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Quench detection method for 2G HTS wire

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Abstract. 2G HTS conductors are increasingly used in various commercial applications and their thermal and electrical stability is an important reliability factor. Detection and prevention of quenches in 2G wire-based cables and solenoids has proven to be a difficult engineering task. This is largely due to a very slow normal zone propagation in coated conductors that leads to formation of localized hotspots while the rest of the conductor remains in the superconducting state. We propose an original method of quench and hotspot detection for 2G wires and coils that is based upon local magnetic sensing and takes advantage of 2G wire planar geometry. We demonstrate our technique experimentally and show that its sensitivity is superior to the known voltage detection scheme. A unique feature of the method is its capability to remotely detect instant degradation of the wire critical current even before a normal zone is developed within the conductor. Various modifications of the method applicable to practical device configurations are discussed.

Introduction

Commercial availability and steady improvement of 2G superconducting wires open up new application areas for HTS coated conductors [1, 2]. New world record performances of critical current (I_c) × single piece length (L) equal to 300,330 A-m have been achieved in routine km long wire production. Enhancement in in-field performance has been achieved *via* Zr-doping and the technology has been transferred into the production line. High-field coils with consistent improvement in performance have been demonstrated with SuperPower® 2G HTS wires. Self field was increased from 0.73 Tesla to above 1 T at 77 K and more than 2 T at 65. At 4.2 K, maximum fields of 10.4 T and 27.4 T, were achieved in self-field and with 19.9 T background, respectively. All these achievement show that 2G high-field magnets are one of the most promising future applications. Effective prevention of quenches in these 2G HTS magnet coils is the most important factor for reliable and safe operation. Unlike low-T_c superconductors, the HTS conductor is less prone to quenching. This is primarily due to a combination of much higher specific heat of the HTS conductor at operating conditions and less steep I-V characteristic (lower n-value) compared to the low-T_c counterparts. At the same time, whenever a quench in HTS wire occurs, its detection and management presents a serious engineering challenge. The same factors that suppress quench occurrence would now result in a very slow development of the thermal instability and inhibit its propagation along the wire. Normal zone propagation velocity reported [3,4] for the practical 2G superconductor wires is in the range of 0.1-1 cm/s which is 10^3-10^4 times less than in the low-T_c materials. Slow developing thermal instability means that a small local hotspot is initially formed in the wire and some significant heating occurs there prior to the surrounding region quenching into the normal state. This leads to a quick local thermal degradation of the YBCO material due to oxygen loss or to a complete wire burnout. At the same time, voltage associated with the formation of localized hot spots is always small, proportional to the hotspot dimensions, which makes it hard to detect the quench signal in the voltage noise background. So far individual voltage monitoring in the magnet sub-sections [5] is still the most common detection method in superconducting magnet technology although a number of other approaches have been pursued, including active ones such as acoustic noise detection [6], passive ones, such as use of a material with high heat capacity (diamond, sapphire) or a semiconductor material (such as ZnO) with strong temperature dependence of conductivity as a surrounding shell between the neighboring turns of the magnet wire [7], and complex active detection techniques based on 3D computer modeling of the thermal response [8]. Such difficulty in quench detection in HTS coils based on voltage signal makes it necessary to develop a new technique.

Conductor configuration and simulation results

In this paper, we propose a simple and practical solution to the quench detection in 2G wire-based cables, coils and magnets. Unlike other approaches, ours takes advantage of the localized nature of the hotspots and their slow temporal evolution to achieve the high detection sensitivity. The method involves sub-dividing the 2G wire in two parts of equal width along the entire wire length, except for the areas adjacent to the current lead. This is done by mechanical slitting, indentation using a sharp knife, dry or chemical etching or other techniques. Superconducting regions (bridges) connecting the two parts are left intact at both ends of the wire. A magnetic field sensor (Hall probe or other) is placed in the slit region, facing the wire surface (see Figure 1). In the superconducting state, the parts of the slit wire would carry equal amounts of transport current. This current creates a magnetic field around the wire that is strongest at the edges where it is also directed mostly normal to the wire surface. However, inside the slit region, the normal field component is fully compensated due to the corresponding components of the two currents in the wire parts being equal in magnitude and opposite in direction**.**

