AC interference from faulty power cables on buried pipelines: A two-step approach

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Abstract
The purpose of the paper is to describe an algorithm for assessing the 50–60 Hz induced voltage and current, from a power cable in fault condition, on a nearby buried pipeline. The calculation method is a two-step approach where both the steps are based on the solution of the transmission line model used first to characterize the inducing power cable and then the induced pipeline. The main result to be pointed out is the importance of the conductive coupling, often not considered, when modelling the phenomenon. In fact, neglecting the conductive coupling yields to underestimate the induced voltage and current along the pipeline.

1 INTRODUCTION

There is a vast literature concerning the issue of 50–60 Hz electromagnetic interference generated by high voltage (HV) power lines on nearby pipelines or on telecommunication cables with metallic elements; if one considers only those handbooks and technical reports that provide a general and all-encompassing information for the problem, one can refer to [1–5]. Nevertheless, almost all the above mentioned literature is focused on the electromagnetic interference produced by HV overhead power lines while only few information can be found in relation with the analogous problem involving HV power cables.

This is justified because the interference distance, or zone of influence, (i.e. the maximum distance between power line and pipeline for which electromagnetic interference has to be considered) related to an overhead power line is much larger than the corresponding one related to a power cable rated at the same voltage. For example, in case of fault conditions, the European Standard [6] establishes an interference distance of 3000 m for an overhead line against an interference distance of 50 m for a power cable. The reason of that is the stronger shielding action due to the power cable metallic sheaths (enclosing the phase conductors and used as a return for the fault current) compared to the one due to the shield wire(s) belonging to overhead power line.

On the other hand, power cables often may share the trench, in which they are laid, with other services such as telecom cables, water and gas pipes; thus, all those facilities must coexist at very close distance and therefore problems of dangerous induced alternating current (AC) voltage and current can arise.

For such a reason, it is important to have at disposal an algorithm that allows to assess the level of electromagnetic interference appearing on metallic pipes and telecom cables laid in proximity of the power cable in order to ensure safety for personnel, that could get in touch with the induced facilities, and to avoid possible damages to the facilities themselves.

The mechanisms through which the power cable generates induced voltage and current on nearby metallic pipes are:

- Inductive coupling
- Conductive coupling

We recall that the inductive coupling is related to the AC emf (electromotive force) induced in the pipe-earth circuit while the conductive coupling is related to the earth over potential produced by the current injected into soil through the earth electrodes. (We remind that such earth electrodes are installed in correspondence of the power cable joint bays and of the terminal feeding station(s)). This second mechanism of electromagnetic coupling between power cable and pipeline is just as important as the inductive one but this point seems to be neglected in literature.

In fact, in many papers or technical handbooks the concept of reduction factor r, associated to the type of cable under study, is adopted in order to assess the inductive interference...
on nearby structures. Such a quantity is defined by:

\[
r = \sum_{i=1}^{N} I_i / I_f \quad (1)
\]

Being \( I_i \) the current in the faulty phase conductor, \( I_f \) the current in the \( i \)-th conductor of the cable and \( N \) the total number of conductors forming the power cable (i.e. phase conductors, sheaths, armourings, additional conductors). In practice, we have that the fraction of fault current, returning to the feeding substation(s), through the earth \( I_e \) (defined as “earth current”) is given by:

\[
-I_e = \sum_{i=1}^{N} I_i = rI_f \quad (2)
\]

In a very first approximation, \( r \) can be considered as a constant quantity depending only on the cable characteristics \([2, 7, 8]\); more refined approaches take into account, with much more precision, of the cable characteristics and, above all, of the position of the fault point along the power cable route \([9, 10]\). Nevertheless, these simplified approaches do not consider the earth over-potential produced by the current injection into soil by the earthing electrodes present along the power cable and by the feeding station(s) earthing grids which is responsible of the conductive coupling with nearby metallic structures.

