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Numerical simulation of the fast processes in HTS tapes under the pulsed current load

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Abstract. This paper presents a numerical layered 2G HTS tape model with the transport current flowing through it. The simulation is performed by using FEM H-formulation method implemented in the Comsol Multyphysics software. The model provides two cooling modes: cryocooler and liquid nitrogen. LN2 cooling mode provides for a complex hysteresis character of the liquid nitrogen boiling curve and the boiling regimes changing possibility between the stationary and the bubble boiling. The delay of the voltage rising with a transport current above the critical value pulse input is shown in the liquid nitrogen cooling case. The possibility of parameters calculating for current redistribution from the HTS to the stabilizing copper layer is shown, and the stabilizing coating thickness effect on the thermal transition critical current value is studied A comparison with experimental results is carried out.

1. Introduction

In recent years, the high-T_c coated superconductors numerical simulation has become quite a popular method for the HTS behaviour predicting and optimizing the devices based on them. The increasing in number of complex devices with HTS current-carrying elements has resulted in 2-D approximations often are not sufficient. This is especially about the cases when the transport current values are close to or even higher than the HTS element critical current. In such cases the superconductor heat generation rate sharply increases. In some cases, thermal bursts are successfully discharged into the liquid refrigerant or can be compensated by cryogenic equipment. If the cooling of the superconductor is efficient and the cryogenic equipment rate is sufficient to maintain the specified thermal regime of the HTS, then there are no fundamental restrictions for use in current-carrying HTS elements of currents significantly higher than the critical one. But in order to calculate accurately such a system, it is necessary to fully simulate a superconductor and calculate the local heat generation in the 3D structure, taking into account the actual cooling and stabilization parameters of coated conductor. An even more challenging task is to simulate “hot” tapes under liquid nitrogen cooling, because for a given liquid during the rapid heat flow growth the additional overheating and boiling up may occur. In this case, the heat-removing LN2 properties in different boiling regimes differ significantly.

This paper presents the results of complex modeling of the HTS tapes with stationary current effects and non-stationary effects with current pulses. The process of transition of multilayer HTS conductors intended for use in electrical equipment from the superconducting state to the resistive and from resistive to normal when currents exceeding the critical current, as well as the stabilizing layer effect on the second-generation HTS tape is investigated. The model is universal and provides options of liquid

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nitrogen and liquid-free cooling. The simulation was performed using the H-formulation of finite element method (FEM) in the Comsol Multiphysics software. The choice of the formulation in the magnetic field components terms is due to the interest of further modeling of the combination of pulsed current loads in conjunction with magnetic field pulses, for the simulation of which the H-formulation has been already successfully tested.

2. Computational model

The simulated system is a layered structure of the superconducting tape containing a substrate, a superconducting layer, and also a stabilizing copper layer (figure 1.). By the others layers we neglect because of their small thickness and small influence on the thermal processes. Due to the proximity of the copper and silver specific conductance values, in the subsequent analysis it considered as a single stabilizer layer with the corresponding equivalent resistance. As characteristics of the sample, the characteristics of HTS tape “SuperOx” (Russia) were selected. The tape width was 4 mm, the superconducting layer (RE) BCO thickness - 1 μm, the copper layer thickness - 3 μm, the Hastelloy C-276 alloy substrate thickness - 0.1 mm The tape critical current was measured at the liquid nitrogen boiling point with a 1 μV / cm criterion and was ~120A, which, in terms of the cross section of the superconducting layer, gives a critical current density ~10^{10} A/m^2.

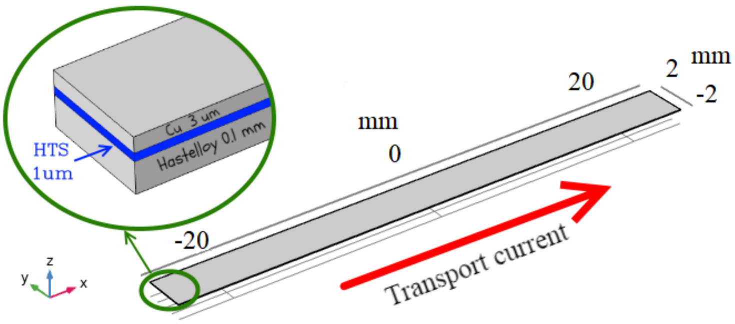

Figure 1. The illustration of the simulated experiment.

