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YBCO 2G tape, superconducting transformer, current limitation

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THE NUMERICAL MODEL OF 2G YBCO SUPERCONDUCTING TAPE IN THE WINDINGS OF THE TRANSFORMER

Abstract

Computer assisted calculations consists in applying software for the simulation of models of certain devices and later analysing their behavior under given conditions corresponding to real working conditions in a specific environment.The paper proposes a circuit model of 2G YBCO superconducting tape created in the PSpice program. The model consists of passive blocks and active user blocks of analogue behavioural modelling (ABM). ABM blocks calculate the conductances, the currents of the individual layers of the superconducting tape, its thermal capacity, the heating power, the cooling power and resulting temperature of the tape. The model uses table of thermal power density passed to the liquid nitrogen vs. temperature. Smooth transition of the YBCO superconductor layer into the resistive state is described by Rhyner's power law. The developed model was used for generating waveforms of thermal and electrical quantities.

1. INTRODUCTION

Superconductors enable to combine magnetic and electrical properties of materials, which can be noticed thanks to the loss of electrical resistance and some peculiar magnetic phenomena under specific conditions. Superconductors are in the superconducting state when the working point determined by temperature, current density and magnetic field intensity is below the critical surface characteristic for each superconducting material.

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A general classification of superconductors is introduced due to the critical temperature value:

- LTS – Low Temperature Superconductor,
- HTS – High Temperature Superconductor.

The critical temperature T_C = 25 K is the point separating LTS and HTS superconductors (Tinkham, 2004).

2. YBCO 2G SUPERCONDUCTING TAPE

2.1. The structure of 2G YBCO superconducting tape

Second generation high temperature superconducting tapes (2G HTS) are called layered or coated conductors. These tapes are usually based on yttrium high-temperature superconductor YBCO. Second generation tapes begin to replace the tapes and wires of the first generation (1G HTS), which were based on bismuth superconductor BSCCO. Characteristic about the second generation tapes in superconducting state is that they conduct current of hundreds amperes at very low losses. Additionally, when the second generation superconductor obtains the resistive state, an unlaminated tape has a relatively high resistance.

High temperature superconducting tapes of second generation are made of several relatively thin layers. A base layer is responsible for electrical and mechanical parameters and in many cases consists of non-magnetic Hastelloy (Ni – 57,00%, Mo – 16,00%, Cr – 15,50%, Fe – 5,50%, W – 4,00%, Co – 2,50%). The thickness of this layer is about 50 μm (Table 1). An optional layer of stabilizer which determines the performance of thermal and also mechanic parameters of the tape, is located at the top and bottom of the tape and has the thickness of about 20 μm. 2G YBCO tape comprises a silver layer having thickness of about 2 μm, YBCO superconducting layer having thickness of about 1 μm, a buffer layer $LaMnO_3$ (LMO) having thickness of 30 nm, a homoepitaxial layer MgO having thickness of 30 nm and a base layer MgO having thickness of 10 nm. Tapes produced by American Superconductor (AMSC) are covered with laminate coating of stainless steel, copper or brass. In turn, SuperPower company produces tapes without a stabilizer (SF series) and tapes with copper stabilizer (SCS series). While comparing these two types of second generation superconducting tapes (Fig.1 and Fig.2), it can be predicted that tapes without a stabilizer show many times higher resistance than tapes with a stabilizer above the temperature T_C (Majka & Kozak, 2009; Tinkham, 2004).

