Continuous Recording of the Transport Properties of a Superconducting Tape Using an AC Magnetic Field Technique

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Abstract—The transport properties of superconductors are commonly characterized by means of a 4-probe measuring technique and the critical current is determined on a certain criterion for the electrical field. An alternative method to investigate the transport properties is to measure the magnetic response of a superconductor in a changing magnetic field. This magnetic technique has the interesting advantage that it can be used to investigate long lengths of (insulated) conductor. A detailed analysis is made to develop a reliable measuring procedure for this new test facility. The magnetic response of a superconductor is modeled in a description for an infinitely long tape with a rectangular cross-section and an arbitrary voltage-current relation. The calculated magnetic profiles, in space and time, are compared with experimental results at 77K. It is demonstrated that the magnetic signal can be used to monitor the quality of a long length of tape (> 500 m) with a high accuracy. Additionally it is shown that the shape of the voltage-current relation can be reconstructed based on the frequency dependence of the magnetic response.

INTRODUCTION

The conventional way of measuring the critical current of superconducting BSCCO tapes is by means of a four points resistive measuring method. Usually this is measured on short pieces (≈ 5 cm) cut from the ends of a long (several hundreds of meters) tape. The properties of a long superconducting tape can in principle vary along the length of the tape. Therefore it is recommended, both for internal (adjustment of process parameters, material choice etc.) and external (product specifications to customer) purposes, to determine the properties of the tape along the whole length with a non-destructive method.

An AC-magnetic field technique is developed for application in a magnetization testbed for quality measurements on long tapes. With the magnetization testbed the magnetic field above a SC. tape, generated by an external field, is measured. The testbed is schematically depicted in Fig. 1. A superconducting tape is wound from one spool to another. Between the two spools a cryostat is placed with a Helmholtz magnetization coil in the middle. The magnetization coil generates an external field perpendicular to the SC. tape. The field near to the tape is measured with a Hall element in the magnetization coil.

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Fig. 1. Magnetization testbed.

In order to measure on multifilament tapes it is possible to couple the filaments by means of an AC-external field. This generates a stronger magnetic signal above the tape compared to the decoupled case. Also the signal is less dependent on the filament shape and more related to the total active superconducting volume in the multifilament tape.

In the next section a short overview of a model developed by Brandt [1] is presented. This is applied in a numerical model to calculate the current distribution and the magnetic field above a tape induced by an external perpendicular field. Thereafter a brief description of the experimental set-up used for the measurements on the magnetic field above a tape is given. The results of calculations at several critical current densities are discussed in relation to measurable magnetic quantities. Then a method is introduced to determine the shape of the voltage-current relation based on the frequency dependence of the magnetic response.

THEORY

The magnetic profile above a superconducting tape depends on the current distribution in the tape. The profile is determined by the geometry of the tape, material properties, and the electromagnetic history.

The physical distribution of superconducting material in a multifilament tape can be rather inhomogeneous. The filaments do not have a perfectly regular cross-section over the length of the tape. In the calculations an approximation for the geometry is made, by considering a mono-block model. The filaments in a multifilament tape can be coupled with an AC-external field. The field amplitude induced above a fully coupled multifilament tape is much larger than in the decoupled case.

As a first step the approximation for a superconducting tape as a long strip with finite thickness is considered to be an effective approximation (see Fig. 2.).

Fig. 2. Geometry of a long strip of superconductor with finite thickness

A. Current distribution

The current density distribution $J(x, y, t)$ induced by a perpendicular applied magnetic field B_a is calculated with the model developed by Brandt [1]. Only currents in z -direction are considered in this model. When everywhere inside the conductor the flux density B and the critical sheet current $J_c d$ are larger than the lower critical field of the superconductor the approximation of $\mathbf{B} = \mu_0 \mathbf{H}$ is valid. In addition a power law relation is assumed for the relation between the electric field E and the current density:

$$\mathbf{E}(J) = E_c \left| \frac{J}{J_c} \right|^n \frac{\mathbf{J}}{J}, \quad (1)$$

with E_c the criterion that is used to determine the critical current density J_c . So far no $J_c(B)$ dependence is included but with a modification this is also possible [4]. The equation of motion for $J(\mathbf{r}, t)$ now reads,

$$\dot{J}_i^* = \frac{N}{b^*} \sum_j Q_{ij}^{-1} \left[(J_j^*)^n - x_j^* \dot{B}_a^* \right], \quad (2)$$

where Q^{-1} is the inverse of an integral kernel Q which contains the relative length of the system. Both indexes i and j are defined as figures locating individual positions on a homogeneous grid over the cross-section (xy -plane) of the strip. The equation is expressed in reduced variables:

$$b^* = b/a \quad x^* = x/a \quad J^* = J/J_c \quad B_a^* = B_a / \mu_0 J_c a.$$

An important advantage of this approach is that the summation j only takes place over the superconductor cross-section area to which the current density is confined. This reduces the calculation time considerably with respect to finite element methods where boundary conditions are defined at a place far away from the conductor.