The H-formulation was implemented using the finite element method (FEM) in the *Comsol Multiphysics* numerical simulation software. The simulation is based on the Ampere and Faraday laws, and the dependent variables are the magnetic field components H_x, H_y, H_z. The nonlinear voltage dependence on current is set by the power law for current-voltage characteristic with the power of n = 25. 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.

The heat generation in the system is calculated by the formula:

$$Q = \boldsymbol{E} \cdot \boldsymbol{J} \tag{1}$$

The currents distribution $\boldsymbol{J}$ in the superconductor is determined by the current load parameters. Since the typical HTS tape self field usually do not exceed 0.1 T, it do not have a significant effect on the tape critical current and we neglect it in the calculations.

The model takes into account the tape layers real thermal characteristics. The critical current dependence on temperature is introduced in accordance with the expression (2) [1]:

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

where α - fitting parameter.

The experimental critical temperature T_c is 92 K. Thermal conductivity, heat capacity and the resistance temperature dependences are entered into the model in the interpolation form for each tape layer [2].

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 liquid nitrogen cooling realized taking into account the LN2 boiling curve [3] and takes place along the entire tape perimeter. For convective and bubble nitrogen boiling [4], appropriate heat transfer coefficients are introduced [5]. For bubble boiling, the heat transfer coefficient is calculated as:

$$\alpha_{boil} = C_h q^{0.624} \left(\rho C_p k\right)^{0.117}, \qquad (3)$$

where ρ – density, C_p – heat capacity, k – thermal conductivity of liquid nitrogen, q – heat flow, C_h – coefficient [4].

The heat transfer coefficient for liquid nitrogen stationary boiling is determined by the temperature difference ΔT at the boundary between the tape and liquid nitrogen and is calculated by the formula:

$$\alpha_{conv} = C_{conv} \Delta T^{1/3}, \qquad (4)$$

C_{conv} – coefficient [5].

Thus, the choice of using one or another heat transfer coefficient depends on the temperature difference ΔT 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 ΔT_{oh} (superheating), the liquid boiling temperature may exceed usual temperature onset bubble boiling delay value ΔT_{cb} (transition from convection to boiling). Therefore, the first type of "if" condition is fulfilled when the temperature difference ΔT reaches the liquid nitrogen overheating temperature ΔT_{oh}, which in general depends on the heater surface material and the boiling liquid properties. In our case ΔT_{oh} is assumed to be constant and equal to 3K. Immediately after ΔT_{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 ΔT_{oh}, but at the temperature difference ΔT_{cb} (the second "if" conditions type), that is, there is a boiling hysteresis. ΔT_{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.

In order to preserve the real geometrical dimensions of all tape layers, when building a model, mesh drawing tools for the mesh of elements, converting a square mesh into a triangular at the individual domains boundaries, and multiscale structuring were used.

3. Results and discussion

In order to evaluate the thermal processes influence the HTS tape current-voltage characteristics were built with a rather slow current flow change (0.5 A/s) and for more fast change (5 A/s) for cases of liquid nitrogen and cryocooler cooling of tape to a temperature of 77.4 K (figure 2). In the 1st case there is no cooling mode influence on critical current, therefore the direct and reverse I-V characteristics are the same. In the case of fast current increasing, the thermal processes start to effect on I-V characteristic. In both LN2 and cryocooler cooling cases the current – voltage characteristic hysteresis is observed, but for the liquid nitrogen cooling case the hysteresis is more clear. This is due to the complex nature of heat transfer to liquid nitrogen during the refrigerant heating, namely the additional overheating during the transition from convection to boiling existence, the heat transfer mechanism from convection to boiling and back repeatedly changing possibility, and the liquid nitrogen boiling curve hysteresis [3]. Indeed, for a given current input rate, the calculation showed that the condition of the liquid nitrogen boiling mode changing was performed twice — at ~ 103A transport current value (current increase) from convective to boiling and at ~ 110A (current decrease) from boiling to convective.

