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Validation of an efficient 3D finite element model for the calculation of losses in three-core armoured power cables

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SUMMARY

Induced losses are a significant part of the total losses generated in HVAC cables. It is widely recognised within the academic and industry communities that the available international standards may in some cases overestimate cable losses and, particularly, loss induced in the armour. Remarkable progress has been made on the loss calculation of three-core armoured power cables during the last decades. Thanks to the increased computational power provided by modern computers, finite element (FE) models have been be developed. However, these 'conventional' FE models are still in some cases resource-consuming or not accurate enough for certain cable designs, because of the large cable length required to be simulated and the emergence of erroneous end effects. In this paper, state-of-the art FE models, capable of reducing the total simulation length down to few centimetres and therefore significantly reducing use of computational resources without loss in accuracy, are presented and validated against earlier published FE model data, as well as published measurement data. In addition, the developed FE models, which prove to be impressively efficient, are validated against in-house measurements. The simulations show very good agreement with measurements in all the cables tested, not exceeding 4% in the worst case.

KEYWORDS

Armour Loss - Cable Ampacity - Cable Twisting - Crossing Pitch - Finite Element Method - Periodic Boundary Condition - Power Cable Modelling - Submarine Cable

1. INTRODUCTION

The rapid growth of offshore wind farm projects has increased substantially the demand for three-core export armoured power cables of higher voltage levels. To increase the economic viability of such projects, it is crucial to reduce the subsea cable cost as much as possible. The loss calculation of such cables is traditionally performed using the IEC 60287-1-1 Standard [1]. However, it is today widely recognised that the IEC method systematically overestimates the losses in the armour of armoured SL-type cables, thus leading to oversized cables. This has led both the academic and industrial communities to seek for a more realistic loss estimation, including measurements in cable specimens, development of analytical calculations and employment of finite element (FE) modelling. CIGRE Study Committee B1 has recently constituted WG B1.64 which deals with these topics.

Several efforts comparing measured loss values with those derived from the IEC method have been reported in literature. The majority of these works [2]-[8] measure the total losses and the positive-sequence impedance of a specific cable sample at power frequency, showing the large deviation of results with respect to existing standards. Similar measuring techniques are also adopted in the ongoing work of CIGRE WG B1.64 that will be part of the upcoming technical brochure. In addition, few works [9]-[13] have also focused on showcasing a series of practical tests that would allow a detailed allocation of the losses to the different metallic components of the cable. This, in turn, requires substantially more measurements and a more detailed analysis methodology. On the other hand, several researchers have developed analytical calculation routines for loss estimation. Equivalent circuit models, seeking to effectively capture the 3D effects on induced losses, have been proposed in [14]. An analytical method is also developed in [15], accounting for the twisting of the armour with respect to the power cores. Both analytical routines [14], [15] are currently discussed in WG B1.64 as candidate formulae to replace the existing IEC method.

In terms of FE modelling, the so-called 2.5D FE model was initially developed to capture the 3D effects arising due to the helical twisting of the different components [2]. After those first attempts, full 3D FE analysis resulted in complex, large models with high execution times, due to the questionable model length that had to be considered. These ‘conventional’ models were proved accurate enough, although end effects were still present due to the doubtful boundary conditions imposed on the model ends [8], [16], [17]. A more efficient approach was reported in [18], proposing the concept of crossing-pitch (CP) length and the application of rotated periodic boundary conditions. The idea was based on the observation that the pattern repeats itself as soon as one particular armour wire returns to its initial relative position with respect to a certain phase, regardless of the orientation of the overall cross-section [19]. The so-called CP model, free of end effects, resulted in a reduced cable length to be simulated, thus significantly reducing the execution time [20].

Besides CP model, an even more efficient 3D FE technique is proposed in [19] and introduces the short-twisted (ST) periodicity. Compared to CP, ST periodicity relies on the observation that the pattern repeats itself as soon as any armour wire, instead of a specific one, reaches the initial relative position with respect to a certain phase, regardless of the orientation of the overall cross-section [13], [19]. Hence, the ST model length is further reduced, thus allowing for execution times practically comparable to those of 2.5D analyses. Although CP model is benchmarked in [18], no extensive validation has been so far provided in literature for ST model. This paper investigates the concept of losses in three-core armoured power cables by comparing measurements with state-of-the-art theoretical models. Loss figures derived from CP and ST models are compared with published FE results, analytical methods and measurements.

