ARMOUR LOSS MEASUREMENTS IN THREE-CORE MEDIUM VOLTAGE CABLES: COMPARISON WITH IEC STANDARDS AND FEM CALCULATIONS

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ABSTRACT

Armour losses are calculated during the design process of submarine cables using IEC 60287-1-1 formulae. Several recent papers underline the possible overestimation of armour losses given by IEC standards. In this paper, armour losses are investigated on a medium voltage three-core submarine power cable. Different Finite Element Method (FEM) calculations and measurements are compared to IEC 60287 calculations and show the overestimation of armour losses given by this standard.

INTRODUCTION

Submarine power cables are designed with armour to protect the cable during storage and laying operation but also from external hazards like anchors or trawling gear. Armour is made of wires, generally steel wires, helically wound around the cores. Such metallic and magnetic armouring provides additional losses when alternating current flows in the cores and thus reduces the cable ampacity.

IEC 60287-1-1 [1] gives formulae in order to estimate amour losses but recent studies highlight that the use of this formulae yield to substantial overestimation of armour losses [2] [3] [4] [5] [6] [7].

The overestimation of armour losses during the design process yields to use a larger cable conductor cross section, thus the development of an accurate model may lead to a reduction of conductor size.

Two different ways were considered to estimate the amour losses: numerically using Finite Element Method and experimentally with measurements on a Medium Voltage (MV) three-core submarine cable. Measurements were performed at EDF Lab Les Renardières.

After a short introduction on the analytical calculation given by IEC standards, this paper presents different models that were used to estimate armour losses: a simple 2D model, the 2.5D model presented in [3] and a 3D model. Then the paper describes the experimental set-up used to measure armour losses and presents results obtained on a medium voltage submarine cable. Results from finite elements models and measurements are compared to calculations made using IEC standards.

CABLE DATA

The cable considered in this study is a 20 kV three-core submarine power cable with 95 mm² copper conductors and thin laminated copper screen. The single armour layer is made with steel wires and covered with PE sheath. The external cable diameter is equal to 86 mm.

ANALYTICAL CALCULATIONS

IEC 60287-1-1 gives formulae to calculate power losses in the different components of the cable (cores, screens, tapes, armour…). Different formulae depending on cable types are given. For a three-core submarine power cable, the armour losses are given by the λ_2 coefficient:

$$\lambda_2 = 1.23 \frac{R_A}{R} \left(\frac{2c}{d_A} \right)^2 \frac{1}{\left(\frac{2.77 R_A 10^6}{\omega} \right)^2 + 1}$$

With R_A the AC resistance of the armour, R the AC resistance of the conductor, d_A the mean diameter of the armour, c the distance between the axes of the conductors and the axis of the three-core cable (mm) and ω the pulsation.

The submarine power cable considered in this study has individual screens. As the screening effect of the screen currents reduces the armour loss, the λ_2 coefficient given above shall be multiplied by the factor below:

$$\left(1 - \frac{R}{R_s} \lambda_1' \right)$$

With Rs the AC resistance of the screen and λ'_1 the ratio of the losses in one sheath due to circulating currents to the losses in one conductor

The formulae in IEC standards comes from the model developed by Carter in 1928 [8] for three-core cable in a non magnetic metallic tube and was experimentally extrapolated by Arnolds in 1939 [9] to consider the magnetic behaviour of the armouring (in CGS units):

$$\lambda_a = \frac{x^2 x_a^2 \left\{ \frac{2(d+s)}{\sqrt{3}(d_a - t_a)} \right\}^2}{\left\{1 + \frac{13}{16} x_a^4 \right\} \left\{1 + \lambda_p \right\}^{0.5}}$$

with $x^2 = 4\omega / R_{dc}$ *where* R_{dc} *is the DC resistance of the conductor,* $x_a^2 = 4\omega / R_a$ *where* R_a *is the DC resistance of the armour, d is the conductor diameter, s the insulation thickness,* d_a *the external diameter of the armour,* t_a *the armour wire diameter,* λ_p *the proximity effect coefficient.*

IEC formula considers that the core and the armouring are laid parallel to each other and doesn't take into account the attenuation effect provided by the twisting of these components with different lay lengths.