In other words, the use of the reduction factor enable us to estimate the inductive coupling only but not the conductive coupling. More in general, as put into evidence in \([11]\), the approach based on the use of the reduction factor has many constraints while a multi-conductor analysis of the power cable enables to overcome such limitations. This is the way we followed to model the power cable and the main points will be described later on.

Furthermore, in all the above mentioned calculation methods the earth is considered homogenous with constant resistivity; this represents another limitation because a two layer soil model is a more realistic approach.

Thus, three are the main purposes of this paper:

- To describe an algorithm able to calculate, with more precision, the earth current so that also the conductive influence on the pipeline can be taken into account.
- To improve the soil representation from homogeneous model to two layer model.
- To make some comparisons between the interference results when considering only the inductive coupling and both inductive and conductive coupling.

2 | OVERALL DESCRIPTION OF THE ALGORITHM

2.1 | General

In order to better describe the algorithm, it is convenient to consider the following three main sub-problems:

1. Study of the power cable in fault condition, by means of a multi-conductor line model.
2. Determination of the per unit length (pul) emf and current generators to be applied to the pipe-earth circuit that respectively model inductive and conductive influence produced by the power cable on the induced pipeline.
3. Study of the pipe-earth circuit aimed to the determination of induced voltage and current along it.

The main simplifying hypothesis at the basis of the calculation method is that the reaction of the induced circuit on the inducing one is neglected; such an assumption is justified because the level of the inducing quantities is always 2–3 order of magnitude higher than the one of the induced quantities.

Thus, the first advantage of the calculation method is that the problem can be studied into two separate and simpler steps:

- (Step 1) Characterizing the inducing system as it would exist alone so neglecting the presence of the induced system.
- (Step 2) Studying the induced system as it would exist alone and taking into account of the influence of the inducing system by means of ideal longitudinal emf and ideal transversal current generators that can be determined on the basis of the results relevant to Step 1.

The second advantage is related to the common characteristic of inducing and induced lines: i.e. they both are represented by long metallic and parallel conductors forming circuits having the earth as return conductor. That allows to adopt, for both of them, the same approach based on the transmission line model. So, one can use the same algorithm twice for calculating voltage and current along the plants under study: first to the power cable and then to the pipeline.

Note also that the two-step approach does not request that power cable and pipeline are parallel: their routes can be any as actually occurs in most of real cases.

It is necessary to point out that we have already applied the two-step approach to the study of 50–60 Hz interference generated by overhead power lines \([12, 13]\); so, certain parts of the algorithm have been already described in those papers and therefore, for brevity reasons, we just sketch the major points.

2.2 | The multi-conductor line algorithm

The multi-conductor model, succinctly described in this paragraph, is based on the discretization of the line by means of a chain composed of a suitable number of \( \pi \) cells of the type shown in Figure 1 having lumped self (continuous line) and mutual (dashed line) impedances and coefficient of admittances.

First, let us define by \( N \) the number of parallel conductors forming the multi-conductor line and by \( n \) the number of points used to discretise the line itself.

Figure 1 represents the \( k \)-th discretization cell and is referred to the \( i \)-th circuit, among the \( N \) coupled circuits, necessary to study the power cable.
In this paragraph we just describe the main points for solving the multi-conductor circuit with lumped elements shown in Figure 1; for a more complete description one can refer to [3] that is particularly tailored to lumped-circuits approximation.

