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Influence of Steel Non-Linearity in Assessing 50–60 Hz Interference on Pipelines

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Abstract—This paper deals with the influence of steel non-linearity when calculating the induced current/voltage on a pipeline circuit with earth return under 50–60 Hz induction by power lines or electrified railway lines. By having at disposal the measured curves of the per unit length pipe internal impedance versus the current flowing in it, one can calculate induced voltage and current on the pipeline-earth circuit by means of the successive approximations method. The paper presents some comparison of the results when ignoring or not the steel pipe non-linearity. In certain cases, the differences can be significant.

1. INTRODUCTION

The problem of 50–60 Hz electromagnetic disturbance generated on pipelines by power lines or electrified railway lines is a well-established issue, and vast literature on it exists [1–18] especially concerning the calculation methods. In spite of that, there is a point that has not been suitably worked out; such a point is taking into account of steel non-linearity when modelling the per unit length (p.u.l.) pipe internal impedance and, consequently, when assessing the level of disturbance induced on the pipeline. (In this regard, it should be remembered that steel is the material constituting the majority of pipes for fluids transportation).

In fact, as far as we know, the models present in literature treat the relative magnetic permeability of steel constituting the pipe as a constant, and consequently, the p.u.l. pipe internal impedance also assumes a constant value.

Such an assumption can be valid when the current flowing in the pipe is small (in the order of some Amperes), but fails when the current is higher. Typically this case may occur when the inducing line is in fault condition so that the inducing current can be very high (in the order of some tens of kiloAmperes), and consequently, the induced current on the pipeline can be in the order of some tens or even hundreds of Amperes. Thus, a more realistic model of the pipeline-earth circuit should take into account of the non-linear behaviour of the pipe internal impedance with respect to the induced current flowing on the pipe itself.

In the light of these considerations, the purpose of the present paper is twofold:

- To present a calculation method for induced voltage and current along the pipeline able to take into account of the p.u.l. pipe internal impedance dependence on the current flowing inside the pipe itself.
- To assess the influence of such parameter on the amplitude of the induced disturbance (i.e., voltages and currents induced on the pipeline); in other words, to estimate the per cent relative error when neglecting the steel non-linearity in the calculation model. In particular, this aspect does not seem to be considered in the literature and therefore this article is intended as a new contribution to fill this gap.

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2. PIPE INTERNAL IMPEDANCE

Firstly, it is useful to recall some points dealing with the concept of internal impedance of conductors.

Let us consider a conductor having volume v; when non-ferromagnetic and linear materials are considered, the general expression for internal impedance Z_{int} at a given angular frequency $\omega = 2\pi f$ is [2]:

$$Z_{int} = \frac{1}{|I|^2} \int_v \sigma \left|\vec{E}\right|^2 dv + j\omega \frac{1}{|I|^2} \int_v \mu \left|\vec{H}\right|^2 dv \tag{1}$$

where I, $\vec{E}$, $\vec{H}$ are respectively the current, electric and magnetic fields in phasor form; σ and μ are the conductivity and absolute permeability of the conductor material and j the imaginary unit.

It is useful to note that the first term on the right hand side of Equation (1) represents the resistance which is associated with the ohmic power losses while the second term represents the inductance which is associated with the magnetic energy stored inside the conductor.

When a ferromagnetic and non-linear material (such as steel) is considered, two important facts have to be taken into account [19]:

- the magnetic permeability is no more constant but is function of the magnetic field, that is:

$$\mu = \mu(H) \tag{2}$$

  the main consequence is that in the presence of a sinusoidal magnetic field H, one has a deformed magnetic flux density field B, i.e., no more sinusoidal but characterised by the presence of harmonics
- due to the phenomenon of hysteresis, a second mechanism of energy dissipation exists, and it can be taken into account by introducing a second kind of resistance

A deeper analysis would request an approach in the time domain, but if the analysis is restricted to the main frequency (to which most of the energy is related) it is possible, in first approximation, to neglect the B field distortion and write a relation between phasor quantities of the type:

$$B = \mu^*(H)\, H \tag{3}$$

$\mu*$ is the complex permeability defined as:

$$\mu^*(H) = \mu'(H) - j\mu''(H) \tag{4}$$

The complex permeability $\mu*$ is a function of the magnetic field modulus H and must be considered as a mean value with respect to time; more in details, the real part μ' is related to the reactive power while the imaginary part μ'' is related to the power dissipated by hysteresis.

