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Induced Voltage in Cable Shielding by Harmonics and Deficiencies in Installation Procedures

Tensión inducida en la pantalla de cables por armónicos y deficiencias en procedimientos de instalación

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Abstract

Insulated cables are widely used for the transportation, distribution, and end-use installations of electrical power. They are also essential for the grid interconnection of new generation systems based on renewable sources. These types of conductors mitigate electrical risks and increase the reliability of the networks. However, induced voltages in the cable shield are a determining factor in their performance, as a very high value can lead to insulation deterioration, breakdowns, risks to individuals, and malfunctioning of electrical installations. This article presents the behavior of induced voltage and current on the cable shield based on installation conditions and the effect of harmonics in the system. Simulation results show that induced voltage in the cable shield increases due to factors such as the presence of harmonics in the system and cable length. To control these induced voltages, the cable installation procedure must be improved, incorporating good practices for transposition and grounding. Thus, for example, it was found that in the presence of harmonics and supraharmonics the voltage induced in the cable shield increases up to nine (9) times compared to the base case of not having harmonics in the system, but if there is an adequate transposition and grounding, that voltage induced in the cable shield only increases three (3) times with respect to the base case.

Keywords: Electric modeling; induced voltage; cables; shielding; insulation; harmonics; grounding; limiting distance.

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Resumen

Los cables aislados son muy utilizados para el transporte, la distribución y las instalaciones de uso final de la energía eléctrica. También son indispensables para la interconexión a la red eléctrica de los nuevos sistemas de generación basados en fuentes renovables. Con este tipo de conductores se mitigan riesgos eléctricos y se incrementa la confiabilidad de las redes. No obstante, las tensiones inducidas en la pantalla del cable son un factor determinante en su desempeño, ya que un valor muy elevado puede provocar el deterioro del aislamiento, averías, riesgos para las personas y mal funcionamiento de las instalaciones eléctricas. En este artículo se muestra el comportamiento de la tensión y la corriente inducida en la pantalla de un cable en función de sus condiciones de instalación y por efecto de armónicos en el sistema. Resultados obtenidos bajo simulación muestran que la tensión inducida en la pantalla de los cables aumenta por factores como la presencia de armónicos en el sistema y la longitud de cable. Para controlar esas tensiones inducidas se debe mejorar el procedimiento de instalación de los cables, con buenas prácticas de trasposición y puesta a tierra. Así, por ejemplo, se encontró que en presencia de armónicos y supra armónicos la tensión inducida en la pantalla de un conductor se incrementa hasta nueve (9) veces en comparación al caso base de no tener armónicos en el sistema, pero si hay una adecuada transposición y puesta a tierra, esa tensión inducida en la pantalla solo se incrementa tres (3) veces con respecto al caso base.

Palabras clave: Modelamiento eléctrico; tensión inducida; cables, blindaje; aislamiento; armónicos; puesta a tierra; distancia límite.

List of symbols and acronyms

r_i	External radio of conductor i
d_{ij}	Distance between conductor center i and j
X_{ii}	Self-reactance of the conductor-ground loop in Ω/m
$X'_{(i)i}$	Internal reactance in Ω/m
$r_e = \frac{\omega\mu_0}{8}$	Ground resistance in Ω/m
$S = S_{AB} = S_{BC} = S_{AC}$	Axial separation between the phase conductors
d	Geometric average diameter of the cable shield
R_i	Effective conductor radius in m
$Z_{c,p}$	Induced impedance between conductor and metallic shield in Ω/m
$r_{c,p}$	Distance between conductor and metallic shield (m)
D_e	Equivalent ground conductor distance in m
XLPE	Cross Linked Polyethilene
SVL	Screen Voltage Shield
R	Conductor resistance in Ω/m
ω	Frequency angular $2\pi f$, f is the frequency of interest
$\bar{p}_g$	Complex parameter of the depth of penetration of magnetic fields into the conductor
μ_0	Vacuum permeability $4\pi \times 10^{-7}$ in H/m
E_a, E_b, E_c	Induced voltage gradient (V/m) on the metallic shield of cables a, b, and c, respectively
I_a, I_b, I_c	current rms of the core of conductors a, b and c, respectively
μ_r	Relative permeability of the cable installation medium $4\pi \times 10^{-7}$ in H/m
ρ	Ground resistivity in Ωm
σ_g	Conductivity of the conductor in S/m
X	Reactance of the conductor in Ω/m
IEEE	Institute of Electrical and Electronics Engineers
EPR	Ethylene Propylene Rubber
PGCC	Parallel Ground Continuity Conductor

