An Investigation of Harmonic Induced Voltages on Medium-Voltage Cable Sheaths and Nearby Pipelines

T. A. Papadopoulos, I. P. Chaleplidis, A. I. Chrysochos, G. K. Papagiannis, K. Pavlou

***Abstract*--This paper investigates the impact of harmonics in underground medium-voltage cables to the induced voltages on the cable sheaths of the excited system as well as the corresponding electromagnetic interference (EMI) to nearby coated pipelines. To evaluate systematically the harmonic induced voltages on both cable sheaths and pipelines a benchmarking analysis is first carried out using the EMTP-RV software. The accuracy of different simulation models is also investigated. The feasibility and practical application of this paper is examined in a cable system excited by current harmonics using data obtained from measurements of the recent relative literature.**

***Keywords*: Cable sheaths, electromagnetic interference, harmonics, induced voltages, pipelines.**

I. Introduction

THE increased use of power electronic-based devices in power systems has raised the scientific interest in harmonic pollution problems [1]. Harmonics cause a series of issues, such as additional conductor and equipment losses, overloading of reactive power compensation capacitors, malfunction of circuit breakers, errors in electric power and energy measurements, and induced voltages to nearby metallic parts [1], [2].

Specifically, harmonics flowing in underground transmission and distribution systems may cause additional to the 50 Hz/60 Hz (fundamental frequency) current, ohmic losses and possible hazardous overvoltages in cable sheaths, as well as electromagnetic interference (EMI) to nearby metallic parts, e.g. pipelines. Both of the above issues have been thoroughly investigated in the literature, regarding induced voltages at the fundamental frequency [3]-[8], whereas only recently harmonic voltage induction has attracted the scientific interest. Harmonic voltage induction, due to the electromagnetic coupling of parallel overhead transmission lines was first referred in [9]. Similar investigations were also carried out in [10], regarding the coupling of voltages and currents on voltage-source converter (VSC)-HVDC overhead transmission lines from neighboring ac lines. Induced harmonic voltages on buried pipelines caused by transmission or distribution lines have been analyzed in [2], through field measurements [11] and circuit-model analysis. Additionally, electromagnetic interference (EMI) issues on pipelines, due to harmonics from a.c. electrified traction systems was holistically assessed in [12].

Additionally, the rapid development of renewable energy sources (RES) in power systems has increased the scientific interest on EMI issues, since such problems may exist in areas of large photovoltaic parks or wind-parks to the grid, where gas, oil or irrigation metallic pipelines may exist [8]. In most of these cases, for the internal network and/or the connection of the RES installations to the grid underground cables are used. There are only few works presenting some preliminary EMI results caused by underground cables to nearby pipelines, but only regarding the fundamental frequency, while there are no similar works about harmonic induction effects. In fact, current harmonics may cause increased voltages, since induced voltages increase with frequency, according to Faraday's law and the zero-sequence pattern of the triplen currents; triplens are harmonics of odd multiples of 3, e.g. 3^{rd}, 9^{th}, 15^{th}, etc..

This paper investigates, for the first time according to the authors' knowledge, the impact of harmonic voltage induction in underground cable systems of distribution networks. The work focuses on the induced voltages and currents on cable sheaths and nearby coated pipelines, the latter being located in the vicinity of the excited cable system. To evaluate systematically EMI due to the presence of harmonics, a benchmarking analysis is carried out. Using this benchmark, the accuracy of different simulation models is also investigated. The feasibility of this research is examined in a cable system excited by current harmonics using data obtained from measurements of the recent literature [2].

II. Problem Assumptions

In general, there are three types of EMI, named as electromagnetic or inductive coupling, electrostatic or capacitive coupling, and resistive or conductive coupling [4]-[7]. In detail:

- The calculation of inductive coupling is the most

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investigated mechanism. Regarding power cables, the nominal and the equivalent pi models (exact) are used, while specifically for pipeline arrangements analytical formulations and numerical simulations have been proposed.

