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Nonequilibrium states in the second-generation HTS composites under overcritical pulsed current impact

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This paper presents the results of studying the processes of epy HTS composites switching from the superconducting to the resistive state at microsecond current pulses. Two modes of pulsed current load were used: with an amplitude of $\sim 1.1I_c$ (the so-called "soft" mode) and with an amplitude of $\sim 3I_c$ ("hard" mode). The possibility of passing supercritical currents through the tape without superconductor characteristics degradation is shown. To explain the processes occurring in the tape during the current pulse, 2D FEA (finite element analyzes) was developed, with the help of which the dynamic resistance of the HTS composite superconducting layer was calculated in the "hard" load mode and nonstationary processes of current redistribution between the different tape layers were demonstrated.

Keywords: HTS composites, superconducting switch, nonequilibrium states, stable switching, irreversible switching.

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Nowadays, high-temperature superconducting (HTS) composites are beginning to replace low-temperature superconductors in switching systems and often become an integral part of devices such as superconducting energy storage devices [1], current limiters [2], MRI tomographs [3]. Experimental studies and numerical simulation of nonequilibrium states arising in superconductors loaded by fast supercritical currents (i.e. those with pulse amplitude exceeding the critical current I_c) are an important task; solving it is necessary to design, build and optimize switching devices of various purposes.

In this paper, we consider switching processes in HTS composite in the „hard" ($\sim 3I_c$) and „soft" ($\sim I_c$) current loading modes. Experimental studies of switching processes in HTS composites under pulsed current loads were performed using commercial tapes produced by SuperOx [4]. 4 mm wide copper-coated HTS tapes were used (HTS layer thickness $1\,\mu$m, silver layer thickness $2\,\mu$m, copper coating thickness $20\,\mu$m, substrate thickness $80\,\mu$m). At liquid nitrogen boiling point the critical current of the composite was $I_c = 150$ A. Pulse current load experiments were performed in the pulse amplitude range of $0-460$ A with pulse duration of $50-250\,\mu$s, the pulse rise edge taking $1.5-5\,\mu$s. Electrical measurements were performed using a four-contact scheme with a 6 mm distance between potential contacts in liquid nitrogen. Fig. 1 shows the current and voltage time dependences in the sample in soft (a) and hard (b) current load modes. In the first current load mode, the pulse amplitude and rise time were 160 A and $3\,\mu$s, in the second mode — 460 A and $1.5\,\mu$s, respectively. In the hard current load mode, when the amplitude of the transport current increases, the sample voltage continues to grow steadily until the current load is completely removed, whereas in the soft current load mode, reversible switching of the HTS composite is observed, so that the sample voltage starts to decrease while the transport current continues to grow. The behavior of superconducting tape when passing a current pulse with a rise time of the order of $1\,\mu$s is radically different from similar results obtained for pulses with durations of the order of milliseconds [5,6], often characterized by a more stable behavior and a build-up of voltage on the sample when the current pulse is applied to it.

To explain the processes occurring in the HTS tape at currents several times higher than the critical one (hard mode), a two-dimensional model based on the finite element analyses (FEA) was developed using the approach described in [7] for numerical analysis of such systems. In contrast to study [7], the computational algorithm was optimized to describe copper-coated composites. The developed model is applicable to estimating currents flowing in each layer of the HTS tape, and the resistance of the superconducting layer $\rho(J, T)$ depending on the applied current and local temperature. The description of the physics of thermal processes is based on the standard equation of heat transfer in solids. The local heat dissipation in all layers of the HTS tape is calculated as the product of the current density and electric field strength. The model also takes into account temperature dependencies of thermal conductivities, thermal capacities, electrical resistivities and densities of all the materials used. As part of the model, the mode of cooling the HTS composite with liquid nitrogen was implemented. This provides for multiple changes in refrigerant boiling modes from convective to bubble and back, additional superheating (delayed boiling) and the hysteresis nature of the liquid nitrogen boiling curve [8,9].