<u>IEC formula gives armour loss factor close to 7,3% for the considered MV cable.</u>

FEM CALCULATIONS

Different models using FEM calculations were developed in order to estimate armour losses: a 2D model, a "2.5D" model presented in [3] and a 3D model. The 3D model is made using COMSOL software and the other ones using FLUX 2D software. Hysteresis losses are not considered in the different models presented in this paper but must be considered for future work.

<u>2D model</u>

Model description

The main hypothesis made with a 2D model is to consider that the core and the armouring are laid parallel to each other.

Figure 1 gives the cable geometry used for 2D FEM calculation. Some components (single phase PE sheaths, fillers...) were not implemented in the model because they do not influence the electrical and/or magnetic behaviour of the cable.

Also, the thickness of the metallic screens was increased to improve the mesh quality and also to prepare the 3D modelling (the screen resistance is the same between the modelling and the tested cable). The mean diameter of the armour is kept constant too. Comparisons between models with thin copper screen and thicker copper screen have been performed. The results are the same and it has been decided to use the model with "ticker" copper screen, which is more convenient in particular in the view of 3D model that will be presented later.

An electrical model is associated to the FLUX 2D model in order to be able to set screen and armour end connections (Figure 2). A resistance in parallel of screen and armour wires allows to define an open or a grounded connection. In this paper, screen and armour are grounded at both ends.

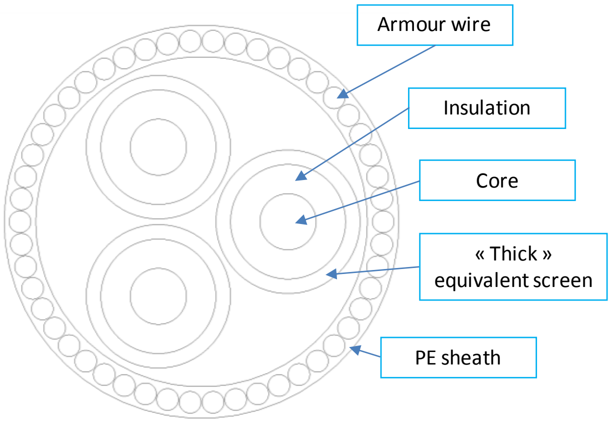

Figure 1: Cable geometry

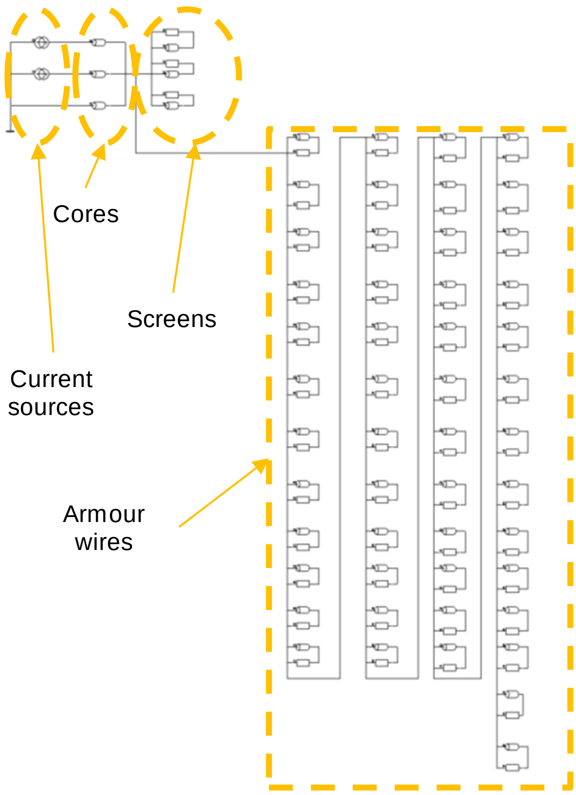

Figure 2: Electrical circuit to set the screen and armour connections

Simulations were performed using resistivity values of metallic cable components at 20°C in order to be compared to measurements. The current considered in the three phase AC conductors is 200 A.

Results

Figure 3 gives the power density distribution in each armour wire. It can be seen that the power density is higher in the wires located in front of a conductor.

