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AC interference on pipelines due to double circuit power lines: A detailed study

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ABSTRACT

The electromagnetic interference between power lines and nearby pipelines has been an important research subject over the last decades. This interference may result in currents and voltages on pipelines that may pose a serious threat to operating personnel and equipment. In addition, the integrity of the pipeline may be threatened due to corrosion. Previously, several research papers and reports focused on a number of issues that affect this interference, presented methodologies for predicting its level and proposed various mitigation methods. Nevertheless, some issues have not been covered in detail yet or remain unclear. The interference between double circuit power lines and nearby pipelines is one of those issues. Therefore, the aim of the authors is to reveal the influence of some important parameters, such as the phase shift and the different loading between the two circuits, the unbalanced loading and the phase sequence. The manuscript provides detailed graphs and numerical data that may be useful for engineers and researchers for evaluating the interference level or in selecting and applying proper protection measures.

1. Introduction

Over the last decades, various utilities have been forced to share the same distribution corridors for their networks. The main reasons for that were the strict environmental regulations that made it very difficult and time consuming to choose another corridor and the higher financial costs a new corridor would inflict. This resulted in situations where gas, water or oil supply utilities are sharing the same rights-of-way with overhead power lines or AC railway systems for several kilometers and in proximity to each other.

The electromagnetic fields generated by power lines result in AC interference to nearby metallic structures, in the form of three mechanisms, namely inductive, conductive and capacitive. Out of these, inductive interference is the most important one, being present both during normal operating conditions of the power line and faults. Therefore, in many cases the underground pipelines used for gas, water or oil supplies are exposed to the effects of induced AC currents and voltages. These voltages and currents may be potentially dangerous for the operating personnel, the pipeline's coating and metal and the equipment connected to it.

Numerous relative studies, reports and standards that deal with this problem have been published. The early studies of [1,2] 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 EPRI reports and related papers [3–5]. Further research efforts led to the proposition of different calculation methods, each one having relative advantages and certain limitations [6–9]. Other papers dealt with the effects of specific parameters on the electromagnetic interference, such as tower configuration [10], multi-layer soil [11], conductor length and angle [12,13], current unbalance on the power lines [14] or power line faults [15].

Of particular interest are the various standards and guides developed. The ITU-T Directives and the Cigré guide [16,17] constitute an excellent introduction to the topic and are particularly helpful to practitioner engineers. In order to provide proper protection for people coming into contact with an exposed part of a pipeline, the CENELEC [18] sets the limit of the induced voltage on a pipeline to 60 V under operating conditions and under different fault conditions of the power line between 60 V (fault duration > 3 s) and 2000 V (fault duration ≤ 0.1 s). On the other hand, NACE imposes a stricter limit of 15 V [19] under operating conditions.

Recently, special focus was given to the case of corrosion due to alternating currents. Previously, AC corrosion was considered negligible compared to DC interference. However, several research efforts proved the opposite, resulting in a relative Guide and a European Standard [20,21]. 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

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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. This level depends on a number of parameters that their influence has been examined in detail in the past. Such are the relative distance between the power line and the pipeline, the soil resistivity and possible multi-layer soil, the type and location of fault, the coating and structure of the pipeline, the length of the common corridor, the type of the exposure (either parallel or not), and the current loading of the power line. Nevertheless, the influence of certain parameters is either inadequately examined in literature so far, or is not addressed at all.

In this manuscript, the authors deal with the case of inductive interference originating from a double circuit power line under normal or unbalanced operating conditions, on a nearby underground pipeline. The aim is to reveal the influence of some important parameters that have not been covered in detail yet, such as:

- the role of phase sequence on power line towers;
- the influence of phase shifts between the two power line circuits;
- the influence of different symmetrical current load on each circuit;
- the influence of unbalanced load on both circuits.

Presenting the structure of the manuscript, in Section 2 a brief review of the calculation method used for this study is given. The analysis is performed based on a specific configuration presented in Section 3. Finally, Section 4 contains a detailed analysis of the above parameters along with the identification of the worst-case scenario that can occur during power line operating conditions.

2. The hybrid method

A hybrid method, first presented in [6], was used to evaluate the induced AC interference. The first step of the method is to construct a 2D model representing the cross section of the studied interference problem. The second step is to analyze it using finite element calculation software, in order to evaluate the self and mutual impedances between all conductors of the problem. The benefit of such approach is that complex geometries can be taken into consideration and the exact structure of the soil is not ignored or simplified. This hybrid method was implemented in an electromagnetic interference software application, *Interfstud* [22], developed by the authors (Fig. 1). The software creates the equivalent electric circuit model of the studied interference problem, as shown in Fig. 2. In order to determine the induced voltages and currents along pipeline length, an iterative method is used.

