Łukasz ADAMCZYK[1], Leszek JAROSZYŃSKI[1], Marcin KAFARSKI[2], Tadeusz JANOWSKI[3], Janusz KOZAK[3], Michał MAJKA[3]

Lublin University of Technology, Institute of Electrical Engineering & Electrotechnologies (1), The State School of Higher Education in Chełm (2), Electrotechnical Institute in Warsaw (3)

The analysis of the process of limiting the short circuit current by superconducting fault current limiters

***Abstract**. The unique features of 2G HTS conductors such as good fault current limiting performance, their superior electromechanical performance, as well as their availability in long-lengths and the low-cost manufacturing, constitute of basic advantages for superconducting fault current limiter (SFCL) applications. The authors of this paper have suggested circuit model of the SFCL made of 2G HTS tape. Numerical simulation has been performed using analog behavioral modeling (ABM) blocks in PSpice.*

Streszczenie.** Unikalne właściwości taśm nadprzewodnikowych 2G takie jak wysoka skuteczność ograniczania prądów zwarciowych, doskonałe właściwości elektromechaniczne jak również dostępność długich odcinków oraz niski koszt wytwarzania stanowią zalety dla zastosowań w nadprzewodnikowych ogranicznikach prądu. Autorzy w publikacji proponują model obwodowy NOP zbudowanego na bazie taśmy HTS 2G. Symulacja numeryczna została wykonana przy użyciu analogowych bloków modelowania behawioralnego w programie PSpice. **(Analiza procesu ograniczania prądów zwarciowych przez nadprzewodnikowe ograniczniki prądu).

Keywords: 2G HTS tape, PSpice, superconducting fault current limiter.
Słowa kluczowe: taśma nadprzewodnikowa drugiej generacji, PSpice, nadprzewodnikowy ogranicznik prądu.

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Introduction

The object of many research groups is to design, build and test a SFCL based on the second generation (2G) HTS tapes, which are now becoming available with suitable performances. Compared to the previous HTS materials, 2G tapes have higher current densities enabling more compact devices that provide lower operating costs. The SFCL is highly attractive for network operators, as it provides a method of dealing with the increasing incidence and severity of fault currents as well as it provides innovative planning of power grid.

During the stage of designing of superconducting fault current limiter, the circuit analysis program PSpice could be a helpful tool. The software contains a very large database of components used for the construction of electric and electronic circuits. For the preparation of the inductive limiter equivalent circuit both active and passive components can be used. Through the use of blocks of analogue behavioral modeling (ABM), there is an opportunity to build and simulate circuits that are made up of the particular layers of superconducting 2G tapes and consider associated thermal phenomena as well [1].

Operation of inductive type coreless SFCL made of 2G HTS tape

The inductive SFCL is simply constructed, it does not need the current leads – cooling costs are low. Nearly no impedance during normal operations plus quick and automatic recovery make SFCL attractive in power system.

During the normal operation resistance of primary winding and the leakage inductance determine the impedance of the limiter. Therefore SFCLs are normally designed to have very low leakage inductance. Current passing through the primary winding generates magnetic field. The primary and secondary coils are wrapped around carcass with a very good magnetic coupling. Alternating current in the primary coil provokes changes the magnetic flux. The changes provided in the magnetic flux induce the electromotive force in the secondary coil. The current in secondary winding may be regarded as opposite to the primary current. The magnetic field generated by the secondary winding compensates the magnetic field generated by the primary winding. As a result, the SFCL impedance is low [2, 3].

When the fault occurs, the increase of the primary current generates large magnetic field and sufficiently large secondary current which exceeds the critical value of the HTS tape. In the transition, the superconducting state of the secondary winding is lost and its resistance suddenly increases. Secondary current decreases and compensating field disappears. Reactance of the primary winding grows rapidly and thereby the device limits fault current. One of the advantages of inductive SFCL made of 2G HTS tape is that the reactive component of impedance can also be adjusted by the ratio of the primary and secondary winding inductances.

The presented solution of coreless construction (fig. 1) consists of one copper winding (wire cross-section 4 mm x 2 mm, innermost winding) and three Kapton insulated superconducting windings made of SuperPower® SF12050 2G HTS tape (outer windings). The 2G tape is 12 mm wide and 0.055 mm thick, thus, the tape connection to the copper terminal uses two 0.8 mm copper platter blocks. All windings were placed in a cryostat and immersed in liquid nitrogen.

