Behaviour of different artificial weak zones in superconducting elements working in inductive fault current limiters

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Abstract. The thermal recovery of superconducting elements working as secondaries in fault current limiters can be enhanced by taking advantage of the removal of heat by conduction from an array of artificial weak zones (AWZ) distributed along the superconductor perimeter (hot parts) to the non-weak segments (cold parts). These results were obtained by studying samples with weak parts in the shape of grooves, all identical in size. In this paper we consider the case in which one of the AWZ is slightly different. Our results show that a change in its length has a negligible effect. On the contrary, a groove which is slightly deeper can be overheated and hence can strongly determine the recovery time of the whole limiter.

1. Introduction
Fault current limiters (FCL) based on bulk high temperature superconductors (HTSC) have been extensively studied [1, 2, 3], but several drawbacks have impeded their practical implantation for the time being. High power applications, in particular, demand FCL working with huge superconducting elements which tend to be quite inhomogeneous because of the presence of weak parts, having a lower critical current density due to the lack of oxygen, cracks, etc. These defects provoke the appearance of hot spots which endanger the thermal stability of the superconducting samples and lead to an unsatisfactory performance (low impedance under a current fault, long thermal recovery times, ...). In previous works [4, 5, 6, 7, 8], the thermal behaviour of inductive FCL based on bulk HTSC samples with artificial weak zones (AWZ) was studied by assuming the non-propagation of the hot spots produced in the AWZ under a current fault. Under this assumption, the superconducting elements (cylinders) were modeled as a set of narrow hot domains (the AWZ) separated by cold domains (the remaining parts of the cylinders). It was found that the heat exchange (by conduction) between the hot and cold domains plays a central role in the thermal behaviour of the superconducting elements and, therefore, in the recovery time of the FCL once the fault has been cleared. Figure 1 shows the temperature distribution at $t = 1\,s$ after a fault provoked in a superconducting element with grooves. This figure was obtained by using a finite element routine (see details in reference [8]) and it shows how the heat produced in the AWZ, $\dot{Q}$, is removed to the adjacent cold segments.

In all the aforementioned works it was assumed that AWZ could be done in such a way that they were absolutely identical. Nevertheless, many fabrication processes could lead to
grooves being slightly different, with dimensions varying just a very small percentage which, in turn, could be maybe enough to alter the normal performance of the SFCL. In this work we study numerically the influence on the performance of the inductive fault current limiter used in previous works [6, 7, 8] of small variations in the dimensions of one AWZ and we will focus on the heating of the superconducting element resulting from the limitation process.

2. Numerical routine
The simulation routine has been described elsewhere [8]. It is studied an inductive limiter whose nominal voltage and current are 6.3 kV and 2.4 kA, respectively. The magnetizing inductance is \( L_n \approx 0.18 \text{ H} \), for a number of turns in the primary coil \( N_p = 56 \). The secondary is a superconducting cylinder of YBCO, grown in such a way that the current circulates along the c-axis, allowing a larger normal-state resistance [9].

The thermal equation is expressed as follows:

\[
C_p \rho \frac{\partial T}{\partial t} + \nabla \cdot (-\kappa \nabla T) - Sh(T - T_0) = J \cdot E, \tag{1}
\]

where the heat capacity of the superconducting material (assumed to be temperature independent) is denoted as \( C_p \), its density by \( \rho \), \( \kappa \) denotes the thermal conductivity and \( h \) the convection coefficient. \( S \) is the area through which heat is exchanged by convection and \( T_0 \) is the bath temperature. Let us remark that we are going to use a 1-D routine, so it is assumed a homogeneous temperature distribution throughout the wall’s width. In these conditions, the importance of the convective coefficient could be somewhat overestimated, as heat is supposed to need some time to travel from the inner wall to the outer surface. To avoid this the convective term has been neglected. Notice that this is not a bad approximation, as heat can be scarcely removed by the coolant during the short time intervals used in these calculations (which are only about 100 ms). This was previously stated by using a finite element routine, so this approach does not yield a noticeable error.

