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The State of Art in the Field of AC Interference caused by Transmission Power-Lines affecting buried Metallic Pipelines

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***Abstract*—This paper outlines the state of the art in the field of AC interference assessment on buried metallic pipelines. In particular, the attention is on pipelines that are located close to high voltage transmission-lines. Due to both the complexity and hazard of AC interference caused by overhead power-lines on metallic buried pipelines, there is an industrial need for reliable simulation software able to provide capabilities for predicting and possibly mitigating coupled voltages on these structures. This electromagnetic interference is present during both normal operating conditions and faults, and it generally consists of an inductive, a conductive, and a capacitive contribution. In particular, the focus of this paper is on the inductive coupling mechanism, but the other two are still discussed. Furthermore, the main risks for equipment and personnel are highlighted, in order to clarify the pivotal importance of performing an accurate analysis of these effects. The two main methods that were used over the course of the years to investigate this topic are described, starting from the circuital analysis. Afterwards, the main physical assumptions are discussed and the field theory is introduced, reporting the main pros and cons compared to the previous approach.**

***Index Terms*— AC interference, electromagnetic compatibility, finite element method, pipelines**

I. Introduction

Nowadays, due to the very high and increasing cost of rights-of-ways, it is a common practice that metallic pipelines (normally made of welded steel, used for the transportation of various substances) share the same distribution corridors with high-voltage (HV) power-lines, as depicted in Fig. 1. Therefore, the pipelines near the power-lines will probably be affected by AC interference. Moreover, the rapid increase in energy consumption, especially in industrialized countries, led to the adoption of higher loads and short-circuit current levels, thus making the problem more acute. This electromagnetic interference can result in electrical shock hazard for people touching the victim pipeline or metallic structures connected to it. The effect can also damage the pipeline's coating or even the related equipment, such as cathodic protection systems or insulating flanges. In addition, the induced currents on the pipeline flowing to the ground may produce corrosion effects, which are able to compromise the whole pipeline functionality. Under fault conditions, in the most severe cases and if no protective measures are taken, the voltages on the influenced pipeline can reach magnitudes up to several kV [1, 2].

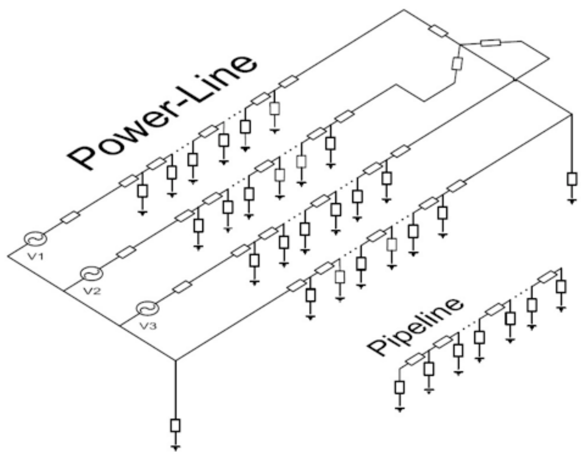

Figure 1. *Circuit representation of a possible interference situation between power-lines and buried metallic pipelines.*

In normal operation, influences are normally much lower, but still dangerous, as potentials in excess of 15V (very easily reached in normal operation conditions) should be considered hazardous. These are the coupling mechanisms that can be assessed [1]:

1. *Electrostatic (or capacitive) coupling:* this results from the capacitance between the line and the pipeline. The metallic structure acts as one side of a capacitor with respect to ground. This is only of concern when the structure is above ground, as underground structures are not influenced because of the screening effect of the earth against electrical fields [3, 4].
2. *Inductive coupling*: electromotive forces are induced due

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to the magnetic field produced by transmission-lines currents. This may happen when the structure is either above or below ground. The structure acts as the secondary of a transformer, in which the primary represents the overhead power line [2]. The magnitude of the effect depends on:

- the magnitude of the current flowing through the transmission line
- the length of the exposure. According to [4], it will be considered that the electrical interference is significant when the induced EMF due to a fault current with earth-return is higher than 10V/km per kA. Such values correspond approximately to a distance between the electrical line and pipeline smaller than , where is the electrical resistivity of the soil, expressed in [Ω/ m].
- the distance between the power line and the pipeline. The inductive coupling alone can generate a voltage of a few kV in the most severe situations.

