Experimental and Numerical Analysis of Energy Losses in Resistive SFCL

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***Abstract*— The resistive SFCL (superconducting fault current limiter) is a superconducting device which may operate both in superconducting state and in normal conducting (resistive) state. The paper presents FEM numerical model (in FLUX2D) of resistive SFCL made using Bi-2212 bifilar coil (NEXANS) cooled by pool boiling cooling technique (liquid nitrogen, 77 K). Real geometry of resistive SFCL is replaced by equivalent, due to energy and current density, geometry of numerical model. The electro-thermal numerical model of resistive SFCL can be used to estimate the energy and maximum temperature in limiter and the time to switch off the current to protect against damage.**

***Index Terms*— superconducting fault current limiter, resistive SFCL, numerical modeling.**

I. Introduction

The superconducting fault current limiters (SFCL) can be used to limit short-circuit current levels in electrical circuits. The SFCL co-operates with the breaker which should switch off the fault current in circuit. In the resistive SFCL, the superconductor is inserted in the circuit directly. The resistive SFCL operates in the superconducting state when the current in the protected circuit doesn't reach rated value and doesn't add a resistance to the circuit. During a fault in the protected circuit the fault current pushs SFCL into normal conducting state and the resistance appears in protected circuit. The current flowing through the resistive SFCL almost does not generate heat when the limiter is in superconducting state but it generates plenty of heat after superconducting transition when the limiter is in resistive state. When the limiter is in resistive state, it is very important not to overheat the device and to keep very short time to come back to the superconducting state after switch off the current by breaker. The electro-thermal numerical model of resistive SFCL can be used to estimate the energy generated by limiter after fault in external circuit and to calculate maximum temperature in limiter and the time to switch off the current by breaker in external circuit which protects the limiter against damage.

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Fig. 1. Superconducting elements of resistive SFCL:
1 – Bi-2212 bifilar coil - C02-034 (NEXANS),
2 – Bi-2223 current leads - CSL-120-L (CAN Superconductors).

II. Resistive SFCL

Superconducting elements of resistive SFCL are presented in Fig. 1. Cryogenics part of resistive SFCL consists of two superconducting current leads (CAN Superconductors CSL-120-L) and superconducting bifilar coil (C02-034 - NEXANS). In C02-034 bifilar coil, the HTS (Bi-2212) material has a metallic shunt as the electrical bypass. In superconducting state, the HTS material has a very small resistivity in comparison to the metallic shunt (Fig. 2) and the current flows mostly through the HTS material. In resistive state the HTS material has much higher resistivity in comparison to metallic shunt and the current is pushed from the HTS material to the shunt. The nominal current of C02-034 bifilar coil = 50 A, and self-field critical current (1 μV/cm) at 77 K = 125 A. We measured it as 112 A (1 μV/cm) and as 138 A (5 μV/cm). The length of superconductor = 5.4 m. Resistance of C02-034 bifilar coil in resistive state at 77 K equals 0.875 Ω. The resistive SFCL is cooled by pool boiling technique using liquid nitrogen (77 K). Fig. 3 presents heat transfer ΔQ from a metal surface to liquid nitrogen (lN_2) at 77 K vs. temperature difference ΔT between surface and lN_2 [2],[1]. For ΔT above 27 K, the surface is blanketed by vapor film giving a small transfer coefficient (film boiling). For ΔT

between 12 K and

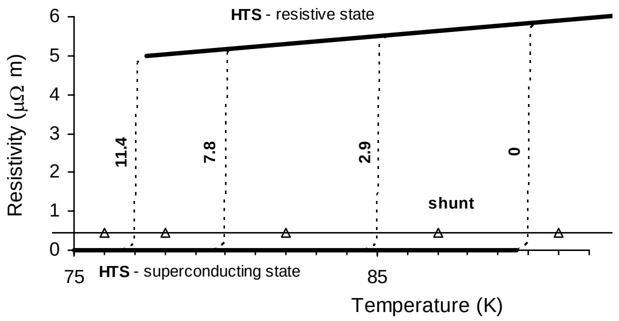

Fig. 2. Resistivity of shunt and HTS [1] vs. temperature for different current density (A/mm^2).