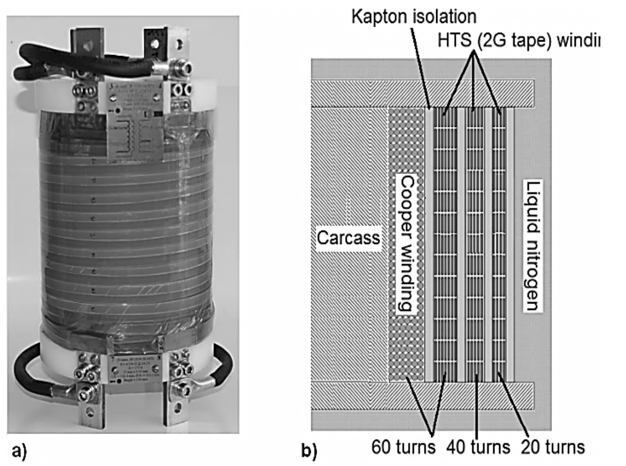

Fig. 1. Superconducting fault current limiter with the secondary windings made of SuperPower® SF12050 2G HTS tape (a) and the drawing of the SFCL cross-section (b)

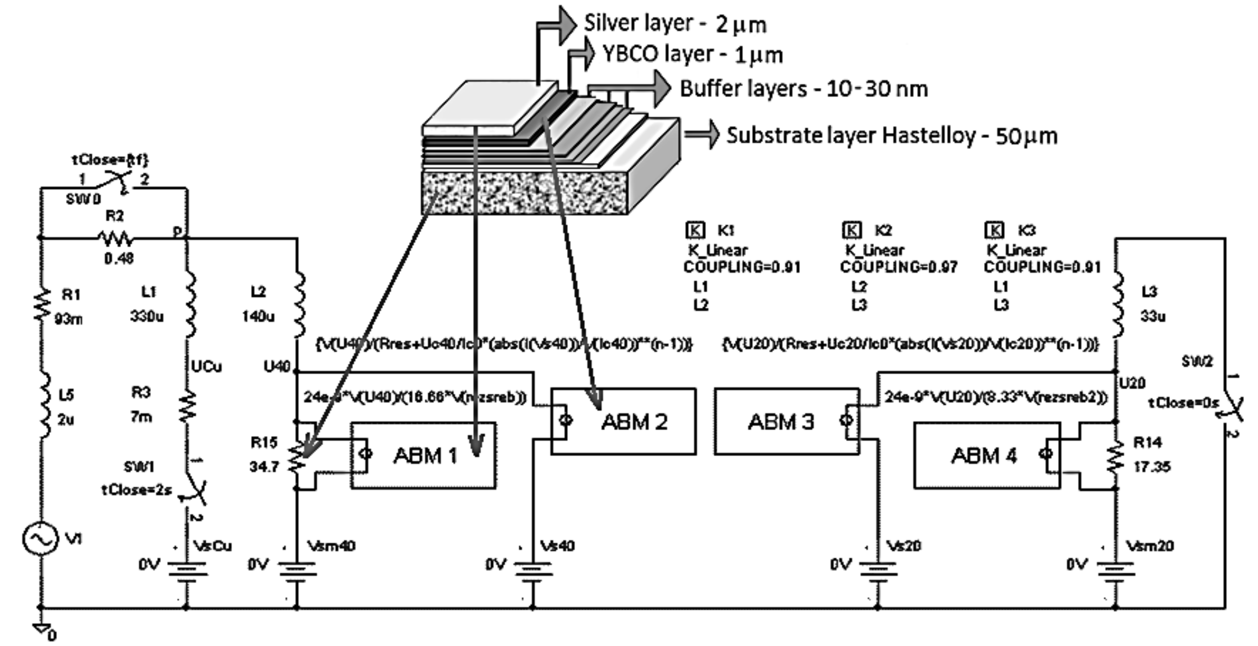

Fig. 2. Diagram of the simulation circuit

PSpice simulation model of the SFCL

The simulation scheme (fig. 2) of the inductive type of superconducting fault current limiter was built with passive and active components, as well as blocks of the voltage-controlled current sources (ABM), which can be defined by any user equation describing the voltage-current relation.

In particular, the diagram shows three SFCL windings (one cooper and two 2G HTS tape), especially the HTS windings are divided for layers (silver, Hastelloy, YBCO) through which the current flows. These layers play an important role with the view of heat transfer phenomena. Tape buffer layers are omitted because of their negligibly small thickness.