3. *Conductive (or resistive) coupling:* this is as a result of faulty currents flowing on and off the power tower. A potential rise of the neighboring soil, with regard to the remote earth, is therefore produced. The pipeline's insulating coating is then subjected to the potential difference between the local earth and the pipeline induced potential, and therefore can be harmed. Conductive coupling occurs between the electrical installation and a nearby pipeline in the following ways:
   - if the pipeline is directly connected to the ground electrode of the power line
   - if the pipeline is located inside the zone of influence of the power line.

Under steady-state conditions, induced voltages depend on the currents in the phases, whereas during phase-to-earth faults the amplitude of the voltages depend on the fault current, and therefore can reach much higher values than in the normal situation. This is true for both the capacitive and the inductive coupling, whereas the conductive coupling exists only during fault conditions.

The fundamental differences between the various kinds of analyses that are usually performed are emphasized, thereby showing that there is no "perfect" method to be utilized for each kind of situation and level of complexity of the given physical configuration. For this reason, more research on this topic is required, in order to provide the industrial world with reliable and fast assessment tools, able to improve both design and maintenance capabilities for these structures.

II. METHODS

A. Circuit analysis

According to [4, 5], the calculation of the voltages appearing on the pipelines is normally worked out in two main steps:

1. Determination of the electromotive force (EMF) induced on the pipeline
2. Calculation of voltages to earth and eddy currents flowing through the pipeline, caused by the aforementioned EMF.

Solving an equivalent circuit therefore faces the problem. If the current flowing through the line conductors is known, the induced electromotive force on the pipeline is given by:

$$E = Z_m I \tag{1}$$

where:

$I[A]$ = magnitude of the current vector

Z_m [Ω/m] = mutual impedance per unit length of the phase conductor-earth (or the overhead ground-earth) and pipeline-earth circuits.

Z_m is usually calculated using one of the simplified Carson's formulae, for example the Carson-Clem approximation:

$$Z_m = \frac{\mu\omega}{8} + \frac{j\mu\omega}{2\pi}\ln\left(\frac{\delta}{D_{pi}}\right) \tag{2}$$

where:

$\omega\,[rad/s]$ = angular frequency

$\mu\,[H/m]$ = magnetic permeability

$D_{pi}\,[m]$ = distance between the pipeline and the given conductor

$\delta\,[m]$ = depth of the earth-return circuit of the current flowing through the conductor. This can be obtained using [1, 6]:

$$\delta = 658.87\sqrt{\frac{\rho}{f}} \tag{3}$$

The zone of influence, i.e., the area affected by the currents flowing on the power line, generally comprises a succession of parallelisms, approaches and crossings between the line and the pipeline. In order to enable calculation of induced voltages, those approaches and crossings must be converted into parallelisms. Subdividing the pipe into short length sections usually performs this task. According to [4], an oblique approach with distances d_1 and d_2 at the ends can be approximated to a parallelism with a separation equal to:

$$d = \sqrt{(d_1 d_2)} \tag{4}$$

provided that $1/3 \le d_1/d_2 \le 3$.

Using the superposition principle, the mutual impedance between each phase and the pipeline can be calculated. The same concept has to be applied if one or more overhead ground wires are being considered, keeping in mind that their respective currents will contribute to reduce the overall tension induced on the pipeline.

It is worth highlighting that both the currents and impedances involved in the calculations are complex quantities, and therefore the resulting total voltage heavily depends on the phases of the currents flowing through the conductors. If there are n conductors in the system, the induced EMF in the given section is:

$$E_{tot}(x) = \sum_{i=1}^{n} E_i(x) \quad (5)$$

where:
E_i = EMF due to the current flowing through the generic conductor.

The pipeline is modeled as a lossy transmission line by series impedance and shunt admittance, as in Fig. 1. As the pipeline has finite impedance to earth, which is distributed along its entire length, the pipe-to-soil potential can be calculated using the transmission-line model, as in [1,6]. The resulting circuit is shown in Fig. 2.

