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A Hybrid Method for Calculating the Inductive Interference Caused by Faulted Power Lines to Nearby Buried Pipelines

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***Abstract*—The interference of power transmission lines to nearby buried pipelines has been a research subject for many years. Especially during fault conditions, large currents and voltages are induced on the pipelines, which may pose a threat to operating personnel and equipment. In this work, a new hybrid method employing finite element calculations and standard circuit analysis is discussed that may be used in order to calculate the induced voltages and currents on a pipeline running in parallel to a faulted line. Nonparallel exposures are converted to parallel ones and dealt with similarly. The fault is assumed to be a single earth-to-ground one and outside the exposure, so that only inductive interference is considered. A specific case taken from literature is used to validate the proposed method. The results obtained are in good agreement with previously published ones. Important parameters such as the earth resistivity, location of grounding and pipeline coating resistance are evaluated, producing graphs that may be useful to engineers.**

***Index Terms*—Electromagnetic reactive interference, finite element methods, pipelines, power transmission faults.**

NOMENCLATURE

$\overline{A}_z$	Magnetic Vector Potential in z-direction (Wb/m).
d	Relative separation between pipeline/power line (m).
D	Pipeline diameter (m).
$\bar{I}_F$	Fault current (A).
$\bar{I}_{pi}$	Current on the i-section of pipeline (A).
$\bar{I}_{gi}$	Current on the i-section of ground wire (A).
$\overline{J}_z$	Total current density in z-direction $(\mathrm{A/m^2})$.
$\overline{J}_z^e$	Total element current density $(\mathrm{A/m^2})$.
$\overline{J}_{sz}$	Source current density in z-direction $(\mathrm{A/m^2})$.
$\overline{J}_{szi}$	Source current density of conductor-i $(\mathrm{A/m^2})$.
$\overline{J}_{ez}^e$	Eddy-current density of element-e $(\mathrm{A/m^2})$.
l	Distance of fault location from source (m).
l_P	Length of parallel exposure of pipeline/power line (m).
r_u	Coating resistance of pipeline $(\Omega \cdot \mathrm{m}^2)$.
R_f	Fault resistance (Ω).
R_{pi}	Leakage resistance of pipeline (Ω).
R_{gi}	Tower grounding resistance (Ω).
$\overline{V}_s$	Source voltage (V).
$\overline{Z}_s$	Source impedance (Ω).
$\overline{Z}_{ij}$	Mutual impedance between conductors i and j (Ω).
$\overline{Z}_{mgi}$	Mutual impedance between i-section of phase wire and i-section of ground wire (Ω).
$\overline{Z}_{mpgi}$	Mutual impedance between i-section of ground wire and i-section of pipeline (Ω).
μ_m	Pipeline's metal permeability.
μ_o	Vacuum permeability.
μ_r	Relative permeability.
ρ	Earth resistivity (Ω/m).
σ	Conductivity (S/m).
ω	Angular frequency (rad/s).

I. INTRODUCTION

THE issue of electromagnetic interference between power transmission lines and pipelines has been a topic of major concern since the early 1960s, mainly due to the following reasons.

- The rapid increase in energy consumption, especially in western countries, led to the adoption of higher load and short-circuit current levels, thus making the problem more acute.
- The ever-increasing cost of rights-of-ways, suitable for power lines and pipelines, along with recent environmental regulations, aiming to protect nature and wildlife, has forced various utilities to share close or even common corridors for both power lines and pipelines. Therefore, situations where a pipeline is laid at a close distance from a transmission line for several kilometers is frequent nowadays.

Electromagnetic interference is present both during normal operating conditions and faults. Generally, it consists of an inductive, a conductive, and a capacitive component, with the inductive part being the dominant one. The capacitive component may be ignored for buried pipelines, while the conductive part arises only in fault conditions and, specifically, in cases where the pipeline is located near the faulted structure. The inductive interference is the result of the magnetic field generated by the power line, which induces voltages in adjacent metallic conductors, like pipelines. Especially during fault conditions, high voltages and currents may be induced to nearby pipelines, which may result in hazards to people or working personnel touching the pipeline or other metallic structures connected to it, even if the fault occurs far away from them. In addition, there is a high

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risk of damaging the pipeline coating, insulating flanges or rectifiers, accelerating corrosion of the metal.