1. Introduction

Electrical cables (insulated conductors) especially those installed underground increase the reliability of the electric power system since they are protected from environmental and atmospheric factors, such as trees or lightning and safety distances are reduced compared to aerial installation [1], [2], [3]. Cables are used throughout the electricity use chain, from generation, through transmission and distribution, to end-use facilities. In addition, they are key in subsea transmission and for the integration of wind and photovoltaic generation systems to the electricity grid. [4]. However, these power generation systems incorporate conversion stages based on power electronics that produce harmonic distortion in voltage and current in spectral bandwidths that exceed 2 kHz [5], [6].

With cables, electrical installations are safer and more reliable [7]. But good practices must be considered in the installation to prevent or limit the appearance of induced voltages in the shield, which can cause electric shocks, circulating currents, breakdowns in the wiring and malfunction of the electrical installations. Thus, in the IEEE 575 standard, limits have been established for these voltages induced in the metallic shield considering different configurations and arrangements. This aspect is key in the design and installation of underground cables [8].

To establish the voltage induced in the metallic shield of a cable, electrical modeling must consider its constructive characteristics, the properties of the medium (terrain) where it is installed, the proximity of other conductor systems whether aerial or underground, among other aspects [9], [10].

For insulation of medium and high voltage cables, oil-impregnated paper insulation first emerged, as well as vulcanized rubber. These insulations had continuous failures due to oil leaks or required insulation of excessive thickness. Around 1950 Cross-linked Polyethylene (XLPE) began to be used and in 1960 Ethylene Propylene Rubber (EPR) appeared, which is a more flexible insulation than XLPE. Both materials have similar electrical characteristics, although EPR has a slightly higher loss factor than XLPE [11], [12].

The analysis proposed in this article is oriented to XLPE insulated cables, installed in clover form and connected to a balanced load. The behavior of the voltage induced in the metallic shield is analyzed before the variation of factors such as: the harmonic distortion of the voltage, the separation between phases, the length of the conductor, the magnitude of the voltage, the method of transposition and the grounding of the metallic shield [9].

XLPE cable electrical modeling and simulation were performed in Matlab Simulink using the Toolbox AC Cable with Bonded Sheaths. Limitations were detected in the model to consider an asymmetric configuration of the wiring, change the installation depth, or simulate unbalanced loads. However, the results obtained show that the voltage induced in the metallic shield of the XLPE cables increases with the presence of harmonics in the system and due to deficiencies in the grounding of the cables.

2. Importance of Induced Voltages in the Metallic Shield of an Electrical Cable

The induced voltages cause overheating in the conductor shield, which reduces the performance of the cable and causes the degradation of the insulation that leads to incipient faults and short circuits. These conditions in turn depend on the magnitude of the load current carried by the cable, the ambient temperature of the medium where the cable is installed, and the power quality characteristics, such as harmonics [9], [13], [14].

The induced voltages also allow the appearance of circulating currents in the metallic shield of the cables, which, depending on their magnitude and frequency, can cause electrocution in a living being on contact with the metallic shield. Therefore, when working with cables, the thresholds of human supportability in contact with an energized element must be considered, in accordance with the provisions of IEC 60479-2 [15].

To mitigate the adverse effects of induced stresses in cables, they have proposed: installing voltage limiting devices in the metallic shield (SVL), adding a parallel ground continuity conductor (PGCC) and carrying out work in the presence of induced voltages under strict procedures [16], [17].

