the parametric analysis of R_f may give an indication of the calculated parameters at each value of the fault resistance.

3. The proposed method

The proposed method combines FEM calculations, Faraday's law and standard circuit analysis in order to calculate the influence of a single phase-to-earth fault on a nearby parallel pipeline. The required input data for the method are:

1) Power line and pipeline geometrical configuration
2) Physical characteristics of conductors and pipeline
3) Location and value of the leakage resistances
4) Air and earth characteristics
5) Power system terminal parameters
6) Fault parameters describing fault location and type

The output data are:

1) The induced voltage and current at any point on the pipeline
2) The currents flowing to earth through the leakage resistances.

3.1. Finite element formulation of the electromagnetic problem

Considering that the cross-section of the system under investigation, shown in Fig. 1a, lies on the x–y plane, the following system of equations describes the linear two-dimensional electromagnetic diffusion problem for the z-direction components $\bar{A}_z$ of the MVP vector and $\bar{J}_z$ of the total current density vector [16,17]:

$$\frac{1}{\mu_0 \mu_r}\left[\frac{\partial^2 \bar{A}_z}{\partial^2 x^2} + \frac{\partial^2 \bar{A}_z}{\partial^2 y^2}\right] - j\omega\sigma\bar{A}_z + \bar{J}_z = 0 \quad (1a)$$

$$-j\omega\sigma\bar{A}_z + \bar{J}_{sz} = \bar{J}_z \quad (1b)$$

$$\iint_{Si} \bar{J}_z \, ds = \bar{I}_i \quad (1c)$$

where σ is the conductivity, μ_o and μ_r are the vacuum and relative permeabilities respectively, ω is the angular frequency, $\bar{J}_{sz}$ is the source current density in the z-direction and $\bar{I}_i$ is the rms value of the current flowing through conductor i of cross-section S_i.

It is shown [16] that the finite-element formulation of Eqs. (1a), (1b) and (1c) leads to a matrix equation, which can be solved utilizing the *Crout* variation of the *Gauss* elimination. Using the solution of this matrix equation, the MVP values in every node of the discretization domain, as well as the unknown source current densities, are calculated. Therefore, for a random element e, the eddy-current density $\bar{J}^e_{ez}$ is calculated using the relation:

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

and the total element current density $\bar{J}^e_z$, being the sum of the conductor-i source current density $\bar{J}_{szi}$ and of the element eddy current density $\bar{J}^e_{ez}$ of Eq. (2a), is obtained by the following equation:

$$\bar{J}^e_z(x, y) = \bar{J}^e_{ez}(x, y) + \bar{J}_{szi} \quad (2b)$$

Integrating Eq. (2b) over a conductor cross-section, the total current flowing through this conductor is obtained.

The FEM package [20], developed at the Power Systems Laboratory of the Aristotle University of Thessaloniki during the last 15 years, has been used for the finite element formulation of the case under investigation. A local error estimator, based on the discontinuity of the instantaneous tangential components of the magnetic field, has been chosen as in Ref. [20] for an iteratively adaptive mesh generation.

3.2. Analysis of currents and voltages

The circuit representation of the system under investigation is shown in Fig. 3. The pipeline $E_1E_2, \ldots, E_N$ runs in parallel to the faulted phase A for a total length l_P. The other phases are not considered in the solution as they are unloaded. The pipeline is grounded at both ends with equal resistances R_T, called terminal resistances, while the resistances $R_1, R_2, \ldots, R_N$ represent the coating defects. The leakage resistances are assumed to be located far from each other.

If we apply Faraday's law in the closed path $E_1E_2H_1H_2$, supposing that reference earth $H_1H_2, \ldots, H_N$ is a conducting plane with infinite conductivity, we get:

$$\oint \overline{E \mathrm{d} l} + \frac{\partial \Phi_1}{\partial t} = 0, \quad (3)$$

where Φ_1 is the flux of the magnetic field through the closed path $E_1E_2H_1H_2$ and can be expressed using phasors as:

$$\Phi_1 = L_{11}\bar{I}_{p1} + L_{F1}\bar{I}_F, \quad (4)$$

with L_{11} being the self-inductance of the first section of the pipeline, I_{p1} its current, $\bar{I}_F$ the fault current and L_{F1} the mutual inductance of the first section of the pipeline due to the fault current in phase A. Contributions to the flux $\Phi_{1,}$ due to the currents flowing in the other sections of the pipeline, are neglected, because of the assumption that leakage resistances are located far from each other. In addition to that, in a two-dimensional field this flux is given in the plane (x, y) by:

$$\Phi_1 = \bar{A}_{zP} l_1, \tag{5}$$

where $\bar{A}_{zP}$ is the z-component of the MVP on the surface of the pipeline and l_1 is the length of the first section.

