Thermal behavior of 2G HTS tape for use in resistive fault current limiters

D F Alferov, P N Degtyarenko, I N Dul’kin, L M Fisher, V P Ivanov, A V Kalinov, V A Sidorov, and I F Voloshin
All-Russian Electrical Engineering Institute, 12 Krasnokazarmennaya Street, 111250 Moscow, Russian Federation
E-mail: sidorov@vei.ru

Abstract. To design a commutative resistive fault current limiter it is important to study load characteristics of a superconducting tape as a non-linear resistive element. We used 2G HTS tapes SF12050 and SF12100 produced by Superpower Co. of 12 mm in width and of 50 and 100 µm in thickness, respectively. The tapes of different length in the range of 10 – 50 cm were studied. A loading current was a 10 ms half-sine pulse of different amplitude up to 1 kA. The pulse was generated using a low and high-voltage LC oscillatory circuit with frequency of 50 Hz. The HTS tape was immersed in liquid N$_2$ (LN$_2$). The temporal dependence of current through the tape and the voltage drop were measured simultaneously. The temporal dependence of the Joule losses and resistance of the tape were computed. The instantaneous values of the tape temperature during and after the loading period were determined. Three cases of the tape arrangement have been studied: (i) a single (isolated) tape, (ii) a bifilar tape, and (iii) a tape placed between two silicon plates. The tape temperature rise during the loading period is shown to govern the energy equation for the adiabatic case. The difference in thermal behavior of these systems is discussed. The cases (i) and (iii) differ from (ii) for relatively low loads. The cooling process is similar for cases (i) and (ii), i.e. the cooling rate is determined by different modes of LN$_2$ boiling curve (film, transition, and nucleate boiling). A method is developed to calculate the cooling curve of the HTS tape immersed in LN$_2$ after the end of current pulse using a steady-state boiling curve of LN$_2$ corrected only for transition boiling mode. The silicon plates are found to promote a cooling process significantly.

1. Introduction
Nowadays the superconducting fault-current limiters (FCL) with high a electromagnetic and thermal stability as well as a reliable operation in electric networks during fault are developed, designed, and manufactured in several advanced countries. According to the engineering requirements to such a system, the surge and steady values of a fault current should not exceed a maximum permissible value. The high temperature superconducting tapes of the second generation (2G HTS) which have been shown to withstand high stress and strain without degradation [1, 2] are seem to be the most suitable material for this application. Therefore, detailed studies of the electric and thermal characteristics of these tapes with multiple current overloads are needed.

We present here a study of the thermal characteristics of two HTS tape specifications, in particular, SF12050 and SF12100 produced by the Super Power Co. The tapes were immersed in LN$_2$ at atmospheric pressure. We studied the thermal characteristics for two stages of FCL
operation. At the first stage, the current pulse is passing through the HTS tape and the dynamic current-voltage characteristics are measured during the all load period including a quench from superconducting to the normal state with a corresponding increase of the tape temperature. At the second stage the cooling behavior of the tape is studied by passing a low dc current through it and measuring its resistance to find the recovery time to the superconducting state. To measure the dynamic current-voltage characteristics, a resistive-shunted circuit has been used. This type of circuit can be very compact with negligible impedance during a normal operation [3]. The results obtained allow one to determine a mode of fault-current limiter operation and can be used for the determination of the Joule losses and temperature rise.

2. Samples and measurements technique
Our measurements have been performed using two samples of the Super Power 2G HTS tape with different length, thickness, and critical current. The surface of superconducting film is covered by a stabilization silver layer of 2 µm in thickness. The thickness d of the hastelloy substrate for SF12050 and SF12100 are equal to 50 µm and 100 µm, whereas the critical current is 250 A and 400 A, respectively.

The dynamic current-voltage characteristics have been measured using an oscillatory circuit (LC) with a frequency 50 Hz. The coil inductance L was 270 µH. The triode thyristor was used as a fault key. All measurements have been performed by means of a standard four probe method with a compensation of the reactive voltage component. The potential clamping silver contacts were settled at the edge of HTS that minimized their influence on the results of measurements. The layer of copper about 15 microns in thickness was put on the tape by a galvanic method to solder the current leads 20 – 25 mm in length to the tape. The distance between voltage taps was about 20 mm for short samples and up to 400 mm for long ones. To measure a sample resistance during a cooling process, a small current, about 1 A, was used. The tape temperature T was determined from the tape resistance R by means of the calibration curve $R(T)$. Comparative studies of the current-voltage characteristics have been performed for a single tape and for the same tape folded in half so that this sandwich forms a bifilar connection and the current in the bifilar tape was equalized to the total current.

3. Experimental results and discussions
Figure 1 shows the temporal dependence of the current and voltage drop on the sample with its loading current of a half-sine pulse period 10 ms. The skewness of current and voltage curves in Fig. 1 arises due to a strong dependence of the circuit heat generation $Q$ on the resistance of the tape during a fault period. The temporal dependence of the HTS tape temperature is shown in Fig. 2.

The large difference between maximum temperatures for single and bifilar tapes at the end of pulse is clear seen at small pulse amplitude. This temperature difference exceeds 40 K. At maximum pulse amplitude it decreases up to 5-10 K. Such a different behavior can be attributed to the increase of a current rise and penetration field rate. Notice that the temperature rise of a bifilar tape is less than for a single tape at the same current amplitudes.

