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Design of ReBaCuO-Coated Conductors for FCL

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***Abstract* - The superconducting (SC) fault current limiter (FCL) can improve the security and the power quality of electric networks; these are the two essential requirements of today. The device must fulfil several requirements in normal and fault operations, and must operate under a variety of conditions. Impedance short-circuits represent the most severe conditions. Proper design of the ReBaCuO coated conductor is essential for safe and optimized operation. The design of the superconducting element is mainly based on thermal criteria. The minimum superconducting element volume is given by its enthalpy and the limiting current through the SC element. The superconducting quantities play only a small role in the design. High resistivity conductor reduces the ReBaCuO volume. Of other considerations to be taken into account, the quench homogeneity is one of the most important for resistive FCLs. The coated conductor architecture and design can help to reduce the consequences of quench inhomogeneity along the conductor. The presented arguments, for a high limiting current forcing the conductor to quench uniformly and for a moderate conductor resistivity to reduce the temperature differences, are supported by experiments carried out utilizing two rather different coated conductors in various limiting conditions.**

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***Keywords* – coated conductor, tape conductor, conductor design, resistive fault current limiter, conductor quench**

Glossary

α_{sc}: SC cross-sectional fraction.

c_p: specific heat per unit volume.

c_p^m: mean specific heat per unit volume of the SC conductor.

k_a: ratio of the transient maximum current to the rated RMS current.

k_s: ratio of the SC limiting current to the critical one.

A, L: cross section and length of the SC element.

R: resistance.

ρ: resistivity.

I_c, I_q: critical and quenched currents.

I_a, V_a: rated current and voltage of the grid (RMS values).

i_{sc}, j_{sc}: instantaneous current and current density through the SC element

v_{sc}, e_{sc}: instantaneous voltage and electric field across the SC element

T_o, T_{max}: operating and maximum temperatures.

Δt: fault hold time.

I_{Ulim}, I_{lim}: unlimited and limited current of the grid (RMS values).

E_{sc}^{Lim}: electric field under limitation regime developed by the SC element (RMS value).

J_{sc}^{Lim}: mean current density under limitation regime through the SC element (RMS value).

E_c: electric field criteria for the critical current.

n: transition resistive index.

f: frequency.

I. INTRODUCTION

The electricity networks are critical infrastructures and the security of power supply is of prime importance today. The voltage quality (no amplitude fluctuations or dips) is another relevant demand. Fault current limiters (FCL) could improve both the security and the power quality by making higher interconnection of the grids possible. However, no very satisfying FCL exists yet for high-voltage networks. High-temperature superconductors (HTS) are extremely attractive materials for FCL application. The first two pre-commercial HTS FCLs were recently commissioned in the United Kingdom and in Germany [1]. Both are based on bulk BSCCO materials. However, the ReBaCuO-coated conductor (CC) exhibits better performance, especially lower AC losses, and its cost may be much lower, at least potentially. Nevertheless, bulk materials can still offer an interesting technical solution meeting severe requirements.

The electricity networks begin now to evolve significantly. Future grids will be “smart grids” where FCLs will play a key role. In the future smart grid architecture, DC links are a perfect option for using FCLs, which remove the bottleneck of absence of zero crossing for DC fault currents. DC currents take full advantage of superconductivity: the total absence of losses, while AC currents inevitably lead to AC losses. The advantages offered by SC FCLs explain the numerous research and development projects throughout the world [2, 3, 4, 5, 6, 7].

The study presented in this article is restricted to resistive FCLs based on the quench of a superconducting (SC) element. Resistive FCLs have the best performance in terms of minimum mass and volume.

The SC element does not always quench over its full length (mass quench). This unavoidable inhomogeneity remains one of the open issues for the FCL. In this paper we show that a suitable design may reduce the consequences of such quench inhomogeneity. The objective of our work is to present analytical expressions permitting one to pre-design a ReBaCuO CC conductor for FCL and to understand the relevant parameters. Such analytical treatment requires many approximations and should be completed by numerical simulations for a more accurate design. The presented expressions may be suitable for other SC materials (BiSCCO and MgB_2) with relatively small adaptations. Experiments carried out on two different conductors from two manufacturers confirmed the theoretical predictions; the design of a safe conductor for FCL is possible.

II. ReBaCuO-COATED CONDUCTOR

A. Architecture and general modelling

The ReBaCuO coated conductor or 2G (second generation) conductor is a complex stack of several layers. Basically, the ReBaCuO layer is deposited on a metallic substrate, on top of several pre-deposited buffer layers, which are electrically isolating. An Ag or Au micrometer-scale shunt layer is deposited onto the superconducting layer to protect it and to provide a low-contact resistance permitting one to inject the current into the ReBaCuO. This structure can be completed by a normal metal coating or by soldered lamination(s) (Fig. 1). For FCL applications, a high-resistance normal conductor is favourable and this is why these tapes are usually made of stainless steel or a suitable nickel alloy.

The substrate must be somewhere in contact with the SC layer. Like any metallic component of an industrial electrical apparatus, the substrate must be referenced, *i.e.*, the substrate electric potential cannot be floating. Otherwise, the substrate may be charged while operating, thus leading to a dielectric breakdown. A single contact is necessary, but this limits the application to low voltages to avoid a dielectric breakdown between the substrate and the SC layer. In the studied case of resistive FCLs, a continuous short circuit between the shunt layer and the substrate must be made as also shown in Fig**. 1**. The short-circuit area should be sufficiently large to avoid degradations due to an excessive local current density. Due to the large area of the cross section of the substrate, its resistance is generally lower than that of the shunt resistance. Therefore, during the quench, the current will be transferred to the substrate through the short-circuit area.

