A novel method of flat YBCO rings development for shield-type superconducting fault current limiters fabrication

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**Article Info**

Article history:
Received 30 July 2011
Received in revised form 15 September 2011
Accepted 18 October 2011
Available online 24 October 2011

Keywords:
Fault current limiter
Shield type
High temperature
Superconductor ring

**Abstract**

The application of flat superconductor rings has been investigated in the structure of inductive shield-type high temperature superconducting fault current limiters, HTc-SFCL. A laboratory scale inductive shield-type HTc-SFCL has been designed and fabricated using flat superconductor rings. The fabrication process has been fully presented. YBCO powder has been used for the fabrication of superconductor rings. This fabrication process, being quite innovative, is introduced completely. The method of the trapped field measurement has been used for the critical current density measurement of the fabricated superconductor rings. The device with nominal current of 2 A was tested in a 30 V circuit. The SFCL successfully limited the fault currents of up to 10 times the nominal current to an approximately fixed value of 3 A. The voltage–current characteristic of the fabricated prototype has also been obtained and has shown compatibility with the fault current limitation results.

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1. Introduction

Based on ability to carry transport current in the presence of high magnetic fields at liquid nitrogen, bulk YBa2Cu3O7−x (Y123 or YBCO, 0 < x < 1) ceramic superconductor has significant potential for practical high field engineering applications. Melt-texture processing is known to be a promising way to fabricate high temperature bulk superconductors (like YBCO). There are some methods to fabricate YBCO samples by melt-texture method that details are elsewhere [1–5]. Because the brittle nature of ceramics makes it hard to machine them into required shapes as rings, shaping is an important aspect of these materials for applications. The shaping aspects of high temperature ceramic superconductors have been undergoing intensive research [6–8]. For making a flat ring of high temperature ceramics the usual method is to fabricate a pellet and drill the center of it [9,10]. In this paper the ring is fabricated directly by use of suitable cast and then it has been annealed by melt-texture method. Commercial high purity YBCO powder (99.99) has been used for superconductor ring fabrication.

The critical current density of fabricated ring is also measured with the method of the trapped field measurement using a magnet device. The fabricated flat superconductor ring has been utilized in the structure of inductive shield-type SFCLs and its impact in the current limitation of SFCLs has been investigated.

The superconducting fault current limiter, SFCL, can be used to limit the short-circuit current level in electrical transmission and distribution networks and is one of the most promising devices for transmission and distribution of electrical energy due to low nominal losses, reliable operation, very short reaction times to fault currents and an automatic response feature without the requirement of an external trigger mechanism [11,12].

An inductive current limiter operates like a transformer that has a shorted superconducting secondary winding. The impedance of this current limiter under normal operating conditions is nearly zero, since the zero impedance of the secondary superconducting winding is reflected on the primary circuit. In the event of a fault, the secondary winding transits from superconducting state. Thus the secondary resistance will increase which will subsequently limit the fault current [13–16].

The secondary winding may be a high temperature superconductor (HTS) bulk cylinder whose function under normal condition is to shield the flux generated by the primary winding from entering the iron core of the current limiter. The primary winding is usually made from copper connected directly to an electric circuit. In the normal operation of the SFCL, according to the induced currents associated with the critical state model, no flux enters the core and the SFCL shows a low inductance. In the fault condition the ampere-turns balance of the transformer is destroyed and flux from the primary winding enters the iron core. The inductance and impedance of the primary winding rapidly increase limiting the fault current of the circuit [12,17]. Various designs have been proposed [11,17–23]. Nowadays, HTS bulks are broadly used in worldwide SFCL projects. References [24,25] discuss the use of HTS bulks in a large-scale SFCL and their advantages. Meanwhile, the application of SFCLs with bulk superconductor material is developing as a
A protection device in power systems and some devices are already installed as in [26]. Furthermore, taking into account the fabrication simplicity and the lower costs of HTS bulks relative to other alternatives, it seems to stay as an important choice for use in future SFCLs. Improvements in HTS properties, such as flux pinning and the ability to grow large grains, have greatly improved the economics of applications that use bulk HTS [27].

