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## Emerald Article: Evaluation of induced AC voltages in underground metallic pipeline

Dan D. Micu, Levente Czumbil, Georgios C. Christoforidis, Andrei Ceclan, Denisa Stet

# Evaluation of induced AC voltages in underground metallic pipeline

Dan D. Micu and Levente Czumbil
*Department of Electrical Engineering, Technical University of Cluj-Napoca, Cluj-Napoca, Romania*
Georgios C. Christoforidis
*Department of Electrical Engineering, Technological Educational Institution of West Macedonia, Kozani, Greece, and*
Andrei Ceclan and Denisa Ştet̡
*Department of Electrical Engineering, Technical University of Cluj-Napoca, Cluj-Napoca, Romania*

## Abstract

**Purpose** – The purpose of this paper is to make a study of electromagnetic interference between electrical power lines and nearby underground metallic pipelines.

**Design/methodology/approach** – The equivalent electrical circuit of the studied electromagnetic interference problem between electrical power lines and nearby metallic pipelines is created and solved using a loop currents technique based on a hybrid method. The used circuit solving technique was implemented in a software application developed by the authors.

**Findings** – The authors have identified the influence of phase sequence on induced voltage level in an underground pipeline for a double circuit electrical power line. Also the effect of different normal operation and phase to earth fault currents have been revealed.

**Practical implications** – The study has been made through a research project with the Romanian gas transportation company, in order to find the proper protection techniques for underground metallic pipelines.

**Originality/value** – The paper reveals the influence of some electrical and geometrical parameters that have not been studied in detail previously.

**Keywords** Electromagnetic induction, Electric power transmission, Pipelines, Double circuit power line, Induced voltage, Phase sequence

**Paper type** Research paper

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## Nomenclature

| *Symbols* | | |
|---|---|---|
| $A_z$[Wb/m] | = | *z*-direction component of magnetic vector potential |
| $J_z$[A/mm$^2$] | = | *z*-direction component of current density |
| $J_{sz}$[A/mm$^2$] | = | source current density |
| $I_i$[A] | = | imposed current on conductor *i* |
| $S_i$[mm$^2$] | = | cross section of conductor *i* |
| $\sigma$[S*m] | = | conductivity |
| $\omega$[Hz] | = | angular frequency |
| $\mu_0$[H/m] | = | free space magnetic permeability |
| $\mu_0$[Wb/m] | = | free space magnetic permeability |
| $\mu_r$ | = | relative magnetic permeability |

| *Definitions, acronyms and abbreviations* | | |
|---|---|---|
| EPL | = | electrical power line |
| ERS | = | electric railway systems |
| MP | = | metallic pipeline |
| MVP | = | magnetic vector potential |

## Introduction

It is well known that in the presence of electromagnetic fields produced by electrical power lines (EPLs) or electrical railway systems (ERS), a.c. voltages are induced in nearby metallic structures. So, in many cases, underground metallic pipelines (MP) are exposed to the effects of induced a.c. voltages. This joint use will create certain electrical hazards and interferences to pipeline facilities, pipeline themselves and to operating personnel, especially if the pipeline is well coated end electrically insulated for cathodic protection purpose (Dawalibi and Southey, 1989).

It must be considered that existing limits imposed by European prEN 50443 Standard Regulation (CENELEC, 2009) are based on maximum admissible fields or induced current inside human body which must be estimated using numerical techniques. Table I presents the limits for the induced a.c. induced voltages for different fault conditions of the EPL (prEN 50443).

To provide a proper protection for operating personnel and pipelines structural integrity, a detailed study of the electromagnetic interference between EPL and nearby underground MP, for different operating conditions, has to be done for each new pipeline placement project or for any existing pipelines exposed to a.c. interference.