This quantity is dependent on a certain number of parameters such as: type of material composing the conductor, geometry, temperature, state of mechanical stress, frequency and other; therefore, on each particular case, a measurement of the complex permeability should be done.

By substituting Eq. (4) into Eq. (1), one obtains:

$$Z_{int} = \frac{1}{|I|^2} \int_v \sigma \left|\vec{E}\right|^2 dv + \frac{\omega}{|I|^2} \int_v \mu''(H) \left|\vec{H}\right|^2 dv + \frac{j\omega}{|I|^2} \int_v \mu'(H) \left|\vec{H}\right|^2 dv \tag{5}$$

The second term on the right hand side of Equation (5) represents the resistance associated to the energy dissipation due to hysteresis while the first and third terms still represent the ohmic resistance and inductance respectively.

Being the magnetic field H, function of the current flowing inside the conductor, the complex magnetic permeability is also function of the current; so, by looking at Eq. (5) one has:

$$Z_{int} = Z_{int}(I) \tag{6}$$

i.e., the internal impedance is a function of the current.

In Fig. 1, two examples of measured values (taken from publication [3]) of the p.u.l. internal resistance and p.u.l. internal reactance of a steel pipe versus the current, at the frequency of 50 Hz are shown. Figs. 1(a) and 1(b) refer to pipes having diameter 80 mm and 160 mm respectively.

The curves clearly show the strong dependence of resistance and reactance on the current flowing in the pipe for values greater than 10 A. For values less than 10 A, a linear behaviour of the steel pipe

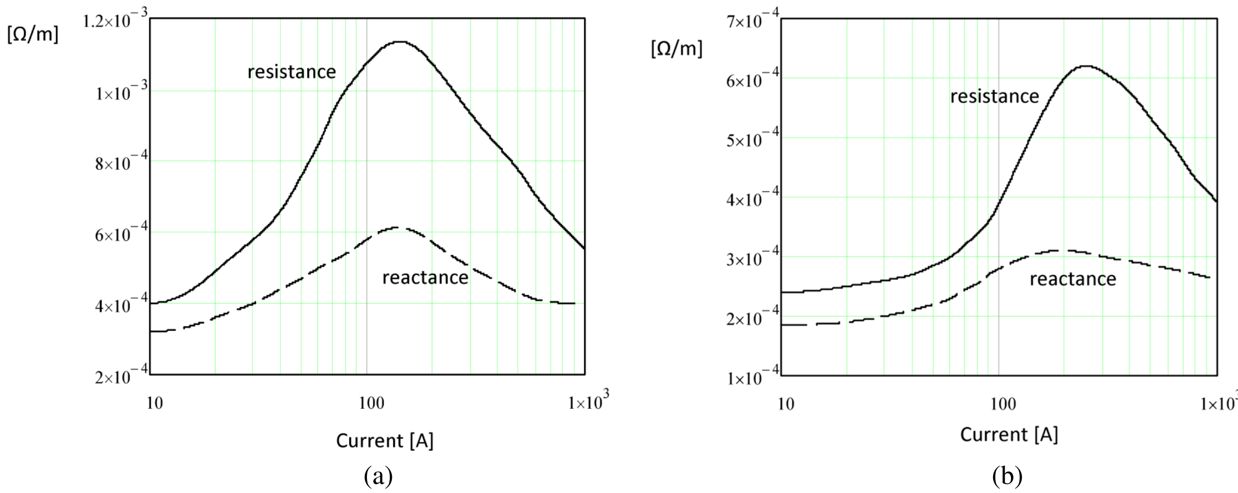


Figure 1. Measured p.u.l. internal impedance of a steel pipe versus the current; $f = 50\,\mathrm{Hz}$. (a) 80 mm diameter, (b) 160 mm diameter.

may be assumed, with good approximation, so that the value of the p.u.l. internal impedance is not dependent on the current.