2. MODELLING TECHNIQUES IN 3D FINITE ELEMENT ANALYSIS

The problem of calculating losses in three-core, wire armoured power cables is hard to solve, due to the complex geometry of this specific cable type: the twisting of power cores and armour wires in different helices implies a 3D problem, which cannot be readily simplified into 2D. Hence, 3D FE models are essential for accurate calculation of losses in all conductive layers. However, due to the complexity of these models, several modelling techniques have been developed in recent years to tackle the high computation burden of the simulations.

2.1 Full periodic 3D FE models

At first glance, a model with length equal to the least common multiple of cores and armour lay lengths is suitable for the accurate simulation of the fields induced by the helical paths of active and passive conductors [16] . However, this approach may not always help in reducing the size of the model. For instance, a cable with typical lay lengths of 3.7 m for the cores and 4 m for the armour wires would require a model length of 148 m. This subsequently would lead to extremely large computational resources needed to solve the model.

2.2 Non-periodic 3D FE models

The simplest approach to reduce the high computational burden of the full periodic FE model is to shorten its length. This results in a non-periodic (NP) FE model in which the relative position between the cores and the armour wires is different at both ends of the geometry. The subsequent imposition of typical boundary conditions forces the induced currents in the sheaths and armour to flow differently than they would do in the full periodic FE model, especially at both ends, since Ampere's law must be fulfilled. This leads to a different distribution of the induced loss density, as indicatively shown for the armour wires in Figure 1a, which is generally identified as end effects [8], [17].

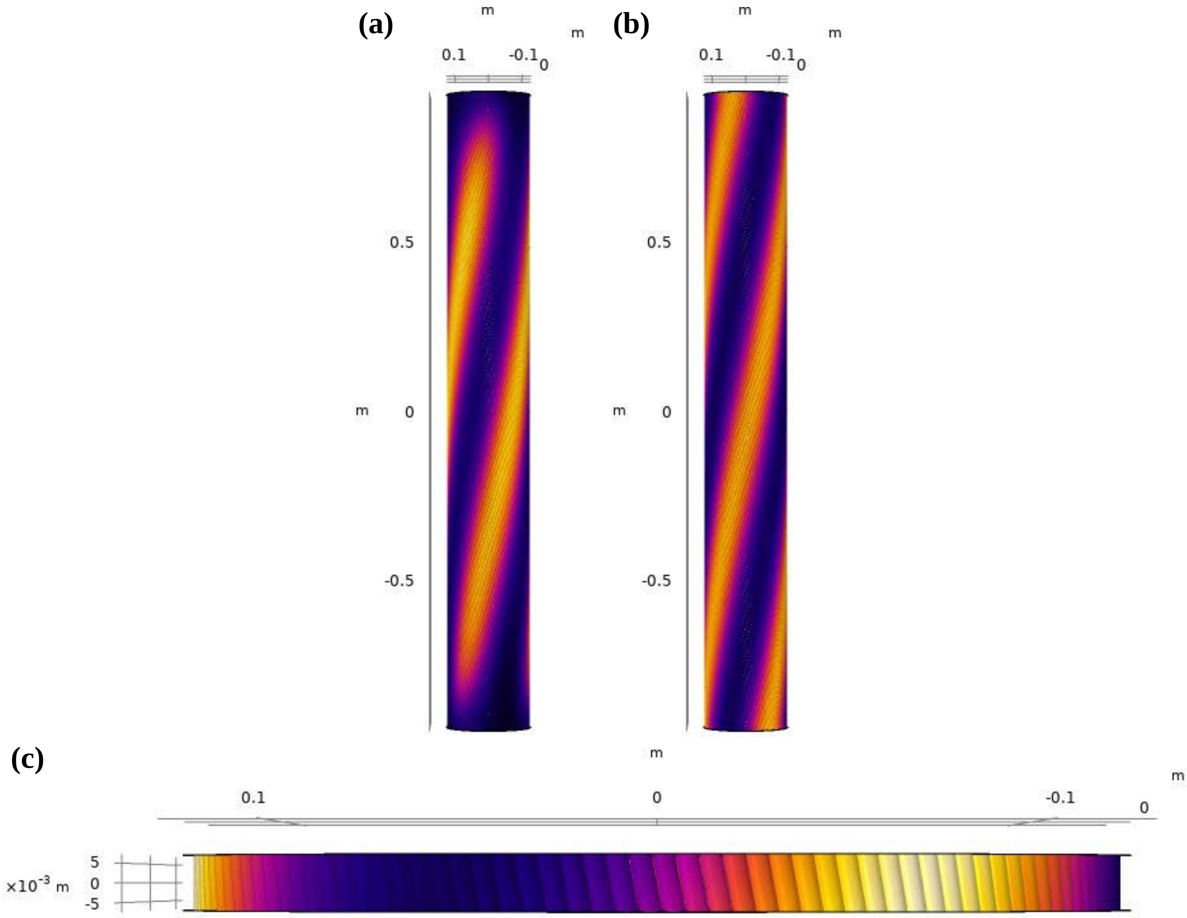

Figure 1: Distribution of armour loss density in (a) NP, (b) CP and (c) ST 3D FE models. Emergence of end effects depending the use of typical or rotated boundary conditions.

