18th International Conference on Renewable Energies and Power Quality (ICREPQ'20)
Granada (Spain), 1st to 2nd April 2020
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.18, June 2020

A 3D parametric thermal analysis of submarine three-core power cables

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Abstract. This paper presents the main features of a 3D FEM-based modelling framework of submarine three-core power cables with the final aim of estimating the ampacity of this type of cables when operating at certain conditions (buried in the seabed in steady-state). This assessment provides valuable information for the cable manufacturer during the design stage and for the owner of the evacuation line mostly in the planning stage, apart from being used as a reference for the development of other less computationally intensive analytic models. Moreover, the paper analyzes the impact that some design parameters have on the temperature of the cable, providing same concluding remarks.

Key words. Three-core, finite element method, armor, twisting, power losses, thermal model, temperature.

1. Introduction

The need for submarine AC power cables is increasing due to the construction or planning of offshore wind farms. Even though the on-shore wind installed power is expected to grow 8 times faster, the worldwide volume of offshore installed capacity will increase around 43 GW in the next 5 years [1].

One of the most employed type of cable is the three-core armored, where the armor is composed of steel wires twisted around the three cores. Mainly due to the presence of this armor, the global and disaggregated cable losses estimation is challenging, and several approaches have been proposed previously [2-10], highlighting the fact that the IEC 60287 standard [11] introduces important errors in the computation of the armor losses since it does not take into account the relative twisting between phases and armor wires. This is of importance because, apart from using it for economic analysis, the losses knowledge is a requirement for the temperature estimation inside the cable, and hence the thermal capacity. Thus, the complexity of solving the combined electro-thermal problem in such complex geometries makes the need of simplifying the problem, being different the assumptions according to the aim of the analysis. For example, for a dynamic rating with availability of measurements, 1D thermal model has been recently proposed [6]. Nonetheless, for a design and planning analysis, simulations based on the finite element method (FEM) models have been extensively employed for the computation of the electrical parameters and the power losses in three-core armored cables. For this task, 2D and 3D approaches are usually considered, although 2D models are preferred [7-10]. In this case, the electromagnetic and thermal problems can be easily coupled and iteratively solved for a cross section of the power cable with low computational requirements (Fig. 1). This way, the power losses in phases, sheaths and armor wires can be obtained as a function of its temperature, providing a valuable tool for analyzing the influence of different environmental conditions and the thermal properties of the seabed on the cable temperature [15-20].

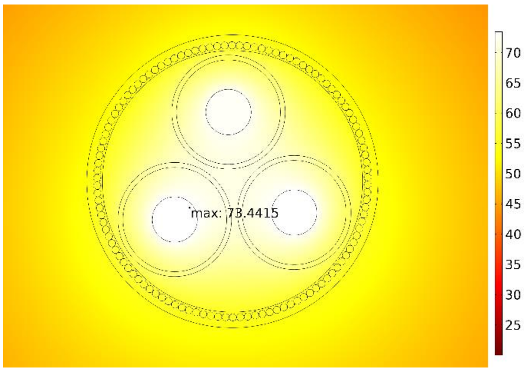


Fig. 1. Temperature distribution (ºC) in a three-core armored cable by means of a 2D FEM electro-thermal model.

Nevertheless, as it is a 2D model, all cable elements are assumed as straight and infinitely long, hence ignoring the relative twisting between phases and armor wires. To a certain extent, this issue may be barely overcome by implementing additional boundary conditions that forces the total net current in the armor to be zero, known as 2.5D approach [7]. Even so, the magnetic flux parallel to the cable longitudinal axis, which is the main source of induced losses in the armor wires, is also ignored. Therefore, the power losses, and hence the cable temperature, are not derived accurately through 2D models.

Consequently, for a more realistic situation, it is convenient to use 3D FEM models, where all the interactions derived from the relative twisting between phases and armor wires are fully kept, hence having an accurate computation of the power losses.

