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DESIGN CONSIDERATIONS FOR A HIGH TEMPERATURE SUPERCONDUCTOR FAULT CURRENT LIMITER

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Keywords: Fault current limiter; Design; Superconductor; Quench; Numerical simulations.

This work analyzes the functional conditions for a high-temperature superconductor (HTS) current limiter model. Introducing a superconducting fault current limiter (SFCL) in a distribution network considerably reduces the overcurrent that occurs due to a fault in the system. The analyzed SFCL conceptual model refers to a resistive limiter model, which operates on the principle of the transition of the superconducting material from the superconducting state to the resistive state when one of the critical parameters of the superconducting state is exceeded, such as the critical current (Ic). Thus, with the occurrence of a fault current for I > Ic, the superconductor goes into a resistive state (phenomenon called "quench") and the current will be diverted to an alternative resistive circuit. The parameters of the quench are analyzed for different current values (50, 100, 200, and 300 A) to determine the protection sizing and operation of an SFCL. They are investigated through numerical simulations with Comsol Multiphysics.

1. INTRODUCTION

The increasingly sustained development of human society implies an increasing global demand for energy, especially electricity. Electricity distribution networks are becoming increasingly demanding, which is why fault currents could appear, which must be controlled to avoid damage of network elements.

In this respect, protection devices known as fault current limiters are necessary to safeguard these networks against damage. A relative new generation of such devices are using the special properties of the high temperature superconductors (HTS). Since the discovery of high temperature superconducting materials (HTS) in 1986, these materials have been developed as a technology and wires/strips of very long lengths (~km) could be manufactured, having various engineering applications. HTS superconducting materials can be cooled down with liquid nitrogen (77 K) having a transition temperature of 92 K. The working principle of these superconducting fault current limiters (SFCL) is based on transition from superconducting state to the resistive state (at 92 K). Currently, worldwide are made efforts to develop superconducting fault current limiters [1]. Although the HTS superconductor current limiters are in a permanent process of research and development, their technical-economic performance has been demonstrated in the numerous projects proposed at the global level both in the USA, as well as in Europe and Asia, with installation and practical testing in the distribution networks of some cities [2].

Two 138kV SFCL type projects were completed in the USA [3]. One of these was proposed by the American company Zenergy Power Inc. and was implemented as a prototype in the distribution network of the state of Ohio in 2011[3]. The limiter used is an inductive type with a saturated core and HTS cable. One of the tests carried out within this project was the consideration of a normal state with a current value of 1 kA RMS, and a symmetrical fault current of 15 kA RMS, which decreased by 32 % using the limiter described above, for one of the geometries proposed in within the project.

The second HYDRA project consisted in the design of a limiter called "Super Limiter™" manufactured by the American company American Superconductor Corporation and was successfully tested in Edison state, in southern California in 2010 [4]. This is a resistive type of limiter made with HTS cable and capable of limiting currents of a much higher value than the previous one, namely from 63 kA to 40 kA (approximately 35-36 %).

Other such current limiters, but this time of only 12 kV, were also introduced in Europe by the German company Nexans SuperConductors GmbH and installed in the grid of the cities of Lancashire, UK and Boxberg, Germany in 2009. These are two resistive type limiters, consisting of a specific arrangement of BSCCO-2212 superconducting coils, with a capacity to limit fault currents from 50 kA to 6 kA (approximately 80 %) [2].

In the period 2008-2009, three current limiters were introduced in the distribution recipes of Korea (22.9 kV Hybrid SFCL), Japan (22 kV SFCL), and China (35 kV Saturable-Core SFCL) in Asia.

By introducing an SFCL in a distribution grid, the overcurrent occurring because of a fault in the system is considerably reduced, as can be seen in Fig.1. This type of limiter has a very low impedance during the normal operation of the system (the superconductor is in a superconducting state), and in the event of a fault, the limiter increases its impedance a lot (the superconductor goes into a resistive state), thus preventing the passage of current in excess through the system, current that would cause damage to the existing electrical equipment by overheating [5].

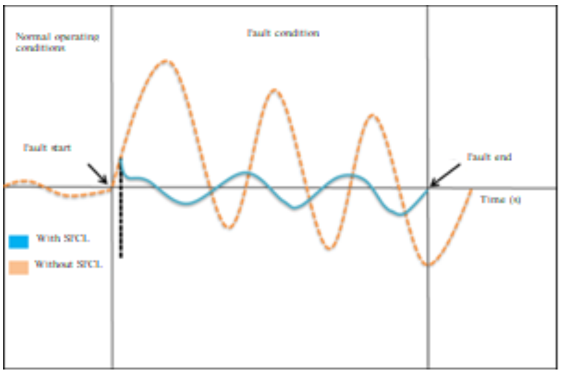

Fig. 1 – The waveform of the current during a fault, with and without SFCL [6].