The calculations and the results shown in the following are based on the curves represented in Fig. 1.

3. CALCULATION METHOD

The circuit pipeline with earth return, under the action of external electromagnetic fields can be discretised by means of a chain composed by a suitable number n of π cells of the type represented in Fig. 2. Note that in Fig. 2 the impedance associated with the generic i-th cell is dependent on current flowing in the i-th cell itself.

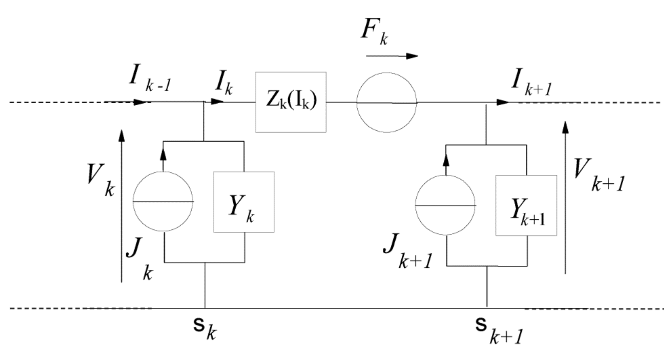


Figure 2. k-th π cell of the equivalent circuit modelling the pipeline with earth return.

In Fig. 2, the ideal longitudinal electromotive force (e.m.f.) generator and the ideal transversal current generators model respectively the inductive and conductive coupling from the power line/railway line on the pipeline.

By looking at Fig. 2 and by applying the Kirchhoff laws to each of the n cells, one obtains the following system, expressed in compact form, where the unknowns $[V]$ and $[I]$ represent voltages and currents induced along the pipeline:

$$\begin{cases} [A]\,[V] - [Z\,(I)]\,[I] = -\,[F] \\ [Y]\,[V] + [A]^T\,[I] = [J] \end{cases} \tag{7}$$

The quantities appearing in Eq. (7) are defined as follows:

$[A]$ is a matrix of $(n \times n+1)$ order given by:

$$[A] = \begin{bmatrix} 1 & -1 & 0 & \cdots & 0 \\ 0 & 1 & -1 & \cdots & 0 \\ \vdots & \vdots & & & \vdots \\ \vdots & \vdots & & & \vdots \\ 0 & 0 & \cdots & 1 & -1 \end{bmatrix} \tag{8}$$

and $[A]^T$ is its transposed. $[V]$ is the vector of voltages of $n+1$ order given by:

$$[V] = \begin{bmatrix} V_1 \\ \vdots \\ V_{n+1} \end{bmatrix} \tag{9}$$

$[I]$ is the vector of currents of n order given by:

$$[I] = \begin{bmatrix} I_1 \\ \vdots \\ I_n \end{bmatrix} \tag{10}$$

$[F]$ is the vector of induced e.m.f generators of n order given by:

$$[F] = \begin{bmatrix} F_1 \\ \vdots \\ F_n \end{bmatrix} \tag{11}$$

$[J]$ is the vector of induced current generators of $n+1$ order given by:

$$[J] = \begin{bmatrix} J_1 \\ \vdots \\ J_{n+1} \end{bmatrix} \tag{12}$$

$[Z([I])]$ is the impedances diagonal matrix of $n \times n$ order given by:

$$[Z\,[I]] = \begin{bmatrix} Z_{11}\,(I_1) & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & Z_{nn}\,(I_n) \end{bmatrix} \tag{13}$$

and $[Y]$ is the admittances diagonal matrix of $n+1 \times n+1$ order given by:

$$[Y] = \begin{bmatrix} Y_{11} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & Y_{n+1n+1} \end{bmatrix} \tag{14}$$

