The dynamic processes in second generation HTS tapes under the pulsed current and magnetic impact

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Abstract. This paper presents the results of complex multiphysical modelling of non-equilibrium states arising in high-temperature superconducting composites under current, magnetic, and combined control switching impacts types. The simulation and analysis of the dynamics of electrophysical and thermal processes occurring in the HTS composites layered structure taking into account the influence of local thermal processes in the composite structure, in particular, heat generation bursts during a pulse, has been performed. The HTS composite switching times from the superconducting to the normal state have been investigated for various current pulses amplitudes in homogeneous magnetic fields. An experimental verification of the numerical model has been carried out.

1. Introduction
Currently, high-temperature composites replace traditional low-temperature superconductors in switching systems and often becomes an integral part of modern devices such as superconducting energy storage devices [1], current limiters [2], MRI tomographs [3]. In such systems HTS key switching occurs through the non-equilibrium states generation, as a rule, under pulsed current, magnetic or local thermal impacts. Simulation of non-equilibrium states arising in superconductors under the single (current, magnetic, thermal) or combined load conditions is necessary for superconducting electronics switching devices designing, optimizing and construction, energy storage and transmission systems designing and improving their energy efficiency. A particularly important task is the numerical study of the switching processes of HTS composites in various temperature conditions under the current and magnetic impacts and the system cooling parameters selection to achieve the minimum switching time without degradation of the HTS elements current-carrying capacity. This is especially true for systems in which liquid nitrogen is used as a refrigerant. Such systems numerical analysis is rather difficult due to the hysteresis nature of the liquid nitrogen boiling curve and the possibility of multiple changes in the boiling regimes of LN2 under non-equilibrium conditions of HTS elements operation [4].

This paper presents the results of complex multiphysical modelling of non-equilibrium states arising in high-temperature superconducting composites under current, magnetic, and combined control switching impacts types. When simulating non-equilibrium states provoked by the pulsed current impact, the switching control is carried out using an additional current pulse with a density $J > J_c$. In the magnetic pulse impact case, the occurrence of non-equilibrium states is caused by the excess of the superconductor critical current in the magnetic field. The experimental magnetic and transport characteristics of GdBa$_2$Cu$_3$O$_{7-x}$ industrial tapes manufactured by SuperOx (Russia) were used as the
input model parameters. In the simulation, the layers of the substrate, superconductor, and stabilizing copper and silver layers are considered. The simulation is performed by using FEM H-formulation method implemented in the Comsol Multyphysics software.

2. Computational model

2.1 Electromagnetic model

The simulated current-carrying system is a high-temperature superconducting tape, which also can be placed in a uniform magnetic field. The geometry of the system is shown in the figure 1.

![Figure 1. General view of the calculated system.](image)

The measurements for the tape modelled were performed on a superconducting tapes produced by SuperOx (Russia) with the 4 mm width, 1 micron thickness of the superconducting layer GdBa2Cu3O7-x is and the critical current - 120 A (criterion 1 μV / cm, 77 K, own field). Within the model framework, each tape contains, in addition to the superconducting layer, a substrate, and also copper and silver thin layers.

To study the behavior of a HTS tapes stack in an external magnetic field and under the pulsed current impact a finite element method was used. The model was developed using the Partial Differential Equations (PDE) form of the Comsol Multiphysics software. The general PDE Comsol equation is (1):

$$
e_a \frac{\partial^2 u}{\partial t^2} + d_a \frac{\partial u}{\partial t} + \nabla \times \Gamma = F. \quad (1)$$

The dependent variable is the magnetic field $u = H(x,y,z)$, entire the space. The parameters of equation (1) are chosen in such a way that equation (1) becomes Faraday's law (2):

$$\nabla \times E + \frac{dB}{dt} = \nabla \times E + \frac{d(\mu_0 \mu_r H)}{dt} = 0, \quad (2)$$

where $E$ - electric field, $B$-magnetic induction, $H$- magnetic field, $\mu_0$ - relative permeability of free space, relative permeability for air and for superconducting elements was set as $\mu_r = 1$. Specifications of the parameters of the equations (1) and more information about H-formulation see [5-10].