The following requirements should be met by the current limiters for them to reach the desired maximum capacity and efficiency in the electricity distribution networks, namely [6]:

- To limit the fault current from the first spike.
- To have very low impedance during normal system operation (this translates into a minimal voltage drop at the level of the entire circuit).

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- Negligible energy losses.
- To be compatible with the design of the existing protection systems.
- Maintenance costs as low as possible.
- High reliability.

Given all these characteristics, superconducting current limiters represent a variant to be considered for replacing existing classic current limiters. They offer numerous benefits regarding the maintenance and protection of electricity distribution grids through stability and efficiency much higher than classic protection systems. The main characteristics that determine the use of superconducting current limiters are the extremely fast response in the event of fault currents in the system, they reduce voltage drops caused by components with high resistivity, they do not need external control and do not introduce unwanted side effects in case of normal operation of the network (there is no energy loss) [5]. At the same time, superconducting current limiters can also be used in high-voltage networks, and their maintenance is relatively simple and does not involve high costs [7]. However, there are also undesirable effects of SFCLs, such as the development of thermal instabilities in the system (the so-called "hot spot") and high production costs caused using HTS materials and cryogenic equipment.

2. HTS SUPERCONDUCTING FAULT CURRENT LIMITER

Due to non-linear variation of the resistivity with temperature of HTS materials, they are suitable for SFCL functioning. The HTS materials used in the construction of SFCL are 2nd generation superconductors, available as tapes with a strong material as substrate. Two kinds of HTS superconducting materials of the second generation (2G) are most used in SFCL construction [8]: YBa2Cu3O7 and Bi2Sr2CanCun-1O2n+ 4 + x. They are commercially named as YBCO and BSCCO materials respectively. The scheme of the resistive type of SFCL is shown in Fig. 2.

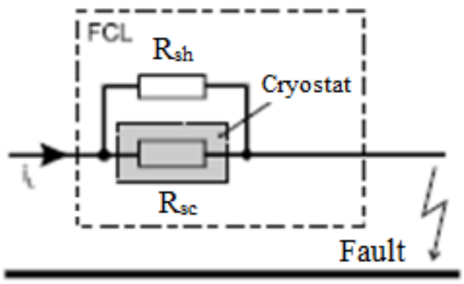


Fig. 2 – Basic electrical diagram of a superconducting current limiter [2].

Its operation (SFLC) is based on the transition of the superconductor from the state of zero resistance to the resistive state when the temperature reaches the transition temperature (T_c) or the current passing through the conductor exceeds the critical current (I_c) value. This phenomenon is called "quench". Due to this characteristic, the superconducting material which is normally at a temperature of 77 K or below, is in a state of zero resistance. Under these conditions, the current passing through it (nominal current in the circuit - I_n) is at a value $I_n < I_c$. When there is a fault in the network and the current in the circuit becomes higher than the critical current of the superconductor ($I_n > I_c$), then the superconductor comes out of superconductivity, acquires some resistance and the current will pass through the resistance R_{sh} which is lower than the resistance of the superconductor in normal state R_{sc} ($R_{sh} < R_{sc}$). Thus, the total current in the circuit will be limited to the I_n value, protecting the load in the circuit.

After removing the overcurrent and returning the superconductor to a temperature lower than the critical temperature ($T < T_c$), then the current I_n returns to the previous circulation, through the superconductor. Resistive SFCLs are much smaller and lighter than inductive ones. Instead, they are vulnerable to excessive heating during the quench [9, 10, 11]. Also, the resistance of the junctions HTS/ copper must be considered for the overall joule heating, subject treated in [12].

3. QUENCH PROPAGATION IN THE HTS WINDING

The quench is the sudden and unexpected transition from superconducting state (T < Tc) to resistive state (T > Tc) of a superconductor material, due different reasons. The main occurrence reasons are:

- Increase of the current: I > Ic.
- External magnetic field fluctuations: B > Bc.
- Environment temperature increasing T > Tc.
- Conductor movement/ vibration.

