FINITE ELEMENT MODELS FOR COMPUTING THE AC RESISTANCE OF MILLIKEN CONDUCTORS

A. Piwonski[1], J. Dular[2], R. S. Rezende[1], R. Schuhmann[1]

[1]Theoretische Elektrotechnik, Technische Universität Berlin, Berlin, Germany
a.piwonski@tu-berlin.de
[2]TE-MPE-PE, CERN, Geneva, Switzerland

Keywords: Coordinate transformation, Finite element method, Homogenization, Milliken conductor, Spatial Fourier series.

Abstract

Milliken conductors are a common design choice for the inner conductors of AC high voltage power cables. Determining their AC resistance numerically is a challenge due to the arising multiscale problem (strand diameter vs. pitch length of the strand layers vs. pitch length of the segments). We propose a finite element model that takes advantages of helicoidal symmetries and homogenization techniques.

1 Introduction

For the transmission of large amounts of energy, high voltage power cables with large cross-sections are widely used (e.g. 3000 mm² copper cross-section). In AC operation, the skin effect prohibits the economical use of a solid inner conductor even at relatively low frequencies such as 50 Hz. This is one of the reasons why these inner conductors are specially designed as so-called segmented or Milliken conductors (see Fig. 1). The entire cross-section is typically divided into five to six electrically insulated segments, which twist around the conductor core. Each segment also consists of insulated layers of strands, which in turn are twisted around the respective segment core (different directions and strengths of twist possible).

Determining the AC resistance is a challenge both numerically (multiscale problem) and metrologically, as no standardized measurement method is available for this, which leads to high relative differences in results for one and the same cable prototype [1]. In recent years, approximate formulas have been developed to determine the AC resistance, but these do not take into account many design parameters such as the number of segments or the different pitch lengths of the strand layers [2, 3]. In addition, some of these formulas were adjusted to the measured resistance, which seems questionable without a standardized measurement method.

To fill this gap, our research focuses on computationally efficient finite element based Milliken conductor models. We reduce the computational costs compared to a brute force 3-D model by exploiting helicoidal symmetries and homogenization methods.

Figure 1: Cross-section of a Milliken conductor with six segments.

2 Homogenization method for helicoidally symmetric cell problems

2.1 Helicoidal symmetry

If applicable, an elegant method to reduce computational costs is to exploit the symmetries of a problem. In previous work we demonstrated how to solve helicoidally symmetric eddy current boundary value problems (ECBVP's) equivalently in 2-D [4, 5]. Here, the key idea is the introduction of a coordinate system in which an equally twisted structure, with common axis of rotation, appears straight (see Fig. 2).

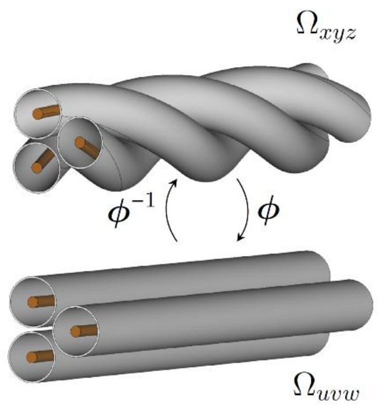

Figure 2: Effect of coordinate transformation applied to helicoidally symmetric structure [5]. The transformed ECBVP can be solved in Ω_{uvw} in 2-D.

Unfortunately, the aforementioned method cannot be applied directly to Milliken conductors, as there are two different twist levels: a) the twist of the segments around the conductor core with characteristic pitch length p_s and b) the twist of the i-st strand layer around its respective segment core with characteristic pitch length $p_{l,i\in N_l}$, where N_l denotes the number of strand layers in a segment.

2.2 Homogenization at strand layer level

We consider the two different twist levels one after the other. Here, the idea is to summarize the effect of the twist at the strand layer level separately in homogenized material properties, which can then be used as massive material at the segments twist level.

Homogenization techniques can appear very different in computational electromagnetics. In this work, we follow the ideas of [6]. In a nutshell, here it is ensured that the averaged apparent power of the homogenized model and the model before homogenization is invariant. This is achieved by introducing a modified, complex-valued reluctivity tensor $\boldsymbol{\nu}_{\mathrm{prox}}$, which summarizes losses due to the proximity effect. Additionally, an impedance Z_{skin}, which is coupled externally to the field problem, summarizes losses due to the skin effect.

