Accurate analytic formula for calculation of losses in three-core submarine cables

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ABSTRACT

Accurate calculation of cable losses is crucial to design optimised and cost effective cable connections. However, for three core submarine cables, a standard calculation method is not available, and the commonly used rating method described in IEC 60287 substantially overestimates the armour losses. In this paper an analytical model to calculate both the sheath losses and armour losses of three-core submarine cables is presented, and compared with 2D and 3D Finite Element calculations and measurements on three different three-core cables.

The model consistently accounts for the relative twisting of the armour with respect to the conductors, which is important to accurately calculate how the armour influences the cable losses, both directly in the armour and indirectly in the cable sheaths. Due to the field dependent permeability and hysteresis losses in the armour, the cable resistance increases with current [2][3][4], a feature that is consistently accounted for in the formulas.

KEYWORDS

Armour losses, submarine cable, XLPE cable

INTRODUCTION

Accurate calculation of power loss in three-core cables is becoming increasingly important in order to cost-optimise the cable design in many submarine applications. Dynamic rating of submarine cables connecting offshore windfarms is one of many examples. Since the conductor temperature increases with cable losses and the armour loss according to IEC 60287 may reach up to 40-50% of the total loss, a too conservative calculation of the armour loss may lead to unrealistically high conductor temperatures and oversized conductors. This paper proposes analytic formulas for armour loss in three-core cables for better cost optimisation. The analytic equations are compared to measurements and FEM-calculations, showing good agreement.

ARMOUR LOSSES

Due to the twisting of both the armour and power phases of submarine three-core cables, the cable parameters are more complicated to estimate than for standard underground cables, having no armour. When averaged over one effective pitch length between the phases and armour, the armour wires will see a zero induced voltage [1]. The losses in the armour are as such only due to eddy currents and hysteresis losses, not circulating currents. This cancellation by stranding was first noted in Ref. [1], and a 2.5D finite element model was developed that showed good comparison with measurements on power umbilicals and power cables at low currents.

As described by IEC 60287-1-1 for armoured single core cables [2], the angle between the armour wires and the power phases influences the armour losses. This is because the magnetic field parallel to the armour wire will behave differently than the magnetic field perpendicular to the armour wire. This was recently incorporated in a circuit model and a Finite Element Model of a three-core submarine cable [3]. From Maxwell's equations it can be derived that the parallel component of the magnetic field is continuous at the boundary between two different materials (1 and 2)

$$H_{||}^{(1)} = H_{||}^{(2)} \quad [1]$$

And the perpendicular component of the magnetic flux density is continuous

$$B_{\perp}^{(1)} = B_{\perp}^{(2)} \quad [2]$$

To study how the armour influences the impedance of a threecore cable Ampères law and Faraday's law is used

$$\nabla \times \left(\frac{1}{\mu}\nabla \times \boldsymbol{A}\right) = \boldsymbol{J} \quad [3]$$

$$\boldsymbol{E} = -\nabla V - \frac{d\boldsymbol{A}}{dt} \quad [4]$$

Ampères law describes how a current creates a magnetic field, and Faraday's law describes how a time varying magnetic field creates an induced current/voltage.

First a single armour wire is studied in a field with both a component parallel $B_{\|}$ and perpendicular $B_{\perp}$ to the wire (see Figure 1). Outside the armour wire there is no current J=0, which gives in cylindrical coordinates for the component parallel to the wire

$$\frac{1}{\rho}\frac{\partial(\rho A_{\varphi}(\rho))}{\partial \rho} - B_{\|} = 0 \quad [4]$$

With solution

$$A_{\varphi}(\rho) = \frac{1}{2}\rho B_{\|} + \frac{C_{out}}{\rho}$$

And inside the armour wire (J≠0)

$$\frac{\partial}{\partial \rho}\left[\frac{1}{\rho}\frac{\partial \rho A_{\varphi}(\rho)}{\partial \rho}\right] - \kappa^2 A_{\varphi}(\rho) = 0 \quad [5]$$

Where $\kappa = (1-j)\sqrt{\frac{\omega\sigma\mu}{2}}$, ω is the angular frequency, σ is the conductivity of the armour wire, and μ is the magnetic permeability. With general solution

$$A_{\varphi}(\rho) = C_{in}\boldsymbol{I_1}(\kappa\rho) \quad [6]$$

Where $\boldsymbol{I_1}(x)$ is the modified Bessel function of first kind (bold is used to differentiate Bessel function from current). Solving with appropriate boundary conditions the solution is