By looking at Figure 1, the generic $k$-th cell is characterized by the following parameters:

- the impedances (self and mutual) matrix $[z]_k$ of $N \times N$ order
- the ideal longitudinal emf generators vector $[f]_k$ of $N$ order
- the ideal transversal current generators vector $[i]_k$ of $N$ order

While the generic $k$-th point is characterized by the following parameters:

- the coefficients of admittances matrix (self and mutual) $[y]_k$ of $N \times N$ order
- the ideal transversal current generators vector $[i]_k$ of $N$ order

In general, these parameters are, more explicitly, given by means of the following relations:

$$ [z]_k = [z]_f + [z]_p + [z]_a $$ \hspace{1cm} (3)

$$ [f]_k = [f]_f + [f]_p + [f]_a $$ \hspace{1cm} (4)

$$ [y]_k = [y]_f + [y]_p + [y]_a $$ \hspace{1cm} (5)

$$ [i]_k = [i]_f + [i]_p + [i]_a $$ \hspace{1cm} (6)

The relations from Equations (3) to (6) have the following meaning:

- the matrices having lower index “$f$” are in relation with the pul parameters of the line and depend on the geometric and physical characteristics of the line and on the length of the $k$-th cell;
- the vectors having lower index “$e$” represent the distributed influence of any external electromagnetic field interfering with the line;
- the matrices having lower index “$p$” describe passive loads inserted along the line (e.g. earthing electrodes, bonding between different conductors, equivalent impedances that model devices or apparatuses);
- the matrices and vectors having lower index “$a$” are in relation with any active lumped load present along the line (e.g. power substations).

By means of Kirchhoff’s laws, applied to the chain of $n-1$ cells composing line, and after some algebraic step, one arrives to the following system of linear equations expressed in compact form:

$$ [Q] [V] = [T] $$ \hspace{1cm} (7)

The unknown is represented by the block vector $[V]$, of $n$ order, whose elements are the vectors $[i]_k$, of $N$ order; each vector $[i]_k$ represents the voltages of the $N$ conductors evaluated in the $k$-th point along the cable. $[Q]$ is a tri-diagonal block matrix (having $n \times n$ order); each element of $[Q]$ is a matrix of $N \times N$ order; more specifically, the elements $[M]_k$ forming the main diagonal of $[Q]$ are given by the relation:

$$ [M]_k = [y]_k + ([z]_k)^{-1} + ([z]_k)^{-1} $$ \hspace{1cm} (8)

The elements $[D]_k$ and $[H]_k$ laying on the lower and upper sub-diagonal of $[Q]$ are expressed by:

$$ [D]_k = - ([z]_k)^{-1} $$ \hspace{1cm} (9)

$$ [H]_k = - ([z]_k)^{-1} $$ \hspace{1cm} (10)

Finally, $[T]$ represents a block vector, of $n$ order, composed by the vectors $[i]_k$ which can be obtained by means of the following relationship:

$$ [i]_k = [f]_k + ([z]_k)^{-1} [i]_{k-1} - ([z]_k)^{-1} [i]_k $$ \hspace{1cm} (11)

Once Equation (7) has been solved, the knowledge of the vectors $[i]_k$ allows for the determination of the currents $[i]_k$ by means of:

$$ [i]_k = ([z]_k)^{-1} ([i]_k - [i]_{k+1} + [i]_k) $$ \hspace{1cm} (12)
We point out that the above algorithm has to be applied twice for assessing the electromagnetic interference on the pipeline: the first time when dealing with the power cable in order to determine the inducing currents (point 1. of Section 2.1) the second time when dealing with the induced pipeline (point 3. of Section 2.1).

It is worthwhile to add a remark about the emf generators \([f]_k^E\) and current generators \([j]_k^E\) appearing in equations (5) and (6) respectively; when describing the inducing multi-conductor line (power cable), their value is zero provided that no external electromagnetic fields, interfering with the inducing line, are present; on the contrary, when studying the victim line (pipeline) their value is different from zero and is related to the influence of the electromagnetic field, produced by the power cable, on pipeline-earth circuit. The calculation of the vectors \([f]_k^E\) and \([j]_k^E\) to be applied to the induced pipe-earth circuit are shortly described in Section 4.

