Efficient computation of losses in metallic sheaths and armor of AC submarine cables

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ABSTRACT

The problem of computing efficiently and accurately the armor losses in three-core AC submarine cables has been of great interest to the offshore cable community for some years. Indeed, the efficiency of the computation method is crucial to allow comprehensive parametric analysis as might be needed in the design study.

An algorithm based on integral equations for performing such calculations with an accuracy comparable (within acceptable tolerances) to state-of-the-art Finite Element Method (FEM) approaches is presented.

In particular, we discuss how exploiting the cable structure periodicity and symmetry leads to huge computational cost reductions.

KEYWORDS

Submarine cables, Eddy currents, Numerical simulation.

INTRODUCTION

The installed capacity of offshore wind farms has steadily increased in recent years. This has led to a growing interest in the accurate rating of submarine power cables that connect offshore generators between themselves and the mainland.
In particular, armored three-core AC submarine cables are quite difficult to model accurately. Both core conductors and armor wires are twisted, with different pitches, and armor wires are stranded either with opposite (contralay) or same (equilay) orientation as the phase cables. This intrinsically 3D geometry affects in a non-trivial way the magnetic behavior of the cable, rendering 2D models inaccurate.
The first studies using 3D FEM revealed that 2D FEM simulations are not reliable for their limited accuracy.
Recently there have been efforts toward the improvement of 3D computational models using FEM [1-3]. These models have the potential of being highly accurate so that they can be considered as a benchmark for validating alternative methods but are computationally demanding both in terms of computer memory (hundreds of GB of memory) and simulation time (hours of computation).
To lower the computational requirements of these 3D FEM models, several recent works have proposed to exploit the symmetries which characterize a submarine cable. By means of progressively more sophisticated use of these symmetries, these approaches have allowed shortening the length of the cable model [1], [4].
In this article, we present an alternative 3D computational method, based on integral equations, which can be used to compute losses in armored three-core cables with good accuracy.
The method considers the presence of both wire armor and conductor sheaths. For the armor, we use the formulation proposed in [5], while for the sheaths we employ a formulation for thin conducting surfaces [6]. These two formulations can be easily coupled to take into account the mutual interaction between armor and sheaths. Both the formulations are based on integral equations, thus, compared to FEM models, they have the advantage of requiring the discretization of the magnetically active regions only.
The exploitation of cable symmetries is taken one step further with respect to [4]: symmetries are used not only for reducing the size of the computational domain but also to confer a block-circulant structure to the matrix of the linear system. This structure can be exploited for reducing computational time and memory requirements during the assembly and solution of the fully coupled linear system of equations arising from the discretization of the proposed integral method.
The algorithm described in this paper has been implemented as part of a suite of simulation tools that are currently in use by industrial system designers in their real industrial activity. The required training for the use of the developed code is very low.

THE SYMMETRY OF CABLE GEOMETRY

The geometry of a submarine three-phase cable features a regularly repeating structure, arising from the helical twisting with pitch P_S of the core conductors and sheaths and the helical twisting with a pitch P_A of the external armor.

This regularly repeating structure allows building the cable geometry by replicating, with appropriate geometrical transformations, a single elementary unit cell. This fact can be exploited to reduce the computational requirements of numerical simulations.

To find the unit cell and the set of transformations that allow describing the entire geometry of the cable, we analyze the geometrical transformations which leave the cable armor Ω^A and the metallic sheaths Ω^S unchanged, at first separately and then jointly.

We consider a xyz cartesian frame whose z-axis coincides with the axis of the cable. Let $R\,(\Theta)$ denote the matrix associated to a rotation by an angle Θ around the z-axis

$$R(\Theta) = \begin{bmatrix} cos(\Theta) & -sin(\Theta) & 0 \\ sin(\Theta) & cos(\Theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad [1]$$

and $\boldsymbol{t}(l)$ denote the vector associated to a translation by a distance l along the z-axis

$$\boldsymbol{t}(l) = \begin{bmatrix} 0 \\ 0 \\ l \end{bmatrix} \qquad [2]$$

If the number of armor wires is N, then the armor geometry is invariant by the transformations

$$\tau_n^{A_1}(\boldsymbol{x}) = R_n^{A_1}\boldsymbol{x}, \quad n = 0, 1, \dots, N-1 \qquad [3]$$