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.

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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 widely 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...
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].

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 \( \Omega \)m. 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 \( \Omega \) for about 0.5 s, with peaks of 25–50 \( \Omega \) 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 \( \vec{A}_{z} \) of the MVP vector and \( \vec{J}_{z} \) of the total current density vector [16,17]:

\[
\frac{1}{\mu_{0}\mu_{r}} \left[ \frac{\partial^2 \vec{A}_{z}}{\partial x^2} + \frac{\partial^2 \vec{A}_{z}}{\partial y^2} \right] - j\omega \sigma \vec{A}_{z} + \vec{J}_{z} = 0 \tag{1a}
\]

\[
-j\omega \sigma \vec{A}_{z} + \vec{J}_{sc} = \vec{J}_{z} \tag{1b}
\]

\[
\int_{S_{i}} \vec{J}_{z} \cdot ds = I_{i} \tag{1c}
\]

where \( \sigma \) is the conductivity, \( \mu_{0} \) and \( \mu_{r} \) are the vacuum and relative permeabilities respectively, \( \omega \) is the angular frequency, \( \vec{J}_{sc} \) is the source current density in the \( z \)-direction and \( I_{i} \) 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 \( \vec{J}_{ec} \) is calculated using the relation:

\[
\vec{J}_{ec}(x, y) = -j\omega \sigma \vec{A}_{e}(x, y) \tag{2a}
\]

and the total element current density \( \vec{J}_{e} \), being the sum of the conductor- \( i \) source current density \( \vec{J}_{sc} \) and of the element eddy current density \( \vec{J}_{ec} \) of Eq. (2a), is obtained by the following equation:

\[
\vec{J}_{e}(x, y) = \vec{J}_{ec}(x, y) + \vec{J}_{sc} \tag{2b}
\]

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 \( E_{1}E_{2} \ldots E_{N} \) 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 \( R_{TN} \), 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 \( E_{1}E_{2}H_{1}H_{2} \), supposing that reference earth \( H_{1}H_{2}, \ldots, H_{N} \) is a conducting plane with infinite conductivity, we get:

\[
\oint_{C} \vec{E} \cdot d\ell + \frac{\partial \Phi_{1}}{\partial t} = 0, \tag{3}
\]

where \( \Phi_{1} \) is the flux of the magnetic field through the closed path \( E_{1}E_{2}H_{1}H_{2} \) and can be expressed using phasors as:

\[
\Phi_{1} = L_{11}\vec{I}_{p1} + L_{1F}\vec{I}_{F}, \tag{4}
\]
with \( L_{11} \) being the self-inductance of the first section of the pipeline, \( I_F \) 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:

\[
\Phi_1 = \tilde{A}_p l_i,
\]

where \( \tilde{A}_p \) is the \( z \)-component of the MVP on the surface of the pipeline and \( l_i \) is the length of the first section.

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

\[
\tilde{U}_{E_i} + \tilde{U}_{E_iH_i} + \tilde{U}_{H_iH_i} + \tilde{U}_{H_iE_i} + j\omega \Phi_1 = 0
\]

where,

\[
\tilde{U}_{E_i} = (\tilde{I}_{p1} - \tilde{I}_{p2}) R_i
\]

\[
\tilde{U}_{E_iH_i} = 0
\]

\[
\tilde{U}_{H_iE_i} = \tilde{I}_{p1} R_T
\]

\[
\tilde{U}_{H_iE_i} = \frac{\tilde{J}_p l_i}{\sigma_p} = \frac{\tilde{I}_{p1} l_i}{\sigma_p S_p},
\]

where \( \sigma_p \) and \( S_p \) are the conductivity and the effective cross-section of the pipeline’s metal respectively.