3.1 QUENCH OCCURRENCE AND PROPAGATION

The amount of energy who can generate a quench in the superconducting tape, is named *Minimum Quench Energy* (Q_{min}). The larger the Q_{min}, the more stable a superconducting device will be. In this respect, two different situations could be:

- if the initial Quench Energy (Q_E) < Q_{min} then, the initial normal zone (NZ) will shrink and finally the conductor recovers entirely the superconducting state;
- if the initial Quench Energy $Q_E > Q_{min}$ than, the NZ expands through the conductor and the tape became resistive.

Another important factor to consider, is the Normal Zone Propagation Velocity (V_{nz}), the rate at which the edge/surface between the normal zone and the superconducting zone moves through the conductor (Fig. 3). The V_{nz} knowledge is important for the protection system design (time of reaction and discharge).

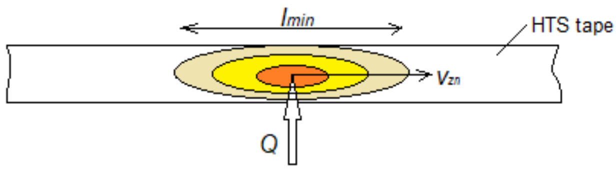


Fig. 3 – Quench occurrence and propagation in an HTS tape.

Figure 3 shows the model of a quench occurrence due to heat generated by a hot spot appeared in the HTS tape.

3.2 HEAT BALANCE EQUATION

To use a model to simulate the normal zone propagation in a HTS tape surrounded by a cryogenic environment, the heat balance equation was considered [12,13]. This equation describes how heat generates and flows in a superconductor. The numerical predictions are based on solutions of this heat balance equation [12]:

$$C(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left[k(T)\frac{\partial T}{\partial x}\right]+P_J+P_q+P_c. \quad (1)$$

where $C(T)$ [J/Km] is the heat capacity, $k(T)$ [Wm/K] the thermal conductivity, T [K] the temperature, t [s] is time and x [m] one-dimensional position. P_J [W/m], P_q [W/m] and P_c [W/m] are the sources and sinks of the heat in the superconducting tape, respectively the joule heating, initial heat generating a quench and the cooling term.

3.3 NORMAL ZONE PROPAGATION VELOCITY AND MINIMUM QUENCH ENERGY

From the heat balance equation, the rise in temperature as result of the heat generated can be calculated. This dynamic temperature profile can then be used to derive the normal zone propagation velocity and the minimum quench energy.

The normal zone propagation velocity describes a steady-state situation. This means that the initial power dissipation P_q = 0 since the energy pulse has already passed and the cooling term P_c is also zero for adiabatic conditions. This results in the equation [12]:

$$C(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left[k(T)\frac{\partial T}{\partial x}\right]+P_J. \quad (2)$$

The initial normal zone produced by initial heating, is expanding through the superconductor in x- direction as in y-direction of the tape surface. The x- direction expanding has a velocity called normal zone propagation velocity (V_{nz}), whose formula is derived from eq. 2, and has the expression [13]:

$$V_{\mathrm{nz}}=\frac{1}{C}\sqrt{\frac{k_n\rho_n}{T_t-T_w}}. \quad (3)$$

where: k_n [W/m K] is the thermal conductivity of the normal zone, ρ_n [Ω m] is the resistivity of the normal zone, T_t [K] is the transition temperature, T_w [K] is the working temperature, $C=\sqrt{C_nC_s}$ where C_n [J/Kg K] and C_s [J/kgK] are specific heat of the resistive and superconducting states respectively.

3.4 MINIMUM QUENCH ENERGY

The initial local Joule heating of a superconductor generated by the minimum quench energy (Q_{min}), produce a local normalization zone of initial length l_{min}. The expression for l_{min} is given by [14]:

$$l_{min}=\sqrt{\frac{2k_n(T_t-T_w)}{\rho_n I^2}}. \quad (4)$$

The minimum energy to produce a quench (Q_{min}) means the energy required to increase the local temperature of the superconductor above the transition temperature inside the normal zone of material length l_{min}. This energy is [12]:

$$Q_{min}=l_{min}\int_T C(T)\mathrm{d}T. \quad (5)$$

4. **2D NUMERICAL MODELING OF A QUENCH IN A YBCO TAPE**

The numerical modeling consists of a 2D model to determine the quench propagation in the longitudinal direction of the YBCO tape. The numerical modeling of a quench is important to determine how fast the quench spreads through the YBCO. The speed with which the quench phenomenon makes the local temperature in the tape, is very important to design the quench detection and protection system. If the local temperature exceeds a critical temperature, then, the tape will be irremediable destroyed.

