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Numerical model of superconducting fault current limiter

Abstract*. The paper presents numerical model (in FLUX2D) of resistive SFCL (Superconducting Fault Current Limiter) made using Bi-2212 bifilar coil (NEXANS) cooled by pool boiling cooling technique (liquid nitrogen 77 K). The USER SUBROUTINES of FLUX2D were used to define advanced temperature and current density relations of physical properties of calculated regions and thermal flux to liquid nitrogen.*

Streszczenie. *Przedstawiono model numeryczny (w FLUX2D) nadprzewodnikowego ogranicznika prądu typu rezystancyjnego. Ogranicznik ten w postaci cewki bifilarnej z nadprzewodnika Bi-2212 chłodzony jest techniką w kąpieli ciekłego azotu (77 K). Do zdefiniowania skomplikowanych zależności właściwości obszarów obliczeniowych i strumienia ciepła w funkcji temperatury i gęstości prądu wykorzystane zostały procedury użytkownika programy FLUX2D (Model numeryczny nadprzewodnikowego ogranicznika prądu) .*

Key words: resistive SFCL, numerical model, FLUX2D, USER SUBROUTINES, electro-thermal coupling problem.

Słowa kluczowe: nadprzewodnikowy ogranicznik prądu typu rezystancyjnego, model numeryczny, FLUX2D, procedury użytkownika, elektro-termiczne zagadnienie sprzężone.

Introduction

Short-circuit current level will be 20 times larger than the rated current [1], [2]. All electrical equipment exposed to the short-circuit current must be designed to withstand in particular the mechanical forces under fault conditions, which are generally proportional to the square of current. The superconducting fault current limiters (SFCL) can be used to limit the short-circuit current level in electrical transmission and distribution networks to 5 times of rated current level [1] [3]. These fault current limiters, unlike reactors or high-impedance transformers, will limit fault current without adding impedance to the circuit during normal operation [4]. In one concept of SFCL – serial resistive limiter, the superconductor is inserted in the circuit directly. During a fault, the fault current pushes the superconductor into a resistive state and resistance, which limits the fault current, appears in the circuit. The resistive SFCL co-operates with the breaker which should switch off the limited current in circuit.

The resistive SFCL is a superconducting device which operates as well in superconducting state as in normal conducting (resistive) state. The resistive SFCL almost does not generate heat in superconducting state but it generates plenty of heat after superconducting transition when it is in resistive state. Thermal phenomena are very important in all superconducting devices. Cooling down to the working temperature and keeping the temperature on adequate low level by good thermal insulation and good cooling conditions decide on superconducting state of device. In normal conducting (resistive) state of limiter 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 maximal temperature in limiter and the time to switch off the current by breaker in external circuit which protects the limiter against damage.

Resistive SFCL

Superconducting elements of resistive SFCL are presented in Fig. 1. Cryogenics part of resistive SFCL consists of two superconducting current leads (CSL-120-L-CAN Superconductors)[5] and superconducting bifilar coil (C02-034 -NEXANS). The superconducting current lead consists of Bi-2223 tube encapsulated in Cu-Ni casing to be protected against damage [5]. The ends of the lead are extended by flat cooper cable and Cu/Nb-Ti wire. The nominal current of this current lead = 120 A, and self-field

