

Inductance Computation of Submarine Three-Core Cables Based on the Partial Element Equivalent Circuit Method

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The per-unit-length series inductance of three-core submarine cables is an important parameter for network analysis and cable design. Starting from an existing Partial Element Equivalent Circuit formulation, an efficient approach is proposed for the computation of this important parameter. The results obtained are compared with those of an FEM reference model.

Index Terms—Partial element equivalent circuit method, submarine cables, inductance.

I. INTRODUCTION

IMPORTANT elements of the electrical system in offshore wind farms are the connections between the substations where the voltage is elevated and the mainland. To this end, high-voltage three-core submarine cables are installed. This has led to a growing interest in the design and accurate rating of such kind of power cables.

The accurate computation of series impedances is crucial for network simulations and in the design phase. The twisted geometry of a three-core cable inherently requires a three-dimensional electromagnetic analysis to take into account all 3D effects [1]. In fact, the helically twisted phase conductors introduce a longitudinal magnetic field component that makes the 2D as well as 2.5D analysis inaccurate [2].

In this work, starting from the Partial Element Equivalent Circuit (PEEC) formulation presented in [3] we derive an approach for the computation of the per-unit-length (pul) series inductance of a submarine power cable.

II. FORMULATION

Let us suppose that the cable is excited by a three-phase AC symmetric system of currents with rms value I as in Fig. 1.

The cable positive sequence pul series impedance is made up of a resistance and an inductance. The former can be obtained from Joule losses, computed as in [3]. The latter (L_{pul}) is related to the time average pul magnetic energy $W_{\text{m,pul}}$ as:

$$L_{\text{pul}} = \frac{2W_{\text{m,pul}}}{3I^2}. \quad (1)$$

Let Ω_0 be a section of the cable of length l [3]. The time average pul magnetic energy can be computed from the magnetic vector potential $\mathbf{A}$ and current density $\mathbf{J}$ as

$$W_{\text{m,pul}} = \frac{1}{2l} \Re \left\{ \int_{\Omega_0} \mathbf{A} \cdot \mathbf{J}^* d\Omega \right\}. \quad (2)$$

The magnetic vector potential can be written as the sum of two terms: the first ($\mathbf{A}_c$) generated by the phase currents

and the second ($\mathbf{A}_s$) generated by the currents induced in the sheaths. Let Ω_{0c} and Ω_{0s} be the intersections between Ω_0 and the domains of phase conductors and sheaths respectively. The integral in (2) can be decomposed in four terms:

$$\begin{aligned} \int_{\Omega_0} \mathbf{A} \cdot \mathbf{J}^* d\Omega &= \int_{\Omega_{0c}} \mathbf{A}_c \cdot \mathbf{J}^* d\Omega + \int_{\Omega_{0c}} \mathbf{A}_s \cdot \mathbf{J}^* d\Omega \\ &+ \int_{\Omega_{0s}} \mathbf{A}_c \cdot \mathbf{J}^* d\Omega + \int_{\Omega_{0s}} \mathbf{A}_s \cdot \mathbf{J}^* d\Omega. \end{aligned} \quad (3)$$

In the full paper, we will show that:

$$\int_{\Omega_{0c}} \mathbf{A}_s \cdot \mathbf{J}^* d\Omega = \left(\int_{\Omega_{0s}} \mathbf{A}_c \cdot \mathbf{J}^* d\Omega \right)^* \quad (4)$$

and also that:

$$\Re \left\{ \int_{\Omega_{0s}} \mathbf{A}_c \cdot \mathbf{J}^* d\Omega \right\} = -\Re \left\{ \int_{\Omega_{0s}} \mathbf{A}_s \cdot \mathbf{J}^* d\Omega \right\}. \quad (5)$$

Using (4) and (5), (2) can be written as

$$\begin{aligned} W_{\text{m,pul}} &= \frac{1}{2l} \Re \left\{ \int_{\Omega_{0c}} \mathbf{A}_c \cdot \mathbf{J}^* d\Omega \right\} \\ &- \frac{1}{2l} \Re \left\{ \int_{\Omega_{0s}} \mathbf{A}_s \cdot \mathbf{J}^* d\Omega \right\}. \end{aligned} \quad (6)$$

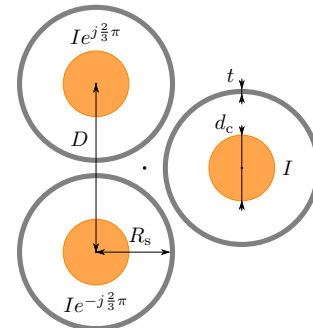


Fig. 1. Three-core cable cross section.

