# Estimating the losses in three-core submarine power cables using 2D and 3D FEA simulations

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## ABSTRACT

*2D and 3D FEA (Finite Element Analysis) simulation models are described and the solutions are discussed in comparison with the losses calculated according to IEC 60287. 2D FEA results have already shown significantly lower armour losses than IEC ones although the compensation of circulating currents in armour wires due to opposed stranding is not considered that way. Armour wire losses calculated by means of 3D FEA are even lower but through interaction of occurring losses shield losses increase. The influence of different magnetic permeability of steel wires and material temperatures is estimated to get an overview of developing losses. Finally, all calculated losses are compared and assessed.*

## KEYWORDS

IEC 60287-1-1; armour losses; three-core submarine power cable; FEM/FEA

## INTRODUCTION

Several recent publications have described and discussed the losses in armour wires of three-core submarine power cables [1] – [4]. Especially in case of larger cables they seem to be much lower than calculated using the IEC 60287 standard. Different approaches with measurements and simulations were made to investigate the losses in submarine power cables and the results clearly outline a too high loss factor $\lambda_2$. Thanks to large computation resources 3D FEA calculations with a huge amount of mesh elements can be performed and evaluated. The simulations are done for a three-core submarine power cable with copper conductors and a cross section of 1200 mm$^2$, screen is made of lead while armour consists of wires of ferritic steel. Consequently several investigations were performed to estimate occurring losses in consideration of magnetic permeability of armour wires and cable temperatures.

## SIMULATION MODEL

The 3D FEA model consisting of conductors (A), screens (B) and armour wires (C) is shown in Fig. 1. It is evident that all metallic components interacting with magnetic fields have to be considered. Other parts, namely semiconducting sheets, optical fibres with surrounding metal wires and XLPE fillers are neglected here.

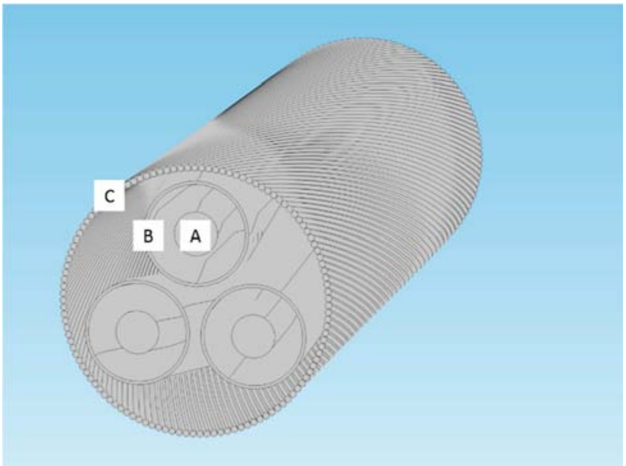


**Fig. 1: 3D FEA Simulation model of submarine power cable**

As a necessary simplification the copper wires of the conductors have to be summarized to reduce the complexity of the simulation model and thus the number of mesh elements. The complex stranding of single copper wires in Milliken conductors and additionally the unknown contacts are easier manageable by measurements than by FEA calculations. Undeniably, there is small difference because of the changed current distribution due to stranding of copper wires but here it is assumed that the effects due to electric and magnetic fields are similar for both massive and Milliken conductors. Stranding of conductors and armour wires is opposed and for both the pitch is in the range of a few metres. Sufficient simulation model length is chosen so that each armour wire crosses every conductor one time. In Table 1 the used material properties are listed.

| | Conductivity at 20°C (S/m) | Cross section (mm$^2$) | Magnetic permeability $\mu_r$ |
|---|---|---|---|
| Conductor | 5.8 $10^7$ | 1200 | 1 |
| Screen | 4.67 $10^6$ | 820 | 1 |
| Armour | 7.25 $10^6$ | 3350 | 50, 300, f(B) |
| Semiconductor | 2 | - | 1 |
| Other components | 0 | - | 1 |

**Table 1: Material and geometrical properties used in FEA simulations**

The material properties are according to IEC 60287-1-1. Investigations with higher temperatures are performed with conductivities determined by temperature coefficients as recommended in IEC, too. Different material parameters for magnetic permeability $\mu_r$ are considered. In cable applications a wide range of different steels with changing properties is conceivable. As the following results show, magnetic permeability has a significant influence on losses in armour wires and other components. As a matter of fact the magnetic permeability is not constant but changes with magnetic flux density. In separate FEA models the flux density dependent magnetic permeability is investigated. A curve is determined from measured hysteresis values of steel wires. Fig. 2 shows the magnetic permeability as a function of flux density.