3. Electromagnetic interference case study

A standard double circuit power line–pipeline interference case study is proposed for the evaluation of the above parameters. Specifically, an underground gas pipeline shares for 15 km the same right-of-way with an 110 kV/50 Hz double circuit power line. The exposure between the pipeline and the power line is considered parallel along the common corridor, with a separation distance of 25 m. The pipeline is buried at a depth of 2 m, in a homogenous soil with a resistivity of 100 Ω m. The power line phase wires are placed on triangular double circuit IT.Sn256 type towers with one

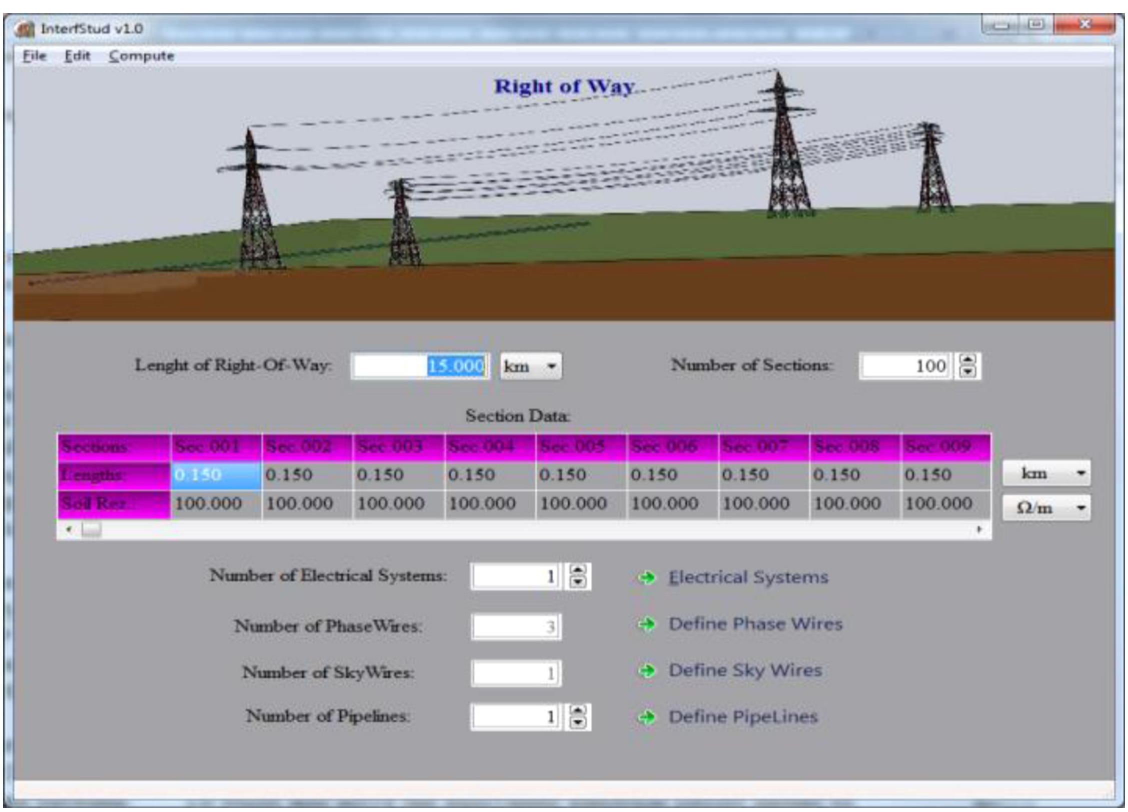

Fig. 1. The developed *Interfstud* EMI software.

