Dynamic voltage-current characteristic of a high-temperature superconductor tape

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Abstract

Vortex motion and its relation to the voltage-current characteristic (VCC) of a superconductor are usually studied in quasi-stationary conditions under the assumption that the transient process related to switching-on transport current or applied magnetic field is over. To study the dynamic characteristic of a superconductor, we investigated both experimentally and theoretically, the response of a single-filamentray Bi-2223/Ag tape to pulsed currents. Both clockwise and anticlockwise hysteresis loops in dynamic VCCs were observed for the same sample, depending on the placement of potential taps at the center or at the edge of the tape. Numerical simulation showed that the obtained experimental results are well explained in the framework of the magnetic diffusion model for superconducting tapes with the power law $E-J$ characteristic (flux creep regime). The loops with different path-tracing were also obtained for superconductors described by Bean’s model.

Keywords: HTS tapes; dynamic voltage-current characteristic; magnetic diffusion

1. Introduction

Hysteresis loops, not related to heating, are typical of dynamic voltage-current characteristics (VCC) of high-temperature superconductors and were the issue of a number of publications. It was suggested that these loops may result from, e.g., order-disorder transition in vortex lattice, inhomogeneity of the flux pinning strength, history effect, etc. (see [1] and references 1-13 therein).

On the other hand dynamic VCCs are influenced by diffusion of magnetic flux into a sample with strongly nonlinear electric-field-current-density ($E-J$) characteristic. Although theoretical analysis of electromagnetic response of superconductors to time-dependent currents and magnetic fields is often performed for an infinite slab, the results are sometimes employed to explain the data obtained for samples of other shapes. It is, however, known that penetration of magnetic flux into thin tapes and strips differs significantly from that for slabs [2].

This paper presents the results of an experimental and theoretical study of transient response of a single-filamentary Bi-2223/Ag tape to applied pulsed currents.

2. Experimental study

Single current pulses of controlled amplitude and duration of about 1 ms were obtained by a discharge of a capacitor in a circuit containing a tested superconducting sample, an inductance, and a resistor 0.11 Ohm inserted in series. The shape of a pulse was close to a half-wave of sinus (see inset in Fig. 1). The current was measured by voltage drop across the resistor. The voltage drop across the sample was amplified by a factor of 1000 and recorded, along with the current curve, by a multichannel data acquisition device with the recording rate 500,000 samples/sec per channel.

The investigated samples of a single-filamentary Bi-2223/Ag tape had the length of 24 mm, thickness of 0.2 mm, and width of 3 mm. The tape was fabricated by the powder-in-tube method [3].

Two pairs of potential taps were soldered to each sample: one pair was placed on the central axis of the tape, another fixed close to the edge. The distance between the taps belonging to the same pair was 10 mm. The samples were immersed in liquid nitrogen (77 K).

The voltage taken from a pair of the taps contains a component induced by changing magnetic flux in the measurement loop formed by the potential wires and the path going through the sample and connecting the...
3. Theoretical study

To understand the origin of observed peculiarities of dynamic VCCs, we analyzed the non-linear magnetic diffusion into a thin tape theoretically. Consider a strip in zero external magnetic field, infinite along the x axis, with the width $2L$ along the y axis and the thickness $2a$, $a \ll L$. Let a transport current $I(t)$ be applied. The electric field $E$ and sheet current density $J$ have only the $x$-components. At $z = 0$, $z$-component of magnetic field can be found as

$$H_z(y,t) = \frac{1}{2\pi} \int_{-L}^{L} j(u,t) du \frac{1}{y-u}. \quad (1)$$

The current is given by

$$I(t) = \int_{-L}^{L} J(y,t) dy \quad (2)$$

Substituting Eq. (1) into the Maxwell equation $\partial E/\partial y = \mu_0 \partial H_z/\partial t$, we obtain:

$$\frac{\partial E}{\partial y} = \frac{\mu_0}{2\pi} \int_{-L}^{L} \frac{\partial j(u,t)}{\partial t} du \frac{1}{y-u} \quad (3)$$