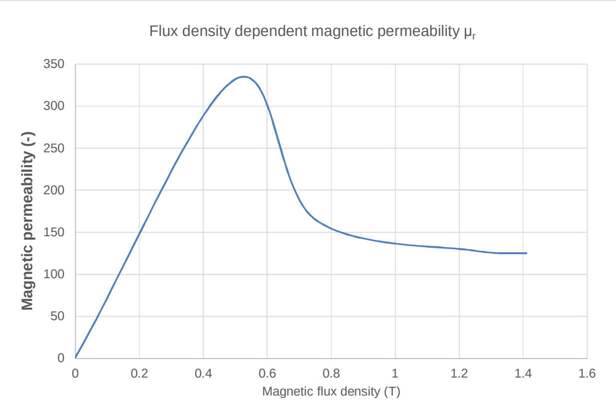


**Fig. 2: Permeability as a function of magnetic flux density**

Therefore the term f(B) means a flux density dependent and thus indirectly conductor current dependent magnetic permeability of steel wires. The additional two-dimensional simulations were performed with the model seen in Fig. 3.

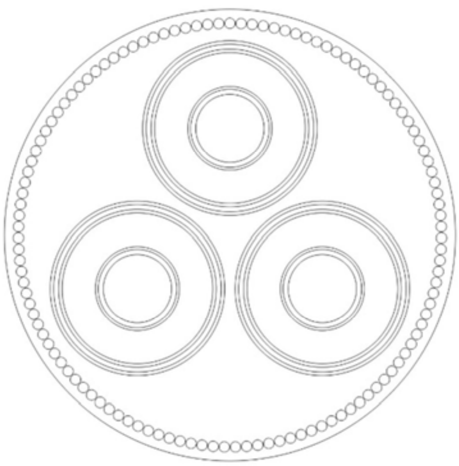

**Fig. 3: Two-dimensional simulation model**

Two-dimensional analyses can be performed much faster in comparison to the three-dimensional ones but the results do not completely reflect reality. A simplified approach to consider the mutual compensation of induced circulating currents is presented in [1]. In the case at hand, three dimensional simulations were used to evaluate the simplified two-dimensional results.

## LOSSES ACCORDING TO IEC STANDARD

In loss calculations according to the IEC standard, skin and proximity effect dependent conductor losses are calculated and using equations (1) and (2), the amount of screen and armour losses is determined.

$$\lambda_1 = \frac{P_S}{P} \qquad (1)$$

$$\lambda_2 = \frac{P_A}{P} \qquad (2)$$

$P_S$ and $P_A$ are screen and armour losses while $P$ is the sum of losses in conductors. The equations used for $\lambda_1$ and $\lambda_2$ are given in [6]. The sum of the losses per meter with a load of 1000 A per conductor for the investigated submarine cable is plotted in Fig. 4. At first the losses for a constant cable temperature of 20 °C are shown in the left respectively for a conductor temperature of 90 °C in the right bar. Here the screen temperature is 80 °C while the armour temperature is set to 60 °C. Temperatures in cable components are dependent on thermal conductivities of the cable, ambient conditions and power losses. The temperatures in screen and armour are estimated according to [7]. However, a precise calculation of temperatures is only possible if all thermal conditions and losses are exactly known. Therefore the used temperatures are in a realistic order but not exact.