Similarly, standards such as IEEE 575 [8], establish limits for the value of voltage induced in the metallic shielding of a conductor, some of which are shown in Table 1.

Table 1. Limit induced voltage on the metallic shield of an electrical cable.

Country	System Rated Voltage (kV)	Limit induced voltage on the metallic shield (V)
EAU	132	65
Oman	132	65
Saudi Arabia	132	100
Turkey	154	150
Kuwait	275	65
Singapore	66	60
Australia	132	150
Corea del sur	154 a 345	100

Table adapted from [8].

In the USA and England, the induced voltage of the metallic shield for cables along their entire length under normal operation should not exceed 65 V and 90 V, respectively. The IEEE 80 standard states that induced voltage at cables shield should not exceed 50 V [18].

3. Factors Influencing the Magnitude of the Voltages Induced in the Metallic Shield of an Electrical Cable

3.1. Cable Installation Procedure

According to [19], the inductions of voltage and current in the metallic shield of the cables depends on the electrical symmetry of the cable systems, the arrangement of the cable laying, the distances between systems and phases, the transposition length, the grounding configuration of the metallic shield, the presence of parallel ground continuity conductors, Soil-specific resistivity and depth of placement.

Likewise, in [20], it is pointed out that a high current in the metallic shield of the cables is due to the mixture or proximity of other buried cables, deficiencies in the transposition and poor connection of the groundings. For its part, in [21], it indicates that the voltage induced in the metallic shield of single-core cables depends on factors such as load current, cable arrangement, line length, and cable spacing.

3.2. Harmonics and Other Electrical Phenomena

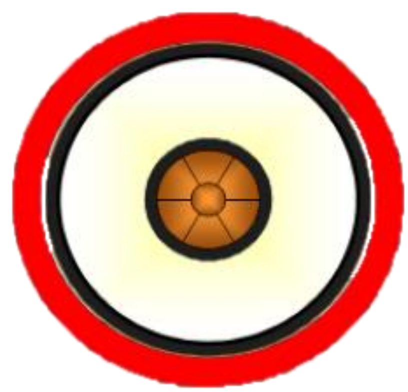
The effect of harmonics on the magnitude of the voltage induced in the metallic shield of the cables is a phenomenon little documented in the literature. However, in [22] indicate that the induced voltage is generally proportional to the order of the harmonic of the conductor voltage, so it is necessary in the design stage of an installation, to evaluate the induced voltage in the metallic shield of the cables, to guarantee the safety and reliability of the installation when it enters into operation.

At harmonic frequencies, various phenomena such as skin effect, ground return loops, capacitive effects, long line effects, geometric imbalances, and cable cross-links, have a marked influence on the performance of electrical conductors [23]. For its part, [24] deduces through frequency domain simulation that the inner and outer impedances of the cables shield increase at higher frequencies and have a greater impact on conductor heating since the current tends to concentrate on the surface of the conductor. Likewise, [25] through field measurements and circuit analysis, it shows that harmonic currents in power lines can cause significant voltage induction in pipes because of higher frequencies and the zero-sequence nature of some of the harmonic currents.

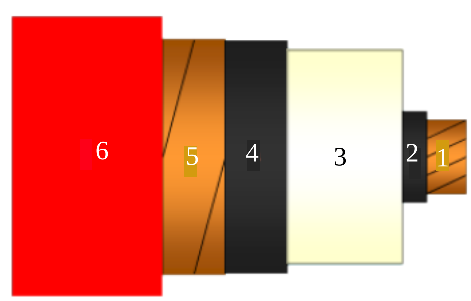
With the development of generation systems based on intermittent renewable sources, the study of the effects of harmonics on wiring becomes especially relevant. For example, in [26] show that, in a 132 MW onshore wind farm, the main reason for the production of current harmonics is the capacitance between conductors and ground which forms a small impedance for harmonic voltages and causes the flow of harmonic currents from the wind farm to the grid.