Many scientific organizations and research institutes have examined the problem, producing various reports, papers and standards. The first attempts to study the above interferences [2]–[5], [16], where based on the widely known Carson's relations [1]. A technical recommendation was developed based on these works, which was revised later [17], as advances in computer technology made it possible to adopt more advanced and sophisticated analytical models. During the late 70's and early 80's, two research projects of the Electrical Power Research Institute (EPRI) and the American Gas Association (AGA) introduced practical analytical expressions that could be programmed on hand held calculators [18] and computerized techniques [19]. In the following years, a joint program of EPRI and AGA led to the development of a computer program [6], [7], [20] that utilizes equivalent circuits with concentrated or distributed elements. The self and mutual inductances are calculated using classic formulae from Carson [1], Pollaczek [8] and Sunde [16]. Furthermore, CIGRE's Study Committee 36 produced a report detailing the different regulations existing in different countries [9] and some years later published a general guide on the subject [21], with a summary of the most important parts reproduced in [10].

More recently, the finite-element method (FEM) was proposed [11] as a means to provide a field solution method. However, due to the large solution area of the problem, only two dimensional FEM calculations were performed. This made the method applicable only to symmetrical cases (e.g., parallel routings) and to cases where the pipeline has a perfect coating, 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.

In order to overcome the above limitations, the authors recently proposed a hybrid method [12], [22], utilizing both FEM calculations and circuit theory. This paper generalizes the previous works by including in the analysis the ground wire(s) and, in addition to that, tests the accuracy of the proposed method by comparing with previously published results from [7].

The method presented may be used to obtain reliable results for several cases involving inductive interference situations. In order to account for conductive interference, three-dimensional FEM calculations would be normally needed. Instead of this, the method utilizes two-dimensional finite-element calculations for the determination of the magnetic vector potential (MVP) on the surface of the conductors. Using the results obtained from the FEM calculations, the self and mutual inductances between the conductors are computed. A circuit model of the specific problem is then constructed and solved using standard methods [19]. The power of the method stems from the utilization of FEM calculations that enables the engineer to deal with complicated configurations, such as when many conductors are present or when the earth is not homogeneous.

In Section II, a description of the configuration studied is provided, while Section III presents in detail the proposed method and the discrete steps that comprise it. Finally, Section IV presents results obtained using the proposed approach.

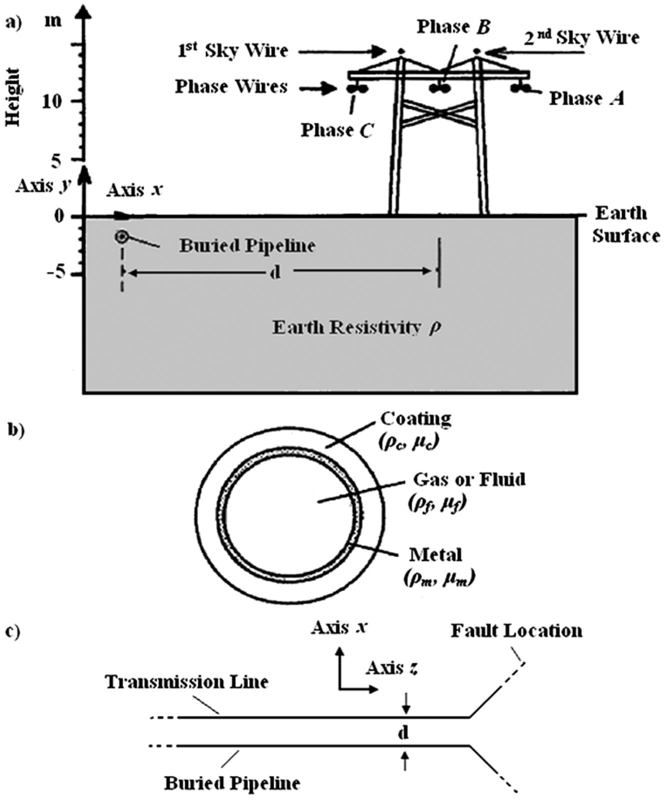

Fig. 1. System under investigation. (a) Cross-section of the system, (b) detailed pipeline cross section, and (c) top view of the parallel exposure.

II. CASE STUDY

A specific configuration, taken from [7] and shown in Fig. 1, was chosen and is studied in this work. The pipeline and the power transmission line are sharing an $l_p = 25$ km long rights-of-way, while at a point, which is $l = 30$ km away from the source, a single phase-to-earth fault is assumed. We take into consideration only the effects due to the inductive interference caused by the power line to the pipeline. This is reasonable since the fault occurs outside the parallel exposure and, therefore, conductive interference may be neglected. Furthermore, the capacitive coupling may be ignored, since the pipeline is buried. This inductive coupling results in induced currents on the pipeline and earth, while voltages appear across the pipeline's surface and to ground.