The armour loss factor, λ_2, calculated with the 2D model is 1,53%.

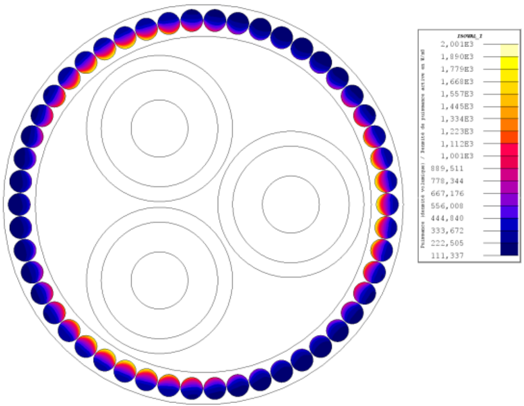

Figure 3: Power density distribution in armour wires with 2D model

"2,5D" approach

Model description

This model is based on the paper presented by Nexans at CIGRE 2010 session. The aim is to take into consideration the stranding effect of the armour wires that finally results in the cancellation of circulating current in armour due to conductor current induction [3].
The model uses the electrical circuit unit of FLUX 2D where armour wires are connected in series to cancel circulating current in armour.

Results

Figure 4 gives the power density distribution in the armour, which is much lower compared to 2D model. It is due to the model construction (cancellation of the net induced current in each armour wire). The armour losses obtained here are only due to eddy current losses as hysteresis losses are not considered in the models presented in this paper. One can ask whether the cancellation of the circulating currents in armour is not a too much optimistic hypothesis.

The armour loss factor, λ_2, calculated with the 2.5D model is 0,11%

The same results were obtained using the 2D model with the associated electrical circuit. Resistances in parallel with armour wires are set to a high value in order to consider the configuration with armour in open circuit. In this configuration, circulating currents are equal to zero and only eddy current losses are present.

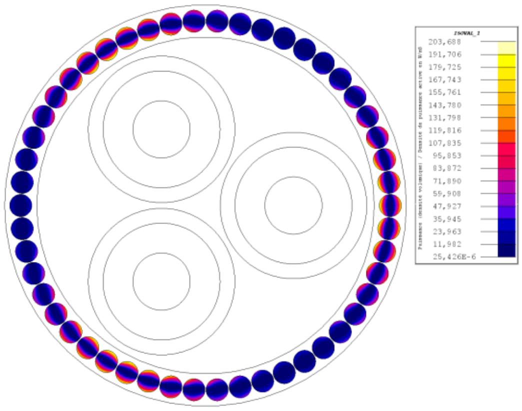

Figure 4: Power density distribution in armour wires with "2,5D" model

3D model

Model description

The more accurate way to consider the twisting of the different cable components on armour losses is to use 3D modelling. 3D model allows considering the different lay lengths of the cable conductors and of the armour wires.
The 3D model, given in Figure 5, is composed of three parts: the central part (complete helical pitch of armour) is used to calculate armour losses and the external part to overcome edge effects.

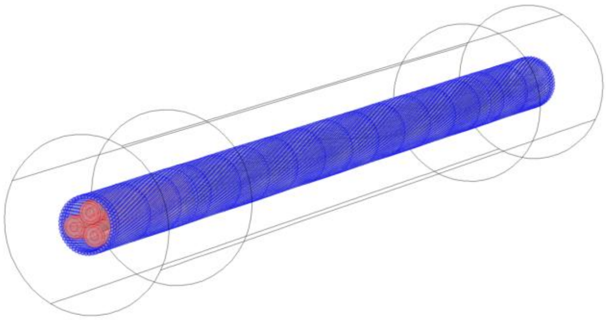

Figure 5: 3D model

The main issue consists in the optimisation of the mesh which number of elements can increase exponentially, especially at the places where small layers are modelled.