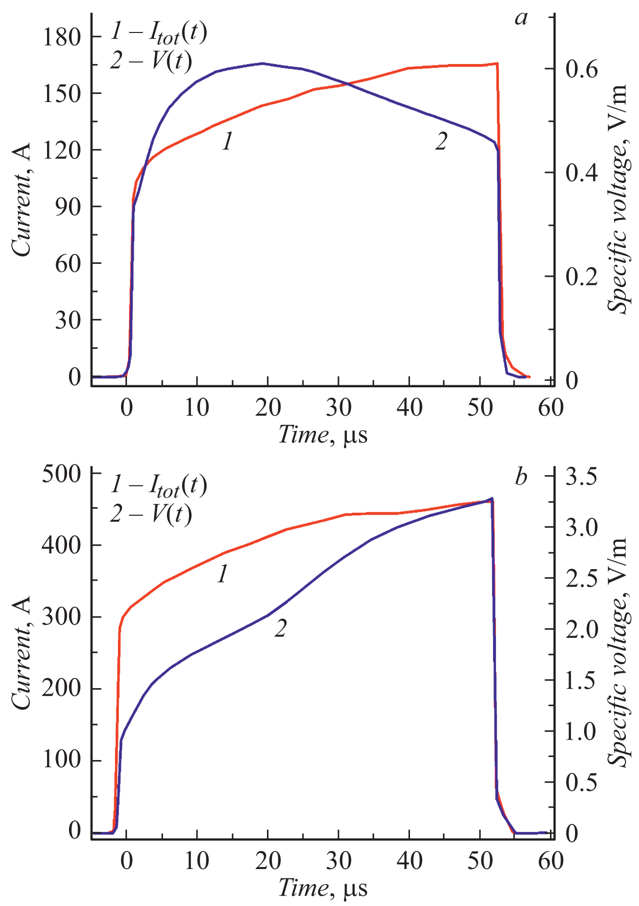

Figure 1. Current and voltage time dependences per unit sample length between potential contacts exposed to a current pulse. *a* is the soft load mode (pulse amplitude 160 A ($\sim I_c$), current input rate 50 A/μs), *b* is the hard load mode (pulse amplitude 460 A ($\sim 3I_c$), current input rate 300 A/μs).

The heat source Q is formed by all layers of the tape, $Q = J(t)E(t)$, where the electric field strength $E(t)$ and the current density $J(t)$ are determined from the experimental data as

$$E(t) = \frac{V_{meas}(t)}{l}, \tag{1}$$

$$J(t) = \frac{E(t)}{\rho_{mat}(T)}, \tag{2}$$

where $V_{meas}(t)$ is the time dependence of the experimentally measured voltage at the distance l between the potential contacts, $\rho_{mat}(T)$ is the resistance of material, its temperature dependence known exactly for all tape layers except the superconducting one. The current in each material I_i^{mat} is determined integrating the current density over the cross-sectional area of the respective layer S_i^{mat}. Using the experimentally measured total current $I_{tot}(t)$ through the HTS tape, the current through the superconducting layer can be found as

$$I_{\mathrm{HTS}}\big(T(t)\big) = I_{tot}(t) - \sum_{i=1}^{n_{mat}} I_i^{mat}\big(T(t)\big). \tag{3}$$

Finally, the resistance of the HTS layer $\rho_{\mathrm{HTS}}(J, T)$ is determined according to expression

$$\rho_{\mathrm{HTS}}(J, T) = \frac{V_{meas}(t)}{J_{\mathrm{HTS}}\big(T(t)\big)} \frac{S_{\mathrm{HTS}}}{l}. \tag{4}$$

It should be noted that, within the scope of this model representation, temperature increase during the current flow through non-superconducting layers leads to an increase in the resistance of these layers and a decrease in the current flowing through them. In that case, the current through the HTS layer will effectively increase (see equation (3)). The resistance of the HTS layer, calculated according to expression (4), will appear the lower, the larger is the current flowing through the superconductor, in the result. This effect causes no significant error in cases when the bulk currents flow via the superconducting layer while the thickness of stabilizing layers is small, as was the case in [10]. In our case though, in the presence of a massive copper layer capable of carrying sufficiently high currents at cryogenic temperatures, it is necessary to introduce a correction factor for the resistance of the HTS layer. In this regard, the model introduces an additional bulk heat source in the region of the HTS layer, its heat release power proportional to hysteresis losses in the HTS layer during the pulse build-up and the actual resistance of the layer [10,11]. The described algorithm was implemented using the Heat Transfer in Solids module of the Comsol Multiphysics software package. Because the geometry of the system reproduces the actual architecture of HTS tapes, special adaptation mechanisms are used to create a finite-element mesh, such as multiscale structuring and drawing the mesh through thin layers of HTS tape [12].

We analyze the processes of current redistribution between the layers of the HTS tape using the example of the harder load mode, in which the nonequilibrium processes are most pronounced. Fig. 2 shows the current time dependences in all layers of the HTS tape during the entire pulse (*a*) and the rising of the current front (*b*). Note that the start of pulse application features expressed elements associated with the processes of redistribution of currents and the setting of equilibrium state in the system (see Fig. 2, *a*). A closer look at the time interval of the current front rise (Fig. 2, *b*) shows that up to the current reaching its value critical for the HTS tape, it all flows through the superconducting layer. Next, the current appears in the copper layer, which has a stabilizing function. Due to its small thickness, the silver layer carries only a very small part of the currents, and the substrate layer does not participate in the redistribution of currents between the tape layers due to its low conductivity. Besides, using the developed approach, it is possible to determine the dynamic resistance