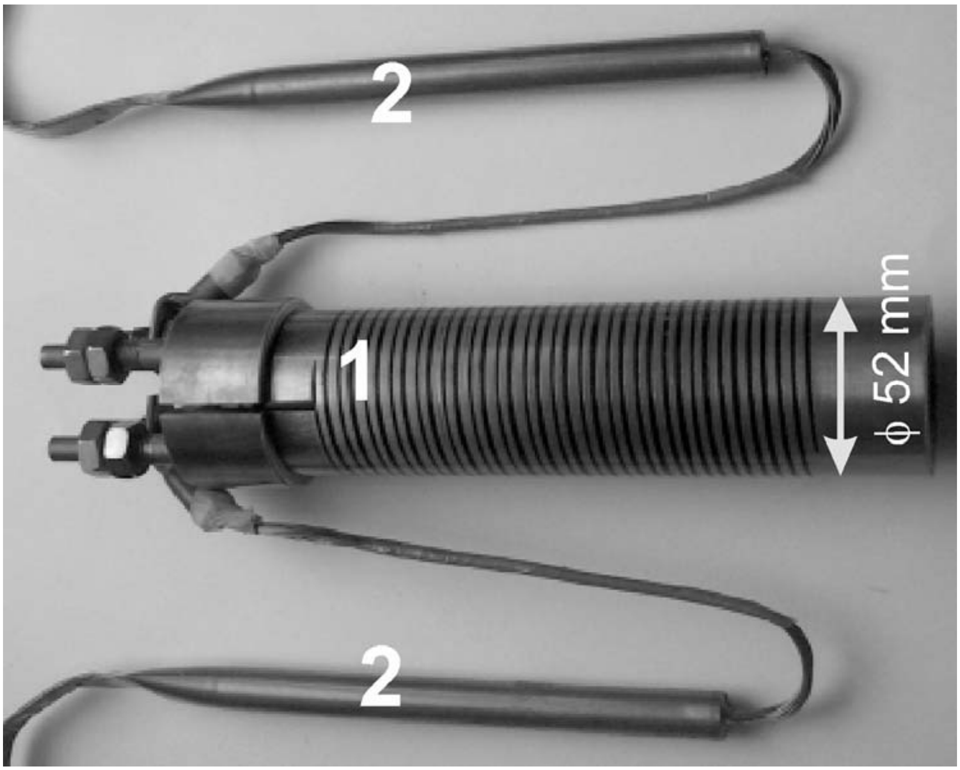

Fig. 1. Superconducting elements of resistive SFCL: 1 – Bi-2212 bifilar coil - C02-034 (NEXANS), 2 – Bi-2223 current leads - CSL-120-L (CAN Superconductors)[5]

critical current at 77 K = 250 A. The length of Cu-Ni casing = 0.3 m and diameter = 0.015 m.

In C02-034 bifilar coil, the HTS (Bi-2212) material have metallic shunt as electrical bypass. In superconducting state, the HTS material have very small resistivity in comparison to metallic shunt and the current flow mostly through the HTS material. In normal conducting (resistive) state the HTS material have 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 at 77 K = 125 A. The length of superconductor = 5.4 m and area cross-section = 7.5 10^{-6} m^2. Resistance in resistive state at 77 K = 0.875 Ω.

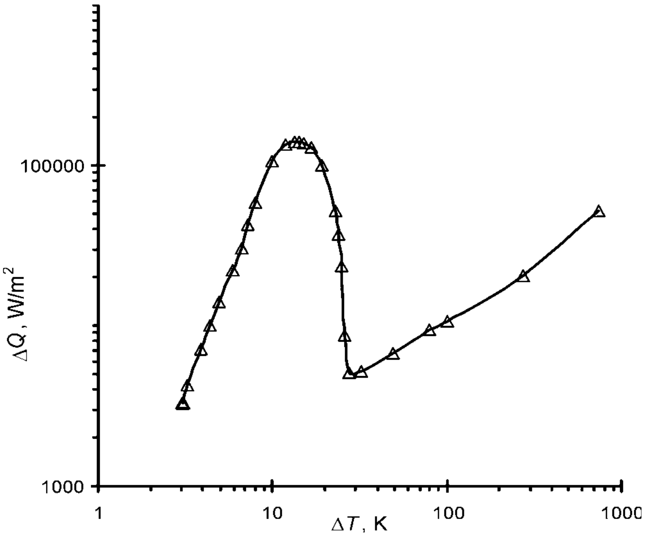

Fig. 2. Heat transfer ΔQ from a metal surface to liquid nitrogen at 77 K vs. temperature difference ΔT between surface and liquid nitrogen under normal atmospheric pressure [6]

The resistive SFCL is cooled by pool boiling technique using liquid nitrogen (77 K). Fig. 2 presents heat transfer ΔQ from a metal surface to liquid nitrogen at 77 K vs. temperature difference between surface and liquid nitrogen. For ΔT in the range between 0 K and about 12 K liquid nitrogen remains in contact with the surface giving a high heat transfer coefficient (nuclear boiling). For ΔT above 27 K the surface is blanketed by vapour film giving a small transfer coefficient (film boiling). For ΔT between 12 K and 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.