This paper studies the electromagnetic interference between a double circuit EPL and a nearby underground gas supply MP. It is analyzed how the induced a.c. voltage in MP varies regarding to different phase wire distribution on EPL towers, for different current loads on the both EPL circuits and in case of a phase to earth fault of the EPL. To evaluate the induced a.c. voltage a hybrid method presented in detail by Christoforidis and Labridis (2005) is used.

| Fault duration t (s) | Induced voltage (RMS value) (V) |
|---|---|
| $t \leq 0.1$ | 2,000 |
| $0.1 < t \leq 0.2$ | 1,500 |
| $0.2 < t \leq 0.35$ | 1,000 |
| $0.35 < t \leq 0.5$ | 650 |
| $0.5 < t \leq 1.0$ | 430 |
| $1 < t \leq 3$ | 150 |
| $t > 3$ | 60 |

**Table I.**
Limits for interference voltage versus earth or across the joints related to danger to people

## The hybrid method

This method combines finite element calculation along with Faradays law and standard circuit analysis.

### *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 (MVP) and $J_z$ of the total current density vector:

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

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

### *Self and mutual inductance calculation*

Using the values of the MVPs, the self and mutual inductances can be calculated using equations (2) and (3). Considering a phase to earth fault which appears in one of phase wires, all the others being neglected, and imposing a certain base fault current on one of the faulted phase (for example $\bar{I}_{Fb} = 1,000A$), with the pipeline current $\bar{I}_P$ set equal to zero, the mutual faulted phase – pipeline inductance can be evaluated using the relation presented by Christoforidis and Labridis (2005):

$$L_{mut} = \frac{\bar{A}_z \cdot l_m}{\bar{I}_{Fb}} \tag{2}$$

where $\bar{A}_z$ 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 $\bar{I}_{Pb} = 1,000A$, with the phase wire current set to zero:

$$L_{self} = \frac{\bar{A}_z \cdot l_m}{\bar{I}_{Pb}} \tag{3}$$

Applying one by one the imposed current on each of the metallic structures present in the studied EPL-MP interference problem, the self and mutual inductance matrix, which describe the inductive coupling between EPL and MP, can be calculated.

### *Equivalent electrical circuit*

After determining the self and mutual inductances corresponding to the studied EMI problem, a generalized equivalent electric circuit is constructed, as shown in Figure 1.

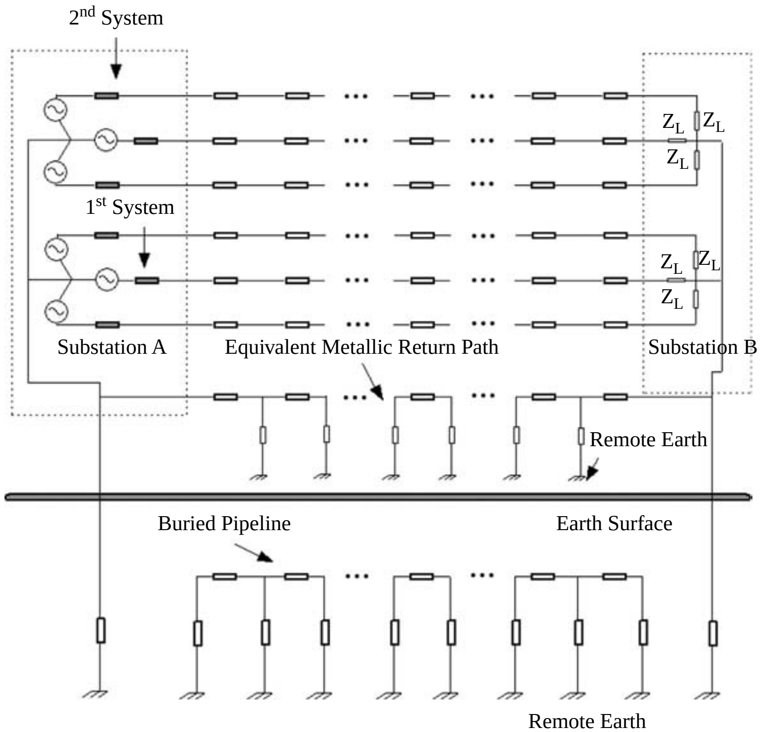



**Figure 1.**
Equivalent electrical model

This electrical circuit model can be solved with any known electrical circuit theory method, to obtain the induced a.c. potentials in MP (Christoforidis and Labridis, 2005; Micu and Czumbil, 2009) (Figure 2).