The power transmission line consists of a pair of HAWK ACSR conductors per phase bundle. The earth is assumed homogeneous, although this is not restrictive to the method. The parameters of the problem were taken from [7, Appendix].

The single phase-to-ground fault is simulated using a standard 60 Hz frequency. A two-dimensional problem is considered without introducing significant error by neglecting end effects and considering infinite length conductors. The assumptions are reasonable for inductive interference calculations and for the lengths of parallel exposures encountered in practical applications. The fault impedance is modeled as pure resistance (R_f), as we consider the fault to be in a steady-state condition.

III. DESCRIPTION OF METHOD

The proposed method combines FEM calculations and standard circuit analysis in order to calculate the inductive coupling caused by a single phase-to-earth fault on a nearby parallel pipeline. The discrete steps of the method are

a) calculate the self and mutual impedances of all conductors using the FEM calculations;
b) construct a circuit model of the problem and solve it using standard methods, so that potentials and currents on a pipeline or other metallic structures are determined.

The need for a hybrid method originates from the fact that FEM calculations may be used effectively only for two-dimensional problems, as a FEM model in three-dimensions would need considerable amount of time to be solved, considering the large area that needs to be modeled. Moreover, employing circuit analysis using classical methods to calculate the self and mutual impedances of the conductors may lead to incorrect results in cases where, for example, terrain irregularities exist or the ground is composed of several layers with different electromagnetic properties. Therefore, the proposed method aims to take advantage of the benefits of the FEM without demanding a significant amount of computational resources and time.

The purpose of this work is to describe the hybrid method in detail and compare results to previously published results. The analysis of more complex situations involving terrain irregularities and ground stratification will be the subject of a following paper.

The required input data for the method are

- power line and pipeline geometrical configuration;
- physical characteristics of conductors and pipeline;
- air and earth characteristics;
- power system terminal parameters;
- fault parameters describing fault location and type.

The output data are

- the induced voltage and current at any point on the pipeline;
- the currents flowing to earth through the leakage resistances;
- the distribution of the current returning through the ground wire(s).

A. Finite Element Formulation

Considering that the cross section of the system under investigation, shown in Fig. 1(a), lies on the $x-y$ plane, the following system of equations describes the linear two-dimensional electromagnetic diffusion problem for the z-direction components $\overline{A}_Z$ of the MVP vector and $\overline{J}_Z$ of the total current density vector [11]

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

$$-j\omega\sigma\overline{A}_Z+\overline{J}_{SZ}=\overline{J}_Z \quad (1b)$$

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

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

It is shown [11] that the finite-element formulation of (1a)–(c) leads to a matrix equation. 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 $\overline{J}_{ez}^e$ is calculated using the relation

$$\overline{J}_{ez}^e(x,y)=-j\omega\sigma\overline{A}_z^e(x,y) \quad (2a)$$

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

$$\overline{J}_z^e(x,y)=\overline{J}_{ez}^e(x,y)+\overline{J}_{szi}. \quad (2b)$$

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

The FEM package [13], 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 [13] for an iteratively adaptive mesh generation.

B. Determination of Self and Mutual Impedances of Conductors

The FEM calculations are used in the described method, as a means of calculating the self and mutual impedances of the conductors present in the configuration. Generally, if there exist n conductors in the configuration and assuming that the per unit length voltage drop $\overline{V}_i$ on every conductor is known for a specific current excitation, the mutual complex impedance $\overline{Z}_{ij}$ between conductor i and another conductor j carrying a certain current $\overline{I}_j$, where all other conductors are forced to carry zero currents, is given by

$$\overline{Z}_{ij}=\frac{\overline{V}_i}{\overline{I}_j} \qquad (i,j=1,2,\ldots,n). \quad (3)$$

Similarly, the self impedance of conductor i may be calculated using (3), by setting $i=j$.

The procedure is summarized as follows [14]:

- by applying a sinusoidal current excitation of arbitrary magnitude to each conductor, while applying zero current to the other conductors, the corresponding voltages are calculated;
- the self and mutual impedances of the j conductor may be calculated using (3).

This procedure is repeated n times, so as to calculate the impedances of n conductors.