3 MODELLING THE POWER CABLE

For our purposes, a HV power cables can be considered as a group of long and parallel conductors that, depending on their own function, are classified as phase conductors, sheaths (or screens), pipes for mechanical protection, additional (or compensation) wires for earth return. Not all these kinds of conductors are present in a generic cable; e.g. in certain cables (Single-Core) one has only phase conductors with their own coaxial sheaths, in certain other cables, (Pipe-Type) all the phase conductors are contained inside a metallic pipe.

Moreover, the phase conductors forming the cable are generally disposed according to typical geometrical configurations such as flat or trefoil or other.

In spite of these differences, common features to any kind of cables are:

- the long parallelism among all the conductors forming the cable itself without any change of the physical and geometrical characteristics along its route; consequently, the system can be described by means of the transmission line model;
- the earth represents a common return conductor for all the metallic conductors forming the cable.

Hence, the model of electromagnetically coupled transmission lines with earth return can be an advantageous tool to study the propagation of voltages and current along the power cable route; in particular, the amount of earth current, that is directly related to the inductive and conductive coupling with nearby buried pipelines, can be directly calculated.

It is necessary to give some information concerning the calculation of the pul impedance and coefficient of admittance matrices \([g]\) and \([j]\) (appearing in Equations (3) and (4) respectively) related to the pul parameter of the power cable; as previously remarked, such parameters depend on the type of power cable as well as on the physical and geometrical characteristics of the conductors that constitute it.

Clearly, for reasons of conciseness, it is not possible to present here the expressions and the procedure for calculating these parameters; the relevant formulas, in the most common and typical cases can be found in: [14–17].

From the knowledge of voltage and current relevant to the power cable conductors along the cable route, it is possible to define the following quantities that will be used later on:

1. The equivalent inducing current of the power cable \(i_{eq}^k\) evaluated in the \(k\)-th cell that is given by:

\[
i_{eq}^k = \sum_{n=1}^{N} i_{eq}^n \quad (13)
\]

where \(i_{eq}^n\) is the current in the \(n\)-th conductor of the power cable evaluated in the \(k\)-th cell; as we shall see in Section 4 this quantity is strictly related to the inductive coupling.

2. The current injected in the soil \(I_j\) by the \(j\)-th earthing electrode along the power cable route that is given by:

\[
I_j = \frac{V_j}{R_{ej}} \quad (14)
\]

where \(V_j\) is the potential of the power cable evaluated in correspondence of the \(j\)-th earthing electrode having resistance \(R_{ej}\); as we shall see in the next paragraph this quantity is strictly related to the conductive coupling.

4 PUL EMF AND CURRENT GENERATORS

In order to determine the ideal pul emf and current generators modelling the inductive and conductive influence of the power cable on the pipe-earth circuit, it is necessary the knowledge of both the power cable and pipeline routes that can be represented by means of broken lines (See Figure 2).

In Figure 2, \(S\) and \(s\) represent the power cable and pipelines abscissa respectively while \(\vec{n}_T(S)\) and \(\vec{n}_T(s)\) are the relevant unit vectors.

As far as the inductive coupling is concerned, one has to determine the pul induced emf \(f_p(i)\) on the pipe-earth circuit from the power cable; according to [18] one has:

\[
f_p(i) = \int_0^L P(s, S) \left( I_{eq}(S) \right) \vec{n}_T(S) \cdot \vec{n}_T(i) \, dS \quad (15)
\]

where \(L\) is the power cable length and \(P(s, S)\) is expressed by:

\[
P(s, S) = \frac{j \omega \mu_0}{2\pi r(s, S)} \frac{e^{-\gamma_{eq} r(s, S)}}{[\gamma_{eq} r(s, S)]^2} \left( e^{\gamma_{eq} r(s, S)} - 1 - \gamma_{eq} r(s, S) \right) \quad (16)
\]
where $\omega = 2\pi f$ is the angular frequency, $\mu_0$ is the vacuum permeability while $R(S,s)$ and $\gamma_{eq}$ are given by:

$$
\rho(S) = \sqrt{(x(s) - X(S))^2 + (y(s) - Y(S))^2} \quad (17)
$$

$$
\gamma_{eq} = \sqrt{\frac{j\omega \mu_0}{\rho_{eq}}} \quad (18)
$$

In Equation (18), the quantity $\rho_{eq}$ is the equivalent resistivity of the soil provided that the latter one is described by a two-layer model; according to [19–20], for inductive effects, a convenient formula for the equivalent resistivity is:

$$
\rho_{eq} = \left[ \frac{1}{\rho_1} + \frac{1}{\rho_2} + \left( \frac{1}{\rho_1} - \frac{1}{\rho_2} \right) \right]^{-2} \left( \frac{1}{\rho_1} - \frac{1}{\rho_2} \right)^{-2} \rho_{eq} \quad (19)
$$

where $\rho_1$ and $\rho_2$ are the top layer resistivity and thickness respectively, while $\rho_{eq}$ is the bottom soil resistivity.

It is necessary to point out that Equation (15) is based on the assumption that the power cable has been replaced by an equivalent inducing conductor that carries the current $I_{eq}(s)$ obtained according to Equation (13). That is justified because the distances between the power cable conductors range from some centimetres (trefoil disposition) to some decimetres (flat disposition) and normally they are much smaller than the smallest distance between power cable and pipeline (at least 1–2 m).

As far as the conductive coupling is concerned, it is known that it is directly related to the soil potential generated by the current injected into soil by the earthing electrodes; so, the starting point is the vector $[I_1]$ that can be calculated, according to Equation (14).

The relationship between the pul current generator $j_p(i)$ and the soil potential $V_{soil}(i)$ evaluated along the pipeline route $i$ is:

$$
j_p(i) = \eta_p V_{soil}(i) \quad (20)
$$

Being $\eta_p$ is the pul pipe admittance to remote earth that will be defined in the next paragraph.

An important point to be dealt with is the earthing electrodes geometry; normally, when considering power cables, they consist of copper strands having the shape of rectangular ring, but, for our purposes, (i.e. calculation of induced voltage and current along the pipeline) it possible, as a first approximation to model it by a point source electrode; in such a way, one has that the total potential $V_{soil}(x, y)$, produced in a generic point $(x, y)$, at the soil surface by all the electrodes along the power cable is [18]:

$$
V_{soil}(x, y) = \sum_{j=1}^{N_e} \frac{I_j}{2\pi \sqrt{(x-x_j)^2 + (y-y_j)^2}} \quad (21)
$$

Where $(X_j, Y_j)$ are the coordinates of the $j$-th earthing electrode and $\eta$ is a function of the ratio $\rho_1/\rho_2$ that can be calculated according to Table 1 by interpolation.

Therefore, by substituting Equation (21) into Equation (20), and by expressing the coordinate of the point $(x, y)$ as a function of the pipeline route (i.e. $x = x(i)$ and $y = y(i)$) one gets:

$$
j_p(i) = \sqrt{\left(\frac{\sqrt{x(i) - X_j} + \sqrt{y(i) - Y_j}}{\sqrt{(x(i) - X_j)^2 + (y(i) - Y_j)^2}}\right)^2}
$$

It is necessary to emphasize that the point source model for the earthing electrodes is acceptable only if aimed to the calculation of the distributed pul current generator along the pipeline. In fact, the pipeline for most of its route is sufficiently far away from the earthing electrodes so that the soil potential calculation by means of the point source model is a good approximation. On the contrary, if the pipeline touch voltage has to be evaluated in regions very close to the earthing electrodes, more sophisticated models that take into account their actual geometry must be used. (See for example [3]).
5 MODELLING THE PIPELINE-EARTH CIRCUIT

In order to determine induced voltages and current along the pipeline circuit with earth return, we still adopt a transmission line model with lumped elements composed by a chain of cells as shown Figure 1; the main difference is that, in this case, the line is composed by only one conductor (See Figure 3).