Tab. 1. The parameters of SCS4050 superconducting tape by SuperPower (*SuperPower Inc.*, 2016)

Type of tape	SCS 4050
Thickness	~ 0.1 mm
Width	4 mm
Minimum bending radius	25 mm
Critical current (at T = 77 K, self-field)	80-100 A
Maximum length of a single section of the tape	> 600 m
Thickness of Ag layer	2 μm
Thickness of Cu layer	40 μm
Thickness of YBCO layer	1 μm
Thickness of Hastelloy C276	50 μm
Resistivity of substrate	$1.24 \cdot 10^{-6}$ Ωm

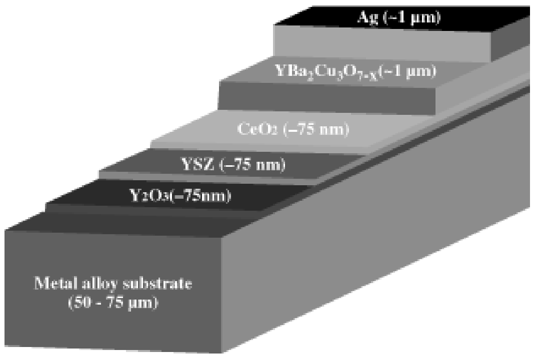

Fig. 1. The structure of second generation superconducting tape by AMSC (*American Superconductor*, 2016)

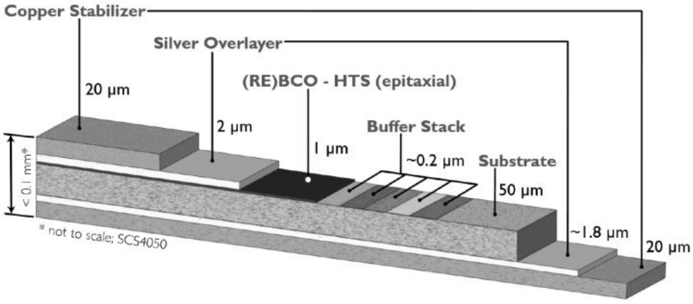

Fig. 2. The structure of second generation superconducting tape by SuperPower (*SuperPower Inc.*, 2016)

Second generation superconducting tapes are usually made of YBCO material. It is a chemical compound comprising yttrium oxide, barium oxide and copper oxide. The general chemical formula of this material is $YBa_2Cu_3O_{6+x}$ ($0 < x < 1$). Figure 3 illustrates the single structure diagram of the superconducting powder.

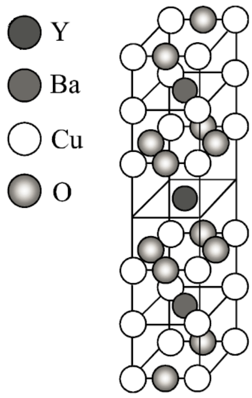

Fig. 3. Single structure diagram of superconducting powder $YBa_2Cu_3O_7$ (Parida, 2012)

3. NUMERICAL MODEL OF 2G YBCO SUPERCONDUCTING TAPE

3.1. Equivalent circuit of 2G YBCO superconducting tape

The modelling object is 2G YBCO superconducting tape. Figure 4 presents the equivalent circuit of the tape. Mathematical model of the superconducting tape consists of three non-linear and one linear resistor in parallel. These resistors include: Hastelloy, a silver layer, a copper layer and a superconducting layer (Czerwinski, Jaroszynski, Majka, Kozak, and Charmas, 2016; Jaroszynski & Janowski, 2014).

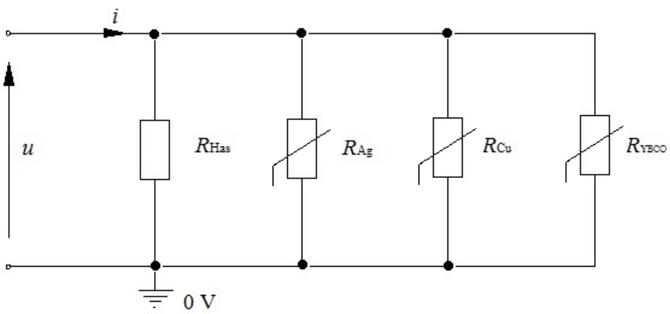

Fig. 4. Equivalent circuit of 2G YBCO superconducting tape

Equivalent diagram of the simulated circuit is shown in Figure 5. This circuit consists of the sinusoidal voltage source V_{sin}, the internal resistance of the power source R_w and the temperature- and current-dependent resistance of the superconducting tape R_{HTS}.