A dedicated software application, intended for academic/research use, was implemented by the authors to build and solve the equivalent electrical circuit model of any EPL-MP electromagnetic interference problem. The *InterStud* EMI software implements a loop currents based algorithm to solve the equivalent electrical circuit defined by the inductive and capacitive coupling between EPL and MP. In case of underground pipelines due the screening effect of the earth against electric fields the capacitive coupling is not present.

## Electromagnetic interference problem

To study the induced a.c. voltages in an underground MP, exposed to the electromagnetic field generated by a double circuit EPL the following EPL-MP interference problem is proposed: an underground metallic gas supply pipeline shares, for 15 km, the same distribution corridor with a 110 kV/50 Hz double circuit power line. The gas pipeline is buried at a depth of 2 m, the soil is considered homogenous with a resistivity of 100 Ωm and the separation distance between EPL and MP is 30 m. A symmetric load of 300 A on each phase of the double circuit power is considered as normal operating condition. Figure 3 shows the cross section of the common distribution corridor.

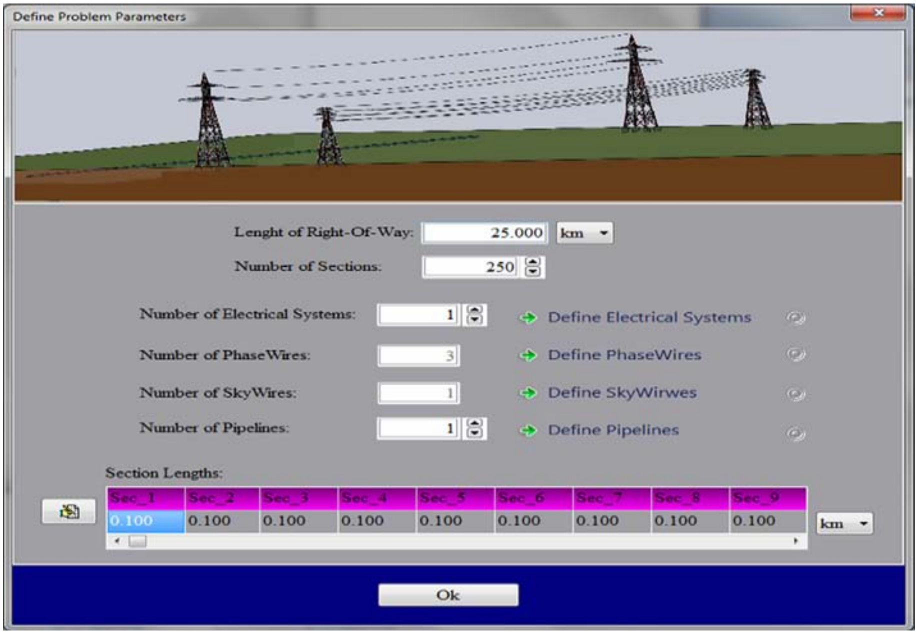



**Figure 2.** Interface of the implemented software

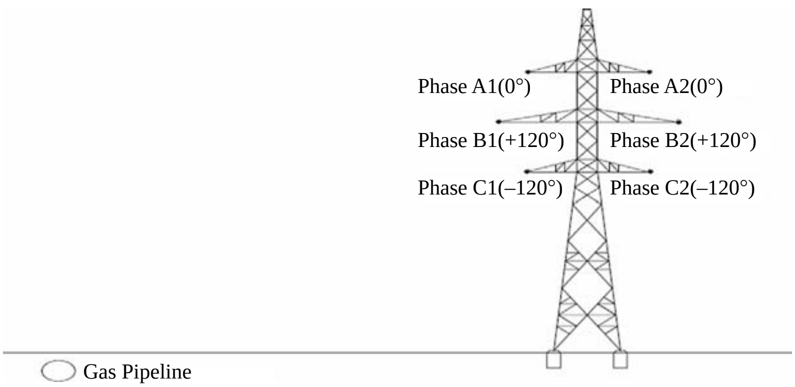



**Figure 3.** Cross section of the common distribution corridor

## Induced a.c. voltage analysis

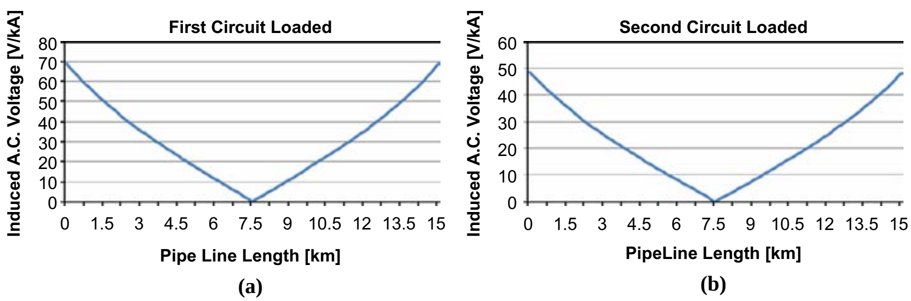
For the proposed EPL-MP electromagnetic interference problem the induced a.c. voltages are studied in case of different phase wire distribution on EPL towers, in case of different current loads on both EPL circuits and in case of a phase to earth fault, which appears far away from the common distribution corridor.

*Phase sequence study*