The time integration is calculated by starting with $J_i(0) = 0$ at time $t = 0$ where after the time is increased with steps dt , putting $J_i(t + dt) = J_i(t) + \dot{J}_i(t)dt$. Because the electromagnetic history has an influence on the present current distribution one has to calculate preceding time steps starting from a well known starting point. This point is taken as the 'virgin state', where no external occurrence has induced any current in the tape. After the sinusoidal applied field has reached its maximum amplitude the field of the tape will also start to alternate periodically. Therefore the analysis is started after one quarter of an applied field cycle. This is observed to be accurate for a sinusoidal applied field.

B Field calculation

When the current distribution in the strip is known, the field due to these currents at any point can be calculated using Biot & Savart law. The field in y -direction at a given point $\mathbf{r}$ is a summation of the influence of all J_i 's,

$$B_y(\mathbf{r}) = \frac{\mu_0}{2\pi} \sum_i \frac{J_i dx dy \sin \varphi(\mathbf{r}, \mathbf{r}_i)}{|\mathbf{r} - \mathbf{r}_i|}, \quad (3)$$

where $\varphi(\mathbf{r}, \mathbf{r}_i)$ is the angle between the field vector and the x -axis.

EXPERIMENTAL SET-UP

An experimental set-up is developed to measure the field above a superconducting tape (see Fig. 3.). A function generator and a power amplifier generate a sinusoidal AC-external field in a copper coil. The magnetic field above the tape is measured with a Hall element. The voltage on the Hall element is proportional to the magnetic field in y -direction (perpendicular to the tape). A scan is made over 50 mm from one side to the other side of a tape, which has a width of 3 mm. The field of the tape is determined by subtracting the magnetic field profile measured without a sample from a profile that is measured with a sample. Finally an offset correction is made by defining the field due to the tape as zero, at a distance of 20 mm from the centre of the tape. The Hall probe voltages are measured with a Lock-In Amplifier that separates the in- and out-of-phase components of the signal. The phase calibration is made by defining the voltage signal when no sample is present as exactly in-phase.

RESULTS

The model calculations are made with the half width a and half height b of the filament area taken as 1.2 mm and 0.1 mm respectively. A grid size of 60×5 points for a quarter of the tape's cross section is used. This gives results, which deviate less than 5 % from those when an infinitely large number of grid points could be used. The $E(J)$ relation defined in (1) is applied with $E_c = 10^{-4}$ V/m. Calculated and measured fields are determined at 0.5 mm above the tape.

Fig. 3. The experimental set-up for determining the field above a superconducting tape exposed to an alternating applied field.

Fig. 4. Calculated current density distribution and field profile above a superconducting strip at a sinusoidal applied field, $B_a = \frac{1}{2} B_p$ and $t = \frac{1}{4}$ period.

To obtain filament coupling in a physical multifilament tape sufficient high induction is required, and therefore the experiments and the calculations on the superconductor are performed at an applied field of 18 mT amplitude and a frequency of 10 Hz. As an example Fig. 4 presents for an applied AC-magnetic field a calculated current density distribution over the cross-section of the tape together with the accompanying field profile above the tape.

The shape of the field above the tape varies for different J_c values and depends on the state of penetration of the applied field. Four different characteristic field dependencies are analysed. The shielding and remanent fields are defined as the field above the centre of the superconductor in presence or in absence of an applied field respectively. For sinusoidal alternating field measurements, this means the field values at the maximum or at zero applied field. The Lock-In Amplifier measures the in- and out-of-phase first Fourier components of the field. An example for a sinusoidal external field applied to a superconducting tape is shown in Fig. 5. The calculated field of the tape and the applied field are plotted against time for different values of J_c . When J_c is high (e.g. 100 A/mm²) the field of the tape reaches a high value of about 7.5 mT and has almost a sinusoidal shape. The tape is in this case not fully penetrated and the current profile is concentrated at the edges of the tape. Saturation due to penetration occurs for a small value of J_c e.g. 5 A/mm². This is indicated by the field curves with a flat top in Fig 5.

Fig. 5. The applied field and the calculated field above a tape versus time for J_c values of 5, 10, 20, 30, 40, 50, 60, 80 and 100 A/mm². Calculated at an applied field of 10 Hz and 18 mT amplitude and $n = 10$ (n -value of (1)).