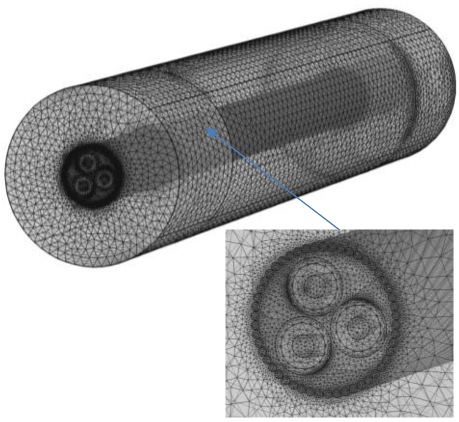

Figure 6: Mesh of the 3D model

Conductor and armour wires of the considered submarine cable have close, but different, twist lengths (around 1m). Thin layers as screens are impossible to model keeping a reasonable mesh size and quality. So, screen thickness is increased in the same way than for the 2D model.

Results

Figure 7 gives the screen and armour losses distribution and shows the impact of helical conductors. Figure 8 shows a 2D-plane view of the armour losses, close to the one obtained with the 2D models.

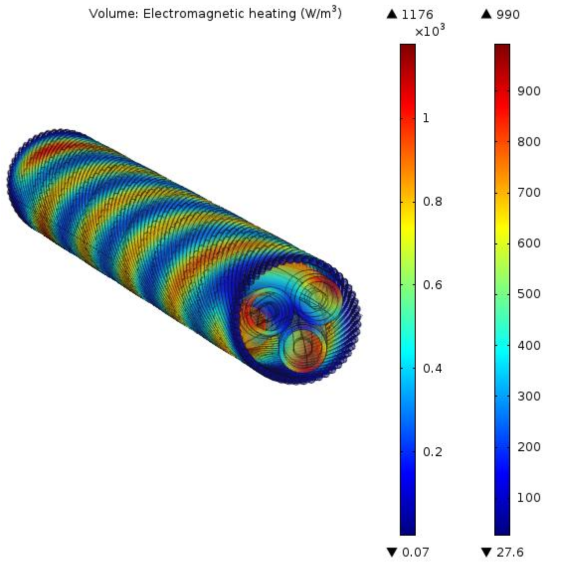

Figure 7: Armour and screen losses distribution with 3D FEM model

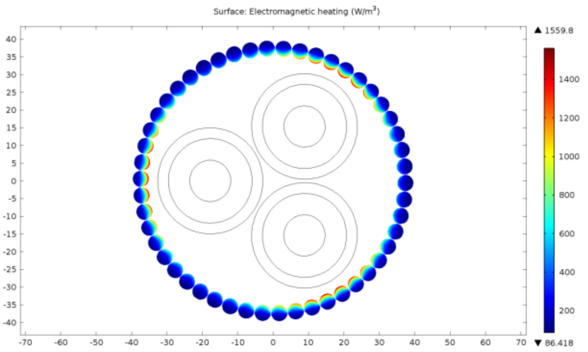

Figure 8: Armour losses distribution with 3D FEM model

The armour loss factor, λ_2, calculated with the 3D model is 1,19%.

MEASUREMENTS OF ARMOUR LOSSES

Experimental set-up

As experimental set-up, a cable loop with two submarine cable samples is used. The first sample is a 50 m cable with armour and the second one is the same cable without armour (10 m long).

The cable loop is composed of the two samples connected in series assuming to have always the same current flowing into the cores.