The resistance nonlinear dependence on the current is given by the power law (3) and the current-voltage characteristic can be written by formula (4):

$$\rho = \frac{E_c}{J_c} \left( \frac{|J|}{J_c} \right)^{n-1}, \quad (3)$$

$$E = \rho \cdot J, \quad (4)$$

where $E_c$ is the electric field which equals 1 μV/cm, corresponding the voltage at critical current value. The experimental dependence of the n-value of the HTS current-voltage power law characteristics on
the magnetic field was used in the model. The critical current density \(J_c\) is determined on the basis of the transport measurements of the used HTS tapes. For a correct calculation, the dependence of the critical current of the HTS on the external magnetic field must be introduced. This can be done using analytical expressions, for example, as described in the source [11], or using the experimental dependencies.

As it was mentioned, in the above formulation, the dependent variable is the magnetic field \(H(x,y,z)\). The magnetic field is calculated as a superposition of external and internal contributions [12]. The internal contribution \(H_s = [H_{sx} \quad H_{sy} \quad H_{sz}]\) is calculated from the solution of the Ampere equation, the external contribution \(H_e = [H_{ex} \quad H_{ey} \quad H_{ez}]\) corresponds to the applied magnetic field. The Direchlet boundary conditions were used. To implement the transport current the Pointwise Constraint boundary condition imposes the necessary restrictions on the transport current application through the end of only the superconducting layer strictly along the x axis according to a given time law. Periodic boundary conditions for dependent variables are superimposed on the ends of the tape. Such the boundary conditions formulation ensures the correct current load determination and the problem convergence.

2.2. Thermal model
The description of the heat transfer physics is based on the expression:

\[
\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q + \rho C_p u \nabla T,
\]

where \(C_p\)-heat capacity, \(\rho\)-density, \(k\)-coefficient of thermal conductivity of the used materials, which depend on temperature for each layer and \(u\) is the temperature velocity field, \(Q\) –all heat sources, including thermoelectric. Local heat generation in the tape is calculated as:

\[
Q = E \cdot J.
\]

The current distribution \(J\) of the superconductor is determined by the conditions of magnetization and is calculated as the solution of the Maxwell equations, realized in the PDE form. The experimental thermal conductivity and heat capacity temperature dependences for each of these layers were introduced into the model as the interpolation [13].

The critical current dependence on temperature is introduced in accordance with the expression (7) [1]:

\[
J_{c0} = \alpha \left(1 - \left(\frac{T}{T_c}\right)^2\right)^{1.5},
\]

where \(\alpha\) - fitting parameter. The experimental critical temperature \(T_c\) is 92 K.

In the model the cryofree tape cooling is performed at the lower boundary, where the cryocooler system power may vary in the range of a real cryocooler cooling system power to maintain the desired cooling temperature. Wherein the tape is placed on a copper bulk that will be considered as a cooling source. The outer boundary of the cryocooler, which is in direct contact with the HTS tape substrate, is set as a cooling source with a determined constant temperature and variable heat sink power.

The simulation was performed for two cooling modes: cooling with liquid nitrogen taking into account the hysteresis nature of the boiling curve and liquid-free cooling over a wide temperature range. The liquid nitrogen cooling realized taking into account the LN2 boiling curve [14] and takes place along the entire tape perimeter. For convective and bubble nitrogen boiling [15], appropriate heat transfer coefficients are introduced [16]. For bubble boiling, the heat transfer coefficient is calculated as:

\[
\alpha_{boll} = C_h q^{0.624}(\rho C_p k)^{0.117},
\]

where \(\rho\) – density, \(C_p\) – heat capacity, \(k\) – thermal conductivity of liquid nitrogen, \(q\) – heat flow, \(C_h\)– coefficient [15].
The heat transfer coefficient for liquid nitrogen stationary boiling is determined by the temperature difference $\Delta T$ at the boundary between the tape and liquid nitrogen and is calculated by the formula:

$$\alpha_{\text{conv}} = C_{\text{conv}} \Delta T^{1/3},$$

(9)

$C_{\text{conv}}$ – coefficient [16].