However, only few publications have addressed the electromagnetic problem through this approach at the time [13-14], since it requires expensive equipment plenty of RAM memory to solve the model. Thus, in this situation is not practical to develop a 3D electro-thermal model. To overcome this issue, [21] proposed a new methodology to greatly reduce the size of the 3D electromagnetic problem to be solved. This new and shorter periodic model strongly reduces the computational requirements, providing accurate results regarding the series impedance and the power losses in the cable [22].

This paper presents new advances in reducing the length of the 3D geometry that makes possible the development of a 3D electro-thermal FEM model for the first time in the literature, and that is now able run in computers with about 64 GB of RAM memory in less than 30 minutes. Through this new approach, an in-depth 3D electro-thermal parametric analysis is presented for a three-core 800 mm^2 145 kV submarine cable, showing the influence of cable design, material properties and ambient boundary conditions on the maximum temperature achieved inside the power cable. Main results will be compared to those derived from 2D FEM models also, where the influence of the relative twisting between phases and armor on the cable temperature cannot be addressed.

2. Problem formulation

The mathematical formulation for the electromagnetic and thermal problems are described next, including main assumptions and the boundary conditions applied.

A. Electromagnetic problem

The electromagnetic problem is solved based on the following assumptions:

1. The conductivity $\sigma(\theta)$ in conductors, sheaths and armor wires depends on temperature:

$$\sigma(\theta) = \frac{\sigma_0}{1 + \alpha(\theta - 20)} \quad (1)$$

   where θ is the unknown temperature, and σ_0 and α are the conductivity and the temperature coefficient of the material at 20 ºC, respectively.
2. The phase currents are sinusoidal and balanced.
3. Sheaths and the armor are solidly bonded, so circulating current may flow.

In this situation, the equation to be solved is

$$\nabla \times \left(\frac{1}{\mu}\nabla \times \vec{A}\right) + j\omega\sigma\vec{A} = \vec{J}_e \quad (2)$$

where $\vec{A}$ is the magnetic vector potential, ω is the angular frequency, σ is the conductivity, μ is the magnetic permeability and $\vec{J}_e$ is the external current density.

The power losses generated in the conductors, sheaths and armor will be used as the heat input for the thermal problem. In particular, resistive losses (P_r) can be derived from the current density $\vec{J}$ as

$$P_r = \int \frac{\vec{J}\cdot\vec{J}^*}{\sigma} d\Omega \quad (3)$$

On the other hand, the magnetic losses generated in ferromagnetic materials (P_{mag}) are also included. This can be done in the frequency domain by means of a complex magnetic permeability in the form of [23]

$$\mu_r = \mu' - j\mu" \quad (4)$$

$$P_{mag} = \omega\mu_0\mu" \int \vec{H}\cdot\vec{H}^* \, d\Omega \quad (5)$$

where μ_0 is the magnetic permeability of vacuum, and $\vec{H}$ is the magnetic field.

The length of the 3D geometry to be simulated is defined in terms of the so called “crossing pitch” (CP), defined as

$$CP = \frac{1}{\frac{1}{P_a} + \frac{1}{P_p}} \quad (6)$$

for a cable where the armor and the phases are twisted in opposite directions (contralay), where P_p and P_a are the lay length of phases and armor wires, respectively.

In [21] it was concluded that periodic boundary conditions can be applied to a model length (L) equal to CP to capture all the electromagnetic interactions involved in the armored cable. However, a subsequent analysis showed that L can be further reduced up to

$$L = \frac{CP}{3} \quad (7)$$

In this situation, the source and destination boundaries where periodicity is to be applied are rotated a relative angle (θ) defined by (Fig. 2)

$$\theta = \frac{2\pi L}{P_a} \quad (8)$$

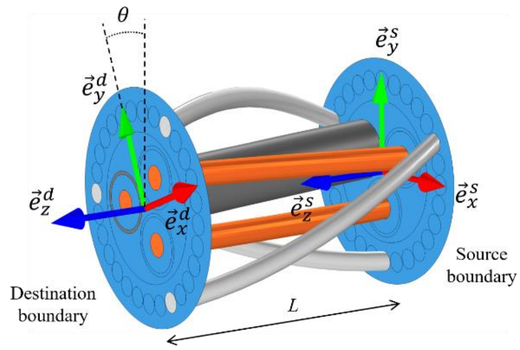


Fig. 2. Relationship between source and destination boundaries for periodic boundary condition.

