Research paper

Comparison study of cable geometries and superconducting tape layouts for high-temperature superconductor cables

Wurui Ta*, Tianchong Shao, Yuanwen Gao

Department of Mechanics and Engineering Science, College of Civil Engineering and Mechanics, Lanzhou University, Lanzhou, Gansu 730000, PR China
Key Laboratory of Mechanics on Environment and Disaster in Western China, The Ministry of Education of China, Lanzhou University, Lanzhou, Gansu 730000, PR China

ARTICLE INFO

ABSTRACT

High-temperature superconductor (HTS) rare-earth-barium-copper-oxide (REBCO) tapes are very promising for use in high-current cables. The cable geometry and the layout of the superconducting tapes are directly related to the performance of the HTS cable. In this paper, we use numerical methods to perform a comparison study of multiple-stage twisted stacked-tape cable (TSTC) conductors to find better cable structures that can both improve the critical current and minimize the alternating current (AC) losses of the cable. The sub-cable geometry is designed to have a stair-step shape. Three superconducting tape layouts are chosen and their transport performance and AC losses are evaluated. The magnetic field and current density profiles of the cables are obtained. The results show that arrangement of the superconducting tapes from the interior towards the exterior of the cable based on their critical current values in descending order can enhance the cable's transport capacity while significantly reducing the AC losses. These results imply that cable transport capacity improvements can be achieved by arranging the superconducting tapes in a manner consistent with the electromagnetic field distribution. Through comparison of the critical currents and AC losses of four types of HTS cables, we determine the best structural choice among these cables.

1. Introduction

High-temperature superconductor (HTS) rare-earth-barium-copper-oxide (REBCO) tapes are very promising for use in high-current cables. HTS materials have excellent properties, including high critical magnetic fields, high current densities, high specific heat values, high thermal conductivities, and low refrigeration power requirements [1,2]. Several successful cabling methods have previously been proposed and developed for use in high-field applications [3–7]. For example, one of these cabling methods involves use of the twisted stacked-tape cable (TSTC) conductor [8], which is formed by stacking flat tapes and twisting them along the axis of the stacked tapes. HTS cable performance is dependent on many of the parameters chosen during the design stage, including the cable layout (e.g., number of tapes used, twist pitch), the tape type, the electromechanical properties of the tape, the former materials and the final cable geometry (which can be round, square, or rectangular).

Several research groups have already performed various experimental and analytical studies of TSTC conductors [9–11]. Takayasu et al. [12] investigated the feasibility of the TSTC method for use with HTS REBCO tapes. They proposed analytical models to calculate the

torsion twist strains in thin HTS tapes. The critical current degradation and current distributions of TSTC conductors were also assessed via calculations of the torsion strain and the magnetic field. Chiesa et al. [13] investigated the mechanical characteristics of TSTC conductors under transverse Lorentz loads. The effects of both localized and uniform transverse loading conditions were investigated. In addition to experimental research and analytical models, modeling processes can be used to attain new developments rapidly. Numerical simulations are suitable for analysis of the electromagnetic behavior and AC losses of HTS systems with more complex structures [14–17]. Several numerical models of the thermomechanical or electrothermal characteristics of HTS cable have been conducted. Breschi et al. [18] presented a finite element model for analysis of the electrothermal behavior of twisted-stack slotted-core cables using COMSOL Multiphysics software. The model can calculate the cable's current sharing temperature and investigate the quench behavior of HTS cables. Savoldi et al. [19] proposed a numerical model to investigate the thermal-hydraulic behavior of HTS cables. De Marzi et al. [20] built a 2D finite-element magneto-static model to estimate the self-fields that occur in HTS cables. The mechanical behavior of TSTC cables under various loads was investigated by Allen et al. [21], who developed structural finite element

---

models of a single REBCO tape and a TSTC cable using ANSYS software. Liu et al. [22] presented a robust optimization method for HTS cables that was based on design for six sigma (DFSS). The optimization results show that the proposed procedure can achieve uniform current distributions and improve the reliability, robustness and quality of the HTS cable significantly. Mao et al. [23] reviewed design optimization of the structural parameters of the multilayer conductors used in HTS cables. In their work, a multi-objective optimization procedure was implemented. Tomassetti et al. [24] proposed a novel approach to HTS cable cross-section design based on the Pareto optimality criterion. The method involved simultaneous maximization of both the engineering current density and the total current flowing inside the tapes when operating under a self-field. However, few studies have attempted to optimize TSTC cables in terms of their geometry and the layout of the superconducting tapes.

In this paper, we use numerical tools to perform a comparison study of multiple-stage cables composed of three TSTC sub-cables to improve the critical current and minimize the AC losses of the cables. The *H*-formulation is used as the basis of a 2D model for analysis of the electromagnetic fields and calculation of the AC losses of each cable. The sub-cable geometry is designed to have a stair-step shape. Three superconducting tape layouts are chosen for evaluation. By calculating the critical currents and the AC losses of the three cable layouts, we determine the optimal HTS cable structure.