Using phasors, we may express (1) as follows:

$$\bar{U}_{E_1E_2} + \bar{U}_{E_2H_2} + \bar{U}_{H_2H_1} + \bar{U}_{H_1E_1} + j\omega\Phi_1 = 0 \tag{6}$$

where,

$$\bar{U}_{E_2H_2} = (\bar{I}_{P1} - I_{P2})R_1 \tag{6a}$$

$$\bar{U}_{H_2H_1} = 0 \tag{6b}$$

$$\bar{U}_{H_1E_1} = \bar{I}_{P1} R_T \tag{6c}$$

$$\bar{U}_{E_1E_2} = \int_{H_1}^{H_2} \bar{E}\mathrm{d}\bar{l} = \frac{\bar{J}_{zP} l_1}{\sigma_p} = \frac{\bar{I}_{P1} l_1}{\sigma_p S_p}, \tag{6d}$$

where s_p and S_p are the conductivity and the effective cross-section of the pipeline's metal respectively.

Finally, Eq. (6) becomes:

$$\bar{I}_{P1}\left(R_1 + R_T + \frac{l_1}{\sigma_p S_p}\right) - \bar{I}_{P2} R_1 + j\omega \\ (L_{11}\bar{I}_{p1} + L_{F1}\bar{I}_F) = 0 \tag{7}$$

Using the same procedure, an equation similar to Eq. (5) may be stated for each of the $(N+1)$ loops, resulting in $(N+1)$ equations. Therefore, for loop i the following equation apply:

$$\bar{I}_{Pi}\left(R_i + R_{i+1} + \frac{l_i}{\sigma_p S_p}\right) - \bar{I}_{Pi-1} R_i - \bar{I}_{Pi+1} R_{i+1} \\ + j\omega(\bar{I}_{Pii} L_{ii} + \bar{I}_F L_{Fi}) \\ = 0 \tag{7a}$$

for $i = 2, N$. While for loop $N+1$ the following relation applies:

$$\bar{I}_{PN+1}\left(R_N + R_T + \frac{l_{N+1}}{\sigma_p S_p}\right) - \bar{I}_{PN} R_N \\ + j\omega(\bar{I}_{PN+1} L_{N+1N+1} + \bar{I}_F L_{FN+1}) \\ = 0 \tag{7b}$$

Assuming that the geometry of the system and the magnetic properties of both the pipeline and the phase A conductor remain constant, the self and mutual inductances per unit length of all sections are equal.

Applying, as previously, Faraday's law Eq. (3) in the loop ABCFGA, an equation involving the source phase voltage U_o is obtained:

$$U_o = I_F(R_G + R_F + Z_S) + \frac{\bar{I}_F l}{\sigma S} \\ + j\omega\left(\sum_1^{n+1} L_{Fi}\bar{I}_{Pi} + L_{FF}\bar{I}_F\right), \tag{8}$$

where the first term on the right hand side of Eq. (6) is the voltage due to the concentrated elements R_G, R_F, Z_S, while σ, S and L_{FF} are the conductivity, the cross-section and the self-inductance of the phase conductor.

Eqs. (7), (7a), (7b) and (8) form a system that can be solved if the self and mutual inductances are calculated.

3.3. Calculation of self and mutual inductances

For the determination of the self and mutual inductances of the problem, the FEM formulation is used. If a certain base fault current $\bar{I}_{Fb}$ is imposed on the faulted phase, e.g. $\bar{I}_{Fb} = 1A$, with the pipeline current set equal to zero, then the computed MVP on the surface of the pipeline can be utilised to determine the mutual inductance L_{F1}. In this case, combining (4) and (5), the following relation is obtained, since $\bar{I}_{p1} = 0$:

$$\bar{A}_{zPb} l_1 = L_{F1}\bar{I}_{Fb}$$

and therefore the mutual inductance is:

$$L_{F1} = \frac{\bar{A}_{zPb} l_1}{\bar{I}_{Fb}},$$

or

$$L'_{F1} = \frac{\bar{A}_{zPb}}{\bar{I}_{Fb}}, \tag{9}$$

the mutual inductance of the pipeline's first section and phase per unit length.

Additionally, the flux of the magnetic field of the closed path ABCFGA, of Fig. 3, is given by:

$$\Phi = \sum_1^{n+1} L_{Fi}\bar{I}_{Pi} + L_{FF}\bar{I}_F \tag{10}$$

while the same flux can be expressed as:

$$\Phi = \bar{A}_z l \tag{11}$$

where $\bar{A}_z$ is the z-component of the MVP on the surface of the phase conductor.

Consequently, since the first term of the right hand side of Eq. (10) is zero, we obtain:

$$L_{FF} = \frac{\bar{A}_z l}{\bar{I}_{Fb}}. \tag{12}$$

In order to calculate the self inductances L_{ii} ($i = 1{:}n+1$) of the pipeline sections the same methodology is followed, except that now we impose a zero fault current