B. Thermal problem

The starting assumptions for the thermal problem are:

1. The temperature gradient in the soil at great distance from the cables is zero (Fig. 3).
2. The power cable is buried in homogeneous soil at a depth of d_p (Fig. 3).
3. All materials have constant thermal conductivity λ.
4. The heat flux between the seabed and the sea water is transferred by convection, with known convection heat transfer coefficient (h) and temperature of the sea water (θ_s) (Fig. 3).

In this situation, the associated steady-state heat transfer equations to be solved are

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial\theta}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial\theta}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial\theta}{\partial z}\right)+q_v=0 \quad (9)$$

$$\lambda\frac{\partial\theta}{\partial n}=h(\theta-\theta_s) \quad (10)$$

where q_v is the heat generated in the power cable (conductors, sheaths and armor) per unit volume (computed from the electromagnetic problem), n is the unit vector normal to the surface, and θ is the unknown temperature.

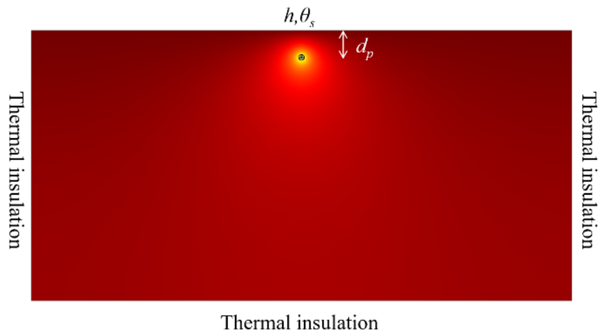


Fig. 3. Thermal boundary conditions.

Since the electrical conductivity of conductors, sheaths and armor wires is temperature dependent, the coupled electromagnetic-thermal problem must be iteratively solved.

3. Case study

The proposed electro-thermal approach is applied to a 800 mm^2 and 145 kV copper conductor buried at d_p = 1 m when the seabed temperature is θ_s = 10 ºC and the convection heat transfer coefficient is h = 20 W/(m^{2}K). All the technical data of the cable and the values of the material properties are shown in Table I and Table II.

Table I. – Cable technical data

Voltage (kV)	145
Conductor	Cu
Cross-section (mm^2)	800
Current (A)	730
Conductor radius (mm)	17.5
Sheath thickness (mm)	3.7
Sheath radius (mm)	43.8
Core lay length (m)	2.8
Wire diameter (mm)	5.6
No of wires	114
Armor radius (mm)	104.5
Armor lay length (m)	3.5
CP (m)	1.56

Table II. – Material properties

	σ (S/m)	α (ºC^{-1})	μ_r	λ (W/(m·K))
Copper	$5.8{\cdot}10^7$	0.00393	1	238
Lead	$4.7{\cdot}10^6$	0.004	1	35
Steel	$7.3{\cdot}10^6$	0.0045	$300-50j$	44.5
XLPE	0	-	1	0.28
Soil	0.5	-	1	1

Through the shortened FEM model proposed earlier, the temperature distribution in the three-core cable is obtained (Fig. 4). In this sense, this work presents the results derived from both 2.5D and 3D FEM electro-thermal models, in order to show its main differences. All simulations are developed using the software Comsol Multiphysics® [24] in a 64 GB of RAM workstation.

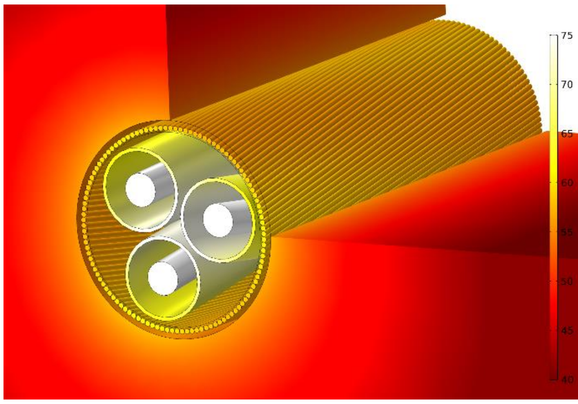


Fig. 4. Temperature distribution in a 3D FEM electro-thermal model.