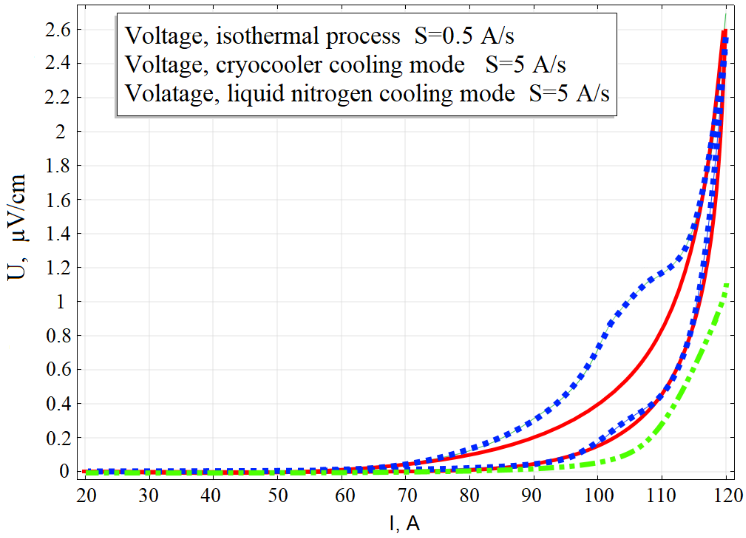

Figure 2. I-V characteristics of HTS tape (77.4 K).

The HTS tape magnetic field change dynamics during the various amplitude transport current flow is shown on the figure 3. One can see that at low currents (to 0.5J_c) the magnetic field is zero at the HTS tape center, which indicates the currents absence in this area. Hereinafter, the J_c is the isothermal critical current value, which is 120 A. The magnetic field begins to appear in the tape center only when the current reaches more than half of critical current (0.6 J_c), and with a further current increase, only the HTS tape magnetic field amplitude changes, but the field profile shape remains unchanged. At approximately the same flowing current values (0.6 J_c ~ 72 A), a nonzero voltage on the HTS tape appears (see figure 2) and the heat generation begins to increase.

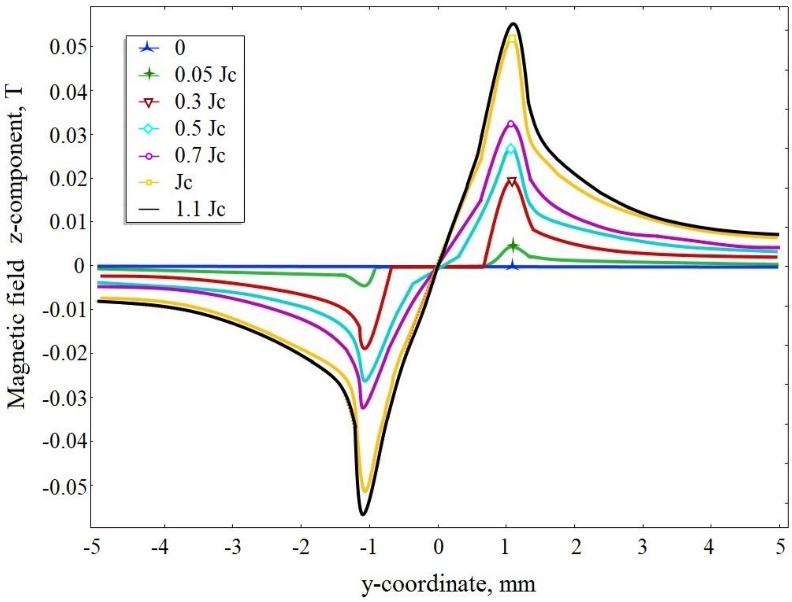

Figure 3. Intrinsic magnetic field distribution across the 2nd generation HTS tape width for various transport current amplitudes. Coordinate y=0 is the HTS tape center.

