pISSN 1229-3008 eISSN 2287-6251
Progress in Superconductivity and Cryogenics
Vol.20, No.1, (2018), pp.19~22
https://doi.org/10.9714/psac.2018.20.1.019

Investigation on stability characteristics of 2G HTS coated conductor tapes with various stabilizer thickness

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(Received 6 December 2017; Revised 26 March 2018; accepted 27 March 2018)

Abstract

The thermal and electrical properties of the conductor are critical parameters for the design and optimization of the superconducting magnet. This paper presents simulation code to analyze electrical and thermal stability characteristics of the second generation (2G) high-temperature superconductor (HTS) by varying copper stabilizer thickness. Two types of commercial 2G HTS coated conductor tapes, YBCO and GdBCO were used in this study. These samples were cooled by Liquid Nitrogen (LN_2) having boiling at 77.3 K and an equivalent electrical circuit model for them is choosen and analysed in details. Also, an over-current pulse test in which a current exceeding a critical current was performed. From the simulation results, the influences of the copper stabilizer thickness on the stability characteristics of these samples are presented.

Keywords: YBCO coated conductor, GdBCO coated conductor, stabilizer thickness, over-current pulse test, Electrical and thermal stability characteristics

1. INTRODUCTION

HTS is preferred over LTS due to its superior properties like higher magnetic field, higher current density, and larger mechanical stress. Also, it is advantageous in terms of cooling cost as it remains in superconducting state at liquid nitrogen (LN2) temperature. Therefore, the HTS wires has attracted greater attention as a better material for superconductor applications and thus rising the mass production by wire manufacturers [1, 2]. However, it is well known that normal zone propagation (NZP) velocity in HTS is slower than that in LTS because HTS has high operating temperature and large heat capacity. Although the stability characteristics of HTS are better than LTS, the NZP velocity of HTS is low, so self-protection characteristic of HTS is difficult to expect like LTS. If the hot spot occurs in the local region it can cause pemanent damage the entire HTS. It is therefore necessary to determine an appropriate stabilizer thickness for the protection of the HTS magnet so that the temperature of hot spot in local region does not exceed the allowable temperature. The investigation stabilizer thickness would be useful for HTS designer to optimize conductor design while saving time and efforts [3, 6].

This paper presents simulation code to investigated the stability characteristics of the 2G HTS tape with different copper stabilizer thickness. The stability of 2G HTS samples have focussed on quench and recovery. Two types of 2G HTS commercial coated conductor with a few layers were chosen which include substrate, superconducting layer, buffer layer, silver, and copper layer. The copper thickness of YBCO and GdBCO are 60 μm, 100 μm and 50 μm, 100 μm respectively [4].

They are immersed in LN2 to ensure a uniform temperature at 77.3 K over the sample while they carry a nominal DC transport current of 90% the critical current. The specifications of these samples are listed in Table I and Table II.

TABLE I
TECHNICAL DATA OF THE INVESTIGATED YBCO TAPE.

Sample	**A**	**B**
Cu Thickness [μm]	60	100
Ag Thickness [μm]	2.5	
YBCO Thickness [μm]	1.0	
Buffer Thickness [μm]	0.16	
Substrate Thickness [μm]	50.8	
Width [mm]	4.2	
Length [mm]	100	
Critical Current (77 K, self-field) [A]	113	108

TABLE II
TECHNICAL DATA OF THE INVESTIGATED GDBCO TAPE.

Sample	**C**	**D**
Cu Thickness [μm]	50	100
GdBCO Thickness [μm]	1.7	
Ag Thickness [μm]	8	
Substrate Thickness [μm]	100	
Width [mm]	5	
Length [mm]	600	
Critical Current (77 K, self-field) [A]	230	

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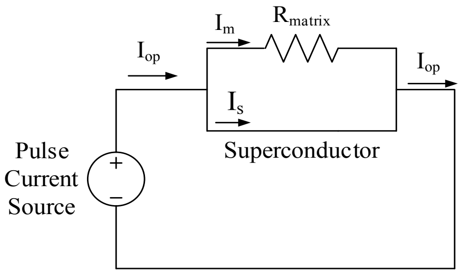

Fig. 1. Circuit model for HTS Tape.