Finally, Eq. \((6)\) becomes:

\[
\tilde{I}_{p1}\left[R_i + \frac{l_i}{\sigma_p S_p}ight] - \tilde{I}_{p2} R_i + j\omega (L_{11} \tilde{I}_{p1} + L_{F1} \tilde{I}_F) = 0
\]

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 applies:

\[
\tilde{I}_{pi}\left[R_i + \frac{l_i}{\sigma_p S_p}ight] - \tilde{I}_{p(i-1)} R_i - \tilde{I}_{p(i+1)} R_{i+1} + j\omega (\tilde{I}_{p(i-1)} L_{ii} + \tilde{I}_F L_{Fi}) = 0
\]

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

\[
\tilde{I}_{pN+1}\left[R_N + \frac{l_{N+1}}{\sigma_p S_p}\right] - \tilde{I}_{pN} R_N + j\omega (\tilde{I}_{pN+1} L_{N+1N+1} + \tilde{I}_F L_{FN+1}) = 0
\]

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:

\[
U_o = I_F (R_G + R_F + Z_S) + \frac{\tilde{I}_F}{\sigma S}
\]

\[+ j\omega \left( \sum_{i=1}^{n+1} L_{Fi} \tilde{I}_p + L_{FF} \tilde{I}_F \right),
\]

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 \( \sigma, S \) 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 \( I_{Fb} \) is imposed on the faulted phase, e.g. \( I_{Fb} = 1A \), 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 \( \tilde{I}_{p1} = 0 \):

\[
\tilde{A}_{p1} l_1 = L_{F1} \tilde{I}_{Fb}
\]

and therefore the mutual inductance is:

\[
L_{F1} = \frac{\tilde{A}_{p1} l_1}{\tilde{I}_{Fb}}
\]

or

\[
L_{F1} = \frac{\tilde{A}_{p1} l_1}{\tilde{I}_{Fb}}
\]

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:

\[
\Phi = \sum_{i=1}^{n+1} L_{ij} \tilde{I}_p + L_{FF} \tilde{I}_F
\]

while the same flux can be expressed as:

\[
\Phi = \tilde{A}_i l
\]

where \( \tilde{A}_i \) 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:

\[
L_{FF} = \frac{\tilde{A}_i l}{\tilde{I}_{Fb}}
\]

In order to calculate the self inductances \( L_i \) \((i = 1:n+1)\) of the pipeline sections the same methodology is followed, except that now we impose a zero fault current...
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 \( I_f \). 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 \( l_i \) from point \( E_{i+1} \). Applying Faraday’s law in the two loops \( E,PNH_iE_i \) and \( H_iH_{i+1}E_{i+1}H_i \), the voltage \( \bar{U}_{PN} \) of the point \( P \) and remote earth \( N \), can be obtained as:

\[
j\omega \bar{A}_i l_i = \bar{U}_{PN} + I_{P_i} \left( R_{i+1} + \frac{l_i}{\sigma S} \right) - I_{P_{i+1}} R_{i+1}
\]

\[
\left( E_iPNH_iE_i \right)
\]

\[
j\omega \bar{A}_i l_i = I_{P_i} \left( R_i + R_{i+1} + \frac{l_i}{\sigma S} \right) - I_{P_{i+1}} R_{i+1} - I_{P_{i-1}} R_i
\]

\[
\left( H_iH_{i+1}E_{i+1}E_iH_i \right)
\]

and combining the above two equations:

\[
\bar{U}_{PN} = I_{P_i} \left( R_i + R_{i+1} \right) - I_{P_{i+1}} R_{i+1} - I_{P_{i-1}} R_i
\]

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:

\[
a = \sqrt{a_1 a_2},
\]

as long as

\[
\frac{a_2}{a_1} \leq 3.
\]

In case \( a_2/a_1 \) is more than 3, the section is divided, as shown in Fig. 4, in order that both \( a_2/a_1 \) 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 certain configuration and circuit parameters, as in Figs. 1 and 2, the fault current may also be estimated as in Ref. [16].
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 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.

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

$$R_s = \frac{\rho}{2d} \left(1 + \frac{8s}{\pi d_t} \right),$$  \hspace{1cm} (16)

where $\rho$ is the ground resistivity, $d_t$ 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
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 $\Omega$, while the leakage resistances are 50 $\Omega$ 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 $\Omega$ m results in a 50% increase
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. 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. 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. 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.

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. Effect of relative distance between power line/pipeline on induced voltages and currents over kA fault current (V/kA, A/kA).
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.