To describe the current I which flows through the superconducting YBCO layer during its transition from the superconducting to the resistive state, the ABM 2 block and the transformed equation (1) for the resistance R was derived from the power law [1]:

$$(1) \qquad R = R_C \left(\frac{I}{I_C} \right)^{n-1}$$

where: R_C – constant (critical resistance), I_C – HTS tape critical current, n – constant exponent.

The ABM 1 block was connected in parallel and used to describe the current I_{SL} which flows through the silver layer on the basis of the equation (2):

$$(2) \qquad I_{SL} = \frac{s_{SL} U}{\rho_{SL}(T) l_{SL}}$$

where: s_{SL} – cross-section area of silver layer, U – voltage, $\rho(T)_{SL}$ – resistivity of silver as a function of temperature, l_{SL} – length of silver layer.

The resistivity changes depend on the temperature using the characteristics for the material [4] introduced to the block TABLE 2 (fig. 5a) in the form of the chart. For the last layer (Hastelloy) taken into consideration in the schema, the constant resistance (resistors R_{14} and R_{15}) on the basis of the characteristics showing very small changes in resistivity as a function of temperature was adopted [5]. For each of the three layers taken into account, the suitable for each winding lengths, cross-sections and the masses of the HTS tape were introduced. Other components in the electrical circuit (fig. 2) describe the electrical parameters of the power supply system including the winding inductance measured in the laboratory tests.

To analyze the thermal phenomena in the investigated limiter, the diagram showing the heat balance for a single element generating the heat should be built (fig. 3).

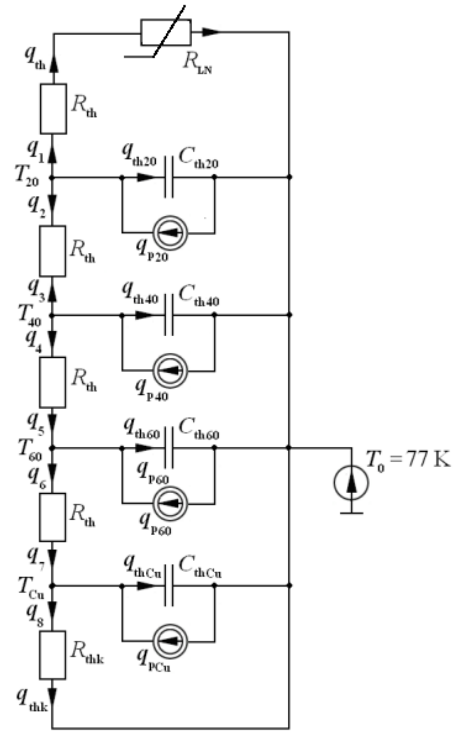

Fig. 3. Equivalent circuit of thermal phenomena in SFCL

The main part of this scheme is the source that generates the heat flux q_p. The thermal energy generated from this source is accumulated in the heat capacity C_{th} and simultaneously it is transferred to ambient. The winding will get the two ways of the thermal conduction, as well as the two thermal resistances R_{th}, in a situation, if the winding is placed with the layer of the insulating material (for instance Kapton). After the integration and addition of the initial temperature T_0 (77 K), the equation for the temperature of a single winding is obtained:

$$T = \int \frac{1}{C_{th}} \left(\frac{T_1 - T}{R_{th1}} - \frac{T - T_2}{R_{th2}} + q_p \right) dt + T_0 \qquad (3)$$

where: C_{th} – heat capacity, q_p – heat flux generated by current flow, R_{th1} R_{th2} – thermal resistances, T_0 – initial temperature (77 K).

Figure 4 shows the courses of the changes of the temperatures in the individual windings of the investigated model of the inductive fault current limiter. The primary winding reaches its maximum temperature, and its maximum oscillation which is related to the course of the instantaneous power. Lower values of the instantaneous power and the direct contact of the secondary winding with the cooling liquid causes lower oscillations of the temperature.