2. NUMERICAL ANALYSIS

2.1. Electrical Circuit Model

The circuit model is shown in Fig.1 which consists of two elements connected in a parallel circuit model. One element being the normal metal and the other is a superconductor element as shown below [2, 5].

Below the critical temperature, current flows only on the superconductor branch. However, if the temperature is increased above the critical temperature then current will share with the metal stabilizer. As a result, there is resistive heating in the metal matrix. The voltage through the sample, $V_s(T)$, may be defined as below:

$$\begin{array}{lll} V_s(T)=0 & T_{op}\le T\le T_{cs}(I_{op}) & (1a) \\ \quad = R_m(T)[I_{op}-I_c(T)] & T_{cs}(I_{op})\le T\le 93 & (1b) \\ \quad = R_m(T)I_{op} & T\ge 93 & (1c) \end{array}$$

where I_{op} is transport current; $R_m(T)$ is matrix resistance and I_c is critical current.

In the current sharing regime, the voltage across the metal and superconductor must be the same because they are in parallel and are defined by equation as follows:

$$V_s(T)=V_c\left[\frac{I_{op}-I_c(T_{op})}{I_c(T_{op})}\right]^n \qquad (2)$$

where n is the superconductor's index.

2.2. Power Density Equation

The power density equation governs the temperature of a unit superconductor volume:

$$C_{cd}(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left[k_{cd}(T)\frac{\partial T}{\partial x}\right]+\rho_{cd}(T)J_{cd}^2-\frac{f_p P_{cd}}{A_{cd}}q(T) \qquad (3)$$

where $C_{cd}(T)$ is the heat capacity per unit volume; $K_{cd}(T)$ and $\rho_{cd}(T)$ are the thermal conductivity and electrical resistivity of the composite, respectively; f_p is the fraction of the composite perimeter; P_{cd} is the total of the composite which is exposed to cryogen; A_{cd} is the composite cross-sectional area; and $q(T)$ is the heat transfer flux on the sample surface.

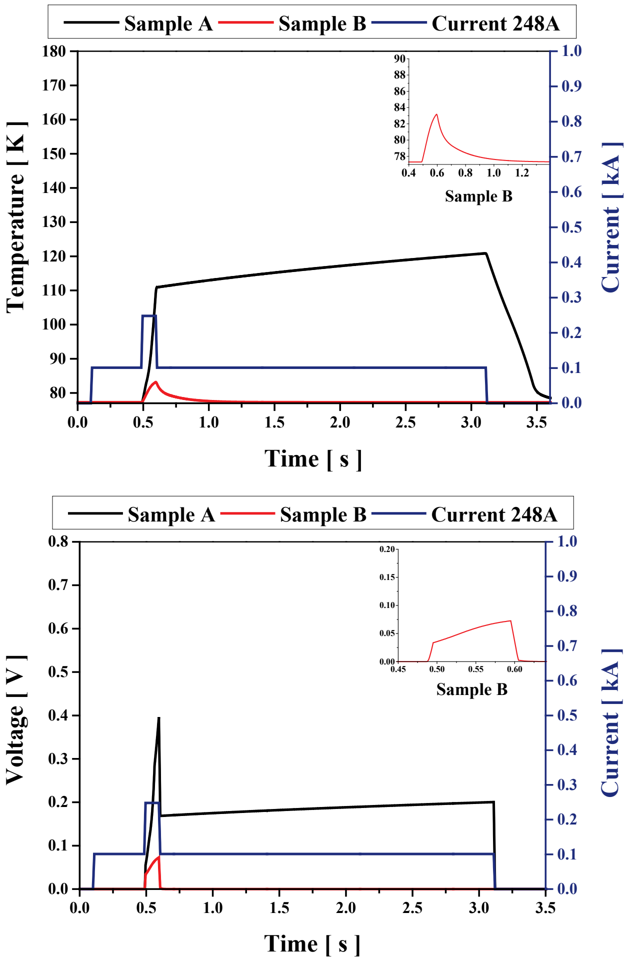

Fig. 2. Set of T(t), V(t) traces for sample A and B to an over-current pulse (2.2 Ic) and cooled by Liquid Nitrogen at 77.3 K.