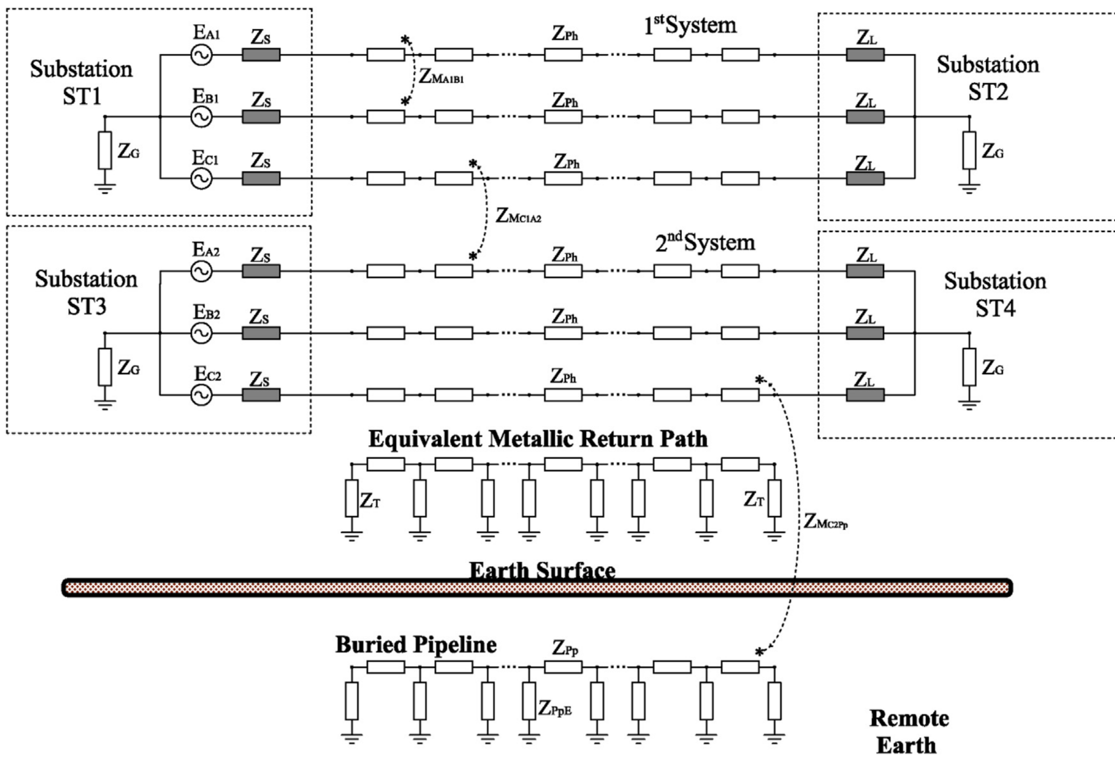

Fig. 2. Equivalent electrical circuit model.

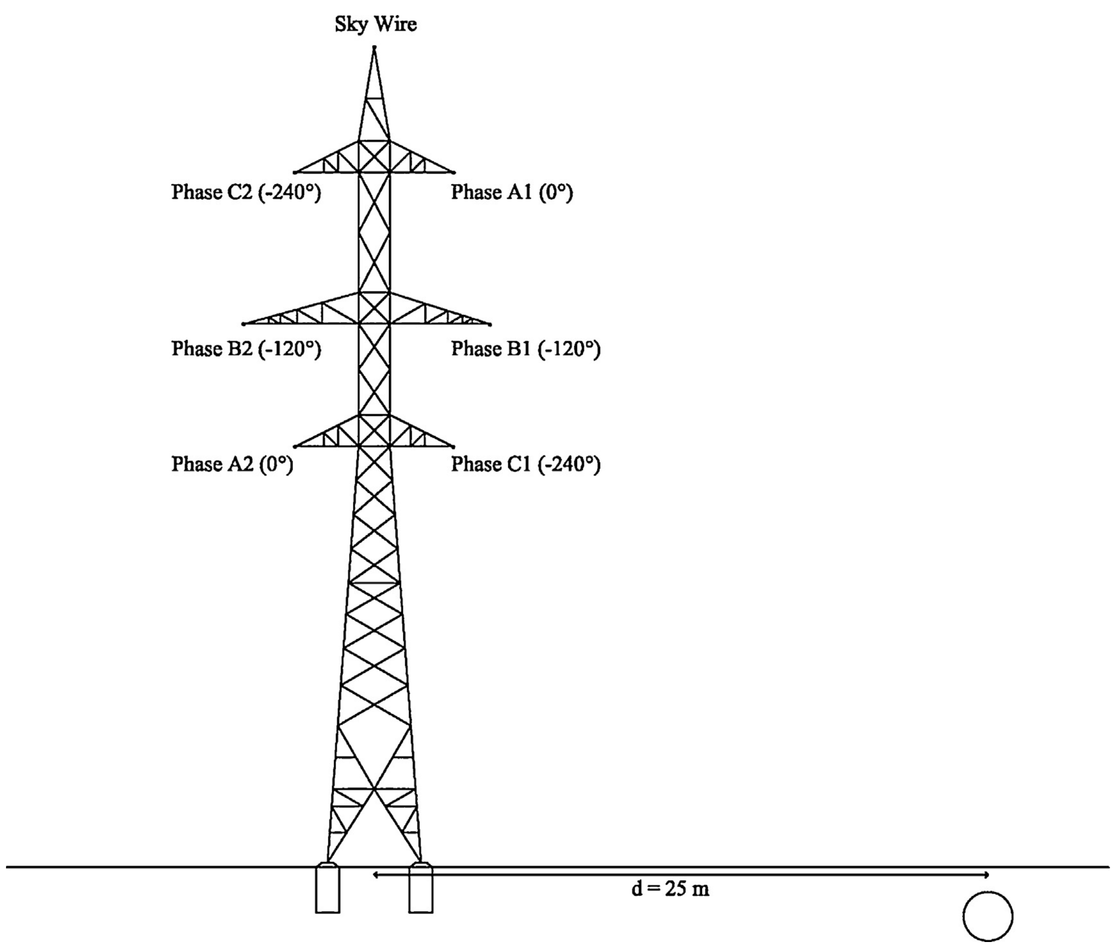

Fig. 3. Cross section of the common distribution corridor.