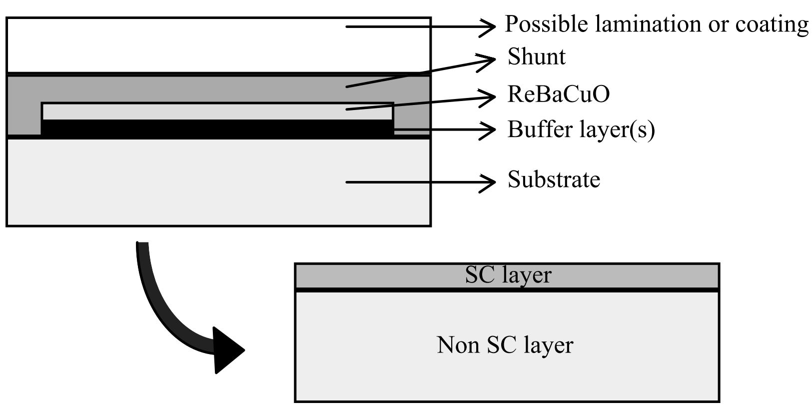

Fig. 1. Schematic cross section of a 2G conductor and its model used (not to scale).

The proposed design is only a rough pre-design. Therefore, the SC conductor can be considered to be an isothermal and homogeneous medium. The temperature is then supposed to be the same through the total cross sectional area and along the full length of the conductor. We consider mean physical characteristics, as shown in Equation (1) for the specific heat per unit volume:

$$c_p(T) = \frac{1}{A_{tot}} \sum_{Layer\,i} c_p^{layer\,i}(T)\, A_{layer\,i}. \qquad (1)$$

Here, c_p^{layer} is the specific heat per unit volume of each layer *i* having a cross section A_{layer}. The 2G conductor is simply modelled by only two layers in intimate contact, the SC and the normal one (Fig. 1). The SC fraction is α_{sc} and the total 2G conductor cross section is A_{tot}.

Fig. 2 shows a simple model of the superconducting length with a current source ($\beta I_c(T)$) in parallel with the non-superconducting resistance ($R_{cond}(T)$) [8]. It is deduced from the SC voltage-current curve. The parameter β depends on the SC conductor. The non superconducting resistance is:

$$R_{cond}(T) = \rho_{cond}(T) \frac{L_{cond}}{A_{tot}} \qquad (2)$$

The resistivity $\rho_{cond}(T)$ is the average resistivity of the different non-superconducting layers in parallel.

Both the resistivity and the critical current depend on temperature. Linear dependencies may be considered in a first approximation:

$$\rho_{cond}(T) = \rho_{cond}(T_o)\,[1 + \gamma(T - T_o)] \qquad (3)$$

$$\begin{aligned} I_c(T) &= I_c(T_o)\,\frac{T - T_c}{T_o - T_c} && (T \le T_c) \\ I_c(T) &= 0 && (T > T_c) \end{aligned} \qquad (4)$$

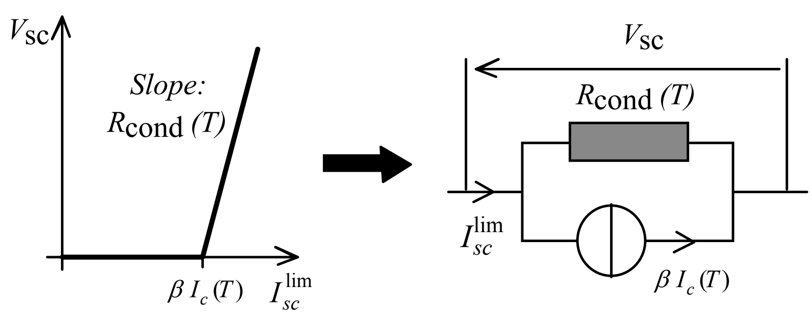

Fig. 2. Simple model of the SC element.

Above T_{c}, the contribution of the SC layer may be in general neglected since its resistance is high compared to the other layers in parallel, especially the substrate and the metallic laminations (if any). The best way to get the very important parameter $\rho_{\text{cond}}(T)$ is to calculate it from the measurement, above T_{c}, of the conductor resistance given by Eq. (2).

The basic assumption of all analytical expressions given in this article is that the behaviour is homogeneous along the full length of the superconducting element.

The electric equations with this SC length representation should be completed by a thermal equation to calculate the temperature for $I_{\text{c}}(T)$ and $R_{\text{cond}}(T)$ (equations (3) and (4)).

The SC branch ($\beta I_c(T)$ current source) disappears when the critical temperature is reached since the critical current becomes zero. The superconducting element is then only modelled by the conductor resistance function of the temperature and the "steady state" SC limiting current is expressed by:

$$I^{sc}_{Lim\,st} = \frac{V_{sc}}{R_{cond}(T)} \tag{5}$$

Here, V_{sc} is the voltage across the SC element. This current is the "steady state" under limiting regime.

From the model, the absolute maximum current or peak current is expressed by:

$$I^{sc}_{Lim\,peak} \approx \beta\, I_c(T_o) + \frac{V_{sc}}{R_{cond}(T_o)} \tag{6}$$

Here, T_o is the operating temperature.

Between the "steady state" and the initial peak, the current difference is at least $\beta I_c(T_o)$.

We will see that the experimental data are in good agreement with this simple model of SC element.

