HVPL Conductor Sag Influence on Induced Voltage Evaluation in Nearby Metallic Structures

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***Abstract*-The electromagnetic interference between high voltage power lines and nearby metallic structures has presented an important research subject over the last decades. The current paper investigates conductors sag influence on the proper evaluation of the inductive coupling between high voltage overhead power lines and nearby metallic structures, emphasizing on underground pipelines. A piecewise hybrid method implemented in the *InterfStud* EMI software, developed by the authors is applied, to analyze the 3D electromagnetic interference problem, calculating induced AC currents and voltages. The evaluation error introduced by neglecting conductors sag is determined for different power line and common right-of-way configurations.**

***Index Terms*—electromagnetic interference, power line conductor sag, induced voltages and currents, pipelines, piecewise evaluation.**

I. Introduction

During the last decades, the strict European environmental regulations and the higher financial costs that would inflict new distribution corridors have forced various utilities to share common right-of-ways for their networks. As a result there are many situations when for several kilometres water, gas or oil pipelines are placed in the near proximity of high voltage power lines or AC railway systems.

As it is well known the electromagnetic field produced by overhead power lines results in AC interference to nearby metallic structures, in form of three mechanisms [1]:

- *the inductive coupling* when time the varying magnetic fields generated by AC transmission line currents induce currents flowing in conducting structures and voltage rises between it and remote earth;
- *the capacitive coupling* that affects only above ground structures and occurs due to the capacitance between the power line conductors and metallic structures;
- and *the conductive coupling* when due to power line faults, current flows to earth through grounding grids leading to a potential rise in the neighbouring soil and nearby metallic structures with regard to remote earth.

Therefore, in many situations underground metallic pipelines are exposed to the effects of induced AC currents and voltages. These voltages and currents may present a serious danger to the operating personnel, the connected equipment and to pipeline's coating and metal structural integrity.

In order to provide proper protection for people coming into contact with an exposed part of a pipeline, the CENELEC [2] sets the limit of the induced voltage on a pipeline to 60V under operating conditions and under different fault conditions of the power line between 60V (fault duration > 3s) and 2000V (fault duration ≤ 0.1s). On the other hand, NACE imposes a stricter limit of 15V [3] under operating conditions.

Regarding underground metallic pipelines structural integrity, a special focus has been given to the case of corrosion due to alternating currents, resulting in a relative Guide and a European Standard [4, 5]. In general, AC current density is the main cause for AC corrosion, since even the highest quality coating has defects, allowing for an exchange of current between the metal pipeline and the surrounding soil. Induced AC voltage on such pipelines is the cause for this mechanism. Therefore, these documents suggest that in order to reduce the AC corrosion likelihood on buried pipelines subject to AC interference, the induced voltage on them should not exceed at any point the following values: 10 V where the local soil resistivity is greater than 25 Ω·m; 4 V where the local soil resistivity is less than 25 Ω·m.

In order to respect these regulations, the level of induced AC interference for any operating scenario that may occur for a specific power line - pipeline configuration, must be evaluated in detail.

As a result, numerous studies, reports and standards that deal with this problem have been already published in a large numbers. The early studies of [6] gave a first insight to the problem, whereas the advances in computer technology made it possible to develop and use more sophisticated tools for the determination of the AC interference on pipelines as presented in various reports and related papers [7, 8].

Afterword, other researcher's efforts led to different calculation methods, each one having relative advantages and certain limitations [9-13]. Next publications deals with the effects of specific parameters on the electromagnetic interference, such as tower configuration, multi-layer soil, conductor length and angle, current unbalance on the power lines or power line faults [14-21, 25].

Nevertheless, the influence of certain parameters is either inadequately examined in literature so far, or is not addressed at all.

Recent studies have been shown that transmission line conductor sag has a great influence on electrical and magnetic field distribution around high voltage power lines [19-21]. Therefore, the current paper investigates the effect of conductor sag on electromagnetic interferences between electrical power lines and nearby underground or above ground metallic pipeline.

II. Conductor Sag Analysis

Overhead electrical power lines are lifted in periodic catenaries. The sag of each conductor depends on individual characteristics of the transmission line and on terrain topography conditions.