3. SIMULATION RESULTS AND DISCUSSION

3.1 YBCO Coated Conductor Samples

Fig.2 shows the over-current simulation results. $I(t)$ begins at a transport current (0.9 I_c), then increases to 2.2 I_c during the 100 ms pulse and returns to 0.9 I_c.

In sample A, at over-current of 248 A (2.2 I_c), the temperature runaway occurred during the current pulse and the sample was virtually damaged. The maximum joule dissipation flux on the test sample surface is 23.4 W/cm^2 which is more than ~1.6 times a peak nucleate boiling flux of ~15 W/cm^2.

On the other hand, the total current during pulse of sample B was 238 A (2.2 I_c). The $T(t)$ and $V(t)$ show that the sample B retain superconducting property even at an over-curent pulse. During the pulse, this sample was in the current-sharing mode. There is resistive heating in the metal matrix which is increasing the temperature of the conductor. However, it is evident from graph that the sample B recovers immediately after the pulse.

Fig.3 shows over-current simulation results in the sample B. $I(t)$ begins at transport current (0.9 I_c), then increases to 3.8 I_c which is 410 A during the 100 ms pulse and returns to 0.9 I_c.

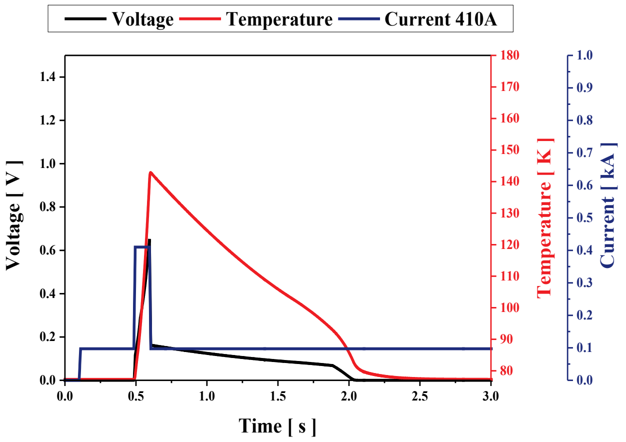

Fig. 3. Set of T(t), V(t) traces for sample B to an over-current pulse (3.8 Ic) and cooled by Liquid Nitrogen at 77.3 K.

The total current during the pulse is 410 A which is almost 4 times the critical current value. The peak joule dissipation has increased to 63.5 W/cm^2, roughly 4.2 times the maximum nucleate boiling heat flux for liquid nitrogen during the pulse. The joule heating flux jumps over the maximum nucleate boiling heat resulting in a much slower recovery with a long tail lasting 2s, suggesting that additional stabilizer protection is required for this sample in the event of quenching.

3.2. GdBCO Coated Conductor Sample

Fig.4 shows the over-current simulation results. *I(t)* begins at transport current (0.9 I_c), then increases to around 1.8 I_c during the 100 ms pulse and returns to 0.9 I_c.

In sample C, the total current during pulse reached 400 A which is around 1.8 times the critical current value. The voltage drops dramatically from 1.4 V to 0.7 V near the end of the pulse. The peak joule heating flux has increased to 18.67 W/cm^2 and reduced to 9.33 W/cm^2 at the end of the pulse. It is evident that the sample is heated and its joule heating flux increased by 1.24 times to maximum nucleate boiling heat flux (15 W/cm^2) as the recovery is not instant, instead, it takes around 0.3 s to recover completely.

In sample D, the voltage trace increases steadily during the pulse and drops suddenly at the very end of the pulse. It implies that heating is matched by cooling system which reduces the sample temperature immediately after the pulse. The peak joule heating flux has increased to 1.3 W/cm^2, well below a maximum nucleate boiling heat transfer flux of 15 W/cm^2. The sample recovers quickly at the end of the pulse.

Fig.5 shows over-current simulation results in the sample D. *I(t)* begins at a transport current (0.9 I_c), then increases to 2 I_c reaching 460 A during the 100 ms pulse and returns to 0.9 I_c.