In order to avoid the disturbances by the edges, the field analysis and loss evaluation are usually performed in a smaller section located in the middle of the model [17], but correct selection of this location can be challenging and scenario dependent [8].

2.3 Crossing-pitch (CP) periodic 3D FE models

An elegant and more efficient modelling technique proposes the concept of CP length and the application of rotated periodic boundary conditions. The idea is based on the observation that a certain electromagnetic field pattern repeats itself as soon as one particular armour wire returns to its initial relative position with respect to a certain core, regardless of the orientation of the overall cross-section [18], [19]. The length required for this repetition is equal to the CP, defined in (1) for contralay and unilay cables, respectively [5].

$$CP = \left| \frac{1}{\frac{1}{L_C} \pm \frac{1}{L_A}} \right| \tag{1}$$

where L_C and L_A are the lay length of cores and armour wires, respectively. The rotated periodicity is applied using special boundary conditions which are set for a perfect matching between the source and destination cable ends. This is achieved by a relative rotation of the coordinate systems to both boundaries using a certain Euler angle θ, defined in (2) [18], [19].

$$\theta = \pm 2\pi \frac{CP}{L_C} \tag{2}$$

where the cores are twisted in counterclockwise and clockwise fashion, respectively. This results in a short cable length to be simulated, thus significantly reducing the execution time.

Thanks to this approach it is possible to analyse complex three-core cables with numerous wires in the armour by solving the electromagnetic field merely in a short portion of the cable length equal to CP. However, the simulation time may still be high, especially in unilay cables where the CP remains large, and it might be necessary to make use of a coarser mesh, thus solving faster, but with the trade-off of less accurate results [13].

2.4 Short-twisted (ST) periodic 3D FE models

A further in-depth analysis of results with the CP model shows that the full electromagnetic behaviour of the cable can be actually found in just a small slice of the cable. The ST periodicity relies on this observation, i.e., that the electromagnetic field pattern repeats itself as soon as any armour wire, instead of a specific one, reaches the initial relative position with respect to a certain core, regardless of the orientation of the overall cross-section [13], [19]. Hence, the ST model length is further reduced as shown in (3) while the Euler angle δ for the imposition of the rotated boundary conditions is per (4).

$$ST = \frac{CP}{N_A} = \left| \frac{1}{\left(\frac{1}{L_C} \pm \frac{1}{L_A}\right) N_A} \right| \tag{3}$$

$$\delta = \frac{\theta}{N_A} = \pm 2\pi \frac{CP}{L_C N_A} \tag{4}$$

where N_A is the number of armour wires. The ST model, shown in Figure 1c, allows for execution times comparable to those of 2.5D FE analyses, regardless of contralay or unilay design.

This paper presents an extensive validation of all these models against already published in literature simulation and measurement data, as well as in-house measurement data.

3. NUMERICAL RESULTS

3.1 Comparison with literature data

In this section, the CP and ST 3D FE models are examined in some of the cable designs presented in [7] and [8]. Results in terms of cable losses are compared against measurements, initially presented in [7] and subsequently reported in [8], the IEC standard, the NP 3D FE model and the analytical formulation of [15], which are all reported in [8]. The accuracy of each modelling technique, where applicable, is assessed in terms of total cable losses by calculating the relative difference compared to the measurement, which is assumed as reference.

3.1.1 Results for Cables 1a

Cable 1a is a 3x1200 mm^2 aluminum cable in contralay configuration with high grade magnetic armour wires [7], [8]. Figure 2 presents the comparison of CP and ST 3D FE models against all modelling techniques reported in [8], for the case of solid-bonding and varying number of armour wires. Similar results are shown in Figure 3 for the case of single-point-bonding.