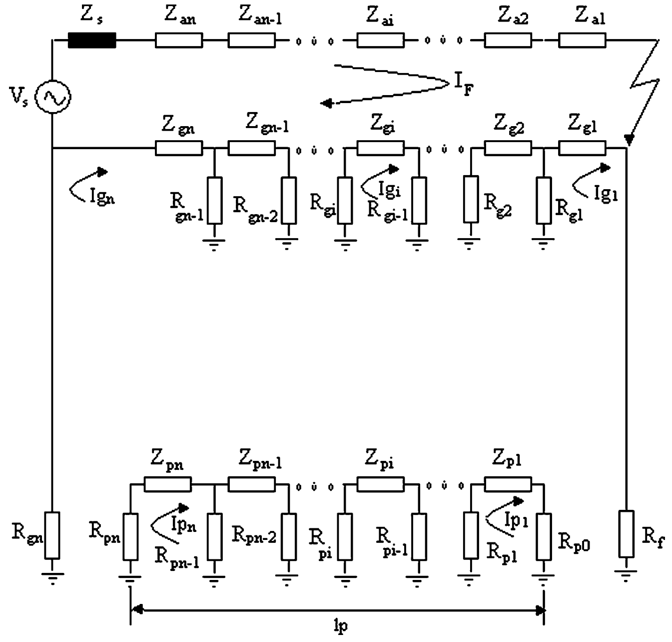

Fig. 2. Circuit representation of the problem.

Applying FEM calculations for the solution of linear electromagnetic diffusion equations as in [14], the values for $\overline{J}_{szi}$ on each conductor i having a conductivity of σ_i are obtained. Therefore, (3) becomes

$$\overline{Z}_{ij} = \frac{\overline{V}_i}{\overline{I}_j} = \frac{\frac{\overline{J}_{szi}}{\sigma_i}}{\overline{I}_j} \qquad (i,j = 1,2,\dots,n). \tag{4}$$

Following the above procedure, effectively linking electromagnetic field variables and equivalent circuit parameters, the self and mutual impedances per unit length of the problem are computed.

By using the FEM to calculate the impedances of the problem instead of utilizing classic formulae, (e.g. Carson's), one can deal effectively with more complex situations, such as when the earth comprises many layers.

C. Circuit Representation of the Problem

Having computed the impedances of the problem, the equivalent circuit is constructed as shown in Fig. 2. We assume that only the faulted line is loaded and that the towers are grounded with resistances R_{gi} $(i = 0,\dots,n)$ at frequent intervals, where n is the total number of the tower groundings existing between the source and fault location. In the circuit representation, the ground wires are replaced with an equivalent metallic return path. In order to account for the fact that the pipeline coating is not perfect, i.e. has defects, the pipeline is modeled in sections utilizing a series of grounding-leakage resistances R_{pi} $(i = 0,\dots,m)$, where m is the total number of leakage resistances and generally $m \neq n$. These resistances may, also, represent regular groundings used as a mitigation measure, mainly ground or polarization cells. In the case that there are not any pipeline groundings throughout the rights-of-way, the leakage resistances are modeled at the same z-axis locations as the tower groundings.

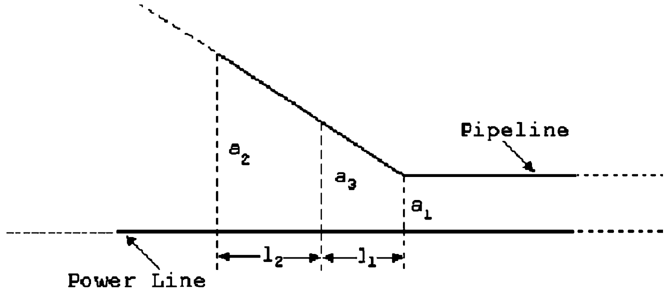

Fig. 3. Example of an oblique exposure.

Generally, one may derive n equations for the ground wire, m for the pipeline and one for the source loop. The unknowns of this system of equations will be the n ground wire loop currents, the m pipeline loop currents and the fault current I_F. The Appendix shows how the system of equations is constructed and how the induced voltage on the pipeline is determined.

D. 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 nonparallel sections may exist. An example of such an oblique exposure is shown in Fig. 3. According to [17] though, an oblique exposure may be considered as a parallel section having a relative distance a from the power line equal to

$$a = \sqrt{a_1 a_2} \tag{5a}$$

as long as

$$\frac{a_2}{a_1} \leq 3. \tag{5b}$$

In case a_2/a_1 is more than 3, the section is divided, as shown in Fig. 3, in order that both a_3/a_1 and a_2/a_3 meet (5b). Furthermore, when high precision is required, more subdivisions should be made, which multiplies the computational time, as the impedances of the problem should be calculated for different relative separations. This situation makes the prospective use of artificial intelligence, for estimating these impedances, very attractive.