- Electrostatic coupling is mainly examined in cases of cables and pipelines located above the ground. In the case of underground systems, e.g. pipelines, electrostatic coupling is negligible at low frequencies, since earth behaves as a perfect conductor [14]. Therefore, regarding power cables, electrostatic coupling is considered only by means of the insulation between cable conductor and sheath.
- Conductive coupling refers to buried metallic conductors exposed to voltage stress when earth potential rise (EPR) occurs, with respect to remote earth. EPR is caused by earth return currents of ground faults and thus is not considered in the current analysis.

In this study, only the inductive coupling is considered regarding the calculation of the harmonic voltages of the cable sheaths and the pipeline.

III. Cable Types and Configurations

Two typical MV underground cable arrangements, namely the trefoil and the horizontal formation are examined, as shown in Fig. 1 [15]. In both arrangements, the cable system consists of a group of three identical MV single-core (SC) cables of type NA2XSY/12/20 kV, 3x95 mm^2 with copper conductors, XLPE main insulation, shield of copper wires and PVC jacket. The properties of the MV cable system are given in Table I. The cables are laid in a 1.0 m depth ditch and the cable sheaths are grounded at both ends through 1 Ω resistances. The cable spacing for the horizontal arrangement is s = 0.15 m. In Fig. 1, the reference of horizontal position (y = 0 m) for the two arrangements is depicted as well as the cable phases. Parallel to the cable system, a metallic gas/oil coated pipeline is assumed. The pipeline has a separation distance d = 1 m from y = 0 m for both cable arrangements. The properties of the pipeline are illustrated in Fig. 2.

The cable system has a length of l = 4000 m. The pipeline is modelled in EMTP-RV with the same length as the cable system, though terminated at both ends to the corresponding characteristic impedance, i.e. 152 Ω, as shown in Fig. 3. Therefore, the pipeline in fact represents a very long line. Homogeneous earth is considered in all cases with soil resistivity and relative permittivity equal to 100 Ω·m and 10, respectively. The above cable and geometry properties constitute the examined base case scenario.

For the simulation of the harmonic induced voltages on the cable sheaths and the pipeline, frequency domain scans are performed using the EMTP-RV software [13]. The nominal pi, exact-pi, and wideband (WB) cable models are considered. Although the examined problem refers to steady-state analysis, the WB model is used since it can be used in time-domain simulations of harmonic distorted voltage and current waveforms. On the other hand, the equivalent-pi is widely adopted for the investigation of EMI problems by means of circuit analysis. The per-unit-length parameters, i.e. self and mutual resistance, inductance and capacitance of the cable system and the pipeline are formulated in a 7x7 matrix.

TABLE I
Cable Data

Parameter	Value
Core conductor radius	0.55 cm
Core conductor /sheath resistivity	$1.7\cdot10^{-8}$ Ω·m
Core conductor / sheath permeability	1
Sheath inner radius	1.3 cm
Sheath outer radius	1.33 cm
Total radius	1.52 cm
Insulation permittivity	2.71
Jacket permittivity	2.3
Insulation / Jacket permeability	1

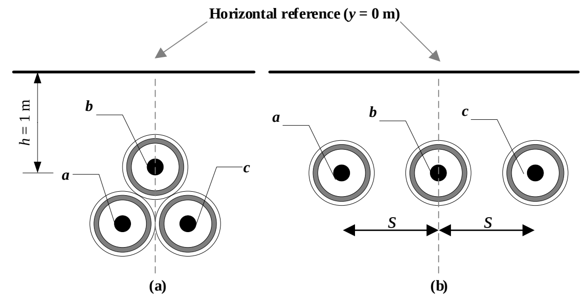

Fig. 1 MV cable in a) trefoil and b) horizontal arrangement.

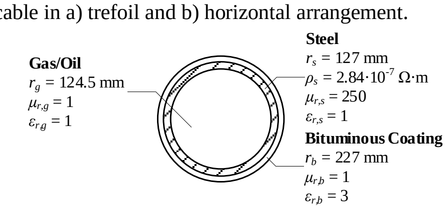

Fig. 2 Geometry and electromagnetic properties of the coated pipeline.