B. Current Definitions for the Superconductor Used in FCL

Any superconducting wire is characterized by critical current defined by the "critical" electric field (E_c), which we assume to be 100 µV/m. This critical current depends on the temperature (Eq. (4)) and the maximum magnetic flux density (its amplitude and direction) applied to the conductor. In addition to the critical current, the resistive transition index "*n*" is another relevant quantity. It characterizes the stiffness of the quench. Around the critical current the electric field may be expressed by:

$$E = E_c \left(\frac{|I|}{I_c(T)} \right)^{n-1} \frac{I}{I_c(T)} \qquad (T < T_c) \tag{7}$$

In superconducting state, if the SC conductor carries AC currents, it experiences AC losses in the SC layer and core losses in the substrate if it is magnetic, as is the case of Ni alloys, for example. In FCL application, these AC losses are mainly self-field losses and the ratio I/I_c plays an important part. The self field losses increase with this ratio at the power between 3 and 4 [9]. The losses also depend on the geometry of the SC element and some geometries (such as bifilar coils for example [3]) are preferable for low losses.

While the critical current is one of the relevant parameters determining AC losses, it is not the most relevant for current limitation. In this case, the most essential parameter is the "quench" current I_q, above I_c. At the steady state quench current, the superconductor remains in thermal equilibrium with the surroundings (rest of the conductor and cooling fluid) and there is no thermal runaway phenomenon. The temperature increase is limited. This quench current depends on the SC properties (J_c and n values) and on the surroundings (cooling conditions). For very short durations the quench current may be higher than in steady state since the transient exchange flux is enhanced and the enthalpy then plays a part. Fig. 3 gives an example of the runaway delay in function of I/I_c [10]. Under the considered cooling conditions, no runaway occurred for currents up to 1.2 I_c: this the steady state quench current. However, for a duration of only 0.1 ms the quench current is strongly enhanced and reaches 2.5 I_c.

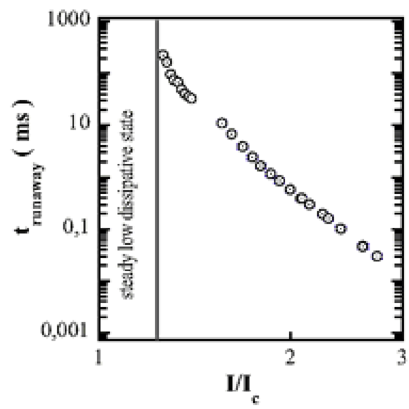

Fig. 3. Runaway delay versus I/I_c [**10**].

The current through the SC element during the current limitation regime is the third relevant current for the SC conductor. This current is I_{Lim}^{sc}. It may be lower than the FCL limiting current (I_{lim}) since there is often a shunt impedance across the SC element (see Fig. 4). It permits one to adjust the limiting current to the utility requirements. This shunt impedance may be a resistance or a reactance with consequences in terms of transient over-voltages for example [11], and power dissipation.

III. UTILITY REQUIREMENTS

These requirements strongly depend on the location and the purpose of the FCL [12, 13]. Fig. 4 represents the grid with FCL in balanced operation: a voltage source with the short-circuit impedance (Z_{grid}), the load impedance Z_{load} and the FCL in series. An important parameter is the unlimited fault current (RMS value: I_{ULim}) given by the rated RMS voltage (V_a) and the short-circuit impedance. Another parameter is the rated current (I_a), which is the maximum steady state RMS current. In normal operation transient currents above the rated value may occur, but only for a limited duration. For example, when an electrical machine starts, it absorbs a larger current until it reaches its steady state operation. The overstepping is limited although the duration may be long (from seconds to minutes). When a transformer is connected, its inrush current can be very large but for a limited duration. These transient over-currents should not trigger the runaway of the SC element, thus they have to be lower than its quench current I_q. This requirement may be very severe. For the Vattenfall FCL provided by Nexans [1] the specification is to withstand 4100 A_{peak} during 50 ms followed by 1800 A_{peak} during 15 s whereas the rated current is 800 A! The maximum transient normal operation current function of duration (τ) is $k_a I_a(\tau)$, where k_a is ratio of the transient maximum current to the rated RMS current. The utility also fixes the limiting current (RMS value: I_{lim}). It depends on the FCL location, the protection coordination etc. Very often the limiting current may be higher during the first peak. It even may be a requirement for protections based on the amplitude of the fault currents[1]. The limiting current generally is not equal the SC limiting current due to the shunt impedance across the SC element (Fig. 4).

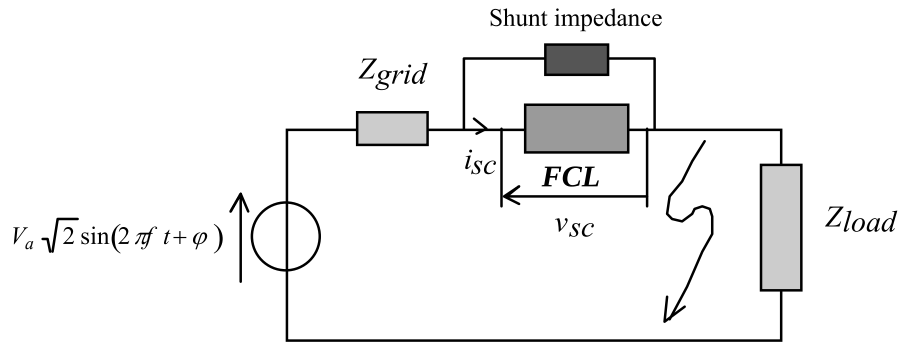

Fig. 4. Simple representation of the power grid with FCL (*f* is frequency).

The relative magnitudes of the different current values are qualitatively illustrated in Fig. 5. Those related to the grid are labelled below the current axis while those of the SC element are above it. The labels with asterisk are time dependent. Their relative positions on the axis are not always those of Fig. 5. The SC limiting current may be lower than the quench current even if one of the conclusions of this article is to show that a SC limiting current higher than the quench current is preferable.