4. XLPE Electrical Cable Modeling

Electrical modeling of underground XLPE cables should consider grounding connections of conductors [2]. Thus, in general, underground cables for distribution and transmission of energy are composed of three concentric conductors and each conductor has in turn two concentric metal sections, in which one is the central conductor and the other is the metallic shield [11], [27]. These two sections are separated by the insulator, as can be seen in Figure 1.



a. Cross section.



b. Longitudinal diagram.

Parts: 1- Phase conductor. 2- Conductor shielding. 3- Insulation. 4- Insulation shielding. 5- Metallic shield- 6- Jacket.

Figure 1. Front and cross section of an XLPE cable. Figure adapted from [11].

In [23] shows a mathematical model to calculate the impedance of a line in XLPE cable considering as a case study a three-phase line in simple circuit in clover configuration, as represented in Figure 2. The resulting parameter matrix is 6 x 6 in size since its metallic shield is included.

Thus, equation (1) is used to calculate proper impedances (Z_{ii}) of the three central conductors and their corresponding metallic shield, selecting the external radius appropriately. Equation (2) is used to calculate all mutual impedances (Z_{ij}) between conductors, for which the parameter of penetration of magnetic fields $\bar{p}_g$ into the conductor is required according to equation (3) (see list of symbols and acronyms).

$$Z_{ii} = \boldsymbol{j}\frac{\omega\mu_0}{2\pi}\ln\left[\frac{r_i + \bar{p}_g}{r_i}\right] \quad (1)$$

$$Z_{ij} = \boldsymbol{j}\frac{\omega\mu_0}{2\pi}\ln\left[\frac{d_{ij} + \bar{p}_g}{d_{ij}}\right] \quad (2)$$

$$\bar{p}_g = \frac{1}{\sqrt{j\omega\mu_0\sigma_g}} \quad (3)$$

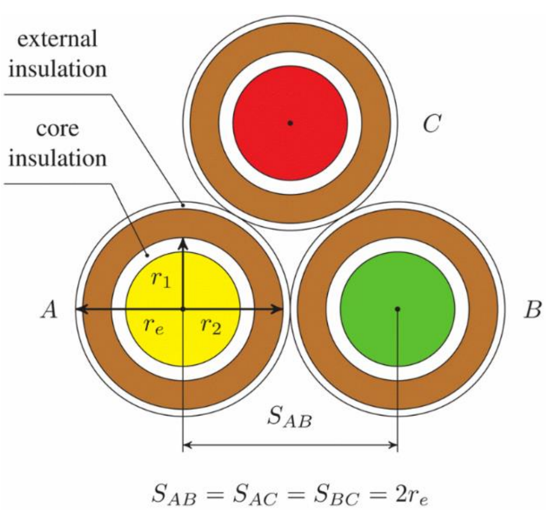


Figure 2. Three-phase line in XLPE cable clover configuration. Own elaboration.

For its part [19] presents the classical Carson equations to calculate the impedance matrix. The proper impedances of the matrix describe the impedance of the respective conductor-ground loop are calculated using equations (4), (5), (6) (see list of symbols and acronyms).

$$Z'_{ii} = (r_e - R) + j\left(X_{ii} + X'_{(i)i}\right) \quad (5)$$

$$X_{ii} = \frac{\omega\mu_0}{2\pi}\ln\left[\frac{D_e}{R_i}\right] \quad (6)$$

$$X'_{(i)i} = \frac{\omega\mu_0}{2\pi}.\frac{\mu_r}{4} \quad (7)$$

Finally, in [28] another model is presented by means of a mathematical arrangement with empirical equations to calculate the mutual impedances between the phase conductors and the metallic shields, between the metallic shields, and the own inductance in the metallic shield. The equations (8) and (9) are used for determining characteristic impedances (see list of symbols and acronyms).

$$Z_{c,p} = \frac{\omega\mu_0}{2\pi}\left[\frac{1}{4} + j\,\frac{1}{\pi}\ln\frac{D_e}{r_{c,p}}\right] \quad (8)$$

The equivalent ground return distance is calculated by:

$$D_e = \frac{1.85}{\sqrt{\frac{\omega.\mu_0}{\rho}}} \quad (9)$$

From the above equations it is observed that the magnitude of the impedances is proportional to the frequency of the conductor load current.