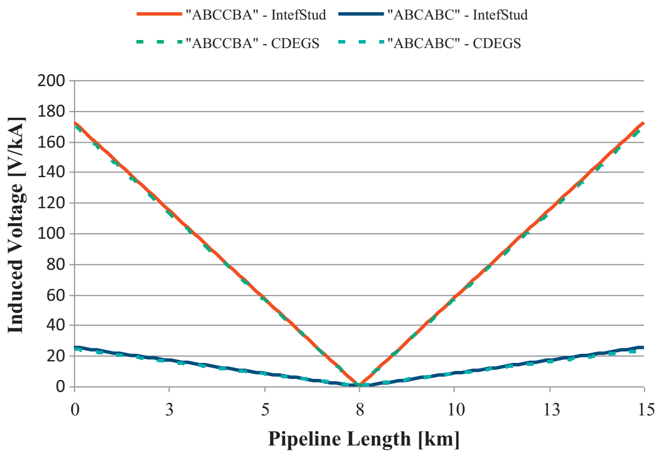

Fig. 4. Induced AC voltage on pipeline over kA of load current (normal operating conditions).

sky wire, as shown in Fig. 3. The two circuits are not in electrical parallel, i.e. they are supposed to feed different loads.

Appendix A contains a detailed description of the electrical and geometrical parameters of the power line and pipeline.

4. Induced AC interference analysis

4.1. Normal operating conditions

Initially, the induced AC interference in the underground pipeline is evaluated under normal operating conditions of the power line, in order to act as a comparison basis for the following sections. As normal operating condition, it is considered that both circuits are active and have a symmetric load of 350 A on each phase.

It is well known that different phase sequences on a double circuit power lines have a great influence on the electromagnetic field around a power line (for instance [23,24]). Therefore the most common low reactance bundle, 'ABCABC', phase arrangement as depicted in Fig. 3 (clockwise reading), and respectively a less common super bundle, 'ABCCBA', phase arrangement on towers is taken into account.

In order to provide estimation for other symmetrical loads, Fig. 4 presents the induced AC voltage over kA of the load current of the double circuit power line. Also, this figure compares the results obtained with the methodology described previously and the commercial CDEGS software [4], showing minimal differences. It can be observed that in case of the super bundle phase arrangement the induced voltages along the pipeline are much higher than in case of the low reactance bundle. The maximum voltages appear at both ends of the distribution corridor, where the pipe is electrically isolated for cathodic protection purpose from the rest of the pipeline. This maximum voltage value, 66.08 V, obtained in case of the super bundle, 'ABCCBA' phase arrangement and 350 A symmetrical load is used in the following sections as a base value for further analysis. The obtained maximum voltage value in case of the low reactance bundle, 'ABCABC' phase arrangement, 10.76 V, represents only 16.28% from it.

It should be mentioned that for normal operating conditions, soil resistivity does not influence greatly the inductive interference. Differences in soil resistivities and even non-homogeneous soils can affect the induced voltages and currents significantly when earth faults are considered.

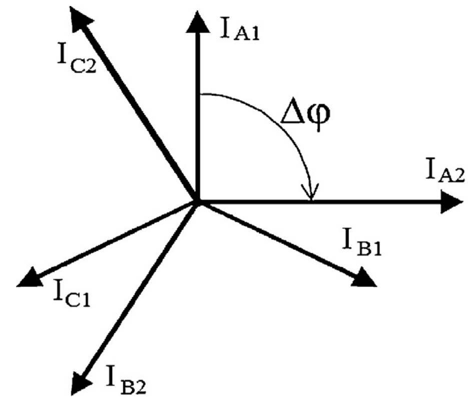

Fig. 5. Phase shift between EPL circuits.

4.2. Phase shift analysis

Let now assume that the double circuit power line is made of two independent single circuits, which connect different network nodes and are placed on the same towers only for a certain distance [25]. In that case, it is very common that phase shifts occur between the current phasor turns of the two circuits (Fig. 5). This is caused by the fact that two circuits carry different amount of active and reactive power.

Previous research [25] proved that neglecting phase shift effects can involve significant errors in magnetic field calculation (up to 50%) leading to underestimation or overestimation. The statistical analysis of a HV Italian double circuit power line presented in [26] showed that the average phase shift between the two circuits could be higher than 90°. In the following the direct effects of phase shifts on induced AC voltages in underground pipelines are studied. The aim is to identify the critical phase shifts that influence the induced voltage evaluation and the error inflicted if these phase shifts are neglected. To evaluate the influence of phase shifts on the induced voltage, a symmetrical 350 A current load is considered on both circuits, as in Section 4.1.

Initially, the super bundle 'ABCCBA' phase arrangement is investigated (Fig. 6), considering phase A of right side circuit as phase origin and applying different phase shifts on the left side circuit from $\Delta\varphi = -180°$ to $\Delta\varphi = 180°$. It must be specified that a $-120°$ phase shift is equivalent to an 'ABCACB' phase arrangement while a 120° phase shift corresponds to an 'ABCBAC' phase arrangement.

