IOP PUBLISHING SUPERCONDUCTOR SCIENCE AND TECHNOLOGY

Supercond. Sci. Technol. **20** (2007) L9–L11 doi:10.1088/0953-2048/20/4/L01

RAPID COMMUNICATION

Theoretical explanation of the non-equipotential quench behaviour in Y–Ba–Cu–O coated conductors

M Breschi[1], Pier Luigi Ribani[1], X Wang[2,3] and J Schwartz[2,3,4]

[1] University of Bologna, Electrical Engineering Department, Italy
[2] Center for Advanced Power Systems, Florida, USA
[3] Florida A&M University-Florida State University, College of Engineering, USA
[4] National High Magnetic Field Laboratory, Florida, USA

Received 14 December 2006, in final form 30 January 2007
Published 19 February 2007
Online at stacks.iop.org/SUST/20/L9

Abstract

$YBa_2Cu_3O_{7-x}$ (YBCO) coated conductors are realized by the deposition of a YBCO film atop thin (10^{-6} m) ceramic buffer layers, previously deposited upon a high resistance nickel alloy. On the other side of the tape a copper layer is often added to create an alternative current path during quenches. Several investigations have shown a different qualitative behaviour of the voltages measured on the nickel and copper sides of the tape. In this work we give a theoretical explanation for this phenomenon and point out the technical consequences it might have for the design of devices constructed using YBCO coated conductors.

The understanding and assessment of quenching phenomena is an important step in the design of superconducting magnets. This field is fairly well understood for magnets using metallic low temperature superconductors. For magnets to be built with high temperature superconducting (HTS) tapes, however, there is little understanding of critical behaviours. This lack of results is especially marked for $YBa_2Cu_3O_{7-x}$ (YBCO) coated conductors (CC) [1]. Different experimental procedures have been adopted using lengths of YBCO CC tape to initiate quenches under controlled environments that simulate those occurring during magnet operation. Several researchers have induced quenches using a current pulse greater than the tape's critical value [2]. With this technique, the quench is initiated in a 'weak' region where the critical current is lower than in the rest of the tape. A different approach to quench initiation has been followed in [3] and [4]. The quench is in this case initiated by a heat pulse through a heater mounted on the tape. In both cases experimental investigations have shown that the voltage traces measured on the nickel substrate and on the silver (or copper) layer have different qualitative behaviours, indicating a contact relationship between nickel and silver (or copper) that cannot be treated as a simple parallel contact [4, 5]. In both cases the voltage traces recorded on the nickel side rise simultaneously along the tape length as soon as the current redistributes from the YBCO layer to the nickel layer at initiation of the quench. On the other hand, the voltage traces along the silver or copper side do not appear simultaneously. The first voltage traces appear across the 'weak' regions in overcurrent experiments and across the heated region in pulsed heater experiments. The voltage signals recorded at distances from the heater arise after a delay and reach much lower values than in the nickel side at the same positions or are too low to be measured.

A dedicated experiment was realized to analyse this phenomenon [5]. A difference in the voltage traces was found *even if continuous direct contact was realized between the silver and nickel layers* along the whole sample. The driving mechanism for this discrepancy remained unclear.

To explain this phenomenon we have developed an electrical model that takes into account that the tape cross section is not equipotential. The conductor is divided into N_{sec} sectors along the length (in this case N_{sec} is set to 140 in order to reach numerical convergence). Each layer sector is represented by means of its longitudinal resistance and self-inductance, as shown in figure 1. The different layers interact through electrical contact resistances between adjacent layers and mutual inductances. The YBCO layer is described through the power law model, $E_{YBCO} = E_c(J/J_c)^n$, where J_c is

0953-2048/07/040009+03$30.00 © 2007 IOP Publishing Ltd Printed in the UK

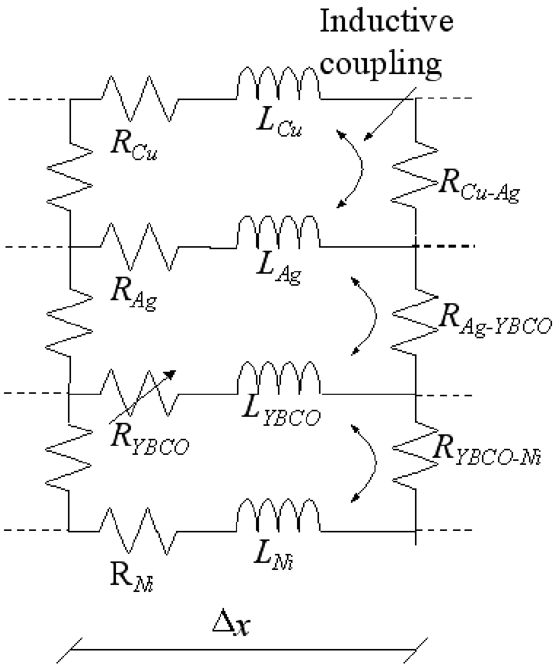

Figure 1. Schematics of the tape elemental sector of the electrical model of the tape.