It is useful to add some explanations concerning the meaning of the elements shown in Figure 3:

- the longitudinal impedances \( Z_{pk} \) are related to the pipe internal impedance and to the earth return contribution; by considering the generic \( k \)-th cell, one has:

\[
Z_{pk} = \bar{Z}_{pk} \left( \xi_{k+1} - \xi_k \right)
\]  

where \( \xi_k \) is the coordinate along the pipeline route evaluated at the \( k \)-th discretisation point and \( \bar{Z}_{pk} \) the pul impedance with earth return relevant to the \( k \)-th cell; suitable formulas for calculating this parameter are given in Appendix.

- the white transversal elements \( Y_{pk} \) are related to the effects to the distributed leakage admittance to soil relevant to the pipeline; they are mainly influenced by the quality of the insulation coating of the pipe (i.e. high admittance for bad insulations and, conversely, low admittance for good insulations); by considering the generic \( k \)-th point one has:

\[
Y_{pk} = \begin{cases} 
\frac{y_{p1}}{2} & k = 1 \\
\frac{y_{pk-1} + y_{pk+1} + y_{pk}}{2} & k = 2, 3, \ldots m \\
\frac{y_{pm}}{2} & k = m + 1 
\end{cases}
\]  

being \( y_{pk} \) the pul transversal admittance relevant to the \( k \)-th cell and \( m \) the number of cells used to discretise pipeline-earth circuit; formulas for evaluating the pul transversal admittance will be given in Appendix. On the basis of this definition, the pipeline admittance \( Y_{pk} \) at the \( k \)-th point is sum of the contribution of the admittances relevant to the two half-cells adjacent to the \( k \)-th point itself.

- the grey transversal elements represent the lumped admittances related to the earthing electrodes existing (if any) in specific points along the pipeline.

It is useful to notice that the circuit shown in Figure 3 allows taking into account of possible variations along the pipeline route (e.g. change of pipe diameter, change of coating characteristics, presence of insulating flanges). In fact, the pul parameters \( \bar{Z}_{p} \) and \( y_{p} \) may vary depending on the cell considered.

Let us consider now the active elements i.e. longitudinal ideal emf generators and transversal ideal current generators.
According to Figure 3, one can see that two different kinds of generators, applied to the circuit, exist:

- Distributed longitudinal emf generators describing the inductive coupling of the power cable with the pipeline; the emf generator \( F_{pk} \) to be applied at the \( k \)-th cell of the pipeline circuit is given by:

\[
F_{pk} = \int_{s_k}^{s_{k+1}} f_p(i) \, dt
\]

being \( f_p(i) \) the pul induced emf on the pipeline circuit given expressed by Equation (15).

- Transversal current generators describing the conductive coupling of the power cable with the pipeline; one can have two different kinds of contribution:

1. A distributed coupling contribution existing along all the route of the pipeline which is in relation with the soil potential and with the pipeline insulating coating quality (white elements in Figure 3)

   The ideal current generator in the \( k \)-th point, modelling the distributed conductive coupling, is given by:

   \[
   f_{pk} = \begin{cases} \int_{s_k}^{s_{k+1}} f_p(i) \, dt & k = 1 \\ \frac{1}{2} \int_{s_k}^{s_{k+1}} f_{p,k-1}(i) \, dt + \frac{1}{2} \int_{s_k}^{s_{k+1}} f_{p,k}(i) \, dt & k = 2, 3, ..., m \\ \frac{1}{2} \int_{s_k}^{s_{k+1}} f_{p,m+1}(i) \, dt & k = m + 1 \end{cases}
   \]

   Where \( f_{pk}(i) \) is the pul current generator related to the soil potential generated by the faulty power cable and expressed by Equation (22). By looking at Equation (22), one can notice that the current generator depends also on the pul admittance to soil of the pipeline; i.e. the distributed conductive coupling is determined not only by the value of the soil potential but also by the pipeline coating characteristics (material, age, level of degradation of the coating). Therefore, pipelines with bad insulating coatings (i.e. high values of p.u.l admittance) are more exposed to distributed conductive coupling.

b. A lumped coupling contribution existing only at the positions corresponding to the pipeline earthing points (grey elements in Figure 3); it is related to the value of the soil potential in those specific positions and to the value of the earthing resistance.