Electro-thermal numerical model

A magnetodynamic application of FLUX2D [7] 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. Simplified geometry of bifilar coil of numerical model in magnetodynamic application of FLUX2D is presented in Fig. 3. The magnetodynamic application of FLUX2D can not be automatically coupled with thermal application so another application was needed for thermal computation of resistive SFCL.

An electro-thermal application of FLUX2D, which is the coupling of an electric conduction problem with a transient thermal problem [7], was used for calculations of temperature, voltage and energy in resistive SFCL during time.

In electric part of solving problem the voltage U is the variable and the following equation is computed [7]:

$$\mathrm{div}(\sigma \cdot \mathrm{grad}\, U) = 0 \tag{1}$$

where: σ - resistivity ($\Omega^{-1}m^{-1}$), U - voltage (V).

In thermal part of solving problem the temperature T is the variable and the following equation is computed [7]:

$$c_{\mathrm{v}} \cdot \frac{\partial T}{\partial t} + \mathrm{div}(-k \cdot \mathrm{grad}\, T) = Q_{\mathrm{H}} \tag{2}$$

where: c_v – specific heat (J $m^{-3}K^{-1}$), T - temperature (K), t - time (s), k – thermal conductivity (W $m^{-1}K^{-1}$), Q_H – density of heat source (W/m^3).

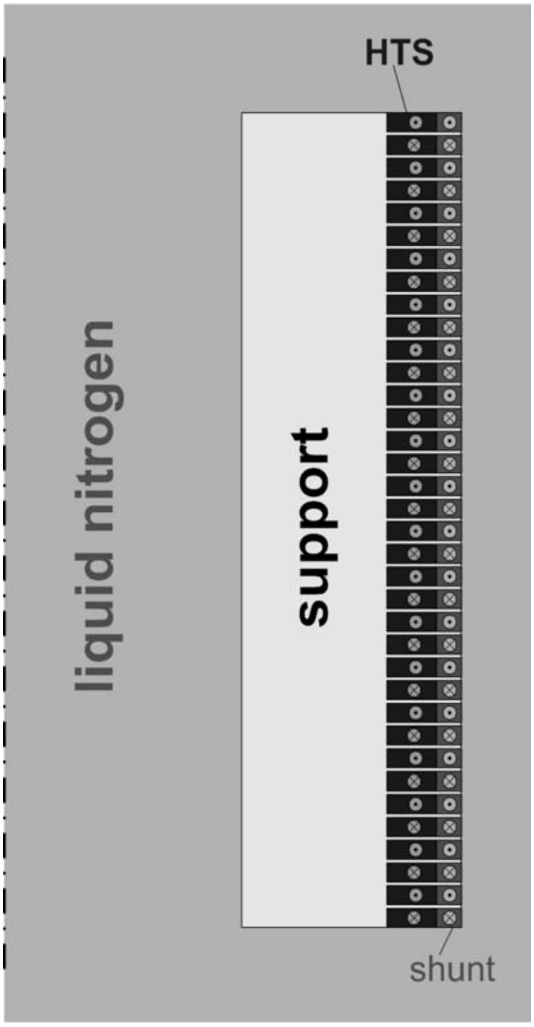

Fig. 3. Simplified geometry of bifilar coil of numerical model in magnetodynamic application of FLUX2D

Table 1. Physical to numerical model computation ratio

name	function	value
energy ratio E/E_1	1	1
current density ratio j/j_1	1	1
resistance ratio R/R_1	$(\pi\,(2r+\Delta r)/\,\Delta z\,)^2$	3714.54
current ratio i/i_1	$\Delta z\,/\,(\pi\,(2r+\Delta r))$	0.0164
voltage ratio V/V_1	$\pi\,(2r+\Delta r)\,/\Delta z$	60.95

where: r, Δr,– inner radius and thickness of limiter, Δz – width of one turn of bifilar coil.

Real geometry of resistive SFCL in a shape of bifilar coil (Fig. 1, Fig. 3) is replaced by equivalent, due to energy and current density, geometry of electro-thermal numerical model shown in Fig. 4. Recalculating ratio for resistance, current and voltage are presented in Tab. 1.

The numerical model consists of 6 calculation objects (Fig. 4): the current input and output represented by shell regions, heat exchange between limiter and liquid nitrogen represented by shell region and the support, superconductor and electric shunt represented by surfacic regions "HTS" and "shunt".