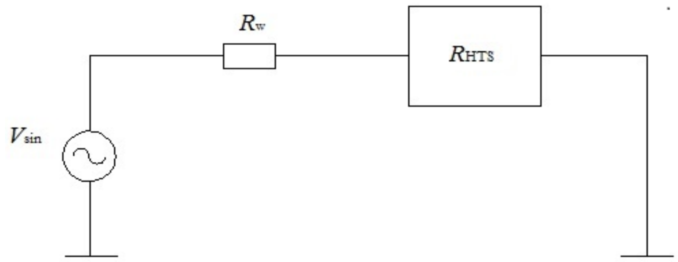

Fig. 5. Equivalent diagram of simulated circuit

3.2. Modelling tool

The model of 2G YBCO superconducting tape was created in the PSpice program. It is a well-known program for circuit design and simulation.

Orcad PSpice enables to:

- design schemes of the analysed circuit,
- choose types and values of elements,
- perform the simulation and display the results in a graphic form,
- use analogue behavioural modelling.

In comparison to circuit modelling finite element method (FEM) subdivides a large problem into smaller, simpler parts that are called finite elements. Due to the high geometric aspect-ratio of superconducting tape, this method leads to the much greater complexity of the calculations than circuit modelling in PSpice program. The second approach seems to be quite effective for the analysis of states when the transport current is higher than I_c (Czerwinski, Jaroszynski, Janowski, Majka, and Kozak, 2014; Janowski, Wojtasiewicz, and Jaroszynski, 2016; Jaroszynski et al., 2014).

PSpice program enables to examine the system for changes in such quantities as:

- voltage,
- current,
- power,
- temperature,
- additional parameters of the model.

3.3. Details of the simulation

The circuit model of 2G YBCO superconducting tape is designed in PSpice program. The model, presented in Figure 6, consists of a passive block PARAM containing the electrical, thermal and geometrical parameters of the tape, and active user blocks of the ABM (analogue behavioural modelling). Voltage blocks calculate the relative temperature (ABM1) in relation to the temperature of liquid nitrogen, the cooling (ABM2) and heating power (ABM3) of the superconducting tape, and the current block calculates the current of the tape (ABM4). For the purpose of current detection in the circuit a secondary DC source (Vpr) with zero voltage (EMF) was used. The model uses tables with the values of power density passed to the liquid nitrogen as the function of temperature (GeStCieLN) and two hierarchical blocks. The first hierarchical block represents thermal capacity (Cth), which is the sum of the thermal capacity of the layer of copper, silver, Hastelloy and the YBCO superconductor. The second hierarchical block calculates the resultant conductance of the tape (G). This block allows for a smooth transition of the YBCO superconductor layer into the resistive state in which the current is described by Rhyner's power law (1) (Czerwinski et al., 2016; Janowski et al., 2016; Jaroszynski et al., 2014).

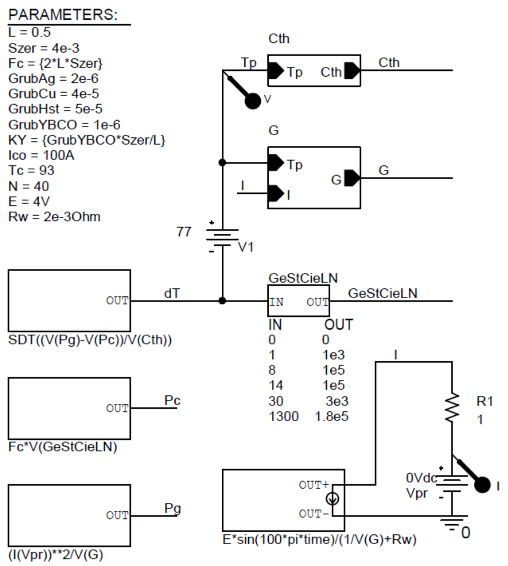

Fig. 6. Electrical circuit of 2G YBCO superconducting tape in PSpice

High temperature superconductors have a non-linear dependence of current density and electric field intensity. GYBCO block (Fig. 7) calculates resistance change (transition into the resistive state) of a superconducting layer in the second generation superconducting tape.