IV. RESULTS

The described method was tested using the configuration of Fig. 1, which was taken from [7]. With respect to inductive interference calculations, the authors of [7] use simplified formulae to determine the self and mutual impedances of all long conductors, such as phase wires, sky wires and pipelines. These impedances are used to construct a circuit model that is solved using the generalized double-sided elimination method [15], so that potentials and currents in the pipeline are determined.

Using similar parameters as in [7, Appendix] and assuming a single earth-to-ground fault in phase A of Fig. 1, the graph shown in Fig. 4 was obtained. This graph shows the effect of terminating the right end of the pipeline with different values of resistance, while the other end is assumed to be insulated.

The results obtained are in good agreement with [7]. Slightly higher values are calculated using our proposed approach, which may be justified by considering the different calculation

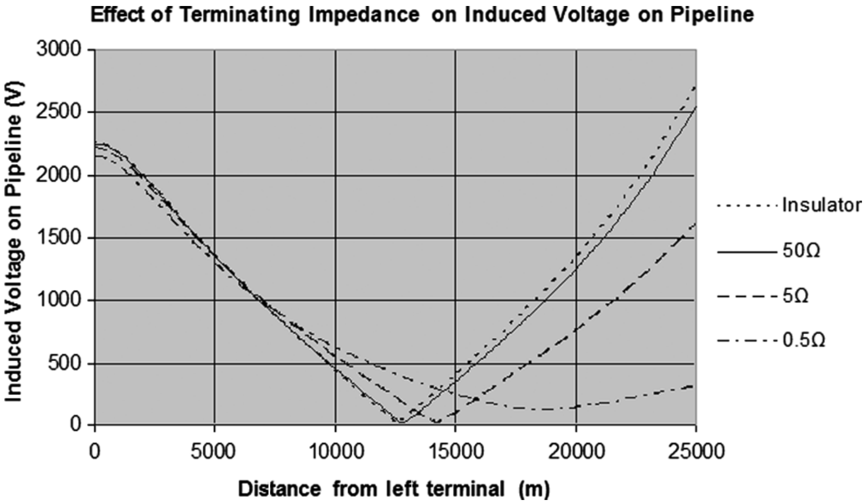

Fig. 4. Effect of terminating impedance on the induced voltage on pipeline. The other end is assumed insulated. The towers are grounded every 250 m. The other parameters are taken from [10].

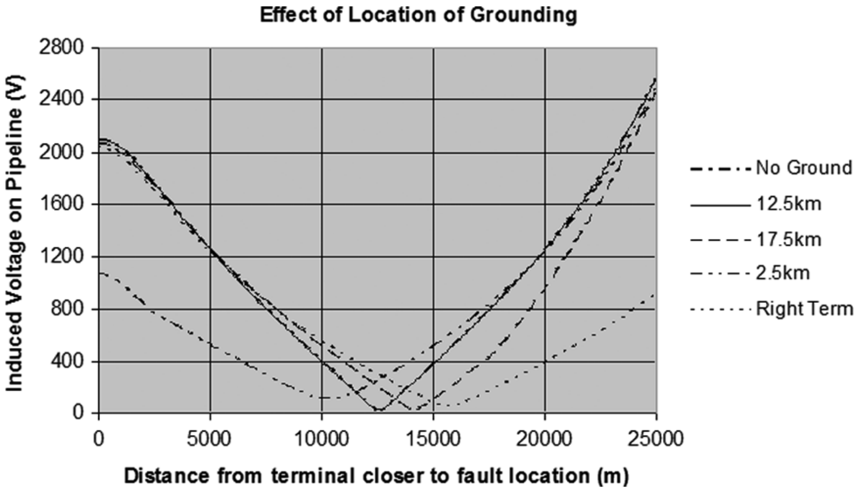

Fig. 5. Effect of placing a grounding of 2 Ω at different locations along the rights-of-way.

method of the self and mutual impedances of the problem using the FEM method.

In order to obtain the graph of Fig. 4, the fault was simulated at 25 km from source, at the end of the parallel exposure. This violates the assumption we made that the fault occurs outside the parallel exposure, in order to account only for the inductive coupling. However, the purpose of this graph is to compare with previously published results. In [7] the authors make two separate simulations one for the inductive and one for the conductive coupling. It may be observed that even when the pipeline is insulated at both ends, the voltage profile is not symmetric, with the end being closer to the fault location having a higher voltage than the other end. This originates from the simulation data used, as the fault resistance is taken equal to 20 Ω, while the resistance of the neutral of the source is 0.2 Ω.