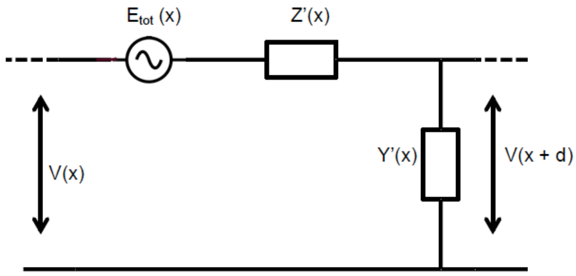

Figure 2. *Section of the pipeline-earth equivalent circuit.*

B. Field theory analysis

The basic idea behind the circuit theory is to find the parameters of an equivalent circuit of the physical configuration to be solved in order to find the leaking currents from the pipeline to earth and the electric potential with respect to the remote ground. The field theory uses instead a completely different approach, based on solving the Maxwell equations. The basic idea is to solve the diffusion equation of the magnetic potential vector over the whole physical domain:

$$\nabla \times \left(\frac{1}{\mu} \nabla \times A \right) = J - \sigma \frac{\partial A}{\partial t} \quad (5)$$

where:
$\boldsymbol{A}[T \cdot m]$ = magnetic vector potential
$\boldsymbol{J}[A/m^2]$ = current density.

If the magnetic permeability is assumed to be constant over the whole domain,

$$\nabla \times (\nabla \times A) = \mu J - \mu\sigma \frac{\partial A}{\partial t} \quad (7)$$

and if the Coulomb Gauge is chosen as the solution for $\nabla \cdot A$, the following equation is obtained:

$$-\nabla^2 A = \mu J - \mu\sigma \frac{\partial A}{\partial t} \quad (8)$$

Equation (7) is a vector equation that represents 3 scalar equations, one for each axis (x, y, z). These equations are obtained if the quasi-stationary approximation is performed, thus stating that $J >> \partial D/\partial t$ in every point of the considered domain, where D is the displacement current. This is true only if the following condition holds true:

$$\frac{r_{p0-p}}{v} << \frac{1}{\omega} \quad (9)$$

where:
r_{p0-p} [m] = Maximum linear extension of the considered physical domain

$v[m/s]$ = Propagation speed of the electromagnetic interaction, which is equal to the speed of light for the considered medium.

As a 3D analysis over the entire zone of influence would be way too demanding in terms of computational time, the majority of the authors chose to perform a 2D approximation, thus assuming that the currents are flowing only in one direction (e.g., the z-direction) and thus solving the diffusion equation only for a section of the given geometry.

Moreover, to easily perform the assessment of the time-varying nature of this phenomenon, the Steinmetz transform is employed, thus obtaining

$$-\left(\frac{\partial^2 A_z}{\partial x^2} + \frac{\partial^2 A_z}{\partial y^2} \right) = \mu J_z - j\omega\sigma\mu A_z \quad (10)$$

where $J_Z = J_Z(x, y)$ and $A_Z = A_Z(x, y)$ are the z-components of J and A.

Due to the complexity of this kind of geometries, the analytical solution of the equation is not an option. Therefore, an approximated solution of the problem described by this partial differential equation is obtained using the finite element method (F.E.M.), sub-dividing the whole domain into many sub-domains, called elements. The unknown function (the magnetic vector potential) is then approximated on the elements, by making use of some kind of interpolation. An element matrix $[K_{el}]$ is written for each element, and a coefficient matrix $[K]$ is then constructed by assembling the element matrices. The same approach is then applied to the sources, thus writing a source-term matrix $[t_{el}]$ for each element and finally constructing the matrix $[t]$. A problem described by partial differential equations can therefore be described by a linear system, whose solution gives the current density in each element of the domain:

$$[K]\left[\bar{A}_z\right] = [t] \quad (11)$$

with $\bar{A}_z$ being the interpolated solution. It is worth highlighting that, due to the presence of the time- varying quantity $j\omega\sigma\mu \boldsymbol{A}_z$ in equation (9), $[K]$ is a complex matrix, whereas it would have been real if the problem was stationary. Once the distribution of the magnetic vector potential has been calculated, the magnetic flux density can be obtained as:

$$B(x,y) = \nabla \times A_z \quad (12)$$

The current density over the whole domain can then be expressed as:

$$J_z = J_0 - j\omega\sigma A_z \quad (13)$$

where the first term of the right hand side is due to the external fields, while the second term represent the effect of the inductive coupling. Evidently, J_0 will be non-zero only on the conductors of the transmission line, while (if $\omega \neq 0$) $j\omega\sigma A_z$ will be responsible for currents flowing through the earth and the pipeline. As can be seen, the effects of the induced fields are always in opposition to the fields