TABLE I
CABLE PARAMETERS.

Parameter	Value
d_c	38.5 mm
t	3 mm
l	20 mm
D	98.66 mm
R_s	43.33 mΩ
σ_s	4.67 MS/m

The first term of the rhs in (6) can be written in terms of the phase conductor pul positive sequence inductance $L_{c,pul}$ as $3L_{c,pul}I^2/2$. The second term is calculated using the PEEC formulation [3].

At power frequency sheaths can be approximated as thin shells and described by a representative surface. PEEC formulation [3] is written in terms of the normal component of the electric vector potential T , which is discretized using linear nodal basis functions on a triangular mesh. The discretized form of (2) is then given by:

$$W_{m,pul} = 3\frac{1}{2}L_{c,pul}I^2 - \frac{t}{2l}T^{t*}LT \quad (7)$$

where the elements of vector $T \in \mathbb{C}^{N \times 1}$ are the values of the potential T at each node of the mesh, while $L \in \mathbb{R}^{N \times N}$ is the inductance matrix introduced by the PEEC method.

Introducing (7) into (1) gives the final expression for the cable pul series inductance

$$L_{pul} = L_{c,pul} - \frac{t}{3lI^2}T^{t*}LT. \quad (8)$$

Being the focus of this work on the contribution of the sheaths on the cable pul series inductance, we assume that the current density over the round cross sections of phase conductors is uniform. Hence, in this preliminary study we neglect skin and proximity effects in the phase conductors so that $L_{c,pul}$ can be computed as

$$L_{c,pul} = \frac{\mu_0}{8\pi} + \frac{\mu_0}{2\pi} \log\left(\frac{2D}{d_c}\right). \quad (9)$$

III. RESULTS

The proposed method is preliminary tested on an infinitely long rectilinear cable in order to be compared against overkilled 2D FEM simulations carried out with a commercial software. The cable parameters are listed in TABLE I, whose meaning is explained in Fig. 1. The current density is assumed to be uniform on the phase conductor cross sections also in the reference FEM model.

Pul inductance is computed as a function of sheath thickness (Fig. 2) and sheath electrical conductivity σ_s (Fig. 3) and a very good agreement with FEM is observed. The simulations are performed at 50 Hz and with unitary currents.

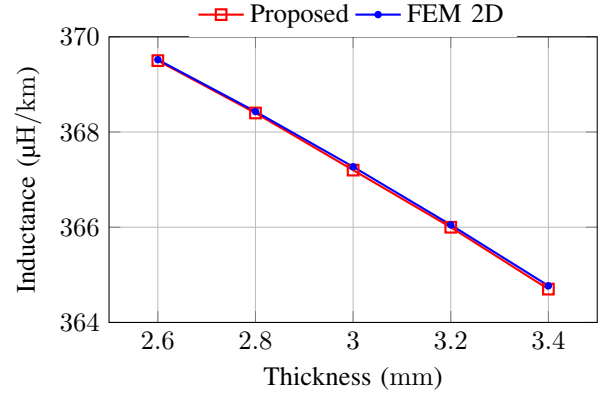


Fig. 2. Inductance as a function of sheath thickness.

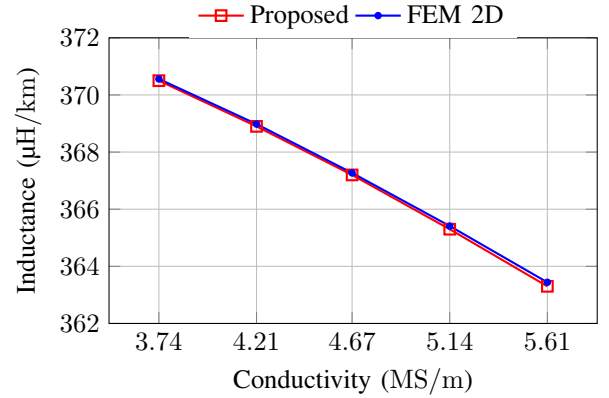


Fig. 3. Inductance as a function of sheath electrical conductivity.

IV. CONCLUSION

A methodology based on PEEC and an energetic approach was presented for the computation of the pul series inductance of a submarine power cable. A very good agreement with FEM was obtained in a preliminary 2D analysis.

In the full paper, the proposed approach will be tested in a realistic 3D twisted cable geometry.

The proposed method could also be compared with an alternative approach based on the computation of the pul voltage drop on the phase conductors by means of their PEEC discretization, following [4].

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