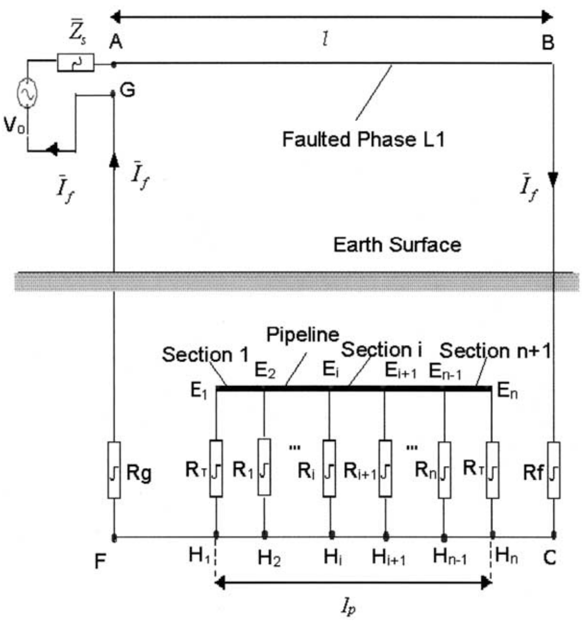

Fig. 3. Circuit model of the system under investigation, in the case of a single earth-to-ground fault.

on the phase conductor and a base current $\bar{I}_{Pb1}$ on the pipeline, e.g. $\bar{I}_{Pb1} = 1A$. Following the previous steps, the self-inductance per unit length of the first section of the pipeline is computed from the relation:

$$L'_{11} = \frac{\bar{A}_{zP}}{\bar{I}_{Pb1}}. \tag{13}$$

Additionally, as was discussed before, the self and mutual inductances of all sections of the pipeline are equal per unit length:

$$L'_{11} = L'_{22} = \cdots = L'_{ii} = = L'_{n+1n+1}$$

$$L'_{F1} = L'_{F2} = \cdots = L'_{Fi} = \cdots = L'_{Fn+1Fn+1}$$

Consequently, by knowing the length of each section of the pipeline, the self and mutual inductances of all sections are computed by simply multiplying the per unit length inductance with the section length.

3.4. Solution of the system of equations

Having computed all the self and mutual inductances, the system of Eqs. (7), (7a), (7b) and (8) comprises $N+2$ equations with $N+2$ unknown quantities, namely the $N+1$ loop currents and the fault current $\bar{I}_F$. There are many ways to solve this system, like the one or double-sided elimination method [13]. The double-sided elimination method is generally recommended and is used here.

3.5. Determination of the pipeline voltage

In order to calculate the voltage across a point on the pipeline and remote earth, Faraday's law is used. Specifically, consider a point P on section i of the pipeline, shown in Fig. 3, that lies at a distance l_z from point E_{i+1}. Applying Faraday's law in the two loops $E_iPNH_iE_i$ and $H_iH_{i+1}E_{i+1}E_iH_i$ the voltage U_{PN} of the point P and remote earth N, can be obtained as:

$$j\omega\bar{A}_z l_z = \bar{U}_{PN} + I_{Pi}\left(R_{i+1} + \frac{l_Z}{\sigma S}\right) - I_{Pi+1}R_{i+1}$$

$(E_iPNH_iE_i)$

$$j\omega\bar{A}_z l_i = I_{Pi}\left(R_i + R_{i+1} + \frac{l_i}{\sigma S}\right) - I_{Pi+1}R_{i+1} - I_{Pi-1}R_i$$

$(H_iH_{i+1}E_{i+1}E_iH_i)$

and combining the above two equations:

$$\bar{U}_{PN} = \frac{\bar{I}_{Pi}[l_z(R_i + R_{i+1}) - R_i l_i] + \bar{I}_{Pi+1}R_{i+1}(l_i - l_z) - \bar{I}_{Pi-1}R_i l_z}{l_i}. \tag{14}$$

This relation applies to loops 2 to N. For the first and the last $N+1$ loop, slightly different equations apply.

4. Oblique exposures

The proposed method can be applied to cases where the power line is parallel to the buried pipeline. However, in many situations this is not the case, as non-parallel sections may exist. An example of such an oblique exposure is shown in Fig. 4. According to [7] though, an oblique exposure may be considered as a parallel section having a relative distance a from the power line equal to

$$a = \sqrt{a_1 a_2}, \tag{15}$$

as long as

$$\frac{a_2}{a_1} \leq 3. \tag{15a}$$

In case a_2/a_1 is more than 3, the section is divided, as shown in Fig. 4, in order that both a_3/a_1 and a_2/a_3 meet Eq. (15a).

5. Results

In order to study the described case, a software program was developed capable of calculating the induced voltages and currents on a buried pipeline, caused by a single earth-ground fault on a closely located parallel transmission line. Given a certain configuration and circuit parameters, as in Figs. 1 and 2, the fault current may also be estimated as in Ref. [16].

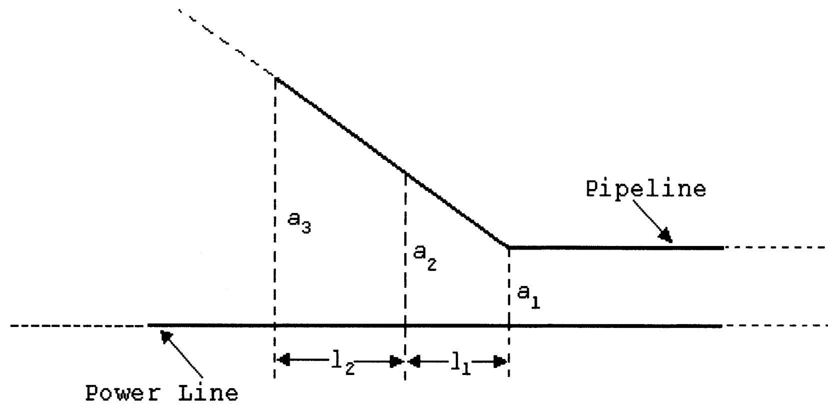

Fig. 4. Example of an oblique exposure.