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produced by the sources, i.e., J_0 [7]

Finally, the currents can be computed, for each medium with $\sigma \neq 0$, as:

$$I_i = \iint_{S_i} J_z \, dS. \tag{14}$$

C. Discussion

1. Circuit analysis:

The rigorous form of the earth-return impedance was originally solved in [8] and [9], and it assumes homogeneous infinite earth and no displacement current. Therefore, these calculations are based on the assumption that the earth is homogeneous with a constant resistivity. The earth, however, is not homogeneous, and its resistivity varies along the depth of the earth layer. Even if considered as an equivalent homogeneous earth, the resultant earth resistivity may be frequency dependent. The assumption of homogeneity may cause a difference in calculated results from actual test results. This approximation is justified for a raw evaluation of AC interference, with only the inductive coupling (in normal operating conditions) being considered. However, the often-multilayered nature of the soil has a strong influence on the conductive coupling amplitude, as shown in [10] and many other works. In addition, if an accurate analysis is needed, then the complex nature of soil must be taken into account even for evaluating the inductive coupling, as stated in [11].

As shown in [3, 12], a proper analysis of the interaction between the effects of inductive and conductive coupling is not a trivial task, due to the great influence that the grounding system of choice has on the magnitude of the conductive coupling effect. However, this is not the only problem; if the pipeline is insulated from earth, then the inductive and conductive coupling are separately calculable. On the contrary, if the pipeline is connected to the earth, the separation of the two effects is not possible, and thus they must be calculated simultaneously (the topic is further investigated in [10]).

However, taking into account the possible presence of layers characterized by different electrical properties using the circuit approach is not impossible, although difficult to implement. Nakagawa, in [13], developed a method where the earth-return path consists of three layers with arbitrary resistivities, permittivities and magnetic permeabilities. However, this leads to much more mathematically demanding tasks. In addition, the soil layers are being considered as parallel to the ground, which is an unlikely event in real geometries.

2. Field theory analysis:

The described method, based on the computation of the spatial distribution of the magnetic vector potential, does not present some of the most problematic issues related to the circuital method. This approach enables a more thorough assessment of both the complex soil nature and the conductive coupling between the various conductors of a given geometry. It is indeed possible to take into account the skin effect as well as the eventually ferromagnetic nature of the pipeline's material, which can further reduce the surface through which the current will flow. Another advantage of the field theory, as shown in [3], is that it enables the use of a proper approach for dealing with "short conductors", i.e., conductors for which the assumption that the axial conductor current attenuates exponentially does not hold true. This assumption normally leads to analytical solutions, like the afore-mentioned transmission-line model, which would lead to errors in this case. The drawbacks of this approach are as stated in the previous paragraphs, much longer computational times, which can constitute a major issue either if large or very fine meshes are being used.

Several works have been developed in order to overcome the heavy computational burden of the "classical" 2D F.E.M. method, employed for example in [14]. One of the more commonly used concepts is employing some kind of hybrid method, taking advantage of both circuit and field theories. This was done in [15], where the standard circuit analysis was used after having computed all the self- and mutual impedances of the given geometry, for a single earth-to-ground fault outside the exposure (therefore, the conductive coupling can be neglected).

III. Conclusion

In this review the main techniques used to perform circuital and field theory analyses for the purpose of investigating the problem of AC interference on buried metallic pipelines have been reported. The circuit analysis offers the advantage of a higher degree of simplicity of implementation, together with very low computational times. The price to be paid for those useful features is a number of (sometimes) brutal simplifying assumptions, which can lead to remarkable errors, especially as the number of conductors, the distances and the level of the current increases. On the other hand, the field theory approach presents a considerably better precision, and enables an accurate description of much more complex physical situations, as for example the presence of short conductors or multilayered soil. These achievements, however, are obtained by greatly extending both the complexity of the implementation and the computational times. This issue has led, as previously mentioned, to the development of alternative approaches, based on hybrid methods, designed in order to take advantage of the accuracy of the field theory and the speed of the circuital approach.

Some software focused on this problem [2, 3] has al-ready been developed, but those programs are based only on one specific approach, thus not giving the chance to analyze the given problem with more than one technique, and then to perform a comparison between the outcomes. Therefore, the industrial world still needs to be provided with more reliable, afford-able and flexible tools, which can be utilized both as a reference for designing new structures and to perform effective mitigations of existing sites.

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