Numerical and experimental analysis of normal zone propagation on 2G HTS wires

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Abstract—In this paper we analyze numerically and experimentally the quench behavior of Cu-stabilized second generation high temperature superconducting (2G HTS) wires at self-field and in adiabatic conditions. The electric field profiles along the superconductor after applying an energy pulse to the conductor have been obtained together with the parameters characterizing the quench: minimum quench energy (MQE) and the normal zone propagation velocity (NZPV). The analysis has been performed at different temperatures, T , between 72 K and 77 K, and at different applied currents, $I/I_c(T) < 1$, I_c being the critical current. Our analysis shows that the numerical results obtained by finite element method (FEM) are closer to the experimental MQE values when the contribution of the thermal mass of the heater is taken into account.

Index Terms—coated conductors, thermal stability, superconductors, quench, normal zone, experimental, numerical, REBCO.

I. INTRODUCTION

SECOND generation high-temperature superconductor (2G HTS), namely REBCO coated conductor, has been the subject of intense research in the last years and has been proven as a candidate of interest for the use in power applications. As the possibility to quench due to disturbances, such as local defects, exists, the study of the stability process in 2G HTS is important to determine their optimal performance in applications.

The usual way to analyse the quench/recovery behavior of superconductors is by applying a heat pulse to the conductor and analyzing the temperature and electric field profiles along the conductor [1-5]. These measurements allow the determination of the relevant properties for thermal stability analysis, such as the minimum quench energy (MQE) and the normal zone propagation velocity (NZPV). These properties depend strongly on the heat capacity and the thermal and electric resistivity of the conductor, and therefore on the thickness of the high-conductivity normal metal matrix, which is normally Ag and Cu. The metal sheath shares transport

current when the current exceeds the superconductor critical current and spreads the local heating along the conductor.

Recent experiments performed on stabilizer-free coated conductors [5] have shown that they have small MQE values (of the order of 5-20 mJ). More important is that the temperature increase during the quench in non-stabilized coated conductors, together with the small NZPV values, results frequently in the damaging or even the burn out of the sample once the quench has been triggered. This effect has also been studied by Fu et al. [6], who analysed the amount of copper required to maintain the hot spot temperature after a quench below a certain threshold value, and to allow the detection of the quench. Therefore, copper should be added to these coated conductors to protect the superconductor from damage caused by quenches.

In this paper we present the analysis of MQE and NZPV values of Cu-stabilized coated conductors under adiabatic conditions. We compare the experimental MQE values with the numerical results obtained using finite element method (FEM) with and without considering the contribution of the thermal mass of the heater. The dependence of the MQE and NZPV values on the exponent n characterizing the current-voltage curves of the superconductor ($V \propto I^n$), is also analyzed.

II. EXPERIMENTAL

A. The sample

The measurements were performed on 2G HTS conductors fabricated by SuperPower, Inc. using Ion Beam Assisted Deposited MgO technology for buffer layers and metal organic chemical vapor deposition for the superconducting layer. The thickness of the Hastelloy substrate and REBCO layer is 50 μm and about 1 μm , respectively. The analyzed sample is a Cu-stabilized sample, which has a 2 μm Ag layer deposited on top of the superconductor layer and then the entire conductor structure is stabilized by electroplating a 20 μm Cu layer on all sides. The width of the sample is 4 mm and the length L is 9 cm plus 1 cm for each current contact.

The electric resistance, thermal conductivity (κ) and specific heat (c_p) of the samples have been measured using a Physical Property Measurement System (PPMS) from Quantum Design. The values are plotted in Fig. 1. The resistance and κ values are dominated by the copper used to stabilize the sample. The resistance at $T < T_c$, needed in the numerical simulation, has been extrapolated from the measured curve (dotted line). Regarding c_p , it must be noted that a rough estimation of these values can be also obtained

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assuming that c_p values of coated conductors are dominated by those of Hastelloy substrate and copper stabilizer, but such estimated values using the values and procedure described in [2], are about 5-10% higher than the measured ones.

The end-to-end I_c of the sample at 77 K, that produces $1\mu\text{V}/\text{cm}$, was 88 A. The $I_c(T)$ values of the sample at self-field are plotted in Fig. 2. The inset of the figure shows the $n(T)$ values for this sample.

B. Quench measurement and simulation

For the quench measurements, the sample is initially at a uniform temperature T_0 below T_c and carries a given current I , well below the corresponding critical current $I_c(T_0)$. The energy was deposited to the wire by passing a rectangular current pulse of duration $t_p=40$ ms to a heater made of a graphite-based paste (ECCOBOND 60L). The heater is about 2mm-long, 0.4mm-thick and 4mm-wide and was placed in the middle of the sample. In Section III we discuss

Fig. 1. Temperature dependence of the thermal conductivity, electrical resistance and heat capacity, obtained experimentally for the analysed wire. The resistance at $T < T_c$, needed in the numerical simulation, has been extrapolated from the measured curve (dotted line).

