Temperature rise in a model of resistive HTS element of a fault current limiter

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Abstract **- We studied the thermal regime of the Ni tape immersed into liquid nitrogen and heated up due to a step-like direct current. The tape cooling after the transport current is switched off has been investigated as well. The aim of this study is to model the thermal regime of a resistive HTS fault current limiter during and after the fault. First, we measured the temporal dependence of temperature rise in Ni tape. An adiabatic approach that is commonly accepted was shown to give a conservative result. The thermal conduction into surroundings is necessary to take into account. This heat transfer mechanism was shown to play also the main role during the cooling. According to our results, the necessary amount of HTS material in a resistive fault current limiter can be significantly reduced if one takes into account the heat transfer to liquid nitrogen.**

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I. INTRODUCTION

Fault current limiters (FCL) based on high-temperature superconductors (HTS) are considered to be prospective equipment for electric power applications. Among different kinds of FCL the resistive type is popular today due to its simplicity and efficiency. It introduces only the active resistance into the electrical network but not the reactance. If a transport current exceeds the critical value, the HTS tape of the FCL that operates on a resistive principle transits abruptly to a normal state. As a result, the Joule losses appear in the HTS tape. A single shot protection is continued about 3-5 cycles of the ac current. This time duration is enough to switch of the part of the electrical network with the short circuit by the conventional current interrupter. The working element should be automatically reset to the superconducting state after several minutes. It is usually accepted that there is no necessity to consider the heat transfer into surroundings during a short time of the fault. In accordance with the concept of HTS fault current limiter presented in [1], it is possible to evaluate the necessary volume V_{HTS} of the superconducting materials for a FCL by the following relation,

$$V_{HTS} = \frac{I_{\lim} V_0 \tau}{C \vartheta}. \qquad (1)$$

where V_0 is a system rms voltage, $I_{\lim}$ is a fault current, τ is a fault duration, C is an effective specific heat of the HTS and stabilizing material, and ϑ is a permissible temperature increment that is accepted to be 100 K [1].

Moreover, the parameter ϑ is defined in [1] within an assumption of the adiabatic heat process. As a matter of fact, the heating process is followed by a conduction heat transfer into liquid nitrogen [2, 3]. Therefore, it is necessary to take into account a transient heat transfer during 3-5 cycles of ac current. This process has been studied by a direct observation by high-speed camera photographs in [3]. According to results of [2, 3] the resistive tape reaches a temperature that can exceed the saturation temperature of liquid nitrogen by more than 20-30 K. Nevertheless, authors of [2] have shown that up to the excess temperature about 40 K the transient heat transfer into liquid nitrogen can be considered in usual way as a thermal conduction mode.

The problem of heat transfer in a transient process have been considered long time ago [4, 5]. The transient heat transfer close to our case has been analyzed in [5]. The equation for a temperature rise of an underground cylindrical electric cable after switching on the current was obtained by the Laplace transformation method. This equation was derived on the assumption that both the heat accumulation and heat transfer into surrounding medium are essential

$$Q_J = \gamma\, C(T) F \frac{d\vartheta(t)}{dt} + P q_S(t)\,, \qquad (2)$$

where $Q_J = I^2 \rho(T)/F)$ in the left hand side of Eq. (2) corresponds to the internal heat generation per unit length of the conductor with constant cross section F due to the Joule losses, I is the direct current through the conductor. The first term in the right hand side of Eq. (2) is related to the heat accumulation in the conductor itself due to its heat capacity while the second term is related to heat transfer by the conduction into the surrounding medium. It is assumed in [5] that temperature of conductor do not depends on any of its coordinates and varies only with time t, i.e. the conductor's temperature excess ϑ is a function only of t (lumped space parameters model). Parameters γ, $\rho(T)$ and $C(T)$ are density and temperature dependence of the resistivity and specific heat of the conductor's material. Parameter P is the perimeter of conductor's cross section, q_S is the heat flux at the surface of conductor.