Apart from grounding a pipeline at its end, there exist situations where a pipeline is grounded at other positions along the rights-of-way. Referring to Fig. 5, it should be noted that the groundings have to be placed at positions near the ends of the pipeline, as the induced voltage, with respect to remote earth, reaches its maximum value there. Placing a grounding at the middle of the pipeline has almost no effect in reducing the amount of induced voltage. One can achieve significant reduction, by placing earth electrodes at both ends of a pipeline. It should be noted, that a large hole or defect on the pipeline coating, at the same positions, has the same effect. However, in that case a large leakage current is flowing to earth through the defect, which may endanger the integrity of the pipeline and accelerate the corrosion of the metal.

The influence of installing pipeline groundings at both its ends may be realized by observing Fig. 6. Even with groundings of relatively high values, like the 10 Ω case, a reduction of approximately 25% from the insulated case is observed.

A very important parameter of the problem is the resistance r_u of the pipeline coating. Fig. 7 shows the effect of the pipeline's coating resistance on the level of the inductive coupling between the power line and the pipeline. It may be realized that the better the coating of the pipeline is, the worse the situation becomes. Consequently, old pipelines, that have a reduced coating resistance, due to being buried for a long time, are less prone to inductive interference from nearby power lines.

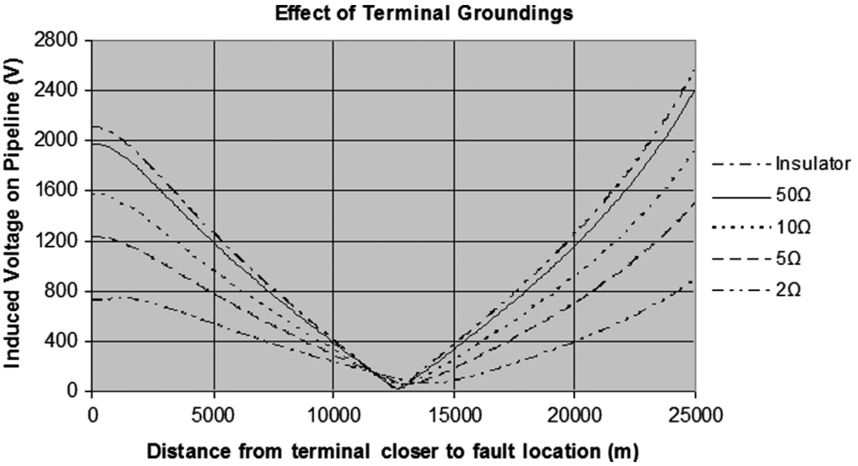

Fig. 6. Effect of terminating both ends of the pipeline with resistances of equal values. The fault modeled at 30 km away from source.

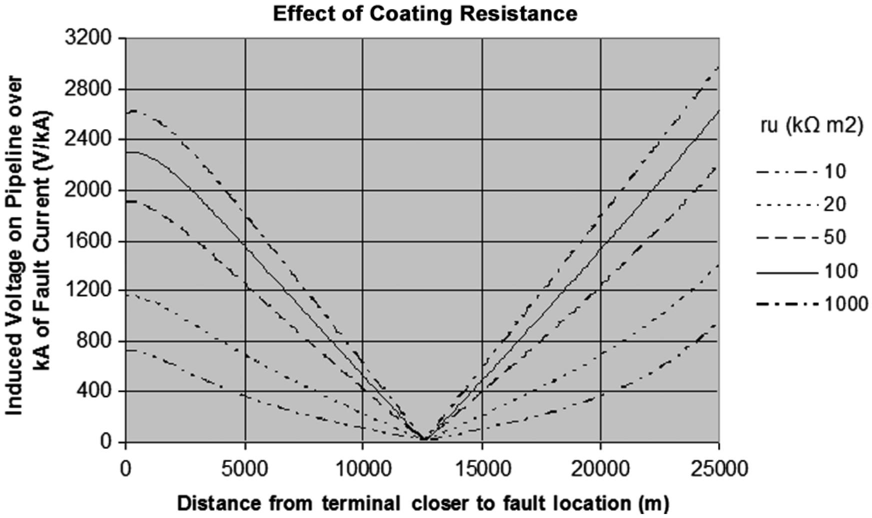

Fig. 7. Effect of coating resistance r_u $(\mathrm{k}\Omega \cdot \mathrm{m}^2)$ of pipeline on the induced voltage. The graph obtained using data from the Appendix.