The impulse of 148 A amplitude transport current was applied to the HTS tape, cooled by liquid nitrogen, at a speed of $S = 428$ A/s, and after reaching the maximum value, the current remained constant. Figure 4 shows the HTS tape current magnitude and voltage dependence on time. The calculated and experimental results are in good agreement. It can be noted that both the experimental and calculated curves demonstrate same delay in the voltage appearance in the tape, when the current amplitude is already ~ 130% of J_c. When the superconductor critical current is exceeded, a sharp increase in heat generation leads to HTS layer overheating and the transition to the resistive state. However, this process does not appear instantly. There is a certain thermal transition critical current value J_{cT}, depending on the pulse input speed, cooling parameters and tape stabilization. This process is also influenced by the temperature delay in the transition of liquid nitrogen boiling regime from stationary to bubbly.

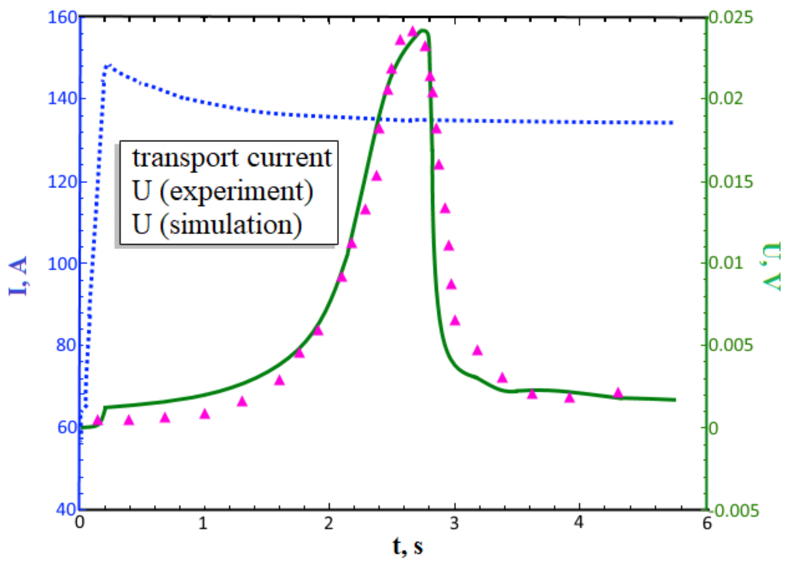

Figure 4. The dependence of the voltage of the HTS tape on time when the flowing current above the critical one.

In addition, for this current flow mode, calculations showed that with a constant transport current above the critical one, the heat flux in the superconducting layer undergoes some oscillations throughout the current load duration [6]. The heat flux increase and decrease at a constant current is the result of current redistribution between the stabilizing and superconducting HTS tape layers.

The current redistribution in the HTS coated sample and the maximum tape layers temperatures during the current load are shown on the figure 5.

While the maximum temperature gradient in the superconducting layer begins to increase, the heating in the copper layer also increases significantly. However, when the temperature gradient begins to decrease in the HTS layer, its growth continues for some time in the copper layer. This suggests a partial current flow from HTS to the copper layer. Then, the SC layer, cooled outside by liquid nitrogen, begins to return to a stable thermal state, the current is redistributed reversely, and the temperature gradient in the copper layer decreases again. It is also important to note that the temperature gradient in the Hastelloy layer follows the shape of the temperature gradient in the SC layer, but turns out to be several orders of magnitude smaller. This suggests that the substrate layer does not participate in electrodynamic processes, but only removes some of the heat from the HTS layer due to the thermal conductivity.