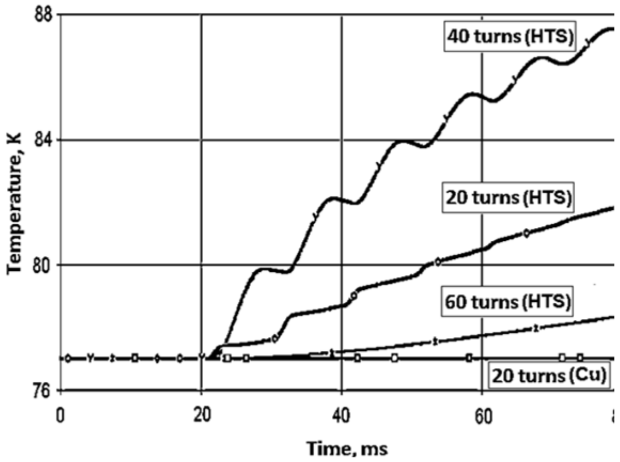

Fig. 4. Courses of temperature changes in the windings

The increases of the temperatures in the subsequent windings approximately, have linear waveform due to the limited diffusivity and thermal inertness of the system. Disconnected superconducting winding HTS 60 accumulates heat (from the winding HTS 40) in its heat capacity. Copper winding connected as a bypass heats about 0.5 K. With the increase of the temperature, the specific heat of the materials also changes. In the final heat balance, the heat transfer to the coolant should also be taken into account. The overall heat balance, which occurs during the heating particular active coils and the mutual exchange of heat between them, the heat flux is got and transferred by the superconducting winding insulation in contact with liquid nitrogen.

$$\frac{T_{20} - T_p}{R_{th}} = q_{LN} A \qquad (4)$$

where: T_p – the temperature at the boundary of Kapton-liquid nitrogen centers, q_{LN} – heat flux passing through the insulation and reaching the boundary (Kapton – liquid nitrogen), R_{th} – thermal resistance, A – area of the heat exchange.

At this point, the heat flux is transferred into liquid nitrogen however, this process occurs at a variable intensity. The reason for this are physical phenomena relying on the change of the heat flux density which is transferred into the liquid nitrogen, according to the temperature differences between the cooling area and the liquid as well (the characteristics of this phenomena has been described in TABLE 7) – fig. 5b. In fact, in the presented equivalent scheme it can be assumed some replacement non-linear thermal resistance associated with the incidence of this phenomena (fig. 5b).

The diagram of the thermal model in the PSpice can be achieved by using controlled voltage sources. This element enables notation of every equation which describes the investigated system and any mathematical operations which were carried out on that system suitable with the specificity of the phenomena. The ABM blocks can be distinguished, as a controlled voltage and current sources which may play a key role in the electrical circuits which parameters are associated with other physical phenomenon described as derivatives of electrical phenomena (e.g. thermal power generated during the current flow).

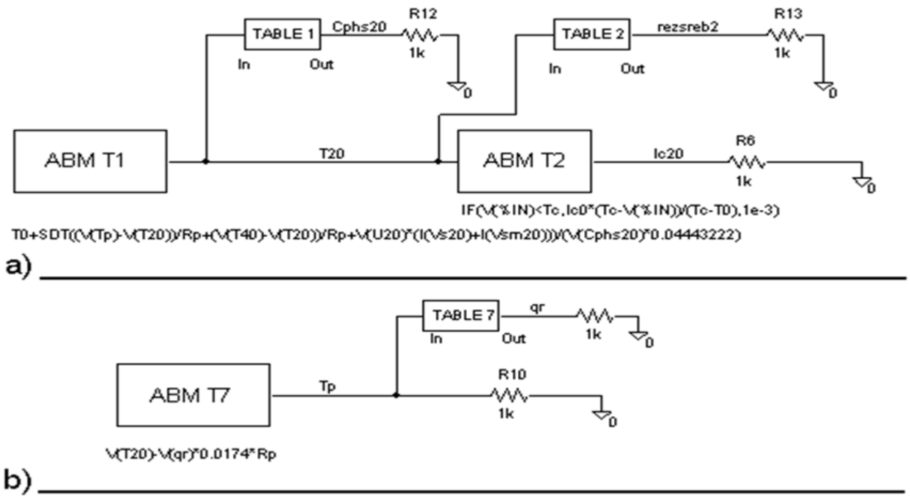

Fig. 5. Diagram of thermal model simulation: a) similar scheme was used for each winding, b) heat transfer into liquid nitrogen

For instance, the thermal module describing the temperature changes in the winding HTS 20 is analyzed by means of a controlled voltage source ABM T1 (fig. 5a). On the basis of heat balance equation (3) another equation was written for this winding. The simulating circuit calculates the current temperature based on the changes in heat capacity (corresponding characteristics were described in the form of the chart in TABLE 1) which is also calculated for the thickest layer of Hastelloy. Using the readout of the actual temperature the program also calculates the change in the resistivity of the silver layer during the heating of this material in the HTS tape. The temperature dependence of the resistivity was described in the form of the chart and entered into the program in TABLE 2.