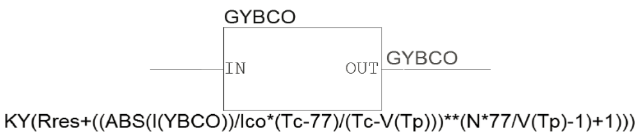

Fig. 7. ABM voltage block calculating the conductance of the YBCO superconducting layer

Exponential dependence (1) describes the relations between current density J and electric field intensity E

$$\frac{E}{E_{\mathrm{c}}} = \left(\frac{J}{J_{\mathrm{c}}(T)}\right)^{n(T)} \tag{1}$$

where: E – electric field intensity, V/m,
E_{c} – critical electric field intensity for HTS, 10^{-4} V/m,
J – current density, A/m^2,
J_{c} – critical current density, A/m^2,
n – exponent depending on the temperature.

The relation between electric field intensity and current density in power law depends on the actual temperature. The temperature affects the critical value of the current and the value of the exponent n. This exponent influences the steepness in rise of current-voltage characteristics and is defined for the purposes of the circuit modelling as:

$$n(T) = n_0 \frac{T_0}{T} \tag{2}$$

where: T_0 – reference temperature, K,
T – temperature of tape, K,
n_0 – exponent in T_0 temperature (for YBCO $n_0 = 15 \div 40$, $T_0 = 77$ K).

Assuming homogenous distribution of current density and electric field intensity, the equation (1) can be written as:

$$\frac{U}{U_{\mathrm{c}}} = \left(\frac{I}{I_{\mathrm{c}}(T)}\right)^{n_0 \frac{T_0}{T}} \tag{3}$$

where: U – voltage, V,
U_{c} – critical voltage, V,
I – current, A.
I_{c} – critical current, A.

After multiplying components of the equation (3) the following dependence can be described as:

$$\frac{U}{I} = \frac{U_c}{I_c(T)} \left(\frac{I}{I_c(T)}\right)^{n_0 \frac{T_0}{T} - 1} \tag{4}$$

The dependence (4) can be presented in the form of resistance:

$$R_{\text{YBCO}} = \frac{U_c}{I_c(T)} \left(\frac{I}{I_c(T)}\right)^{n_0 \frac{T_0}{T} - 1} \tag{5}$$

where: R_{YBCO} – the resistance of YBCO layer, Ω.

Critical current $I_c(T)$ in the equation (5) can be illustrated by the linear relationship:

$$I_c(T) = I_{c0} \frac{T_c - T}{T_c - T_0} \tag{6}$$

where: T_c – critical temperature, K,
I_{c0} – critical current in T_0 temperature, A.

After substitution into the equation (5) the dependence (6) of critical current $I_c(T)$ the equation is:

$$R_{\text{YBCO}} = \frac{U_c}{I_c} \left(\frac{I}{I_{c0} \frac{T_c - T}{T_c - T_0}}\right)^{n_0 \frac{T_0}{T} - 1} \tag{7}$$

After including the critical electric field intensity, the equation is:

$$R_{\text{YBCO}} = \frac{E_c \cdot L}{I_c} \left(\frac{I}{I_{c0} \frac{T_c - T}{T_c - T_0}}\right)^{n_0 \frac{T_0}{T} - 1} \tag{8}$$

where: L – length of tape, m.

The conductance of the superconductor is the reciprocal of resistance:

$$G_{\text{YBCO}} = \frac{1}{R_{\text{rez}} + R_{\text{YBCO}}} \tag{9}$$

where: G_{YBCO} – the conductance of YBCO layer, S,
R_{rez} – residual resistance (a small value higher than zero needed to perform the convergent calculations, in this program equals 10^{-15} Ω).