Fig. 2. Measured critical current, I_c , of the studied tape as a function of the temperature. The inset shows the n -values characterizing the current-voltage curves of the superconductor ($I \propto I^n$).

the effect of t_p and the ECCOBOND on the experimental results.

During the measurements, the sample was placed in vacuum and was mounted in a cryocooled cryostat. Two ends of the sample were thermally anchored to the 2nd stage of the cold head of the cryocooler. The temperature of the sample can be varied using a Lakeshore 331 temperature controller.

Time-resolved electric field measurements along the sample have been carried out by means of a Data Acquisition (DAQ) device. Five voltage taps were attached to the sample to measure the voltage along the conductor. The current is turned to zero 0.5-1s after having injected the heat pulse, in order to prevent permanent damage of the sample during the quench. A thermocouple was soldered onto the sample, near the heater, in order to measure the temperature increase rate $\Delta T/\Delta t$ during the quench and also to monitor the sample cooling down process after a quench.

The numerical results have been obtained by solving the one-dimensional (1D) heat balance equation using finite element method (FEM) and the c_p , κ and resistance values of Fig. 1. The boundary conditions are $T(x=-L/2) = T(x=L/2) = T_0$ where $L = 9$ cm. Since the n -value is almost constant in the temperature range of interest (see inset Fig. 2), we used a constant n -value, $n=25$, in the simulations. The case of critical state model, CSM, has also been simulated for comparison.

Fig. 3 shows the heating power per unit volume $G(T)$, given by $G(T) = I \cdot E(T)/A$, where E is the electric field and A is the cross-sectional area used for the simulations for the cases of $n=25$ and CSM. When the temperature of the sample increases above $T_g(I)$, where $I = I_c(T_g)$, the current is shared between the superconducting layer and the metal matrix. $E(T)$ is calculated as two parallel electric impedances: the linear ohmic dependence of the metal matrix and the power-law voltage-current relation of the superconductor. It is observed that the linear dependence in the current sharing regime ($T_g \leq T \leq T_c$) is only observed for the case of CSM, but not for finite n .

III. RESULTS AND DISCUSSION

A. Minimum quench energy (MQE)

The MQE values are derived experimentally and numerically by analyzing the time dependence of the electric

Fig. 3. Temperature dependence of $G(T)$ for $I=79$ A and $T_0=77$ K for the cases of $n=25$ (solid line) and CSM (dotted line).

Fig. 4. Measured and simulated MQE values as functions of the reduced current (I/I_c). Solid square and circle symbols correspond to the measured values. Solid lines are the values obtained numerically using the thermal and electrical properties described previously. The dashed lines correspond to the values obtained when the specific heat of the heater is taken into account.

Fig. 5. Measured and simulated NZPV values as a functions of the reduced current (I/I_c). Solid symbols correspond to the measured values. Solid lines are the values obtained numerically using the thermal and electric properties described in II. The dashed lines correspond to the numerical values divided by 1.2.

field after applying a heat pulse to the conductor to determine the critical energy value at which a quench is initiated. The obtained values are plotted in Fig. 4 as a function of the reduced current, I/I_c , at two different operating temperatures, 72 K and 77 K. Solid symbols (squares and circles) correspond to the measured values. Solid lines are the values obtained numerically using the thermal and electric properties shown in Fig. 1. As is observed, the measured values are the same order of magnitude as the calculated values, but higher than the latter by approximately a factor of 1.4 in the entire range of the electrical current used in this experiment. Indeed, by applying this correction factor, the two sets of data almost coincide.

In order to analyse the reason for this discrepancy between numerical and experimental values, we have calculated MQE values taking into account the c_p of the heater itself. The obtained MQE values are plotted as dashed lines in Fig. 4 and

Fig. 6. (a) Instrumentation diagram showing the positions of the heater and voltage taps.. (b) and (c) Measured voltages (solid lines) and calculations (dotted lines) during a quench for $T=77$ K and $I=79$ A= $0.9I_c$. From left to right V_{12} , V_{23} , V_{34} and V_{45} with voltage taps lengths of 9, 3, 3, 3 mm, respectively. (b) MQE= 23 mJ, using values shown in Fig. 1. (c) MQE= 27 mJ using $1.2c_p$ and the same resistance and κ values as in (b).

are very close to, but still smaller than the measured ones by about 20%. This indicates that the thermal mass of the heater may contribute to higher experimental MQE values. The heater used in this work was made as small as possible (0.4mm-thick, 2mm-wide and 2mm-long) but due to considerably high c_p value of the graphite-based heater $c_p=0.225$ J/g $^{\circ}$ K $^{-1}$ at 77 K, and although its density is small (around 1.5 g/cm 3) its contribution is not negligible. The contribution of the electrical wires used to inject the current to the heater would probably be the cause of the additional 20% difference (as discussed in Section III.B).