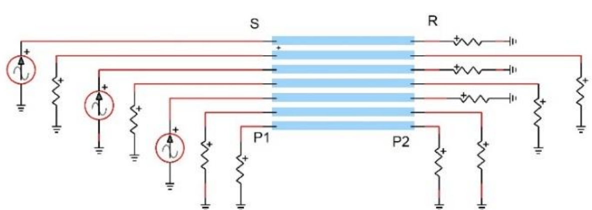

Fig. 3 EMTP-RV simulation model.

IV. Benchmarking Analysis

A. Theoretical analysis

For benchmarking, the harmonic induced voltages at the cable sheaths as well as at the pipeline are simulated using the exact-pi model in EMTP-RV. The properties of the base case scenario are considered. The main objective of this analysis is to resolve and compare the impact of each harmonic on the induced voltages in a consistent way. The cable system is excited by odd harmonic currents of the 1^{st} (60 Hz) to 15^{th} order, by applying sequentially the corresponding current sources at cable end S. Each injected current harmonic has 1 pu magnitude. The phase sequence of the harmonics follows the positive-zero-negative sequence pattern, starting from the 1^{st} and followed by the 3^{rd}, 5^{th} and so on. Therefore, harmonics of order 1, 7 and 13 are positive sequence, harmonics of order 3, 9 and 15, i.e. triplen harmonics, are zero sequence and of order 5 and 11 are negative sequence.

To provide in-depth understanding of the influence of individual system components on the harmonic induced voltages, the theoretical background of [16] is adopted. The harmonic induced voltage along a distributed-parameter line (L) at a distance x from its sending end caused by a single power line (C) carrying a current $\mathbf{I}_h$ of harmonic order h can be approximated by [16]:

$$\mathbf{V}_{x,h} = \frac{(R_1 + R_2)\cdot \mathbf{z}_h \cdot x - R_1 \mathbf{Z}_h}{R_1 + R_2 + \mathbf{Z}_h} \cdot \left(-\frac{\mathbf{z}_{m-h}}{\mathbf{z}_h} \mathbf{I}_h \right) = \mathbf{K}_h \cdot \mathbf{I}_h \,, \qquad (1)$$

where R_1 and R_2 are the grounding resistances at the ends of line L, $\mathbf{z}_h$ is the series impedance of line L, $\mathbf{z}_{m\text{-}h}$ is the mutual impedance between lines L and C and $\mathbf{Z}_h = \mathbf{z}_h \cdot \ell$, where ℓ is the total length of line. Therefore, the total induced voltage $\mathbf{V}_{xtot}$ caused from a three-phase system will be given as the vector sum of the resulting voltages $\mathbf{V}_{xA,h}$, $\mathbf{V}_{xB,h}$ and $\mathbf{V}_{xC,h}$ corresponding to each current:

$$\mathbf{V}_{x-tot,h} = \mathbf{V}_{xA,h} + \mathbf{V}_{xB,h} + \mathbf{V}_{xC,h}\,. \qquad (2)$$

Specifically, the induced voltage for positive, zero and negative sequence harmonics can be described in generic form by (3), (4) and (5), respectively.

$$\mathbf{V}_{xtot_{pos},h} = \mathbf{K}_{A,h} \cdot I_A \angle 0^o + \mathbf{K}_{B,h} \cdot I_B \angle -120^o + \mathbf{K}_{C,h} \cdot I_C \angle 120^o, \quad (3)$$

$$\mathbf{V}_{xtot_{zero},h} = \mathbf{K}_{A,h} \cdot I'_A \angle 0^o + \mathbf{K}_{B,h} \cdot I'_B \angle 0^o + \mathbf{K}_{C,h} \cdot I'_C \angle 0^o, \qquad (4)$$

$$\mathbf{V}_{xtot_{neg},h} = \mathbf{K}_{A,h} \cdot I''_A \angle 0^o + \mathbf{K}_{B,h} \cdot I''_B \angle 120^o + \mathbf{K}_{C,h} \cdot I''_C \angle -120^o. \quad (5)$$

B. *Simulation of induced voltages*

The profiles of the harmonic induced voltages of the cable sheath at phase *a* and of the pipeline for both cable arrangements are presented in Figs. 4 and 5, respectively. Note that in this case 40 exact-pi equivalents of 100-m are used in cascaded form. The induced voltages at the two ends for all harmonic orders present a phase shift of 180°, as results also from (1)-(5), assuming $R_1 = R_2$ and $x = \ell$. Due to this phase shift, the harmonic voltage profiles along the sheath as well as along the pipeline acquire maximum values at the ends, while at the middle, i.e. at $x = \ell/2 = 2000$ m, becomes zero. The lower harmonic induced voltages at the cable sheath compared to that of the pipeline are due to the lower value of the grounding resistance, since the pipeline is terminated at 152 Ω.