The shell regions are defined on the boundary domain [7]. 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".

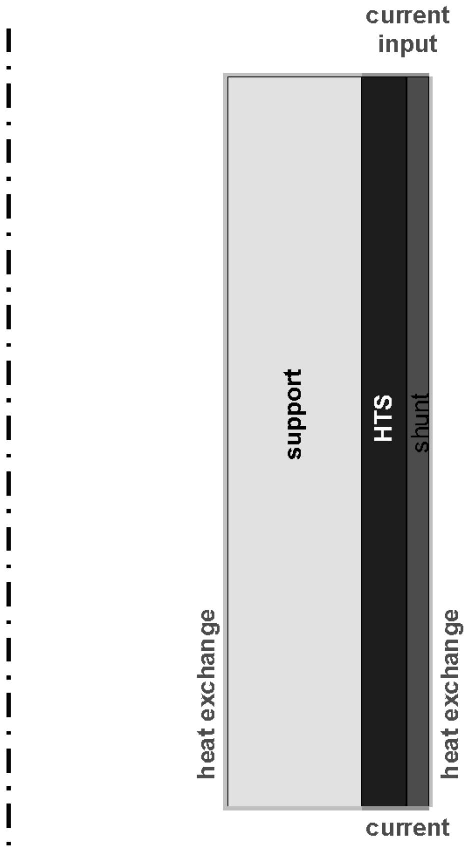

Fig. 4. Simplified geometry of resistive SFCL of numerical model in electro-thermal application of FLUX2D

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 the liquid nitrogen by shell region "heat exchange". Neuman non-homogeneous boundary condition in case of convection, radiation coefficients or thermal flux transfer on shell region "heat exchange" is given by [7]:

$$k \cdot \frac{\mathrm{d}(T)}{\mathrm{d}n} = -\Phi_\mathrm{H} - h \cdot (T - T_\mathrm{a}) - \varepsilon \cdot (T^4 - T_\mathrm{a}{}^4) \qquad (3)$$

where: k - thermal conductivity (W $m^{-1}K^{-1}$), Φ_H - thermal flux from/to the outside (W/m^2), h - convection exchange coefficient (W $m^{-2}K^{-1}$), ε - radiation exchange coefficient, T – temperature (K), T_a - ambient temperature (K).

Properties of domains of numerical model

In the FLUX2D [7] the material properties are defined in CSLMAT module. Tab. 2 presents list of models and values of properties and sources of calculating regions.

Tab. 2 List of models and values of properties and sources of calculating regions [7],[8],[9],[10],[11],[12],[13],[14]

region	property or source	Unit	model of property or source	value
"HTS"	isotropic resistivity	Ω m	user define	by USRSIG
	isotropic specific heat	J m^{-3} K^{-1}	scalar linear, $V=V_0(1+aT)$	$V_0=3.22\ 10^6$ a=0.003752
	isotropic thermal conductivity	W m^{-1} K^{-1}	scalar constant	4.7
	source	-	eddy currents	-
"shunt"	isotropic resistivity	Ω m	scalar constant	$45.65\ 10^{-8}$
	isotropic specific heat	J m^{-3} K^{-1}	scalar linear, $V=V_0(1+aT)$	$V_0=79228$ a=0.00383
	isotropic thermal conductivity	W m^{-1} K^{-1}	scalar constant	18
	source	-	eddy currents	-
"support"	isotropic specific heat	J m^{-3} K^{-1}	scalar linear, $V=V_0(1+aT)$	$V_0=43129.5$ a=0.0038
	isotropic thermal conductivity	W m^{-1} K^{-1}	scalar linear, $V=V_0(1+aT)$	$V_0=0,67$ a=0.00333
"heat exchange"	thermal flux to the outside	W m^{-2}	user define	by USRPWD
"current input"	current going in the domain	A m^{-2}	constant	fixed
"current output"	current going out the domain	A m^{-2}	constant	fixed