4.1 THEORETICAL CONSIDERATION

4.1.1 MATHEMATICAL MODEL

The 2D model consist of 2 coupled problems: stationary Conductive Media DC to determine the current density in the tape and the heat source that occurs while the tape is connected to a DC power supply, and a time dependent Heat Transfer to determine how fast the local temperature rises above the critical temperature when a quench occurs.

Conductive Media DC [15]:

$$-\nabla\cdot d(\sigma\nabla V-\mathbf{J}^e)=dQ_j, \quad (6)$$

$$\mathbf{n}\cdot\mathbf{J}=\mathbf{n}\cdot\mathbf{J}_0, \quad (7)$$

$$V=0, \quad (8)$$

$$\mathbf{n}\cdot\mathbf{J}=0, \quad (9)$$

where, d [m] is the thickness, σ [S/m] is the electric conductivity, $\mathbf{J}^e$ [A/m²] is the external current density, Q_j [A/m³] is the current source, **n** is the normal vector outgoing out of plane, **J**, $\mathbf{J}_0$ [A/m²] is the current density and V [V] is the electric potential.

Heat transfer [15]:

$$\rho C_p\frac{\partial T}{\partial t}+\nabla\cdot(-k\nabla T)=Q+q_sT. \quad (10)$$

$$T=T_0. \quad (11)$$

where, ρ [kg/m³] is the density, C_p [J/kgK] is the heat capacity, T, T_0 [K] is the temperature, t [s] is the time, Q [W/m³] is the heat source, q_s [W/m³K] is the production/absorption coefficient.

4.1.2 COMPUTATIONAL DOMAIN OF A YBCO TAPE SAMPLE

Fig. 4 – HTS tape, type YBCO, sample.

Figure 4 shows the computational domain representing the sample of the HTS tape used to evaluate the quench phenomenon.

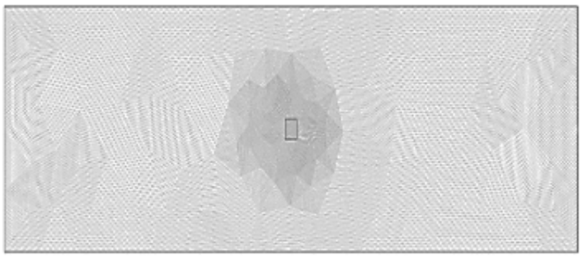


Fig. 5 – Mesh characteristics.

The mesh shown in Fig. 5 has 65536 triangle elements.

4.1.3 CHARACTERISTICS AND INITIAL VALUES OF THE PARAMETERS FOR THE NUMERICAL MODEL

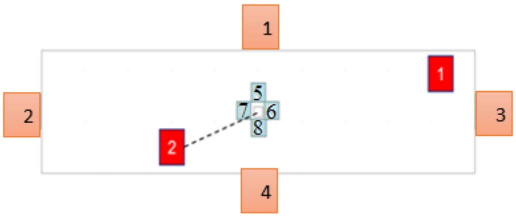


Fig. 6 – Subdomains (red) and boundary conditions (cyan) for the computational domain.

Figure 6 shows the subdomains and boundary conditions used in numerical simulation and presented in Table 1.

Table 1

Boundary conditions.

Boundary	Condition	
	Conductive media DC	Heat Transfer
1, 4	Electric insulation	Temperature
2	Current density	Temperature
3	Ground	Temperature
5, 6, 7, 8	Continuity	Continuity

The characteristics and initial values of the parameters for the numerical model are described in Tables 2 and 3.

Table 2

Parameters for conductive media DC simulations.

Parameter	Value	Units
Thickness (d)	0.11	mm
Electric conductivity (σ)	5.998e7	S/m
Current density(J_0)	Depends on the current	A/m^2

Table 3

Parameters for heat transfer simulations.

Parameter	Value	Unit
Thermal conductivity (k)	375.5	W/mK
Density (ρ)	8700	kg/m^3
Heat capacity (Cp)	98.54	J/kgK
Heat source (Q)	Depends on the current	W/m^3
Temperature (T)	50	K

4.2 NUMERICAL MODELLING RESULTS (QUENCH PROPAGATION IN A YBCO TAPE)

For the numerical modelling were taken in consideration 4 cases of different currents: 50 A, 100 A, 200 A and 300 A.

