Leszek JAROSZYŃSKI, Dariusz CZERWIŃSKI

Lublin University of Technology, Electrical Engineering and Computer Science Faculty

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Overcurrent characteristics of second generation superconducting tape SF4050

***Abstract**. Authors made measurements for the SF4050 high-T_C superconductor coated tape produced by SuperPower Inc. The measurements were performed for the AC current amplitudes exceeding the critical value of this tape. The numerical model of the tape was build using PSpice environment. The model assumes the nonlinearities of tape parameters as the functions of temperature, as well as the variable cooling conditions during transient state. Simulation results were compared with measurement data.*

***Streszczenie.** Autorzy przeprowadzili pomiary dla taśmy SF4050 z warstwą nadprzewodnika wysokotemperaturowego produkowanej przez SuperPower Inc. Badania wykonano dla prądu zmiennego o amplitudach przekraczających wartość krytyczną prądu taśmy. Przy wykorzystaniu środowiska PSpice zbudowano model numeryczny uwzględniający nieliniowość parametrów taśmy i warunków chłodzenia. Wyniki symulacji porównano z danymi pomiarowymi. (**Właściwości taśmy nadprzewodnikowej drugiej generacji SF4050 dla prądów powyżej wartości krytycznej**).*

Keywords: high temperature superconductor, HTS coated tape, superconducting fault current limiters, quench propagation.
Słowa kluczowe: nadprzewodnik wysokotemperaturowy, taśma nadprzewodnikowa drugiej generacji, nadprzewodnikowy ogranicznik prądów zwarciowych, propagacja strefy rezystywnej.

Introduction

Advancements in the manufacturing of the second generation (2G) high-T_C superconductor coated tapes, allows for the production of superconducting fault current limiters (SFCL) of unique characteristics. The analysis of the phenomena in YBCO coated conductors during transient state is very important for the reliable operation of superconducting device. A study of transient voltage responses in HTS materials has been performed in the past twenty years; transitions of thin YBCO films from superconducting to resistive state and back induced by a current pulse have been observed [1-3].

In our earlier research we developed simple and efficient PSpice models for bulk HTS components and first generation (1G) tapes used for SFCLs [4-6]. Then, we modified the model for 2G HTS coated conductors [7]. Emphasis was put on the temperature dependent material parameters and the heat exchange coefficient in LN_2 bath for currents higher than the critical value. In this paper we continue the verification of this approach and we compare simulation results and laboratory data for SF4050 2G HTS tape produced by SuperPower Inc.

Measurements

The HTS layer thickness in the SF4050 tape is around 1 μm, what permits for the relatively high critical current value ranging from 110 A to 118 A at 77 K (self-field). Substrate is made of nonmagnetic metal alloy – Hastelloy C276. This tape has no copper stabilizers. Basic tape parameters are shown in Table 1.

Table 1. The parameters of the SF4050 tape

Parameter	Value
Tape width	4 mm
Tape thickness	55 μm
Critical current at 77 K (DC, self-field)	110-118 A
Critical temperature	93 K
HTS (YBCO) layer thickness	1 μm
Silver overlayer thickness (upper/lower)	2.0/1.8 μm
Buffer stack thickness	0.2 μm
Substrate (Hastelloy C276) thickness	50 μm
Substrate resistivity	125 μΩcm

The experiment involved voltage measurements from the probes soldered to the HTS tape (7 probes spaced 2 cm, 6 tape segments) when it was supplied for a short time with AC current greater than the critical value. The tape was immersed in liquid nitrogen bath (LN_2) under atmospheric pressure. The voltages were measured differentially on each of tape segments (Fig.1).

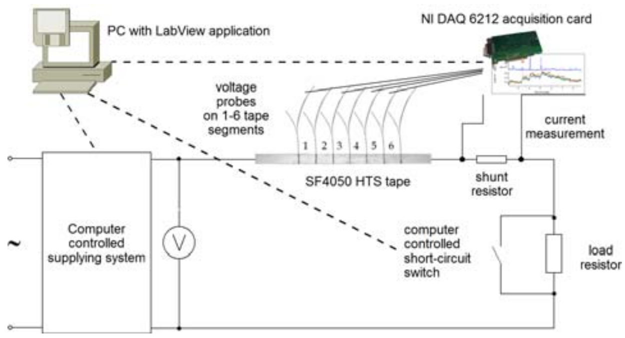

Fig.1. Measurement arrangement for HTS tapes

Test stand, shown in Figure 2, consists of three main elements: examined tape, data acquisition equipment and supplying system. The SF4050 tape with soldered measuring probes is placed in the liquid nitrogen bath (1). Computer controlled supplying system (3) allows for automatic switching of the supply voltage and for the computer control over current amplitude. Data acquisition stand (2) contains: National Instrument DAQ Card, PC computer and data acquisition software written in LabView environment.