Fig. 6 presents the maximum induced voltage at pipeline ends for different phase shifts compared to a no phase shift case. Analyzing the obtained induced AC voltage values we can conclude that

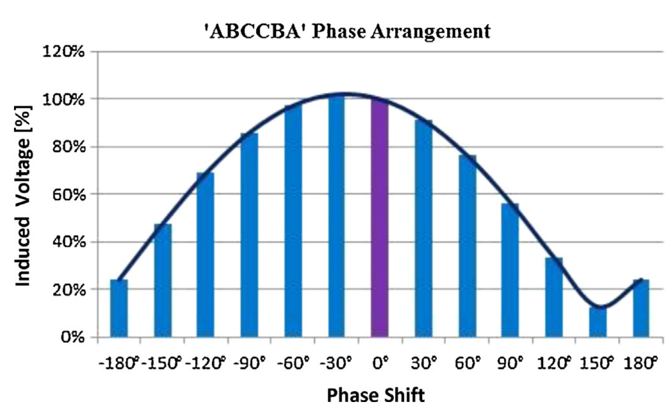

Fig. 6. Induced voltage with respect to no phase shift case for different phase shifts for the 'ABCCBA' phase arrangement.

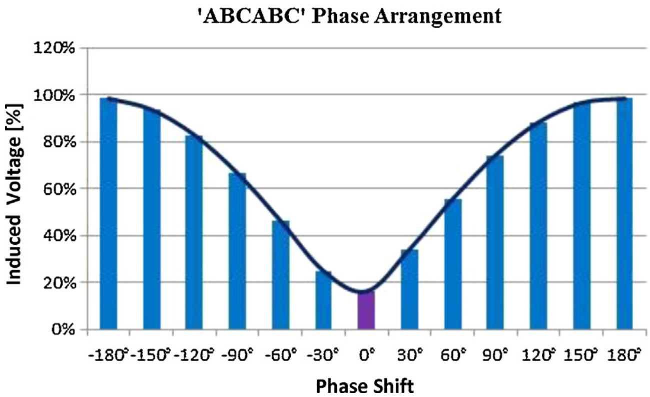

Fig. 7. Induced voltage with respect to no phase shift case for different phase shifts for the 'ABCABC' phase arrangement.

neglecting the phase shift between the two EPL circuits produces an estimation error less than 10% for phase shifts lower than ±30°. However, if this ±30° limit is exceeded, the estimation error increases dramatically. A more detailed analysis showed that the maximum induced voltage (67.54 V representing 102.21%) is obtained for a −24° phase shift, while the minimum induced voltage is obtained for a 157° phase shift (7.73 V representing 11.70%).

An identical study has been done for the low reactance bundle 'ABCABC' phase arrangement (Fig. 7), considering phase A of right side circuit as phase origin and applying different phase shifts on the left side circuit from $\Delta\varphi = -180^\circ$ to $\Delta\varphi = 180^\circ$. Here, a −120° phase shift is equivalent to an 'ABCBCA' phase arrangement while a 120° phase shift corresponds to an 'ABCCAB' phase arrangement.

Fig. 7 depicts the maximum induced voltage obtained at pipeline ends for different phase shifts, compared to a no phase shift case, applied to the same super bundle, 'ABCCBA' phase arrangement. It is important to note that in this case even a small phase shift can produce considerable errors. A detailed analysis showed that for this phase arrangement the maximum induced voltage (65 V representing 98.60%) can be obtained for a 172° phase shift, while the minimum induced voltage is obtained for a −6° phase shift (10.1 V representing 15.28%). Compared to the no phase shift situation of the low reactance bundle the obtained maximum voltage value represents a 506% increase, while the minimum value represents a 6% decrease.

The above analysis leads to the following recommendations, applicable to cases where the AC interference of an existing double circuit EPL to a neighboring MP, is to be determined:

- The phase shift in a double circuit EPL should be taken into consideration during the calculations only if historical data about the variation of the phase shift are available. In that case, the mitigation schemes can be very cost effective.
- If phase shift historical data are not available, the calculations should be performed taking the worst-case phase shift.

4.3. Current load study

In the previous sections, both power line circuits were considered carrying equal and symmetrical loads. In reality though, this assumption is very unlikely to be true. Therefore, the scope of this section is to evaluate the influence of different symmetrical loads at each power line circuit on the induced AC interference.

Initially, the super bundle, 'ABCCBA' phase arrangement is considered and the current load in each power line circuits is varied from 0 A to 700 A. A zero load in one of the two circuits is equivalent with an operating condition when only one of the circuits is active, whereas the other one (with the 0 A load) being a reserve line. In case of a fault condition on the first circuit the reserve line became

