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Current density distribution in 2G HTS tape in an external magnetic field

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Abstract

This paper describes the method of study of the critical current density distribution across a tape in a background magnetic field. We measured the current distribution by the scanning Hall probe method. Then we measured field across a tape by a set of 10 Hall probes placed on a single substrate. By comparison of data from these two experiments we determined positions of Hall probes at a tape. Then we measured the current distribution of current density across a tape inside a magnet in parallel and perpendicular magnetic field of 30 mT. The details of measuring method and results are presented.

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Keywords: HTS tapes; current distribution; magnetic field measurements; Hall probes

1. Introduction

In recent years the technology of production of 2G wires made considerable progress. The 2G HTS tapes with 4-mm wide and critical current up to 200 A in self-field are now available [1]. As one can see in [1] and [2] properties of 2G HTS tape of SUNaM are better than properties of 1G HTS tape produced by Sumitomo Inc. In spite of still high prices using of 2G tapes in research and development of various HTS devices becomes more prospective. Due to their shape, structure and the production technology HTS tapes are rather anisotropic, especially in weak magnetic fields. It was found recently that their critical currents depend not only on direction of magnetic field and current but on their mutual orientations, i.e. on Lorentz force directions [3]. The suggestion was made that this

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phenomenon is connected with non-uniformity of critical current density across a tape [3]. That is why, along with other characteristics of 2 G wires, it is important to know the distribution of critical current density across a width of a tape. It is very important for design of various HTS devices especially of those where HTS tapes are working in weak magnetic fields, such as power cables, transformers, machines, etc. For example, a non-uniformity of the critical current density across a tape may lead to a change of current capacity of a superconducting cable by ~10% [3]. It is necessary to reveal weak places of HTS 2G tapes for prevention of failure of HTS devices.

The measurement of the current density in HTS tapes was realized many years ago. The main four methods are described in [4]. They are: the magneto-optical imaging, the scanning Hall probe, the magneto-scan and the Hall probe array technique.

In this paper we present a technique to measure the distribution of the critical current density across the width of 2G tapes in self and external magnetic fields. We present results of measurements and data obtained as a result of the analysis. It is shown that the distribution of the critical current density can be quite non-uniform while the critical current along a length could be uniform.

2. Reconstruction of the current from a magnetic field

To reconstruct the critical current density across a tape one can use measurements of the magnetic field near a tape by Hall probes and further conversion from magnetic field to a current.
The conversion is based on the Biot-Savart law:

$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{I[\vec{r}\times d\vec{r}]}{r^3}. \quad (1)$$

If we imagine HTS tape as many parallel sub-tapes then the Biot-Savart law can be represented as [5]:

$$h_x = -\frac{j(y-\eta)}{2\pi\{(x-\xi)^2+(y-\eta)^2\}}d\xi d\eta, \qquad h_y = \frac{j(x-\xi)}{2\pi\{(x-\xi)^2+(y-\eta)^2\}}d\xi d\eta. \quad (2)$$

Here η and ξ are dimensions of across of HTS tape. These equations permit to calculate the components of the magnetic field – vertical (h_y) and horizontal (h_x). The directions of the components and position of Hall probes are illustrated in Fig. 1.

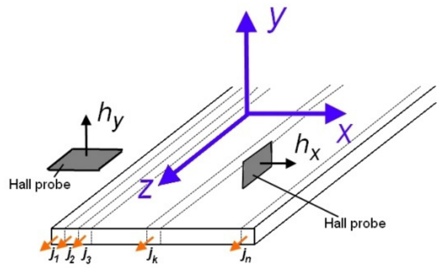

Fig. 1. Positions of Hall probes near an HTS tape and directions of axes.

In our case the measurement of the distribution of the current density across a tape was performed on 2G HTS tapes. Their thickness are very small (η) and can be neglected that significantly simplifies the calculation. If to consider a magnetic field as a superposition of fields of sub-tapes, it results to the equation below

$$B_i = \sum_k A_{ik} j_k, \quad (3)$$

where $A_{ik} = -\mu_0 \frac{(x_i-\xi_k)d\xi}{2\pi\{(x_i-\xi_k)^2+(y_i)^2\}}$ for h_y component of 2G HTS tape, j_k – current density in k-th sub-tape. The solution of this ill-conditioned equation was described by Tikhonov's regularization [6] and was realized before in [7].

3. Method of measurements

Our method of reconstructing of the critical current across a tape is the measurement of magnetic field with a Hall probe (HP) near the HTS tape and applying the conversion from field to current. Two techniques can be used as described below.