For a linear E-J characteristic (Ohm law) $E = \rho_n J / 2a$, where $\rho_n$ is a constant resistivity, Eq. (4) can be presented in dimensionless form:

$$\frac{\partial e}{\partial \xi} = \frac{n \mu_0 L}{\pi \rho_n} \int_{-1}^{1} \frac{\partial e(u,\zeta)}{\partial \zeta} du \frac{1}{\xi-u} \quad (4)$$

where $e = E/E_0$, $\xi = y/L$, $\zeta = u/\tau$ and the normalization parameter $E_0$ can be arbitrarily chosen. From (4), the characteristic time $\tau$ of magnetic diffusion is

$$\tau = \frac{\mu_0 L}{\pi \rho_n} \quad (5)$$

Suppose now the strip is characterized by a power law (flux creep regime) $E = \rho(y,J,J_y)^n$, where $J_y$ is the critical sheet current density. Since the E-J characteristic is non-linear, the diffusion time depends on the current pulse amplitude $I_0$. To rewrite Eq. (3) in dimensionless form we define the scaling sheet current density $\rho_0 = I_0 / 2L$ and the corresponding electric field $E_0 = E(J_0,J_y)^n$. This gives

$$\frac{\partial e}{\partial \xi} = \frac{\mu_0 J_0 L}{2\pi n E_0} \int_{-1}^{1} \frac{\partial e(u,\zeta)}{\partial \zeta} du \frac{1}{\xi-u} \quad (6)$$

The characteristic diffusion time can be chosen as

$$\tau = \frac{\mu_0 J_0 L}{2\pi n E_0} \frac{\mu_0 L_0}{4\pi n E_0} \quad (7)$$

For simulation of the diffusion we integrate Eq. (3) with respect to $y$, substitute $E = \rho(y,J,J_y) J / 2a$ and obtain:

$$\rho(y,J,J_y) J = \frac{\mu_0 n L}{\pi} \int_{-L}^{L} \frac{\partial j(u,t)}{\partial t} \ln|y-u| du + C(t) \quad (8)$$

![Graph](image-url)
Fig. 2. Calculated dynamic VCC for edge-assigned taps: (a) - flux creep model, (b) - Bean's model. The curves were obtained for current pulses \(I=I_0\sin(\pi t/36\tau)\) with three different amplitudes \(I_0\). Spheres mark the DC VCC. Insert: the composite tape.

Fig. 3. Calculated dynamic VCC for centrally-assigned taps: (a) - flux creep model, (b) - Bean's model; the current pulse is \(I=I_0\sin(\pi t/36\tau)\). Spheres mark the DC VCC.

where \(C(t)\) is unknown. Eqs. (2) and (8), determining both the current distribution in a tape and the function \(C(t)\), were solved numerically; the algorithm description is given in [6]. The calculations were performed for a superconducting composite similar to the tested tape (see Fig. 2, inset) with a superconductor inside an Ag matrix and occupying the central part of the tape, \(|y| \leq l = 0.8L\) (similar results were obtained also for other values \(l/L\)).

Expressions (5) and (7) cannot be directly applied to the diffusion in a superconducting composite. For example, for Bean’s model \((n \rightarrow \infty)\) Eq. (7) correctly gives zero diffusion time for a superconductor, in this case the diffusion time for a composite tape is mainly determined by diffusion in a normal matrix. In calculations we used the dimensionless units with the time scale chosen for normal metal strip according to Eq. (5). In these units, the resistivity of the normal conducting parts near the tape edges, \(L \leq |y| \leq L\), is equal to 1. For the central part, \(|y| \leq l\), containing the superconductor, two models were considered. First, we used the flux creep model with the resistivity corresponding to the experimental data above, \(\rho(J) = 0.015 |J/J_c|^3\) \((n = 4)\). Second, the calculations were performed for Bean’s model modified to account for the presence of normal matrix: \(\rho(J) = 0\) at a sheet current less than the critical value \(J_c\) and \(\rho(J) = \text{sign}(J)(|J| - J_c)\) for \(|J| > J_c\). For the tested tapes, Eq. (5) gives the characteristic time \(\tau = 2.5 \cdot 10^{-5} s\); the critical current \(I_c = 2lJ_c\) is 4.6 A. In simulations, the current pulse was \(I = I_0\sin(\pi t/36\tau)\) where \(I_0\) is the amplitude in the units of \(I_c\). The simulation results are shown in Fig. 2-4.