Localized external heat flux, poor heat exchange and material imperfections along the wire cause local degradation of the critical current density and are the usual causes for hotspot formation. However, slow thermal relaxation and non-uniform distribution of material defects in the wire make simultaneous formation and synchronous (within a few milliseconds of one another) growth of the resistive regions in wire parts highly unlikely. As the critical current (I_c) of one part is reduced for whatever reason, the excess current flows in the other part. It is important to stress that the balance between the two currents is determined by the ratio of dynamic resistances of the parts, not the absolute value of the resistance. The latter may be, in fact, quite small ($<10^{-10}$ Ohm) and result from the onset of thermally-activated flux creep rather than the steady flux flow. This constitutes the key advantage of the proposed detection scheme. In practice, current redistribution between parts occurs first at whatever minute manifestation of resistance in either part; it develops at the same rate as the local I_c is suppressed and it *precedes* the appearance of a practically detectable voltage across the wire.

Current redistribution between the parts in turn produces unbalanced out-of-plane magnetic field in the gap region, as sketched in figure 2. Such field is readily detectable with an appropriate field sensor placed at a convenient point at the middle line of the wire, for instance near one of the ends. A simple estimate of the magnetic field change due to current redistribution in a practical conductor configuration can be made using the expression [9] for the field at a distance *y* from the middle line of the current-carrying strip:

$$H(y) = \frac{I_c}{2a\pi} ArcTanh\left[\frac{a^2 - b^2}{y^2 - b^2}\right]^{1/2}, \quad |y| > a \qquad (1)$$

where $2a$ is the strip width, I_c is the critical current, and $b = a(1 - I^2 / I_c^2)^{1/2}$).

For simplicity, we neglect magnetic interaction between the parts and assume that the net field in the middle of the slit H_m is simply a superposition of the two individual contributions:

$$H_m = \frac{I_c}{2a\pi}\left(ArcTanh\left[\frac{a^2-b_1^2}{(a+w)^2-b_1^2}\right]^{1/2} - ArcTanh\left[\frac{a_2^2-b_2^2}{(a+w)^2-b_2^2}\right]^{1/2}\right) \qquad (2)$$

Here $2w$ is the width of the slit, $b_1 = a(1-I_1^2/I_c^2)^{1/2}$ and $b_2 = a(1-I_2^2/I_c^2)^{1/2}$.

Here we use the same I_c for both terms, assuming that the field is sensed in the portion of the wire outside of the device winding, where quench occurrence is least likely and field penetration is only dependent upon the magnitude of the transport current. This also implies that only self-field is present at that location.