3.1. Continuous method (the scanning Hall probe method)

This method allows measuring the magnetic field near a tape continuously in many points above the tape. In this measurement the exact position of the Hall probe is known. We developed a special measuring device with a moving mechanism and digital measurement of the magnetic field was realized. The sketch of a measuring device is shown in Fig. 2.

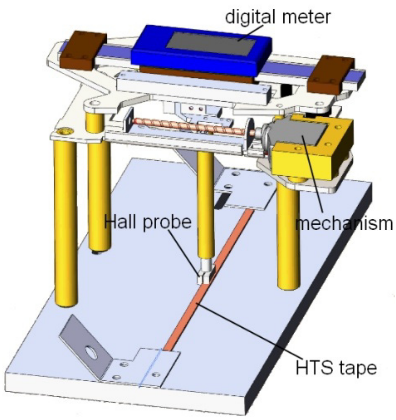

Fig. 2. Measuring device for continuous measurements of magnetic field across an HTS tape.

For the measurement an HTS tape is fixed by current leads on the device plate and immersed into a liquid nitrogen bath. The gear launches the mechanism movement of a Hall probe across a tape and automatic recording of magnetic field is started and it reads ~20 points at every1 mm.

The advantage of this method is the possibility to measure the magnetic field in a wide area across a tape. This provides the opportunity to measure a field in many different points. In the paper [8] a similar method of the critical current reconstruction by measuring the perpendicular magnetic field was described.

In spite of many advantages this method has its drawbacks. The first is the size of the device. The size of the device does not allow using it inside common magnets, for example like in [9].

The second disadvantage is that the measurement could be conducted with a probe placed on the moving mechanism. Therefore, the only way of the measurement is to put a certain current in a sample and to perform field measurements with this current. No measurements with changing current are possible.

3.2. Discontinuous (discrete) method (the Hall probe array method)

The other method is the discrete one, which is simpler to realize. In this method the set of several Hall probes is placed above the tape and the field should be measured in few points. Obviously the main disadvantage of this method is the limitation on the field measured points. Therefore, the accuracy of the current reconstruction from measurements is limited as well. On the other hand this method features small dimensions and could be used inside a magnet and with current changing.

The set of Hall probes used in our measurements and its location during measurements is shown in Fig. 3. We used a set with 10 Hall probes placed on a single thin substrate with sizes 6.0 mm × 2.0 mm. It allows us to record simultaneously magnetic field in 10 points at the same line above a tape.

The advantages of using of Hall probe set (HP set) are the following:

- The small size of the HP set allows to perform measurements in any conditions including inside a magnet;
- The measurements in several points are conducted simultaneously;
- Measurements with changing transport current and magnetic fields are possible.

With all of above advantages the only drawback is the number of data measured. With the moving the Hall probe more than hundred points of the field are measured, therefore, the result of the current reconstruction from a field becomes more precise. In the case of a set with 10 Hall probes only the number of points is less. Therefore the results are less accurate and more conditional. Moreover, the HP set is installed manually that is why some mistakes are possible in exact position determination.

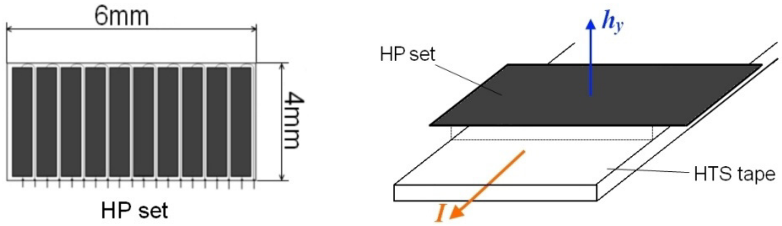

Fig. 3. The set of Hall probes used and its position during measurements.

3.3. Combined method

As it was mentioned above, the continuous method cannot be used in an external magnetic field. Thus the combination of two methods was developed with use of both methods described.

The continuous method provides an accurate current density distribution across the width of a tape without external field. Then we perform measurements by a discrete method and compare the magnetic field magnitudes and the current density distribution with those obtained by the continuous method. It allows retrieving accurate positions of the Hall probes set. After that we can perform measurements with the HP set in an external magnetic field. Thus, we can obtain the current density distribution in an external magnetic field with reasonable accuracy.

4. Results

Here, as an example, we present measurements and calculations made in liquid nitrogen with 2G HTS tape from SuperPower M3-747-2MS with a width 4 mm.