3.4. Simulation results

The simulation takes into the account the following factors: the sinusoidal voltage source with the amplitude of 4 V, frequency 50 Hz and internal resistance $2{\cdot}10^{-3}$ Ω, the length of tape 0.5 m, the width of tape $4{\cdot}10^{-3}$ m, the thickness of a silver layer $2{\cdot}10^{-6}$ m, the thickness of a copper layer $4{\cdot}10^{-5}$ m, the thickness of Hastelloy $5{\cdot}10^{-5}$ Ω, the thickness of YBCO layer 10^{-6} m, the critical current of the tape I_{C0} = 100 A, the critical temperature of superconductor T_C = 93 K, the temperature of liquid nitrogen T_0 = 77 K, Rhyner's law exponent n_0 = 40.

3.4.1. Thermal capacity of 2G YBCO tape

The hierarchical block Cth (Fig. 8) enables to calculate the thermal capacity of 2G YBCO tape. This block comprises thermal capacity of a copper layer Cth_{Cu}, a silver layer Cth_{Ag}, Hastelloy Cth_{HST}, YBCO superconductor Cth_{YBCO}. The calculations are based on the dependence of the thermal capacity for individual layers of the tape as a function of temperature, as can be seen in Fig. 9, Fig. 10 and Fig. 11. This data allows to create tables with specific heats of copper layer Cw_{Cu}, silver layer Cw_{Ag}, Hastelloy Cw_{HST}. The constant value of 185 J/(kg·K) is accepted as the specific heat for the superconducting layer Cw_{HST}. The calculations also include the density Υ of the individual layers in the superconducting tape, which are presented in Table 2.

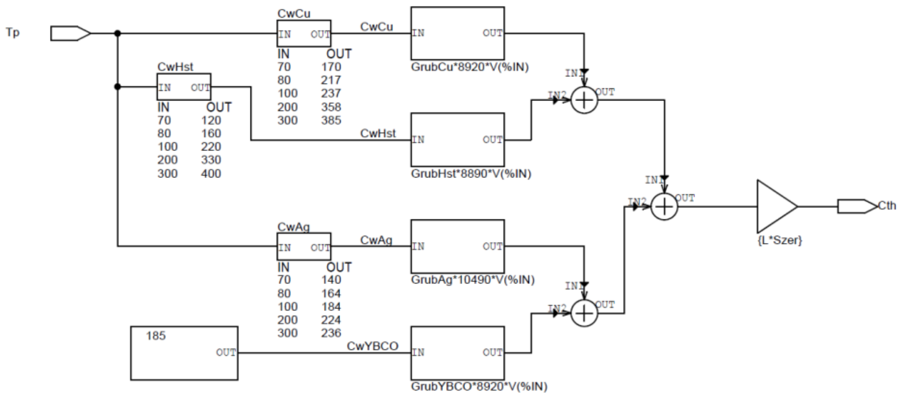

Fig. 8. Subcircuit calculating thermal capacity of 2G YBCO tape

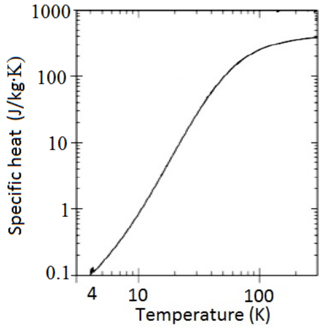

Fig. 9. Specific heat of copper vs. temperature (Matula, 1979)

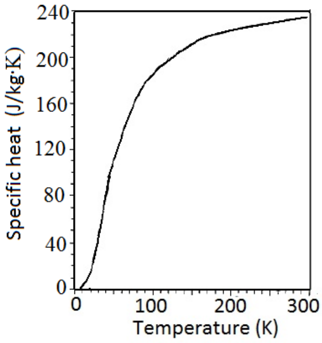

Fig. 10. Specific heat of silver vs. temperature (Smith & Fickett, 1995)