For a start it is considered that only one circuit is in use and the other one is a reserve line. Considering the left side circuit being the active one, with normal operating symmetrical current load of 300 A, and the right side circuit being the passive one, the induced a.c. voltage is evaluated with the presented hybrid method. An ABC phase distribution is considered on the pylon, like in Figure 3 (where phase A is at 0°, B is at 120° and C is at 240°). After that the right side circuit is considered to be the active one and the left side circuit the passive one. In order give an estimation for other symmetrical loads Figure 4 shows the induced a.c. voltage reported to kA of current load for both cases when the left side circuit is active and, respectively, when the right side circuit is active.

It can be observed that the maximum level of induced a.c. voltage is obtained at the ends of the distribution corridor, where the pipeline is electrically isolated for cathodic protection purpose. The induced voltage obtained in the second case not exceed the maximum value from the first case, because the separation distance between pipeline and active phase wires is bigger and the passive phase wires work like mitigation wires for the pipeline.

If both circuits are loaded and a symmetrical current load of 300 A is considered in each phase of the two circuits with a basic ABC-ABC phase distribution on EPL towers, then the induced a.c. voltage in the underground MP is almost double than the cases when only one of circuits was loaded. In this case the maximum induced voltage level reaches 34.5 V. Figure 5 shows the reported induced voltage levels along the pipeline length.




**Notes:** (a) left circuit is loaded; (b) right circuit loaded

**Figure 4.**
Induced a.c. voltage in normal operating conditions

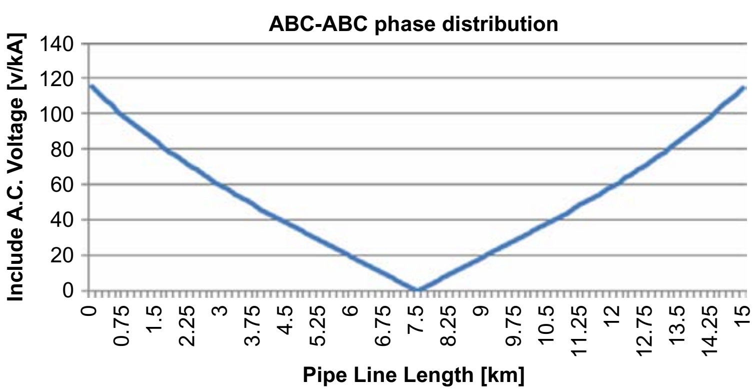
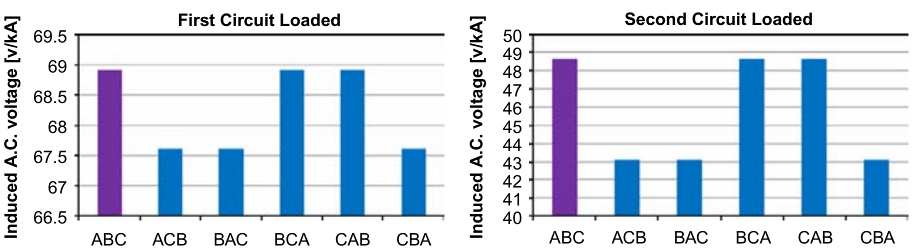