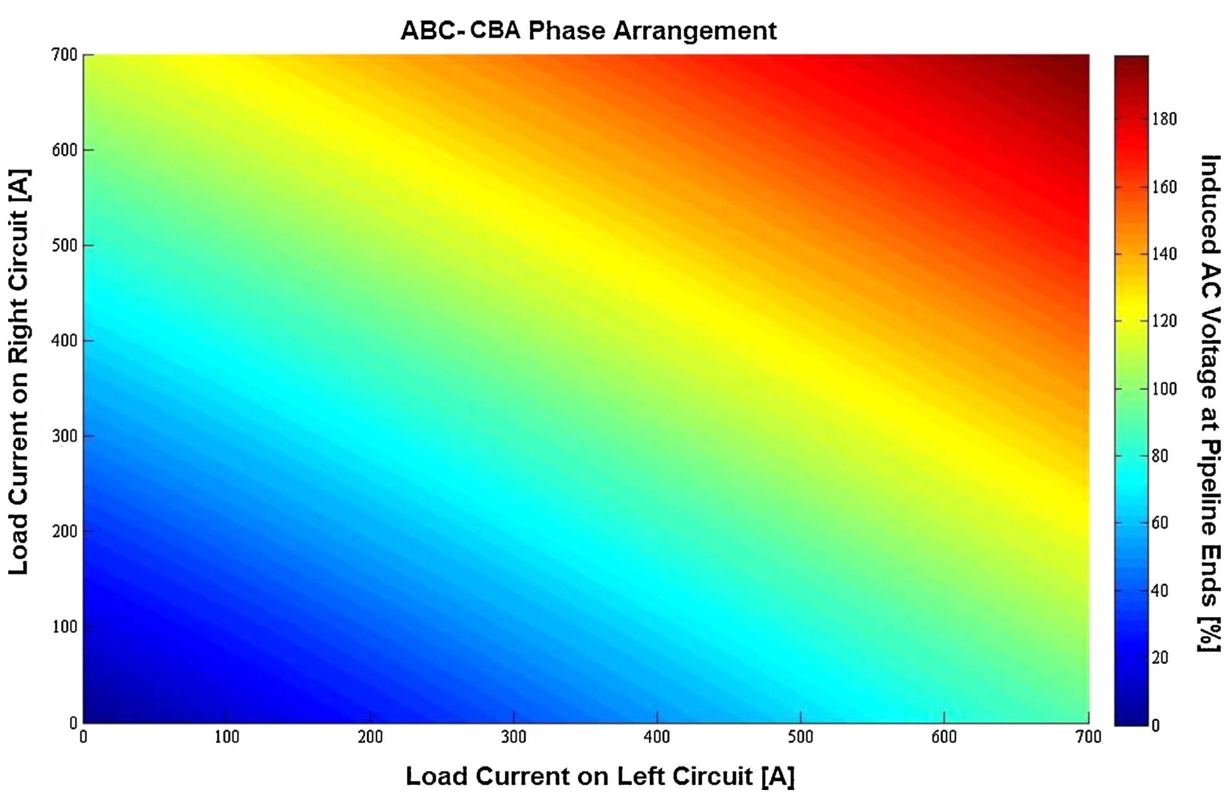

Fig. 8. Induced AC voltage variation at pipeline ends with EPL current load in 'ABCCBA' phase arrangement, with respect to symmetrical 350 A loading in both circuits.