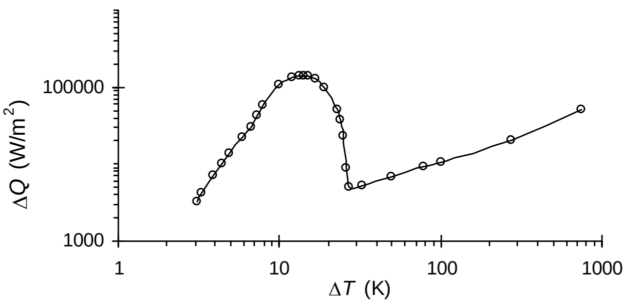

Fig. 3. Heat transfer ΔQ from a metal surface to lN_2 at 77 K vs. ΔT between surface and lN_2 under normal atmospheric pressure [2], [1].

27 K the transition, having a negative slope, is unstable. If heat generated in limiter is so small that temperature rises by no more than 12 K, full advantage may be taken of the nuclear boiling transfer. It takes place either when the resistive SFCL is in superconducting state or for a very short time in resistive state [1].

III. Numerical Model

A magnetodynamic application [3] of FLUX2D connected to external circuit (FEM-circuit) was used to analyze the magnetic field distribution in superconductor in resistive SFCL. This analysis has shown that (as expected) the superconducting material in that resistive SFCL can be treated as influenced by self-magnetic field only [1]. The magnetodynamic application of FLUX2D can not be automatically coupled with thermal application [3]. The numerical calculations for resistive SFCL presented in the paper are made using an electro-thermal application (FEM) of FLUX2D, which is the coupling of an electric conduction problem with a transient thermal problem [3].

A. Geometry of Numerical Model

Real geometry of resistive SFCL in a shape of bifilar coil (Fig. 1) is replaced by (equivalent due to energy and current density) geometry of numerical model shown in Fig. 4. Recalculating ratio depending on geometry of limiter equals 0.0164 for current and equals 60.95 for voltage [1]. The numerical model consists of 6 calculation objects (Fig. 4): the

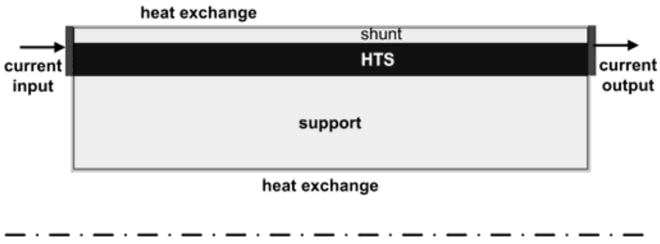

Fig. 4. Simplified geometry of FEM numerical model of resistive SFCL in electro-thermal application of FLUX2D [1].

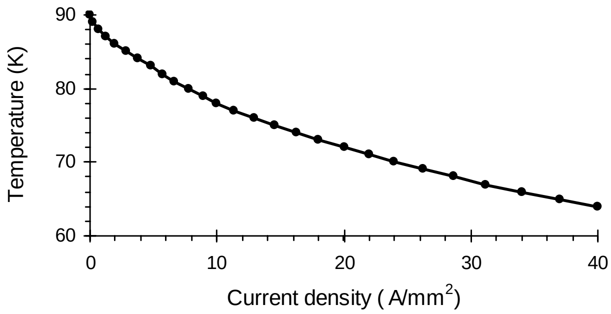

Fig. 5. Critical temperature of Bi-2212 bifilar coil vs. current density (self magnetic field) [7]-[9], [1].

current input and output represented by shell [3] regions, the heat exchange between limiter and lN_2 represented by shell region and the support, the HTS and the electric shunt represented by surfacic [3] regions.