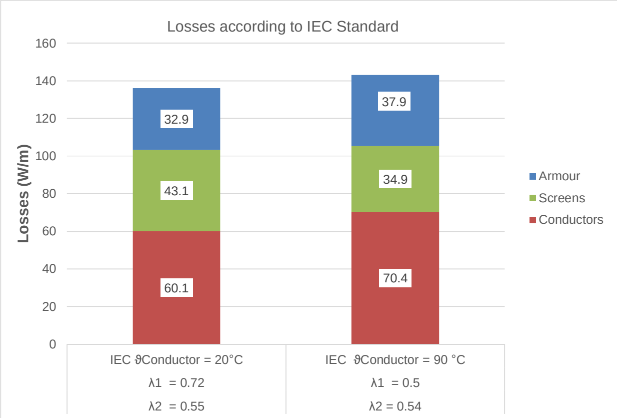


**Fig. 4: Losses in a three-core submarine power cable[1]**

As it can be seen, screen and armour losses play a significant role as they are in the same order of magnitude as the losses in the conductors. Conductor losses increase with higher temperatures due to lower conductivity whereas screen losses decrease. Armour losses increase as well, but in fact there is no considerable difference in loss factor because conductor losses increase at the same time. In accordance with the

[1] Estimated losses are for round conductors with $k_p$ and $k_s$ = 1. To estimate losses of Milliken conductors, smaller factors are used so conductor losses are lower. However, screen and armour losses remain the same due to correspondingly higher estimated loss factors. Purely physical consideration confirms that fact. Armour and screen losses are caused by the current flowing through a conductor so, consequentially, these losses are not affected by the amount of losses which occur in the conductor.

results presented in [4] and [5], a maximum of armour and screen losses can be expected considering a temperature dependent material resistivity.

## 2D AND 3D FEA RESULTS

In Fig. 5 and Fig. 6 the FEA results are pictured and further the 2D and 3D simulations are discussed. Losses with regard to volume are plotted as a graphical surface where only parts with losses have been visualized.

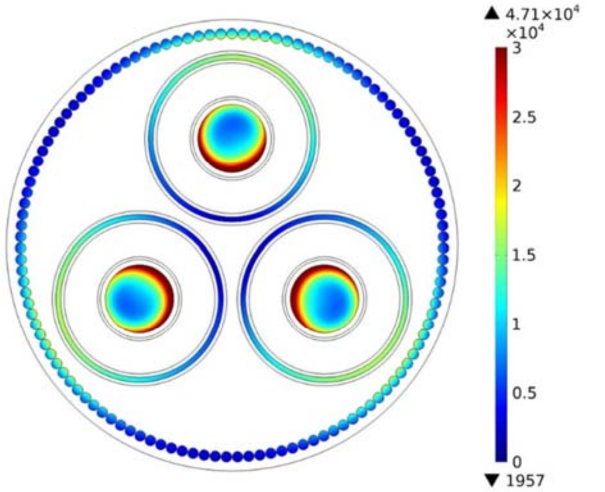


**Fig. 5: Calculated distribution of two-dimensional loss density (W/m$^3$) T = 20 °C; $\mu_r$ = 50**

All material properties are used as listed in Table 1 and the current per conductor is set to 1000 A (corresponding to the calculation of IEC losses). The influence of skin and proximity effect can clearly be seen. Screen losses in the inner regions are lower than in the outer ones and the characteristic distribution in conductors occurs as expected.

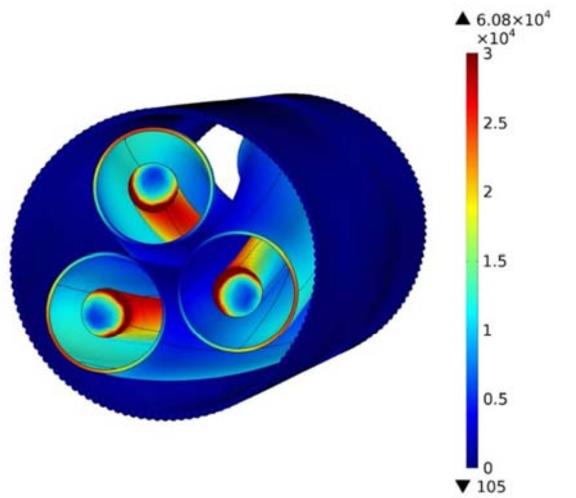


**Fig. 6: Calculated distribution of three-dimensional loss density (W/m$^3$) $\mu_r$ = 50**

The same graphical range is used for 2D and 3D FEA solution. As it can be interpreted by the pictures, in general loss distributions are similar - as they should be - but the amount of losses, especially in conductors and armour wires differs. The evaluated losses for all components are compared to IEC estimated losses in Fig. 7 and Fig. 8.