It should be noted that, for the development of this analysis, and in order to have comparable results from both 2.5D and 3D models, the inner region of the three-core cable has been simplified, replacing all non-conductive elements (such as fillers, etc.) by a homogenized material with the thermal properties of the XLPE insulation.

On the other hand, and as mentioned previously, a complex relative permeability is employed in the armor wires. In particular, two complex values are considered in this study, denoted as shown in Table III.

Table III. – Relative permeability for the armor wires

μ^c_{100}	μ^c_{300}
100-50j	300-50j

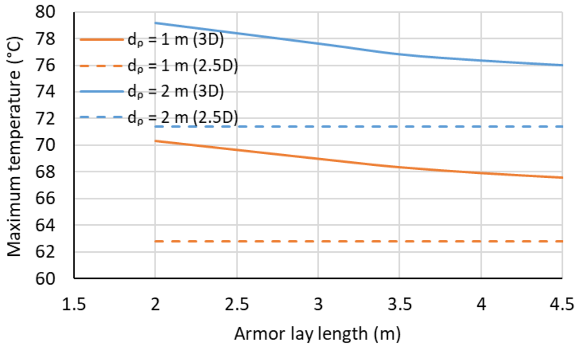
4. Parametric analysis

An in-depth 3D electro-thermal parametric analysis is presented next for the selected cable. Its main goal is to show those aspects that are only affordable by means of 3D FEM models, and show the errors derived from the use of 2.5D FEM simulations also.

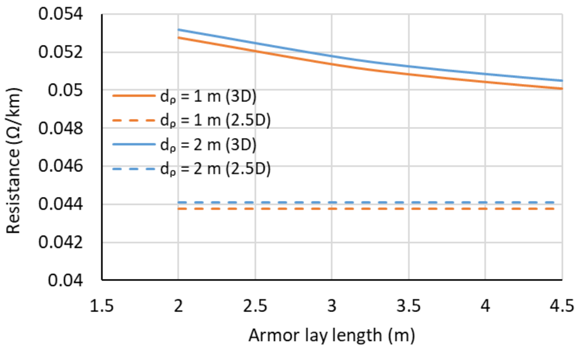
In the following, the influence of the armor lay length, the depth of burial, the sea water temperature and the armor permeability on the maximum temperature of the power cable, its series impedance and the power losses is analyzed.

A. Armor lay length and burial depth

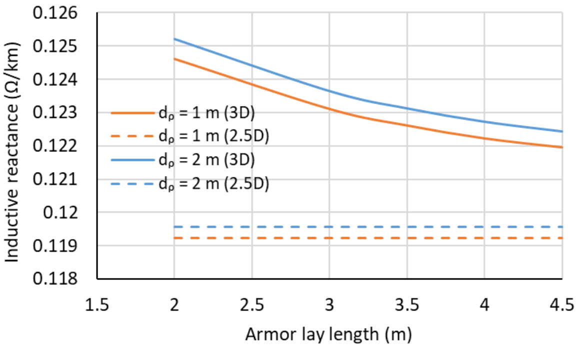
In contrast to 2.5D FEM models, the main contribution derived from the use of fully coupled 3D FEM electro-thermal simulations is the possibility of analyzing the influence of the relative twisting between armor and phases on the maximum temperature achieved by the armored cable. This is done in this study through variations in the armor lay length. Thus, Fig. 5 shows how this parameter influences on the maximum cable temperature (Fig. 5 (a)), its per-unit length resistance (Fig. 5 (b)) and inductive reactance (Fig. 5 (c)) for two different burial depths.