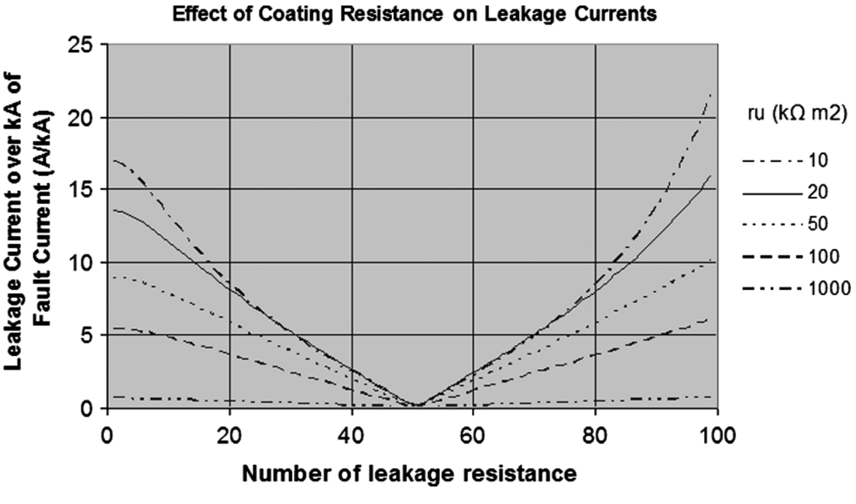

Fig. 8. Effect of coating resistance r_u $(\mathrm{k}\Omega \cdot \mathrm{m}^2)$ of pipeline on the leakage currents flowing through the leakage resistances. Leakage resistances are modeled each 250 m of the pipeline.

Nevertheless, the leakage currents flowing through the leakage resistances are, in that case, much higher. Fig. 8 shows the leakage currents over kA of fault current. It may be observed that the degradation of pipeline coating from $\mathrm{ru} = 50\ \mathrm{k}\Omega \cdot \mathrm{m2}$ to $10\ \mathrm{k}\Omega \cdot \mathrm{m2}$ results in more than doubling the amount of leakage current flowing through the pipeline leakage resistances located near both ends.

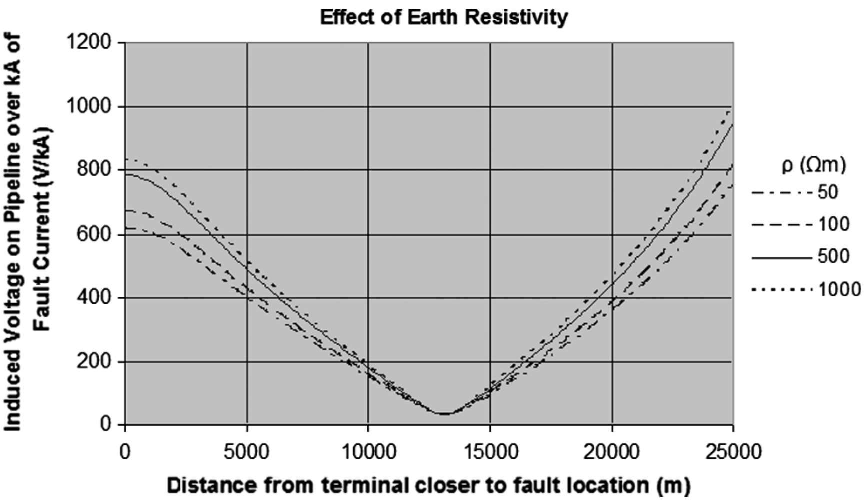

Fig. 9. Effect of earth resistivity on induced voltage on pipeline. The pipeline is grounded at both terminals with 5 Ω resistances.

Another factor that affects the inductive interference studied here is the value of the earth resistivity. While earth is assumed to be homogeneous, this is not a restriction for the proposed method. Earth profiles with several layers, having different resistivities, both in depth and length may be modeled accurately. A parametric analysis is shown in Fig. 9, when the pipeline is assumed to be grounded at both ends with 5 Ω impedances and earth is assumed to have one layer. A reduction in the induced voltage of approximately 25% is calculated comparing the case of a rocky ground ($1000\ \Omega \cdot \mathrm{m}$) and the case of a wet ground ($50\ \Omega \cdot \mathrm{m}$).