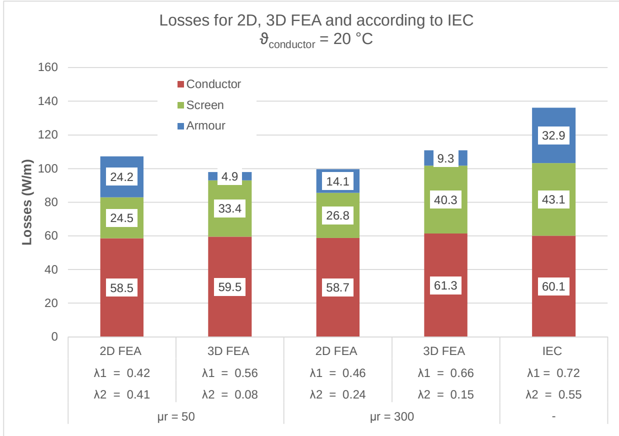


**Fig. 7: Comparison of simulated and estimated losses for an overall temperature of 20 °C**

The overall temperature is 20 °C. The losses that occur for higher temperatures are more interesting and therefore further calculations were executed.

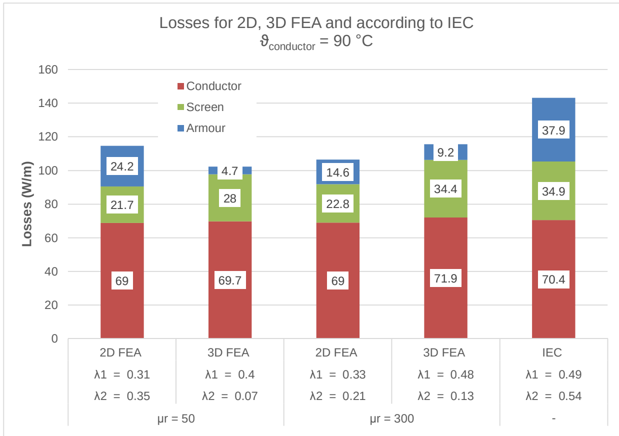


**Fig. 8: Comparison of simulated and estimated losses for temperatures of 90 °C, (conductor) 80 °C (screen) and 60 °C (armour)**

Obviously temperature increase results in higher conductor losses while screen losses decrease as expected. Contrary to IEC standard, armour losses decrease respectively the losses are not considerably affected. In this context it is interesting that each sum of all 3D FEA losses is nearly the same as calculated with constant temperatures of 20 °C. Nevertheless inner losses are more critical than outer ones due to low thermal conductivity of insulating materials. Comparing the figures of screen losses, considerably lower FEA results can be seen than calculated by IEC, except for a magnetic permeability of 300 (see Fig. 7 and Fig. 8 3D FEA $\mu_r$ = 300) where values are nearly identical. 3D FEA armour losses are low compared to losses according to the standard and even 2D FEA armour losses are noticeably smaller. The difference of 2D and 3D FEA armour losses gives an impression about the amount of circulating currents compared to eddy currents. Due to the compensation of circulating currents in 3D FEA models, armour losses must be caused by eddy currents. As a further interesting fact, screen losses increase due to the interaction of induced currents in the components. Missing circulating currents in amour wires, as in reality, result in larger circulating screen currents. Increasing screen losses through higher magnetic permeability (compare 3D FEA $\mu_r = 50$ and 3D FEA $\mu_r = 300$) can be determined confirming results of other authors [1]. The losses in armour and screen calculated with IEC standard and FEA are plotted as a function of conductor current in Fig. 9 and Fig. 10. In both diagrams all losses are for an overall temperature of 20 °C.