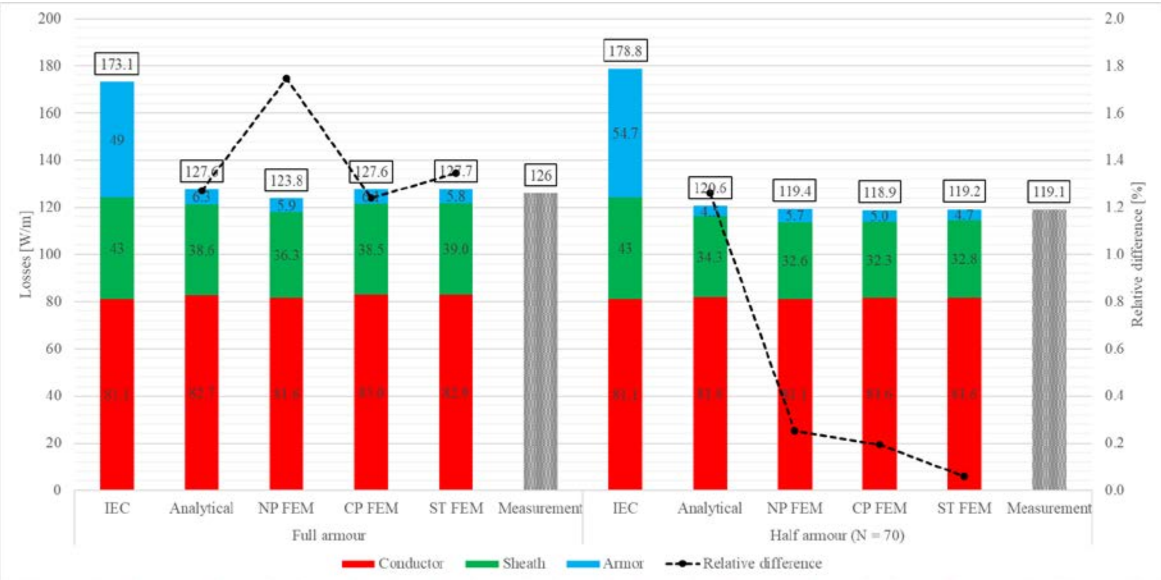

Figure 2: Cable 1a in solid bonding with varying number of armour wires. Comparison of CP and ST 3D FE models against measurements, IEC 60287, NP 3D FEM and the analytical formulation of [15].

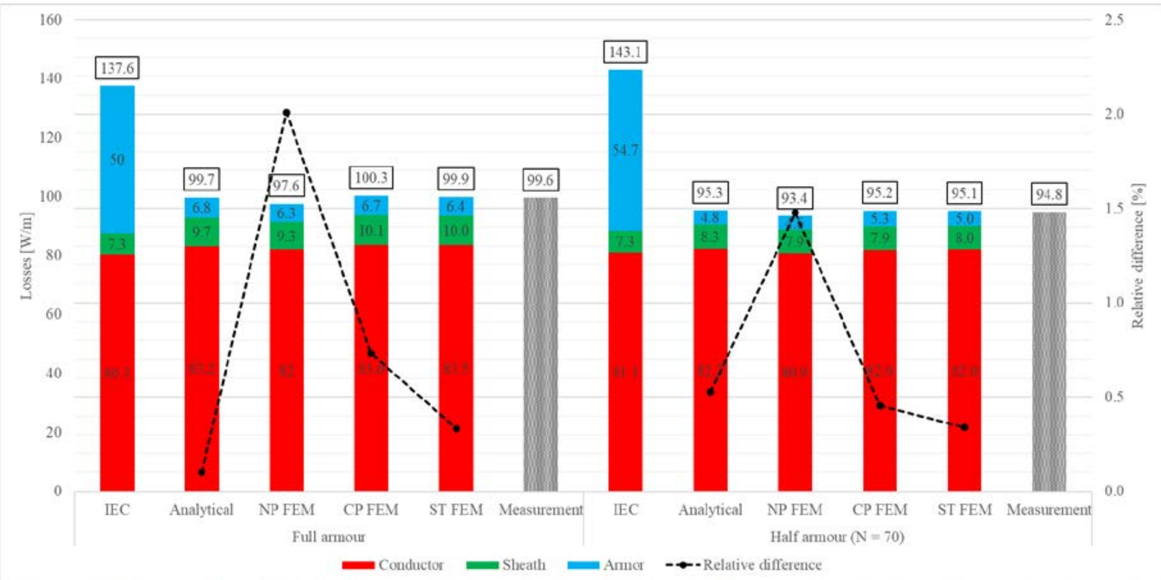

Figure 3: Cable 1a in single-point bonding with varying number of armour wires. Comparison of CP and ST 3D FE models against measurements, IEC 60287, NP 3D FEM and the analytical formulation of [15].