Using the fabricated flat superconductor rings, a prototype SFCL has been fabricated and tested in a circuit. Faults have been imposed and the experimental test results have been reported.

2. The structure of the SFCL

According to part 1, a two dimensional view of the SFCL structure – due to the existing axial symmetry – is shown in Fig. 1. The primary copper winding has been split into two windings and the superconductor flat ring is placed between these two winding parts.

3. Flat superconductor ring fabrication

3.1. Casting

A four piece cast is used for casting of the flat YBCO ring, as shown in Fig. 2. The YBCO powder is pulverized thoroughly and poured with acetone, for its better flow and to fill the cast in a better form. The amount of powder is determined from the bulk YBCO material density of approximately 5 g/cm³ with the volume of the ring determined in the design process. With the dimensions of the ring as in Fig. 3, the amount of powder used was approximately 8 g.

As the preliminary fabrications showed some cracks on the upper surface of the ring, after press and removing the uppermost piece of cast, due to the pressures on this surface from bilateral forces, as shown in Fig. 2, the inner part of the cast, where the YBCO powder is poured, is impregnated with silicon rubber which harnesses the bilateral forces and a sound ring is obtained.

3.2. Pressing

The obtained flat ring through casting process is put under continuous pressure of 375 MPa which is chosen to be higher than known pressures in past bulk productions [28,29]. A sample flat ring, with given dimensions, is obtained after pressing it as shown in Fig. 3. For a ring having specific dimensions as in Fig. 3, a force of 20 Tons would be required. The cast has been put under this force for 24 h. As the silicon rubber penetrates the surfaces of the ring which have been in contact with it, these surfaces are scraped with thorn in order to get a high purity flat superconductor ring.

3.3. Annealing

The formed bulk flat ring should be put in the furnace for crystal formation. Two processes may be followed in annealing: the diffusion and the melt-texture. The temperature profiles of these methods defer both in terms of the temperature magnitude and in terms of the duration of the process. The critical current density of the superconductor rings obtained through these processes would be different. The temperature reaches a higher level in the melt-texture method rather than the Diffusion Method. So the formed polycrystals have larger sizes and the critical current density is higher. For this work, in the melt-texture process the ring was heated up to 1030 °C with a ramp of 10 °C/min without overshooting and was hold constant at this temperature for 70 min. Then the sample was cooled down quickly to 970 °C and was hold at this temperature for 24 h. At the end, the oxygenation was performed at the temperature range between 400 and 600 °C for 20 h.

Fig. 1. The structure of the proposed SFCL.

Fig. 2. The four piece cast for bulk ring production.
Via measuring the critical current density of the ring, its characterization and the difference between two methods may be determined which is performed in part four. The fabrication process for larger scale flat rings essentially remains unchanged. A larger ring certainly requires an elevation of all the ring fabrication apparatus i.e. a larger cast, an elevated press machine, larger annealing system. Quantitatively, the pressing force is proportional to the area of the flat ring and the furnace effective size is proportional to the size of the flat ring e.g. for a ring with doubled dimensions, the needed material increases by a factor of eight, the pressing force should be increased by a factor of four and the furnace effective size should be doubled. It should be mentioned that utilizing this fabrication method, the larger the flat ring is, the less would be the waste of material relative to the machining of the solid parts.

4. Critical current density measurement

To calculate $J_c$, the method of the trapped field measurement has been used. The superconductor bulk is immersed in liquid nitrogen in a styrofoam chamber. The chamber is set under the magnetic field. For the production of a uniform magnetic field, a tuneable magnet device has been used which has an adjustable gap (between 0 and 8 cm), and a cross sectional area of 14 cm x 14 cm. The magnet has the capability to produce uniform magnetic flux densities up to 2 T. The magnetic field is increased from a low value (several mT) in several steps. At each step, the chamber is taken off the magnetic field and the magnetic flux density trapped at the ring center is measured using a digital hall sensor magnetometer. The measurement result is presented in Fig. 4. As it is apparent from Fig. 4, increasing the imposed magnetic field, the trapped flux density distribution in the superconducting ring remains approximately constant in 170 mT.