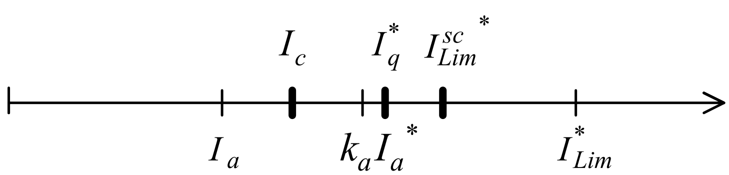

Fig. 5. The different currents related to the SC conductor (labels above axis) and to the grid (below).

The grid may experience a very wide range of faults. Faults depend on the type of grid (distribution, transmission, *etc.*), its structure (number and length of cables for example), and its location (town or rural). The three-phase short-circuit leads to the highest fault currents, but is a rare event, only a few percents of all the faults. Most of the faults are single-phase short-circuits with the earth. The corresponding fault currents are lower and depend on the grounding impedance that can be high. Moreover, objects causing a fault may have non zero impedance. A tree branch is an example. A fault due to an electric arc also exhibits impedance, which depends on time. It is important to emphasize that a fault current may take any value below the three phase clear short-circuit. The FCL must be designed to survive all kinds of faults, especially low current amplitude faults: they are the most severe for the

[1] Some switchgears on the grid open if the current oversteps a given value. When the limiting current is lower than this threshold value, the switchgear will not open and that is definitively inadmissible. Utilities do not want to change the today's protection system due to the FCL.

superconductor[2]. The tests of the FCL under variable voltage amplitude make possible to investigate the FCL response to such conditions.

After a fault the circuit must be inevitably isolated by a switchgear opening (O). However, it closes (C) very quickly again to provide continuity of service. In France, for overhead lines, the first closing time is only 300 ms. In the case of permanent fault it opens again (O-C-O, O-C-O-C, … duties). Most of the faults are indeed transient and disappear at the time of the circuit isolation. Birds between two phases are an example: they provoke an electric arc, which disappears when the switchgear opens. The short closing times may result in a severe specification for SC FCL.

The delay for opening after a fault is fixed by the utility and depends on the location. It can be very long (1.2 s for example) to guarantee the chronometric selectivity (time increase at each switchgear level).

IV. THE SC ELEMENT DESIGN

A. Permanent Operation

The transient overcurrent ($k_a I_a(\tau)$) should be lower than the quench current:

$$k_a \; I_a(\tau) \leq I_q \tag{8}$$

In a conservative manner, since the quench current oversteps the critical current, the first design equation is:

$$k_a \; I_a = I_c = J_c \; \alpha_{sc} \; A_{tot} \tag{9}$$

The permanent operation thus defines the SC cross section.

B. Limitation Regime

The limitation regime gives the main constraints for the SC element. In this regime the dissipated power levels are very high and the thermal exchange with the cooling fluid may be neglected in a first approximation. In the following, the conditions are thus supposed to be adiabatic.

C. Conductor Minimum Volume

As the thermal conditions are adiabatic, all the energy is dissipated in the SC conductor during the limitation period and causes the corresponding temperature increase. So the minimum SC volume ($Volume_{min}$) and length (L_{min}) are given by the simple following thermal balance equation:

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[2] When a fault has an impedance, the current is low but it is a fault that has to be cleared! Likewise, single phase faults induce in general low current amplitude due to rather high ground impedance.

$$Volume_{\min} \int_{T_o}^{T_{\max}} c_p(T)\, dT = L_{\min}\ A_{tot}\ c_p^m\ (T_{\max} - T_0) = \int_0^{\Delta t} v_{sc}(t)\, i_{sc}(t)\, dt \qquad (10)$$

$$Volume_{\min} = L_{\min}\ A_{tot} = \frac{\int_0^{\Delta t} v_{sc}(t)\, i_{sc}(t)\, dt}{c_p^m\ (T_{\max} - T_0)} \qquad (11)$$

The notation in these equations is:

- c_p^m: conductor specific heat per unit volume averaged between T_o and T_{max},
- $v_{sc}(t)$: instantaneous voltage across the SC element,
- $i_{sc}(t)$: instantaneous current through the SC element,
- Δt: fault hold time determined by the switchgear capacity,
- T_{max}, T_o: maximum and operating temperatures.

Furthermore, two RMS quantities are introduced (V_{sc} and $I_{sc}^{\lim}$):

$$\int_0^{\Delta t} v_{sc}(t)\, i_{sc}(t)\, dt = V_{sc}\ I_{sc}^{\lim}\ \Delta t \qquad (12)$$

The amplitude of the voltage across the FCL is nearly constant. The grid is a voltage source (see Fig. 4) with RMS value V_a. However, taking into account the voltage drop across the grid impedance the RMS voltage applied to the superconductor is V_{sc}. An approximate expression for V_{sc} is:

$$V_{sc} \approx V_a \left(1 - \frac{I_{Lim}}{I_{ULim}}\right) \qquad (13)$$

Here, I_{Ulim}, I_{lim} are the unlimited and limited currents of the grid (RMS values). In contrast to the voltage, the current varies strongly with time due to the non linear behaviour of the superconductor and the temperature dependence of the conductor resistance. The quantity $I_{sc}^{\lim}$ is then an average RMS current during the fault hold time through the SC element.

The minimum volume is then expressed by:

$$Volume_{\min} = L_{\min}\ A_{tot} = \frac{V_{sc}\ I_{sc}^{\lim}\ \Delta t}{c_p^m\ (T_{\max} - T_0)} \approx \frac{V_a \left(1 - \frac{I_{Lim}}{I_{ULim}}\right) I_{sc}^{\lim}\ \Delta t}{c_p^m\ (T_{\max} - T_0)} \qquad (14)$$

In the minimum volume equation, there is only one free parameter (and not completely), the SC limiting current $I_{sc}^{\lim}$. Superconductivity plays no part in the minimum conductor volume except for the maximum temperature. The specific heats per unit volume are rather similar for all ReBaCuO materials. Note that the minimum conductor volume does not depend on its resistivity. The minimum volume is proportional to the fault hold time. Its minimum value is fixed by the switchgear capacity (about 50 ms). For utility requirements (O-C duties) the fault hold time must be sometimes longer. To reduce the conductor volume through a short hold time an additional switchgear (SC-S) in series with the SC element can be added as shown in Fig. 6. The main switchgear (M-S) has a longer fault hold time to meet the utility requirements (O-C duty).