Therefore, to determine the span of phase and sky wires between two consecutive towers, let consider an unseated conductor with a w per unit length weight suspended at the same level with two supports separated by a horizontal distance D (figure 1) [22].

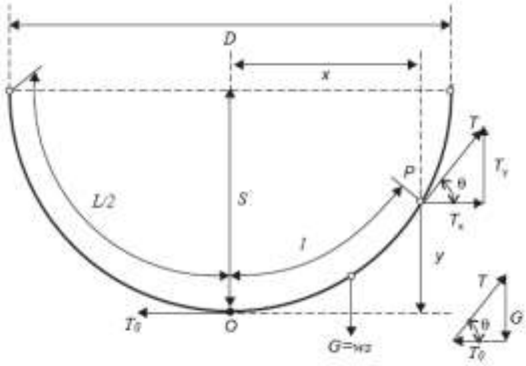

Fig. 1. Conductor suspended between supports placed at the same.

At equilibrium the tension in any point P along conductor span curve can be described by its horizontal component T_x equal to conductor tension T_0 in origin O and its vertical component T_y equal to conductor weight G in that point:

$$T_x = H; \; T_y = G = w \cdot l \tag{1}$$

Considering a very short conductor portion in the region of point P the length of this section can be written as a relation to conductor position variation:

$$dl^2 = dx^2 + dy^2 \text{, with } \frac{dy}{dx} = \tan\theta = \frac{T_y}{T_x} = \frac{w \cdot l}{T_0} \tag{2}$$

therefore:

$$dx = \frac{dl}{\sqrt{1 + \left(\frac{w \cdot l}{T_0}\right)^2}} \tag{3}$$

By integrating equation (3) at both sides we obtain:

$$x = \int \frac{dl}{\sqrt{1 + \left(\frac{w \cdot l}{T_0}\right)^2}} = \frac{T_0}{w} \cdot \sinh^{-1}\left(\frac{w \cdot l}{T_0}\right) + C_1 \tag{4}$$

with C_1an integration constant which value can be identified to be equal to 0 by placing point P in origin O, when $x = 0$ and $l = 0$.

Therefore, the following relationship between conductor section OP length and point P position was determined:

$$l = \frac{T_0}{w} \cdot \sinh\left(\frac{w \cdot x}{T_0}\right) \tag{5}$$

Applying the obtained relation for the situation when $x = D/2$ and $l = L/2$, the total conductor span curve length L can be expressed based on separation distance D between conductor lifting supports:

$$L = \frac{2T_0}{w} \cdot \sinh\left(\frac{w \cdot D}{2T_0}\right) \tag{6}$$

On the other hand introducing relation (5) in equation (2) the position variation for the very short dl conductor portion on OY axis can be determined:

$$dy = \sinh\left(\frac{w \cdot x}{T_0}\right) \cdot dx \tag{7}$$

integrating this equation at both sides we obtain:

$$y = \int \sinh\left(\frac{w \cdot l}{T_0}\right) dx = \frac{T_0}{w} \cdot \cosh\left(\frac{w \cdot l}{T_0}\right) + C_2 \tag{8}$$

with C_2an integration constant which value can be identified to be equal to $-T_0/w$ by placing point P in origin O, when $x = 0$ and $y = 0$.

Therefore, point P position along conductor span is described by the following relationship between its coordinates x and y:

$$y = \frac{T_0}{w}\left[\cosh\left(\frac{w \cdot l}{T_0}\right) - 1\right] \tag{9}$$

From equation (2) and (9) the total conductor tension T in point P:

$$T = \sqrt{T_x^{\,2} + T_y^{\,2}} = T_0\sqrt{1 + \left(\frac{G}{T_0}\right)} = T_0\sqrt{1 + \left(\frac{dy}{dx}\right)} \tag{10}$$

will be defined by:

$$T = T_0 \cosh\left(\frac{w \cdot x}{T_0}\right) \tag{11}$$

and the maximum tension value obtained at conductor lifting ends is given by [22]:

$$T = T_0 \cosh\left(\frac{w \cdot D}{2T_0}\right) \tag{12}$$

Therefore, the sag or deflection of the conductor for a span length *D* between supports is given by:

$$S = \frac{T_0}{w}\left[\cosh\left(\frac{w \cdot L}{2T_0}\right) - 1\right] \tag{13}$$

However, conductor tension in power line phase and sky wires changes continuously according to temperature and wheatear and so does the conductor span length and cross section [23]:

$$\Delta l = l_0 \cdot \frac{\Delta T}{M \cdot A}, \text{ with } \Delta T = T_f - T_i \tag{14}$$

where: T_i is the initial conductor tension, ΔT is the change in conductor tension according to temperature or wheatear, *M* is conductor elasticity modulus and *A* is the actual conductor cross section.