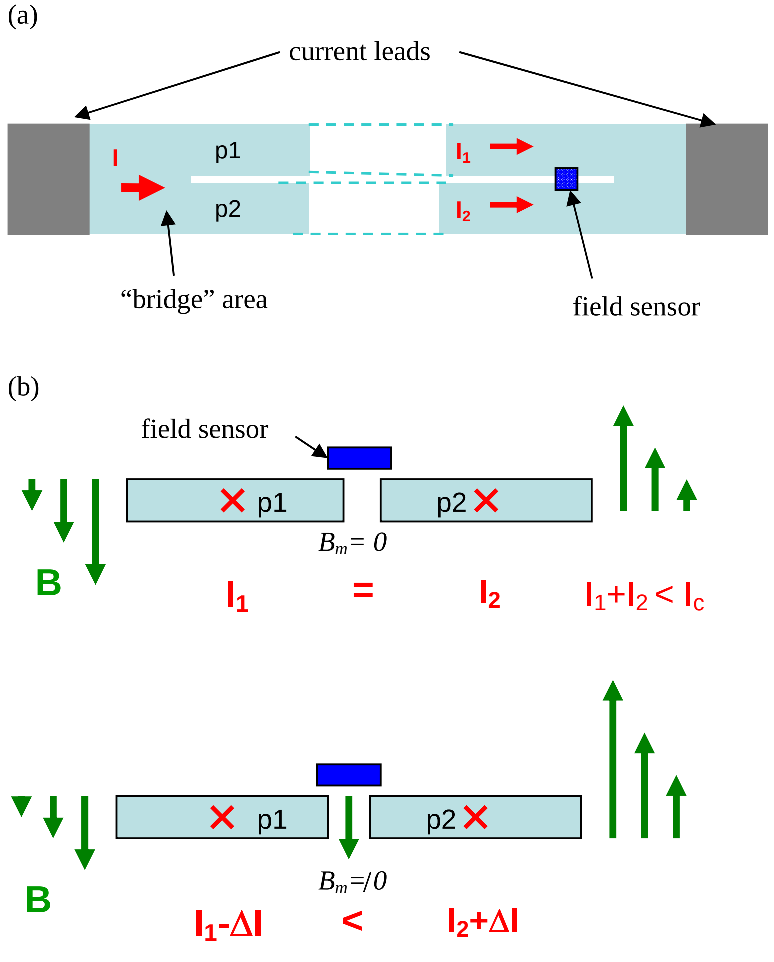


Figure 1. (a) Sketch of the 2G wire divided into two equal parts, p1 and p2, with superconducting bridges remaining near the current contacts. A field sensor is placed at the slit line, near the wire end

(b) (top) Normal cross-section of the wire with equal transport currents flowing in the two slit portions. Normal component of the magnetic field is fully compensated along the middle line.

(bottom) When current is partially redistributed from p1 to p2, the non-compensated perpendicular magnetic field B_m appears in the slit region.

As w<<a, we can use $ArcTanh(x) = \frac{1}{2}\ln\left(\frac{1+x}{1-x}\right)$ and, after simplifying, write:

$$H_m = \frac{I_c}{4a\pi}\left[\ln\left(\frac{2(a^2-b_1^2)}{aw}\right) - \ln\left(\frac{2(a^2-b_2^2)}{aw}\right)\right] \quad (3)$$

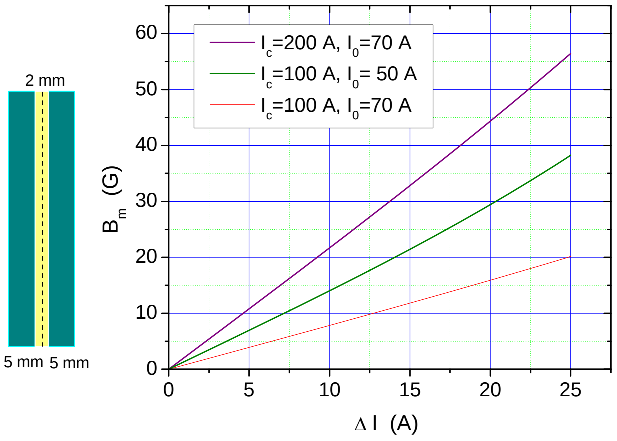


Figure 2. Results of the simulation using eq. (3) for different I_c and transport currents. Two 5 mm wide superconducting parts are separated by a 2 mm wide gap. Currents $I_0+\Delta I$ and $I_0-\Delta I$ are flowing in the two superconducting parts. Field induction B_m at the middle line of the wire is plotted here as function of ΔI.

Results of the simulation of the field induction with eq. (3) using realistic wire parameters are shown in Figure 2. Field at the middle line increases near-linearly with the non-balanced portion of the current. The smaller ratio of I_0/I_c results in the higher amplitude of the magnetic field for the given unbalanced current. One should note that the actual dependence of the field in the gap upon the current imbalance will be more complex due to a hysteretic behaviour of the superconducting critical state in the part where current is reduced. Nevertheless, the simple estimate as above should produce a correct order of magnitude estimate of the magnetic field magnitude.

Experimental

A 30 cm long piece of SuperPower’s 2G wire (Type SF12050, width 12 mm, thickness 50 μm) has been patterned using wet etching to form a non-superconducting stripe along its middle line that is ~ 1.5 mm wide and 22 cm long. The miniature GaAs Toshiba Hall sensor THS116 with an active area of 0.05 mm^2 was positioned at the stripe line, approximately 2 cm from its end and powered with a battery-based current source. The field sensitivity of the Hall sensor at operational conditions (77 K) is 6.9×10^{-5} V/Gauss.

In order to simulate a development of a local hotspot, a heater made of 5 turns of 0.4 mm Ni-Cr wire and installed in mechanical and thermal contact with the back side of the wire at a distance of approximately 8 cm from the end of the strip line opposite to the Hall sensor. The wire is held together with the heater using a piece of cardboard from the superconductor side (see figure 3, bottom). The heater is powered with two heavy-duty 6V batteries, connected in parallel. During the heat pulse the current in the heater (R = 0.8 Ohm) is 3.8 A, resulting in ~ 11 W of power being locally dissipated at the wire.