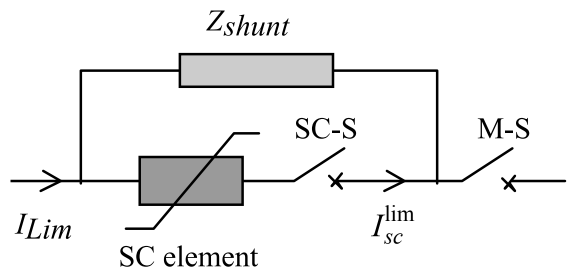

Fig. 6. Additional switchgear (SC-S) to reduce the SC volume; M-S is the main gear.

The maximum temperature must be below the temperature that damages the SC properties, *i.e.*, below 400 K/500 K. Consequently a maximum temperature of 300 K is often assumed to have some safety margins.

The maximum temperature can also be fixed according to the superconducting recovery times: the higher is the maximum temperature, the longer is the recovery time. Fig. 7 presents an example of the recovery time in function of the maximum temperature reached when the superconducting element with the AMSC[3] conductor is isolated.

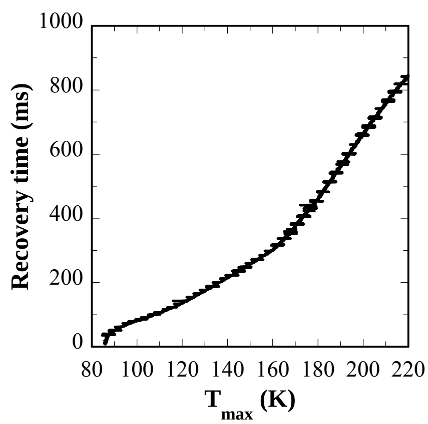

Fig. 7. Example of recovery time versus maximum temperature for an AMSC conductor operating at 77 K.

This figure shows that the maximum temperature must be rather low, roughly under 150 K, to obtain recovery times suitable for utilities (300 ms). This low temperature value leads to a too large SC volume. So during the recovery of the SC element, the line current passes through the shunt impedance (Fig. 6). There is, however, a voltage drop across this shunt impedance, but it exists only during the recovery duration. As soon as the SC element has recovered, the SC-S switchgear is closed. The shunt impedance is then short-circuited. If, for power quality reasons, the shunt impedance voltage drop is not possible, a second SC element must be added. It is put in operation at the closing time after the fault with dedicated switchgear. This solution is very expensive.

[3] AMSC is the acronym of American Superconductor Corporation.

D. Current Density and Electric Field in the Limitation Regime

The current density in the limitation regime is given by the thermal adiabatic balance equation:

$$\int_{T_c}^{T_{max}} \frac{c_p(T)}{\rho_{Cond}(T)}\, dT = \int_0^{\Delta t} j_{sc}^2(t)\, dt \tag{15}$$

It is the equation for hot spot temperature calculation classically used for SC magnet protection [14]. The mean RMS SC current density during limitation ($J_{sc}^{\lim}$) can be introduced:

$$\int_0^{\Delta t} j_{sc}^2(t)\, dt = J_{sc}^{\lim 2}\, \Delta t \tag{16}$$

$$J_{sc}^{\lim} \approx \sqrt{\frac{\int_{T_c}^{T_{max}} \frac{c_p(T)}{\rho_{Cond}(T)}\, dT}{\Delta t}} \tag{17}$$

Even if it is not strictly true, this current density is proportional to $I_{sc}^{\lim}$:

$$J_{sc}^{\lim} \approx \frac{I_{sc}^{\lim}}{A_{tot}} \tag{18}$$

The local electric field can be introduced. Neglecting the inductive effects, the electric field during limitation is expressed by the thermal balance equation:

$$\int_{T_c}^{T_{max}} \rho_{Cond}(T)\, c_p(T)\, dT = \int_0^{\Delta t} e_{sc}^2(t)\, dt \tag{19}$$

The RMS electric field under limitation, $E_{sc}^{\lim}$, is:

$$\int_0^{\Delta t} e_{sc}^2(t)\, dt \approx E_{sc}^{\lim 2}\, \Delta t \tag{20}$$

It is approximately proportional to $V_{sc}^{\lim}$:

$$E_{sc}^{\lim} = \sqrt{\frac{\int_{T_c}^{T_{max}} \rho_{Cond}(T)\, c_p(T)\, dT}{\Delta t}} \approx \frac{V_{sc}^{\lim}}{L_{\min}} \tag{21}$$

For these two quantities ($J_{sc}^{\lim}$ and $E_{sc}^{\lim}$) the considered temperature lower limit is T_c not T_o, since the resistivity of the SC layer is not well known under the critical temperature. It depends on the current amplitude for example.

The different approximations made above are the reason why the minimum volume given by Eq. (14) cannot be calculated again from equations (17), (18) and (21).

E. The SC Limiting Current and SC Volume

From equations (17) and (18), the SC limiting current is given by:

$$I_{sc}^{\lim} = A_{tot} \sqrt{\frac{\int_{T_c}^{T_{max}} \frac{c_p(T)}{\rho_{Cond}(T)} dT}{\Delta t}} \tag{22}$$

The SC limiting current can be adapted to requirements by properly choosing the whole conductor cross-section and its resistivity. From the conductor volume point of view, the SC limiting current should be as low as possible to reduce the conductor volume given by Eq. (14). However, this is dangerous if the conductor is not fully homogeneous. Unfortunately, this is the reality in practice, as opposed to our simplified model.