The \( E - J \) curves are parametrized by the set of equations:
E = \begin{cases} 
E_0 \left( \frac{|J|}{J_{c0}} \right)^n \left( 1 - \frac{T - T_0}{T_c - T_0} \right)^{-n} \text{sign}(J) & |J| \leq J_b(T) \text{ and } T < T_c \\
E_0 \left( \frac{J_b(T)}{J_{c0}} \right)^n \left( 1 - \frac{T - T_0}{T_c - T_0} \right)^{-n} \text{sign}(J) + 
\rho_n [J - \text{sign}(J)J_b(T)] & |J| > J_b(T) \text{ and } T < T_c \\
\rho_n (1 + \gamma(T - T_c)) & T \geq T_c 
\end{cases}

where \( E \) is the electric field in the superconducting cylinder, \( E_0 \) is the electric field at the critical current density, \( J_{c0} \) (it is assumed the usual criterion \( E_0 = 1 \, \mu \text{Vcm}^{-1} \), \( n \) is the flux-creep exponent, \( J_b(T) \) the boundary current density value separating the flux-creep and flux-flow regimes and \( T_c \) the critical temperature. The normal state resistivity at \( T_c \) is denoted as \( \rho_n \), and \( \gamma \) is the temperature coefficient which allows the calculation of the ohmic resistance from \( T_c \) to ambient temperature.

The variation of the critical current density (and that of \( J_b(T) \), as well) with \( T \) is calculated as usual, i.e. by using the linear approximation

\[ J_c(T) = J_{c0} \left( 1 - \frac{T - T_0}{T_c - T_0} \right). \]

In all the calculations, the cylinder’s height is \( z = 1 \, \text{m} \), its diameter is \( \phi = 0.62 \, \text{m} \) and the wall thickness is \( e = 2 \, \text{cm} \). Its critical current density at \( T = 77 \, \text{K} \) is \( J_{c0} = 2 \times 10^7 \, \text{Am}^{-2} \), \( J_b = 1.25 \times J_{c0}, C_b = 100 \, \text{JKg}^{-1}\text{K}^{-1}, \rho = 5000 \, \text{Kgm}^{-3} \), and \( T_0 = 77.3 \, \text{K} \). A parameter \( a \) is defined as a function of the wall thickness and the depth of the grooves, \( \Delta \), as the ratio \( a = (e - 2\Delta)/e \) (so it would be the unity for an ungrooved sample). \( \rho_n = 150 \, \mu \Omega \text{m} \) is the normal state resistivity of the material at the onset temperature and \( \kappa_{||} = 10 \, \text{Wm}^{-1}\text{K}^{-1} \) the thermal conductivity (given by the parameter \( a \)) which is let to vary. The length of the cold domains is always \( \ell_c = 0.5 \, \text{cm} \), while that of the grooves is \( \ell_i^h = 0.5 \, \text{cm} \) except for the unlike weak zone, which varies from 0.45 cm to 0.55 cm. The parameter \( a_1 \) is always 0.80 and \( a_0 \) goes from 0.72 to 0.81. The dimensions of all the samples used in this work are gathered in Table 1.

### 3. Results

First of all, let us remember how is the performance of a set of identical AWZ in a superconducting cylinder (so \( \ell_i^b = \ell_i^h \) and \( a_0 = a_i \)). Figure 2 shows the primary current and the temperature excursions obtained when the cylinder C1 is used. The current in Figure 2(a) is strongly limited from the first half cycle, in more or less the same way that it would be done with a homogeneous cylinder. Concerning the temperature variation, shown in Figure 2(b), it can be seen that that of the ungrooved segments does not change at all, and they remain at 77 K. On the contrary, the weak zones heat up till about 100 K. In fact, they accomplish the current limitation.
Table 1. Resume of the dimensions of the samples used for the calculations. See text for details.

