Journal of Physics: Conference Series **709** (2016) 012011 doi:10.1088/1742-6596/709/1/012011

Analysis of normal zone propagation in superconducting tapes initiated by thermal disturbances

M Lebioda, J Rymaszewski[1]
Institute of Electrical Engineering Systems, Lodz University of Technology, Stefanowskiego 18/22, 90-924 Lodz, Poland

[1]E-mail: jacekrym@matel.p.lodz.pl

Abstract. The normal zone formation in superconducting elements during the current flow is a dangerous process, which may lead to the irreversible destruction of materials. Results of the experimental and simulation studies of the normal zone propagation process in 1G (BSCCO) and 2G (ReBCO) superconducting tapes are presented in this paper. The obtained measurement and simulation results confirm the key role of the metallic shield of HTSC tapes in the heat transfer and the thermal stability.

1. Introduction

A phenomenon of the normal zone formation in superconducting elements during the current flow is a dangerous process, which may lead to the irreversible destruction of materials (see figure 1). The evolution of the normal zone is caused by thermal, electrical or magnetic disturbances close to a superconductor. A local increase of resistance and, consequently, an increase of the generated Joule heat associated with the transport current flow are the results of this phenomenon [1]. This process is particularly dangerous in case of the high current devices.

Figure 1. 2G superconducting tape burned out due to developed normal zone, initiated by thermal disturbance.

The operating current of these devices can be close to the critical current of superconducting tapes, especially during emergency situations. A metal stabilizer coating the superconductor is therefore very important in development of this zone [2,3]. A local destruction of superconductivity causes the transport current redirection from the superconductor to the metallic sheath. If the thermal conductance of the stabilizer is appropriately large the heat rapidly diffuses within the element. The high speed of the normal zone propagation velocity (NZPV) is therefore required to protect the superconducting materials from the destruction.

Designing of superconducting devices such as electromagnets or fault current limiters requires knowledge of the normal zone propagation in the windings [3-6]. Devices with superconducting coils, built so far, used the LTS superconducting wires, i.e. Nb_3Sn, Nb-Ti. The second generation (2G) superconducting tapes (ReBCO) actually become the most attractive material for the windings. 2G HTS tapes offer unprecedented mechanical (high tensile strength and mechanical stability) and electromagnetic parameters (very high critical current and upper magnetic field), especially in liquid nitrogen temperatures. The great advantage of the 2G tapes is high thermal stability resulting from the very small thickness of the superconducting layer in relation to a substantially thicker layer of metallic substrate. The temperature margin for coils made of high temperature superconducting materials is greater by an order of magnitude in comparison to the low temperature superconductors and the heat capacity is greater by 2-3 orders. Unfortunately, the NZPV in 2G tapes is on the order of 1 mm/s to 10 mm/s [2-5,7-9], which is very much lower than that of LTS wire (NZPV > 10 m/s) [10]. As a consequence, the heat dissipation doesn't relocate and the appearing hot spots could be very high and destructive in this case. A large resistance at the superconductor-stabilizer interface is a reason of the small zone velocity. All these features make it difficult to design the stable electromagnet with 2G coils.

The authors have plans to design and construct the superconducting electromagnet with HTS coils [11]. Therefore, the analysis of the normal zone propagation becomes necessary. Results of the experimental and simulation studies of the normal zone propagation process in superconducting tapes are presented in this paper. The 1G (BSCCO) and 2G (ReBCO) superconducting tapes, cooled in the liquid nitrogen, were examined and compared.

2. Experiment

A special sample holder, made of the nylon (polyamide) rod, is presented in figure 2. The tape with a length of 25 cm was wound around the rod. This design minimizes the influence of heat from the current electrodes to analyze the region of the tape. Many voltage taps were arranged on both sides of the samples' surface to examine the propagation process. The measuring system was prepared for measurements of the normal zone propagation velocity.