By means of some algebraic steps, from the two equations composing system (7) one can write:

$$[I] = \left([A]\,[Y]^{-1}\,[A]^T + [Z\,[I]]\right)^{-1} \left([A]\,[Y]^{-1}\,[J] + [F]\right) \tag{15}$$

In such a form, it is possible to solve Equation (15) by means of the successive approximations method, that is by means of an iterative procedure corresponding to the following equation:

$$[I]^{i+1} = \left([A]\,[Y]^{-1}\,[A]^T + \left[Z\,[I]^i\right]\right)^{-1} \left([A]\,[Y]^{-1}\,[J] + [F]\right) \tag{16}$$

Formula (16) expresses the current vector $[I]^{i+1}$ at the $i+1$-th step as function of the current vector $[I]^i$ at the i-th step.

At each step and for each cell, the internal impedance of the pipe has to be determined by means of the experimental curves shown in Fig. 1. In general, a few iterations (3–5) are enough to find the numerical solution of Eq. (16) within a relative per cent error less than 1%. Once the vector $[I]$ has been determined, the vector $[V]$ can be calculated by means of the second equation of system (7).

A convenient initial vector $[I]^1$ for the iterative procedure can be the one corresponding to the value:

$$[I]^1 = \left([A]\,[Y]^{-1}\,[A]^T + [Z_{lin}]\right)^{-1} \left([A]\,[Y]^{-1}\,[J] + [F]\right) \quad (17)$$

where $[Z_{lin}]$ is the impedances diagonal matrix evaluated by assuming, for the p.u.l. pipe internal impedance, the constant value existing in the region of linear behaviour for the steel pipe. With reference to Fig. 1, such a region can be the one corresponding to current values lesser than 10 A.

As far as the formulas of the total p.u.l. impedance of the pipe-earth circuit as well as of the p.u.l. admittance to earth of the pipe are concerned, one may refer to [2, 3, 21].

It is useful to notice that the algorithm above described has been already successfully applied to assess the 50 Hz shielding factor of telecommunication cables having a metallic sheath provided with armouring composed by steel tapes [22, 23].

4. EXAMPLE OF APPLICATION AND SENSITIVITY ANALYSIS

The purpose of this paragraph is twofold:

- On one hand, to present an example of application of the algorithm above described by applying it to a real case.
- On the other hand, starting from the results of the calculations, to make some general considerations about the influence of steel non-linearity in 50–60 Hz electromagnetic interference calculations by doing a sensitivity analysis with respect to the more affecting parameters.