The objective of this paper is to experimentally and theoretically study the transient process of metal tape heating after an abrupt switching on the current (during the first 50 ms) and the tape cooling after the current is switched off. We show that this process can be described by thermal conduction only. The model [5] is modified to take into account both the strong variation of the electrical resistivity and specific heat of the resistive tape material with a temperature and the form factor of the considered conductor. The computer simulation results correlate well with the experimental data. Thus, the modified model describes the heat transfer process in HTS tape of the resistive FCL. Consequently, our results show that the necessary amount of HTS material in a resistive fault current limiter can be significantly reduced if one takes into account the heat transfer to liquid nitrogen.

II. EXPERIMENTAL

To experimentally model the process of heating the HTS tape of the FCL, a sensitive element, specifically, a nickel tape with $\delta = 0.15$ mm in thickness, $w =$ 0.9 mm in width, and $L =$ 0.24 m in length was used. The tape was immersed in liquid nitrogen. The tape $V - I$ characteristics and accordingly its resistance were measured by the usual four-probe method. The current leads were connected to a stabilized dc source. The dc current had a computer-generated step-like form with different values of the step height I in the range from 10 to70 A corresponding to current density J in the range of about 7-50 kA/cm^2. The duration of the heating process was 50 ms. The temporal dependence of the current $I(t)$ and voltage drop $V(t)$ along the tape was measured 10^5 times per second by means of a data acquisition system. The temperature dependence of the Ni tape resistivity $\rho(t)$ was independently measured and is shown in Figure 1).

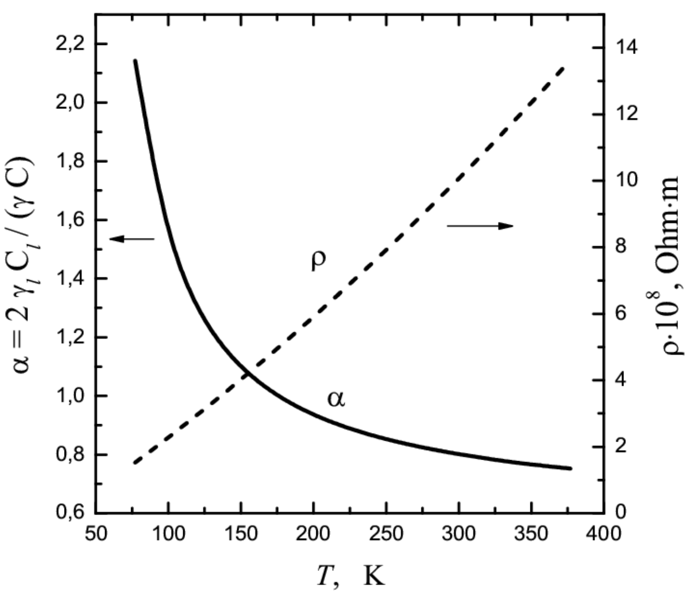

Fig. 1. Temperature dependence of the parameter α [see equations (9) and (10) and related text] and electrical resistivity ρ of the Ni tape.

The temporal dependence of the tape temperature T is determined on the basis of the measured *I(t)-V(t)* characteristics and the initially determined resistivity $\rho(T)$. The experimental results for different currents *I* are shown in Figure 2 by solid lines.