(a)



(b)

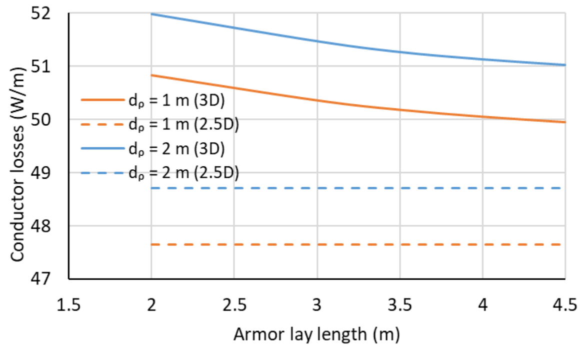


(c)

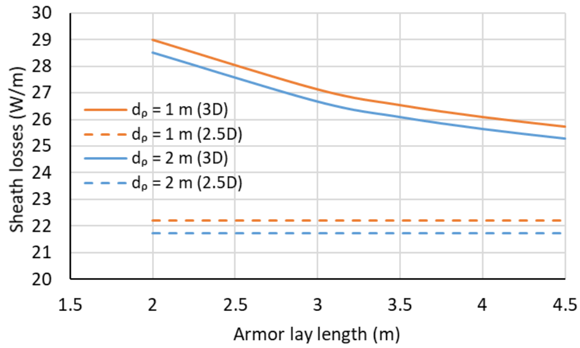
Fig. 5. Influence of the depth of burial and the armor lay length on (a) the cable maximum temperature, (b) the per-unit length resistance and (c) inductive reactance (θ_s = 10 ºC, μ^{c}_{300}).

As can be observed, the three parameters increase as the armor is getting more twisted (shorter lay length). However, the more remarkable result is the great differences observed in 2.5D and 3D FEM simulations, especially on the cable temperature and per-unit series resistance, presenting differences up to 11 % and 17 %, respectively for shortest armor lay length considered. Conversely, the per-unit series reactance presents a maximum difference in the order of 5 %. In addition, it is also observed that both FEM models show a similar increase in the cable temperature when the cable is buried at more depth, as expected.

On the other hand, Fig. 6 shows the influence of the armor lay length and the depth of burial in the conductor (Fig. 6(a)), sheaths (Fig. 6(b)), armor (Fig. 6(c)) and the total losses (Fig. 6(d)). As mentioned previously, great differences are observed in the results derived from each FEM model, where those derived by 2.5D FEM simulations are well below those obtained by 3D FEM models. Particularly, it is clearly seen how power losses increase as the armor is getting more twisted, especially in the sheath losses, something that it is not noticeable in 2D analyses. Thus, for the range considered in the armor lay length, differences up to 24 %, 90 % and 16 % in the sheaths, armor and total losses are observed, respectively, while it is below 6 % for the conductor losses.



(a)



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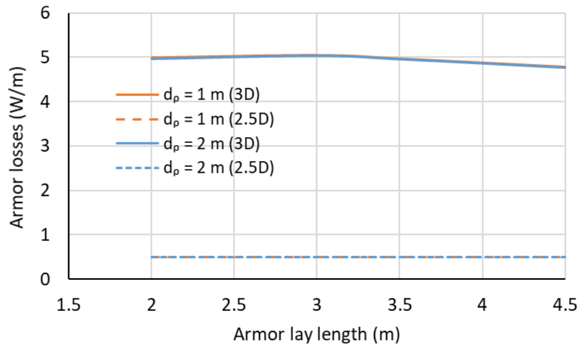
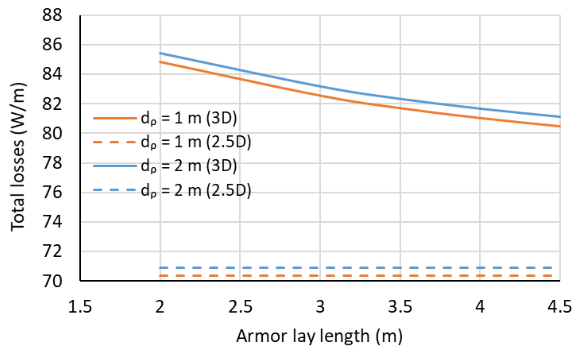