**Figure 5.**
Induced a.c. voltage in normal operating conditions (both circuits are loaded)

Studies of the electric and magnetic field around double circuit power lines show that these are considerably influenced by phase wire distribution on EPL towers (by phase sequence). Mazzanti showed that the variation between two different phase sequences can be up to 45 percent (2006). Therefore, it should be studied what is the direct effect of different phase distributions on the induced a.c. voltages in underground MP.

Figure 6 shows the maximum induced a.c voltage obtained at pipeline ends for all the possible phase distribution cases, when the left side circuit is active and the right side circuit is passive, respectively, when the right side circuit is active and the left side circuit is passive. There are only two different values, one for a positive order phase sequence (ABC, BCA or CAB) and another one for a negative order phase sequence (ACB, BAC or CBA). In case of the left side circuit being active the difference between the values obtained for the two different phase sequences, is negligible, so any of the presented cases could be considered appropriate. However, in case when the right side circuit is the active one the difference between the phase sequence is quite considerable so no more the phase distribution on EPL towers can be neglected negligible, any of the presented cases could be considered appropriate.

Figure 7 shows the maximum values of the induced a.c. voltage in MP for any possible different phase sequences when both EPL circuits are loaded with symmetrical normal operating condition current load. It can be observed that the highest induced voltage levels are obtained for basic positive order (ABC-ABC) phase sequence and, respectively, for the negative order (ACB-ACB) phase sequence.




**Notes:** (a) left circuit loaded; (b) right circuit loaded

**Figure 6.**
Induced a.c. voltage for different phase sequences

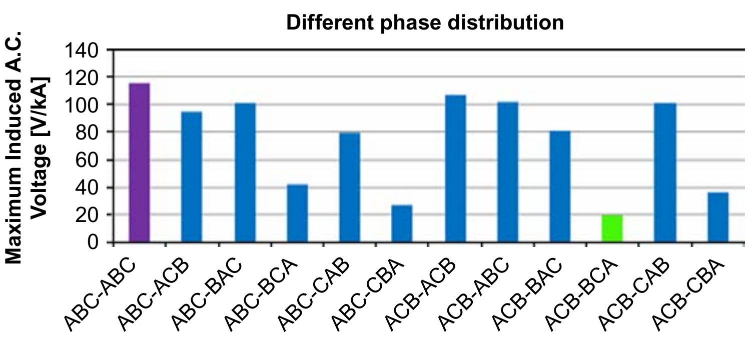



**Figure 7.**
Induced a.c. voltage for different phase sequences (both circuits are loaded)

Meanwhile the lowest induce a.c. voltage levels are obtained for a revers positive order (ABC-CBA) phase sequence and, respectively, a revers negative order (ACB-BCA) phase sequence. This is similar with the values of the magnetic field presented by Mazzanti (2006a, b).

Analyzing the presented results the authors concluded that neglecting the phase distribution on EPL towers can result in overestimating the real values of induced voltages between 10 and 75 percent. Also the authors propose the use of an optimal reverse order (ACB-BCA) phase distribution on EPL towers in order to reduce the magnetic fields generated by EPL and the induced a.c. voltages in nearby underground MP.

*Current load study*

As a second objective, it was studied the influence of different current loads for the two circuits of the EPL, in case of the basic and the optimal phase distribution on pylons. A normal operating condition of a 300 A symmetrical current load was considered as a 100 percent load for each circuit. First the right side circuit (Figure 3) was kept at 100 percent (300 A) current load and the left side circuit was varied from 85 percent (255 A) to 115 percent (345 A) current load with a 5 percent (15 A) step. Then the left side circuit was kept at 100 percent current load and the right side circuit was varied from 85 to 115 percent current load.