To illustrate how dangerous it is to choose a low SC limiting current, we consider the following example. Let the theoretical SC limiting current be half of the critical current. We assume that only 60 % of the SC element length quenches. The steady state SC limiting current is given by the SC element resistance of Eq. (2) proportional to the given length and is consequently:

$$I_{sc}^{\lim} = \frac{I_{sc\ theoretical}^{\lim}}{0.6} = 0.83\, I_c \tag{23}$$

As the SC current is lower than the critical one, the 40 % non-quenched part of the SC element remains superconducting whereas the 60 % quenched part experiences a dangerous temperature excursion above T_{max}. The normal zone propagation velocity is very low (some mm/s). The dissipated energy is by a factor of $(0.83/0.5)^2$ higher than the energy needed to reach T_{max}. This is why it is certainly safer to have a SC limiting current higher than the quench current:

$$I_{sc}^{\lim} > I_q(\Delta t) \tag{24}$$

This forces the total length to quench in the case of impedance short circuit.

The coefficient k_s is the ratio of the SC limiting current and the critical current:

$$J_{sc}^{\lim}\ A_{tot} = I_{sc}^{\lim} = k_s\, I_c = k_s\, J_c\, \alpha_{sc}\, A_{tot} \tag{25}$$

To fulfil the inequality (Eq. (24)) k_s must be higher than one. The minimum conductor volume for a single phase may then be expressed by:

$$Volume_{\min} = L_{\min}\ A_{tot} \approx k_s \frac{k_a\, I_a\, V_a \left(1 - \frac{I_{Lim}}{I_{ULim}}\right) \Delta t}{c_p^m \left(T_{\max} - T_0\right)} \tag{26}$$

In this expression the only remaining free parameter is k_s, because the fraction is fixed by utility requirements and the specifications for absence of conductor degradation or recovery ($T_{\max}$).

A safer quench through a high k_s value increases the conductor volume but it has no influence on the SC volume. The SC fraction may be derived from equations (17) and (25):

$$\alpha_{sc} = \frac{J_{sc}^{\lim}}{k_s\, J_c} = \frac{1}{k_s\, J_c}\sqrt{\frac{\int_{T_c}^{T_{\max}} \frac{c_p(T)}{\rho_{Cond}(T)}\, dT}{\Delta t}} \tag{27}$$

With Eq. (26), the SC volume is:

$$SC\_Volume_{\min} = \alpha_{sc}\ Volume_{\min i} = \frac{1}{J_c}\sqrt{\int_{T_c}^{T_{\max}} \frac{c_p(T)}{\rho_{Cond}(T)}\, dT}\ \ \frac{k_a\ I_a\ V_a \left(1 - \frac{I_{Lim}}{I_{ULim}}\right)\sqrt{\Delta t}}{c_p^m\ \left(T_{\max} - T_0\right)} \tag{28}$$

Equation (28) shows that k_s has no influence on the SC volume, which certainly is one the most expensive parts of the CC. Therefore, high SC limiting current increases the conductor volume but not that of the SC. The upper value for k_s is given by the maximum limiting current specified by the utility. To get the maximum value of k_s, the shunt impedance is not used at all. The lowest limiting current is given by the grid coupling FCL [12, 13] and may limit the k_s value. Equation (28) shows also that high resistivity reduces the SC volume whereas it has no direct influence on the whole conductor volume given by Eq. (14). The SC volume is inversely proportional to the square root of the electrical conductivity. However, a relatively low resistivity is of interest in the case of a partial quench, because it can limit the temperature rise of the quenched part. This is particularly true for an impedance fault (see Section V.), because in that case the grid behaves approximately as a current source and not as a voltage source.

V. INFLUENCE OF THE CONDUCTOR RESISTIVITY

We have also developed numerical modelling of a SC coated conductor. Also in this model the temperature is supposed to be the same across and along the conductor, which is then an isothermal block. As in the previous model of Section II.*A*., the conductor consists of two parts connected in parallel: the SC and the normal conductor (the shunt and the substrate). However, the superconductor is modelled here by a power law defining the dependence of critical current and the resistive transition index *n* on the temperature. The heat exchange with the bath is represented by exchange power whose dependence is a nonlinear function of the temperature difference between the bath and the conductor. The model is in good agreement with experimental data. We have used this model to study the consequences of conductor inhomogeneity. We considered two nearly identical conductors in series, with one having critical current 10 % lower than the other. The lengths of the two parts were identical (5 m each). There was no thermal conduction between the two conductors. Fig. 8 shows the influence of the normal resistivity of the conductor on the maximum temperature $T_{\max}$ *versus* the applied voltage. Numerical simulations show that varying the voltage gives very similar results to varying the fault current amplitude. As we have seen, it is very important that the SC FCL safely operates even when the fault current amplitude is low. From test point of view, it is easy to vary the voltage amplitude whereas it is complicated to vary the fault current amplitude at constant voltage amplitude.

In the left plot, the AMSC conductor resistivity was assumed [15], while in the right plot this resistivity was multiplied by a factor two. Other parameters were the same (I_c, *"n"*, A_{total}, c_p, short circuit conditions, *etc*.). This comparison shows that higher conductor resistivity results in significant excursion of T_{max} in the conductor having 10% lower I_c, but only for low voltages (or impedance faults). At low voltages, the maximum temperature difference between the low I_c and high I_c parts increased from 25 K to 100 K (Fig. 8) when the conductor resistivity was doubled. Experiments of Section VI confirmed that result. It indicates that the CC resistivity should be preferably moderate, even if it would increase somewhat the SC volume given by Eq. (28).