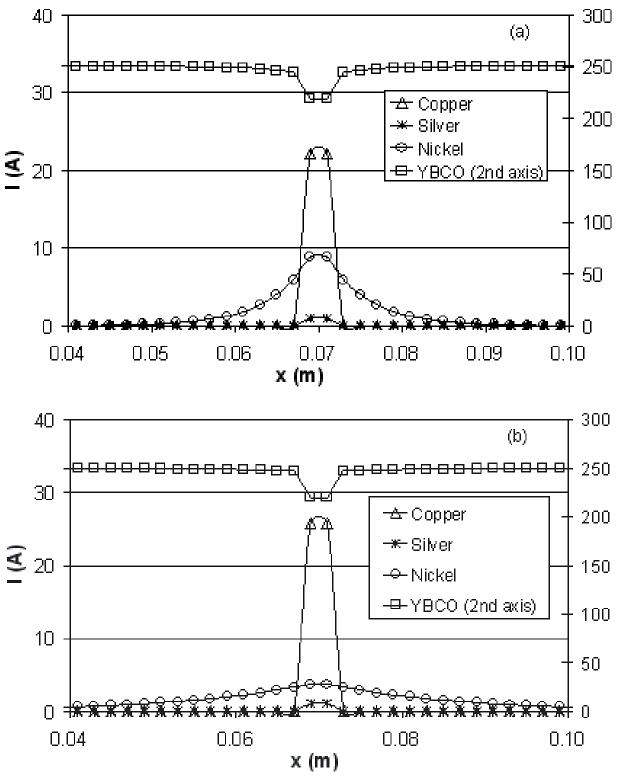

Figure 2. Currents at the end of the heat pulse with $k = 10^4$ (a) and $k = 10^5$ (b).

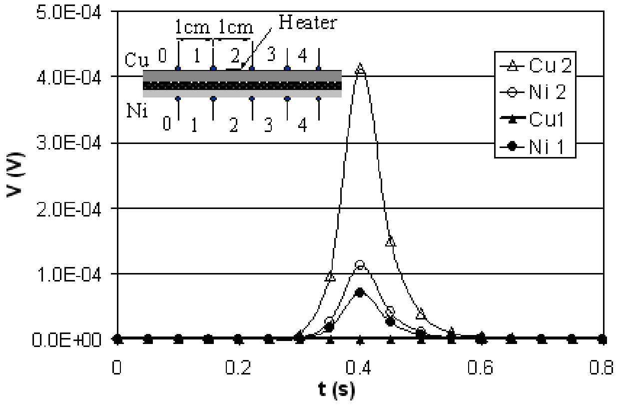

Figure 3. Voltages calculated with $k = 10^5$ after the heat pulse across the heater and at 1 cm from the heater.

the critical current density, E_c the reference electric field and E_{YBCO} the electric field corresponding to the current density J.

The contact resistances between the layers are affected by a large uncertainty. A parametric study has therefore been carried out to understand their relevance. We performed a series of simulations in which we parametrically varied the ratio $k = R_{\mathrm{YBCO-Ni}}/R_{\mathrm{Cu-Ag}}$, setting $R_{\mathrm{Cu-Ag}}$ as a constant. The transverse resistance $R_{\mathrm{Cu-Ag}}$ is mainly due to the solder between the Cu and the Ag layers. The transverse resistance $R_{\mathrm{YBCO-Ni}}$ is mainly due to the buffer layer between the YBCO and the Ni layers. As the buffer layer is highly resistive, the contact resistance $R_{\mathrm{YBCO-Ni}}$ is much higher than the contact resistance $R_{\mathrm{Cu-Ag}}$. In all simulations, a 14 cm long tape carries a 250 A transport current. The thicknesses of the main tape layers are as follows: $\delta\_\mathrm{Cu} = 50~\mu\mathrm{m}$, $\delta\_\mathrm{Ni} = 75~\mu\mathrm{m}$, $\delta\_\mathrm{Ag} = 3~\mu\mathrm{m}$, $\delta\_\mathrm{YBCO} = 1~\mu\mathrm{m}$. Starting from $t = 0.1$ s, the tape is subjected to a 300 ms heat pulse along a 4 mm long central region. During the heat pulse the current redistributes from the YBCO to the adjacent layers, as shown in figure 2 for $k = 10^4$ and $k = 10^5$. Note that with increasing k, the YBCO/Ni current transfer length increases, while the peak current in the Ni decreases. Figure 3 shows the voltages arising across region 2, located around the heater, and across region 1, placed at 1 cm from the heater. Apart from the voltage directly across the heater, the Cu voltages are negligible. The Ni voltages, however, assume measurable values even a few centimetres from the heater. This is in agreement with the observations reported in [4] and [5] and is a direct result of the difference in the current transfer lengths from YBCO to Cu and Ni. In the heater region the Cu carries significantly more current, but the Ni and Cu voltages are comparable, due to the large resistance of the Ni layer relative to the Cu layer. Elsewhere, the difference in the current transfer lengths determines the presence of current in the Ni where there is no current in the Cu. It is therefore possible to measure voltages in the Ni, while the Cu voltages are either negligible or only measurable after the temperature has propagated sufficiently. This faster propagation of the Ni voltages could be used for quench detection. The general definition of a single *quench propagation velocity*, which is correct in symmetric low temperature superconducting conductors, does not seem to be well suited for YBCO coated conductors. A detailed analysis indicates that the voltage propagation velocity in the Cu is distinct from that in the Ni. A question for further study is the size of the actual normal region, as compared to the lengths of detectable voltage in the Ni and Cu.

In conclusion these results could influence ongoing research on conductive buffer layers. An alternative is to use the contact resistances as a tool that can be tuned to obtain useful voltage signals for quench detection. If this can be attained without significantly reducing the minimum quench energy, a viable solution to quench detection in YBCO coated conductors may emerge.

References

[1] Hirabayashi I *et al* 1999 *IEEE Trans. Appl. Supercond.* **9** 1979
[2] Lue J W *et al* 2002 *Proc. ICMC* vol 48 (Wisconsin, USA: American Institute of Physics) p 321
[3] Trillaud F *et al* 2003 *Cryogenics* **43** 271
[4] Wang X *et al* 2005 *IEEE Trans. Appl. Supercond.* **15** 2586
[5] Duckworth R C *et al* 2003 *IEEE Trans. Appl. Supercond.* **13** 1768