Thus, the choice of using one or another heat transfer coefficient depends on the temperature difference $\Delta T$ and heat flux into liquid nitrogen $q$ and is set using the conditions “if”. Since in some liquids, including liquid nitrogen, during the rapid heat flow growth the additional overheating may occur (boiling moment delay) by several degrees $\Delta T_{\text{oh}}$ (superheating), the liquid boiling temperature may exceed usual temperature onset bubble boiling delay value $\Delta T_{\text{cb}}$ (transition from convection to boiling). Therefore, the first type of “if” condition is fulfilled when the temperature difference $\Delta T$ reaches the liquid nitrogen overheating temperature $\Delta T_{\text{oh}}$, which in general depends on the heater surface material and the boiling liquid properties. In our case $\Delta T_{\text{oh}}$ is assumed to be constant and equal to 3K. Immediately after $\Delta T_{\text{oh}}$ is reached, a developed bubble boil begins. When the heat flux decreases, the return from bubble boiling to convection does occur not at the temperature difference $\Delta T_{\text{oh}}$, but at the temperature difference $\Delta T_{\text{cb}}$ (the second “if” conditions type), that is, there is a boiling hysteresis. $\Delta T_{\text{cb}}$ can be found from the condition of heat transfer coefficients equality in the natural convection and bubble boiling modes. Thus, the choice of heat transfer equation coefficients occurs automatically at each time step of the solution.

When constructing the elements mesh, the mesh broach and multiscale structuring tools were used, and the superconducting layer was divided into 2 layers in hight in order to have two layers in HTS thicknesses.

3. Results and discussion

In the 2G HTS simulation, the tape was subjected to the pulsed current loads from 0.5 $J_c$ to 3 $J_c$, and to magnetic fields impact up to 2 T. It was founded, that there is a thermal transition critical current $J_{c\tau}$, which can be differ from the «isothermal» critical current of the tape $J_c$ and depends on the cooling and load parameters [17]. Figure 2 shows the time dependences of the HTS sample voltage for current pulses of several different amplitudes, but with the same front rise time. It can be seen that the increased voltage at a current pulse of $\sim 1.2 \times J_c$ may decrease, while the transport current continues to exceed the superconductor critical current. In addition, there is a time delay in the occurrence of a voltage in the HTS tape during a pulse. This time dependence was also observed in the experiment. The inset in figure 2 shows the calculated and experimental HTS tape voltage dependences on time for the current injection rate $S = 428$ A / s with amplitude 148A ($\sim 130\%$ of $J_c$).

The calculated and experimental dependences are in good agreement. It can be also noticed that there is a sample voltage occurrence delay while the transport current magnitude remains constant and exceeds the critical current on the value of $\sim 30\%$. These is due to the thermal equilibrium establishing processes and the features of heat removal to liquid nitrogen when changing the boiling regimes (from convective to bubbling and conversely). In the liquid nitrogen case, the hysteretic character of the LN2 boiling curve and the presence of an additional thermal delay of bubble boiling onset (overheating) play an important role in thermal processes. Immediately after the current load start, the heat generation on the HTS tape begins to increase, while the cooling parameters are largely determined by the liquid forced movement speed and its effect on the boiling and heat transfer processes. The fluid velocity increase delays the onset of boiling, since heat transfer from the surface is provided by the forced convection. A sharp heat generation on the sample leads to the refrigerant boiling, after which the thermal equilibrium establishing processes in the system and nitrogen boiling mode changing to convective begin. In this case, very rapid liquid mixing absence, characteristic of bubble boiling, leads to a sharp heat removal decrease and can lead to secondary overheating on the sample surface and reboiling. After the boiling start, forced convection continues to play a significant role, competing with heat transfer due to vaporization. As long as the liquid refrigerant is able to quickly remove the heat released on the HTS tape, a sharp increase in voltage on the sample does not occur. From this point of view, in the presence
of sufficiently productive cryotechnics, there are no fundamental restrictions on the use of currents that significantly exceed the superconductor critical current. After the excess heat was removed by the refrigerant due to the more intensive heat removal during nitrogen boiling, the voltage stabilizes. In the simulation, the absence of direct accounting of fluid motion and the formation of a bubble phase in LN2 is compensated by the use of dynamic heat transfer coefficients for various liquid nitrogen boiling modes. Calculations showed that the main heat release during a pulse occurs in the superconducting layer. Part of the heat is removed through the massive substrate layer, but the main part in the redistribution of currents between the layers under supercritical loads is taken by the copper layer, which performs current stabilization of the tape and additional thermal stabilization of the tape.