Therefore, to determine conductor span geometry between two consecutive electrical towers the actual horizontal conductor tension has to be evaluated. This can be evaluated according to a given conductor sag ($S = H_M – H_m$) by solving the following equation:

$$\frac{S}{2D} \cdot \alpha = \sinh^2\left(\frac{D}{4\alpha}\right) \tag{15}$$

where: H_M is the maximum conductor height, H_m is the minimum conductor height at mid-span and is a mechanical parameter of the conductor defined by:

$$\alpha = \frac{T_0}{w} \tag{16}$$

As a result the position of any point P along the conductor span curve will be given by the following relationship between the coordinates (x, y) [21]:

$$y(x) = H_m + 2\alpha \sinh^2\left(\frac{x}{2\alpha}\right) \tag{17}$$

III. Induced Currents and Voltage Evaluation

To evaluate the induced AC voltage in the underground pipeline, and evaluate the influence on conductor sag a hybrid method presented in detail in [9] and implemented by the authors in dedicated software application, *InterfStud* [18]. The applied hybrid method combines finite element calculation with Faradays law and equivalent electrical circuit analysis.

A. Finite Element Calculation

Considering the cross-section of the system under investigation and the fact that end effects can be neglected, the studied electromagnetic interference problem can be reduced to a 2D one in the X-Y plane.

The following system of equations describes the linear 2D electromagnetic diffusion problem for the *z*-direction components A_z of the magnetic vector potential and J_z of the total current density vector:

$$\begin{cases} \frac{1}{\mu_0 \mu_r} \cdot \left[\frac{\partial^2 A_z}{\partial x^2} + \frac{\partial^2 A_z}{\partial y^2}\right] - j\omega\sigma A_z + J_{sz} = 0 \\ - j\omega\sigma A_z + J_{sz} = J_z \\ \iint_{S_i} J_z ds = I_i \end{cases} \tag{18}$$

where J_{sz} is the source current density in the *z* direction and I_i is the imposed current on conductor *i* of S_i cross section.

Equation (18) is solved using dedicated finite element calculation software in order to compute the magnetic vector potentials on the surface of the each metallic structure (phase wires, sky wires and pipeline).

B. Self and Mutual Inductance Calculation

Using the values of the magnetic vector potentials, the self and mutual inductances can be calculated using the relations (19) and (20).

Considering a fault current which appears in one phase and all the other phases are neglected, than, if a certain base fault current is imposed on one of the phase wires (for example $\overline{I}_{Fb} = 1000\,A$, with the pipeline current $\overline{I}_P$ set equal to zero), the mutual inductance pipeline-phase wire will be [18, 24]:

$$L_{mut} = \frac{\overline{A}_z \cdot l_m}{\overline{I}_{Fb}} \tag{19}$$

where $\overline{A}_z$ is the MVP on the surface of the pipeline and l_m is the length of the pipeline.

In order to evaluate the self-inductance of the pipeline, the same methodology is followed, except that now we impose a certain current on the pipeline, for example $\overline{I}_{Pb} = 1000\,A$:

$$L_{self} = \frac{\overline{A}_z \cdot l_m}{\overline{I}_{Pb}} \tag{20}$$

Applying a permutation of the fault current on each of the phases, by the exposed relations, one can determine the mutual inductances between all the phase conductors and MP.

C. Equivalent Electrical Circuit Approach

The equivalent electrical circuit corresponding to a power line – nearby metallic pipeline electromagnetic interference problem (figure 2), implemented in the developed *InterfStud* software applications obtained by dividing the common distribution corridor in a number of equivalent parallel exposure sections, and evaluating the self and mutual inductance matrix with the above mentioned hybrid method. Usually the length of a section selected to be equal to the distance between to electrical towers or is set by power line/pipeline direction changes.