The shell regions are defined on the boundary domain [3]. The shell regions are very specific regions, which have a special function according to the applications. In electric part of solving problem the shell regions are used to define current going in and out the limiter. The current flows between shell regions through surfacic regions “HTS” and “shunt”.

In the thermal part the shell region is used to define a thermal flux transfer. The heat generated in the limiter by current is transferred to lN_2 by shell region “heat exchange”.

B. Properties of Domains of Numerical Model

The thermal conductivity, the electrical resistivity and the specific heat are defined for regions “HTS” and “shunt”. The thermal flux to the outside is defined for shell region “heat exchange”. The region “support” doesn’t conduct electric current and is defined only by thermal parameters: the thermal conductivity and the specific heat [1], [4]-[10].

The resistivity of “HTS” and thermal flux through “heat exchange” to the outside depend on temperature. These dependences are too advanced and can not be defined by standard models of properties and sources of FLUX2D. The user subroutines USRSIG and USRPWD [1], [3] and FORTRAN programming are required. The electric resistivity of superconductor is a function of temperature, magnetic field and current and it changes its value almost immediately during superconducting transition. By defining fixed current in the SFCL instead of voltage boundary conditions on the ends of the limiter, the “HTS” region resistivity dependence on current density, magnetic field and temperature is reduced to temperature dependence only (assuming self-magnetic field only). Every change of current in SFCL needs a modification of parameter of USRSIG subroutine. Fig. 2 presents resistivity of "HTS" region vs. temperature for different current density. A 3-variables (temperature, current density, magnetic field) function defining resistivity of superconductor is replaced here by the 1-variable (temperature) function with a parameter (current density). The value of temperature at which HTS has superconducting transition is calculated in USRSIG basing on function presented in Fig. 5 and the parameter of USRSIG (current density) [1]. USRPWD subroutine defines heat transfer through "heat exchange" shell region to coolant and has values as shown in Fig. 3.

IV. Results

The temperature and the voltage in limiter should either rise very slowly (or don't rise) when limiter is in superconducting state, or rise very fast when limiter is in resistive state. Fig. 6 and Fig. 7 present maximum temperature and voltage in limiter vs. time for different related current density $J/J_{c\,77\,K}$ in limiter, where $J_{c\,77\,K}$ is a critical current density of limiter at temperature equals 77 K and under self magnetic field. They show that for $J/J_{c\,77\,K}$ between 93 % and 96.5 % the limiter can work improperly because the temperature and voltage start to rise after significant delay. This effect was observed during measurement of static *V-I* characteristic of physical model of resistive SFCL for higher values of $J/J_{c\,77\,K}$. For $J/J_{c\,77\,K}$ = 140 % we noticed delay in start of voltage rise higher than 2 s. The fact that this effect appears for higher than computed value of current we explain by significant variety of area cross section along bifilar coil. Measured [9] difference between maximum and minimum critical current for each individual turn of bifilar coil is near 16 %. We measured then the width of one turn of our bifilar coil is between 2.1 mm and 3.4 mm so we should expected the difference between maximum and minimum critical current in the individual turns near 62 % in C02-034 bifilar coil. It was, in our opinion, the main reason of damage of our limiter in well protected measurement arrangement. For the current near $I/I_{c\,77\,K}$ = 140 % ($I_{c\,77\,K}$ critical current at 77 K and self-magnetic field of C02-034 bifilar coil – due to NEXANS) there was no voltage on limiter and no significant evaporation of nitrogen. The current just burned one turn of coil without pushing the limiter into resistive state. Fig. 8 presents energy transferred to lN_2 vs. time for different $J/J_{c\,77\,K}$. It shows that the heat transferred to the coolant is significant and cannot be neglected as in [11]. Fig. 8 shows that the volume of evaporated nitrogen in limiter (proportional to energy transferred to lN_2) is not proportional to the current in limiter. As Fig. 9 and Fig. 10 show, the measurement of this parameter does not give proper information of overheating of limiter. Maximum temperature rises but volume of evaporated nitrogen falls for specific values of $J/J_{c\,77\,K}$. It can be explained by much smaller coefficient due to film boiling in comparison to high heat