| Sample | $a_0$ | $a_i$ | $\ell^h_0$ (cm) | $\ell^h_i$ (cm) | $\ell^c$ (cm) | $\phi$ (m) | $z$ (m) |
|--------|-------|-------|-----------------|-----------------|--------------|----------|--------|
| C1     | 0.80  |       | 0.50            |                 |              |          |        |
| C2     | 0.79  | 0.80  | 0.50            | 0.50            | 0.62         | 1.25     |        |
| C3     | 0.72  |       | 0.50            |                 |              |          |        |
| C4     | 0.72  |       | 0.50            |                 |              |          |        |
| C5     | 0.81  |       | 0.50            |                 |              |          |        |

Figure 2. (a) Limited current during the actuation of the SFCL based on a grooved cylinder. (b) Temperature excursion of the ungrooved samples and the AWZ when they are identical.

Figure 3 shows what is the influence of a longer or shorter AWZ. In this case, a variation of 10% is allowed. It can be observed in Figure 3(a) that the longer groove of cylinder C2 heats up only a bit more than the rest. On the contrary, as displayed in Figure 3(b), if the groove is shorter (cylinder C3) its temperature firstly follows that of the other AWZ, but suddenly it starts to cool down (and this goes on very slowly as dissipation stills continues). Therefore, when the length of one of the grooves is different from that of the rest, the main difference is that it contributes a bit more or less to the total impedance. Although it can reach a higher temperature, the difference seems not to be excessive.

Let us see now what would occur in case the depth of the groove is changed. Figure 4(a) shows the behaviour of the cylinder C4, with a slightly different groove characterized by $a_0 = 0.79$, i.e. 1.25% smaller than $a_i = 0.8$ (with $\epsilon = 2$ cm this implies an error of about 200 $\mu$m). As
Figure 3. Temperature excursions when $\ell_0 > \ell_i$, (a), and $\ell_0 < \ell_i$, (b).

this groove has a lower critical current, it arrives promptly to the dissipative state and heats up noticeably more than the rest of grooves. This is even more dramatic in case the difference in depth is increased till 10% (cylinder C5), as indicated in Figure 4(b). As can be seen, the temperature of the weakest zone largely doubles that of the rest of grooves. This represents a serious problem, as surely the open circuit time (during which the current is zero) is not going to be long enough to allow this groove to recover the bath temperature. On the contrary, the temperature curves for the case in which $a_0 = 0.81$ (i.e. 1.25% greater than $a_i = 0.8$, corresponding to the cylinder C6) is displayed in Figure 4(c). As the critical current of the groove with a lower depth is a bit higher, the rest of grooves enter before in the dissipative state and the consequence is that the unlike groove behaves as any of the ungrooved segments in the sample.

4. Conclusions
We have studied the thermal behaviour of HTSC samples with artificial weak zones in the shape of grooves operating in fault current limiters. The study has been focused on the influence of non-identical grooves on the performance of the SFCL. We have slightly increased and decreased both the length and depth of one of the grooves, and we have studied how this affects the temperature distribution in the cylinder. Our results show that a small difference in the unlike groove’s length does not provoke dramatic changes in its temperature, so it affects in a moderate way the thermal recovery. A groove whose depth is a bit lower than that of the rest of grooves does not participate in the current limitation, and remains, as a cold segment does, still in the superconducting state. On the contrary, if a groove is deeper than the rest, its temperature rapidly grows. Although all the grooves contribute to the current limitation, the unlike groove
Figure 4. Temperature excursions when $a_0$ is 1.25% smaller than $a_i$, (a), and $a_0$ is 10% smaller than $a_i$, (b). (c) Temperature evolution when $a_0$ is 1.25% greater than $a_i$.

determines the recovery time. This indicates that AWZ must be carefully fabricated to avoid a bad performance of the whole current limiter.

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