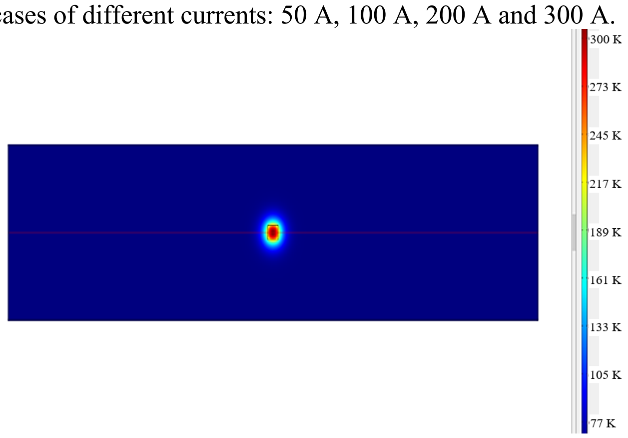


Fig. 7 – Surface color map (temperature) representing the quench occurrence (“hot spot”).

Figure 7 captures the moment when the quench occurs, and a “hot spot” can be seen on the surface of the HTS tape.

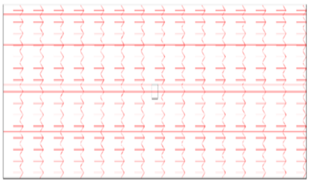


Fig. 8 – Electric current path and direction.

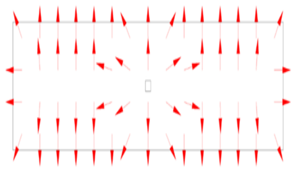
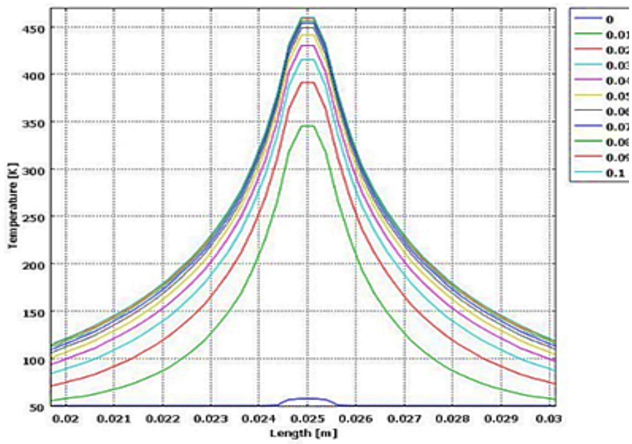


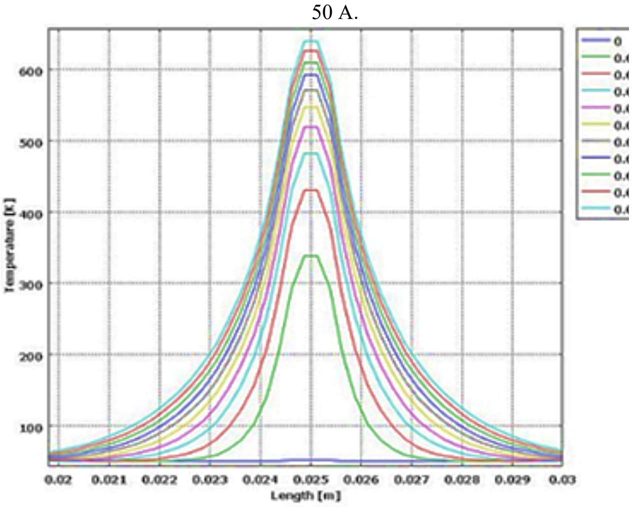
Fig. 9 – Heat flux propagation.

Figures 8 and 9 show the electric current path and direction, respectively the heat flux propagation along the HTS tape sample.