4.1 Calculation of induced voltages in the metallic shield of an XLPE electrical cable.

For an XLPE conductor array in cloverleaf and single-circuit configuration, as shown in Figure 2, the voltage gradient induced on the metallic shield is calculated, as outlined in IEEE 575 of 2014 [8], with equations (10), (11) and (12) (see list of symbols and acronyms).

$$E_a = j\omega I_a(2\times10^{-7})\left(-\frac{1}{2} + j\,\frac{\sqrt{3}}{2}\right)\text{Ln}\left(\frac{2S}{d}\right) \quad (10)$$

$$E_b = j\omega I_b(2\times10^{-7})\text{Ln}\left(\frac{2S}{d}\right) \quad (11)$$

$$E_a = j\omega I_c(2\times10^{-7})\left(-\frac{1}{2} - j\,\frac{\sqrt{3}}{2}\right)\text{Ln}\left(\frac{2S}{d}\right) \quad (12)$$

From the equations it is seen that the voltage induced in the metallic shield is proportional to the frequency of the conductor current.

5. Results of a Case Study

Matlab Simulink *was* used with the *Toolbox AC Cable with Bonded Sheaths* to simulate the electrical parameters of an XLPE conductor and the operating conditions of the cables. The voltage induced in the metallic shield is calculated for different scenarios.

The circuit used in the simulation is shown in Figure 3.

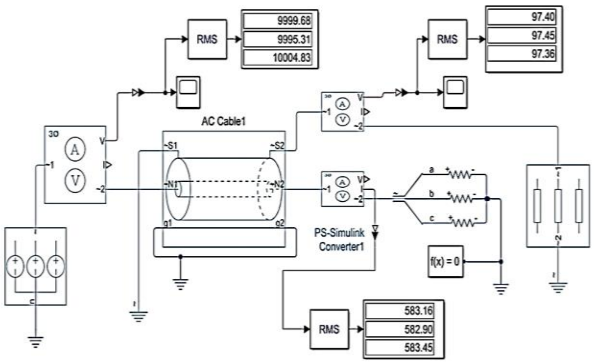


Figure 3. Matlab/Simulink Representative Circuit of an Underground Conductor (AC Cable with Bonded Sheaths). Own elaboration.

5.1. Scenario 1 considering variation in the length, voltage, and gauge of the conductor.

Table 2. Magnitude of voltage induced (V) in the metallic shield for XLPE cable using different operating voltages, gauges, lengths and with harmonic.

Operating voltage, gauge and nominal insulation	Length in km			
	1	2	3	5
13,2 (2 @ 15 kV)	17,84	52,33	46,74	124,25
13,2 (1/0 @ 15 kV)	22,94	68,47	59,34	165,32
13,2 (2/0 @ 15 kV)	26,36	79,05	68,32	196,38
34,5 (1/0 @ 35 kV)	25,28	80,05	65,69	232,27
34,5 (2/0 @ 35 kV)	30,88	86,58	81,37	283,19
115 (750 @ 115 kV)	69,51	152,22	192,55	364,94
115 (1000 @ 115 kV)	77,79	165,85	214,51	395,72
115 (1250 @ 115 kV)	86,6	180,04	237,85	424,06

Own elaboration

For this scenario, the following input data where used:

- Conductor shield grounded at the leading end and open at the trailing end (1 MΩ).
- 2,4 of relative permittivity of the XLPE insulation.
- Cloverleaf configuration for the circuit.
- Line divided into three equal parts.
- Transposition of metallic shield.
- Ground in wet conditions.
- Conductor loaded to 80% of its capacity.
- Harmonics of 3rd, 5th, 7th, and 9th order, with magnitudes in per unit: 0.01, 0.008, 0.005 and 0.001, respectively.
- Resistivity of the return earth 100 Ω*m.