As the bars and the relative differences on the right y axis indicate, the results by the CP and the ST 3D FE models are in very good agreement with the measured ones, demonstrating their high accuracy. In addition, they have a relatively very good match with the corresponding of the NP 3D FE model and the analytical formulation of [15]. On the other hand, the losses according to the IEC standard differ to a significant extent, as expected, especially in the armour losses which are greatly overestimated. Finally, the decreased number of armour wires leads to lower losses in the armour, but also to lower losses in the sheaths due to the reduced magnetic flux in the cable interior.

3.1.3 Results for Cable 3

Cable 3 is a 3x1600 mm^2 copper cable in unilay configuration with high grade magnetic armour wires [7], [8]. The CP length of (1) is approximately equal to 8.2 m, making the use of the CP 3D FE model time consuming. On the other hand, the ST length of (3) is approximately equal to only 6.4 cm, highlighting its superiority in terms of efficiency and low computational burden. Figure 4 shows the comparison of ST 3D FE model against measurements, the IEC standard, the NP 3D FE model and the analytical formulation of [15], for both bonding configurations. Again, a good agreement is found between all modelling techniques and measurements, with the exception of the IEC standard, validating the use of the ST 3D FE model.

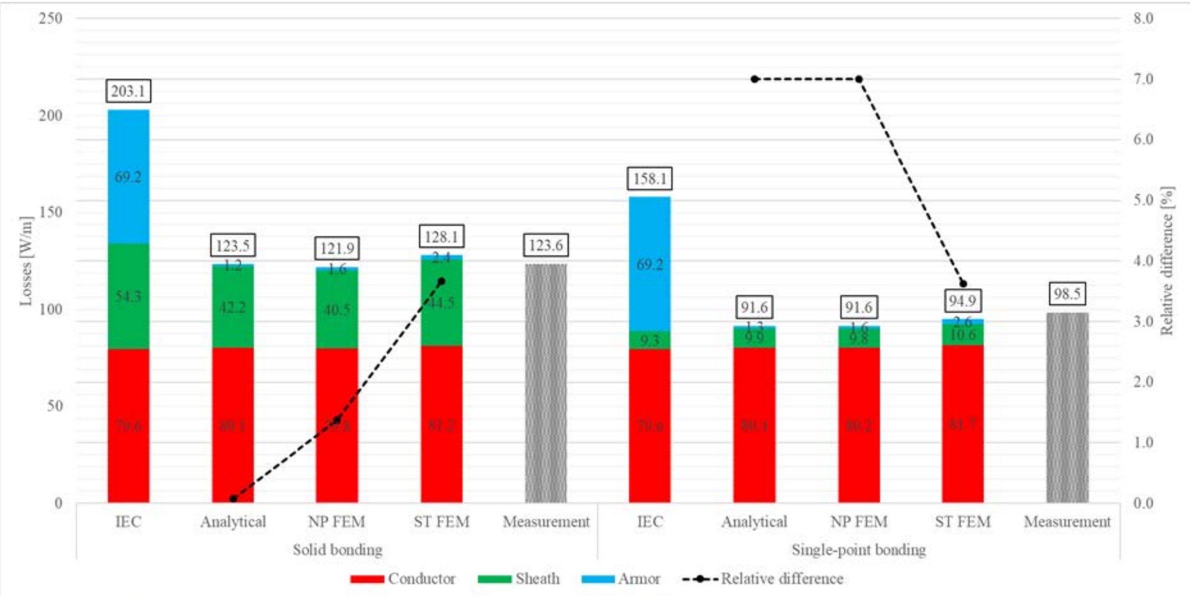

Figure 4: Cable 3 in solid and single-point bonding. Comparison of ST 3D FE model against measurements, IEC 60287, NP 3D FEM and the analytical formulation of [15].

3.1.4 Results for Cable 4

Cable 4 is a 3x2000 mm^2 aluminum cable with double flat armour consisting of low grade magnetic wires [8]. In this case, an extension of the ST 3D FEM model has been developed, which simulates the double flat wire armour based on the concept of ST periodicity. Specifically, the inclusion of the second armour layer relies on the search for the least common multiple once more. The second armour layer with a specific number of armour wires will fit in a ST fashion if it has the same twist as the cores or contains an additional integer number of consecutive switched positions for its wires [19]. If the resulting value is not close enough to the actual lay length of the second armour layer, the search can be repeated to the next periodicity plane. The search finishes when the desired cable geometry is adequately reproduced, taken also into account a user-defined tolerance on the three lay lengths to keep the computational effort low. Figure 5 presents the developed ST 3D FE model for cable 4 with a final model length of approximately 39 cm, based on the solution of the abovementioned optimisation problem.