The current-voltage characteristics of the wire measured with the heater turned on and off are shown in Figure 4. A reduction of the wire critical current of 16 A (from 200 A to 184 A) due to the localized heating is observed. Next, measurements of the sample voltage and Hall voltage were done at various transport current flowing in the sample. Two Keitheley 2182A nanovoltmeters were used in fast buffer acquisition mode, one for the sample voltage and another for the Hall voltage. Both nanovoltmeters were software triggered simultaneously and 1000 measurement points were continuously acquired by each of them, at a rate of 60 points/s. During the acquisition cycle the heater was turned on manually (by connecting it to the battery bank) for a time interval of approximately 4 seconds. Results of the measurements are collected in Figure 5.

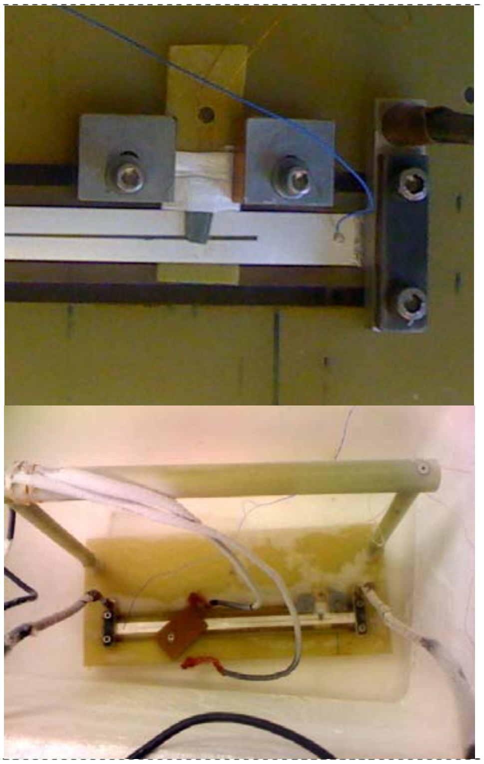


Figure 3. (top) Patterned wire installed in the test assembly, with voltage contacts attached and Hall sensor installed at the slit line of the wire. (bottom) Entire test assembly with the Hall sensor and the heater is immersed in liquid nitrogen

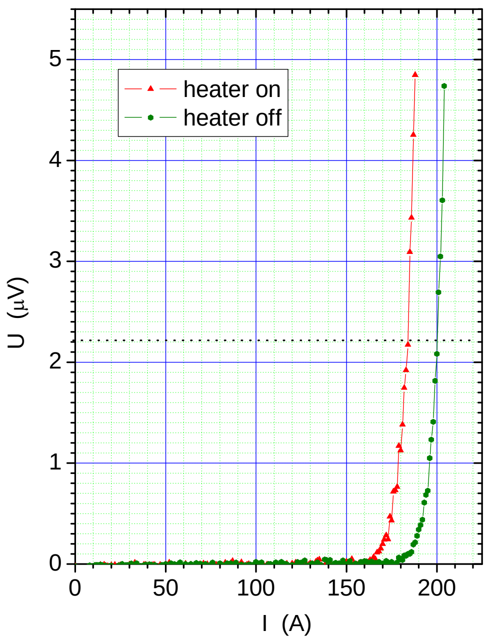


Figure 4. Current-voltage characteristics of the patterned wire with heater on and off. I_c (heater off) = 200 A; I_c (heater on) =184 A (as measured with 1 μV/cm voltage criterion)

Note that while the voltage across the wire is observed only when the net transport current exceeds the critical value for the wire, the non-balanced perpendicular magnetic field in the slit regions appears much earlier, at transport currents that are significantly lower than the wire I_c. This clearly demonstrates the sub-critical detection capability of the method. When comparing voltage and Hall sensor data, it is evident that fast detection of local I_c degradation condition using the voltage monitoring scheme would be very challenging due to a low signal-to-noise ratio, while it is a much easier task when using a Hall sensor. In fact, the signal-to-noise ratio of the Hall sensor-based detection method appears to be at least 100 times better than that of the voltage detection method. This high sensitivity provides a significant advantage for the early quench (actually, pre-quench) detection in the superconducting wire.