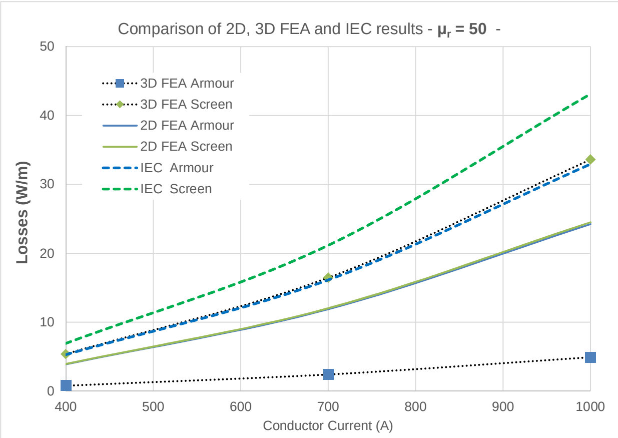


**Fig. 9: Comparison of screen and armour losses. Magnetic permeability $\mu_r = 50$**

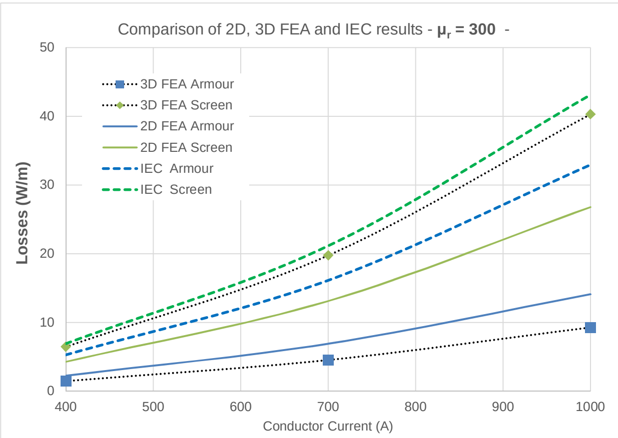


**Fig. 10: Comparison of screen and armour losses. Magnetic permeability $\mu_r = 300$**

Results are shown for a magnetic permeability $\mu_r$ of steel wires of 50 respectively 300. In case of armour wire permeability of 50 the 2D FEA armour and screen losses are nearly of the same magnitude. The marks show the 3D FEA losses which are calculated for three different conductor currents. The 3D FEA losses are approximately 15 % ($\mu_r = 50$) and 25 % ($\mu_r = 300$) of the IEC losses whereas the screen losses are about 60 to ~ 100 % of the IEC ones. Another interesting point is the comparison of the estimated loss factors $\lambda_1$ and $\lambda_2$. The following figures (Fig. 11 and Fig. 12) show the loss factors for different magnetic permeability at 20 °C.

