A Two-Dimensional Current Mapping in Superconducting Tapes

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Abstract. It is well known that the Hall probe magnetic imaging represents a powerful technique for the investigation of the magnetic field distribution in superconducting materials of many different types and geometries. In this report we present a new method of the evaluation of current distributions in thin superconducting tapes and films from the data of two-dimensional magnetic field profiles measured over the sample surface. We have analyzed standard algorithms of critical current calculation from the magnetic map and shown that the correct realization requires magnetic field mapping on the region in many times larger than the area of superconducting sample. To avoid this disadvantage we have developed a new modified calculation algorithm of two-dimensional 2D distribution of supercurrents. Realization of this modified algorithm needs sufficiently smaller area of measured magnetic field. An application of modified algorithm for 2D current mapping in superconductive tapes has shown a high efficiency of our approach. Obtained results may be used in real practical set-up for quality control of commercial superconductors.

1. Introduction

Tape coated with a high-temperature superconductor (HTS) cannot be manufactured without characterizing the critical current characterization of long segments for quality control. End-to-end transport measurements are usually used to define the performance limit but do not provide information about the number and sizes of weak links along the tape. On the other hand, there is an opportunity of definition spatial distribution and the value of the critical current by measurement of the trapped flux or induced magnetic field and calculation of the current distribution corresponding to it. The solving of this problem is resulted in the inversion of Biot–Savart law. We have analysed standard approaches of solving the problem [1] and have developed a new modified calculation algorithm of two-dimensional distribution of supercurrents in thin superconducting tapes and films.

2. Modified algorithm

Standard algorithm was described in detail in Ref. [1]. To use standard algorithm it is necessary to measure distribution of the magnetic field (B_x(x,y)) in the area in some times exceeding dimensions of the sample.

In this paper we suggest the modified algorithm of definition supercurrents using data of magnetic field measurements directly above the sample and only one set of points abroad the sample (fig. 1). The measured area can be reduced to the specified size in case of absence in considered system any currents except supercurrents of the sample. Thus the magnetic field in distant areas from the sample...
can be calculated by magnetic field measurements near the specimen. Numerical realization of this idea allows to determine the magnetic field in the space sufficiently large for solving the problem of inversion.

We suggest that at infinity the magnetic field is equal to zero. Therefore, if we know the magnetic field distribution above the sample and one set of measurements out of sample (i.e. area I, fig 1), the function $B_z(x,y)$ in all space is the solution of Dirichlet edge problem [2]. The problem of definition of a field outside of the sample is correct. We offer the most simple and accurate method of the solution this problem using iterative procedure. It is necessary to find the value of the magnetic field in the area II (on a grid fig. 1 this area is marked by squares). The initial value of the magnetic field is assumed equal to zero. Value of the magnetic field in the area I (on a grid fig. 1 this area is marked by circles) does not change at iterations and it is equal experimental value. According to the Biot–Savart law supercurrents in the sample determine magnetic field in the area II, that finishes an iterative step.

We have investigated convergence of the given iterative process. Since all transformations of the field and the current are linear by these values, the iterative algorithm of definition of the magnetic field $B_{z\,II}^{n+1}$ in the area II on (n+1)th iterative step can be given by the following general compact type:

$$B_{z\,II}^{n+1} = M(B_{z\,I}) + N(B_{z\,II}^n)$$

where $B_{z\,I}$ experimentally determined magnetic field in the area I, $M$ and $N$ linear operators assigned by iterative process described above. These operators have an unwieldy writing and therefore are not presented in this work in an obvious form.

The norm of the operator $N$ has to be less than unit to converge the iterative process. We have checked up implementation of this condition for the grid on which the problem was solved (fig. 1) and convinced that the iterative process converges. Note that convergence is defined only by geometry of the grid and does not depend on experimental values of the magnetic field $B_{z\,I}$ in mesh points of the area I.

Solution of the problem of inversion Biot–Savart law implies obligatory regularization. We have analyzed basic filters for regularization described in the literature. The most suitable method of regularization for our experimental technique of magnetic field measurements has been developed by Tikhonov (for details see Ref. [3, 4, 5])

3. Results and discussions

From the beginning note that efficient and correctness of experimental method, method of calculation and regularization have examined on test measurements. Then we have investigated commercial HTS 2G tapes.

To measure magnetic flux distribution in superconducting tape we have used Hall probe technique. Beforehand refrigerated tape up to 77.4 K was located in the area of magnetic field (0.4 T), that was created by permanent magnets. Then magnets were moved away from the tape and scanning was carried out in zero external field.

In additional the direct research of HTS tapes the experimental method allows to carry out control the homogeneity of magnetic substrates magnetization which are used for manufacturing of 2G wires. As an example the surface of Ni tape magnetization is shown in the figure 2.
Fig. 2. The surface of magnetization of Ni tape.

Fig. 3. At the left: the surface of the trap magnetic flux distribution of 2G HTS tape. On the right: the illustration of the induced currents in HTS tape, corresponding to the trap magnetic field distribution.

Fig. 4. Surfaces of distribution of current components in 2G HTS tape. On the left: \( J_y(x,y) \) the current along the tape. On the right: \( J_x(x,y) \) the current across the tape.
Tapes of various architecture and characteristics, both new and earlier used have been investigated. In this paper we demonstrate only the most typical observed experimental data and the corresponding calculations.

Figure 3, 4 show the distribution of trap magnetic flux in HTS 2G tape and restored surfaces of currents (across and along the tape see fig. 3 on the right). Architecture of the tape: substrate Ni-5%W alloy (deformation texturing), buffer stack Y$_2$O$_3$/YSZ/CeO$_2$ (~75 nm, high rate reactive sputtering), YBCO (~1 µm, metal organic deposition of TFA), Ag (DC sputtering).

The magnetization surface profile corresponds to the Bean model. Note that magnetic flux distribution displays moderate inhomogeneity which corresponds to the inhomogeneity of the current distribution in the tape. Surfaces of currents distribution testify to the circular course of the induced currents.

Let's consider separately components of the current along ($J_y(x,y)$) and across the tape ($J_x(x,y)$) (fig. 4). Distribution $J_y(x,y)$ non-uniform, that in turn results in nonzero distribution $J_x(x,y)$. That is owing to imperfection of the tape, non-homogeneity of its properties, arise overflows of currents, flows (appearance of nonzero component of the current across the tape). Similar results have been received for other tapes.

It is necessary to note, that tapes repeatedly used show larger inhomogeneity of current distribution, than in the tape considered above.

4. Conclusions
We have presented new method of the evaluation of current distributions in thin superconducting tapes and films from the data of two-dimensional magnetic field profiles measured over the sample surface which allows to reduce area of measurement of a magnetic field. We have checked up efficiency and the correctness of our method and used it for research commercial HTS 2G tapes and Ni substrates. Received results can be strictly important for the quality control of made HTS tapes.

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