For the case under investigation, a fault current of 1780 A was calculated, with the fault resistance equal to 20 Ω. Different fault current values will be calculated if some of the parameters, like the fault resistance or the fault location, are changed. However, since the induced voltages and currents are proportional to the fault current, it is more convenient to present the results obtained over kA of the fault current.

In the following it is assumed that the pipeline is grounded at both ends with terminal resistances of 5 Ω. In order to realize the effect of possible defects on the pipeline coating, Figs. 5–10 contain plots of the cases where leakage resistances take different values, ranging from 10 to 5000 Ω. Moreover, it is assumed that these resistances are located at each km of the pipeline. As the induced voltages and currents depend on the relative separation d between the power line and the pipeline, two cases are shown here, for $d = 25$ and 70 m, respectively. For each case, three graphs are included, one for the induced voltage, one for the induced current and one for the leakage current that flow through the defects.

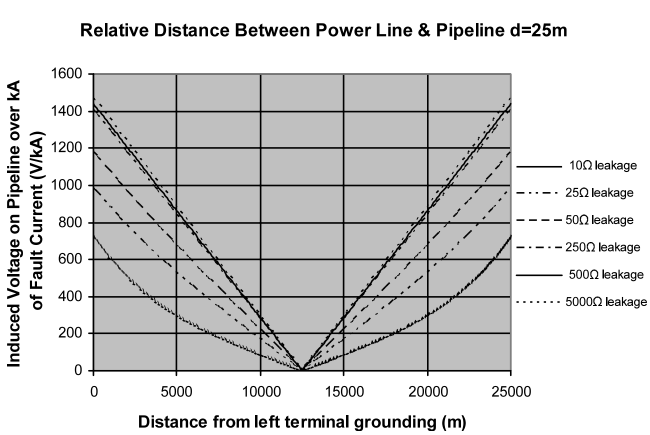

Fig. 5. Induced voltages on the pipeline over kA of fault current (V/kA) in the system of Fig. 1 versus distance from left terminal, for 5 Ω terminal resistances and 10, 25, 50, 250, 500 and 5000 Ω leakage resistances located at each km of the pipeline. Relative separation between pipeline and power line is 25 m.

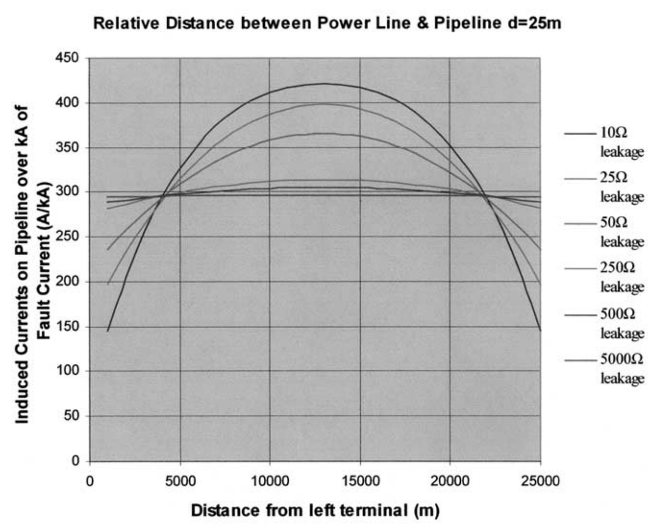

Fig. 6. Induced currents on the pipeline over kA of fault current (A/kA) in the system of Fig. 1 versus distance from left terminal, for 5 Ω terminal resistances and 10, 25, 50, 250, 500 and 5000 Ω leakage resistances located at each km of the pipeline. Relative separation between pipeline and power line is 25 m.

Generally, the resistance R_x of a defect can be determined by the following formula [18]:

$$R_x = \frac{\rho}{2d}\left(1 + \frac{8s}{\pi d_f}\right), \tag{16}$$

where ρ is the ground resistivity, d_f is the defect diameter and s is the coating thickness. For the case under investigation, a defect having a diameter of 0.5 m leads to a leakage resistance of approximately 150 Ω. In case of a more humid ground with $\rho = 50$ Ω m, the value of the leakage resistance is halved.