The critical current density

When a certain applied field amplitude and frequency is selected in the experiment then the measured magnetic signal of the tape is determined by the properties of the tape. The measured $B(t)$ profile has to be interpreted to obtain a value for J_c in the tape. The model calculation is used to investigate the relation of the in- and out-of-phase first Fourier components and the shielding and remanent field with the J_c in the tape. The results for $B = 18$ mT and $f = 10$ Hz are presented in Fig. 6.

The in- and out-of-phase first Fourier components follow the curves of the shielding and remanent fields but deviations can be seen. In this calculation the applied field amplitude is 18 mT. With use of a critical state approximation of Forkl [2] for this configuration it is derived that this applied field amplitude equals the field of full penetration at a critical current density of 65 A/mm².

The shielding field is proportional to the current density. However, the in-phase first Fourier component is not proportional and deviates for small J_c up to 65 % at $J_c = 5$ A/mm² from the shielding field.

The remanent field is proportional to J_c for low critical current densities ($\ll 65$ mT). In this range the out-of-phase first Fourier component behaves very similar to the remanent field, therefore this signal is of most interest for J_c determination in a practical situation. For higher current densities the out-of-phase first Fourier component deviates up to 16 % at 60 A/mm² from the remanent field.

Frequency response and the $E(J)$ relation.

In the calculations and the measurements it is observed that the field above the tape increases for higher frequencies. The following consideration is made to interpret this effect. When a tape is exposed to a sinusoidal applied field, the mean electric field E in the tape is proportional to the applied field frequency f . In addition one can consider the field above the tape B_{tape} under certain circumstances (J_c low with respect to B_a) to be proportional to the critical current density [3]. So we have:

$$E \sim f \quad \text{and} \quad B_{tape} \sim J_c. \quad (4)$$

Fig. 6. Calculated relation between the shielding and remanent fields above a tape and the output of a Lock-In Amplifier. Calculated at an applied field of 10 Hz and 18 mT amplitude and $n = 10$.

When these two relations are combined, the relation between B_{tape} and frequency should exhibit the same dependence as the relation between the electric field and the critical current density, with (1) we find:

$$B_{\text{tape}}(f) = cf^{1/n}, \quad (5)$$

where c is a constant and n is the n -value of (1). Fig. 7 shows on log-log scale the field versus frequency dependencies. The shielding and remanent fields are calculated at two different n -values ($n = 5$ and 15). When an attempt is made to describe these results with equation (5) the obtained n -values at the shielding fields are a term 0.50 lower ($n = 4.50$ and 14.50) than those that were used in the $E(J)$ relation for the calculation. For the calculated remanent fields the obtained n -values using (5) match with those used for the calculation. These results are valid to the second decimal place.

Experiments

For comparison, the in- and out-of-phase first Fourier components of the field above a single-filament tape are measured. The results are depicted in Fig. 8. The obtained n -values with use of (5) are $n = 15$ for the in-phase component and $n = 34$ for out-of-phase component of the field above the tape. The lowest value ($n = 15$) is in good agreement with VI measurements on similar tape samples. As with the calculated fields the obtained n -value for the in-phase component is lower than for the out-of-phase component, however this difference is now much larger. The difference can be due to a stronger $J_c(B)$ dependence of the shielding field, but an inhomogeneous distribution of the $E(J)$ dependence in the tape might also influence the results.

Fig. 7. Calculated fields above a SC. tape versus frequency. Calculations at $J_c = 3 \times 10^7 \text{ A/m}^2$ and $B_a = 18 \text{ mT}$ on a strip of superconductor.

Fig. 8. Measurements of fields above a superconducting singlefilament tape versus frequency. Measured at $B_a = 18 \text{ mT}$.

CONCLUSION

The magnetic field above a superconducting tape induced by an external field is modelled with Brandt formulae [1] and measured in experiments, to relate the alternating field response with I_c . To achieve more realistic results an extension of the model with a $J_c(B)$ relation could be performed. At strong applied fields with respect to the critical current density, the linear behaviour of the out-of-phase first Fourier component of the field above a superconducting tape can be directly used as a measure of J_c .

Besides J_c determination a n -value determination can be a valuable additional feature of a magnetisation testbed. Because of an assumed proportional relation between E and f and between J_c and the field above the tape B_{tape} , a relation is evaluated for the $B_{\text{tape}}(f)$ dependence. The frequency dependence of the field measured above the tape can be described well with a power law dependence. The value of the exponent ($1/n$) obtained in the in-phase component of the magnetic field is in good agreement with VI-measurements on similar tape samples ($n = 5$).

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