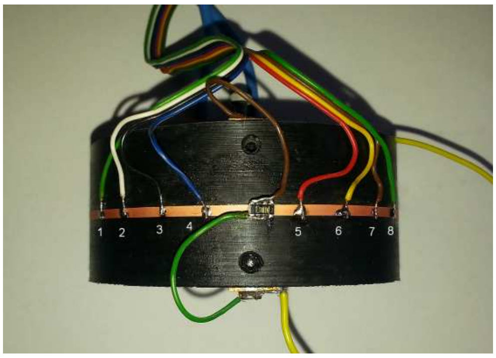

Figure 2. 2G sample tape with voltage taps and SMD resistor as a heater.

The main element of the system is the digital oscilloscope TDS5032B characterized by the high sampling speed (up to 5 GS/s) with the differential amplifier ADA400A, which enables the precise (with 1 µV resolution) acquisition of the signal on the voltage electrodes (probes) of the superconductor in the static and dynamic states. Both the transport current source and the heater current source are software controlled which allows full control over the process of the developing of the normal zone. Thermal disturbances were initiated by the heater made of SMD resistors 2512 (12.5 Ω). Two different types of superconducting tapes were examined: 1G – BSCCO 2223 – NST Zerome Hercules (width – 4 mm, thickness – 0.4 mm, measured critical current 50 A) and 2G –

ReBCO – SuperPower® SCS6050AP, sliced to a width approximately 2 mm (thickness – 0.1 mm, measured critical current 65 A). The sample holder with the tested tape was placed in a liquid nitrogen bath. The block diagram of the measurement system is presented in figure 3.

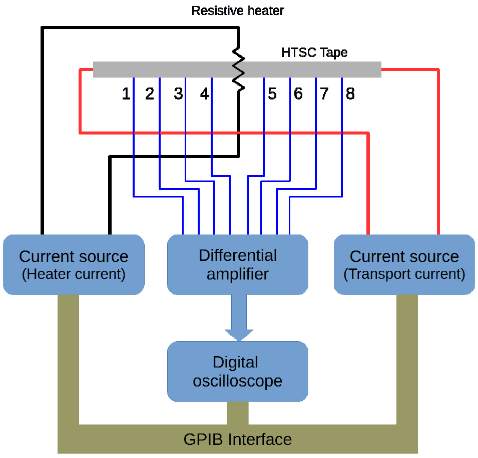

Figure 3. Block diagram of measurement system.

3. Results

Measurements were made for various parameters of the transport current and heating current sources (single or multi impulses). The following figures are merely examples of the obtained results. Figure 4 presents comparison of voltages' changes associated with the thermal local disturbance for both type of tapes: BSCCO and ReBCO. The local loss of stability for current lower than critical has been observed. It should be noted that the dynamics of changes and the voltage attained are higher in ReBCO sample. The thermal pulse applied on the samples is shown in the rapid increase of voltage. The rising of voltage is nearly linear and slight thermal fluctuations have been observed close to peak voltage. This could be the result of change of the boiling intensity. In case of the BSCCO sample a lower dynamic of voltage changes and non-linear rising of the voltage have been observed. This is the result of fast propagation of heat flux along the samples. The high thermal conductivity and the large thickness of BSCCO metallic stabilizer are the reasons for this behavior. The intense thermal fluctuations have not been observed in this case.

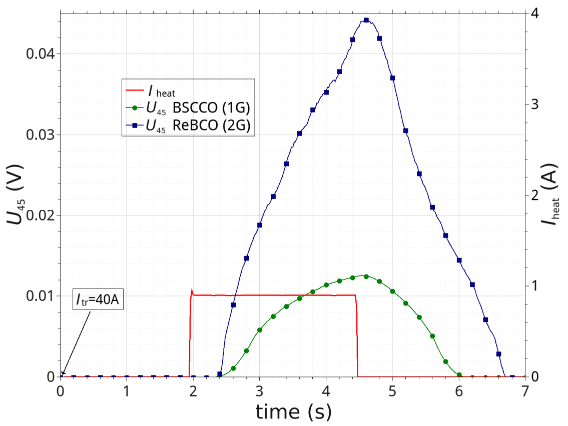

Figure 4. Voltage change on 1G and 2G samples caused by the thermal pulse (I_{heat} = 0.9 A, t_h = 2.5 s, $E \sim 25$ J). Transport current, I_{tr} = 40 A, lower than critical current.