We have also calculated the temperature rise of the tape for one of the most typical current amplitude of 793 A (Fig. 3). We considered the adiabatic heating as well as the heat transfer to LN$_2$ by thermal conductivity. The experimental data and calculated curve for the adiabatic case coincide within an accuracy about of 10 %.

Figure 4 shows a cooling process of a tape for two different cases. The recovery time for a single tape changes from 0.5 s for small current amplitudes to 1.3 s for greater amplitudes. In this case smooth running of cooling curves occurs too but near 170 K a slope of a cooling curve changes and the cooling curve has a kink. Such a behavior is governed by a stability failure of film boiling and transfer from a film to transition boiling at higher temperatures than for
a steady-state boiling curve. The recovery time of the tape placed between two silicon plates $52 \times 12 \times 0.8 \, \text{mm}^3$ is from 0.5 s for small current amplitudes to 0.8 s for large amplitudes and cooling curves are smooth up to LN$_2$ temperature (Fig. 4 a. Such a behavior can be explained as follows. A heat flux from the tape is transferred to the silicon plates. Owing to their high thermal capacity and conductivity, the temperature rise in plates is lower with respect to the tape. As a result, the boiling film is not formed on the plate boundary, so the heat can be effectively transferred to LN$_2$.

The cooling process for a single (isolated) tape is studied in the initial temperature range between 170 K and 277 K that corresponds to the excess temperatures $\vartheta$ over a saturation temperature of LN$_2$ between 93 K and 193 K. The steady-state heat transfer curve of saturated liquid nitrogen at atmospheric pressure with saturation temperature $T_S = 77$ K which is often called boiling curve of LN$_2$ is depicted in Fig. 5 in a double logarithmic scale. The tape surface heat flux $q$ is presented as a function of the excess temperature $\vartheta = T - T_S$. The boiling curve is seen to contain five sections with different heat transfer modes (1 - Natural convection, 2 - Nucleate boiling, 3- Critical heat flux, 4 - Transition boiling, and 5 - Film boiling) (see, for

Figure 1. The temporal dependence of current and voltage drop in HTS sample for different amplitudes of loading current for a single tape (a) and a bifilar tape (b). Corresponding current amplitudes are shown in the legend. The distance between voltage taps $l = 2.15$ cm.

Figure 2. The temporal dependence of temperatures in single (open symbols) and bifilar (solid symbols) tapes for different current amplitudes, $l = 2.15$ cm.

Figure 3. The temporal dependence of measured and calculated temperatures in the HTS tape for current amplitude 793 A. Bottom curves refer to a bifilar whereas upper curves refer to a single tape, $l = 2.15$ cm.
Figure 4. Cooling a tape placed between two silicon plates (a) and a single (isolated) tape (b). The tape was heated previously by current with amplitude values given in the legends.

Figure 5. Boiling curve of liquid N\textsubscript{2} at atmospheric pressure.
Portion 1 - 0 < \vartheta \leq 1.96,
2 - 1.96 < \vartheta \leq 11.3,
3 - 11.3 < \vartheta \leq 12.6,
4 - 22.6 < \vartheta \leq 30,
5 - \vartheta > 30

The boundaries between different heat transfer modes of a steady-state boiling curve are designated in Fig. 5 by letters a, b, c, and d.

According to the experimental data shown in Fig. 4 b, the cooling for short and long samples starts from the initial temperature excess corresponding to the film boiling mode (for example, point f in Fig. 5). A slope of all cooling curves in the film boiling mode 5 is near the same (see Fig. 4 b and a portion f-e of straight line 5 in Fig. 5). It varies to another value when the heat transfer mode is changes abruptly from film boiling mode to the transition one. However, the vapor film collapse takes place at temperature excess \(\theta_e\) higher than \(\vartheta_d\) which corresponds to the minimum heat flux for the steady-state film boiling mode. According to our experimental data for the tape SF12100 of 50 cm in length (see Fig. 6), the temperature excess \(\theta_e\) is related to the maximum temperature excess \(\vartheta_f\) at the starting point of cooling.

To calculate the subsequent cooling of the tape, we assume that for transient cooling the transition curve corresponds to the straight dotted line e-c with an arrow directed from e to c. Parameters for this straight line in transient regime can be determined using preliminary founded values \(\vartheta_e\) (see Fig. 4) and \(q_e\) from the steady-state film boiling curve.

Figure 7 shows the comparison of measured and calculated cooling curves for HTS tape SF12100. A calculation has been performed using the method described above. A rather good correlation can be observed. Possibly, the deviation may be connected with the asymmetrical heat transfer to liquid N\textsubscript{2} owing to the asymmetrical tape geometry and, consequently,
nonuniform temperature profile across the tape. We think that this is the main reason of a time shift between experimental and calculated curves since the nonuniform heat transfer is not taken into account.

Thus, the temporal dependence of current through the tape and the voltage drop were measured simultaneously. The temporal dependence of the Joule losses and resistance of the tape were computed. The instantaneous values of the tape temperature during and after the loading period have been determined. The experimental data and calculated curve for the adiabatic case are shown to coincide within an accuracy about of 10%. The cooling rate is determined by different modes of LN$_2$ boiling curve (film, transition, and nucleate boiling). The method is developed to calculate the cooling curve of the HTS tape immersed in LN$_2$ after the end of current pulse using a steady-state boiling curve of LN$_2$ corrected only for transition boiling mode. The surrounding silicon plates are found to promote a cooling process significantly. The developed model describing the cooling process of the HTS tape can be used to determine the recovery time of the SFCL superconducting coils after a fault.

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