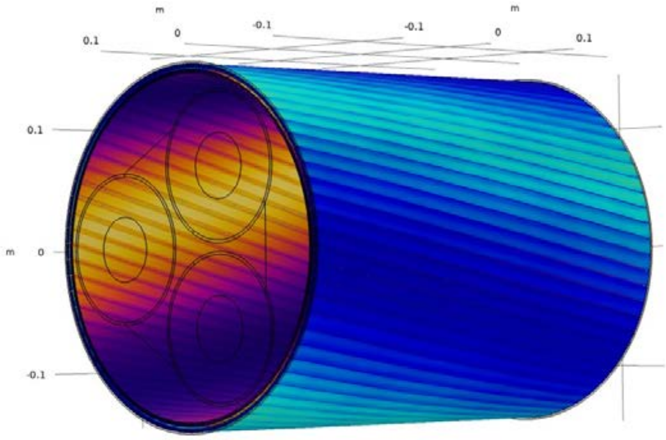

Figure 5: Extended ST 3D FE model for cable with double flat armour. Distribution of armour loss density in both layers with different colors. Absence of end effects due to rotated boundary conditions.

Figure 6 shows the comparison of ST 3D FE model against measurements, the IEC standard and the NP 3D FE model for both bonding configurations. Again, a good agreement is found between all modelling techniques and measurements, with the exception of the IEC standard for the solid-bonding case. Results validate the use of the ST 3D FE model even in the case of cables with two armour layers, highlighting also its great efficiency in terms of execution time.

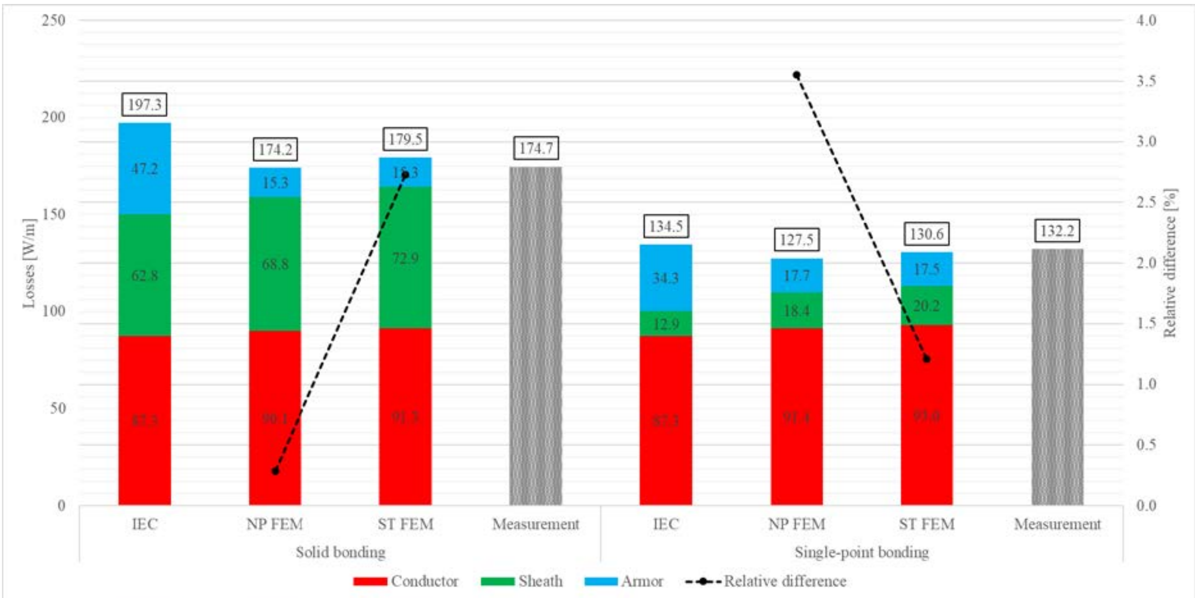

Figure 6: Cable 4 in solid and single-point bonding. Comparison of ST 3D FE model against measurements, IEC 60287 and NP 3D FEM.

3.1.5 Analysis of computational burden

All simulations have been performed in a workstation with two processors Intel® Xeon® Platinum 8276 and 512 GB of RAM memory. Table 1 summarises the relevant statistics for some of the simulations, including the model length, the average element quality, the degrees of freedom (DoF) and the execution time. It is evident that the longer model length of the CP 3D FE model results in a lower average element quality, higher number of DoF and higher execution time, but a relatively high degree of accuracy. On the other hand, the ST 3D FE model is more efficient due to its shorter model length, which allows for a finer mesh, improving the mesh quality and consequently the overall accuracy. Even in the more complex cases of unilay configurations or designs with double armour, the ST 3D FE model performs reliably and efficiently, with high accuracy.