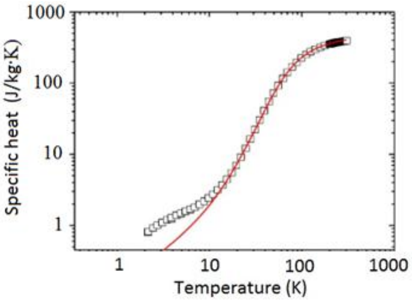

Fig. 11. Specific heat of Hastelloy vs. temperature (Lu, Choi, and Zhou, 2008)

Table 2. Material density of individual layers in the superconducting tape (Czerwinski et al., 2014)

Υ_{Cu}	8920 kg/m^3
Υ_{Ag}	10490 kg/m^3
Υ_{YBCO}	6300 kg/m^3
Υ_{HST}	8890 kg/m^3

3.4.2. The conductance of copper, silver, Hastelloy and YBCO layer

In this model the conductance of 2G YBCO tape is calculated using the hierarchical block G (Fig. 6). The calculations are based on the dependence in the resistivity ρ of copper and silver layers as a function of temperature, which are presented in Fig. 12 and Fig. 13. The resistivity for Hastelloy is of constant value and equals $1.24 \cdot 10^{-6}$ Ωm. The calculations also include the thickness of individual layers, as well as the length and the width of the superconducting tape. The developed conductance model of 2G YBCO tape was used for generating conductance waveforms of copper layer G_{Cu}, silver layer G_{Ag}, Hastelloy G_{HST} (Fig. 14).

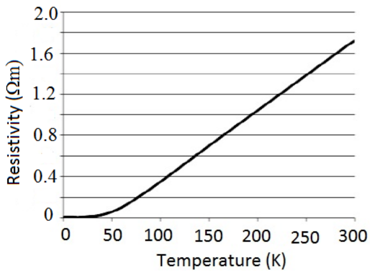

Fig. 12. Change of copper resistivity vs. temperature (Matula, 1979)

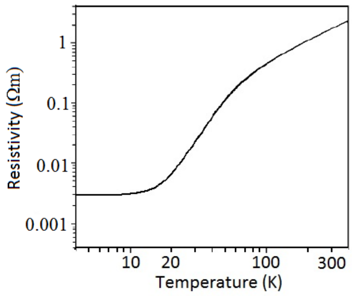

Fig. 13. Change of silver resistivity vs. temperature (Smith et al., 1995)

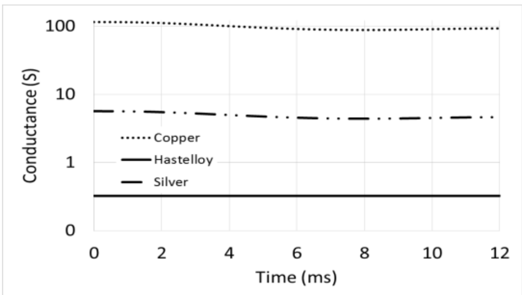

Fig. 14. Conductance waveforms of copper layer G_{Cu}, silver G_{Ag}, Hastelloy G_{HST} vs. time

Due to the large differences in conductance of individual layers in the superconducting tape, waveforms have been developed on a logarithmic scale. The values of conductance for copper layer G_{Cu}, silver layer G_{Ag} and Hastelloy G_{HST} are constant in the analysed time and have values respectively of 100 S, 8 S, 0.5 S.

Figure 15 presents the conductance waveforms of YBCO superconducting layer vs. time.

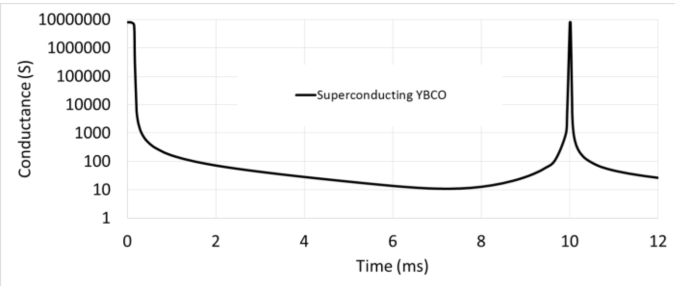

Fig. 15. Conductance waveforms of superconducting layer G_{YBCO}

The conductance of the superconducting layer G_{YBCO} reaches the maximum about 8 MS when the current in the circuit tends to zero.