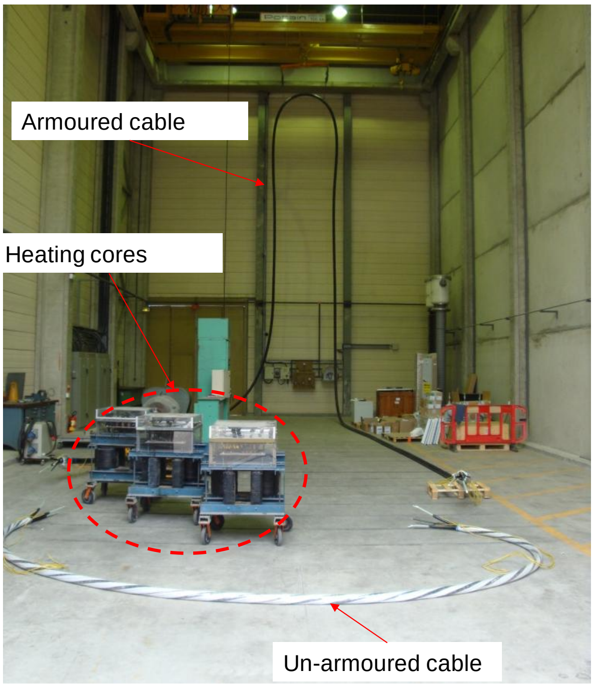

Figure 9: installation of cable samples at EDF Lab Les Renardières

Cable samples are short circuited at both ends and currents in the cores are induced using heating cores connected to the 50 Hz power network.
Different configurations have been considered for screen and armour connections but the configuration with screens in open connections and armour connected to the earth is the only one used to calculate the armour losses.
Different currents and voltages are measured in or across the cables with and without armour:

- Currents in cores, screens and also residual currents in the earth connections of the cable screens.
- Voltages induced across screens, cores and armour

Analysis of measurement results

The measurements of currents and voltages allow calculating the losses at different locations in the cable loop. Armour losses are determined through a power distribution analysis. They are determined with the following equation:

$$P_a = P_{tot} - P_{core\_na} - P_{core\_a} - P_{connec}$$

Where P_a the armour losses, P_{tot} the total power dissipated in the loop, $P_{core\ na}$ and $P_{core\ a}$ the core losses respectively in the sample without and with armour P_{connec} losses in connections.

Core losses are estimated using:

$$P = \frac{1}{nT} \int_{nT} u(t).i(t)dt$$

With u(t) and i(t) the measured voltage and current, n an integer and T the time period.

The low level of armour losses that have to be measured in the studied submarine cable involve to consider the uncertainty of the different measurement devices that were used.

The measured armour loss factor is then less than 2 % of the total core losses.
The uncertainty of measurements doesn't allow to be more precise.

COMPARAISON OF CALCULATED RESULTS AND MEASUREMENTS

Figure 10 gives a summary of the different armour loss factors obtained in this study.

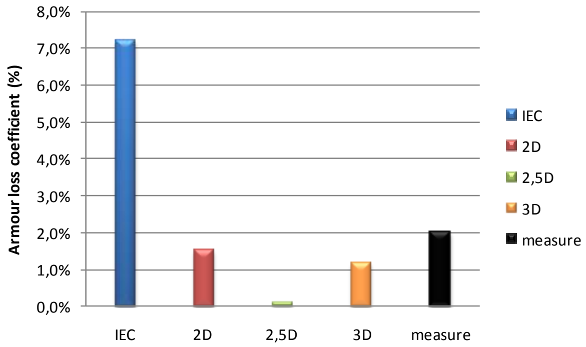

Figure 10: Assessment of the armour loss factor (IEC, FEM and measured)

Measurements made directly on MV submarine power cable not allow calculating precisely the armour losses. Nevertheless considering uncertainty of the measurements, it can be determined that this armour loss factor is comprised in the interval 0-2%. Measured armour loss factor is lower than the one given by IEC.
FEM models show also armour loss factor lower than IEC. Armour loss factor given by 2D and 3D models is close to the measurements. Difference between 2D and 3D models is about 22%, showing the impact of the twisting effect.
Regarding "2,5D" model, the armour loss factor is much lower probably due to the strong hypothesis made (no circulating currents in armour). Unbalanced currents and induced voltages but also localized contacts between armour wires can create circulating currents in the armour.

CONCLUSION

Armour losses in MV submarine power cable are investigated in this paper using Finite Elements Models and laboratory measurements and are compared to results calculated by IEC standard formulae.
It has been shown that, in all the cases, amour loss factor is lower than the one calculated with IEC formulae.
The set-up used for measurements needs improvements to address more accurately the armour losses. Especially, better results will be obtained if armoured and un-armoured cable samples have the same length. In this case, "simple" differential power analysis will be possible.
FEM models must be improved to consider hysteresis losses.
Measurements on high voltage submarine cable with larger cross section of conductors are also of interest. The use of larger cross section of conductors leads to higher armour losses, easier to measure.
Particular armour design must be also studied as for example double armour [4], armour with insulated armour wires or non-magnetic wires, or armour with a combination of steel and PE armour wires.

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