Table 1: Indicative statistics for the simulation of the different cable designs.

	Cable 1a Full armour Solid-bonding		Cable 1a Half armour Solid-bonding		Cable 3 Solid-bonding	Cable 4 Solid-bonding
	CP 3D FEM	ST 3D FEM	CP 3D FEM	ST 3D FEM	ST 3D FEM	ST 3D FEM
Model length	1.8947 m	1.3631 cm	1.8947 m	1.3631 cm	6.392 cm	39.012 cm
Average element quality	0.4229	0.6242	0.4266	0.6231	0.5901	0.5858
DoF	7,359,616	688,429	4,069,799	697,190	1,842,027	3,153,552
Execution time	32 min 27 sec	2 min 14 sec	17 min 20 sec	2 min 12 sec	4 min 51 sec	14 min 5 sec

3.2 Comparison with in-house measurements

Besides the measurement data published in literature, in-house measurements, done on the basis of [11], for a three-core, wire armoured power cable have been performed and presented in this section as reference to validate the ST 3D FE model. Measured losses are allocated to components in the following manner: Conductor (DC plus Skin) loss corresponds to the square of the phase current multiplied by the measured conductor DC resistance augmented by the skin effect factor, which is calculated as per the IEC standard [1]; sheath circulating loss corresponds to the square of the sheath current per phase multiplied by the measured sheath DC resistance; non-circulating loss, which consist of all the remaining loss components, i.e., conductor proximity, sheath eddy current, armour eddy and hysteresis losses. Total cable losses are measured with an uncertainty not higher than 3% [11].

The cable tested is a typical export cable of nominal voltage 155 kV which consists of a 3x1000 mm^2 copper conductor and a contralay configuration with low grade magnetic round armour wires. Losses derived by the IEC standard, the analytical formulation of [15] and the ST 3D FE model are compared against measurements in Figure 7 for solid bonding configuration, at both ambient and elevated temperatures. It is noted that the method presented in [15] has been further improved during the last two years and this, improved, though not ultimate, version is used in the present section. The improved understanding of losses in submarine power cables will be further introduced in the CIGRE working group B1.64 and the adaptions to the analytical code will be part of the coming technical brochure. The applied current of conductor is 1250 A in both ambient and elevated temperature cases. It is evident the IEC standard deviates significantly from the values measured in terms of non-circulating losses: the IEC relative difference ε reaches up to 88% for the elevated measurement set-up, whereas the corresponding ST 3D FE percentage is about 3%. Also considering total cable losses, the IEC and ST 3D FE relative differences differ remarkably, i.e., about 21% and 3%, respectively. The ST 3D FE model appears to represent cable losses quite consistently if compared to both measured and values derived from the analytical formulation suggested by [15].

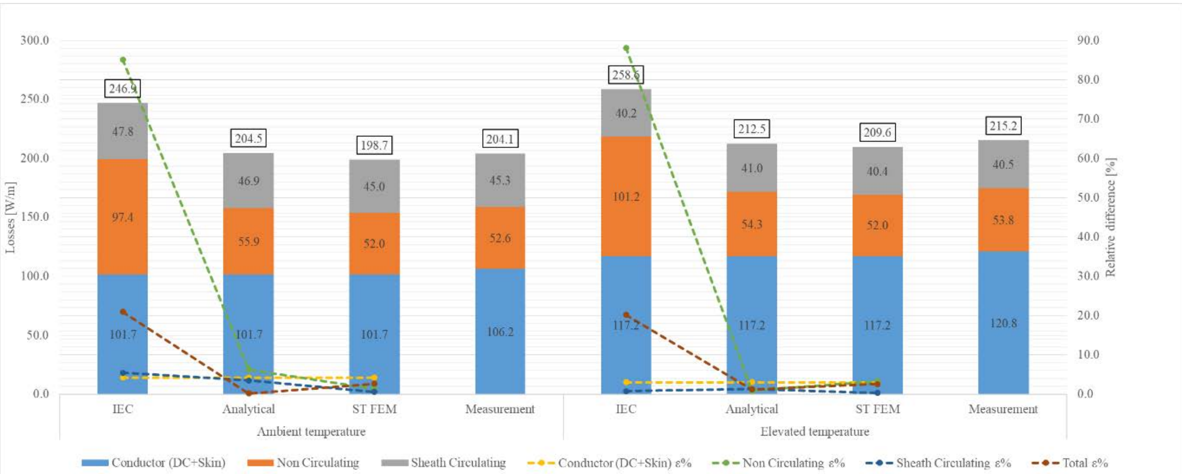

Figure 7: Cable in solid bonding at ambient and elevated temperature. Comparison of ST 3D FE model against in-house measurements, IEC 60287 and the analytical formulation of [15].