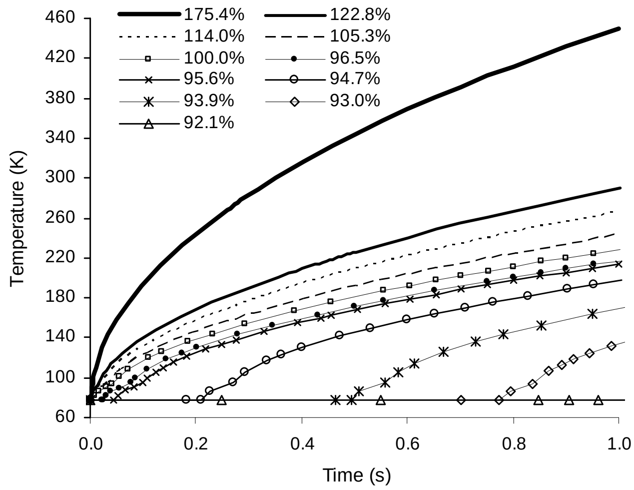

Fig. 6. Maximum temperature in limiter vs. time for different $J/J_{c\,77\,K}$.

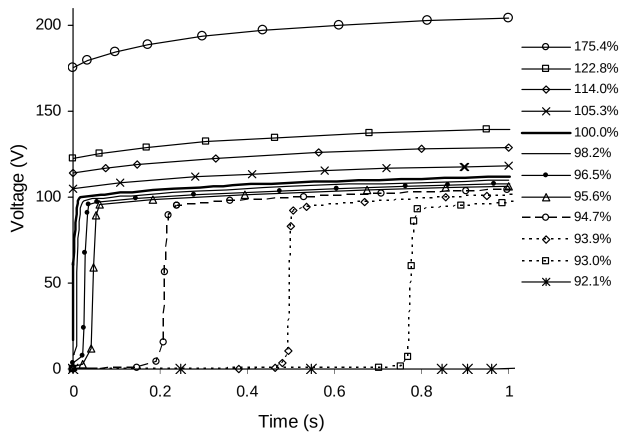

Fig. 7. Voltage in limiter vs. time for different $J/J_{c\,77\,K}$.

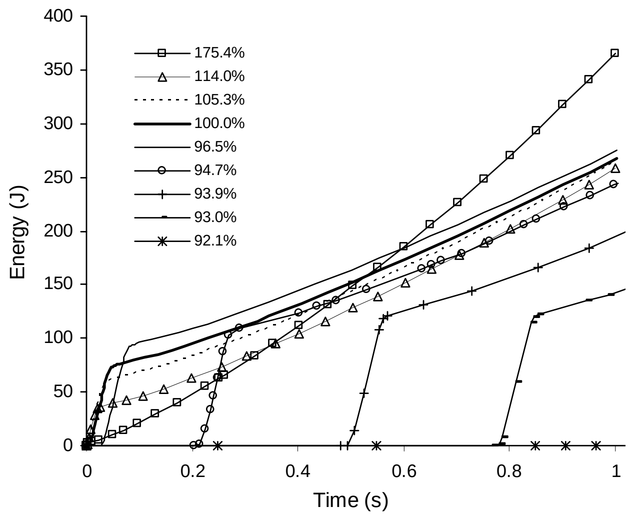

Fig. 8. Energy transferred to lN_2 vs. time for different $J/J_{c\,77\,K}$.

transfer coefficient due to nuclear boiling when ΔT between limiter and lN_2 rises above 12 K. The surface of limiter is blanketed by vapor film and much more of energy dissipated in limiter heats limiter than is transferred to lN_2.