Fig.2. Test stand for measuring the electric response of the tape: 1 – HTS 2G tape in LN_2 bath, 2 – data acquisition, 3 – computer controlled supplying system

Before the overcurrent test, current of low value was passed through the tape for the observation of waveforms in steady state. After this, the overcurrent switch was turned on automatically by computer-controlled supplying system. The amplitude of the quench current was also set in the supplying system. Current and corresponding voltage waveforms were recorded for supplying current higher than the critical value.

For the tape batch the manufacturer reported the critical current value I_C=115 A. The exemplary measurement results are presented in Figure 3.

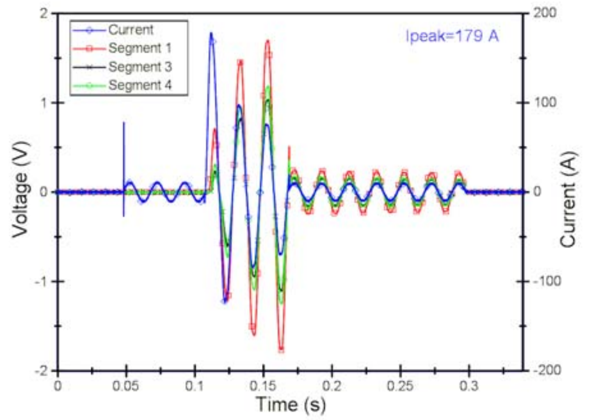

Fig.3. Voltage and current waveforms for tape segments that lost stability (I_m/I_C=1.56)

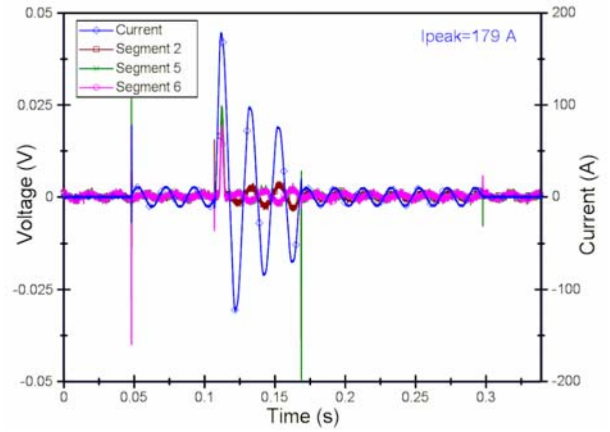

Fig.4. Voltage and current waveforms for tape segments that lost superconductivity (I_m/I_C=1.56)

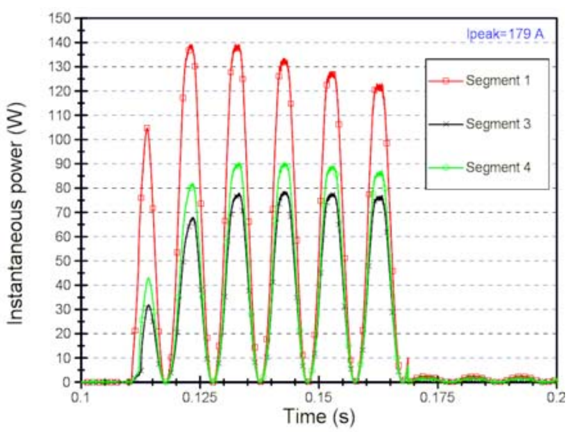

Fig.5. Instantaneous power waveforms for tape segments that lost stability (I_m/I_C=1.56)

In other segments of tape the superconductivity loss can be also observed (Fig. 4). However in that case there is no stability lost and the voltage in the segments 2, 5, 6 does not grow to the value observed in Figure 3. The peak of voltage waveforms in Figure 4 can be observed in the first half period of sine. After this the amplitude of the acquired voltages oscillates around the value before quench.

Measurements of instantaneous current and voltage allow for calculating the instantaneous power. The waveforms of the instantaneous power for segments 1, 3, 4 are shown in Figure 5. Knowing the instantaneous power it is possible to calculate heat and in the next step, the temperature of measured segment [7].

In the range I_{peak}/I_c of 1.0-1.56 the examined tape loses thermal stability in random segments during the 60 ms overcurrent exposure. This may be explained by the inhomogeneity of HTS parameters and/or cooling conditions.

Tape numerical model

HTS coated tape simulations can be performed with the use of finite element method. The ratio of thickness of superconducting layer to HTS tape width can be as high as 1:12000. So extremely thin subdomains are very difficult to mesh and to analyse using finite element method [8].

In this experiment, computer simulation of the SuperPower 2G HTS tape was completed using PSpice and its analogue behavioural modelling blocks. Information on material parameters, especially on these temperature dependent such as resistivity, specific heat and LN_2 bath heat transfer coefficient were collected from bibliography and tabularised. Non-linear circuit components were built of voltage- and current-controlled sources [4-7].