From the graphs in Figs. 5–10, it may be realized that in order for the leakage resistances to play a considerable role in reducing the induced voltage, they have to be small, which, unfortunately, means that the defects have to be large. For high values of leakage resistances above 250 Ω there is less than 5% reduction. Also, it

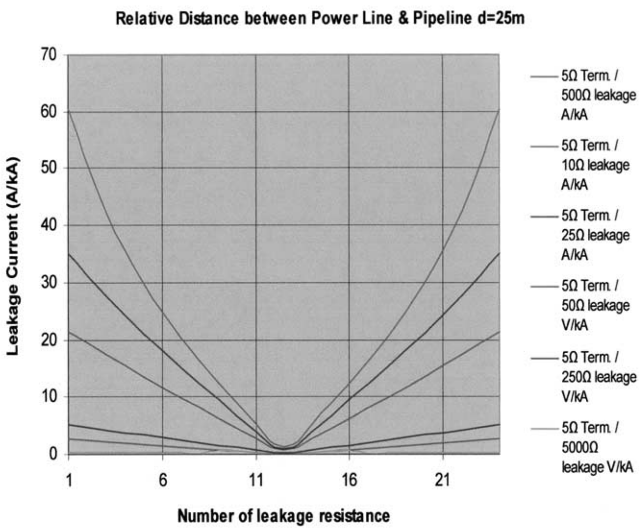

Fig. 7. Leakage currents over kA of fault current on the defects of the coating of the pipeline versus distance from left terminal, for 5 Ω terminal resistances and 10, 25, 50, 250, 500 and 5000 Ω leakage resistances located at each km of the pipeline. Relative separation between pipeline and power line is 25 m.

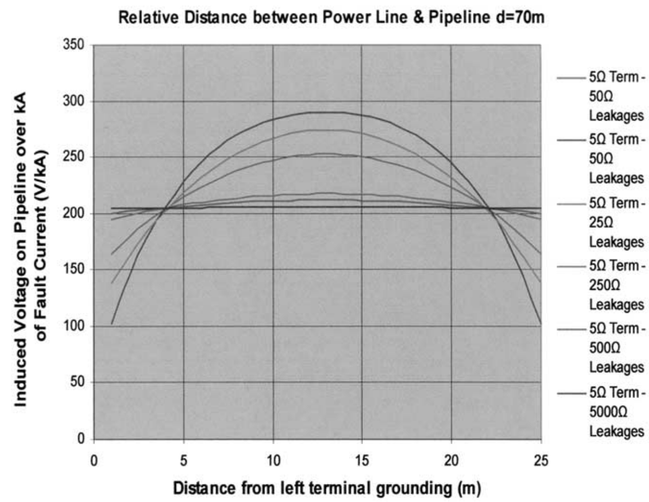

Fig. 9. Induced currents on the pipeline over kA of fault current (A/kA) in the system of Fig. 1 versus distance from left terminal, for 5 Ω terminal resistances and 10, 25, 50, 250, 500 and 5000 Ω leakage resistances located at each km of the pipeline. Relative separation between pipeline and power line is 70 m.

must be noted that although small leakage resistances reduce the induced voltage on a pipeline, the leakage current flowing through them is considerably high. This can endanger the integrity of the pipeline and accelerate the corrosion of the metal.

The relative separation *d* between power line and pipeline is an important factor that influences the inductive interference studied here. Figs. 11 and 12 show the induced voltages and currents on the pipeline for different relative separations. Changing the relative separation from 25 to 70 m a 30% decrease on the induced voltage on the pipeline is achieved. Beyond 1000 m the inductive interference becomes negligible.

The effect of earth resistivity and fault resistance on the induced voltages and currents on the pipeline may be realized by inspecting the graphs shown in Figs. 13–15. For these cases the pipeline is assumed grounded at both ends with resistances of 50 Ω, while the leakage resistances are 50 Ω as before. The earth resistivity is an important factor that has to be taken into account for the calculation of the induced voltages and currents on the pipeline. Specifically, from inspection of graphs 13 and 14, it may be realized that a change of earth resistivity from 30 to 1000 Ω m results in a 50% increase

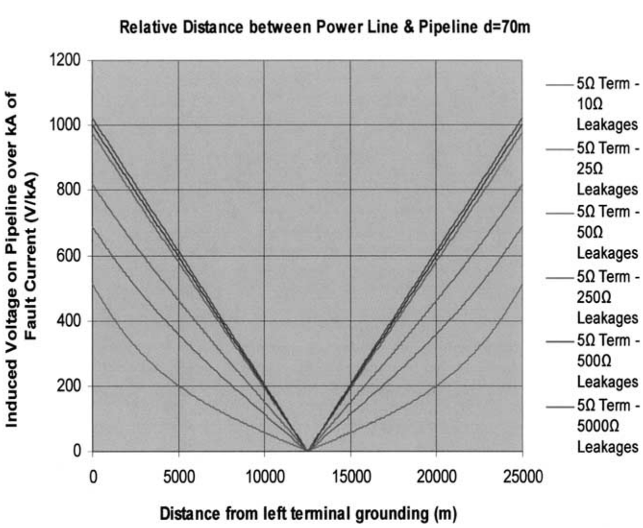

Fig. 8. Induced voltages on the pipeline over kA of fault current (V/kA) in the system of Fig. 1 versus distance from left terminal, for 5 Ω terminal resistances and 10, 25, 50, 250, 500 and 5000 Ω leakage resistances located at each km of the pipeline. Relative separation between pipeline and power line is 70 m.