As it was mentioned above, first the distribution of the current density was measured by using the continuous method. The result of the field measurements across the HTS tape without an external field at a current of 50 A is shown in Fig. 4. Then we calculated the current density distribution by using the conversion described above. We made reversal conversion from the current distribution (Fig. 5) to the field for validation of our calculation. This reversal calculation from current to field permits to check if some errors were made during the direct field to current calculations. The results of the conversion are presented in Fig. 6. In this figure measurements are marked with symbols and the result of the conversion by solid line. As it can be seen in Fig. 6, the distribution received from the reverse conversion of the current density coincides with the measurements without external field.

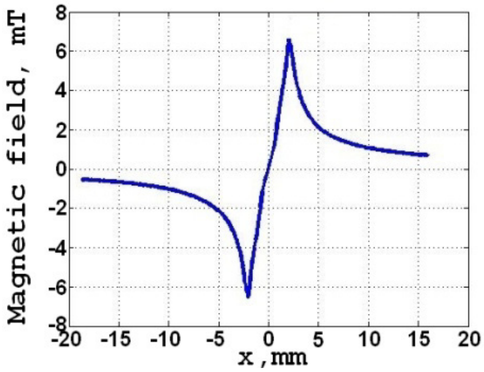

Fig. 4. Magnetic field of the HTS tape with a transport current of 50 A, no external field.

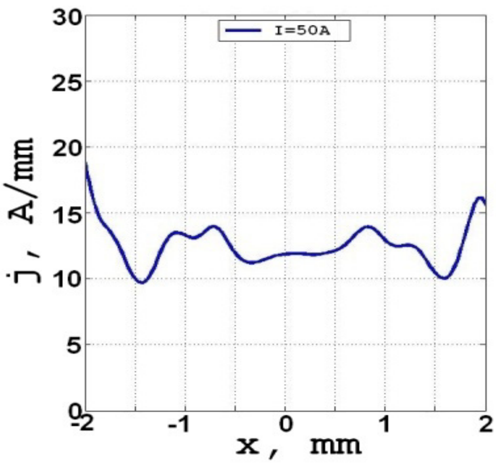

Fig. 5. Distribution of current across 2G HTS tape without external field. Non-uniformity of current density across a tape is seen.

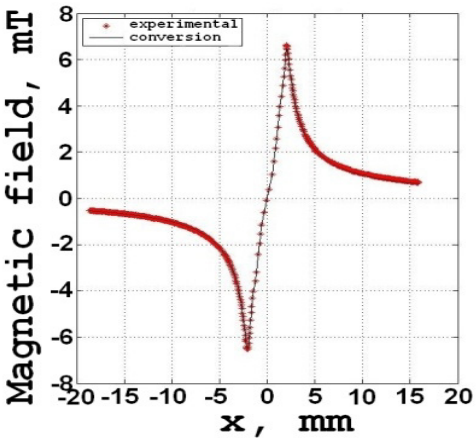

Fig. 6. Magnetic field from HTS tape and comparison with reversal conversion from current density distribution to fields.

The second measurements were discrete ones. Two HP sets (with 10 Hall probes each) were placed in one line above the HTS tape to get more points. The data from the Hall probes measurements are presented in Fig. 7. One can see that data from HP sets measurements do not coincide slightly. This happened due to uncertainty of the exact positions of the HP sets installed. To find out the correct HP sets positions we compared and adjusted discrete measurements to the continuous ones as shown in Fig. 8. This permits us to get exact positions of HP sets for discrete measurements, namely the distance of Hall probes from HTS tape and position of the edges of HTS tape in relation to the HP sets. After this we could perform measurements with discrete probes at external magnetic field with knowledge of the exact position of the HP sets.

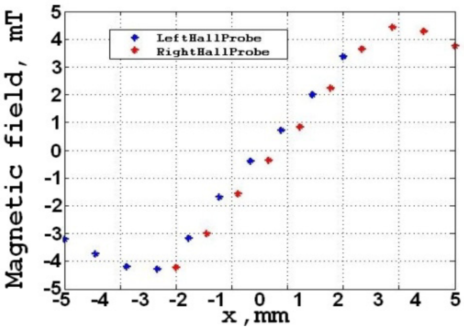

Fig. 7. Magnetic fields from HTS tape measured by discrete HP sets without adjusting.