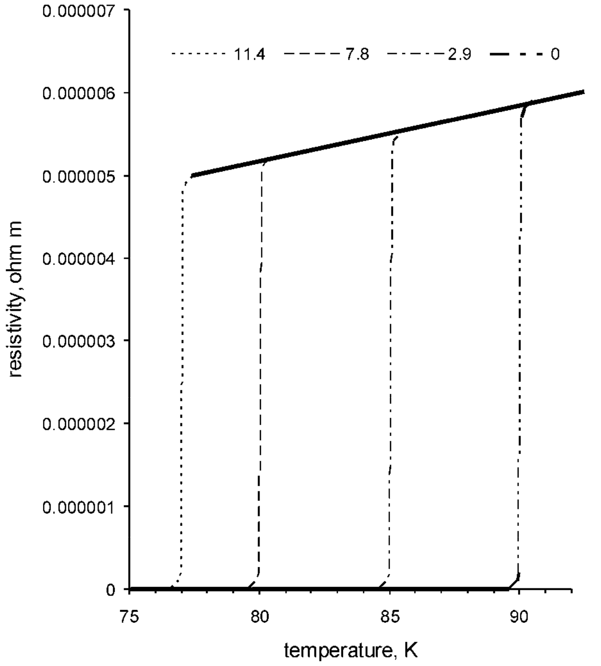

Fig. 5. Resistivity of "HTS" region vs. temperature for different current density (10^6 A/m^2)

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. The resistivity of "HTS" and thermal flux to the outside of "heat exchange" dependences on temperature are too advanced and can not

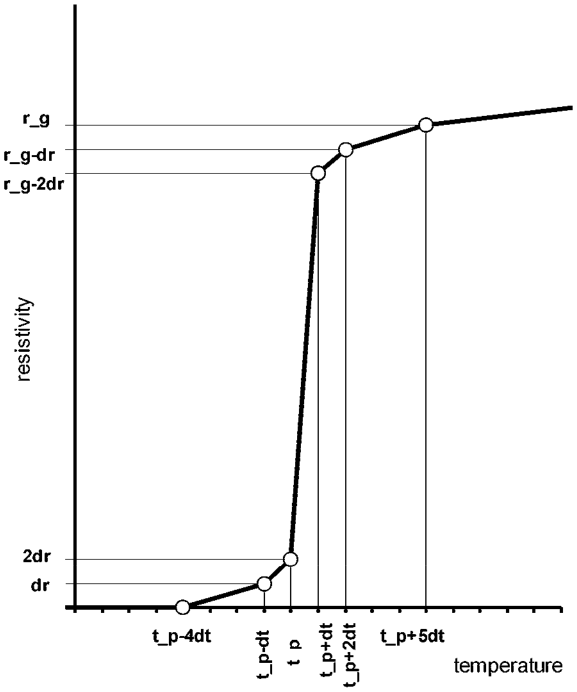

Fig. 6. Simplified resistivity of “HTS” region vs. temperature defined by USRSIG

```
        SUBROUTINE USRSIG(UCOEF , SIGT)
        REAL            UCOEF(1)
        DOUBLE PRECISION  SIGT(2,2)
                include 'intpol'
                include 'pbgen'
                integer n, i                    ! n=9
                real tt(9), t(9),a,b,t,at,bt,ro,t_p,cur,dt,dr,r_g,r0
                DATA pt / 0, 2,7.8,8.9,10,11.4,20,28.6,40/
                DATA tt /90,86, 80, 79,78,  77,72,  68,64/
                cur = UCOEF(2)
                r0 = 2e-4
                dt = 0.1
                dr = 0.01
                t_p = 90
                IF (cur .EQ. 0) GOTO 45
                n = 9
                DO i=1, n-1
                  a  = tt(i)
                  b  = tt(i+1)
                  at = pt(i)
                  bt = pt(i+1)
                  IF (cur .LE. bt) GOTO 44
                END DO
44              t_p = (a-b)*(bt-cur)/(bt-at)+b
45              t = SNGL(VA)
                a = t_p+5*dt
                r_g = 1.5/223*(a-76.9)+0.5
                ro = r0
                IF (t .LE. (t_p-4*dt)) GOTO 55
                ro = dr*(t+4*dt-t_p)/(3*dt)+r0
                IF (t .LE. (t_p-dt)) GOTO 55
                ro = dr*(t+dt-t_p)/dt+dr+r0
                IF (t .LE. t_p) GOTO 55
                ro = (r_g-4*dr-r0)*(t-t_p)/dt+2*dr+r0
                IF (t .LE. t_p+dt) GOTO 55
                ro = dr*(t-t_p-dt)/dt+r_g-2*dr
                IF (t .LE. (t_p+2*dt)) GOTO 55
                ro = dr*(t-t_p-2*dt)/(3*dt)+r_g-dr
                IF (t .LE. (t_p+5*dt)) GOTO 55
                ro = 1.5/223*(t-76.9)+0.5
55              ro=1e-5*ro
                SIGT(1,1) = 1/(ro*EPSMU)
                SIGT(2,2) = SIGT(1,1)
                SIGT(1,2) = 0
                SIGT(2,1) = 0
        RETURN
        END
```