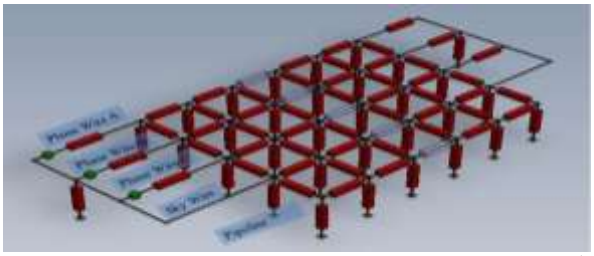

Fig. 2. The equivalent electrical circuit model implemented by the InterfStud.

In order to properly evaluate, the induced AC current and voltages in nearby metallic pipelines, for the presented case studies the authors divided the common right-of-way in S_n section per each catenary on which conductor sag, determined according to conductor length, weight and weather conditions, is approximated by equivalent horizontal straight conductors.

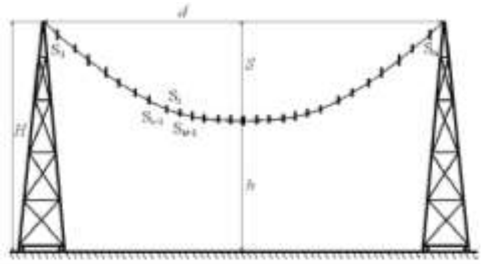

Fig. 3. Piecewise section representation of catenary.

IV. Investigated Electromagnetic Interference Problems

In order to determine the evaluation error introduced by neglecting conductor sag in the calculation process of the induced A.C. interferences due to inductive couplings, different common distribution corridor configurations has been analyzed. [18, 25]

A. Triangular single circuit power line configuration

In the first investigated right-of-way an underground metallic pipeline is placed in the vicinity of single circuit 110kV/50Hz power line is considered as in figure 4:

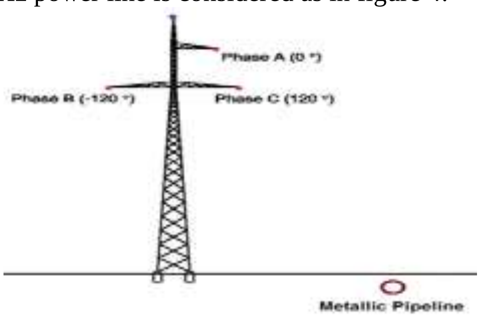

Fig. 4. Cross section of the investigated right-of-way configuration.

The exposure between the pipeline and the power line is considered parallel along 6km of common distribution corridor, with a separation distance of 20m. The pipeline is buried at a depth of 1.8m, in a homogenous soil with a resistivity of 100Ω·m. It has a 1422mm outer diameter a 22mm wall thickness and 4.2 mm polyetilene insulation. The power line phase wires are placed in a triangular layout on IT.Sn102 type towers with one sky wire. Table I presents conductors positioning on electrical towers:

TABLE I
Conductors Position OnIT.Sn102 Towers

Conductor	Height	Position
Phase A (0°)	21.4 m	2.85 m
Phase B (-120 °)	17.2 m	4.35 m
Phase C (-240 °)	17.2 m	-4.35 m
Sky Wire	24.7 m	0 m

Considering an average 350A symmetrical current load on power line phase wires, a 300m span between two consecutive electrical towers and a 4.5m conductor sag the induced currents (figure 5) and voltages (figure 6) were evaluated along pipeline length.

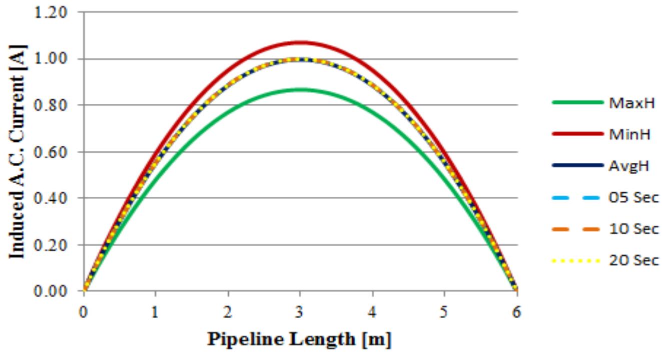

Fig. 5. Induced A.C. current along pipeline length.