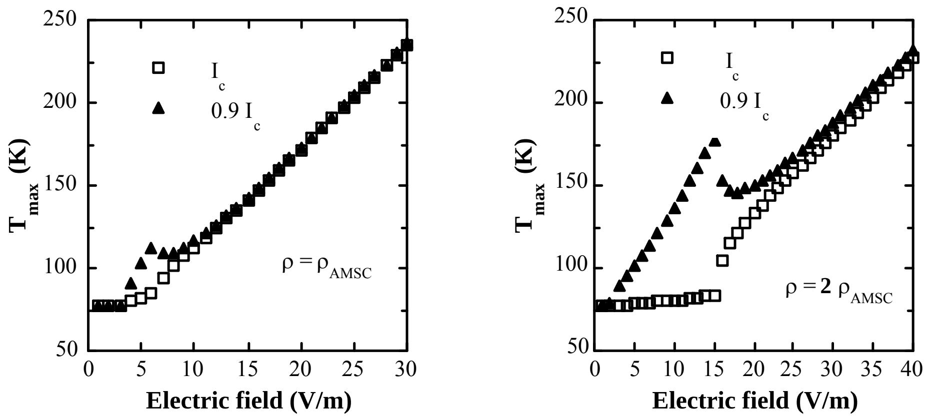

Fig. 8. Influence of conductor resistivity on the T_{max} versus applied voltage when a 10 % I_c reduction occurs in half of the length of the conductor. The left plot assumes the resistivity of the AMSC conductor. The right plot assumes twice that value.

VI. CONDUCTOR COMPARISON AND CURRENT LIMITING EXPERIMENTS

A conductor for a FCL is designed from all the specifications, including k_s. For available conductors, all the parameters are fixed and k_s can be calculated from equations (17) and (25).

Table 1 shows the main characteristics of the two CC we evaluated for FCL suitability. The resistivity is the conductor equivalent average resistivity between 90 and 300 K. From these data the relevant parameters during current limitation were calculated and are given in Table 2 (*f*or Δt = 50 ms; T_{max} = 300 K). The coefficient k_s is rather different for the two conductors: $k_s = 2$ for the AMSC conductor and $k_s = 0.7$ for that fabricated by SuperPower (SP). According to the discussion in Section IV.E., the conductor with large k_s value should exhibit a safe homogeneous behaviour whereas the conductor with a k_s value lower than 1 could have an inhomogeneous behaviour for impedance or low-voltage short circuits.

Table 1. Main characteristics of two YBCO CCs Evaluated for FCL.

Parameter	AMSC 344 S [15]	SuperPower (SP) SF 1210 [16]
A_{tot} (mm^2) α_{sc}	4.3 x 0.16 0.0058	12 x 0.106 0.0094

ρ_{sc} (μΩm)	0.138	0.226
I_c (A) (77 K, 0 T)	85	350
J_c (MA/m^2) (77 K, 0 T)	21 250	29 250

Table 2. Calculated parameters for the two YBCO CCs (Δt = 50 ms ; T_{max} = 300 K).

Parameter	SP	AMSC
E_{lim} (V/m)	58	40
J_{Lim}^{SC} (MA/m^2)	193	247
k_s	0.7	2

Fig. 9 shows the time evolution of the current and electric fields measured along a 10 m long AMSC conductor at low voltage (0.27 V_a). The rated voltage (V_a) corresponds to the applied electric field calculated from Eq. (21) with T_{max} = 300 K. The electric fields are the measured voltages divided by the distance between the voltage taps (about 1 meter) along the conductor. The ten (10) superposed $E_{lim}(t)$ plots indicate that the quench was homogeneous even under these unfavourable conditions. This could be correlated with temperature calculations [17]. The current evolution explains in part this homogeneous behaviour. It exceeds the critical value (85 A) by more than a factor of 4 in the first peak, and remains high even after it, as could be expected at the high k_s value, which forces the conductor to quench. Even for a voltage as low as 0.12 V_a the quench remains homogeneous along the sample.

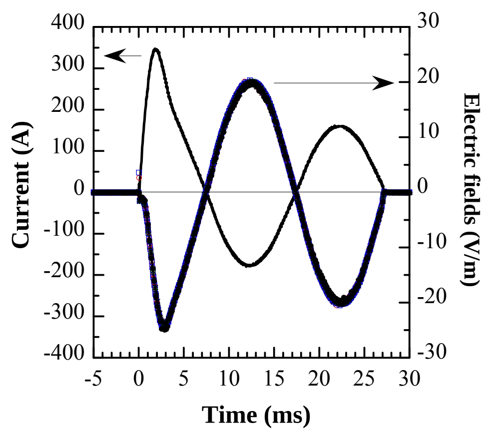

Fig. 9. Current and electric field versus time measured on a 10 m long AMSC conductor at 0.27 V_a. The $E_{lim}(t)$ plot is the superposition of the (10) such curves measured at 10 positions along the conductor.

Fig. 10 shows a different behaviour with a one-meter- long Super Power conductor measured at a voltage of 0.26 V_a. The electric fields are rather different along the sample indicating inhomogeneous quench. The temperature calculations lead to the same conclusions [17]. As expected for the low value of k_s = 0.7, the current evolution with time is different than in the AMSC conductor. The peak current is only 2.3 times of I_c and is rather sharp. The current decreases rapidly after the first peak and its amplitude becomes lower than the critical current (350 A). This does not force the conductor to quench. However, by increasing the voltage to 0.47 V_a, the quench becomes homogeneous as shown in Fig. 11. The current evolution with time is noticeable on this figure. The peak is very sharp and the current is strongly reduced afterwards.