Figure 2. The dependence of the HTS tape voltage on time for various amplitudes current pulses. The inset shows a similar experimental and calculated dependences for the current injection rate $S = 428 \, \text{A} / \text{s}$ and the current amplitude $148 \, \text{A}$.

Figure 3 shows the fragments of the HTS tape current-voltage characteristics for various copper stabilizing layer thicknesses. It is clearly seen that the copper coating thickness increasing leads to a decrease in the growth rate of the electric field in the tape, while the tape without a stabilizing coating shows a significantly faster increase in voltage at lower transport currents. In this case, with a not so significant excess of the HTS critical current, the entire tape resistance approaches the metal layers’ resistance. The inset to figure 3 shows the maximum temperatures in the HTS tape layers modelled. It can be seen that the main part of the heat is generated in the HTS layer, however, the copper layer also accounts for a significant part of the heat released in the tape. In the absence of a stabilizer, all this heat must be either removed by the substrate, or compensated by the cryogenic equipment or the liquid nitrogen, otherwise it will have a negative effect on the tape current-carrying capacity. However, the calculation showed that an excessive increase in the copper coating thickness negatively affects the thermal transition critical current. So, for HTS tapes with a 0.5 mm Cu layer thickness, the critical thermal transition current turned out to be lower than for HTS tapes with a 40 μm layer of copper (not shown in the graph). This is explained by the fact that when the copper layer is too thick, liquid nitrogen cooling, occurring on all HTS tape sides, is less effective. Indeed, in the case of the cryocooler cooling,
a significant decrease in the thermal transition critical current with increasing copper thickness was not observed, since the main heat removal in this case occurs through the substrate.

Figure 3. The dependence of the electric field in HTS tapes with different thicknesses of the stabilizing copper layer on the applied current. In the inset, the maximum temperature in all layers of the stabilized HTS tape during the pulse.

Figure 4 shows the calculated dependences of the thermal transition critical current $J_{ct}$, normalized to the HTS tape critical current in the own field at 77K, with additional exposure to an external uniform magnetic field.

Figure 4. Normalized dependence of the thermal transition critical current on an external magnetic field.

The calculation showed a decrease in the critical current of the thermal transition with an increase in the external magnetic field, which is due to the suppression of the critical current of the superconductor. Lowering the temperature led to a significant increase in $J_{ct}$. In fact, if the power of cryogenic equipment
is sufficient, then there are no fundamental restrictions on the use of currents in the devices that significant exceed the critical current of the superconductor, but do not exceed the thermal transition critical current under the loads. In addition, cryocooler cooling in higher magnetic fields turned out to be more efficient than liquid nitrogen cooling, but the issue of the cooling power expended in this paper was not considered.

4. Conclusions

This paper presents the results of complex multiphysical modelling of non-equilibrium states arising in high-temperature superconducting composites under current, magnetic, and combined control switching impacts types. The simulation was performed for two cooling modes: cooling with liquid nitrogen taking into account the hysteresis nature of the boiling curve and liquid-free cooling over a wide temperature range. It is shown that with efficient cooling, local bursts of heat generation can be successfully removed by liquid refrigerant or be compensated by cryogenic equipment; in this case, there are no fundamental restrictions to use the currents significantly exceeding the HTS critical current. The dependence HTS tape voltage and the thermal transition to the normal state parameters on the transport current amplitude is calculated, which depends on the ratio of the rate of heat propagation released on the superconductor and leading to a decrease in the critical current, and the pulse duration. The conditions for the flow of currents from the superconducting to the stabilizing layers are revealed, and the influence of the stabilizing layer thickness on the local thermal and electrodynamic processes in HTS were studied.

Complex numerical model that takes into account the features of HTS switching from the superconducting to the resistive state in a wide range of real operating temperatures under various cooling conditions will be in demand for power engineering modern switching systems developing. This model will help to optimize the cost of the system cooling to achieve the required switching speeds, which will ensure high devices stability, safety, the possibility of multiple HTS switching and increase the uptime.

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