Electric properties of the SF4050 tape may be described in a simplified parallel form as shown in Figure 6. Equivalent circuit of a single tape consists of two non-linear resistors representing high temperature superconductor and silver over-layer and the linear resistor for the substrate C276. YBCO buffer stack was neglected in this approach.

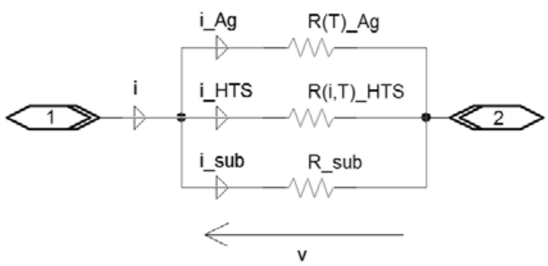

Fig.6. Equivalent circuit of the HTS tape SF4050

Resistivity of the silver over-layer is considered as temperature-dependent. Hastelloy resistivity is stable in wide temperature range and its temperature dependence is neglected. Ignoring magnetic field influence, electrical properties of high temperature superconductor may be described by equation (1)

$$E(J) = E_C\left[J / J_C(T)\right]^{n(T)} \quad (1)$$

where: E – electric field strength, E_C – constant (transition criterion for HTS, 1 μV/cm), J – current density, J_C – temperature dependent superconductor critical current density, n – temperature dependent power law n-exponent.

To calculate temperature we assumed that the tape mass is uniformly heated by electric current and cooled by cryogenic bath. The tape cooling rate was determined by the different modes of liquid nitrogen boiling i.e.: nucleate, transition and film boiling.

Neglecting radiation, it leads to the equation (2) and the equivalent circuit shown in Figure 7

$$T = T_0 + \frac{1}{C_{\mathrm{th}}(T)} \int_{t_0}^{t_1} \left[u \cdot i - q_{\mathrm{LN2}}(T) \cdot A_{\mathrm{th}} \right] \mathrm{d}t \tag{2}$$

where: T_0 – temperature of the cooling bath, C_{th} – thermal capacity of the tape, u – tape voltage, i – tape current, q_{LN2} – cooling heat flux density, A_{th} – cooling area.

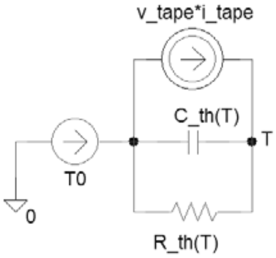

Fig.7. Equivalent circuit for thermal phenomena in tape segment

Computer simulation results

To reproduce HTS tape inhomogeneity observed during laboratory tests in a simplistic manner, we prepared simulation circuit consisting of two tape segments connected in series. Segment nr I was parameterized as 10 cm long and for critical current I_c=115 A. Segment nr II had length of 2 cm and I_c=100 A.

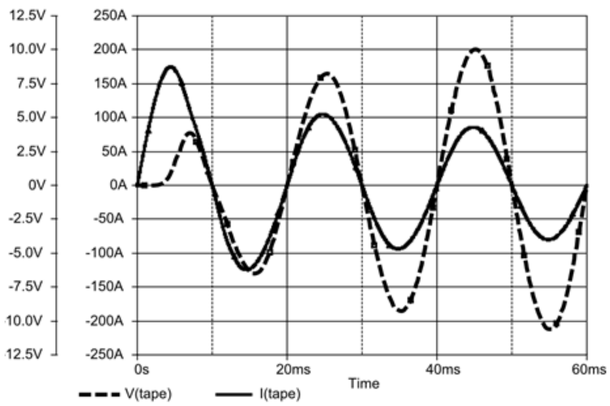

Fig.8. Tape voltage V(tape) and current I(tape) (l_{tape}=10+2 cm, I_{peak}=179 A)

Figure 8 illustrates overall tape voltage and current waveforms for the initial amplitude of I_m=179 A. It corresponds very well with laboratory data, what can be considered as the general validation of the model.

Instantaneous power of 2 cm part taken from section I and instantaneous power of tape section II are depicted in Figure 9.

Figure 10 contains the comparison between laboratory data and the computer simulation. Part (a) of this figure depicts average temperature of three tape segments indirectly calculated from the real voltage and current wave-forms. Part (b) shows simulation results (average tempe-ratures) for long section nr I and short tape section nr II.

Discrepancy between measured and simulated temperature may have three main reasons: simplified computer model takes into consideration neither heat radiation, nor heat conduction between tape segments, nor the influence of the voltage probes on the thermal behaviour of the real tape. It needs further investigation and modification.