In Fig. 6, the harmonic induced voltages at the end *R* of the cable sheaths of the horizontal cable arrangement are summarized by means of a bar chart. It is shown that the induced sheath voltages of each phase differ slightly for each harmonic. The phase where the highest value is observed differs with the harmonic order. Specifically, for the positive, zero and negative sequence harmonics the highest values are obtained in phase *c*, *b* and *a*, respectively. The induced sheath voltages for the trefoil arrangement are similar at all cable phases, thus results only of phase *a* are considered in the analysis.

To investigate the influence of the harmonic order on the induced sheath voltages, results at the end *R* of the cable sheath at phase *a* for the horizontal and the trefoil cable arrangements are compared in Fig. 7. For both cable arrangements the induced sheath voltages of the same sequence, increase slightly with the harmonic order by means of the Faraday law. For example, for triplen harmonics the induced sheath voltage of the 15th harmonic acquires the highest values followed by the 9th and finally the 3rd.

Moreover, it is evident that in the horizontal cable arrangement the induced sheath voltages of the positive and negative sequence are significantly higher compared to the trefoil case. This is due to the geometric asymmetry in the horizontal arrangement, resulting into different mutual coupling from each current currying conductor and thus by means of (3) and (5) to consequently higher magnetic field levels and induced voltages. On the other hand, the harmonic induced voltage levels of the triplen harmonics are slightly lower in the horizontal arrangement compared to the corresponding of the trefoil. Due to the zero-sequence pattern of triples, the total harmonic induced voltage of (4) in this case is actually the algebraic sum of $\mathbf{V}_{xA}$, $\mathbf{V}_{xB}$ and $\mathbf{V}_{xC}$. Therefore, since each of the $\mathbf{V}_{xA}$, $\mathbf{V}_{xB}$ and $\mathbf{V}_{xC}$ acquires higher values in the horizontal arrangement compared to the trefoil, due to the larger cable spacing, it is evident that the induced sheath voltages of the 3rd and odd multiples will be higher in the latter case.

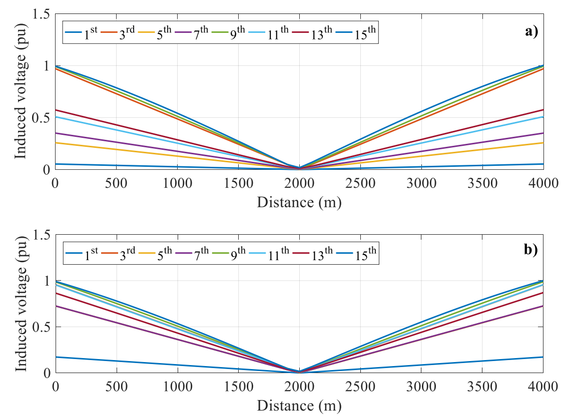

Fig. 4 Harmonic induced voltage profiles along the cable sheath *a* for a) trefoil and b) horizontal cable arrangements.

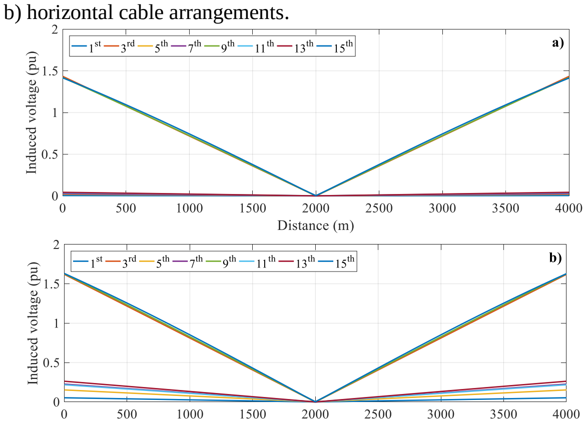

Fig. 5 Harmonic induced voltage profiles along the pipeline for a) trefoil and b) horizontal cable arrangements.

