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# Superconducting Fault Current Limiter optimized design

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ABSTRACT

The SuperConducting Fault Current Limiter (SCFCL) appears as one of the most promising SC applications for the electrical grids. Despite its advantages and many successful field experiences the market of SCFCL has difficulties to take off even if the first orders for permanent operation in grids are taken. The analytical design of resistive SCFCL will be discussed with the objective to reduce the quantity of SC conductor (length and section) to be more cost-effective. For that the SC conductor must have a high resistivity in normal state. It can be achieved by using high resistivity alloy for shunt, such as Hastelloy®. One of the most severe constraint is that the SCFCL should operate safely for any faults, especially those with low prospective short-circuit currents. This constraint requires to properly design the thickness of the SC tape in order to limit the hot spot temperature. An operation at 65 K appears as very interesting since it decreases the SC cost at least by a factor 2 with a simple LN2 cryogenics. Taking into account the cost reduction in a near future, the SC conductor cost could be rather low, half a dollar per kV A.

## 1. Introduction

Faults are rather rare events in grids but cannot be avoided. The grids are protected against them but without satisfying solution today. The solution is indeed to artificially limit the fault current by introducing impedances. So the peak current value does not oversize too much some devices such as transformers and can be cut by a mechanical switchgear some tens of ms after the fault. These impedances bring harmful voltage drops in normal operation. Many interesting grid architectures are impossible due to the requirement to limit fault currents. The issue is still more critical for DC grids compared to AC grids. The absence of zero crossing of the DC current makes its cutting much more difficult. This issue is a bottleneck for HVDC meshed grids. Some HVDC circuit breakers have been developed but they are very expensive and still limited in terms of currents to be cut.

So there is definitely a demand of a better solution for protection. The Fault Current Limiter (FCL) appears as an outstanding technical solution by providing a variable impedance: very low in normal operation and high in fault conditions. Superconductors offer inherently this property through their highly non-linear electric field versus current intrinsic characteristic. So the SCFCL appears as a greatly interesting device for the grids. The works about SCFCL started a long time ago with low $T_c$ superconductors (LTS-NbTi) [1] then with high $T_c$ superconductors (HTS-BSCCO, YBCO, $MgB_2$).

Numerous SCFCL are operating in the grid worldwide [2–5] but the market hardly takes off. The order of two SCFCL for permanent installation in the United Kingdom grid [6] shows that it changes. The still high cost of the SCFCL is one hurdle. This article shows how to reduce the cost of the SC element through a suitable design.

## 2. Studied SCFCL and material

There is all a zoo of SCFCL [7] but the resistive type presents many advantages in terms of footprint and weight inter alia. Only the resistive type will be considered in this article.

For the SC material three choices are possible: BSCCO, YBCO and $MgB_2$. The BSCCO appears now less attractive than YBCO Coated Conductors (CC), available today in lengths suitable for SCFCL and with high performances. The YBCO CC cost remains high but with perspectives of strong reduction in the future. One main advantage compared to BSCCO is certainly the much lower AC losses with direct cost consequence for cryogenics (investment and operation).

$MgB_2$ presents a cost significantly reduced compared to YBCO CC but should operate at much lower temperature, typically 20 K. The cryogenic cost (cost to remove the losses dissipated at the operating temperature) is considerably higher; Carnot's formula shows an increase of 480% and 370% at 20 K compared to 77 K and 65 K respectively. Due to the geometry of $MgB_2$ conductors compared to YBCO CC, $MgB_2$ shows inherently stronger AC losses.

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Higher AC losses and larger cost removal hardly makes $MgB_2$ AC FCL viable compared to YBCO one. $MgB_2$ FCL could be possible for DC grids. Cryogenics remains anyways difficult. The use of liquid nitrogen, which is a fully industrial fluid is no more possible. Liquid hydrogen is much less common in the industry and presents security issues. A cooling fluid offers the best solution for a short recovery time. This is the delay for the SC element to return to its superconducting state and so to be put in operation again after a limitation.

The following will thus concern YBCO resistive FCL.

## 3. YBCO CC conductor (Fig. 1)

This configuration is asymmetric mainly for easy injection of the current in the YBCO layer and low AC losses. With this configuration the current has only to cross the very thin silver layer to be injected in the YBCO layer with a very low contact resistance, down to tens of $n\Omega\,cm^2$ with proper implementation [8]. The AC losses are minimum considering the face-to-face configuration [9] when the distance between the two YBCO layers with currents in opposite direction is minimum. On the other hand this YBCO conductor configuration prevents from short bending radii but this is not an issue for a SCFCL. The winding radii are in general large. The minimum bending radius ($R_c$) is given by the critical strain in traction [10]:

$$R_c > \frac{e_{cond}}{2\varepsilon_t^{irr}} \qquad (1)$$

The quantities $\rho$ and $c_p$ refer in the following to the conductor with all its $K$ components (cross-section $A_k$) in parallel.

$$c_p = \frac{1}{A_{cond}}\sum_{k=1}^{K} c_p^k A_k \quad \text{and} \quad \frac{1}{\rho} = \frac{1}{A_{cond}}\sum_{k=1}^{K}\frac{A_k}{\rho_k} \qquad (2)$$

This assumes that the behavior is homogeneous through the cross section. This point will be discussed shortly in Section 5.