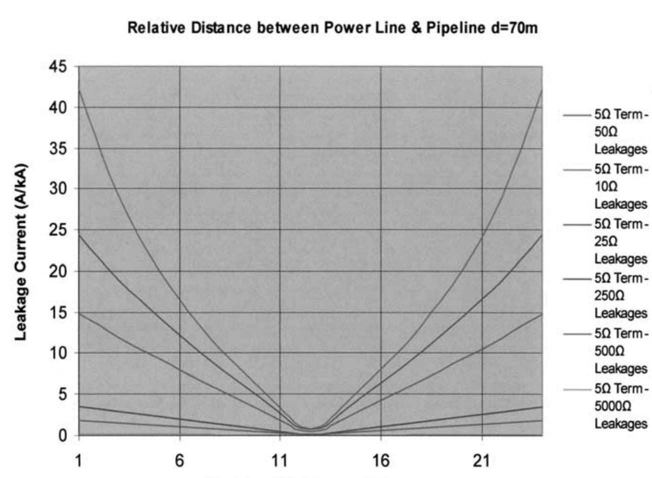

Fig. 10. Leakage currents over kA of fault current on the defects of the coating of the pipeline versus distance from left terminal, for 5 Ω terminal resistances and 10, 25, 50, 250, 500 and 5000 Ω leakage resistances located at each km of the pipeline. Relative separation between pipeline and power line is 70 m.

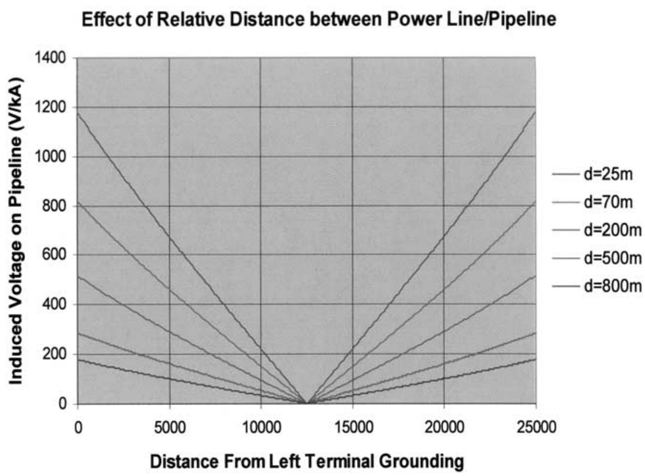

Fig. 11. Induced voltages on the pipeline over kA of fault current (V/kA) in the system of Fig. 1 versus distance from left terminal, for 5 Ω terminal resistances and 50 Ω leakage resistances located at each km of the pipeline, for relative separation between pipeline and power line 25, 70, 200, 500 and 800 m.

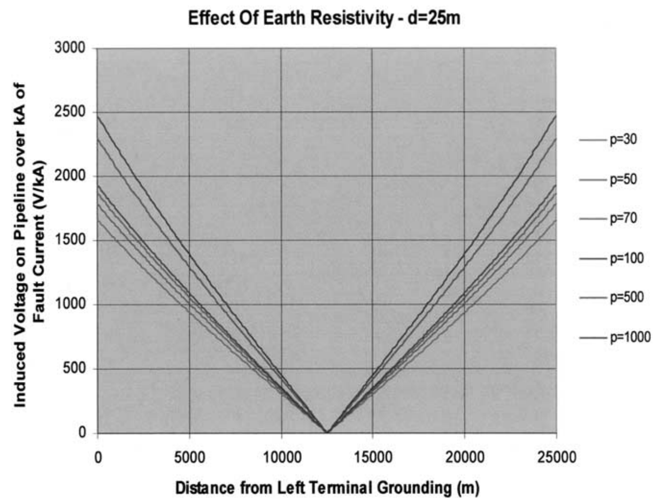

Fig. 13. Induced voltages on the pipeline over kA of fault current (V/kA) in the system of Fig. 1 versus distance from left terminal, for 50 Ω terminal resistances and 50 Ω leakage resistances located at each km of the pipeline, for values of earth resistivity of 30, 50, 70, 100, 500, 1000 Ω m. Relative separation between pipeline and power line is 25 m.

in the induced voltage on the pipeline approximately. The value of earth resistivity mainly affects the values of self and mutual impedances calculated with the FEM method. On the other hand, fault resistance is a parameter that influences directly the fault current calculated with the proposed method, while self and mutual impedances remain unaffected. Fig. 15 show that the fault current decreases almost linearly with increasing value of the fault resistance. Knowing the fault current, one may determine the level of inductive interference on the pipeline by utilizing the previous graphs showing the unknown parameters over kA of fault current. It must be noted that the effect of relative power line/pipeline separation and pipeline leakage resistances on the fault current is negligible comparing with that of the fault resistance.