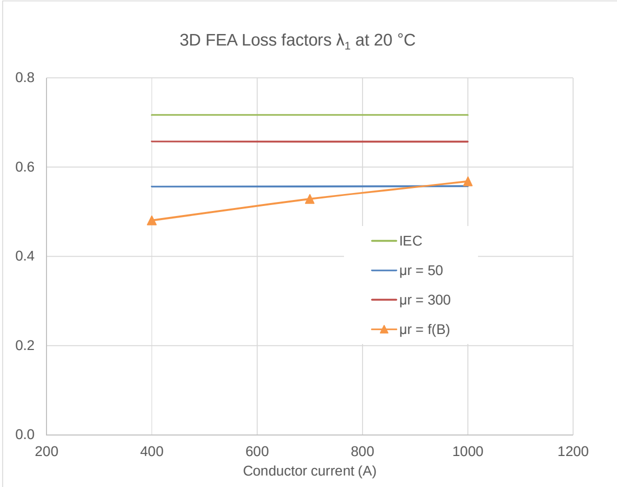


**Fig. 11: Loss factor $\lambda_1$ calculated wit 3D FEA**

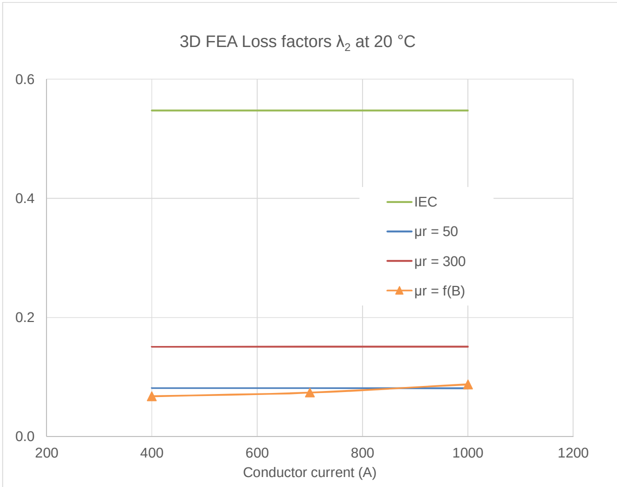


**Fig. 12: Loss factor $\lambda_2$ calculated wit 3D FEA**

When applying an overall equal temperature and a constant magnetic permeability, loss factors are the same for the whole current range as well as they are in the IEC standard. Implementing a magnetic field dependent permeability according to Fig. 2 results in a slightly changing loss factor $\lambda_2$ with increasing conductor current, but the magnitude of loss factor is nearly identical to the values of $\mu_r = 50$. In case of lower conductor currents, the calculated loss factor $\lambda_1$ is noticeably lower than for higher ones. Curves of loss factors for higher temperatures have the same shape, only the amount of these loss factors differs according to calculated losses. However, for higher currents (i.e. for a cable operating in the range it is designed for) there is no meaningful difference in loss factors $\lambda_2$ and $\lambda_1$ when applying a flux dependent permeability. Fig. 13 gives an overview of the estimated loss factors for different conditions.

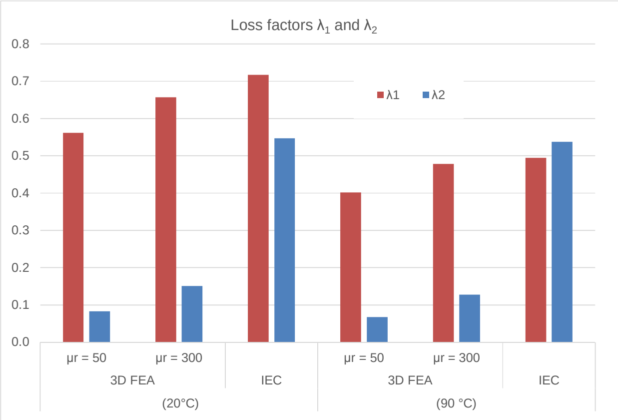


**Fig. 13: Overview of loss factors**

The summarized calculated values clearly show the overestimated armour loss factor $\lambda_2$ in IEC. Additionally, the screen loss factor $\lambda_1$ is slightly overestimated for some parameters. Magnetic permeability affects loss factors in similar orders as temperature gradients do.

## CONCLUSIONS

FEA simulations confirm former assumptions and measurements regarding too high loss factors $\lambda_2$ of three-core submarine power cables when calculated according to IEC. 2D FEA simulations results already show noticeable lower armour losses, while more realistic 3D FEA values clearly underline the overestimated loss factor $\lambda_2$. Additionally, screen losses are lower than calculated, but the difference is smaller and dependent on armour wire parameters. Calculated 2D FEA screen losses are lower than expected because of compensation of induced currents in screens due to, in the model, circulating currents in armour wires which do not occur in reality. Of course losses in cables are temperature dependent. An approximately proportional reduction of losses in screens with a temperature increase can be found in FEA calculations as well as in values according to IEC. When comparing FED and IEC armour losses at a temperature change deviating results can be observed. On one hand, calculated armour losses due to FEA are much less affected by temperature changes than according to IEC. On the other hand, with exception of one value, armour losses decrease (slightly) with temperature rise, contrary to IEC. Magnetic flux density dependent magnetic permeability results in conductor dependent armour and screen losses but the values for an implemented function determined by measurement were similar to a constant permeability of 50.

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