3.4.3. The current of copper, silver, Hastelloy and YBCO layer

The controlled current source was used for each layer of the superconducting tape, which allowed to calculate the instantaneous current of individual layer. Figure 16 illustrates the initial current waveforms in the copper layer I_{Cu}, silver layer I_{Ag}, Hastelloy I_{HST}, YBCO I_{YBCO} and total current of superconducting tape I_{HTS}. Tape current I_{HTS} in a longer span is also depicted in Figure 17.

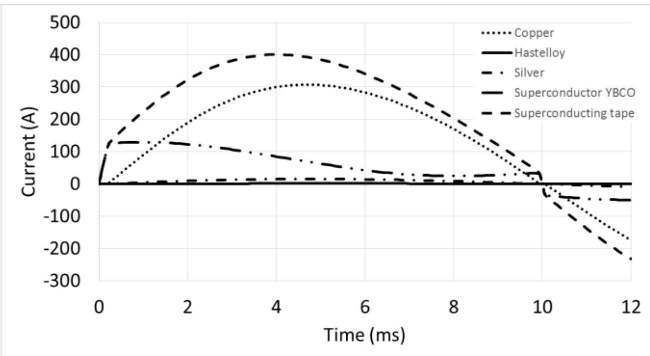

Fig. 16. Current waveforms in cooper layer I_{Cu}, silver I_{Ag}, Hastelloy I_{HST}, superconductor I_{YBCO} and the total current of superconducting tape I_{HTS} vs. time

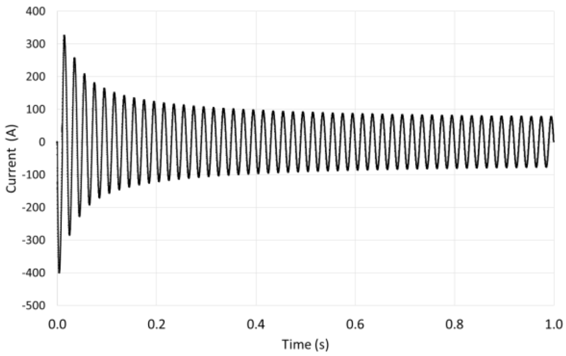

Fig. 17. Waveform of the total current of superconducting tape I_{HTS}

After setting the supply voltage in a period of time (0 – 0.2 ms) the current flows only through YBCO layer. The maximum of current I_{YBCO} is about 120 A and then, starts to decrease due to the fast heating of the tape. The copper layer allows for the flow of current I_{Cu} at the maximum 300 A. The peak current of superconducting tape I_{HTS} is 405 A. This value is reached in 4 ms. After 300 ms current I_{HTS} proceeds to the quasi-steady state, the amplitude is less than 100 A. The silver and Hastelloy layers conduct relatively small currents of about a few amperes.

3.4.4. Temperature, heating and cooling power of superconducting tape

Figure 18 presents a six-element table GeStCieLN with the values of heat flux density (W/m^2) passed to the liquid nitrogen vs. temperature difference ΔT. The table was based on the dependence of the heat flux density passing through the metal surface and the liquid nitrogen vs. temperature difference ΔT (Fig. 19).