Fig. 7. USRSIG subroutine (FORTRAN) to define value of resistivity of “HTS”

be defined by standard models of properties and sources of FLUX2D. The use subroutines USRSIG [8][9] and USRPWD [10] 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. From mathematic point of viev, a 3-variables (temperature, magnetic field, current density) function defining resistivity of superconductor is replaced by the 1-variable (temperature) function with a parameter (current density).

Fig. 5 presents resistivity of “HTS” region vs. temperature for different current density. The value of resistivity of “HTS” is computed in USRSIG according to a simplified function presented in Fig. 6. The USRSIG in FORTRAN is presented in Fig. 7. The USRSIG has one parameter - value of current density in SFCL. Due to this parameter the value of critical temperature *t_p*, according to Fig. 8, is computed. Then, the value of minimal resistivity of “HTS” in resistive state *r_g* is computed due to:

$$r\_g = (1.5/223*(t\_p+5*dt - 76.9) + 0.5)*10^{-5} \qquad (4)$$

where: *r_g*, *t_p* and *dt* are shown in Fig. 6.

Basing on calculated values of *t_p* and *r_g* and assumed values of *r0*, *dt* and *dr*, the resistivity of “HTS” is calculated (USRSIG, Fig. 7).

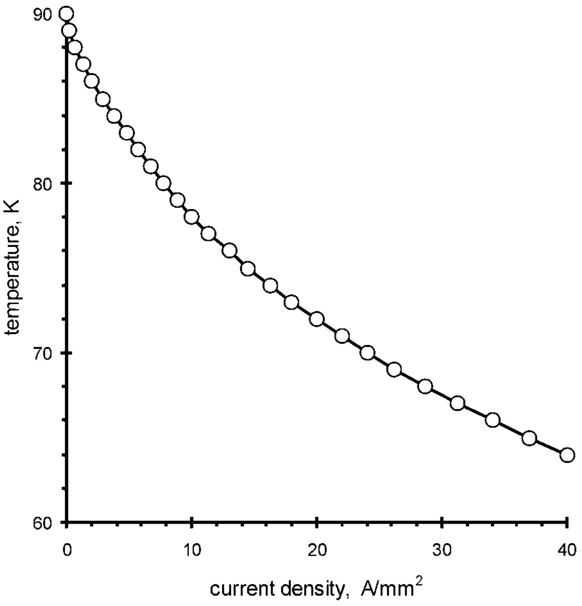

Fig. 8. Critical temperature of Bi-2212 bifilar coil vs. current density (self magnetic field) [14], [15], [16],[17]

It is assumed that during computation the temperature difference between “heat exchange” shell region and coolant doesn’t exceed 10 K and USRPWD which defines heat transfer to coolant has values as shown in Fig. 9. The USRPWD in FORTRAN is presented in Fig. 10.

Numerical results

Fig. 11 presents the time to reach ΔT between surface and liquid nitrogen equals 10 K vs. related current density $J/J_{c\,77\,K}$ in limiter, where $J_{c\,77\,K}$ is a critical current density of