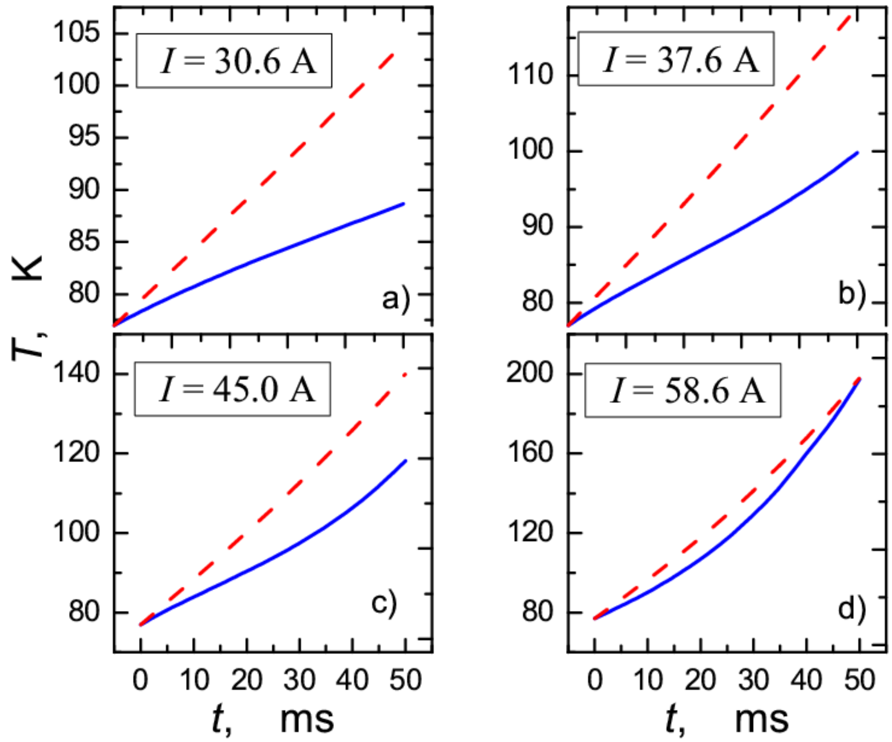

Fig. 2. Temporal dependence of the tape temperature for different values of current I indicated in figures. Solid lines correspond to the experimental data. Dashed lines correspond to the adiabatic case.

It is of interest to compare these results with evaluations for the adiabatic case. The temporal dependence of the temperature in this case can be expressed as,

$$t = (\gamma / J^2) \int_{T_s}^{T} (C(T)/\rho(T)) dT, \qquad (3)$$

where $J = I/(w\delta)$ is the current density, T_s is the saturation temperature of liquid nitrogen. Results of the temperature rise calculations for adiabatic case are shown by dashed lines in Figure 2. All experimental data are clearly seen to lie below than the adiabatic curves. Such a behavior shows that the heat transfer to liquid nitrogen plays an essential role even at the beginning of the transient process.

III. THEORY

The main contribution to the heat transfer for short times is well known to give two mechanisms: the thermal conduction into surroundings and the natural convection. The former mechanism acts at early stages of a heat transfer process whereas the latter is effective at the subsequent stages. The estimation of the minimum "delay time" t_d, after which free convection is initiated around a cylindrical wire immersed into liquid nitrogen, gives $t_d > 0.35$ s [6]. The duration of the heating process in our experiment does not exceed 0.05 s. Therefore, only the conduction heat transfer into liquid nitrogen is considered here.
The problem under consideration is governed by a set of thermal balance equations which have the simplest form in a case of a cylindrical sample. If the current I flows through a cylindrical wire of radius r_c immersed into a heat-absorbing medium, the following instantaneous heat balance equation per unit length is valid:

$$Q_J = \gamma\, C(T)\, \pi r_c^2 \frac{d\vartheta_S(t)}{dt} + 2\pi r_c q_S(t)\,, \qquad (4)$$

where ϑ_S and q_s are the temperature excess over the liquid nitrogen saturation temperature and heat flux at the surface of the conductor. The excess temperature ϑ_S is assumed to be the same and uniform throughout the wire length and cross section and varies only with time. Such an approximation is equivalent to assuming the infinite thermal conductivity of the conductor material. All values in Eq. (4) are given except $\vartheta_S(t)$ and $q_s(t)$. To determine these values, an additional heat conduction equation has been used in [5] for annular ambient region around the conductor.

The following 1D transient heat conduction equation, initial, and boundary conditions are valid for the circular region around the cylindrical wire (for ambient medium, specifically, for liquid nitrogen which assumed to be the solid body with thermal parameters of liquid nitrogen):

for $r_c < r < \infty$ $t > 0$

$$\frac{\partial\vartheta(r,t)}{\partial t} = \varepsilon_l \left\{ \frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial\vartheta(r,t)}{\partial r} \right] \right\}, \qquad (5)$$