Figure 8 shows the maximum induce a.c. voltage levels obtained for different symmetrical current loads in case of the basic phase distribution on EPL towers. Results are compared to the case when a 100 percent current load is applied to both EPL circuits. It can be seen that the induced voltage level in MP is proportional to the current load in the two EPL circuits. When the value of the current load increases in any of the two EPL circuits, the induced a.c. voltage rises as well in the underground pipeline.

For the optimal phase distribution if the left side circuit current load is increased than as it was expected the induced a.c. voltage in MP is increased. But while for the basic phase sequence a 5 percent current load increase created a 3 percent induced voltage increase, in this case a 5 percent current load increase creates a 17 percent increase in the induced voltage level. Meanwhile an increase of the right side circuit current load produce a decrease of the induced voltage level. This is a result of the fact that actually, the right side circuit is compensating the influence of the left side circuit on the underground MP (Figure 9).

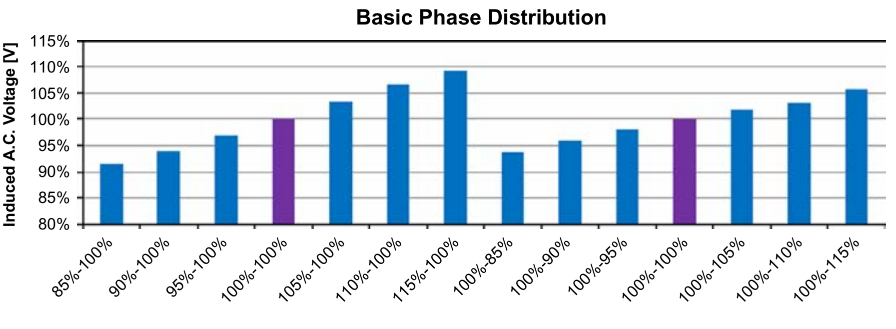



**Figure 8.**
Induced a.c. voltage variation with EPL current load (basic phase distribution)

*Phase to earth fault study*

The third objective of this paper is to study the influence of a phase to earth fault of the EPL on the induced a.c. voltage. It is considered that a phase to earth fault appears far away from the common distribution corridor, so that the conductive coupling between EPL and MP can be neglected as well as in normal operating condition (Figure 10).

In Figure 11 it is shown the induced voltage in underground pipeline reported to the fault current, if the phase to earth fault appears on phase A of the left side circuit