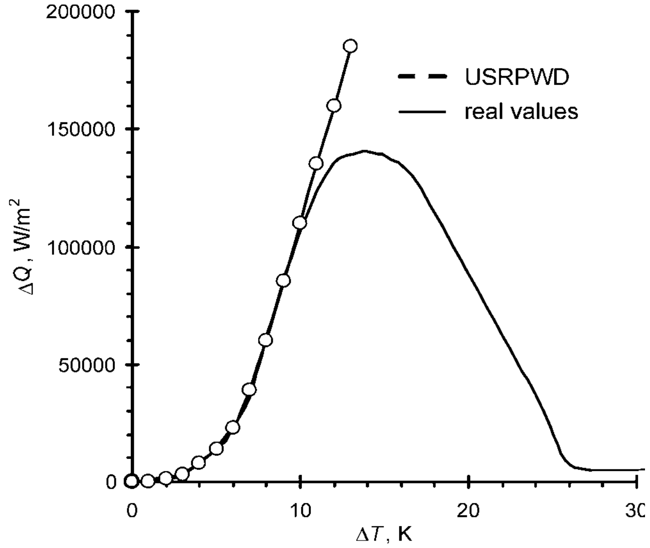

Fig. 9. Heat transfer ΔQ to liquid nitrogen vs. ΔT and simplified ΔQ defined by USRPWD

```
    SUBROUTINE USRPWD(UCOEF , PWD)
    REAL    UCOEF(1), PWD
            include 'intpol'
            integer n, i
            real t(10), p(10), a, b, tt, at, bt, ta
            DATA t /0, 1, 2, 3, 4, 5, 6, 7, 8, 9/
            DATA p /0, 1, 10, 30, 76, 140, 230, 390, 600, 850/
            tt = SNGL(VR)
            PWD = 0
            IF (tt .LE. 77) GOTO 22
            ta = SNGL(TAMB)
            tt = tt - ta
            n = 10
            DO i=1, n-1
             a  = t(i)
             b  = t(i+1)
             at = p(i)
             bt = p(i+1)
             IF (tt .LE. b) GOTO 11
            END DO
11          PWD = ((b-tt)*(bt-at)/(b-a)-bt)*100000
22          PWD = UCOEF(2)*PWD
            RETURN
    END
```

Fig. 10. USRPWD subroutine (FORTRAN) to define heat transfer to liquid nitrogen

limiter at temperature equals 77 K and under self magnetic field. It shows how fast the limiter reaches the ΔT = 10 K for the current densities higher than critical current value.

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 normal conducting (resistive) state. Fig. 12 and Fig. 13 present maximal temperature and voltage in limiter vs. time for different related current density $J/J_{c\ 77\ K}$ in limiter. They show that for the current value in limiter when $J/J_{c\ 77\ K}$ is between 92.1% and 94.7% the limiter can work improperly because the temperature and voltage rise with significant delay. This effect was observed during measurement of static *V-I* characteristic of physical model of resistive SFCL. Fig. 14 presents energy transferred to the liquid nitrogen vs. time for different related current density $J/J_{c\ 77\ K}$. It shows that the volume of evaporated nitrogen in limiter (proportional to energy transferred to liquid nitrogen) is not proportional to the current in limiter. The measurement of this parameter does not get proper information of overheating of limiter. When temperature difference ΔT between limiter and liquid nitrogen rises above 12 K, high heat transfer coefficient due to nuclear boiling is replaced by a much smaller coefficient due to film boiling. The surface of limiter is blanketed by vapour film and much more of energy dissipated in limiter heats limiter than is transferred to liquid nitrogen. So temperature rises very fast without significant rise of volume of evaporated nitrogen. This dangerous effect was observed during experiments with physical model of resistive SFCL.

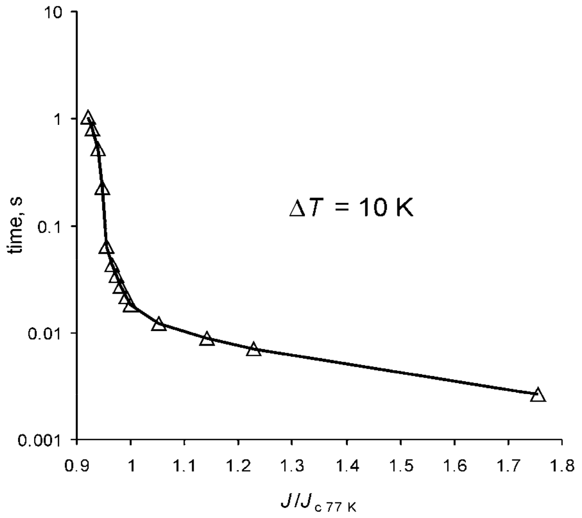

Fig. 11. Time to reach ΔT between surface and liquid nitrogen equals 10 K vs. related current density $J/J_{c\ 77\ K}$