Figure 5 shows time characteristics of the voltage between taps 4 and 5, localized near the heater on ReBCO tape. A much higher increase in voltage (over 100 mV on 20 mm) compared to the characteristics shown in figure 4 can be noted. This is caused by a larger amount of current transport (I_{tr} = 50 A) and higher pulse energy of heat (although shorter pulse duration). The voltage increase is

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due to the development of normal zone, which started near the heater. The thermal runaway was observed for the pulse duration t_h = 800 ms (energy E ~ 35 J). The positive feedback drives this process and this could end up burning out the tape if it does not comply with safety system (quench detector). Simultaneous measurements of the voltage between taps 4 and 5 as well as 5 and 6 showed that the resistive zone does not reach area between taps 5 and 6. The estimated value of the NZPV is relatively small and does not exceed 3 mm/s. For the shorter pulses this phenomenon does not occur and the voltage starts to decrease after reaching the maximum. It should be emphasized that a considerable part of the heat generated by the heater is absorbed by the liquid nitrogen.

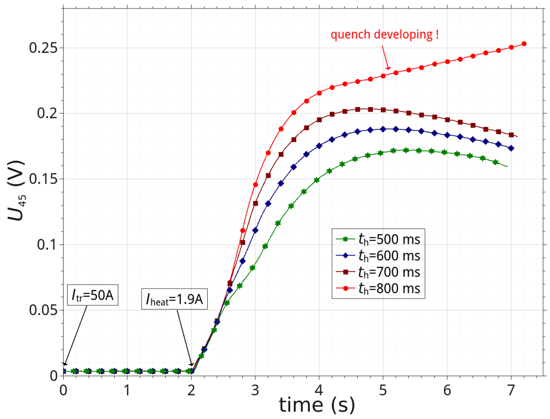

Figure 5. Time characteristics of voltage on 2G sample for thermal pulses with various width (I_{heat} = 1,9 A). Transport current, I_{tr} = 50 A, lower than critical current.

The low propagation velocity in 2G tapes favors the local accumulation of heat, which significantly affects the condition of heat exchange with the refrigerant. A significant shift in the time between current pulses in the heater and a voltage response of the sample is shown in figure 6. After every subsequent thermal pulse a marked increase in the voltage on the sample is observed. The low velocity of the resistive zone propagation leads to permanent loss of thermal stability.

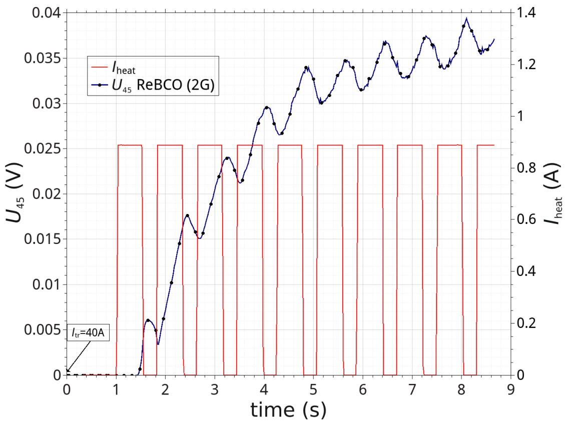

Figure 6. Voltage response on multiple thermal pulses for 2G sample (pulses width t_h = 0.5 s, transport current I_{tr} = 40 A).

