Numerical modeling of the switching processes in the second generation HTS tapes under the electric pulses impact

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Abstract. This paper presents the results of complex multiphysical modeling of nonequilibrium states arising in high-temperature superconducting composites under the pulsed current impact. The time dependences of the voltage on the superconducting tape under the influence of current pulses for the pulse amplitudes from 0.6 to 2 values of the critical current of the tape are obtained. Two linear modes of the sample voltage behavior during the electric current load are distinguished. A stable HTS sample switching at the current pulse amplitudes less than 1.7 $J_c$ and the development of irreversible dynamic thermal instability for the higher currents are shown. The simulation was performed by the finite element method in the Comsol Multiphysics software package.

1. Introduction
Currently, there is growing interest in creating the fast switching devices of the latest switching systems based on high-temperature superconducting composites that can be successfully applied in 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. Current and magnetic impacts are the most common methods of HTS switching. Therefore, it is necessary to have information about the behavior of HTS tapes under steady and non-steady current and magnetic loads, the behavior of HTSs with transport currents exceeding the critical current, as well as under load conditions that can lead to degradation of the superconducting characteristics of materials. This is especially true for the 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 LN$_2$ under non-equilibrium conditions of HTS elements operation [4,5]. It is necessary to investigate the superheat and stability of superconducting tape at currents above the critical under conditions of cooling with liquid nitrogen (taking into account the actual parameters of boiling). This paper presents the results of complex multiphysical modeling of nonequilibrium states arising in high-temperature superconducting composites under the pulsed current impact for the current pulse amplitudes below and above the HTS element critical current. The simulation and analysis of the dynamics of electrophysical processes occurring in the HTS composites layered structure was performed taking into account the influence of local thermal processes in the composite structure. The HTS composite switching times from a superconducting to a normal state are studied for various current pulses amplitudes (from 0.6 to 2 values of $J_c$).
2. Numerical analyses

2.1 Electromagnetic model

Currently, special importance attaches to the numerical methods of the HTS modeling, allowing to obtain the system physical characteristics under full input parameters control. The most often used method to simulate a vortex system taking into account the defective structure of HTS is the Monte Karlo [6]. To simulate the macroscopic characteristics of the superconducting elements of devices and constructions, it is advisable to use grid methods. To study the behaviour 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):

$$ e_a \frac{\partial^2 u}{\partial t^2} + d_a \frac{\partial u}{\partial t} + \nabla \times \Gamma = F $$

(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):

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

(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 [7-12].

The resistance nonlinear dependence on the current is given by the power law with the experimental n-value dependence on current and magnetic field. For a correct calculation, the dependence of the critical current of the HTS on the external magnetic field can be introduced using analytical expressions, for example, as described in the source [13], or using the experimental dependencies.

To implement the current load 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:

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

(5)

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:

$$ Q = E \cdot J $$

(6)

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 [14].

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

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

(7)

where $\alpha$ - fitting parameter. The experimental critical temperature $T_c$ is 92 K.
The liquid nitrogen cooling realized taking into account the LN2 boiling curve [15] and takes place along the entire tape perimeter. For convective and bubble nitrogen boiling [16], appropriate heat transfer coefficients are introduced [17]. For bubble boiling, the heat transfer coefficient is calculated as:

\[
\alpha_{\text{boil}} = C_\text{h} q^{0.624} (\rho C_p k)^{0.117}, \quad (8)
\]

where \( \rho \) – density, \( C_p \) – heat capacity, \( k \) – thermal conductivity of liquid nitrogen, \( q \) – heat flow, \( C_h \) – coefficient [16].

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:

\[
\alpha_{\text{conv}} = C_{\text{conv}} \Delta T^{1/3} \quad (9)
\]

\( C_{\text{conv}} \) – coefficient [17].

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”. Thus, the choice of heat transfer equation coefficients occurs automatically at each time step of the solution.