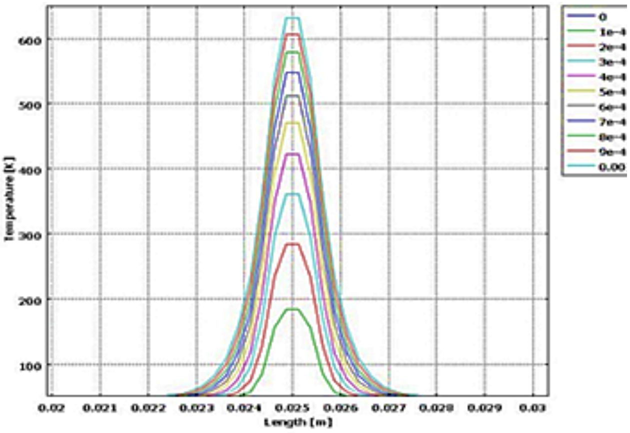
To protect the integrity of the HTS layer, there is a restriction impose to the maximal temperature rise (T_{max}) of the tape. So, the following numerical analysis considers a maximum temperature of 450 K, accepted to preserve the integrity of the tape. Due to the transition from superconducting state to the resistive state (normal state) the occurrence of a resistive point having at the beginning a certain resistance (R_i) will become the source of the heating under Joule effect. Under the high value of the current passing through the tape, the normal zone will increase as the temperature rise, as fast as twice of the velocity V_{nz} of the normal zone propagation. The time (Δt) needed to attain the maximal temperature (T_{max}) will give the length of the normal zone (resistive zone) and hence, the maximal resistance attained (R_{max}). The proper functioning of the limiter will require a parallel mounted resistor (R_S) to deviate the high current from superconductor path to the shunt. Obviously, the condition $R_S \leq R_{max}$ will be respected.



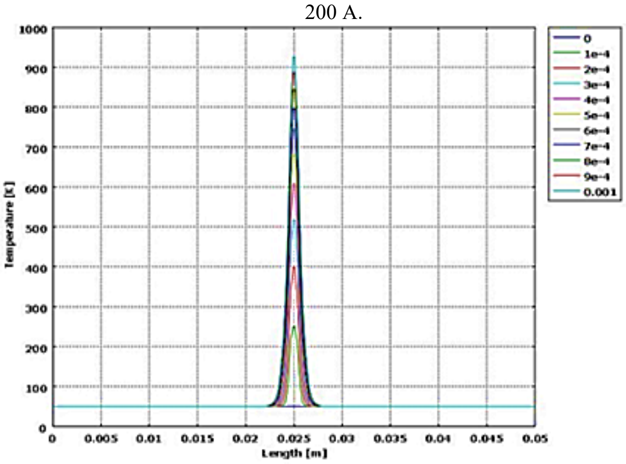
50 A.



100 A.



200 A.



300 A.

Fig. 10 – Temperature rise when quench occurs for different currents.

Figure 10 presents the modeling result of the temperature rise in the HTS tape for several current values through the tape. The numerical results on the normal zone propagation velocity and the corresponding length of the normal zones (l_{nz}) are summarized in Table 4. The computed time (Δt) corresponds to the maximal accepted value of the local temperature in the tape (450 K).

Temperature rise after quench is initiated in the HTS tape, for a current of 50 A (Fig. 10.a), for a current of 100 A (Fig. 10.b), a current of 200 A (Fig. 10.c), and a current of 300 A (Fig. 10.d). The Ox axis represents the length of the normal zone.

Following the 2D modelling, it has been determined how fast the initiated quench makes the temperature rise to a maximal value, above the critical temperature, at which the YBCO tape could be damaged irreparably. The results are summarized in Table 4.

Table 4

Quench characteristics for maximum temperature reached in the YBCO tape.

I [A]	50	100	200	300
T [K]	450	450	450	450
P [W]	35	70	140	210
Δt [ms]	7	0.9	0.21	0.14
l_{nz} [m]	0.1	0.06	0.03	0.015

The results of the numerical simulations obtained in COMSOL Multiphysics show, as clearly as possible (as expected), that the higher the current value, the faster the increase in the temperature of the HTS winding, reaching even values at tens of microseconds or even shorter than that. The normal zone length (*l_{nz}*) generated during the time Δt, gives the possibility to compute the resistance (R_s) of the protection shunt to be mounted in parallel, contributing to the design and sizing of a superconducting resistive current limiter.

5. CONCLUSIONS

In this paper was presented a conceptual model of a superconducting fault current limiter, the operation principle and the parameters of the quench occured in a superconducting winding. The quench was analyzed troughth numerical modeling in COMSOL Multiphysics. The analysis considered the thermal and electrical characteristics of the HTS superconducting material, YBCO superconducting tape type. Numerical simulations for quench analysis were performed for currents of 50 A, 100 A, 200 A and 300 A (Fig. 9).

They highlighted the maximum temperature occurring in the winding and the temperature increase time (from 7 ms to 0.14 ms). The data obtained allows both extrapolation for higher currents and proper sizing of the superconducting part of an SFCL. In these regards, the amount of superconducting tape can be computed, which is the most important part when starting to design a specific SFCL.

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CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

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Ion Dobrin: 40%

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