4. Model

The model is implemented in COMSOL Multiphysics package. The main assumptions for the model are the following: electrical and thermal parameters of the materials are temperature dependent (including cryogenic temperatures), the boiling crisis has been included in the description (heat transfer coefficient is also temperature dependent) [11,12]. The equation of electrical conduction for solids and the equation of heat conduction are used. Other assumptions are described in the previous articles of authors [1,11-13]. The model allows, among others, to analyze local temperature changes of the superconducting tape, also just below the heater and in close proximity. Significant dimensions and the high thermal capacity of typical temperature sensors make proper measurements impossible. Figures 7 and 8 show typical simulation results. In figure 7, the process of heating of the tape, which is the effect of the heat pulse, can be observed. The effect of movement of the heating (resistive) zone (shifting of curves T_0 and T_1) is visible. The determined value of the NZPV is in this case approximately 50 mm/s. Despite the end of the heat pulse, the resistive zone continues to expand along the tape, which is caused by the heat generated by the transport current in the resistive area (figure 8). The direction of heat flow vectors confirms this assumption. The visible effect of the positive thermal feedback can lead to thermal damage of the tape (see figure 1).

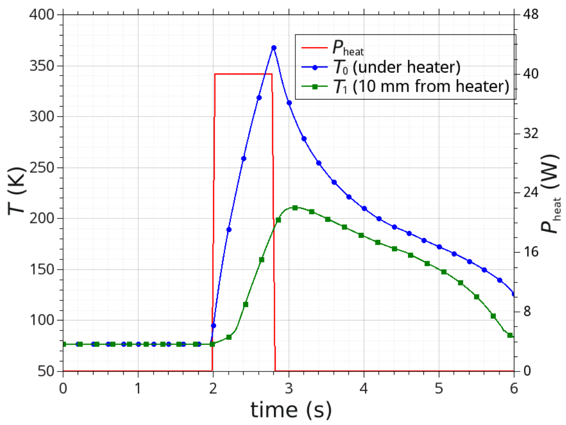

Figure 7. Time evolution of temperature of 1G tape as a result of heat pulse.

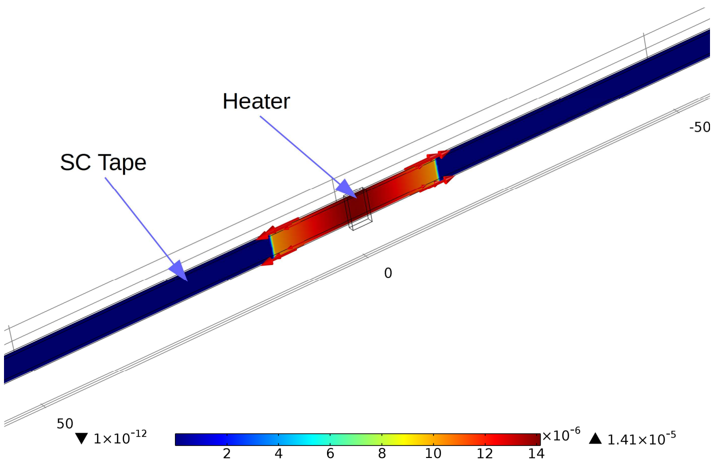

Figure 8. Distribution of superconductor resistivity and vectors of heat flux after end of the heat pulse ($t = 3$ s, transport current $I_{tr} = 80$ A, heat pulse energy $E_h = 32$ J).

5. Summary

This study investigated the development of the normal zone in two different types of superconducting tapes – 1G (BSCCO 2223) and 2G (ReBCO). The thermal local disturbance results in a change of electrical parameters of both types of HTSC tapes. A dynamics of local parameters' changes is high in case of 2G tape. This is the result of particular construction of the tape, where the thermal conductivity and capacity are slight. The development of the normal zone in this type of tape has been observed. The zones propagation after local heat source extinction has been noticed. The transport current maintains the heating process, which is the result of slow rate of the thermal resistive zone propagation. A local heat accumulation can be a main reason of damage of HTSC tapes. The coincidence between the experimental and simulation results and, in both cases, the occurrence of positive feedback between the transport current and the propagation of the normal zone have been observed. Experimental studies for 2G tapes have proven that the value of the NZPV is very low (<3 mm/s). The thermal runaway have not been observed for examined BSCCO tapes. The simulation research has shown that the NZPV for 1G tapes is about 50 mm/s. The proposed mathematical model allows the observation and analysis of the experimentally inaccessible phenomena. The obtained measurement and simulation results confirm the key role of metallic shield of HTSC tapes in heat exchanges.

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