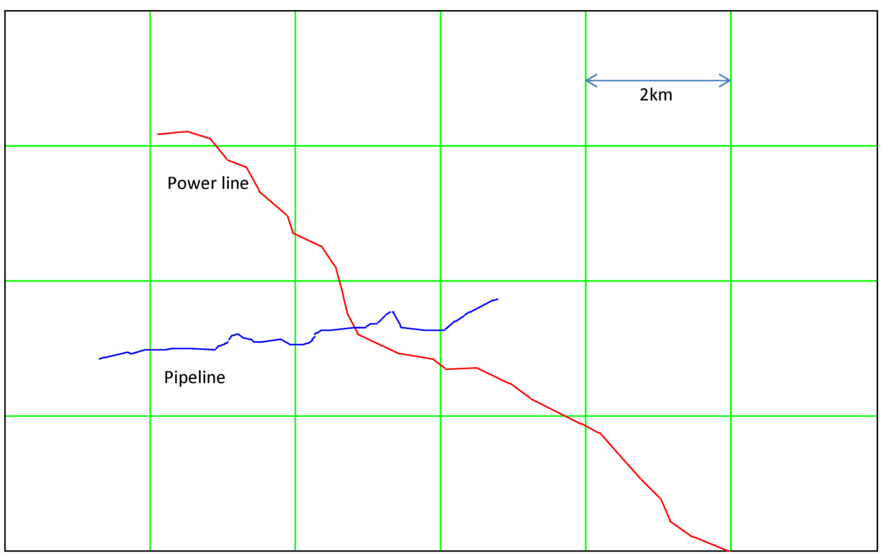
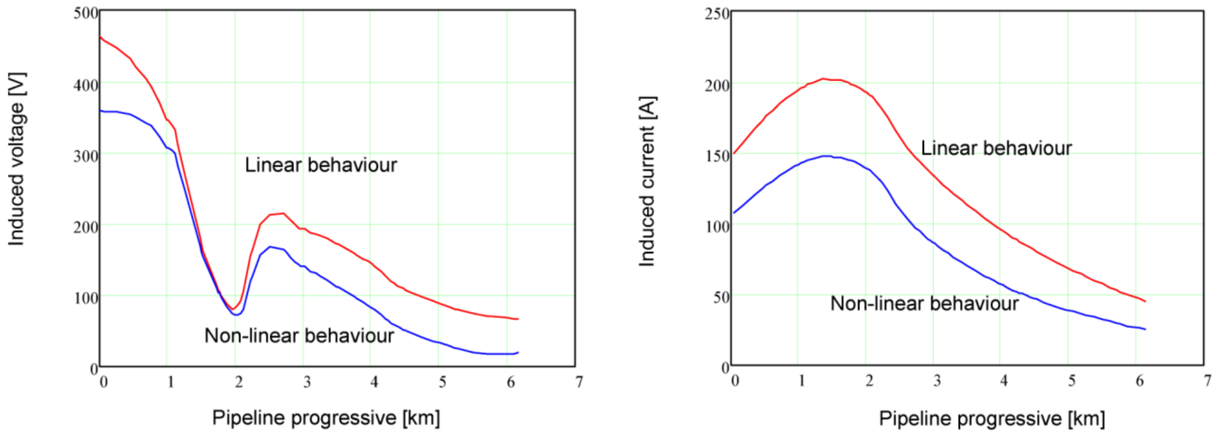


Figure 3. Lay-out of inducing power line and induced pipeline.

The example studied consists of a buried pipeline (6.167 km long and earthed at its terminal points) under the induction by a 380 kV–50 Hz power line which is 12.1 km long and in fault condition; the fault is fed by two stations, and the fault current from one side is 5.225 kA and 6.548 kA from the other; the soil resistivity is 100 Ωm. In Fig. 3, the layouts of both the plants are shown, and the fault occurs very close to the crossing point of the two layouts.

In Fig. 4 the results of the interference, i.e., induced voltage and current, along the pipeline progressive are shown. In each figure, two curves are present: a first curve corresponding to the case of



(a) (b)

Figure 4. Comparison between the results of interference when taking into account or not the steel non-linearity effect. $R_{ins} = 3 \cdot 10^6\,\Omega\text{m}^2$, $R_e = 5\,\Omega$. (a) Induced voltage. (b) Induced current.

a constant p.u.l. pipe internal impedance (linear behaviour) and a second curve obtained by taking into account of steel non-linearity (non-linear behaviour) according to the measured values of pipe internal impedance represented in Fig. 1(a).

The results of this particular example show a significant difference between the results of the two approaches for both voltage an current; in particular they are both higher when the linear model is adopted.

These results are quite expected; in fact by looking at Fig. 1, one can notice that when adopting the non-linear behaviour for the p.u.l. pipe internal impedance, such a parameter assumes higher values with respect to the linear behaviour (values of the curves corresponding to 10 A). Thus, the value of the current circulating in the pipe-earth circuit is higher in the linear model (lower impedance) than in the non-linear one (higher impedance); hence, also the current leaked into soil is higher in the linear model, and consequently the same holds for the values of the voltage to earth.

Nevertheless, in order to do a more systematic analysis, it is convenient to compare the results when varying those passive parameters that mostly influence the amount of current circulating in the pipe-earth circuit because it is the latter quantity that plays the main role in the phenomenon.