(c)



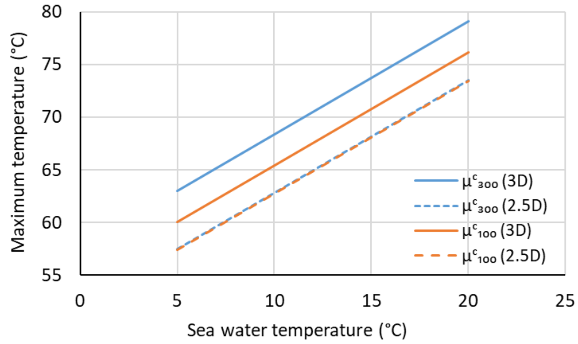
(d)

Fig. 6. Influence of the depth of burial and the armor lay length on (a) the conductor, (b) sheaths, (c) armor and (d) total losses (θ_s = 10 ºC, μ^{c}_{300}).

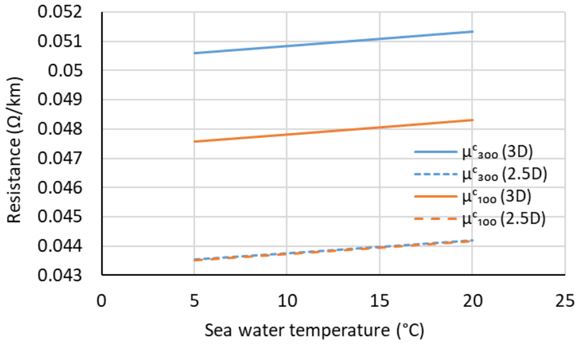
As a consequence, it is clear that the use of the proposed fully coupled 3D FEM model is highly recommended for obtaining an appropriate behavior in terms of the cable series impedance and its current rating.

B. Sea water temperature and armor permeability

In Fig. 7 it is shown the influence of the sea water temperature and the complex permeability of the armor wires on different parameters, such as the maximum cable temperature (Fig. 7 (a)), the per-unit length series resistance (Fig. 7 (b)) and the total power losses (Fig. 7 (c)), for a cable buried at d_p = 1 m with armor lay length P_a = 3.5 m.



(a)



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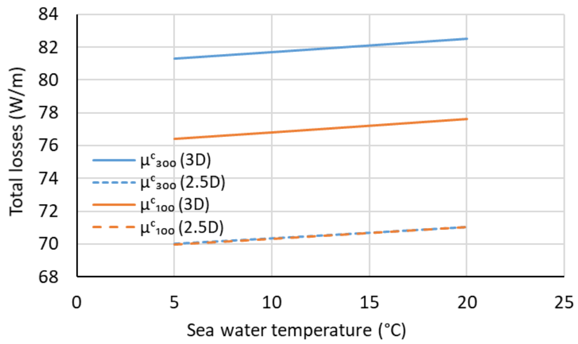
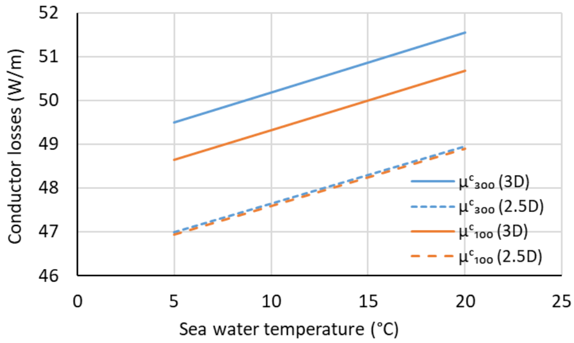


(c)

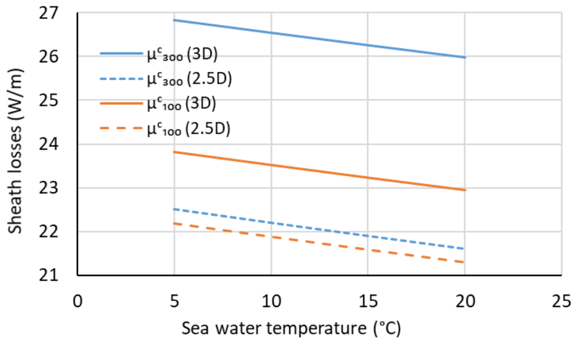
Fig.7. Influence of the sea water temperature and the magnetic permeability on (a) the cable maximum temperature, (b) the per-unit length series resistance and (c) the total losses (d_p = 1 m, P_a = 3.5 m).