To extract the influence of skin and proximity effect separately, the cell problem, i.e., one layer of twisted strands (see Fig. 3, left), is excited as following:

a) Skin effect excitation: A fixed total current is imposed (at a given frequency) into each of the twisted strands.
b) Proximity effect excitation: The layer of twisted strands is subject to homogeneous external magnetic fields (separated in transversal and longitudinal direction) and zero total current is imposed.

The skin effect excitation and the proximity effect excitation with a longitudinally directed external magnetic field can be solved by methods presented in [4, 5]. However, the excitation with transversally directed magnetic fields needs an extension of the formulation. Here, the magnetic field $\boldsymbol{H}_{uvw}$ fully depends on three variables u, v, w in the space Ω_{uvw}, i.e., the computation cannot be directly reduced equivalently to a 2-D problem. In short, this is based on the fact that the transversal external field does not follow the helicoidal symmetry.

Since the geometry is periodically w.r.t. the pitch length $p_{l,i\in N_l}$ though, the following separation of variables and spatial Fourier series is possible [7]:

$$\boldsymbol{H}_{uvw}(u,v,w) = \sum_{k=-\infty}^{+\infty} \boldsymbol{H}_{uvw,k}(u,v) f_k(w), \qquad (1)$$

with the modes $f_{k<0} = \sqrt{2}\,cos(kw/\beta)$, $f_{k>0} = \sqrt{2}\,sin(kw/\beta)$, $f_{k=0} = 1$, where $\beta = 2\pi/p_{l,i\in N_l}$. It can be shown, that for the case of a constant transversally directed external magnetic field only the modes $k = \pm 1$ are non-zero [7].

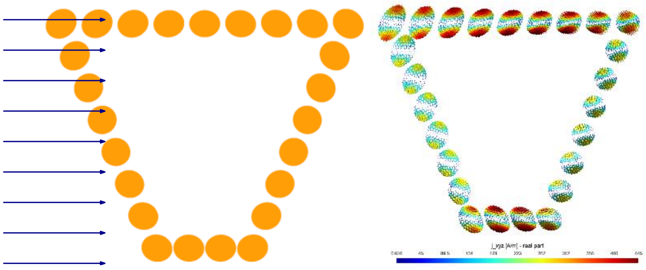

Figure 3: Left: Outermost strand layer of a segment subjected to a transversally directed, homogeneous external magnetic field, right: real part of the resulting induced current density at cross section $z = 0$.

With this approach, it is still possible to solve the ECBVP on a 2-D cross-section at drastically lower computational costs compared to a brute force 3-D model (see Fig. 3, right). A detailed analysis and verification will follow.

References

[1] CIGRE working group D1.54. "Basic principles and practical methods to measure the ac and dc resistance of conductors of power cables", *CIGRE Technical Brochures*, ISBN: 978-2-85873-599-0, (2023).

[2] IEC technical committee 20. "IEC 60287-1-1: Electric cables - Calculation of the current rating - Part 1-1: Current rating equations (100 % load factor) and calculation of losses - General", *International Standard*, ISBN: 978-2-8322-6937-4, (2023).

[3] CIGRE working group B1.03. "Large cross-sections and composite screens design", *CIGRE Technical Brochures*, (2005).

[4] A. Piwonski, J. Dular, R. S. Rezende and R. Schuhmann. "2-D Eddy Current Boundary Value Problems for Power Cables With Helicoidal Symmetry", *IEEE Transactions on Magnetics*, **59**, pp. 1-4, (2023).

[5] A. Piwonski, L. Di Rienzo and C. de Falco. "Efficient computation of sheath losses in three-core AC submarine cables", *IEEE International Conference on High Voltage Engineering and Applications*, pp. 1-4, (2024).

[6] R. V. Sabariego, P. Dular and J. Gyselinck. "Time-Domain Homogenization of Windings in 3-D Finite Element Models", *IEEE Transactions on Magnetics*, 44, pp. 1302-1305, (2008).

[7] J. Dular, F. Henrotte, A. Nicolet, M. Wozniak, B. Vanderheyden and C. Geuzaine. "Helicoidal Transformation Method for Finite Element Models of Twisted Superconductors," *IEEE Transactions on Applied Superconductivity*, **34**, pp. 1-15, (2024).