6. Conclusions

A hybrid method for calculating the induced voltages and currents on a pipeline with defects on its coating was introduced. The method combines FEM calculations, Faraday's law and standard circuit analysis in order to compute the induced voltages and currents on the pipeline as well as the current that flows to earth

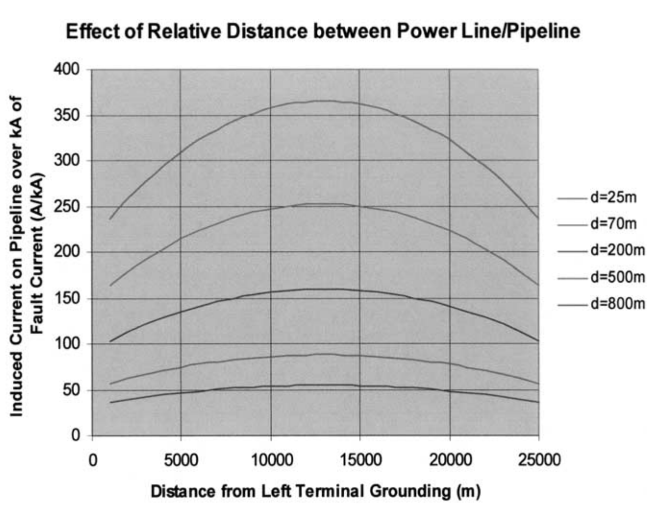

Fig. 12. Induced currents on the pipeline over kA of fault current (A/kA) in the system of Fig. 1 versus distance from left terminal, for 5 Ω terminal resistances and 50 Ω leakage resistances located at each km of the pipeline, for relative separation between pipeline and power line 25, 70, 200, 500, 800 m.

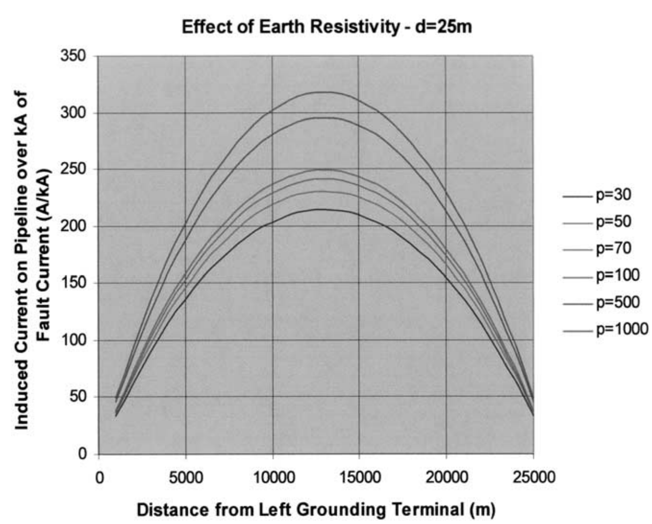

Fig. 14. Induced currents on the pipeline over kA of fault current (A/kA) in the system of Fig. 1 versus distance from left terminal, for 50 Ω terminal resistances and 50 Ω leakage resistances located at each km of the pipeline, for values of earth resistivity of 30, 50, 70, 100, 500, 1000 Ω m. Relative separation between pipeline and power line is 70 m.

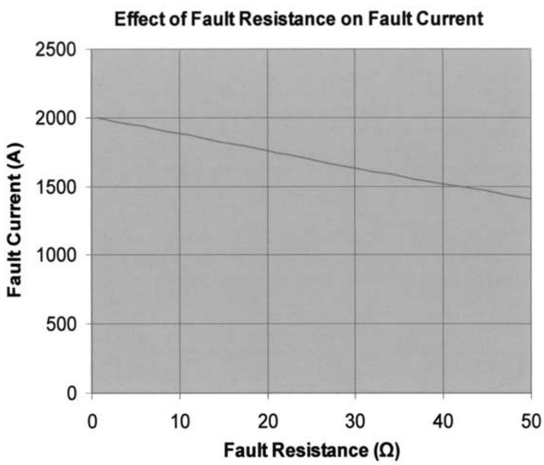

Fig. 15. Fault current calculated in the system of Fig. 1 versus value of the fault resistance for relative separation between pipeline and power line 25 m, earth resistivity 100 Ω m and 50 Ω terminal resistances and 50 Ω leakage resistances located at each km of the pipeline.

through possible defects. Results presented suggest that the smaller the leakage resistances are the better the mitigation of the induced voltage on the pipeline is. Unfortunately, in that case the high currents flowing to earth through the coating defects pose a threat to the integrity of the pipeline. Other factors that have to be considered are earth resistivity, fault resistance and the relative distance between power line/pipeline that affect the level of inductive interference on the pipeline. However, these factors are independent of the presence of defects on the pipeline coating and generally affect the inductive interference on the pipeline.