The simulation circuit also includes the phenomena of reducing the critical current in the superconducting layers in HTS tape under the influence of rising temperature. In accordance with the well-known formula the block of ABM T2 influences the changes of the critical current I_C for the temperature of the superconducting wire:

$$I_C(T) = I_{C0} \frac{T_C - T}{T_C - T_0} \tag{5}$$

where: T_C – critical temperature, T – actual temperature, I_{C0} – critical current at temperature T_0.

Test results and discussion

Comparing two very similar waveforms – laboratory and simulation (fig. 6) two relevant conclusions can be drawn.

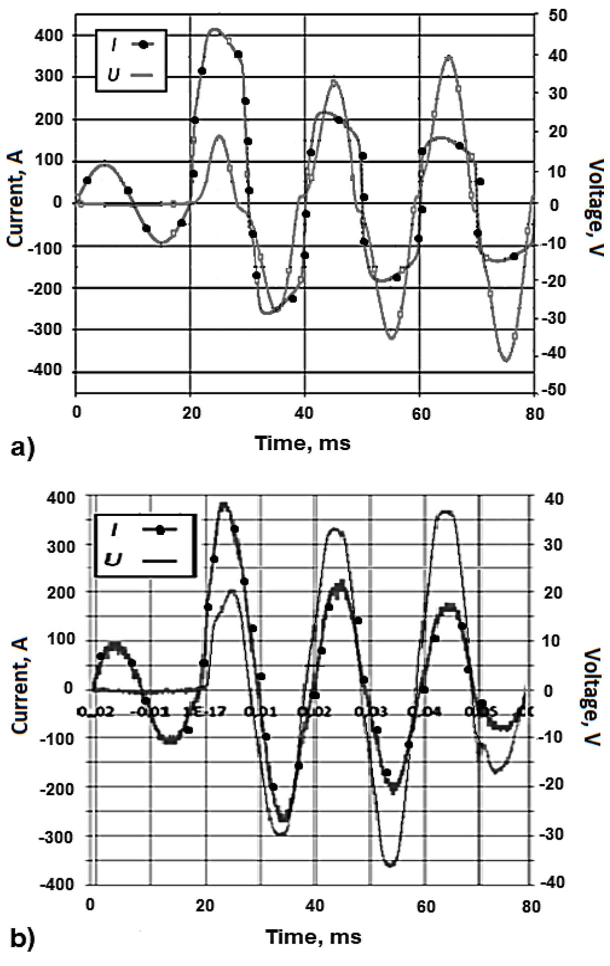

Fig. 6. SFCL current and voltage waveforms (a – simulation, b – laboratory test)

First and foremost, the simulating circuit reflects the character of the superconducting limiter with regard to thermal phenomena, simultaneously excluding any noticeable influence of the magnetic field on the superconducting tape. Secondly, the differences in amplitudes in the subsequent half-periods of the current waveforms (not more than a few percent) can be explained by the effect of internal resistance instability of the power supply, as well as inhomogeneity of HTS tape.

The PSpice allows to view all the waveforms of electric quantities at any node in the simulation circuit and to perform any mathematical operation on the recorded waveforms. The simulated temperature of each of the windings can be also analyzed.

Conclusions

Simulations carried out in the program for the circuit analysis of PSpice are giving satisfactory results. Assuming that the superconducting wire is homogeneous and there is no local magnetic field intensity large enough to affect the tape stability, a method to a general analysis of this type of limiter construction can be adopted.

The advantage of this technique is the ability to simulate any type of the fault current limiter together with the equivalent circuit of the power network in which it could work.

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***Authors**: Łukasz Adamczyk (MSc, Eng), E-mail:lukasz7744@o2.pl, Leszek Jaroszyński (PhD, Eng), E-mail: l.jaroszynski@pollub.pl Lublin University of Technology, Institute of Electrical Engineering and Electrotechnologies, Nadbystrzycka 38A, 20-618 Lublin, Poland, Marcin Kafarski (PhD, Eng), E-mail: marcin24@pronet.lublin.pl, The State School of Higher Education in Chełm, Tadeusz Janowski (Professor), E-mail: t.janowski@iel.waw.pl, Janusz Kozak (PhD, Eng), E-mail: j.kozak@iel.waw.pl, Michał Majka (PhD, Eng), E-mail: m.majka@iel.waw.pl, Electrotechnical Institute in Warsaw, Pożaryskiego 28, 04-703 Warsaw.*