Physica C 518 (2015) 122–125

Contents lists available at ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

Numerical modeling of twisted stacked tape cables for magnet applications

Francesco Grilli [a,*], Victor M.R. Zermeño [a], Makoto Takayasu [b]

[a] Karlsruhe Institute of Technology, P.O. Box 3640, 76021 Karlsruhe, Germany
[b] Massachusetts Institute of Technology, Cambridge, MA, USA

ARTICLE INFO

Article history:
Received 26 January 2015
Accepted 16 March 2015
Available online 21 March 2015

Keywords:
Numerical modeling
Finite element method
AC losses
3-D simulations
Twisted stacked tape cables
Superconducting magnets

ABSTRACT

In view of high-temperature superconductor (HTS) magnet applications, the concept of Twisted Stacked Tape Cable (TSTC) made of HTS coated conductors is very promising because of the easy manufacturing process and of the very high tape length usage efficiency. For the use of these cables in magnet applications, where the cables carry high current while subjected to the strong magnetic field generated by the rest of the magnet, the possibility of being able to calculate in detail current and field distributions is very welcome, particularly for evaluating the cable's performance during the charge of the magnet. The numerical modeling of this kind of cable is particularly challenging because of the twisted geometry. In this paper, we use a 3-D finite element model to compute the magnetization AC losses of a twisted superconductor and current repartition among the tapes in a cable composed of four HTS coated conductor tapes. The utilized model is able to simulate not only twisted geometries, but also the contact resistance of the electrical terminations used to inject the current. The latter can importantly influence the current repartition between the tapes, especially in short samples. The model is also able to take into account the angular dependence of the critical current on the local magnetic field, whose relative orientation with respect to the tape needs to be locally evaluated as a consequence of the twisted geometry.

1. Introduction

High-temperature superconductors (HTS) are being considered for manufacturing superconducting magnets [1]. Among HTS tapes, rare earth-based coated conductors are the most promising, especially in virtue of their ability of maintaining a high critical current in large background magnetic field. In order to reach the necessary current capacity and mechanical stability for magnet applications, HTS coated conductors need to be assembled into cables. Among the configurations that have emerged, one can list the Roebel cable [2], the conductor-on-round-core (CORC) cable [3] and the twisted stacked tape cable (TSTC) [4]. The performance of those cables, most notably their effective critical current, the current distribution among the composing tapes, and the dissipation during field ramps, is strongly influenced by the superconductor's properties, the cable geometry and the electromagnetic interaction between the tapes. Numerical models can be of great help to estimate a cable's behavior and to optimize its design.

In this paper, we present numerical modeling results for TSTC cables, using a full 3-D finite-element (FE) model we have recently developed. Among the main features of the model, there are the possibilities of simulating twisted geometries and of including the termination resistances. These latter can profoundly influence the way current partitions among the tapes. The model is used to compute the dissipation during time-varying magnetic fields in a twisted superconductor and the current distribution among tapes when the current is ramped in a cable composed of four HTS tapes. In the work presented here, we use parameters for the superconductor at 77 K (mainly because we have experimental data available for that temperature). The model, however, can also be used with geometries and parameters typical of high-field magnets at lower temperature.

2. Model description

The model is based on the 3-D version [5] of the *H*-formulation of Maxwell's equations for transient problems [6]. The superconductor – representative of a 4 mm wide *REBCO* (*RE* = rare earth) coated conductor – is simulated with a power-law resistivity (power index $n = 21$)

$$\rho = \frac{E}{E_c}\left|\frac{J}{J_c}\right|^{n-1} \tag{1}$$

---

[*] Corresponding author. Tel.: +49 721 6082 8528; fax: +49 721 6082 7350.
E-mail address: Francesco.grilli@kit.edu (F. Grilli).

http://dx.doi.org/10.1016/j.physc.2015.03.007
0921-4534/© 2015 Elsevier B.V. All rights reserved.

where the critical current density J_c depends on the local magnetic flux density and its orientation with respect to the superconductor. For the simulations carried out in this work, we used an elliptical dependence of J_c as in [7].

$$J_c = \frac{J_{c0}}{\left(1 + \frac{\sqrt{(kB_{\parallel})^2 + B_{\perp}^2}}{B_c}\right)^b} \tag{2}$$

where j_{c0} = 21.218 GA m^{-2}, k = 0.275, b = 0.6, B_c = 32.5 mT and $B_{\parallel}$ and $B_{\perp}$ are, respectively, the parallel and perpendicular components of the magnetic flux density.

One can construct a 3-D model of twisted geometries by drawing the transversal cross-section first and then extruding it with a multi-step copy-and-rotate process. This allows preserving the same mesh along the direction of extrusion, which facilitates the imposition of periodic boundary conditions at the two ends of the simulated domain. Furthermore, the use of structured meshes allows having a direct control of the mesh density and consequently of the number of degrees of freedom [8]. Typically one twist pitch (or a fraction of it, if the considered working conditions allow for it) is simulated [9,10].