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Appendix A: Nomenclature

Symbol	Description
U_o	source voltage (V)
Z_s	source impedance (Ω)
R_f	fault resistance (Ω)
R_g	neutral ground resistance (Ω)
R_T	terminal ground resistance of pipeline (Ω)
R_i	leakage resistance of pipeline (Ω)
ρ	earth resistivity (Ω/m)
s	coating thickness (m)
σ_m	pipeline's metal conductivity (S/m)
A_z	magnetic vector potential (MVP) in z-direction (Wb/m)
A_{zP}	MVP on the surface of the pipeline in z-direction (Wb/m)
E	electric field density (V/m)
J_z	total current density in z-direction (A/m^2)
σ	conductivity of phase wire (S/m)
σ_p	conductivity of the metal of pipeline (S/m)
$\mu_{r,m}$	pipeline's metal permeability
μ_o	vacuum permeability
μ_r	relative permeability
ω	angular frequency (rad/s)
l_P	length of parallel exposure of pipeline/power line (m)
l	distance of fault location from source (m)
J_{sz}	source current density in z-direction (A/m^2)
I_i	RMS value of current through conductor i (A)
S_i	cross-section of conductor i (m^2)
S	cross-section of phase conductor (m^2)
S_p	effective cross-section of metal area of pipeline (m^2)
J^e_{ez}	Eddy-current density of element e in z-direction (A/m^2)
J^e_z	total element current density (A/m^2)
J_{szi}	source current density of conductor i (A/m^2)
Φ	flux of magnetic field (Wb)
I_F	fault current (A)
I_{pi}	induced current on the i section of pipeline (A)
D	relative separation between pipeline/power line (m)
d_f	diameter of defect (m)
L_{FF}	self inductance of phase wire (H)
L_{Fi}	mutual inductance of phase wire and section-i of pipeline (H)
L'_{Fi}	mutual inductance of phase wire and section-i of pipeline per unit length (H/m)
L_{pi}	self inductance of section-i of pipeline (H)
L'_{Pi}	self inductance of section-i of pipeline per unit length (H/m)

References

[1] J.R. Carson, Wave propagation in overhead wires with ground return, Bell System Technical Journal 5 (1926) 539–554.
[2] H. Böcker, D. Oeding, Induckttionsspannung an pipelines in Trassen von Hochspannungsleitungen, Elektrizitatswirtschaft 65 (1966) 5.
[3] G. Kaiser, Die Elektrischen Konstanten von Rohrleitungen und Ihre Messung, ETZ-A 87 (1966) 792–796.
[4] E.D. Sunde, Earth Conduction Effects in Transmission Systems, Dover Publ, New York/USA, 1968.

[5] J. Pohl, Influence of high voltage overhead lines on covered pipelines, CIGRE Paper No. 326, June, 1966.
[6] B. Favez, J.C. Gougeuil, Contribution to studies on problems resulting from the proximity of overhead lines with underground metal pipelines, CIGRE Paper No. 336, June, 1966.
[7] Technical Recommendation No. 7, Arbitration agency for problems of interference between installations of the German Federal Post Office and the Association of German power utilities, Verlags und Wirtschaftsgesellschaft der Elektrizitätswerke mbH—VHEW, 1982.
[8] J. Dabkowski, A. Taflove, A mutual design consideration for overhead AC transmission lines and gas pipelines, EPRI Report EL-904, vol. 1, 1978.
[9] M.J. Fraiser, Power line induced AC potential on natural gas pipelines for complex rights-off-way configurations, EPRI. Report EL-3106, AGA. Cat. No. L51418, April, 1984.
[10] F.D. Dawalibi, R.D. Southey, Y. Malric, W. Tavcar, Power line fault current coupling to nearby natural gas pipelines, volumes 1 and 2, EPRI/AGA Project 742, EL-5472/PR176-510, November, 1987.
[11] F.P. Dawalibi, R.D. Southey, Analysis of electrical interference from power lines to gas pipelines Part I: computation methods, IEEE Trans. Power Delivery 4 (3) (1989) 1840–1846 (July).
[12] F.P. Dawalibi, R.D. Southey, Analysis of electrical interference from power lines to gas pipelines Part II: computation methods, IEEE Trans. Power Delivery 5 (1) (1990) 415–421 (January).
[13] F. Pollaczek, On the field produced by an infinitely long wire carrying alternating current, Electrische Nachricten Technik vol. III, 1029 (9) 339–359 (in German). French translation also available in Revue Generale de l' Electricite 29 (22) (1931) 851–867.
[14] P. Kouteynikoff, Résultats d' une Enquete Internationale sur les Régles Limitant les Pertubations Créés sur les Canalisations par les Ouvrages électriques, ELECTRA (110) (1987).
[15] Guide on the influence of high voltage AC power systems on metallic pipelines, CIGRE Working Group 36.02, 1995.
[16] K.J. Satsios, D.P. Labridis, P.S. Dokopoulos, Currents and voltages induced during earth faults in a system consisting of a transmission line and a parallel pipeline, European Transactions on Electrical Power (ETEP) May/June, 8 (3) (1998).
[17] K.J. Satsios, D.P. Labridis, P.S. Dokopoulos, Finite-element computation of field and Eddy currents of a system consisting of a power transmission line above conductors buried in nonhomogeneous earth, IEEE Trans. Power Delivery, July, 13 (3) (1998).
[18] W. von Baeckmann, W. Schwenk, W. Prinz, Handbook of Cathodic Corrosion Protection, Theory and Practice of Electrochemical Protection Processes, 3rd ed., Gulf Publishing Co, Houston, TX, 1997.
[19] F.P. Dawalibi, Ground fault current distribution between soil and neutral conductors, IEEE Trans. Power Apparatus Systems PAS 99 (2) (1980) 452–461 (March/April).
[20] D.P. Labridis, Comparative presentation of criteria used for adaptive finite element mesh generation in multiconductor Eddy current problems, IEEE Trans. Magnetics 36 (1) (2000) 267–280 (January).