The ideal current generator modelling the conductive coupling through a pipeline earthing electrodes is given by:

\[
J(r^*) = \frac{V_{soil}(x^*(r^*), y^*(r^*))}{R_{pe}}
\]

Where \( R_{pe} \) is the value of the earthing resistance of the electrode placed at abscissa \( s^* \), along the pipeline route, and corresponding to the point \((x(r^*), y(r^*))\).

![FIGURE 4 Layouts of power cable and pipeline](image)

As far as the solution of the circuit shown in Figure 3 is concerned, it is again based on the algorithm already outlined in Section 2.2.

6 | EXAMPLES OF APPLICATION

In this section we describe two examples of application of the proposed calculation method to two cases of electromagnetic interference between a 132 kV–50 Hz power cable and a nearby pipeline.

In the first example, the layouts of both the plants is shown in Figure 4, where \( s \) and \( j \) are the power cable and pipeline abscissas respectively.

The power cable, having length of 2.262 km, is a single-core cable with trefoil disposition of the conductors and cross-bonding of the sheaths; it is fed by two stations having earthing grid resistance equal to 0.5 \( \Omega \); it is provided with two joint bays where the sheaths are interrupted and connected among them and to the earthing electrode having a resistance equal to 10 \( \Omega \).

The steel pipeline having diameter 0.2 m and thickness 3 mm is 1.876 km long and has no earthing points along its route; it is provided with a polyethylene sheath having an insulation resistance of 90,000 \( \Omega \) m².

The soil is modelled by two horizontal layers; the top layer is characterised by thickness \( D_1 = 1 \) m and resistivity \( \rho_1 = 50 \Omega \) m, while the second layer by resistivity \( \rho_2 = 100 \Omega \) m.

We studied two cases characterized by different fault points along the power cable:

1. Fault point in station 1 with fault current \( I_f = 10.5 \) kA fed by station 2.
2. Fault point in joint bay 2 with fault currents \( I_{f1} = 1.9 \) kA fed by station 1 and \( I_{f2} = 3.1 \) kA fed by station 2.

In both the cases we calculated induced current \( I_p \) and voltage \( V_p \) along the pipeline and we compared the results when considering:

- only the inductive coupling
- both inductive and conductive coupling.

Figures 5 and 6 show the results relevant to cases (1) and (2) respectively.
By looking at Figures 5 and 6 it is evident that the results, when considering only the inductive or both inductive and conductive influence from the power cable, are significantly different.

In particular, these examples demonstrate that neglecting the conductive coupling yields underestimated results for both current and voltage.

Another conclusion which could be drawn is that the use of the reduction factor, often used for estimating the earth current, should be limited only to those cases where the conductive coupling can be neglected (i.e. pipeline route very far from earthing electrodes and low values for the soil resistivity).

Related to this cases we present now a second example that it is also useful to make a comparison between the calculation method here presented (A) and a second method (B) based on the use of the reduction factor and the calculation of the induced voltage and current along the pipeline by means of an analytical solution [3] that can be applied when the pul induced emf on the pipeline \( f_p(s) \) can be determined in analytical form.

The power cable, having length of 3 km, is a three single-core cable with trefoil disposition of the conductors and the sheaths are bonded between them and connected to earth in correspondence of the stations earthing grid having a resistance of 0.5 \( \Omega \); the fault point is supposed to be at station 2 with a fault current of 10 kA and the reduction factor has been considered equal to 0.15 according to [2] and [7].