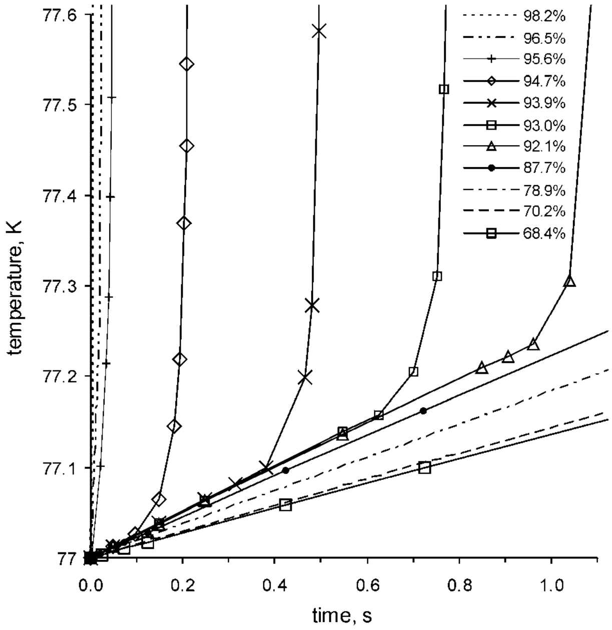

Fig. 12. Maximal temperature in limiter vs. time for different $J/J_{c\ 77\ K}$

Summary

Numerical model of resistive SFCL is made using electro-thermal module of FLUX2D which is the coupling of an electric conduction module with a transient thermal module. The electric resistivity dependence on current density, magnetic field and temperature is taken into account in calculation by advanced USRSIG subroutine and proper type of boundary condition.

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

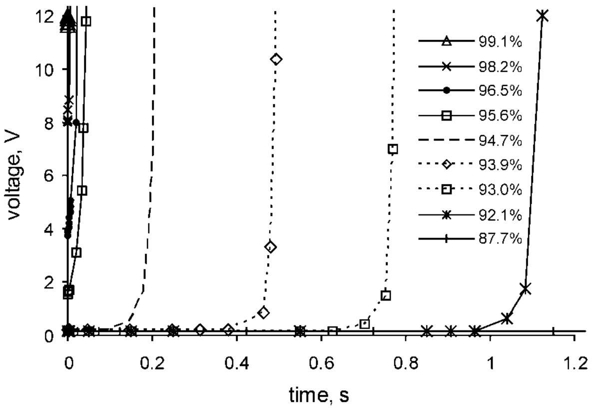

Fig. 13. Voltage in limiter vs. time for different $J/J_{c\,77\,K}$

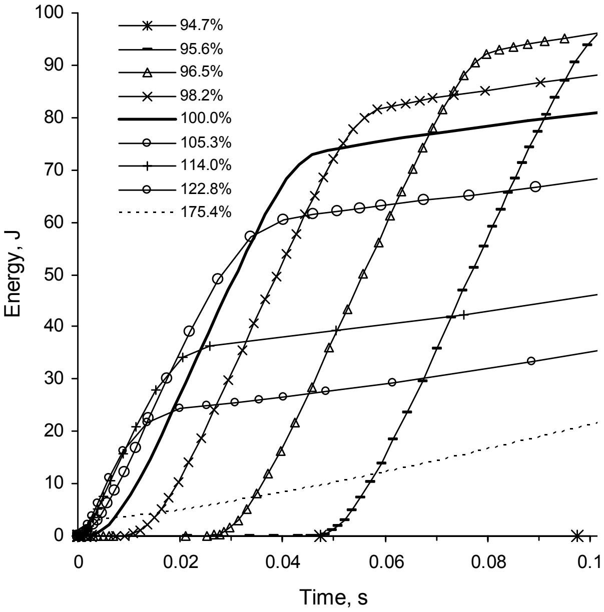

Fig. 14. Energy transferred to the liquid nitrogen vs. time for different $J/J_{c\,77\,K}$

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

The USRPWD subroutine is used to define heat transfer to coolant under assumption that temperature difference between limiter and coolant doesn't exceed 10 K. The proper computation using presented numerical model is limited by this assumption. Because the temperature in limiter rises very fast for current in limiter above critical current value so the USRPWD subroutine should be modified for a longer time computations.

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