for $r_c \le r < \infty$

$$\vartheta(r,0) = 0, \qquad (6)$$

for $t > 0$

$$\vartheta(r_c,t) = \vartheta_S(t), \qquad (7)$$

$$-k_l \frac{\partial\vartheta(r,t)}{\partial r} = q_S(t). \qquad (8)$$

Here, $\vartheta(r,t)$ is the temperature excess function of radius and time for ambient medium over the saturation temperature of liquid nitrogen, ε_l is the thermal diffusivity of ambient medium, which is equal to $k_l/(\gamma_l c_l)$, where k_l, γ_l and c_l are the thermal conductivity, density, and specific heat of the ambient medium (liquid nitrogen), r_c is the wire radius. The exact dimensionless solution [5] obtained for the cylindrical conductor heated due to internal heat generation by the constant Joule losses at constant physical properties of a conductor material and surrounding medium can be presented as,

$$\vartheta_S k_l/Q_J = \frac{2[\alpha(T)]^2}{\pi^3}\int_0^\infty \frac{(1-\exp(-u^2\varepsilon_l t/r_c^2)}{u^3 f(u)}du, \qquad (9)$$

where

$$f(u) = [uJ_0(u) - \alpha J_1(u)]^2 + [uY_0(u) - \alpha Y_1(u)]^2, \qquad (10)$$

The terms $J_0(u), J_1(u), Y_0(u)$, and $Y_1(u)$ in Eq. (10) are the Bessel functions of the first and second kind, zero- and first-order correspondingly. The parameter α in Eqs. (9) and (10) is equal to a doubled ratio of volume heat capacities of the surrounding medium and the wire $\alpha(T) = 2\gamma_l C_l/[\gamma\, C(T)]$. The temperature dependence of this parameter is presented in Fig. 1.

Thus, Eqs. (9) and (10) allow one to determine in a explicit closed form the temporal variation of the temperature excess ϑ_S for a metal conductor immersed into liquid nitrogen at constant Joule losses and constant physical properties of conductor material and surrounding medium.

These equations are used to interpret the results of our experiment performed for the Ni tape. The physical parameters of this tape depend strongly on the temperature. Specifically, the resistivity $\rho(T)$ that defines the Joule losses $Q_J = I^2\rho(T)/(\pi r_c^2)$ and heat capacity $C(T)$ are not constant. The temperature dependence $\alpha(T)$ that is inversely proportional to $C(T)$ and resistivity $\rho(T)$ are shown in Fig. 1. The parameter α is seen to decrease about twofold in the temperature range 77 K-180 K.

If ρ and α are temperature dependent parameters, Eq. (9) for every given time instant can be considered as an implicit equation with respect to ϑ_S. A solution of this equation allows one to obtain the temporal dependence of the temperature excess ϑ_S in a cylindrical wire.

The results considered above are related to cylindrical conductors. High temperature superconducting materials of the second generation are produced in the tape form. Specifically, our experiment was performed using the Ni tape of a rectangular cross section. Therefore, it is desirable to develop a procedure that can enable one to make an evaluation of the tape temperature regime on the basis of above presented solutions for a cylindrical wire. To do this, the cylindrical conductor with a radius r_c and the tape with rectangular cross section are considered. A comparison of the instantaneous heat balance equations for these cases shows that to get the equal Joule losses and heat capacities for both cases, the cross section areas of the cylindrical wire and rectangular tape should be equal, Hence, it follows that the radius of an equivalent cylinder that should be substituted into Eq. (4) is equal to $r_c = \sqrt{w\delta/\pi}$. However, the surface area of a cylinder at such transformation is reduced by a factor $(w+\delta)/\sqrt{\pi w\delta}$ as compared with the corresponding area of the rectangular tape. To take into account this difference, the calculated value of ϑ_S should be multiplied by a form factor $K = \sqrt{\pi w \delta}/(w+\delta)$ to obtain the corresponding value for the tape with rectangular cross section.

IV. RESULTS AND DISCUSSION

A. Heating Process

The results of the calculations presented in Figure 3 are in a good accordance with the experimental data. The best agreement in the whole time range exists for relatively low currents, see Figure 3(a) and (b). A deviation is observed for higher currents. The experimental data lie higher than the calculated ones as seen in Figure 3 (c). On further current increase the experimental curve reaches the adiabatic one and even intersects it, see Figure 2 (d).