The results of the magnitude of the induced voltage in the shield of the XLPE conductor are shown in Table 2 and Figure 4. There it is shown that, as the length of the conductor and operating voltage increase, the voltage induced in the conductor shield also increases, for all conductor gauges considered. In most cases the voltage induced on the metallic shield exceeded 50 V, which is the limit recommended by the IEEE 80 standard.

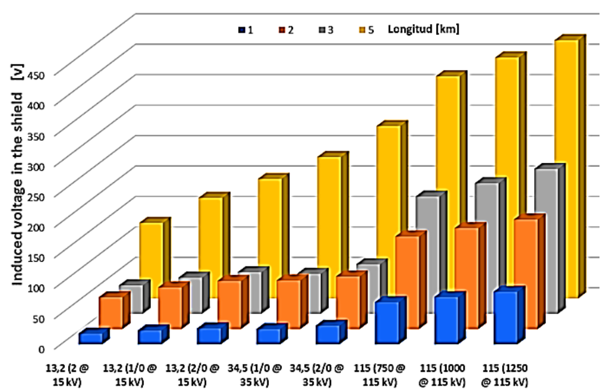


Figure 4. Results of the magnitude of the induced stress with the variation of the lengths and with harmonic. Own elaboration

5.2. Scenario 2 for a 35 kV XLPE cable considering variation in the number of transpositions and including supra harmonics.

For this scenario, the following input data where used:

- Conductor shield grounded at the leading end and open at the trailing end (1 MΩ).
- Operating voltage 34.5 kV.
- Line length of 1 km.
- 2,4 of relative permittivity of the XLPE insulation.
- Cloverleaf configuration for the circuit.
- Line divided into three equal parts.
- Transposition of metallic shield.
- Ground in wet conditions.
- Conductor loaded to 80% of its capacity.
- Harmonics of 3rd, 5th, 7th, and 9th order, with magnitudes in per unit: 0.01, 0.008, 0.005 and 0.001, respectively.
- Harmonics of 3rd, 5th, 7th, and 9th order, with magnitudes in per unit: 0.02, 0.015, 0.01 and 0.005, respectively.

- Supra harmonics of 35th, 37th, 39th and 41st order, with magnitudes in per unit: 0.01, 0.008, 0.005 and 0.001, respectively.
- Resistivity of the return earth 100 Ω*m.

The results are presented in Table 3. For this scenario, it can be concluded that increasing the amount of sectioning where the cable shield is transposed allows reducing the induced voltage. The presence of harmonics and supra harmonics in the network increases the magnitude of the voltage induced in the cable shield.

Table 3. Induced voltage in the metallic shield of a 35 kV XLPE cable, with harmonics and supra harmonics, varying the number of transpositions.

Number of sectioning	No harmonics	1) Harmonics [3,5,7,9] [0.01,0.008,0.005,0.001]	2) Harmonics [3,5,7,9] [0.02,0.015,0.01,0.005]	4) Supra Harmonics [35,37,39,41] [0.01,0.008,0.005,0.001]
1	11,08	31,37	77,93	103,96
2	7,54	25,28	70,99	52,03
3	5,68	30,94	76,88	49,19
4	5	27,53	73,12	45,31

Own elaboration

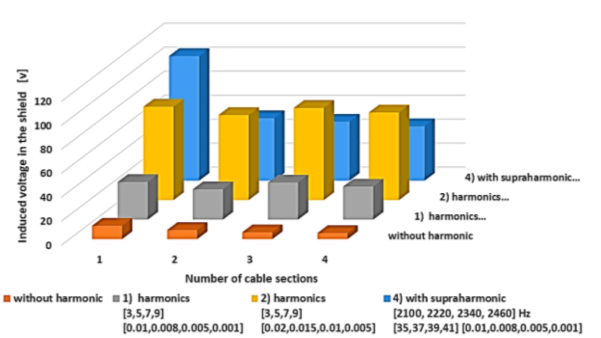


Figure 5. Induced voltage in the metallic shield of a 35 kV XLPE cable, without and with harmonics and supra harmonics, varying the number of transpositions. Own elaboration.