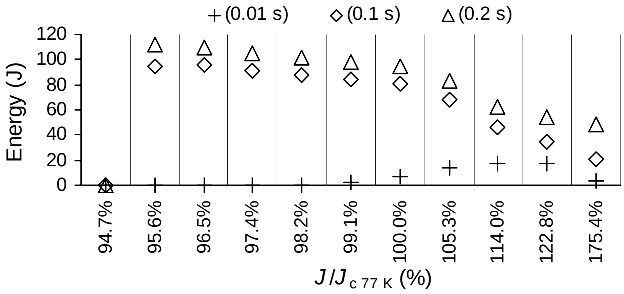

Fig. 9. Energy transferred to lN_2 for different $J/J_{c\ 77\ K}$ and time.

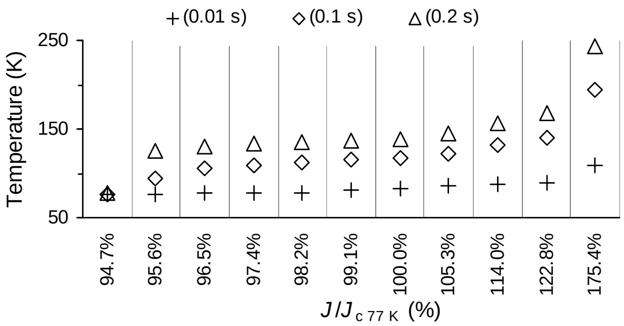

Fig. 10. Maximum temperature for different $J/J_{c\ 77\ K}$ and time.

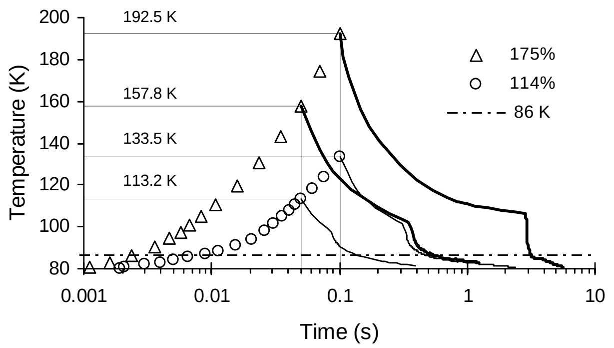

Fig. 11. Temperature vs. time for different $J/J_{c\ 77\ K}$ and for different time to switch off the current by breaker.

This dangerous effect was observed during experiments with physical model of resistive SFCL.

The NEXANS doesn't give any information about dangerous level of temperature for the bifilar coil so we present what will happen in limiter when current is switched off after 0.05 s and 0.1 s (after the fault). Fig 11 shows the differences in maximum temperature and in time of reactivation of limiter switched off by breaker after 0.05 s and 0.1 s for $J/J_{c\ 77\ K}$ equals 114 % and 175 %. The temperature rises to 157.8 K and 192.5 K when current ($J/J_{c\ 77\ K}$ = 175 %) is switched off after 0.05 s and 0.1 s. For $J/J_{c\ 77\ K}$ = 114 % the temperature rises to 113.2 K and 133.5 K respectively. It is assumed that the rated current can be switched on again, when temperature in limiter falls below 86 K ($I_{c\ 86\ K}$ = rated current). So the time of reactivation equals 0.14 s for $J/J_{c\ 77\ K}$ = 114 % when current is switched off after 0.05 s. It rises to 0.5 s when current is switched off after 0.1 s. The time of reactivation equals 0.57 s for $J/J_{c\ 77\ K}$ = 175 % when current is switched off after 0.05 s. It rises to 3.19 s when current is switched off after 0.1 s (Fig. 11).

V. Conclusion

FEM numerical model of resistive SFCL is made using electro-thermal module of FLUX2D which is the coupling of electric conduction module with transient thermal module.

For the specific range of current value the limiter can work improperly because the temperature and voltage rise with significant delay.

The volume of evaporated nitrogen in limiter is not proportional to the current in limiter and measurement of this parameter does not give proper information of overheating of limiter.

The time to switch off the current by the breaker should be below 0.05 s not to overheat the limiter and to keep short time of reactivation.

Our limiter seems not to be completely destroyed and we hope that we will be able to repair it by shorting damaged turns.

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