While superconducting bridges at wire ends are essential for sub-critical current redistribution and detection to take place, the low-resistive normal metal bridges can be a viable practical alternative. Of course, the sensitivity of the method in the creep regime will be much reduced in this case.

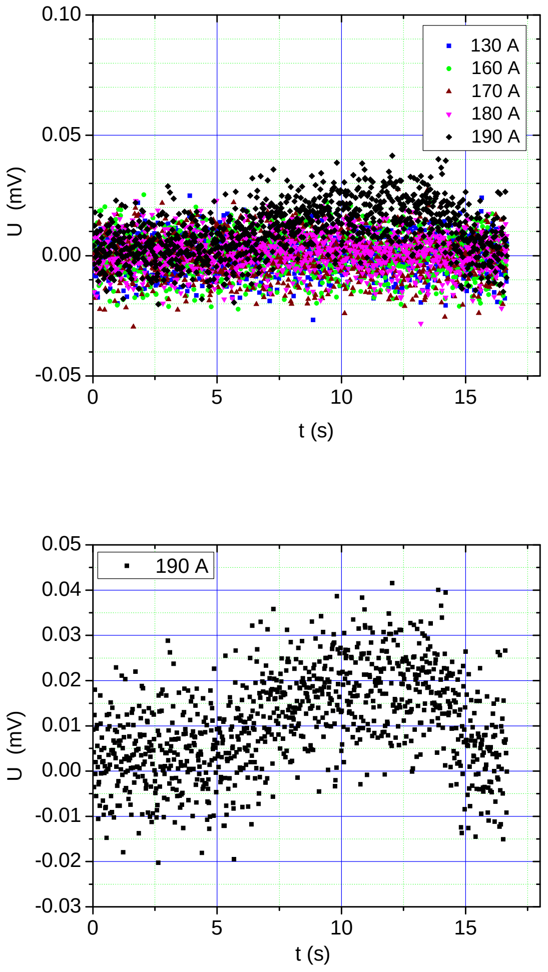
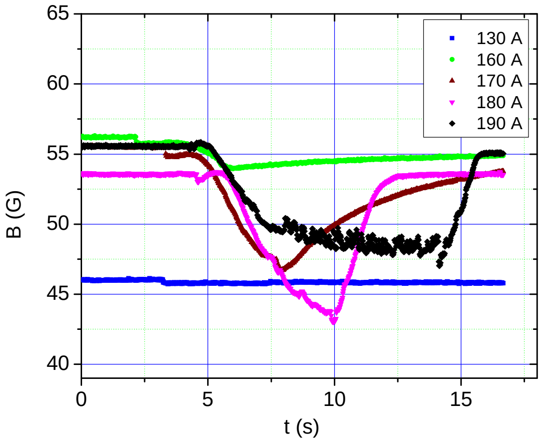


Figure 4. (top) Voltage across the wire acquired at various transport currents during the application of heat pulse. Fast unfiltered buffer acquisition mode of the nanovoltmeter was used and it results in the significantly larger noise compared to the slow filtered measurement mode, as in Figure 4.

(middle) Scaled-up measurement result for the transport current of 190 A. Mean amplitude of the detected voltage is consistent with the I-V curves shown in figure 4.

(bottom) Hall signal measured simultaneously with the voltage (using the second Keithley 2182A nanovoltmeter, also in buffer acquisition mode). Current redistribution between the parts yields 3-9 Gauss of unbalanced magnetic field in the slit region. Field offset is due to the electrical imbalance of the Hall sensor and the ambient background magnetic field; it changes slightly after each experiment.



Future improvement of the proposed detection technique can be done by subdividing the wire into a larger number of separated parts (striation) and using a Hall sensor array commensurate with the striation period as a multi-channel field balance detector. In this way, spatial resolution of the technique (across the width of the wire) will be improved, allowing a further boost in sensitivity and detection of even smaller regions of the thermal I_c degradation within the 2G HTS conductor.

Conclusion

In conclusion, a novel technique for quench detection in 2G superconducting wires is proposed, based on the continuous wire modification (slitting) along the length and use of Hall sensor as the current balance detector. Sensitivity of the technique is far superior to the standard voltage detection scheme. A pre-quench condition characterized by a localized thermal degradation of the critical current of the wire and increase in the flux creep rate is readily detectable with the proposed technique which makes it unique and suitable for practical applications.

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