In this run, heating reaches a peak joule heating flux of 18.01 W/cm^2, more than 1.2 times the maximum nucleate boiling heat transfer flux for liquid nitrogen and falls around 7.67 W/cm^2 at the end of the pulse. Recovery, instead of almost instant as the previous run, has a short tail lasting around 0.3 s. Although the over-current increase to 2 times the critical current which is significant higher than the previous run, the sample remains undamaged. It is clear that the thickness of Cu-lamination stabilizer has protected the sample.

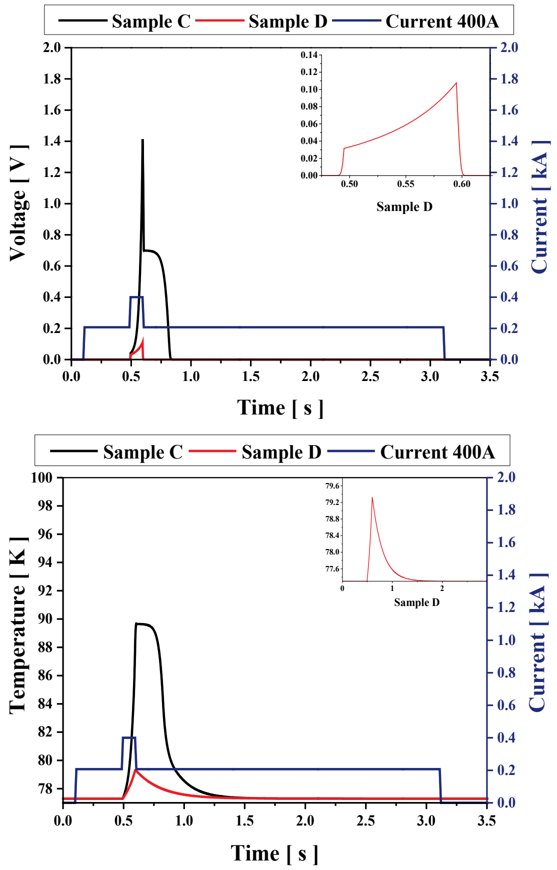

Fig. 4. Set of T(t), V(t) traces for sample C and D to an over-current pulse (~1.8 Ic) and cooled by Liquid Nitrogen at 77.3 K.

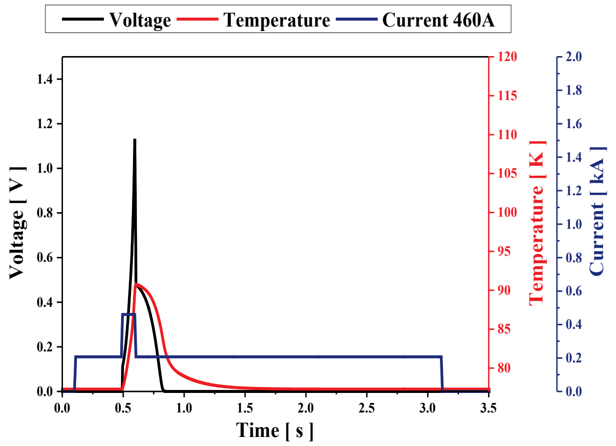

Fig. 5. Set of T(t), V(t) traces for sample D to an over-current pulse (2 Ic) and cooled by Liquid Nitrogen at 77.3 K.

4. CONCLUSION

In summary, this study has investigated on stability properties of 2G HTS coated conductors considering various copper stabilizer thickness. The results clearly demonstrates that the thickness of copper stabilizer is critical and should be considered to improve the electrical and thermal stability of 2G HTS coated conductor. As the transport current increases above the critical current value, current sharing with the metal matrix occurs thus saving the superconductor from burn-out. We could improve stability by attaching additional lamination layer. These results would be useful for HTS coil designer to optimize their conductor design with improving electrical and thermal stability.

ACKNOWLEDGMENT

This work was supported in part by the Human Resources Program in Energy Technology of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), grant funded by the Ministry of Trade, Industry & Energy, and by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP), Republic of Korea. (Nos. 20164030201230 and 2016R1A2B4007324)

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