3. Results and Discussion

A numerical analysis of the electrophysical and thermal processes occurring in 2G high-temperature superconducting tape subjected to the electric current pulses load from 0.6 to 2 values of the tape critical current was carried out. The simulated tape characteristics within the model is set on the base of the industrial SuperOx tapes characteristics. The tapes width was set as 4 mm, the GdBa2Cu3O7-x superconducting layer thickness - 1 \( \mu \)m, and the copper and silver layers thickness - 20 \( \mu \)m. The HTS tapes critical current was measured experimentally and amounted to 150 A. This value is introduced as the input model parameter (liquid nitrogen, self-field, criterion of 1 \( \mu \)V/cm). Figure 1 shows the time dependences of the HTS sample voltage when the sample is subjected to the electric current pulses loads of various amplitudes (from 0.6 \( J_c \) to 2 \( J_c \)). The total pulse duration was 40 ms, the impact front rise time ~ 20 ms. It can be seen that in all the cases presented, there is a time delay in the voltage appearance on the sample, due to the thermal processes dynamics features of HTS tapes in the selected cooling and load mode. In the case of liquid nitrogen, the LN2 boiling curve hysteretic character and the presence of an additional thermal delay in the onset of the bubble boiling (overheating) play an important role in the thermal processes. Immediately after the start of the pulse application, active heat generation on the HTS tape begins, and the cooling parameters are largely determined by the speed of the forced movement of the liquid and its effect on the boiling and heat transfer processes. An increase in the fluid velocity 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 establishing thermal equilibrium processes in the system observed and the change in the boiling mode to convective begin. In this case, the absence of rapid mixing of the liquid, characteristic for the bubble boiling, leads to a sharp decrease in heat dissipation and can lead to secondary overheating on the sample surface and re-boiling.

So, in the case when the applied pulse amplitude is 90 A (0.6 \( J_c \)), the time delay is ~ 10 ms, while with a current pulse of 195 A (1.3 \( J_c \)) thermal instability develops more sharply, which leads to an earlier occurrence of voltage. In this case, the current redistribution between the HTS layer and the stabilizing layers does not occur. It is worth noting that for the other two cases (1.7 \( J_c \) and 2 \( J_c \)) the voltage on the sample appears later (time delay is ~ 13 ms). This behavior is due to the fact that at the faster electric current input rate (12.75 kA / s and 15 kA / s, respectively), the heat generation rates in the HTS layer become so large that the critical current locally significantly decreases. This leads to an early currents redistribution between the HTS layer and stabilizing layers of the tape. Moreover, when the part of currents flows in a copper layer, which is in the direct contact with the refrigerant, the heat cooling efficiency increases and the currents can be redistributed to the HTS layer a second time.
Thus, the heat removal features influence for a supercritical current load allows to increase the operating time of the stabilized HTS element without the occurrence of high voltages.

**Figure 1.** The time dependence of the sample voltage at the various current pulse amplitudes. The dashed line is the current load development dynamic.

In addition, for all current load modes described in this work, there is a short voltage increase on the sample after the end of the current growth (20 ms). This is also due to the thermal processes dynamics and the heat removal parameters in the liquid nitrogen cooling mode. However, in some cases, the sample voltage begins to decrease, while the sample current magnitude remains constant (time interval of 20–40 ms). When the current amplitude increases above 1.7 Jc, the heat removal power becomes insufficient for the HTS tape cooling and the voltage ceases to decrease in the time interval of 20–40 ms. Thus the voltage disappears only after the current load is completely removed. In this case, the currents redistribution between the HTS tape layers is observed. At a current pulse of 2Jc, the heat generated in the HTS layer and the stabilizing layers does not have time to be removed and it accumulates, which leads to a continuous increase in the HTS tape voltage, and subsequently to the HTS element transition to the normal state.

**Figure 2.** The HTS tape maximum voltage dependence on the current pulse amplitude. The pulse duration is 40 ms, the front rise time - 20 ms. The HTS tape critical current -150 A
Figure 2 shows the dependence of the maximum sample voltage on the applied current pulse value. Two linear modes can be distinguished. The first mode (from 0.6Jc to 1.7Jc on the graph) is characterized by the appearance of voltage on the sample during the period of increasing current load and the thermal equilibrium establishment when the direct current flows through the sample. The second mode is characterized by the development of irreversible thermal instability during the current pulse and the HTS element transition to the resistive state. Similar modes were also observed experimentally [18].

4. Conclusions
This paper presents the results of complex multiphysical modeling of nonequilibrium states arising in high-temperature superconducting composites under the pulsed current impact. The simulation was performed by the finite element method in the Comsol Multiphysics software. When simulating nonequilibrium states provided by the current impact, the switching is controlled by a current pulse of amplitude from 0.6 Jc to 2 Jc. The modeling and the analysis of the electrophysical processes dynamics occurring in the HTS composites layered structure was carried out taking into account the influence of local thermal processes in the composite structure. The time dependences of the superconducting tape voltage for the current pulses amplitudes from 0.6 to 2 of the tape critical current values are obtained. A stable HTS sample switching is shown at the current pulse amplitudes of less than 1.7 Jc and the development of irreversible dynamic thermal instability for the higher currents are shown. Two linear modes of the sample voltage behavior during the electric current impact are distinguished. For the first mode (from 0.6Jc to 1.7Jc), a stable HTS element switching is observed with an ongoing current load. The second mode is characterized by the development of irreversible dynamic thermal instability during the current pulse and the HTS element transition to the resistive state until the current load is completely disconnected.

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