2. Cross-sectional geometry and superconducting tape layouts

The TSTC conductor was originally developed by Takayasu et al. [8] The basic cable is formed by applying a torsional twist to a stack of flat tapes along the stacking axis. Several of the basic cables are then twisted to form a multi-stage cable. Fig. 1(a) shows the cross-section of a triplet TSTC conductor that is composed of three square sub-cables. Copper was selected as the material for both the jacket and the former. Previous studies have shown [20] that the magnetic field inside the HTS cable has a nonuniform distribution. Therefore, we designed the sub-cable groove geometry to have a stair-step shape (see Fig. 1(b)) that may be able to maximize the performance of the superconducting tapes and thus improve the transport capacity of the cable.

We selected three superconducting tapes with different critical currents and arranged them in the stair-step groove using different layouts. Fig. 2 shows the three superconducting tape layouts. In the original square TSTC conductor, the critical current I_{c0} (0 T, 77 K) for all the superconducting tapes is 120 A. In Layout 1, a tape with a critical current of $I_{c0} = 150$ A is placed at the top of the groove while a tape with a critical current of $I_{c0} = 100$ A is placed at the bottom of the

groove. In Layout 2, all superconducting tapes have the same critical current of $I_{c0} = 120$ A. Layout 3 uses the opposite configuration to that of Layout 1.

3. Computational model

3.1. Model description

A 2D finite element model of the triplet TSTC conductor was established using COMSOL Multiphysics software. In this model, we assume that the current in the longitudinal direction always flows uniformly within the superconducting tapes. Changes in the cable cross-sectional geometry and the layout of the superconducting tapes therefore mainly affect the distributions of the magnetic field and the current density in the cross-section. The 2D model is thus both accurate and computationally efficient and can be used to simulate the electromagnetic behavior of the cable. In this model, each sub-cable consists of 30 superconducting tapes (tape thickness: 100 μm). The widths of these tapes are 2 mm, 4 mm and 6 mm. The outer diameter of the cable is 21 mm. The regions to be solved contain superconducting zones, copper zones and an air zone, as shown in Fig. 3. The air region is specified as the outer circle and the radius of this 'air' circle is five times larger than the actual outer radius of the cable.

3.2. Basic equations

The *H*-formulation [25,26] is used to calculate the electromagnetic field distribution and the AC loss of the cable. Substitution of Ampere's law into Faraday's law yields the governing equation for the magnetic field **H** of the HTS tape (similar processes are available for the metal jacket and the former):

$$\mu_0 \frac{\partial \mathbf{H}}{\partial t} + \nabla \times (\rho \nabla \times \mathbf{H}) = 0, \tag{1}$$

where μ_0 is the permeability of a vacuum. The resistivity ρ of the HTS tape is given in accordance with the power law as

$$\rho = \frac{E_0}{J_c(B)} \left| \frac{J}{J_c(B)} \right|^{n-1}, \tag{2}$$

where $E_0 = 10^{-4}$ V m^{-1} is the electric field criterion for the critical current density, and n is the power law exponent. The critical current density $J_c(B)$ satisfies the modified Kim model [27]:

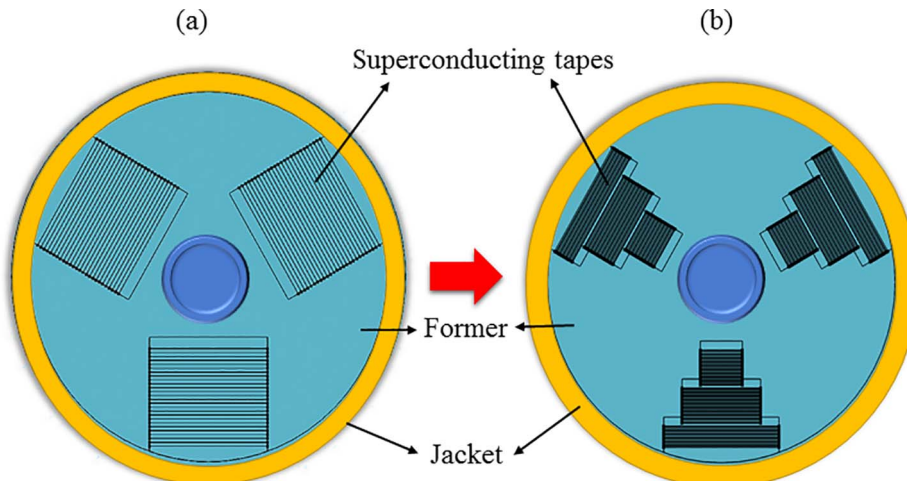$$J_c(B) = \frac{J_{c0}}{\left(1 + \frac{|B|}{B_0}\right)^\alpha}. \tag{3}$$

Fig. 1. (a) Cross-section of a triplet TSTC conductor composed of three square sub-cables; (b) cross-section of a triplet TSTC conductor composed of three stair-step-shaped sub-cables.