Similarly, in Fig. 8, the harmonic induced voltages at end P_2 of the pipeline are analyzed. High harmonic induced voltages are observed for the 3rd harmonic and its odd multiples, exceeding significantly the corresponding voltage levels excited by the positive and negative sequence harmonics. This is due to the fact that, since the pipeline is located at a distant point away from the cable system, i.e. the source of the EM field, the induced voltage caused by a symmetrical positive or negative sequence is almost eliminated by means of the vector sum of the total flux density, as described by (3) and (5).

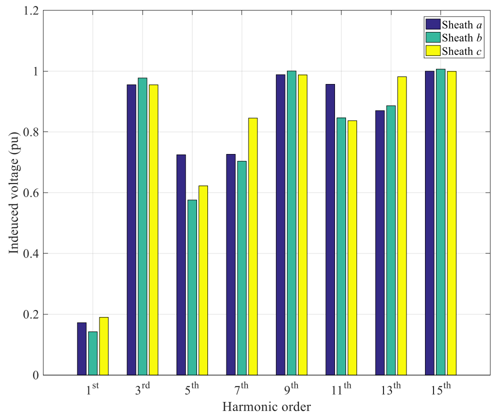

Fig. 6 Harmonic induced voltages at end *R* of cable sheaths for the horizontal arrangement.

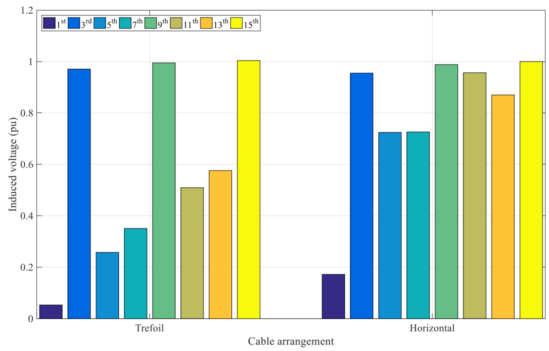

Fig. 7 Harmonic induced voltages at end *R* of cable sheath *a*. Different cable arrangements.

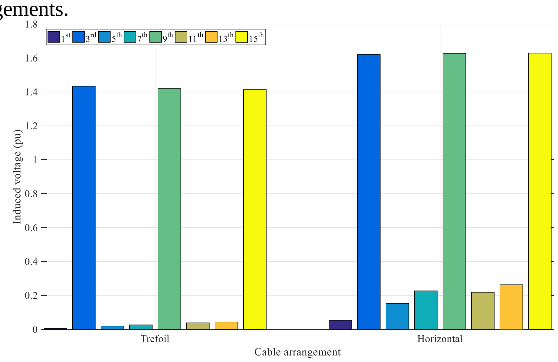

Fig. 8 Harmonic induced voltages at end P_2 of the pipeline. Different cable arrangements.

C. Comparison of simulation models

The exact-pi model is used for the accurate calculation of the induced voltages in cable configurations, since the model results are based on the exact solution of the distributed parameter transmission line equations [15].

Additionally, the accuracy of the WB and the nominal-pi cable models available in EMTP-RV and ATP-EMTP is also evaluated. The nominal-pi is a simplification of the exact-pi and can be used for the analysis of electrically short cables, i.e. at low frequencies and short lengths [15]. The WB model uses complex poles and zeros for the rational approximation of the frequency-dependent characteristic admittance and wave propagation matrices; it also takes into account the frequency dependence of the modal transformation matrix. Thus, can be considered as the most accurate time-domain model, especially for underground cable systems modelling [15]. In all simulations, the fitting process of the relevant WB transfer functions is performed in the frequency range from 0.01 Hz to 100 kHz using 50 poles and convergence tolerance 0.01.