Our results show that Cu-stabilization of coated conductors leads to an increase of MQE values of about one order of magnitude compared with those without Cu-stabilization [5].

It must be noted that the difference between the measured and experimental MQE values in the 2G HTS samples is more pronounced than in MgB $_2$ /metal conductors analysed previously, which could probably be attributed to the smaller cross-sectional area of 2G HTS (0.38 mm 2 vs. 1.1 mm 2 of the MgB $_2$) [8].

B. Normal zone propagation velocity, NZPV

Fig. 5 shows the experimentally (solid symbols) and numerically obtained (solid lines) NZPV values at 72 K and 77 K. As we can see, the simulated values are about 1.2 times higher than the measured ones. NZPV values have been calculated from the time delay between $V_{34}(t)$ and $V_{45}(t)$ curves, outside the zone between voltage taps 1 and 2, where the heater is placed, as it can be seen in Fig. 6.

Fig. 7. Calculated MQE and NZPV values as a function of the reduced current, I/I_c , at $T=77$ K for $n=25$ and CSM.

Both MQE and NZPV results suggest that there is an experimental effect that makes the real thermal mass of the sample to be higher than we have considered in the simulations. This would be due to the additional thermal mass contribution of the soldered wires for measuring the voltage along the sample. This has been proven experimentally; in a separate experiment, we changed the voltage wire size from 0.1mm to 0.2mm in diameter, and the measured NZPV values became 1.4 times (instead 1.2) lower than the simulated ones.

A typical measurement of the voltages obtained between adjacent voltage taps is plotted in Fig. 6(a) together with the simulations obtained for the properties shown in Fig. 1. As shown in Fig. 6(a), the time delay between voltages $V_{34}(t)$ and $V_{45}(t)$ is smaller in the calculation than in the experiment; and in the normal state (i.e. for $V_{12}>15$ mV and $V_{23}, V_{34}, V_{45}>5$ mV), the numerical dV/dt values are higher than the experimental ones, which means that the calculated temperature increase during a quench is higher in the numerical case. As result, the numerical NZPV values are higher than the measured ones. When higher values of $c_p(T)$ are used in the calculation ($1.2c_p$) the agreement between the measured and numerical $V(t)$ curves is rather good [Fig. 6(b)].

The NZPV is of great importance in applications. In order to protect the superconducting devices against quench, it is desirable that NZPV be as high as possible, so as to prevent the formation of hot spots which would cause permanent damage to the device. Our measured NZPV values are in the range of 2-7 cm/s for the analyzed conditions, which is typical for 2G HTS conductors [2,4]. Compared with similar conductors but without Cu-stabilization, these conductors are advantageous since protection of the conductor from damage caused by quenches is more feasible [6].

C. The effect of the n -value and the duration of the pulse

Fig. 7 shows the MQE and NZPV values obtained numerically for $n=25$ and CSM. It can be seen that for finite n -value case MQE is higher than for CSM case while NZPV is smaller. This is due to the considerably smaller heating power in the current-sharing regime for finite n -value case (see Fig.3), even when n -value is as high as 25 as in this case. Therefore, it is not valid or not accurate to use CSM assumption to predict MQE and NZPV values.

Since MQE values depend on the pulse duration, t_p [9], it is important to fix this value to get the MQE(I, T) dependence. The use of $t_p=40$ ms is arbitrary, but it has been chosen since it is much higher than the time step of the measurements (0.3ms) and allows the MQE measurement at low currents. Nevertheless, it must be noted that MQE is not very sensitive to the change in t_p when t_p is in the ranging of a few tens of ms. For instance we have obtained MQE values of 43, 46, 52 and 56 mJ for $t_p=5, 10, 40$ and 100 ms, respectively, for $T_0=72$ K and $I/I_c=0.8$.

IV. CONCLUSION

We have analyzed experimentally and numerically the MQE and NZPV values of a Cu-stabilized 2G coated conductor. We found that a numerical model based on 1D heat diffusion with non-linear heat generation, typical of finite n -values, can satisfactorily describe the experimentally observed quench behavior of these conductors. We also found that the thermal mass of the heater and wires contributes to the increase of the experimental MQE values, which are higher by a factor 1.4 than the values obtained numerically using FEM. Moreover, the electrical wires used to measure the voltage along the sample could be the cause of the $\sim 20\%$ difference between the numerical and experimental NZPV values. It must be noted the importance of using a finite n value, and not the CSM, to get accurate results with the FEM calculations. Our results show that Cu-stabilization of coated conductors leads to an increase of MQE values of about one order of magnitude compared to those conductors without Cu-stabilization [5].

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