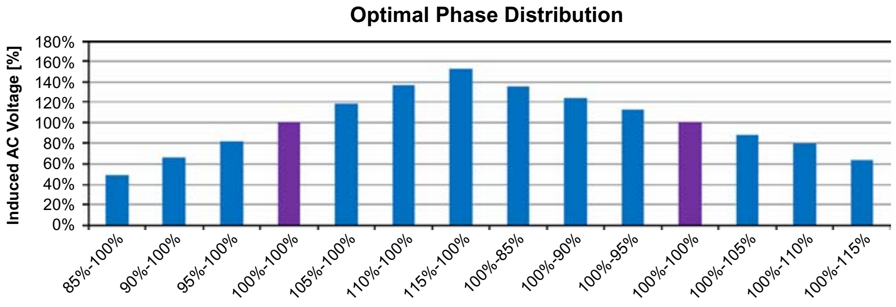



**Figure 9.**
Induced a.c. voltage variation with EPL current load (optimal phase distribution)

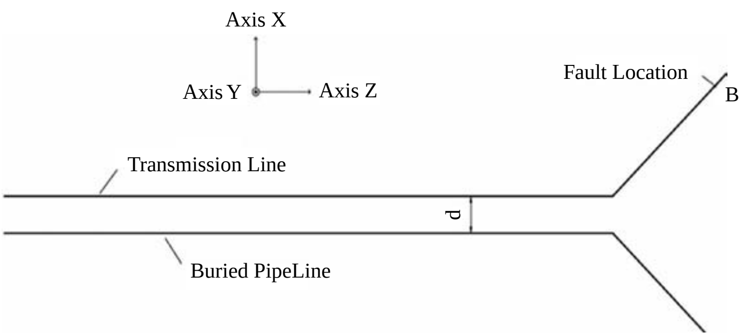



**Figure 10.**
Top view of the parallel exposure – phase to earth fault

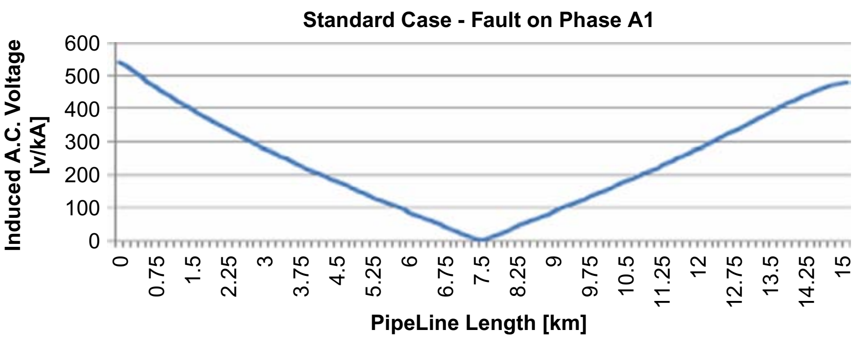



**Figure 11.**
Induced a.c. voltage in case of a phase to earth fault

(phase A1). Both circuits are loaded and a basic phase distribution on EPL towers is used. Phase A1 is considered to be loaded with an 1,500 A fault current and all the other phases with normal operating condition 300 A load currents, so the induced a.c. voltage in MP is around 820 V, at the ends of the MP.

To study the effects of different phase to earth faults, the 1,500 A fault current was imposed one by one in each phase of the two EPL circuits for both the basic and the proposed optimal phase sequence. The obtained results revealed the fact that in case of a phase to earth fault, phase distribution on EPL towers has insignificant influence on induced voltage levels. A greater influence it has the relative position of the faulted phase according to the underground MP (Figure 12).

Detailed studies of phase to earth faults have revealed that if the current load in the unfaulted phases are neglected when the induced voltages are evaluated than the obtained results are 30 percent higher than in case when this load currents were taken into consideration. This is a result of the fact that the current loads in the unfaulted phases compensate the effects of the faulted phase load current.

## Conclusion

The aim of the paper was to realize a detailed study of the induced a.c. interferences in an underground metallic pipeline exposed to the magnetic field created by a double circuit electrical power. In order to could be provided a proper protection to operating personal and MP's structural integrity the induced voltage was evaluated using a hybrid method.

Analyzing different phase distributions on EPL towers it is observed that using a proper phase distribution the induced a.c. voltage in MP can be reduced significantly. A reverse order ACB-BCA phase distribution is proposed to be used.

In case of different current loading applied on the two circuits, if the proposed reverse order phase distribution is used, then the current load in the right side circuit has a compensating effect over the left side current load influence. A minimum value of the induced a.c. voltage is obtained when right side current load reaches 120 percent of the left side current load.

If a phase to earth fault appears, the induced a.c. voltage in the underground metallic pipeline depends more on the relative distance between the faulted phase and pipeline, than on the phase distribution on EPL towers.

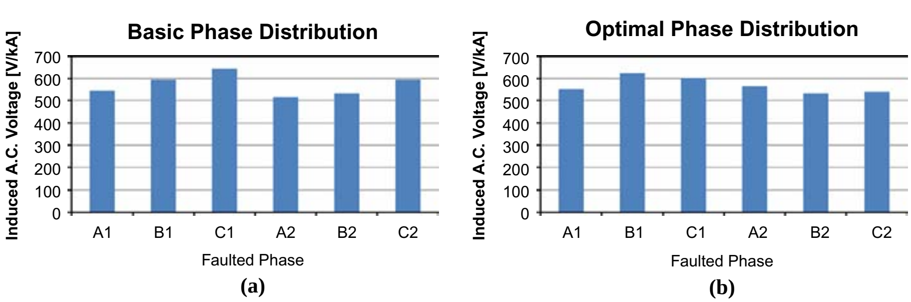



**Figure 12.**
Induced a.c. voltage for different phase to earth faults

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**Corresponding author**
Dan D. Micu can be contacted at: Dan.Micu@et.utcluj.ro