Acknowledgements

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Appendix A: Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_0$</td>
<td>source voltage (V)</td>
</tr>
<tr>
<td>$Z_s$</td>
<td>source impedance ($\Omega$)</td>
</tr>
<tr>
<td>$R_f$</td>
<td>fault resistance ($\Omega$)</td>
</tr>
<tr>
<td>$R_g$</td>
<td>neutral ground resistance ($\Omega$)</td>
</tr>
<tr>
<td>$R_T$</td>
<td>terminal ground resistance of pipeline ($\Omega$)</td>
</tr>
<tr>
<td>$R_l$</td>
<td>leakage resistance of pipeline ($\Omega$)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>earth resistivity ($\Omega/m$)</td>
</tr>
<tr>
<td>$s$</td>
<td>coating thickness (m)</td>
</tr>
<tr>
<td>$\sigma_m$</td>
<td>pipeline’s metal conductivity (S/m)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_z$</td>
<td>magnetic vector potential (MVP) in $z$-direction (Wb/m)</td>
</tr>
<tr>
<td>$A_{zp}$</td>
<td>MVP on the surface of the pipeline in $z$-direction (Wb/m)</td>
</tr>
<tr>
<td>$E$</td>
<td>electric field density (V/m)</td>
</tr>
<tr>
<td>$J_z$</td>
<td>total current density in $z$-direction (A/m$^2$)</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>conductivity of phase wire (S/m)</td>
</tr>
<tr>
<td>$\sigma_p$</td>
<td>conductivity of the metal of pipeline (S/m)</td>
</tr>
<tr>
<td>$\mu_{r,m}$</td>
<td>pipeline’s metal permeability</td>
</tr>
<tr>
<td>$\mu_o$</td>
<td>vacuum permeability</td>
</tr>
<tr>
<td>$\mu_r$</td>
<td>relative permeability</td>
</tr>
<tr>
<td>$\omega$</td>
<td>angular frequency (rad/s)</td>
</tr>
<tr>
<td>$l_p$</td>
<td>length of parallel exposure of pipeline/power line (m)</td>
</tr>
<tr>
<td>$l$</td>
<td>distance of fault location from source (m)</td>
</tr>
<tr>
<td>$J_{sz}$</td>
<td>source current density in $z$-direction (A/m$^2$)</td>
</tr>
<tr>
<td>$J_i$</td>
<td>RMS value of current through conductor $i$ (A)</td>
</tr>
<tr>
<td>$S_i$</td>
<td>cross-section of conductor $i$ (m$^2$)</td>
</tr>
<tr>
<td>$S$</td>
<td>cross-section of phase conductor (m$^2$)</td>
</tr>
<tr>
<td>$S_p$</td>
<td>effective cross-section of metal area of pipeline (m$^2$)</td>
</tr>
<tr>
<td>$J_{ee}$</td>
<td>Eddy-current density of element $e$ in $z$-direction (A/m$^2$)</td>
</tr>
<tr>
<td>$J_e$</td>
<td>total element current density (A/m$^2$)</td>
</tr>
<tr>
<td>$J_{sz,i}$</td>
<td>source current density of conductor $i$ (A/m$^2$)</td>
</tr>
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<td>$\phi$</td>
<td>flux of magnetic field (Wb)</td>
</tr>
<tr>
<td>$I_F$</td>
<td>fault current (A)</td>
</tr>
<tr>
<td>$I_{pi}$</td>
<td>induced current on the $i$ section of pipeline (A)</td>
</tr>
<tr>
<td>$D$</td>
<td>relative separation between pipeline/power line (m)</td>
</tr>
<tr>
<td>$d_f$</td>
<td>diameter of defect (m)</td>
</tr>
<tr>
<td>$L_{FF}$</td>
<td>self inductance of phase wire (H)</td>
</tr>
<tr>
<td>$L_{Fi}$</td>
<td>mutual inductance of phase wire and section-$i$ of pipeline (H)</td>
</tr>
<tr>
<td>$L_{Fi}'$</td>
<td>mutual inductance of phase wire and section-$i$ of pipeline per unit length (H/m)</td>
</tr>
<tr>
<td>$L_{pi}$</td>
<td>self inductance of section-$i$ of pipeline (H)</td>
</tr>
<tr>
<td>$L_{pi}'$</td>
<td>self inductance of section-$i$ of pipeline per unit length (H/m)</td>
</tr>
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</table>

References