Loss figures derived by the IEC standard, the analytical formulation of [15] and the ST 3D FE model are compared against measurements in Figure 8 for single-point bonding configuration at ambient conditions for a conductor current equal to 1250 A. Again, the ST 3D FE model seems to be much closer to measurements compared to the IEC method in both non-circulating and total cable loss terms (5% compared to 66% for non-circulating loss). The slightly higher difference of measured total loss in single-point bonding case compared to solid bonding one (5% at single-point instead of 3% at solid bonding) might be attributed to the circulation of sheath-to-sheath currents due to the presence of semiconducting jackets above each cable cores, as also discussed in [21].

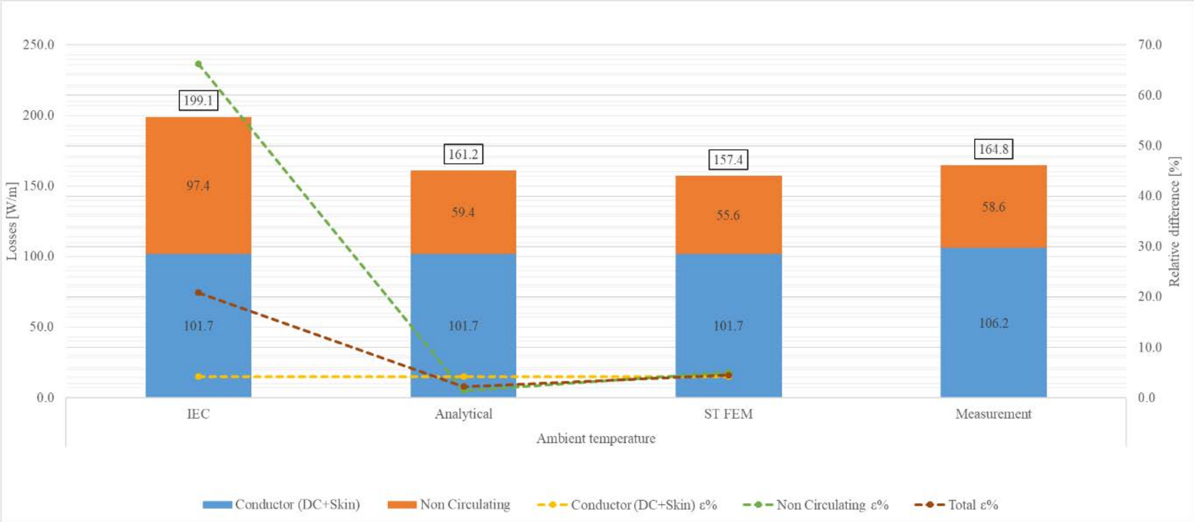

Figure 8: Cable in single-point bonding at ambient temperature. Comparison of ST 3D FE model against in-house measurements, IEC 60287 and analytical formulation of [15].

4. CONCLUSIONS AND FUTURE WORKS

An efficient 3D finite element approach is presented in this paper for loss calculation in three-core armoured cables. The so-called ‘short-twisted’ periodic model and its extension to cables with double armour layers are capable of reducing the total solution time down to minutes, without any loss in accuracy. The proposed model is verified against conventional FE approaches from the literature, as well as other analytical methods and measurements. In terms of total cable losses, the relative difference from measurements does not exceed 4%. Being valid, relatively easy to use and very efficient, the new ‘short-twisted’ model proves to be the ideal solution for quick and accurate cable loss calculation. At the same time, more realistic cable losses, which are significantly lower than those predicted by the international standards in some cases, occur, thus allowing for further design optimisation and, consequently, reduction in fixed cable costs.

Although the validity of the proposed model is demonstrated in this paper, this relates to cables consisting of metallic sheathed power cores, which is the typical design for export submarine cables. Cables consisting of combined wire-screen and metallic foil power cores, are mostly preferred for turbine-to-turbine interconnections. The proposed model needs to be extended to accurately cover this inter-array cable type. Furthermore, the presence of semiconducting layer, being often present in submarine cables, are not at all simulated in the context of the present study. These two points will be considered in future works.

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