The steel pipeline having diameter 0.4 m and thickness 11 mm is 10 km long, and its layout crosses the power cable layout as shown in Figure 7(a). Moreover, it has no earthing points along its route and is provided with a polyethylene sheath having an insulation resistance of 90,000 \( \Omega \) m².

The soil is supposed to be homogeneous with a resistivity of 100 \( \Omega \) m.

Due to the fact that the earthing grids of the stations are located sufficiently far away from the pipeline layout, the conductive coupling can be neglected in this case so that only the inductive coupling on the pipeline is considered.

The results of the calculation are shown in Figures 7(b,c); as we can see, the two different methods are in good agreement between them.

To conclude we just give some information concerning the software needed to perform the calculation; we have imple-
mented the program by means of a suitable mathematical oriented software on a normal personal computer having 4 GB RAM.

The calculation time depends, of course, on the computer that one has at disposal but also on the number of cells used to discretise both power cable and pipeline. In our cases the number of cells was about 100 for both the plants in both the two examples and the calculation time was few minutes.

7 CONCLUSIONS

We have described an algorithm for the evaluation of 50–60 Hz electromagnetic interference from power cables in fault condition on nearby pipelines based on a two steps calculation procedure.

The main points of merit of the algorithm are:

- The description of the power cable by means of a multi-conductor model; in fact, that allows for a more precise calculation of the current in the soil that is responsible of the electromagnetic coupling with the pipeline-earth circuit. In such a way, not only the inductive but also the conductive coupling can be taken into account.
- Extension from homogeneous soil model to two-layer soil model.
- Possibility to study cases when inducing and induced structures are not parallel as actually occurs in most of real situations.

Moreover, the paper puts into evidence the importance of the conductive coupling when evaluating the electromagnetic interference; in fact, taking into account of the inductive coupling only, leads, in many cases, to underestimate induced voltage and current on the pipe-earth circuit.

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Appendix A
As far as the pipeline pul impedance is concerned, one has:

\[ z_p(\Gamma) = z_{\text{int}} + \frac{j\omega\mu_0}{2\pi} \ln \left( \frac{a + d}{a} \right) + \frac{j\omega\mu_0}{2\pi} \ln \left( \frac{1.85}{d \sqrt{\frac{\omega\mu_0}{\rho_{eq}}} + \Gamma^2} \right) \]  

In Equation (A.1), \( z_{\text{int}} \) is the pul internal impedance of the pipe (see [1–3] for suitable expressions in order to calculate it), the second addendum is related to the pul inductance of the pipe insulating coating and the third addendum is the contribution related to the earth return [18]; in Equation (A1), \( a \) is the pipe radius, \( d \) is the pipe insulating coating thickness and \( \Gamma \) is a constant that will be defined later on.

As far as the pul admittance is concerned, one has from [18]:

\[ y_p(\Gamma)^{-1} = y_{\text{ins}}^{-1} + \frac{\rho_2^2}{\pi} K_0 (\Gamma a) + \frac{\rho_1 - \rho_2}{\pi} K_0 \left( a \sqrt{\Gamma^2 + \left( \frac{\eta}{2D} \right)^2} \right) \]  

where \( y_{\text{ins}} \) is the pul admittance related to pipe insulating coating (see [1] for the relevant expression), \( K_0 \) is the modified Bessel function of the second kind and zero order and \( \eta \) is a function of the ratio \( \rho_1/\rho_2 \) already defined by means of Table 1 in Section 4.

The quantity \( \Gamma \) appearing in Equations (A1) and (A2) is solution of the following transcendental equation:

\[ \Gamma = \sqrt{z_p(\Gamma) y_p(\Gamma)} \]  

Note that the above formulas can also be employed for calculating some among the pul parameters of power cables; e.g. the impedance and admittance of the sheath-earth circuit (for Single-Core cables) or the impedance and admittance of the pipe-earth circuit (for Pipe-Type cables).