The variation of earth resistivity mainly affects the mutual impedances between the conductors of the problem, calculated using the FEM method. A higher earth resistivity results in higher values of mutual impedances and therefore makes the inductive coupling more severe.

V. CONCLUSIONS

A hybrid method was presented that may be used to determine the inductive coupling between a pipeline and a faulted power line. The method combines FEM calculations 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 through the pipeline's leakage resistances. Utilizing this method, complicated situations involving many conductors or nonhomogeneous ground may be dealt with without unnecessary simplifications or assumptions. The method was tested comparing the results with results published using other techniques. Good agreement between results was shown.

The results presented in this paper suggest that the worse the pipeline coating is the better the mitigation of the induced voltage and current on the pipeline becomes. Unfortunately, in that case the high currents flowing to earth through the leakage resistances pose a threat to the integrity of the pipeline. The case of installing earth electrodes at various points along the rights-of-way was studied, leading to the conclusion that the optimum position is at both ends of the pipeline, where the higher values of induced voltage are calculated. Finally, the earth resistivity, a parameter affecting the mutual impedances between the conductors of the configuration, has been investigated.

APPENDIX

A. System Solution

Referring to Fig. 3, the n equations of the ground wire loops may be stated

$$(-Z_{gi} + Z_{mgi})I_F + T_{pi}I_{gi} - R_{gi-1}I_{gi-1} - R_{gi}I_{gi+1} + Z_{mpgi}I_{pi} = 0 \quad \text{(B.1)}$$

for $i = 1$ *to* n, where,

$$T_{pi} = (R_{gi-1} + Z_{gi} + R_{gi}), \quad I_{g0} = 0$$

and $Z_{mpgi} = 0$ for $i = m + 1$ *to* n.

Similarly, the m equations of pipeline loops may be written

$$(-Z_{mpgi} + Z_{mpi})I_F + T_{pi}I_{gi} - R_{pi-1}I_{pi-1} - R_{pi}I_{pi+1} + Z_{mpgi}I_{gi} = 0 \quad \text{(B.2)}$$

for $i = 1$ *to* m, where

$$T_{pi} = (R_{pi-1} + Z_{pi} + R_{pi}) \quad \text{and} \quad I_{p0} = 0.$$

Finally, the last equation may be derived from the source loop as follows:

$$\sum_{i=1}^{n} H_i I_F + \sum_{i=1}^{n} (Z_{mgi} - Z_{gi})I_{gi} + \sum_{i=1}^{m} (Z_{mpi} - Z_{mpgi})I_{pi} = U_0 \quad \text{(B.3)}$$

where $H_i = (Z_{ai} + Z_{gi} - 2Z_{mgi})$.

Slightly different equations may be devised in the case where the pipeline left terminal is located far away from the source. This is done by neglecting the mutual coupling effect for the pipeline sections from the left terminal to the beginning of the common rights-of-way.

$$\overline{U}_{PN} = \frac{\bar{I}_{Pi}\left[l_Z(R_{pi}+R_{pi+1}) - R_{pi}l_i\right] + \bar{I}_{Pi+1}R_{pi+1}(l_i - l_Z) - \bar{I}_{Pi-1}R_{pi}l_Z}{l_i} \tag{B.5}$$

Concerning the above equations, all the impedances are determined using the FEM calculations, as was analyzed in Section III-B. The resistances R_{gi} and the source voltage are input values to the problem, while the leakage resistances R_{pi} are determined from the coating resistance of the pipeline. The coating resistance r_u of a pipeline is usually much less than the value provided by the manufacturer, especially when the pipeline is buried, while it decreases with time. One may determine the leakage resistances R_{pi}, as in [17], using the formula

$$R_{pi} = \frac{r_u n'}{\pi D} \tag{B.4}$$

where D is the pipeline diameter and n' is the number of leakage resistances per unit length of the pipeline.

Equations (B.1), (B.2) and (B.3) form a system of $(\mathrm{n}+\mathrm{m}+1)$ equations, which may be solved using standard methods as in [15].

Having calculated the unknown fault current and the loop currents of the ground wire and pipeline, the voltage across a point on the pipeline and remote earth may be easily determined using Faraday's law [12]. Specifically, the voltage of a certain point P of section i of the pipeline, lying at a distance l_z from the starting point of the next section, may be determined from the relation shown in (B.5) at the top of the page where l_i is the length of section i.

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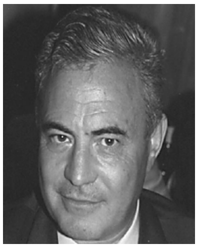

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