To determine the evaluation error introduced by neglecting conductor sag simulations has been made considering power line phase wires and the sky wire as straight conductors placed at maximum height (tower height), at minimum mid-span height, and respectively at an average height evaluated according to conductor span geometry. Also it was analyzed the situation when the conductor span is represented by 5, 10 and respectively 20 equivalent straight conductor sections.

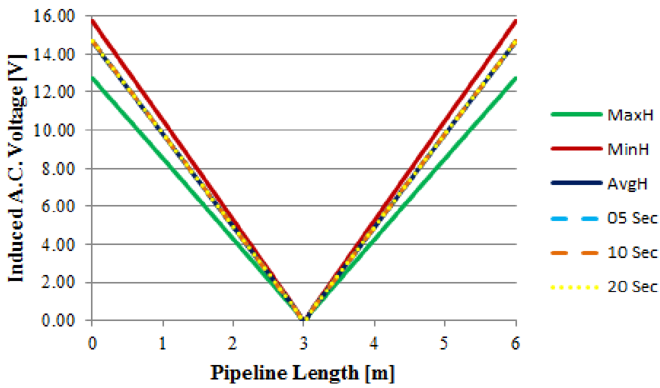

Fig. 6. Induced A.C. voltage along pipeline length.

Calculated induced current and voltage values have been compared to the 20 equivalent sectionper conductor span case and the determined evaluation errors are presented in table II:

TABLE II
OBTAINED EVELUATION ERRORS
FOR DIFFERENT CONDUCTOR SAG APROXIMATIONS

	MaxH	MinH	AvgH	05 Sec	10 Sec	20 Sec
Induced Voltage	13.21%	7.13%	0.19%	0.03%	0.01%	0.00%
Induced Current	13.19%	7.13%	0.19%	0.03%	0.01%	0.00%

It can be observed that neglecting conductor sags along the common right-of-way a 13% respectively a 7% evaluation error is introduced in the calculation process when phase wires are considered straight conductors placed at tower height and respectively at mid-span height. In case of the average height placed straight conductor the evaluation error was less than 1%. For a more detailed analysis of the conductor sag influence on induced AC interference computation, the variation of the evaluation error with regard to the separation distance between the power line and the underground pipeline was determined:

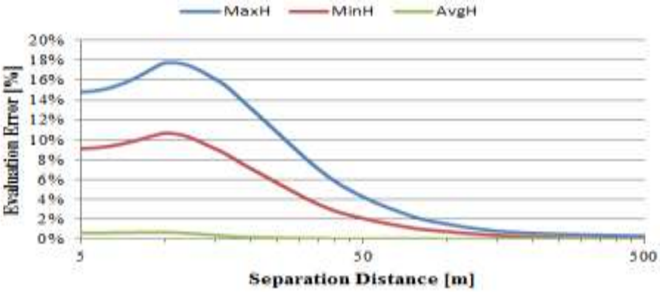

Fig.7. Evaluation error of induced voltages for different separation distances

From figure 7 it can be concluded that for separation distances higher than 50m the conductor sag influence can be neglected because the introduced evaluation error is less than 5%, for both the cases when phase wires are considered straight conductor placed at tower height and respectively at mid-span height.

B. Horizontal single circuit power line configuration

In the second studied power line – underground pipeline common right-of-way (see figure 8) the metallic pipeline is considered to be placed next to 400kV/50Hz single circuit overhead line. Pipeline dimensions and positioning, soil resistivity and right-of-way length are considered as in the first case, while power line phase conductors are placed horizontally on IT.Sn133 type towers with one sky wire, as in table III is presented:

TABLE III
CONDUCTORS POSITION ONIT.Sn133 TOWERS

Conductor	Height	Position
Phase A (0º)	26.7 m	-12 m
Phase B (-120 º)	26.7 m	0 m
Phase C (-240 º)	26.7 m	12 m
Sky Wire 1	29.7 m	-8.5 m
Sky Wire 2	29.7 m	8.5 m

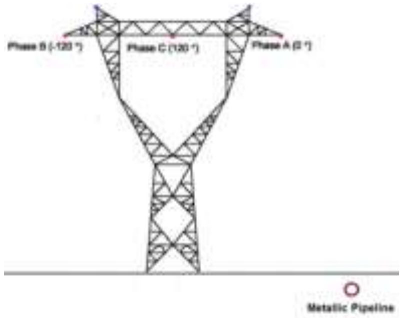

Fig. 8. Cross section of the investigated right-of-way configuration.