Thus, the parameters considered are:

- Insulation resistance of the pipe R_{ins}: i.e., the resistance offered by the pipe insulating coating (generally bitumen or plastic material, such as polyethylene) and by the soil to the transversal current that flows from the pipe to the (remote) earth through the unit surface. If ρ_{ins} and d are the pipe insulating coating resistivity and thickness respectively, one has $R_{ins} = \rho_{ins} d$. Such a parameter is inversely proportional to the pipeline p.u.l. conductance. See [20] for more details.
- Value of the earthing resistance R_e: in fact, the pipeline can be earthed in discrete points along its route by means of earthing electrodes. In the example under consideration, the pipeline is supposed to be earthed at both its termination by means of earthing resistance having value R_e.
- Value of the p.u.l. pipe internal impedance $z_{int} = z_{int}(I)$ according to the curves in Fig. 1.

Therefore, the results that follow have been obtained by considering these values for the parameters above described:

- R_{ins} [$3 \cdot 10^8\,\Omega\text{m}^2$, $3 \cdot 10^7\,\Omega\text{m}^2$, $3 \cdot 10^6\,\Omega\text{m}^2$] corresponding to high, average, low level of pipe insulation respectively.
- R_e [no earthing points, $10\,\Omega$, $5\,\Omega$]
- z_{int} [curves in Fig. 1(a), curves in Fig. 1(b)]