The termination resistances are simulated in a disconnected domain and the current is passed from each resistance to the corresponding HTS tape by means of integral constraints. More details can be found in [11].

3. Results

Two aspects of high-current magnet cables are important and can be analyzed with the modeling tool presented here: their dissipation when the magnet is charged and the way the current is partitioned among the tapes.

3.1. AC losses in background field

When high-current cables are used in magnet applications, they dissipate power because they are subjected to the varying magnetic field generated by the magnet itself. Although there are no alternating currents involved, this problem usually goes under the classification of "AC loss" problem, because the dissipation dynamics occurring during a field ramp are essentially the same as those encountered in AC conditions (namely, time-variation of the magnetic flux). In order to test our model for this kind of computation, we therefore considered the case of a twisted 4 mm wide HTS tape subjected to a background field of given orientation at 50 Hz. The relative orientation of the field with respect to the tape changes along the tape's length (see Fig. 1a). Where the field is perpendicular to the tape, the local current density and field distributions inside the superconductor resemble those of a thin superconducting strip; where the field is parallel, they resemble those of a superconducting slab. As a consequence, in certain positions the field is higher than the applied one, because of the demagnetizing effect: those are the positions where the power dissipation is the highest. As reported in [10] the average power loss density

$$P = 2f \int_{1/(2f)}^{1/f} \int_{\Omega} J \cdot E d\Omega dt \bigg/ \int_{\Omega} d\Omega \tag{3}$$

of the twisted tape lies between those of a straight tape subjected to purely parallel or perpendicular field. In (3), f is the frequency of the external field and Ω is the superconductor's domain (a volume or a surface in 3-D or 2-D, respectively).

In view of the observed thin strip/slab behavior described above, one can think of using an alternative modeling technique for the purpose of AC loss computation: simulating a straight tape with a field of fixed given orientation and performing one simulation for every possible field orientation. The AC losses of the twisted case can then be computed as the average of the losses of a straight tape with varying field orientation. These simulations can be performed in a 2-D model, since nothing varies along the direction of the tape length (other than the orientation of the external field with respect to the tape). We chose 32 uniformly distributed angles between 0° and 360°, in correspondence of the 32 blocks in which the twisted geometry is divided (the blocks are visible in Fig. 1a). Fig. 1b shows the variation of the power loss density with the angle of the field, as well as the average value. In the analyzed field range (5–100 mT) this average value is very similar (maximum difference 1.7%) to that calculated with a full 3-D simulation – see Fig. 2a. However, the total computing time of the alternative approach is much shorter: for example, for an applied field of 20 mT, it is 20 times shorter. This reduction of computing time can be understood by noting that the 2-D geometry contains of course much fewer degrees of freedom than the 3-D one (typically ~10,000 against ~200,000); and the fact of having to perform 32 simulations to consider the different field orientations increases the total computation time only linearly, i.e. by a factor ~32. On the contrary, the simulation of a single 3-D case takes a very long time, because the computation time increases much more than linearly with the numbers of DOFs [12]. Another clear advantage of the 2-D approach is that, since the simulations are independent of each other, they can be truly parallelized and assigned to different cores, which leads to an even further reduction of the computing time.

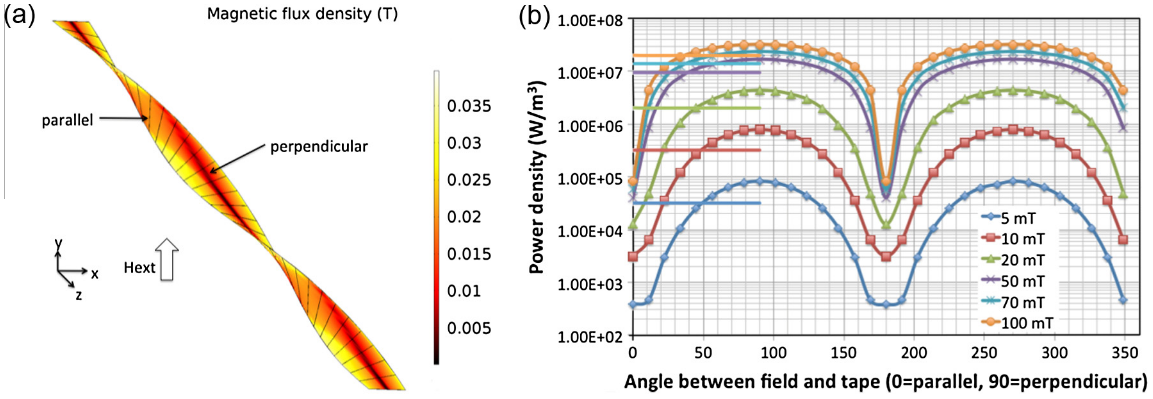

Fig. 1. (a) Distribution of the magnetic flux density for an applied field of 20 mT, taken at the peak instant. (b) Power density calculated with the 2-D model with varying orientation of the applied field. The straight lines represent the average value over the 360° rotation.