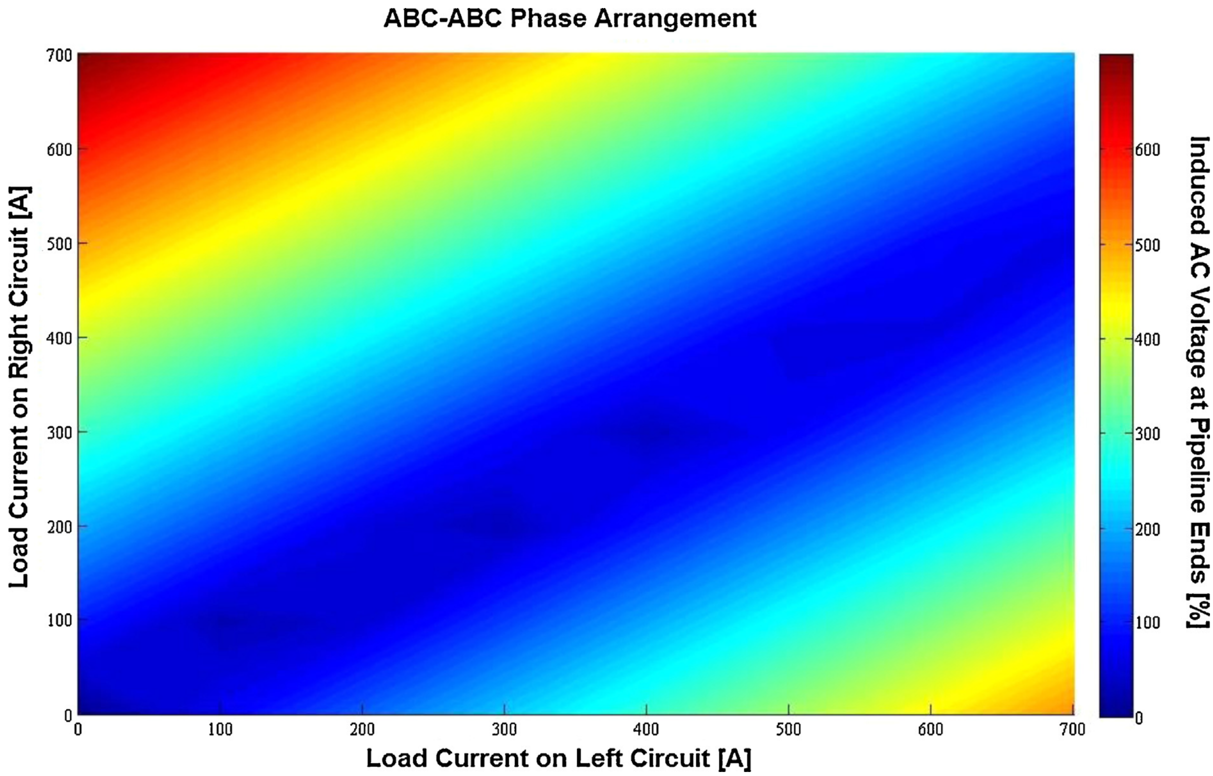

Fig. 9. Induced AC voltage variation at pipeline ends with EPL current load in 'ABCABC' phase arrangement, with respect to symmetrical 350 A loading in both circuits.

active replacing the faulted one. Fig. 8 presents the induced AC voltage level on the pipeline for different load currents, compared to the case when both circuits have the same symmetrical current load of 350 A.

Observing Fig. 8, for the super bundle phase arrangement, both power line circuits have the same behavior: an increase of the current load in any circuit produce a proportional increase of the induced voltage value. The right side circuit though, being closer to the pipeline, has a greater influence on the induced voltage than the left side circuit.

A similar study for the low reactance bundle, 'ABCABC' phase arrangement is depicted in Fig. 9. The induced voltage on the pipeline is calculated when the symmetrical load current in both power line circuits is varied from 0 A to 700 A. Results are compared to the normal operating condition when both circuits are symmetrically loaded with 350 A and the same phase arrangement is applied.

Analyzing the results from Fig. 9, we can conclude that the current loads in the power line circuits have opposite influence on the induced voltage level. An increase of the right side circuit current load produce an increase of the induced voltage level, while an increase in the left side circuit produce a decrease of the induced voltage. Actually, the left side circuit's current load is compensating the influence of the right side circuit. The minimum value of the induced AC voltage in the pipeline is obtained if the left side circuit current load reaches 125% of the right side circuit current load. After that the induced voltage starts to increase with the left side circuit load.

Moreover, one should be extremely careful when doing calculations in case in which the exact phase arrangement is taken into consideration. In the case of the left circuit being lightly loaded comparing to the right one, large differences are observed when compared to the case of symmetrical and equal loading of both circuits.

4.4. Unbalanced load study

Studies on electrical power lines [27,28] have shown that unbalanced current loads can occur in power line circuits during normal operating conditions. These unbalanced current loads can have a significant influence on AC interference levels in underground pipelines. In [14] the influence of current unbalance in the closest phase to the pipe for different single circuit power line configurations is evaluated. As a further contribution, this section presents a detailed case study of current unbalance in each phase of the double circuit power line, in order to evaluate the influence of different current unbalances and to identify the worst case, which can occur in normal operating conditions.

Unbalanced current loads on power line circuits are due to different energization conditions on the phase wire and are expressed using the following quality factors, based on symmetrical components of the current phasors: negative-sequence coefficient (k_I^-), zero-sequence coefficient (k_I^0) and total unbalance coefficient (k_I):

$$k_I^- = \frac{I_-}{I_+}\,(\%) \tag{1}$$

$$k_I^0 = \frac{I_0}{I_+}\,(\%) \tag{2}$$

$$k_I = k_I^- + k_I^0\,(\%) \tag{3}$$

Statistical data presented in [29] showed that the unbalance levels are less than 1% for EHV and less than 2% for HV power lines, and usually they are as result of the zero-sequence component. Consequently, the influence of unbalanced current load on induced voltage levels in the underground pipeline is studied when a 2% zero-sequence unbalance is considered in each power line circuit.

Table 1
Phase current values.

Phase wire	Amplitude (A)	Phase (°)
Phase A	357	0
Phase B	346.553	−118.998
Phase C	346.553	118.998

Table 2
Maximum induced voltage in case of different unbalanced current loads.

Unbalance type	Phase arrangement	
	'ABCABC' (V)	'ABCCBA' (V)
No unbalance	10.76	66.08
2% on right circuit	10.58	66.24
2% on left circuit	10.89	66.39
2% on both circuits	10.68	66.56

Table 1 presents the unbalanced current loads for each power line phase considering a 350 A symmetrical current load base.

The maximum induced voltage that appears at pipeline ends, has been evaluated for both low reactance bundle, 'ABCABC' and respectively super bundle, 'ABCCBA' phase arrangements. Table 2 presents the obtained result when no current unbalance is applied, when a 2% unbalance is applied only on right side circuit or only on left side circuit and respectively when the current unbalance is applied to both power line circuits.

From Table 2 it can be observed that in case of the low reactance bundle phase arrangement a 2% current unbalance in the right side circuit produce a 1.75% decrease of the induced voltages in the pipeline, while a 2% current unbalance in the left side circuit produce a 1.25% increase. If the unbalanced currents are applied to both circuits then the effects of current unbalance are compensating each other producing a 0.78% induced voltage increase compared to the situation when no current unbalance was applied. In the situation when the super bundle, phase arrangement was considered, it can be observed that applying a 2% current unbalance to any of the two power line circuits produce an up to 1% increase of the induced voltage in the underground pipeline.