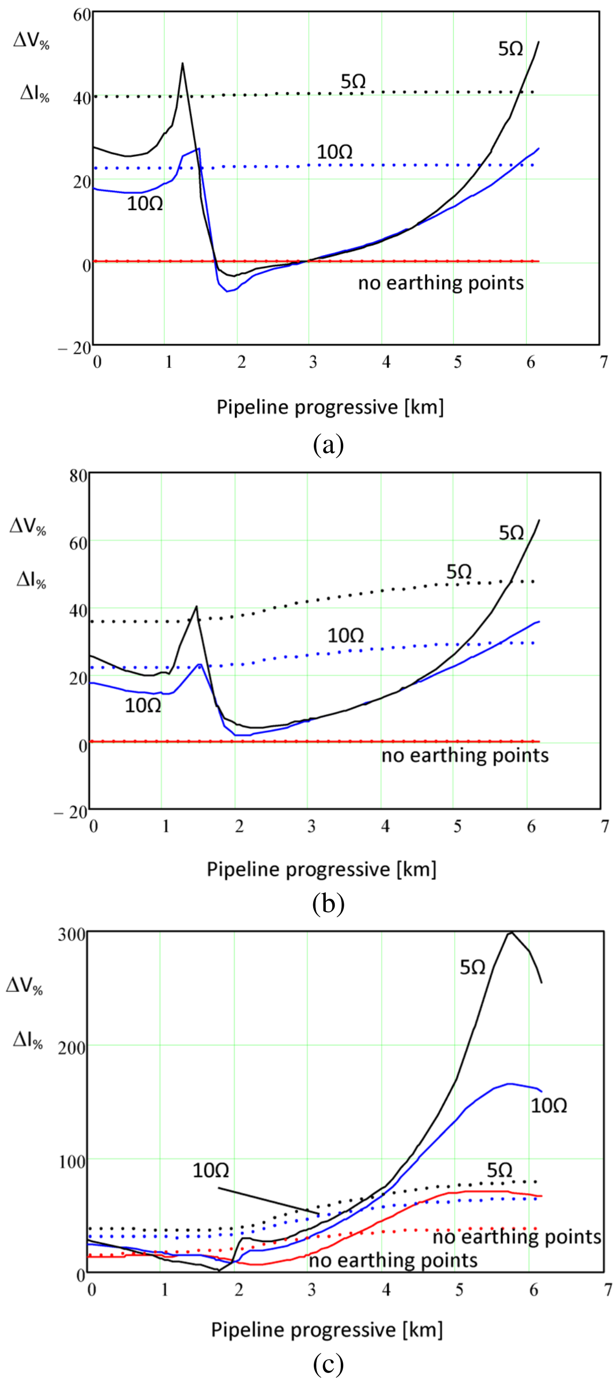


Figure 5. $\Delta V\%$ (continuous line) and $\Delta I\%$ (dotted line) versus pipeline progressive for different values of R_e; values of z_{int} according to Fig. 1(a). (a) $R_{ins} = 3 \cdot 10^8\,\mathrm{m}^2$, (b) $R_{ins} = 3 \cdot 10^7\,\mathrm{m}^2$, (c) $R_{ins} = 3 \cdot 10^6\,\mathrm{m}^2$.

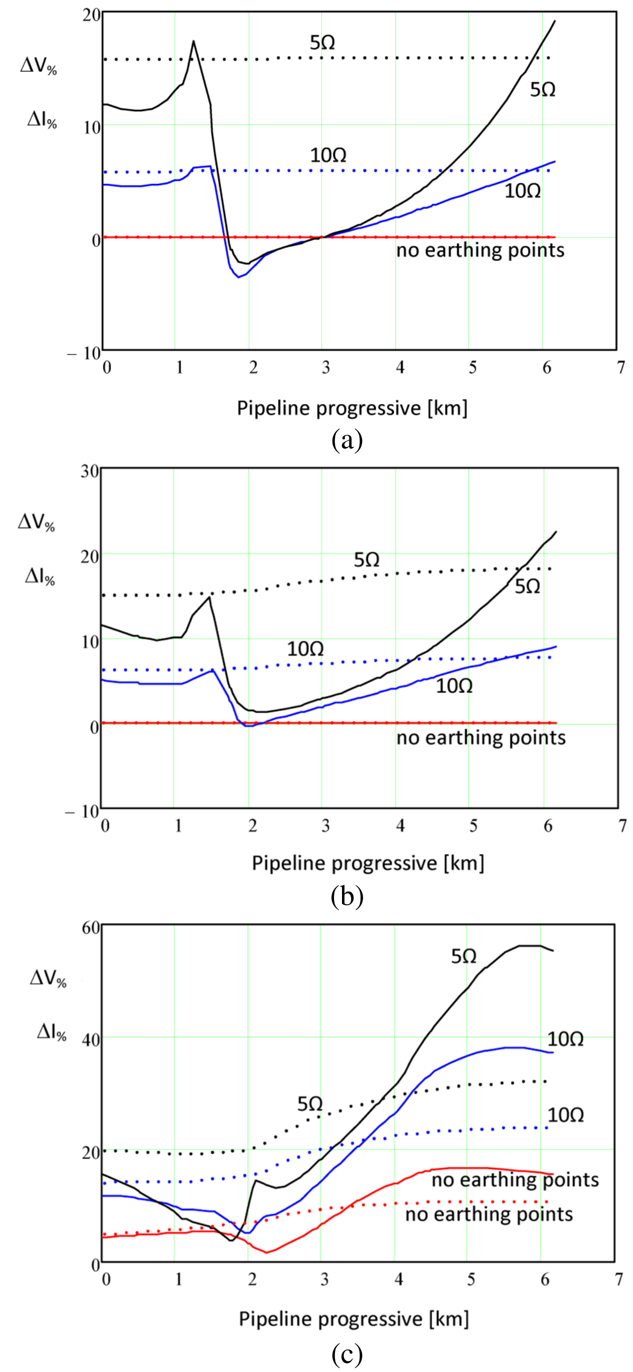


Figure 6. $\Delta V\%$ (continuous line) and $\Delta I\%$ (dotted line) versus pipeline progressive for different values of R_e; values of z_{int} according to Fig. 1(b). (a) $R_{ins} = 3 \cdot 10^8\,\mathrm{m}^2$, (b) $R_{ins} = 3 \cdot 10^7\,\mathrm{m}^2$, (c) $R_{ins} = 3 \cdot 10^6\,\mathrm{m}^2$.