In order to determine the evaluation error introduced by neglecting conductor sag power lines phase wires were represented by straight conductors placed at maximum height (tower height), at minimum mid-span height, and respectively at an average height evaluated according to conductor span geometry. Induced voltage values obtained for a 600A symmetrical load on phase wires (figure 9), were compared with results evaluated for the situation when the conductor span is represented by 5, 10 and respectively 20 equivalent straight conductor sections (table IV).

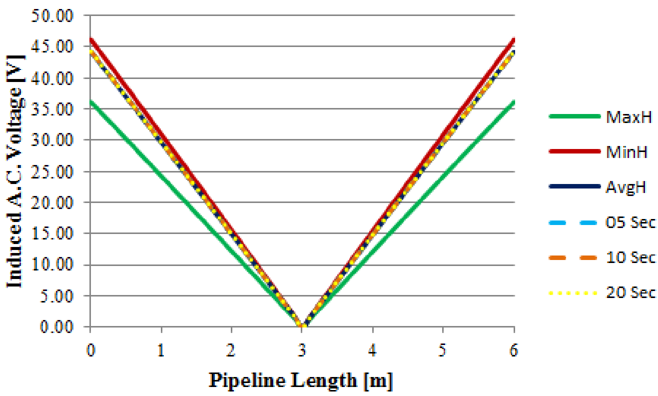

Fig. 9. Induced A.C. voltage along pipeline length.

TABLE IV
OBTAINED EVALUATION ERRORS
FOR DIFFERENT CONDUCTOR SAG APPROXIMATIONS

	MaxH	MinH	AvgH	05 Sec	10 Sec	20 Sec
Induced Voltage	14.63%	8.16%	0.40%	0.03%	0.01%	0.00%

It can be observed that neglecting conductor sags along the common right-of-way a 15% respectively a 8% evaluation error is introduced in the calculation process when phase wires are considered straight conductors placed at tower height and respectively at mid-span height. While in case of the average height placed straight conductor the evaluation error was less than 0.5%.

Figure 10 presents a more detailed analysis of conductor sag influence on induced AC interference computation, by analyzing the variation of the evaluation error with regard to the separation distance between the power line and the underground pipeline.

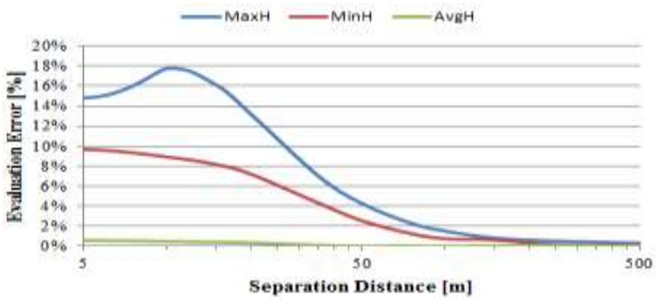

Fig. 10 Evaluation error of induced voltages for different separation distances

V. CONCLUSIONS

The paper studies the influence of power line conductor sag on the electromagnetic interferences induced in nearby underground metallic pipelines.

Two different power line configurations were studied by representing phase wires as straight conductors placed at tower height, at mid-span height respectively at an average height determined in correlation to conductor span geometry. Obtained induced voltage and current values were compared to the situation when conductor span was represented by 5, 10 and respectively 20 equivalent straight conductor sections.

Evaluation error values presented in figures 7 and 10 had showed that in case of power line – pipeline electromagnetic interference problems, phase wires can be modelled as straight conductors placed at an average height determined in correlation to conductor span geometry without affecting the accuracy of the obtained results. However, neglecting the presence of conductor sag and placing phase wires at tower height or at mid-span height could introduce evaluation errors up to 40% according to separation distance between power line conductors and the underground metallic pipeline.

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