4.5. *Worst case scenario*

Analyzing the results obtained at the previous sections, it has been identified the worst case scenario for normal operating conditions with the same current load on both power line circuits. This is obtained for the super bundle, 'ABCCBA' phase arrangement with a 2% current unbalance due to the zero-sequence component

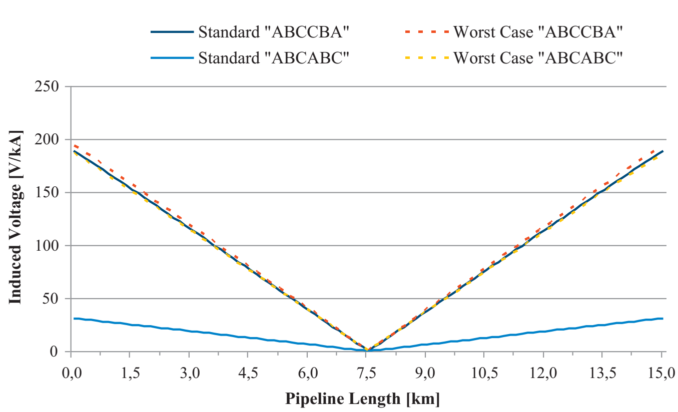

Fig. 10. Worst case scenario for the low reactance and super bundle phase arrangements.

and −24° phase shift between left and right side circuits. Obtained results are presented in Fig. 10 and compared to symmetrical load on both circuits case. The increase of induced AC voltage level in the underground pipeline due to this worst case scenario is around 3%.

For the low reactance bundle, 'ABCABC' phase arrangement worst case scenario is described by a 2% current unbalance due to the zero-sequence component and a 172° phase shift between left and right side circuits. In this case a 507% induced voltage level increase is obtained compared to the symmetrical load on both circuits case. This value represents 98.8% of the induced voltage value obtained for the super bundle phase arrangement situation with the same symmetrical load on both circuits.

5. Conclusions and future work

The electromagnetic interference between a double circuit electrical power line and an underground metallic pipeline has been studied, using a power line–pipeline interference analyses software developed by the authors (*Interfstud*), emphasizing on the influence of some important parameters not covered in detail in literature and identifying the possible worst-case scenario for normal operating conditions.

Studying unbalanced load currents in power line phase wires, the authors concluded that a 1% unbalance might lead to an increase of up to 20% in the induced AC voltage at pipeline ends. Also, a significant over or under estimation of the induced AC interference level may occur if phase shifts higher than 30° between power line circuits are neglected.

However, the most important factor in evaluating the induced AC voltage level is the actual phase sequence on power line towers. In any case, it is proved that selecting a certain phase sequence for an AC interference study may lead to significant computational errors, if phase shifts or unbalanced loading are not taken into consideration at the same time.

Overall, neglecting the influence of the above presented parameters may lead to considerable over or under estimation of induced AC interference in underground metallic pipelines, which can affect the efficiency of chosen protection or mitigation techniques.

Future work would include the generalization of this study by taking into consideration the capacitive coupling between phase conductors of the circuits of the problem. Multiconductor cell analysis could be used to account for both inductive and capacitive coupling simultaneously [30,31]. Moreover, a study including fault conditions, taking into account conductive coupling as well, would provide further insight to the problem. At that case, a detailed investigation of the influence of soil structure would be necessary.

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Appendix A.

Table 3 presents the sky wire and phase wire positions according to earth and tower middle point.

Further electrical and geometrical parameters of the conductors present in the proposed interference case study are given below:

Table 3
Conductors position on tower.

Conductor	Height (m)	Position (m)
Circuit 1 phase 1 (A1)	28.4	3.2
Circuit 1 phase 2 (B1)	22.2	5.3
Circuit 1 phase 3 (C1)	17.2	3.2
Circuit 2 phase 1 (A2)	17.2	−3.2
Circuit 2 phase 2 (B2)	22.2	−5.3
Circuit 2 phase 3 (C2)	28.4	−3.2
Sky wire	33.5	0

Phase wires
- Diameter $\phi = 21.8\,\text{mm}$
- Conductivity $\sigma = 36.5 \times 10^6\,\text{S/m}$
- Relative permeability $\mu_r = 1$

Sky wires
- Diameter $\phi = 8\,\text{mm}$
- Conductivity $\sigma = 3.52 \times 10^6\,\text{S/m}$
- Relative permeability $\mu_r = 250$

Pipeline
- Inner radius $r_i = 0.195\,\text{m}$
- Outer radius $r_o = 0.2\,\text{m}$
- Coating thickness $r_c = 0.1\,\text{m}, \delta_c = 0.1\,\text{m}$
- Conductivity $\sigma = 3.52 \times 10^6\,\text{S/m}$
- Relative permeability $\mu_r = 250$
- Coating resistivity $\rho_c = 10 \times 10^6\,\Omega\,\text{m}$

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