In order to quantify the gap between the results when taking into account or not the influence of steel non-linearity, it is useful to define the per cent relative difference between the results:

$$\Delta V_{\%} = \frac{|V_l| - |V_{nl}|}{|V_{nl}|}100 \tag{18}$$

$$\Delta I_{\%} = \frac{|I_l| - |I_{nl}|}{|I_{nl}|}100 \tag{19}$$

V_l and I_l are the results obtained by ignoring the the non-linear characteristic of the p.u.l. pipe internal impedance while V_{nl} and I_{nl} are the corresponding results obtained by taking into account the non-linearity effects.

Figs. 5 and 6 show the per cent relative differences $\Delta V_{\%}$ and $\Delta I_{\%}$ for different values of the parameters R_{ins}, R_e and z_{int} versus the pipeline progressive.

By looking at them, one can do the following remarks:

1. No differences exist when the pipe is well isolated from the soil, i.e., for very high values of insulation resistance R_{ins} and when no earthing points exist; in fact, in such a case the current circulating in the pipe-earth circuit is small and thus the steel behaviour is linear. Consequently the p.u.l. pipe internal impedance is constant and does not depend on the current.
2. If the pipe has earthing points and/or the value of the insulation resistance R_{ins} is low, the difference between the two models is the more significant the lower is the insulation level (related to the values of R_{ins} and R_e) of the pipe with respect to the soil.
3. The difference between the two models (linear and non-linear) are larger when the non-linearity effects are more intense (i.e., by considering the curves in Fig. 1(a) instead of the ones in Fig. 1(b)).
4. The quantities $\Delta V_{\%}$ and $\Delta I_{\%}$ are practically always positive along the pipeline route. This means that the interference results obtained by means of the linear model are larger with respect to the ones of the non-linear model.

It is necessary to add that other cases of interference calculations also have been considered in the present study, and for brevity reasons the results are omitted. Nevertheless, the results confirmed, from the qualitative point of view, the same remarks expressed at the previous items 1–4.

5. CONCLUSIONS

This paper presents a study concerning the influence of the steel non-linearity when calculating the 50–60 Hz electromagnetic interference by power or railway lines on pipelines. No attention seems to be paid, in literature, concerning this issue, thus, the present paper has to be intended as contribution in filling this gap.

The results show that when certain values of induced current flowing in the pipe-earth circuit are reached, the differences in considering or not the steel non-linearity can be significant. Thus, in principle, a correct evaluation of the induced voltage and current along the pipeline would request the knowledge from measurements of the p.u.l. pipe internal impedance (Like in the examples shown in Fig. 1).

Nevertheless, in practice, this information is only very seldom available, so one is forced to adopt the linear model when interference calculations are requested.

On the other hand, interference calculations are aimed to electrical safety for people (staff) getting in touch with the pipe and for devices or apparatuses connected to the pipe itself.

Luckily, by remembering item 4, at the end of the previous paragraph, the use of the linear model yields cautionary results, and this justifies the common approach of neglecting the non-linear behaviour of the pipe p.u.l. internal impedance when dealing with 50–60 Hz electromagnetic interference calculations.

Moreover, it is important to remark the role played by the intensity of the inducing electromagnetic field acting on the pipeline because it contributes, together with the electrical characteristics of the pipe-earth circuit to determine the level of induced current able to trigger the non-linear behaviour of the pipe steel.

In practice, this means that the non-linear behaviour is important especially in fault condition of the power line/railway line because, in this case, one has high and imbalanced inducing currents of the order of some kiloamperes or even some tens of kiloamperes.

On the contrary, in the case of normal operating condition of the power line/railway line, due to the lower level of inducing field, it is more difficult that the induced current on the pipeline is able to trigger the non-linear behaviour. That occurs only in particular cases, e.g., very long and close parallelisms between the inducing line and the pipeline.

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