The relative difference defined in (6) is calculated for the results obtained by the WB and the nominal-pi models, assuming the exact-pi as reference.

$$diff\,(\%) = \left|V_{WB/nominal-pi} - V_{exact-pi}\right| / V_{exact-pi} \,. \qquad (6)$$

In Figs. 9 and 10 the resulting relative differences of the calculated induced voltages of the cable sheath at phase *a* and at the pipeline are compared, respectively. Results reveal that the nominal-pi model and the WB match very accurately the exact-pi solution for all harmonic orders. This is more evident for the induced sheath voltages, since differences are lower than 1.5 % in all cases. Regarding the induced harmonic voltages at the pipeline, for the nominal-pi model differences increase slightly with the harmonic order. By analyzing the results obtained by the WB model, differences are observed only at specific frequencies, though they do not surpass 6 %; the differences are mainly attributed to the error introduced in the fitting of the WB transfer function. Therefore, it can be generally concluded that both the WB and the nominal-pi models can be used for the accurate calculation of the harmonic induced voltages on cable sheaths and pipelines for the examined frequency range and for cable lengths up to 4 km.

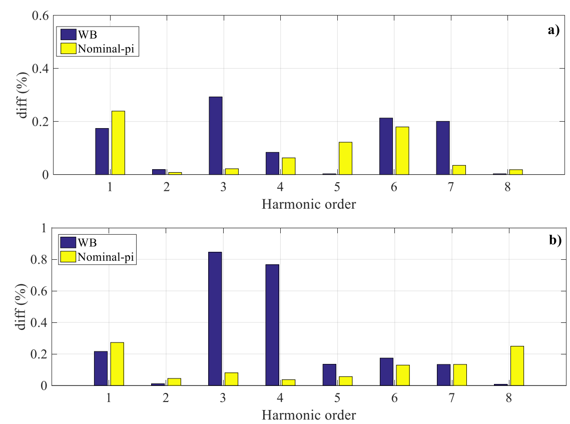

Fig. 9 Comparison of the harmonic induced voltages at end *R* of cable sheath *a* for a) trefoil and b) horizontal cable arrangements.

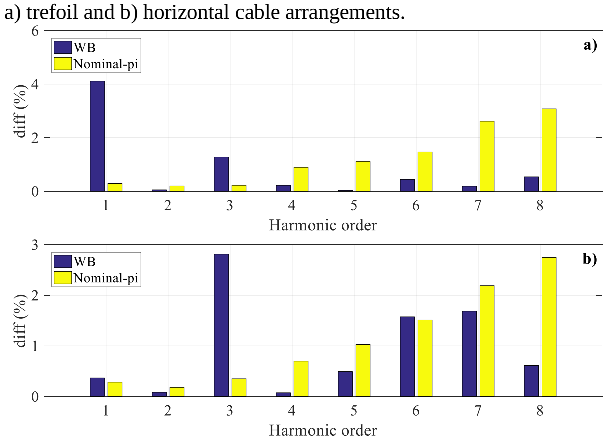

Fig. 10 Comparison of the harmonic induced voltages at end *R* of the pipeline for a) trefoil and b) horizontal cable arrangements.

V. RESULTS WITH MEASURED DATA

To investigate the impact of harmonics on the induced voltages on the cable sheaths and the pipeline, considering measured harmonic currents, the data of Table I are used. Table I data are based on field measurements in 14.4 kV and 25 kV feeders [2]. In this case the current harmonic magnitudes are significantly lower compared to the fundamental at 60 Hz.

TABLE I: AVERAGE HARMONIC SEQUENCE CURRENTS

Harmonic order	Sequence	Normalized value (p.u.)
1st	Positive	1.000
3rd	Zero	0.070
5th	Negative	0.052
7th	Positive	0.022
9th	Zero	0.016
11th	Negative	0.006
13th	Positive	0.003
15th	Zero	0.002

In Fig. 11 the harmonic induced voltages at the cable sheath *a* and the pipeline are compared for the two cable arrangements for the base case scenario (ℓ = 4000 m).