Fig. 1 shows that the conductor is designed when its three dimensions are known: $w_{SC}$, $L_{SC}$ and $e_{cond}$.

## 4. YBCO CC conductor design

The YBCO CC tape acting as FCL must be designed so that it sustains every possible kind of fault in the grid. In the following section we will present how the geometric parameters, $w_{SC}$, $L_{SC}$ and $e_{cond}$, can be defined sequentially, and the interest of adjusting the equivalent resistivity of the tape to minimize the conductor cost for a given application.

### 4.1. Conductor width ($w_{SC}$)

Knowing that the thickness of the YBCO layer is fixed by the elaboration process, the critical current ($I_c$) of the YBCO CC tape is given by its width and written $I_{c-w}$. In normal operation of the grid the limitation should not be triggered by some limited over-currents. The rated current ($I_a$) of the grid is the maximum steady state current in RMS value but this current can be overstepped in transients for example when some large motors are starting. We define the quench current of the FCL as the current which leads to a thermal runaway, it depends on the cooling conditions but is always higher than the critical current but only slightly due to the high resistive index transition ("$n$" value) of the YBCO layer. By assuming that the quench current equals the critical current, we thus obtain a small margin of operation. Therefore it must be higher not only to the rated current ($I_a$) but to the peak current in the grid normal operation. This can be written ($k_a \cdot I_a$), with $k_a$ a multiplying factor taking into account all kind of possible transient increase of current (including the square root two factor in case of AC grid). So we get the conductor width:

$$w_{SC} = \frac{k_a I_a}{I_{c-w}} \quad (k_a I_a = I_c = I_{c-w} w_{SC}) \qquad (3)$$

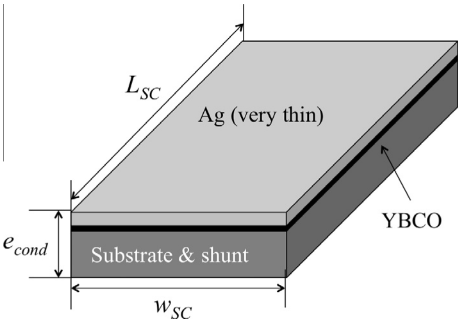

**Fig. 1.** Simplified cross section of the YBCO coated conductor.

Eq. (3) shows that $I_{c-w}$ should be as high as possible to reduce the width. $I_{c-w}$ depends on the tape performances and on the temperature. Already high (300–400 A/cm-w 77 K, self field) $I_{c-w}$ will still rise in the following years. It increases by lowering the temperature. So an operation in liquid nitrogen at 65 K appears very attractive: we still benefit from the large advantages of liquid nitrogen and from significantly higher critical currents. Since liquid nitrogen freezes at 63 K, 65 K is the minimum practical temperature. The critical current is at least doubled at 65 K compared to 77 K: this is a very significant improvement for only a slightly more complicated cryogenics. A supplementary cryogenic loop with a vacuum pump and a heat exchanger is required. The temperature is regulated by the control of pressure in the heat exchanger. Another advantage is the possibility to easily adjust the operating temperature and through it the threshold value of the SCFCL. The cryogenic cost increases but only by 20% at 65 K compared to 77 K according to Carnot.

### 4.2. Conductor length ($L_{SC}$)

The conductor length $L_{SC}$ only has an impact in case the prospective current is high compared to the critical current, which leads to a homogenous quenching of the superconductor and thus a homogenous increase of its temperature. In this case the length is mainly given by thermal considerations. Some approximations will be done to get analytical formula for $L_{SC}$. They give nevertheless good orders of magnitude. The main approximation is that some tape characteristics such as the averaged normal state resistivity ($\rho$) and specific heat per unit volume ($c_p$) do not vary with temperature. The thermal operations will be considered as adiabatic, without any exchange with the bath. The inductance of the SC element is neglected as well. We will consider the simplest electrical circuit (Fig. 2) represented by a voltage source (amplitude $V_a$, the rated circuit voltage) in series connection with an impedance ($Z_{grid}$, Thévenin equivalence). The circuit is closed by the SCFCL for a clear short-circuit (zero impedance).

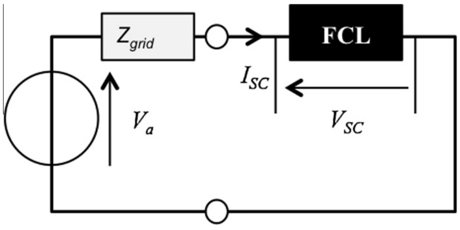

**Fig. 2.** Simplified grid representation with the SCFCL for a clear short circuit.