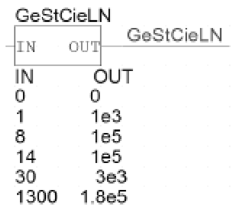

Fig. 18. Six-element table with heat flux density passed to the liquid nitrogen vs. temperature difference ΔT

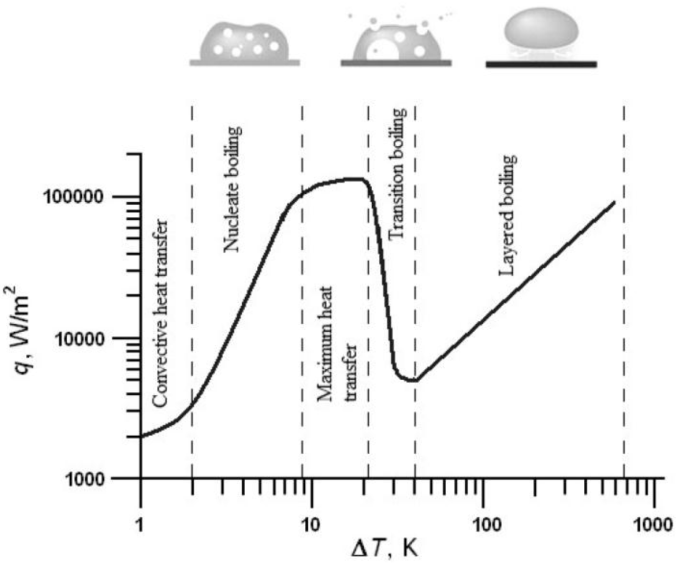

Fig. 19. Heat flux density passing between the metal surface and liquid nitrogen bath vs. temperature difference Δ*T* (Lu J. et al., 2008)

Figure 6 shows voltage blocks calculating change of temperature (ABM1) in relation to the temperature of liquid nitrogen, the cooling power (ABM2) and the heating power of superconducting tape (ABM3).

The change in temperature, cooling and heating power of superconducting tape vs. time are presented respectively in Fig. 20 and Fig. 21.

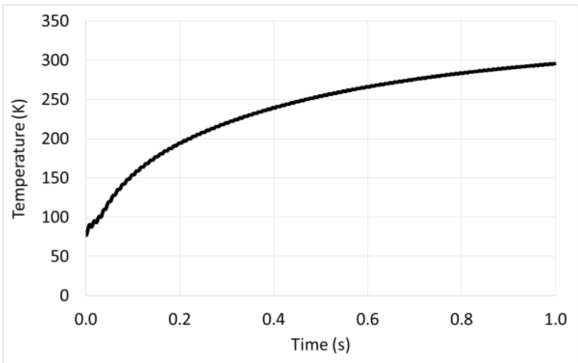

Fig. 20. Temperature of superconducting tape as a function of time

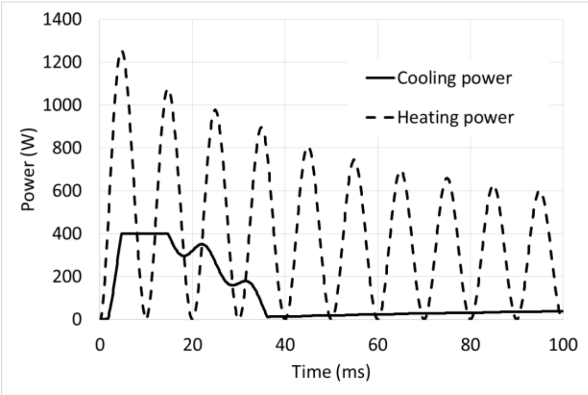

Fig. 21. Heating power and cooling power of the superconducting tape in a function of time

The temperature of superconducting tape increases and after 1 s it reaches the highest value $T = 293$ K. The maximum cooling power of the superconducting tape equals 400 W. The peak heating power of the tape is 1.45 kW, and during the experiment decreases to about 0.57 kW.

4. CONCLUSIONS

The rapid growth in information technology, the development of software and the computer calculations make the computer simulations one of The basic tools to examine and analyse the physical devices and phenonema.

PSpice program allows to design computer models of superconducting elements.

Blocks of the ABM (analogue behavioural modelling) in electronic circuit simulation enable to analyse the transients of the superconducting tape which is used in the windings of superconducting transformers.

Thanks to PSpice program and active user blocks of behavioural modelling, the electrical circuit simulation seems to be a reliable tool for the analysis of superconducting materials in transitional conditions.

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