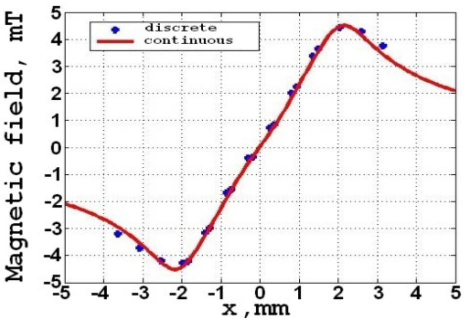

Fig. 8. Combined method: adjusting discrete measurements to the continuous ones permits to find exact positions of discrete HP sets.

The HTS tape with HP sets installed has been placed in the magnet described in [9]. We present here two measurements: with magnetic field of 30 mT that was parallel and perpendicular to the HTS tape surface.

The magnetic fields generated by currents in the HTS tape measured by the HP sets in perpendicular magnetic field of 30 mT are shown by symbols in Fig. 9a. In Fig. 9b the current distribution recalculated from the field measurements is shown. Similar results for the magnetic field parallel to the HTS tape surface are presented in Figs.10a and b.

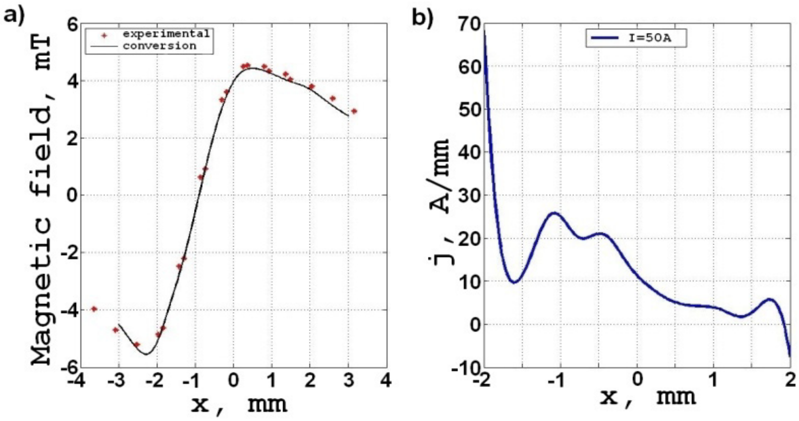

Fig. 9. The HTS tape in external perpendicular magnetic field 30 mT: a) magnetic field measured by HP sets (marks) and reversal conversion from current density distribution to fields; b) current density distribution reconstructed.

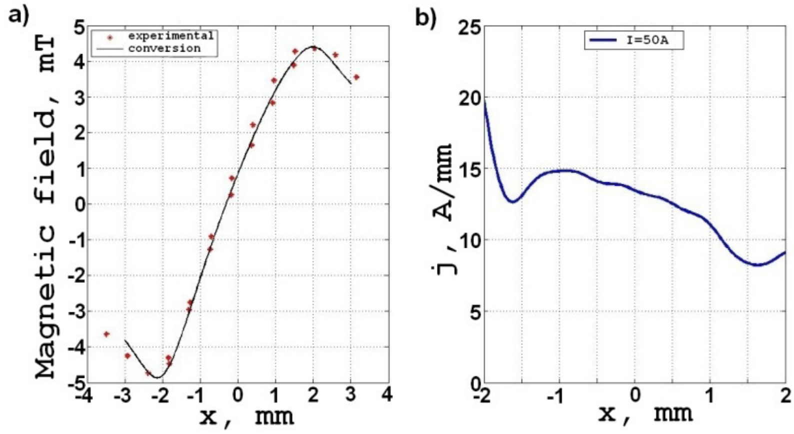

Fig. 10. The HTS tape in external parallel magnetic field 30 mT: (a) magnetic field measured by HP sets (marks) and reversal conversion from current density distribution to fields; (b) current density distribution reconstructed.

One can see that the current density distributions are different for two directions of magnetic fields. Current redistribution in perpendicular field is more sounding when the external field is parallel to the tape surface. The method of measuring the current redistribution with discrete HP sets permits to get results at external magnetic field.

5. Conclusion

We presented a method for the measurements of the current density distribution across the width of HTS tapes in external magnetic field by using sets of discrete Hall probes. The positions of the discrete Hall probes sets are first verified by continuous measurements by Hall probe that improves the accuracy of the discrete measurements. Knowledge of the transverse current density distribution permits to predict the behavior of HTS tapes when used in electro-technical devices. It also permits to study current density redistribution in HTS tapes in magnetic fields and with changing transport current.

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