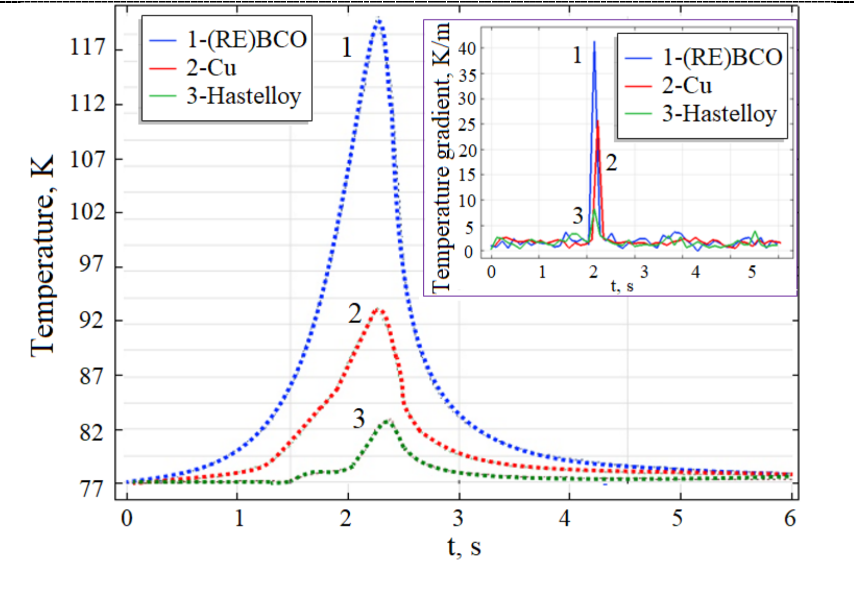

Figure 5. Dependence of the maximum temperature on time for different layers of HTS tape (insert - maximum temperature gradient on time for different layers).

The stabilizing copper layer influence on the processes occurring in the HTS tape under the overcritical current loads was also considered. It was found that, unlike a tape with a stabilizer, for a tape without copper coating, the critical current of thermal transition is determined by the instantaneous heat release value. For this reason, for HTS tapes without a stabilizing layer, the thermal transition occurs already with a small excess of the critical current (~ 105% of J_c). The critical thermal transition current for the stabilized tape was ~ 1.92 J_c *(T0)*. That is, a copper-coated tape can pass flowing currents almost 2 times the critical current at the coolant temperature. In addition, the calculation for several other copper coating layer thicknesses showed that the copper stabilizer thickness decrease leads to a decrease in J_{cT} , and an increase in it leads to an insignificant increase in J_{cT} or even a decrease. So, J_{cT} for HTS tapes with a 1 μm Cu thickness was ~ 1.42 J_c *(T0)*, for 5 μm thickness ~ 2.01 J_c, and for a 30 μm copper thickness ~ 1.64 J_c. This is the result of the fact that the stabilizer layer thickness excessive increase leads to less efficient heat transfer to liquid nitrogen. The question of the stabilizing layers thickness influence on HTS tapes characteristics for different pulsed current load modes is an interesting topic for further researches.

4. Conclusions

A numerical model for electrodynamic and thermophysical processes in 2G HTS tape under the pulse current load has been developed. As part of the thermal-coupled model cryocooler or liquid nitrogen cooling modes are possible. It has been found that there is some limiting current above the critical one, at which excessive heat release in the HTS tape does not have time to be removed by the cooling system and a superconducting transition occurs. With a fast rate of the current increasing in liquid nitrogen cooling case the local overheating of the tape HTS layer is occur and the current redistribution between the superconducting and stabilizing layers is possible.

Due to the low conductivity, the substrate does not participate in the currents redistribution, but only removes the heat from HTS layer due to own good thermal conductivity. It has been investigated that the presence of a stabilizing Cu-Ag layer with 3 μm thickness leads to the thermal transition current increasing almost 2 times more as compared with open tape. However, a too thick stabilizer layer prevents effective heat removal to liquid nitrogen and reduces the thermal transition critical current.. All this suggests the principal possibility of using stabilized HTS tapes in electrical equipment with currents substantially exceeding the critical current of HTS up to the moment when thermal bursts in the superconducting layer can be compensated by cryogenic equipment and stabilizing layers. Comparison of the calculation results with experimental data shows a good agreement.

The developed model can be successfully applied for the calculation of current-carrying elements of various designs based on second-generation HTS tape, as well as for optimizing various practical applications.

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