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Influence of current ramp rate on voltage current measurement of a conduction-cooled HTS magnet

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Abstract

High-temperature superconductors (HTS) have notably different voltage current characteristic compared to the low-temperature superconductors (LTS). Due to the anisotropy and slanted electric field – current density characteristics the loss of stability in a Bi-2223/Ag magnet is viewed as a global temperature increase inside the coil rather than a local normal zone. Therefore, the quench current depends strongly on the cooling conditions. In this paper a finite element method based analysis method is presented and example runs are carried out in order to explain in detail the influence of the current ramp rate and cooling on the voltage current characteristics of a conduction-cooled Bi-2223/Ag coil at 20 and 45 K. The results show that in certain operation conditions the coil critical current has a maximum value with respect to the ramp rate used in the measurements.

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1. Introduction

In liquid helium cooled LTS magnets the stable DC operation current can be determined accurately with the voltage per unit length criterion [1]. However, the properties of HTS coils are notably different and the same criteria do not apply. Because the superconductor index number n of HTS tapes is small, electric field exists in the wire even before the critical current I_c is exceeded. Thus, some ohmic heat is generated already at subcritical currents. These resistive losses warm up the magnet and thereby the thermal runaway current depends on the ramping rate. The computational stability analysis for HTS magnets at DC currents is already well established [2–4] and the understanding about electric field distribution inside HTS magnets has matured [5,6]. However, it is not yet completely clear, how the maximum stable DC operation current can be determined from the measured voltage–current V–I characteristics although some rules of thumb have been proposed [7,8].

The results from V–I measurements are difficult to interpret due to the changing magnetic field during the current ramp. The changing field creates magnetization and eddy current losses that raise the temperature and thereby lower the quench current I_q. In order to maintain the stable operation cooling has to overcome dissipated heat that would otherwise lead to a thermal runaway. In LTS coils which have high n-values and operate at liquid coolant the measured critical current has decreased with increased ramp rate due to AC losses [9–11]. Similar behaviour has also been found in Bi-2223 tapes [12]. However, in HTS magnets the analysis of AC losses during a V–I measurement has not been carried out so far. In this paper, a stability model which takes into account AC losses is developed. The model is used to simulate V–I measurements in a high quality Bi-2223/Ag coil.

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2. Computational model

In order to better understand the stability and quench behavior of the HTS magnet during the $V(I)$ measurement, a numerical stability model which takes into account the losses due to the changing magnetic field was created. The model is based on the heat conduction equation

$$\nabla \cdot k(T)\nabla T + Q(T) = C_p \frac{dT}{dt}, \quad (1)$$

where T is the temperature, k the thermal conductivity, Q the volumetric heat generation power and C_p the volumetric specific heat. Eq. (1) was solved with the finite element method. Since the used numerical model for stability considerations in HTS coils at DC currents is presented in detail in [2,13] we concentrate here on how to model losses created by changing magnetic fields.

Hemmi et al. has presented a model how to combine the heat conduction equation with Maxwell's equations in HTS tapes carrying transport current [12]. However, this model cannot be conveniently applied on the magnets because then the electromagnetic boundary conditions should be defined on the surface of each turn. Therefore, the heat conduction equation was not combined directly with Maxwell's equations but the heat generation was solved separately.

In superconducting systems losses arise due to the current in the conductor and due to the external magnetic field. In practice, these self field and magnetization losses cannot be distinguished from each other but it is a widely used approximation to divide heat generation into two parts as

$$Q = Q_{self} + Q_{mag}, \quad (2)$$

where Q_{self} is the self field loss and Q_{mag} the magnetization loss.

Here it was assumed that the changes in self field are small if compared to the changes in the external field. Then the self field losses consist only of resistive losses due to the slanted $E(J)$ characteristic. We use the power law approximation

$$E(J) = E_c\left(\frac{J}{J_c}\right)^n, \quad (3)$$

where J_c is the critical current density, n the index number and E_c is the electric field criterion. Then the self field losses can be given

$$Q_{self} = \lambda E_c\left(\frac{J^{n+1}}{J_c^n}\right). \quad (4)$$

where λ is the volumetric fraction of the superconductor in the magnet.

Next, we calculate the penetration field B_p for the tape. According to the Bean model the penetration field is

$$B_p = a\mu_0 J_c \quad (5)$$

where a is the half of the tape thickness and μ_0 the permeability of vacuum. Equation estimates that the B_p is 53 mT. Thus, B exceeds the B_p in all tapes when current is higher than 5 A. Therefore constant $\mathbf{B} = \mu_0\mathbf{H}$ in the tape cross-section can be assumed. Next, the magnetization losses are derived following the same principle as in [14,15]. When the field directions in Fig. 1 are used the average dissipated power per unit volume is

$$Q_{mag} = \frac{1}{S}\int_S \frac{\lambda J_c E^{1+1/n}}{E_c^{1/n}} ds = \frac{\lambda J_c}{S E_c^{1/n}} \int_S |x\dot{B}|^{1+1/n} ds. \quad (6)$$

Here current ramps $I(t) = K_I t$, where K_I is the ramp rate, are studied. During a ramp the current creates the magnetic flux density $B(t) = K_B I(t) = K_B K_I t$, where K_B is the magnetic flux density at the current of 1 A. If the filamentary region inside a HTS tape is assumed to be elliptical Eq. (6) reduces to

$$Q_{mag} = \frac{\lambda J_c (K_B K_I)^{1+1/n}}{E_c^{1/n}} \frac{\alpha^{2+1/n} a^{1+1/n}}{\pi} \frac{n}{3n+1} X(\alpha, n, \phi), \quad (7)$$

where

$$X(\alpha, n, \phi) = \int_0^{2\pi} \frac{|\cos(\theta)|^{1+1/n}}{[\cos^2(\theta-\phi) + \alpha^2 \sin^2(\theta-\phi)]^{(3n+1)/2n}} d\theta \quad (8)$$

is evaluated numerically.

In practise both J_c and n depend on $\mathbf{B}$ and thereby vary during the current ramp. The $J_c(\mathbf{B})$ and $n(\mathbf{B})$ data used here is presented in Fig. 2.

In the normal conducting interface eddy current losses P_{ed} were calculated from

$$P_{ed} = K_{ed}\sigma(B, T)\left(\frac{dI}{dt}\right)^2, \quad (9)$$

where K_{ed} is a geometry dependent factor calculated using 3d FEM and σ the electrical conductivity of copper [16].

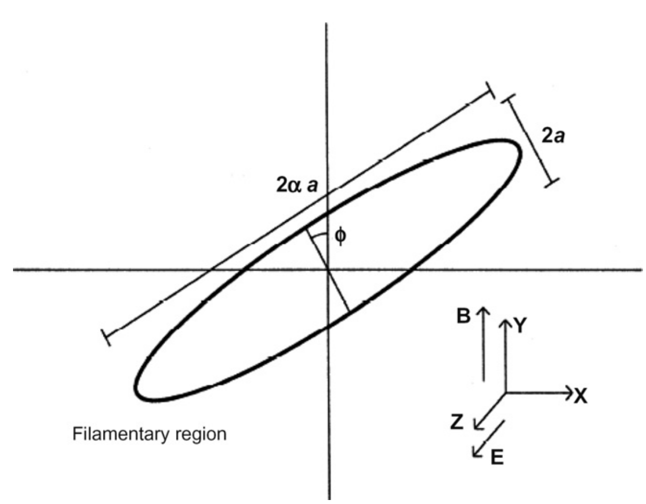

Fig. 1. Geometry of filamentary region in a HTS tape and field directions.