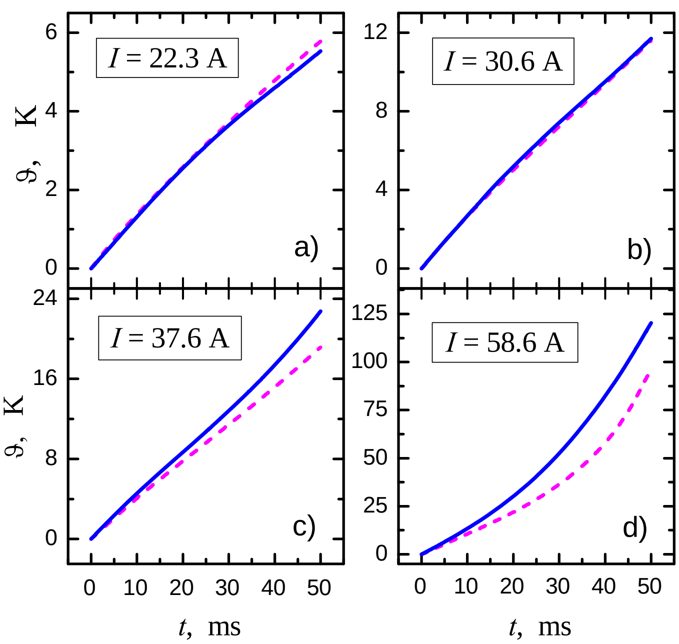

Fig. 3. Temporal dependence of the tape temperature excess for different values of current *I* indicated in figures. Solid lines correspond to experimental data.

There exist different reasons which can be responsible for the observed deviations of the calculated curves from experimental ones in Figures 3(c) and (d). One of the possible reasons consists in a formation of an additional thermal resistance between the tape surface and liquid nitrogen. Such a resistance may be a vapor layer on the tape surface. According to data presented in [3], this layer appears within several dozen milliseconds after the current is switched on.

It should be pointed out that when the temperature along the tape is uniform, the slope of experimental curve at any point should not exceed the corresponding slope of the adiabatic curve. This statement is correct for curves shown in Figures 2(a) - (c). However, the slope of the experimental curve in Figure 2 (d) exceeds the adiabatic one, beginning at $t = 30$ ms. This circumstance means that non-uniform temperature distribution appears in that case. It is well known that the process of heating by stable current can become unstable for metals with positive derivative $\mathrm{d}\rho/\mathrm{d}T$ [7]. In this case, an overheating zone or hot spot can appear. The investigations of these states and their properties are beyond the scope of this study.

In accordance with heat balance equation, the Joule losses effect on the temporal dependence of the temperature excess ϑ. Therefore, the value of $\vartheta(t)$ is defined by the Joule dissipation energy that is released in the conductor from the beginning of its heating, minus the part of the energy E_S that is transferred into liquid nitrogen. The relative value $\beta = E_S/E_J$ is shown in Figure 4. This value is seen not to depend significantly on t and is about 0.4 to 0.6. Specifically, this leads to noticeable decrease of the tape temperature excess with respect to the adiabatic case (see Figure 2).

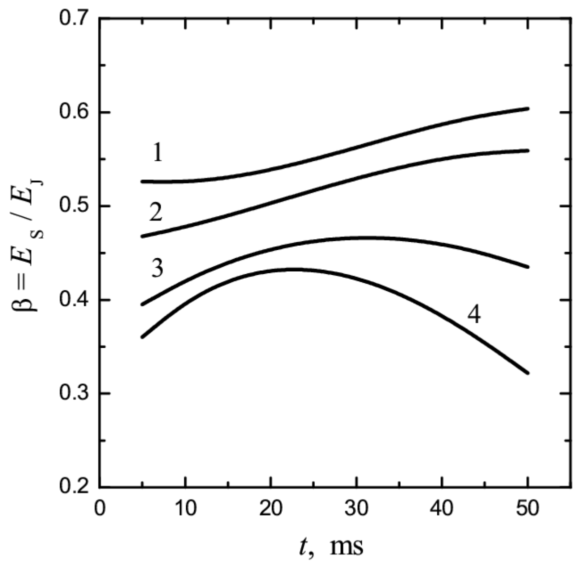

Fig. 4. Temporal dependence of the parameter $\beta = E_S/E_J$ for different transport currents. Curves 1 to 4 correspond to $I = 22.3$ A, 30.6 A, 37.6 A, and 41.6 A, respectively..