4. Discussion

The clockwise and anticlockwise loops in dynamic response of the same single-filamentary BSCCO tape were observed experimentally. Simple estimates show that, in our case, these loops and the difference between dynamic and DC VCCs cannot be explained by heating.

A number of other explanations for clockwise and anticlockwise dynamic loops has been suggested [1, 7]. These explanations were based mostly on considerations for an infinite slab and it was concluded that the anticlockwise loop cannot be observed in a homogeneous sample in the frame of the flux creep mechanism [1].

Using the magnetic diffusion model for a thin superconducting tape with the power law or Bean’s E-J characteristics we were, however, able to simulate the experimental loops (Figs. 2 and 3). The direction of path-tracing depends on the placement of potential taps: at the edge or at the center. For both models we obtained broad
clockwise loops at the edge (Fig. 2) and narrow anticyclclockwise loops at the tape centre (Fig. 3). This difference is clearly explained by the non-uniformity of electric field in the tape (Fig. 4). The loop width increases with the pulse amplitude.

There is another difference between the tape and slab configurations. The characteristic magnetic diffusion time decreases with slab thickness and dynamic hysteresis loops disappear in thin slabs. In a tape, the characteristic time of diffusion is determined by the VCC and not by the tape thickness (Eq. (7)); the time is finite even for infinitely thin films and the loops do not disappear. Thus, the slab model is not always applicable to finite size samples.

Our simulation showed that magnetic diffusion is significant even for sinusoidal current pulses with the rise time 18 times larger than the characteristic diffusion time for the metal matrix. As one can see from Fig. 4, the evolution of the electric field in the tape includes two stages. First, the electric field front propagates inside the tape with the velocity determined mostly by the rise rate of the applied current. This stage takes about $7\tau$ for the case considered in Fig. 4. For Bean's model, this is the time of the appearance of electric field at the center, which occurs at the current of about $1.1I_c$ (Fig. 3b). The second stage of the flux penetration is determined by the magnetic diffusion. For Bean's model, this stage is characterized by the diffusion in the metal matrix alone with the characteristic time $\tau$. For the power law VCC, the time depends on the pulse amplitude and can be larger. This explains broader loops computed with the flux creep model (Figs. 2 and 3). Due to diffusion into the normal matrix, the voltage drop at the edge appears from the very beginning of the current pulse (Fig. 2). This effect disappears in a homogeneous tape with $I = I_c$.

We note also the difference between the experimental and calculated VCCs for the edge taps: there are no intersection points in calculated loops. A likely explanation is inaccuracy of the subtraction procedure used in processing of the experimental data. Indeed, applying the same procedure to the calculated data we got similar self-intersecting loops.

The obtained VCCs differ mainly in the region of low currents and voltages, where a criterion of 1-10 $\mu$V/cm for the critical current value determination is usually applied. Hence the obtained value depends on location of the measurement taps and the dynamic curve branch (ascending or descending). If the ascending branch is used to determine the critical current by means of the edge measurements (Fig. 2), the measured value of critical current decreases with the increase of the pulse amplitude or, equivalently, with the rise of the current ramping rate. The critical currents obtained from the descending branch increase with the pulse amplitude growth.

5. Conclusion

The experimental and theoretical investigation of the dynamic VCCs of single-filamentary Bi-2223/Ag tapes showed that the dynamic VCCs deviate substantially from the DC VCC. The clockwise and anticyclclockwise hysteresis loops in dynamic VCCs can be observed for the same sample depending on the location of potential taps: at the edge or center of a tape. The measured critical current and its change with the pulse amplitude also depend on the location of the potential taps and on the VCC branch chosen for the critical current determination. More accurate measurement of VCCs and critical currents can be obtained using the central taps because the dynamic loops are narrower in this case. It was shown that the observed features of the dynamic characteristics of single-filamentary superconducting tapes can be explained in the framework of magnetic diffusion and flux creep.

References