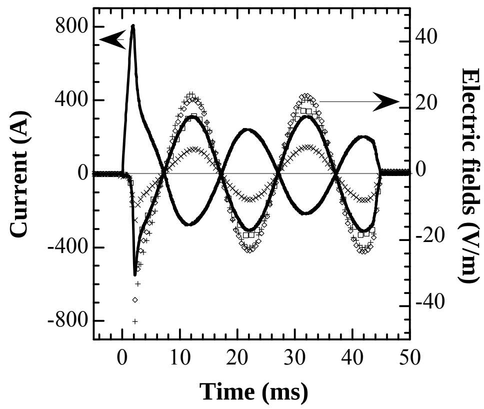

Fig. 10. Current and electric field along 1 m length of SuperPower conductor at 0.26 V_a.

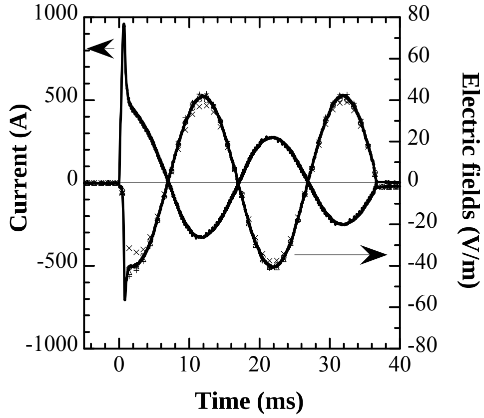

Fig. 11. Current and electric field along 1 m length of SuperPower conductor at 0.47 V_a.

Fig. 12 shows the first peak current and the "steady state" limiting current versus the electric field measured for the two conductors. These data were obtained at different voltages. The electric field is the total voltage divided by the full length of the conductor. The currents are normalised to the critical current at 77 K. The two conductors show rather different behaviours, correlated with the k_s values. The first peak exceeding the critical current is more pronounced for the AMSC conductor, which also exhibits a much higher steady state limiting current. Fig. 13 shows the same quantities plotted versus the theoretical maximum temperature (T_{max}), which is a more relevant parameter for the FCL than the electric field. The maximum temperature was calculated from Eq. (21).

Fig. 12 also justifies our simple approach to modelling of the SC element (Fig. 2), especially for the AMSC conductor, because the model hypothesis (quench over the full length) is valid in this case.

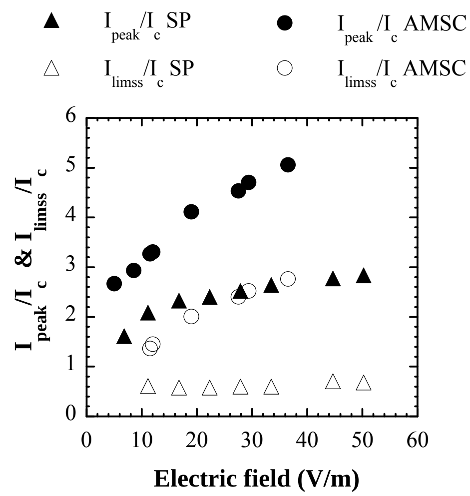

Fig. 12. First peak and steady state limiting current normalised to I_c versus the electric field.

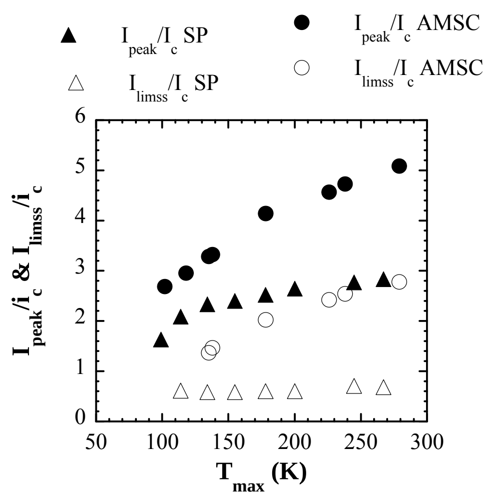

Fig. 13. First peak and steady state limiting current normalised to I_c versus the maximum temperature.

VII. CONCLUSIONS

We proposed an analytical design of ReBaCuO-coated conductors suitable for fault current limiters. Several hypotheses and assumptions were necessary to obtain the analytical expressions, but they allowed us to identify the relevant parameters and perform the first pre-design. Numerical simulations remain indispensable for a more accurate design.

In the limitation regime, the SC conductor for FCL is mainly defined by thermal criteria. Its minimum volume is given by utility requirements, the maximum acceptable temperature rise for the conductor and the “steady state” SC (through the whole conductor) limitation current. The coefficient k_s is the ratio of this current to the critical current. This is the only free parameter available for the conductor design. Utility requirements give the upper limit of k_s, especially for FCLs used in grid coupling. The minimum conductor volume is proportional to k_s. It could be interesting to choose low k_s but then, especially if $k_s < 1$, the low SC limiting current does not force all the conductor to quench and can lead to dangerous local temperature increase, ressembling the usual case of inhomogeneous quench. Therefore, it is preferable to have a high k_s value with a larger conductor volume, to make the quench more homogeneous. Furthermore, this does not increase the SC volume, which is k_s independent. The coefficient k_s may be adjusted through the total cross section and the resistivity of a conductor. Although the conductor resistivity has no influence on the whole conductor minimum volume, it affects the SC volume and high resistivity reduces it. However, high resistivity leads to high local temperature rises during inhomogeneous quenches.

We compared experimentally the performance of two existing YBCO CC conductors with different k_s. Our measurements confirmed that a high k_s is favourable for a homogeneous quench under low voltages: high k_s assures satisfactory behaviour under impedance faults that are a most common reality to cope with in a real grid.

We believe that the presented expressions may be suitable for other SC materials (BiSCCO and MgB_2) with relatively small adaptations.

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