B. Cooling Process

One of the most important features of the resistive FCL is the time duration before it automatically resets to the superconducting state after the fault. Therefore, it is of interest to study the cooling process of the resistive tape after its preliminary heating to the excess temperature ϑ. To make a measurement of the recovery time, the Ni tape was preliminary heated by the transport current during 50 ms. Then the current was decreased abruptly down to 1 A and the $V-I$ characteristics was measured. The temporal dependence of the tape temperature is shown in Figure 5. The measurements were performed after the preliminary heating by a current I =21 A and 28 A.

It is possible to calculate numerically the temporal dependence of $\vartheta(t)$ after the heating procedure. This problem is successfully solved for a cylindrical conductor in the transient regime if only the heat transfer by thermal conduction is taken into account. An exact analytical solution for cooling in this case can be found [5]:

$$\frac{\vartheta_S(t)}{\vartheta_S(0)} = \frac{4\alpha(T)}{\pi^2}\int_0^\infty \exp(-u^2\varepsilon_l t/r_c^2)\frac{\mathrm{d}u}{uf(u)}. \qquad (2)$$

This equation can be used to evaluate the temporal dependence of the temperature decrease during the cooling process for a conductor of a rectangular form (tape) if the equivalent radius r_c mentioned above is substituted into Eq. (2).

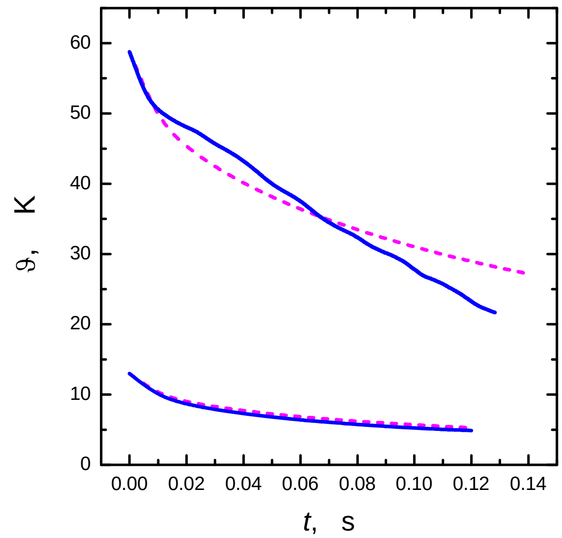

Fig 5. Temporal dependence of the tape excess temperature during the cooling process.

Dashed lines in Figure 5 representing the calculation results agree rather well with the experimental curves. Thus, the heat conduction mechanism is the main one in both the heating and cooling processes. According to these results, the recovery time turns out to be less than several seconds; that is acceptable for the HTS tape of FCL.

V. CONCLUSION

According to obtained results, the conduction heat transfer from the heated tape into liquid nitrogen must be taken into account. This heat transfer mechanism is shown to play also the main role during the cooling process. This fact leads to a significant decrease of the amount of HTS material that is necessary for the FCL operation. Indeed, the expression (1) should be modified to take into account the heat transfer into surroundings,

$$V_{HTS} = \frac{I_{\lim} V_0 (1-\beta)\tau}{C\vartheta}. \qquad (3)$$

This means that the HTS volume can be about two times lower than it was calculated for the adiabatic case. Considerably more significant reduction can be obtained if it is possible to make τ lower than 100 ms. This can be done if a vacuum high speed circuit breaker considered in [8, 9] is introduced into the fault current system. These breakers can currently operate at $I \le 10$ kA, $V_0 \le 20$ kV, and $\tau < 10$ ms.

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