5.3. Scenario 3 considering variation in % load and including supra harmonics.

For this scenario, same input data of scenario 2 where used, but the conductor load percentage was varied and using three transpositions. The results are presented in Table 4.

Table 4. Magnitude of the induced voltage in the XLPE cable shield at 34.5 kV, in the presence of harmonics and load variation.

% Load	No harmonics	1) Harmonics [3,5,7,9] [0.01,0.008,0.005,0.001]	2) Harmonics [3,5,7,9] [0.02,0.015,0.01,0.005]	4) Supra Harmonics [35,37,39,41] [0.01,0.008,0.005,0.001]
50	4,77	15,88	44,63	32,85
80	7,54	25,28	70,99	52,03
100	9,36	31,49	88,31	64,55

Own elaboration

For this scenario, it can be concluded that by increasing the conductor load percentage, the induced voltage in the cable shielding also increases. The presence of harmonics and supra harmonics in the network increases the magnitude of the voltage induced in the cable shield.

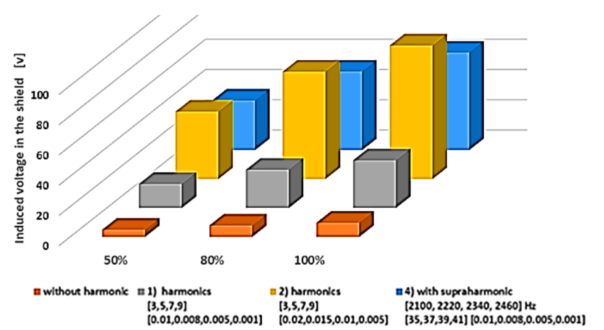


Figure 6. Magnitude of the induced voltage in the XLPE cable shield at 34.5 kV, in the presence of harmonics and load variation. Own elaboration.

6. Conclusions.

To obtain the induced voltage in the metallic shield of electrical cables, factors such as wiring configuration, transposition cycles, grounding resistance, distance between conductors, the number of sectioning and grounding of the metallic shield, conductor length and the presence of harmonics in the network must be considered in the modeling. The results of the case study show that harmonics have a great impact on increasing the induced voltage of the conductor, in addition to increasing power losses, temperature and thermal stresses in the cables.

Within the findings of the research, the role of ground resistivity, the transposition of metallic shield grounding and effective metallic shield grounding is highlighted. These aspects will have to be improved to achieve the reduction of the levels of induced voltage in the metallic shield of the cables.

When determining the number of sectioning in which the conductor transposition will be performed, the influence of harmonics on the increase in induced voltage must be considered at the design stage. The oversizing of the sectioning of the conductor must be evaluated to contemplate the affectations by harmonics or otherwise establish the mechanisms for its mitigation.

Finally, given the great influence that harmonics have on the magnitude of the voltage induced in the metallic shield of cables, it is recommended that the calculation of the induced voltage be included in the design stage of underground networks or lines. For cables already in operation, it is recommended to measure harmonic levels and make the indicated adjustments to control the high induced voltage values on the conductor's shield.

7. Recomendations.

Poor representation of cable components and mathematical modeling will lead to errors in calculation of induced voltage at cable shield. It should be borne in mind that electrical models of steady-state conductors were developed mainly for fundamental frequency (50 Hz or 60 Hz), so more research should be done on the effects derived from harmonics and supra harmonics introduced by non-inertial sources such as photovoltaic and wind systems. It is also important to characterize the environment where the conductor is installed (temperature, ground resistivity) and consider electrical phenomena such as transients and overvoltage.

8. Acknowledgments.

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