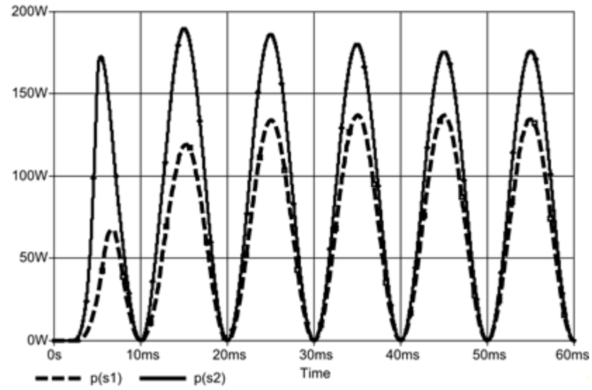

Fig.9. Instantaneous power of tape segments. For comparison: p(s1) – 2 cm part of section nr I, p(s2) – section number II (2 cm long)

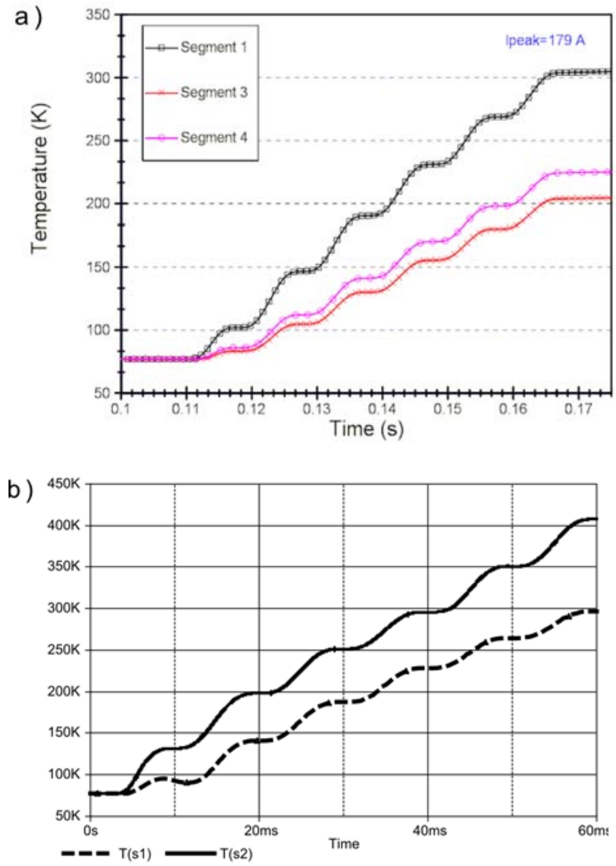

Fig.10. Measured (a) and simulated (b) temperatures: T(s1) – tape section nr I, T(s2) – tape section nr II

Current distribution between tape layers during 60 ms overcurrent exposure is shown in Figure 11.

During first 5 ms weak tape segment nr II (I_c=100 A) completely quenches and the normal metal layers take over the current pulse (Fig.11b). It results in a rapid heat generation. After initial 15 ms, phenomena in both tape segments proceed nearly identical. Slight difference in silver resistivity is caused by the different amplitudes of temperature upsurges appearing in the first half-period of sine.

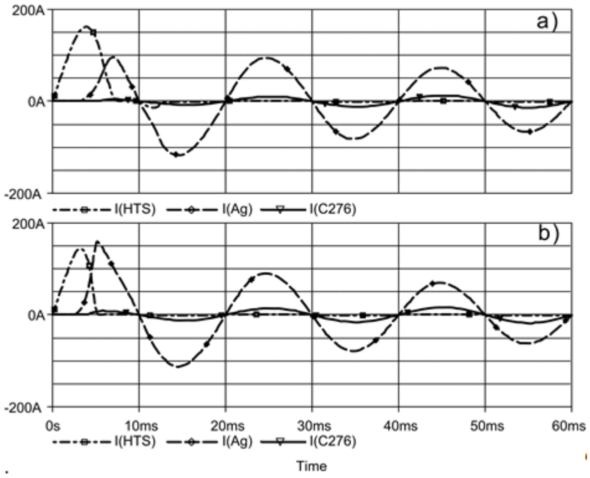

Fig.11. Current distribution between tape layers in section I (a) and section II (b) of the tape (I_{peak}=175 A)

Conclusion

The simplified approach makes the model both fast and reliable as well. The numerical results show very good agreement with the measurements made for SF4050 tape. The applied model is versatile and may represent after simple parameter modifications, other types of YBCO coated conductors and superconducting coils built of 2G HTS used for current limiting devices.

***Authors**: dr inż. Leszek Jaroszyński, e-mail: l.jaroszynski@pollub.pl, dr hab. inż. Dariusz Czerwiński, e-mail: d.czerwinski@pollub.pl; Lublin University of Technology, Electrical Engineering and Computer Science Faculty, ul. Nadbystrzycka 38A, 20-618 Lublin*

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