Again, great differences are presented between 2.5D and 3D FEM results, although similar behavior is observed in both approaches, showing that the maximum temperature of the armored cable increases with the sea water temperature, as expected. Also, the increasing rate is similar for 2.5D and 3D FEM models, but the maximum cable temperature is about 4 ºC higher in the 3D model when increasing the armor complex permeability since this parameter seems to have no influence on the results derived by 2.5D simulations. In this sense, similar conclusions are derived for the series resistance in Fig. 7(b), where the armor permeability seems to have important influence only on 3D FEM simulations. Eventually, it should be remarked how 2D models provide results far from those derived from 3D models, especially for the power losses (Fig. 7(c)), where a relative difference of about 14 % for μ^c_{300} is observed.

Thus, at this point, from the results provided by 2.5D simulations one may wrongly conclude that the influence of the armor permeability is negligible on all the three parameters represented in Fig. 7 (dashed lines for μ^c_{100} and μ^c_{300} are overlapped).



(a)



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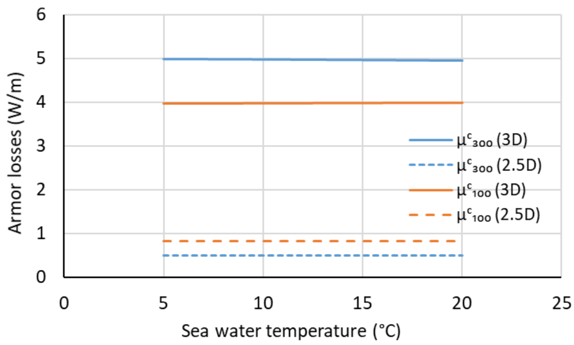

(c)

Fig.8. Influence of the sea water temperature and the magnetic permeability on (a) the conductor, (b) sheath and (c) armor losses (d_p = 1 m, P_a = 3.5 m).

On the other hand, and regarding the influence of the sea water temperature, interesting results are derived if power losses are disaggregated (Fig. 8). Thus, while conductor losses increase with the sea water temperature as expected, the armor losses remain stable and the sheath losses decrease unexpectedly. This may be a consequence of an increasing sheath resistance that reduces the value of induced currents.

5. Conclusions

This paper presents the development of a fully coupled 3D FEM electro-thermal model of three-core armored cables for the first time in the literature. This new framework brings a new tool for optimizing cable design and its current rating in terms of cable layout and material properties, all this reducing the computational requirements so that it can be run in computers with less than 64 GB of RAM.

Through this new approach, an in-depth 3D electro-thermal parametric analysis is presented for a three-core 800 mm^2 145 kV submarine cable, showing the influence of cable design (relative twisting between armor and phases), material properties and ambient boundary conditions, not only on the maximum temperature inside the power cable, but also on the series impedance and the power losses.

Main results are compared to those derived from 2.5D FEM models also, highlighting the fact that 2.5D simulations may lead to erroneous conclusions, mainly when analyzing the influence of the armor permeability. Additionally, the impact of the armor twisting is something that cannot be addressed through 2D geometries. As a consequence, it is clear that the use of the proposed fully coupled 3D FEM model is highly recommended to obtain an accurate behavior in terms of the losses and current rating, and additionally as a tool to assist in the cable design optimization.

Acknowledgement

This research has been supported by the Agencia Estatal de Investigación and Fondo Europeo de Desarrollo Regional (AEI/FEDER UE) under the project ENE2017-89669-R.

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