The induced sheath voltages of the positive and negative sequence are almost eliminated in the trefoil arrangement. On the contrary the 3rd harmonic acquires high levels, exceeding that of the fundamental at 60 Hz. For the horizontal arrangement, the induced sheath voltages of the triplen harmonics are close to the corresponding of the trefoil arrangement, as analyzed in the previous section. However, higher induced voltages are observed for the positive and negative sequence components compared to the trefoil cable arrangement. Moreover, the highest induced sheath voltage level is obtained for the 60 Hz component. These are mainly due to the geometry asymmetry of the horizontal arrangement.

In Fig. 11b, it is shown that in both cable arrangements the 3rd and the 9th harmonic induced voltage on the pipeline is significant, exceeding the corresponding at the fundamental frequency. This is more evident in the trefoil cable arrangement, since the induced voltage at the 3rd and the 9th harmonic is almost 30 and 7 times, respectively, higher than that at the fundamental frequency.

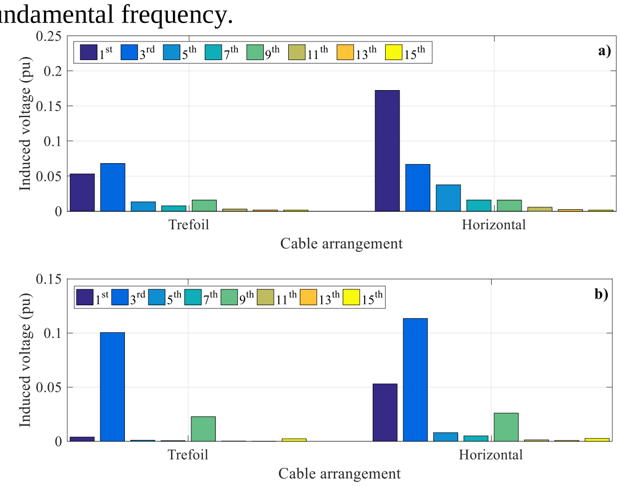

Fig. 11 Harmonic induced voltage levels at a) end *R* of cable sheath *a* and b) at end P_2 of the pipeline. Different cable arrangements.

A. Influence of pipeline separation distance

The influence of the horizontal separation distance *y* is investigated on the harmonic induced voltages at the pipeline ends P_1 and P_2. The separation distance between the examined cable system and the pipeline is assumed varying, from 1 to 50 m, i.e. the interference limit according to [17]. Fig. 12 demonstrates the variation of the induced harmonic voltages at end P_2 for the trefoil and the horizontal arrangements. Similar results are also obtained for node P_1.

Generally, the induced harmonic voltage levels are reduced and are practically eliminated, as *y* increases. However, in the trefoil arrangement the 3rd and the 9th induced voltages as well as the 1st, 3rd and 9th in the horizontal arrangement remain significant even for *y* = 50 m. In both cable arrangements the induced voltage level of the 3rd harmonic is over 4% pu for all examined cases. These voltage levels are higher compared to the corresponding of the fundamental for *y* = 1 m. Specifically, for the horizontal arrangement, it can be observed that for *y* = 1 m the induced voltage at 60 Hz is higher than that of the 9th. However, for *y* greater than 10 m the opposite behavior is observed.

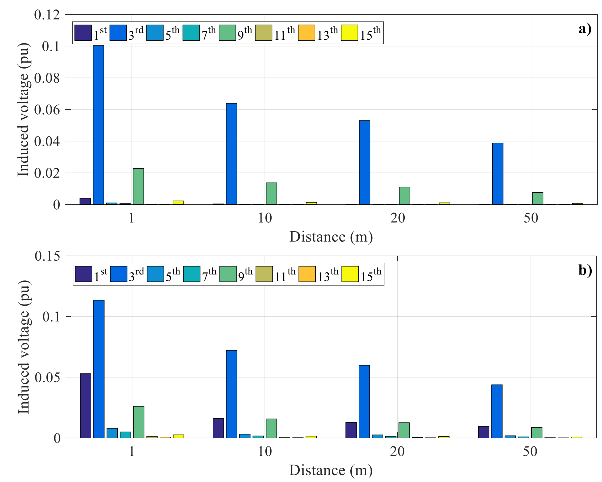

Fig. 12 Influence of distance on the harmonic induced voltage levels at the pipeline for the a) trefoil and b) horizontal cable arrangements.