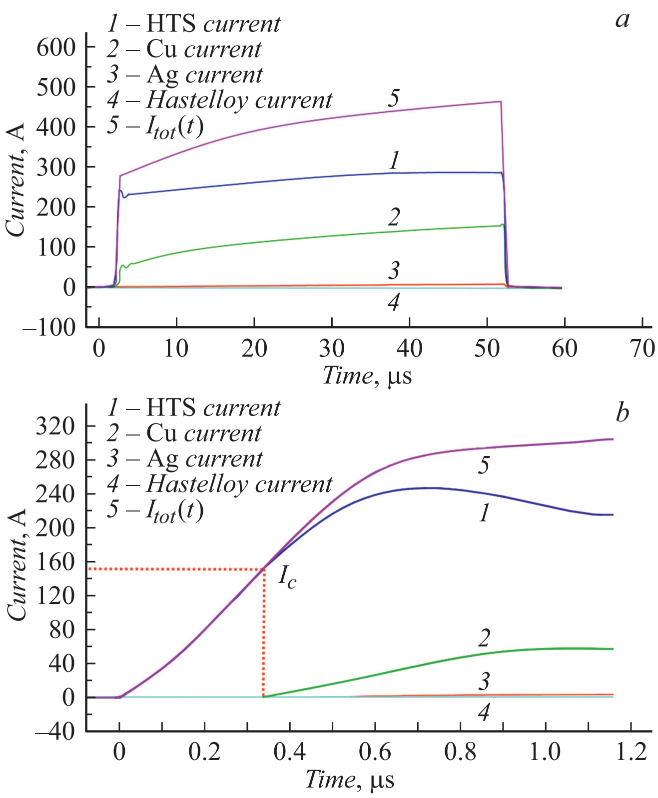

Figure 2. Current time dependences in all layers of HTS tape during the entire pulse (*a*) and the current front rise (*b*).

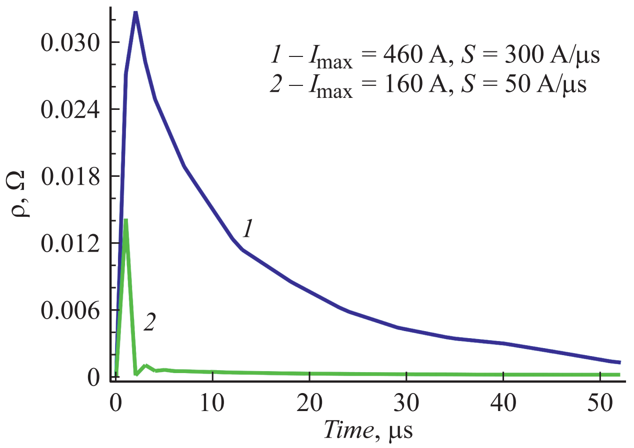

Figure 3. Dynamic impedance of the HTS composite tape layer in hard (pulse amplitude 460 A ($\sim 3I_c$), current input rate 300 A/μs) and soft (pulse amplitude 160 A ($\sim I_c$), current input rate 50 A/μs) load modes. Pulse duration is 50 μs.

of the HTS layer of the tape, which can be integrated into models with a circuit diagrams to calculate the parameters of devices with superconducting elements in the circuit. The dynamic impedance of the HTS tape layer during a 50 μs current pulse in hard and soft load modes is shown in Fig. 3. Note that the calculated resistance is not a general characteristic of the material, but takes place only under the given conditions of exposure. Therefore, this calculated resistance of the HTS layer may only be used to describe devices operating in similar load modes.

Thus, this study demonstrates the possibility of passing a pulsed current with an amplitude 3 times higher than the tape critical current without degradation of superconductor characteristics through an HTS tape. In such a case a switch is observed in the SC resistive state, which persists until the end of the pulse action. Simulating nonstationary processes demonstrated the dynamics of current redistribution between the layers. It is shown that using the developed model it is possible to determine the critical current and dynamic resistance of HTS layers. The obtained data can be used to design high-speed switching devices based on high-temperature superconducting composites. Note that experimental data presented in this paper were obtained using HTS tapes with a high degree of critical current homogeneity. The computational model also considers the case of complete homogeneity of tape layers and ideal thermal and electrical contact between them. However, the presence of inter-grain boundaries and temperature instability of magnetic fluxes may affect significantly the switching processes in case of highly inhomogeneous HTS layers [13]. In addition, separate attention should be paid to the issues of tape stabilization under pulsed current influences and the influence of heat redistribution processes in the layers [6,14]. Experimental and numerical study of these issues is the subject of further research.

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Conflict of interest

The authors declare that they have no conflict of interest.

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