Current-Voltage Behaviour and Surface Overheating of HTS Tapes Over $I_c$

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Abstract. Modelling and design of superconducting fault current limiters (SFCL) requires accurate prediction of current-voltage behaviour and thermal response of HTS tapes carrying electrical current over $I_c$, since these characteristics affect the electrical behaviour of the SFCL during a fault. An experimental method was developed to measure current, voltage and surface temperature on short HTS tapes for electrical field values above $I_c$ (1 $\mu$V/cm), up to 10 mV/cm. The measurements were performed under different thermal exchange conditions with current pulses having different duration and amplitude. The experimental results allowed to validate a numerical model for HTS tapes in overcurrent conditions.

1. Introduction

The development of electrical power distribution networks claims for significant improvements in stability and reliability. The introduction of superconducting fault current limiters (SFCL) represents an effective solution to provide uninterrupted power supply to customers, to improve power quality, to allow grid interconnections and distributed generation.

Bi-2223 tapes, commercially available with self-field critical current at 77 K in the range 80-150 A over considerable lengths, can be regarded as possible candidates for the construction of SFCL prototype notwithstanding their low normal state resistivity [1]. Second generation HTS tapes, based on Y-123 coated conductors, are under development, and will be available in the next years with typical performances more suitable for SFCL (higher critical current and higher normal state resistivity).

An experimental method was developed to measure current, voltage and surface temperature on short HTS tapes for electrical field values above $I_c$ (1 $\mu$V/cm). The experimental results allowed to validate a numerical model for HTS tapes in overcurrent conditions.

2. Superconducting samples

Numerical simulations and experimental measurements have been performed on commercial multifilamentary Ag-sheathed Bi-2223 tapes (first generation HTS tapes) with critical currents up to 140 A. They represent today’s state-of-the-art, and they are candidates for the construction of power device prototypes. Electrical measurements have been performed on short samples (0.35x4x100 mm).
3. Numerical model for HTS tape

A Numerical model has been developed to describe and predict the electric field $E$ on the HTS tape as a function of the tape temperature $T$ and of the current flowing in the tape $I$ [1]. $E(I,T)$ calculation is based on the logarithmic polynomial expression (1):

$$
\log \left[ E_{\text{calculated}} \right] = \sum_{k=0}^{4} A_k \cdot \left\{ \log \left[ \frac{I_{sc}(I,T)}{I_c(T)} \right] \right\}^k
$$

(1)

The tape is subjected only to its magnetic self field, and the influence of temperature is taken into account by the “current to critical current ratio” $I/I_c(T)$. Only the current flowing in the superconducting filaments $I_{sc}$ is taken into account; current flowing in the silver sheath is subtracted from total current $I$.

The dependence of critical current on temperature is described by the following polynomial expression (2):

$$
\frac{I_c(T)}{I_c(T=77 \text{ K})} = C_3 \cdot \left( X \right)^{C_4} + C_5 \cdot \left( X \right)^{C_6} \text{ with } X = C_1 \cdot \left( C_2 - T \right)
$$

(2)

Best fit parameters $A_k$ in equation (1) and $C_i$ in equation (2) have been obtained from experimental data.

4. Experimental method

A novel experimental method was developed in order to investigate current-voltage behaviour and thermal response of HTS tapes carrying electrical current over $I_c$, thus to provide input parameters and to validate the numerical model proposed.

The adopted set-up for $U(I,T)$ investigation is similar to the set-up used for thermometric AC loss measurements on HTS [2]. It consists in a ceramic shell surrounding the superconducting tape, directly immersed in the liquid nitrogen bath at 77.4 K (figure 1).

![Figure 1. Sample arrangement scheme.](image)

Current contacts are soldered to the edges of the tape outside the shell, voltage taps are soldered on the enclosed section of the tape; a tiny E-type thermocouple is also soldered in the centre of the enclosed section to measure the surface heating. An heater foil is placed on the external surface of the shell. Macor, a machinable ceramic, ensures enough thermal capacity to stabilize the sample temperature, and it provides also the suitable grade of thermal insulation from the bath. The ceramic shell can be regarded as an heat sink whose temperature is controlled by the heater. The voltage drop over the sample and the voltage signal from the E-type thermocouple are read by a digital DC nanovoltmeter. $U(I)$ measurements are performed as 4-probe $I_c$ measurements; distance between voltage taps is 40 mm [3].

The electrical behaviour of a superconducting tape strongly depends on its temperature $T$, but thermal phenomena are much slower than superconducting phenomena. During thermal transients we are allowed to suppose the superconductor obeys its “static” current-voltage-temperature characteristic $U(I,T)$ regardless the time derivative of temperature.
For current values below Ic the heat generation in the superconductor is negligible, so its temperature can be kept constant and controlled by the heater: in this way it is possible to perform Ic(T) measurements. When the current in the superconductor exceeds Ic, the sample temperature begins to increase due to self-heating. Figure 2 shows the thermal transient corresponding to a 205 A current pulse (corresponding to 1.3 Ic) over 10 seconds, starting from T0 = 77.4 K (heater off). As shown in figure 3, it is possible to deduce the U(T) characteristic for the current value corresponding to the pulse amplitude. Measurements allowed to directly investigate U(I,T) characteristics up to I = 2 Ic, T = 100 K and E = 10 mV/cm.

![Current Pulse (I = 205 A)](image)

**Figure 2.** Thermal and electrical response to a current pulse (205 A).

![Temperature Transient (T0 = 77.4 K)](image)

**Figure 3.** U(T) characteristic evaluated from the response to a current pulse (205 A).

5. Results and discussion

The U(T) diagrams of a Bi-2223 Ag-sheated sample are plotted in figure 4 for different current values and for temperatures between 77.4 K (heater off; ΔT = 0 K) and 100 K (ΔT = 23 K).

Figure 5 shows the E(I,T) characteristic of the superconducting tape calculated by the numerical model; fit parameters are obtained from experimental data. The electric field E is plotted versus the “current to critical current ratio” I/Ic(T) which takes into account the influence of the temperature; experimental data points are also shown.

Measured V(I,T) agrees with calculated E(I,T) over the range of I, T values investigated, thus providing the validation of the model.
6. Conclusion

A simple and reliable experimental method was developed to measure current, voltage and surface temperature on short HTS tapes for electrical field values above \( I_c \), up to 10 mV/cm.

The \( U(T) \) characteristics of Bi-2223 Ag-sheathed samples have been investigated for current values above \( I_c \) for sample temperatures ranging between 77.4 K and 100 K, thus providing the input parameters for the model. Measured \( U(I,T) \) agreed with calculated \( E(I,T) \) over the range of \( I, T \) values investigated.

The experimental method and the numerical model proposed allow accurate prediction of the current-voltage behaviour and thermal response of HTS tapes in the range of practical interest for FCL modeling and design.

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References

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