B. Influence of soil resistivity

Next, the influence of soil resistivity on the harmonic induced voltages is examined. As shown in Fig. 13 for the horizontal cable arrangement, the calculated induced sheath voltages of all harmonics are practically unaffected by the soil resistivity. Similar remarks can be also concluded for the trefoil arrangement; thus, results are not presented.

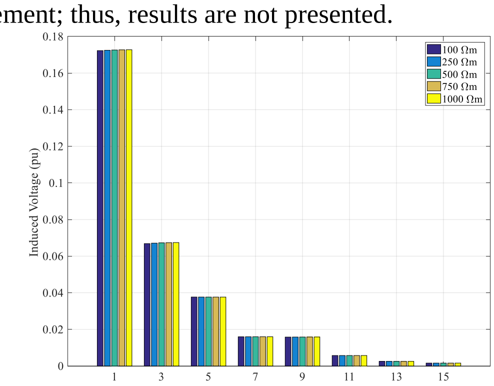

Fig. 13 Influence of soil resistivity on the harmonic induced voltage levels at the cable sheath *a*. Horizontal cable arrangement.

In Fig. 14, the harmonic induced voltages at the pipeline end P_2 are illustrated for trefoil and horizontal arrangements. Only the harmonic induced voltages of the fundamental (used as reference) and of triplen harmonics are presented. Since triplen harmonics are zero sequence, they are the mostly affected harmonics. As shown, the level of the induced voltages of the triplen harmonics increases slightly with soil resistivity for both cable arrangements. In general, the effect of earth conduction effects would be more significant with the asymmetry in the injected currents.

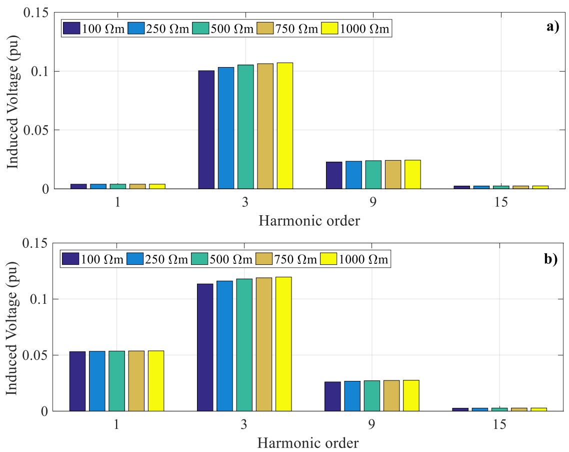

Fig. 14 Influence of soil resistivity on the harmonic induced voltage at the pipeline for the a) trefoil and b) horizontal cable arrangements.

VI. Conclusions

Harmonic induced voltages on cable sheaths and pipelines, excited by MV underground cables systems were investigated using the EMTP-RV software. From the conducted analysis, the main findings are summarized as follows:

- Induced cable sheath and pipeline voltages caused by triplen harmonics can be significantly higher than the induced voltages of the fundamental frequency at 60 Hz. This might be also evident in cases of large separation distances between the cables and the pipeline, e.g. 50 m.
- Harmonic induced voltages caused by triplen harmonics are higher in the trefoil cable arrangement compared to the horizontal. The opposite behavior is observed for the positive and negative-sequence harmonic induced voltages.
- The nominal-pi and the wideband simulation models perform very accurately in all examined cases, compared to the exact-pi. However, further investigations are needed considering longer cable systems as well cross-bonding configurations.
- The soil resistivity affects slightly the harmonic induced voltages in case of triplen harmonics. In the case of positive and negative-sequence harmonics the effect of earth conduction is negligible.

Future work will include the influence of proximity effect as well as the use of a 3D based formulation (taking into account also border effects) for the calculation of the cable per-unit-length parameters and the induced voltages and currents. Additionally, more complex configurations will be examined to evaluate harmonic induced voltages under real cases.

VII. Acknowledgment

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