This phenomenon is explained with Bean model which is stated as (1), [30]

$$\frac{dB}{dr} = \mu_0 J_c$$  \hspace{1cm} (1)

where $B$ is the flux density inside the bulk superconductor, $r$ is the radius from the center of the bulk and $J_c$ is the critical current density of the bulk.

According to the Bean model, the flux density distribution in the bulk ring is shown in Fig. 5, for five different applied magnetic flux density levels.

According to Fig. 5, and based on (1), increasing the applied magnetic field beyond level (3), the current density remains constant in $J_c$ over the whole bulk ring width, so the trapped flux density in the ring tends to a constant value, which is also seen in Fig. 5. It also may be deduced that at the center of a superconductor bulk of internal radius $r_i$ and the external radius $r_o$ carrying a current density of $J_c$, the magnetic flux density would be determined as (2).

$$B = \mu_0 J_c (r_o - r_i)$$ \hspace{1cm} (2)

With $r_o = 17$ mm and $r_i = 11$ mm, for $B = 170$ mT, $J_c$ is found to be 2254 A/cm$^2$.
5. Fabrication and test of the prototype SFCL

A prototype has been made with the fabricated flat YBCO ring of obtained $J_c$. The design parameters of the fabricated SFCL are presented in Tables 1 and 2. A view of this SFCL is shown in Fig. 6.

Splitting the copper winding into two parts and placing the flat superconductor ring between these two coils has the additional advantage of making the cooling of the superconductor ring more efficient.

The fabricated prototype SFCL has been used in a test system and its limitation characteristics have been verified. To cool the system, the device has been immersed in the 77 K liquid nitrogen.

A typical single phase system of 30 V and 50 Hz, with the internal source inductance of 2 mH and the line resistance and inductance of 0.2 $\Omega$, 2 mH, as shown in Fig. 7, is employed for the test system and two fault cases are investigated.

### Table 1
Parameters of the flat superconductor ring.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal radius of the flat superconductor ring</td>
<td>11 mm</td>
</tr>
<tr>
<td>External radius of the flat superconductor ring</td>
<td>17 mm</td>
</tr>
<tr>
<td>Height of the flat superconductor ring</td>
<td>3 mm</td>
</tr>
</tbody>
</table>

### Table 2
Copper winding and core parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turns number of the copper winding</td>
<td>200</td>
</tr>
<tr>
<td>Diameter of the copper wire</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Internal radius of the copper winding</td>
<td>12 mm</td>
</tr>
<tr>
<td>External radius of the copper winding</td>
<td>16 mm</td>
</tr>
<tr>
<td>Height of the copper winding</td>
<td>40 mm</td>
</tr>
<tr>
<td>Radius of the core</td>
<td>10 mm</td>
</tr>
<tr>
<td>Relative permeability of the core</td>
<td>500</td>
</tr>
</tbody>
</table>

5.1. Results

The practical test results of the fault current limitation are shown in Fig. 8, for the fault case 1 and in Fig. 9, for the fault case 2, and are compared with the current without using SFCL.

The fault current in fault case 1, without using SFCL, may be calculated from the line voltage and the system impedances as $I_f = V_m/\left(2\pi f L s\right) = 47.7$ A. For the fault case 2, the independent fault current without SFCL would be as $I_f = V_m/\left(\sqrt{R^2 + (2\pi f (L + L_s))^2}\right)$ = 23.6 A. As the transients in the fault current without SFCL, are negligible from both the amplitude and duration point of view, as may also be seen in Fig. 9, thus it is not included in the calculation. It’s deduced from the experimental results in Fig. 8, and Fig. 9, that the shield-type SFCL with flat YBCO rings has limited the fault currents to approximately 3 A in both cases. The current limitation factor $(I_{\text{short cord}}/I_{\text{limitted}})$ in case 1 would be $47.7/3 \approx 16$ that means the fault current is suppressed by a factor of 16. For the case 2 the current limitation factor is $23.6/3 \approx 8$. Thus the use of flat superconductor
rings in the SFCL structure has resulted in adequate limitation characteristics.

In the activated mode of the SFCL, the superconductor shield is broken, and the inductance of the SFCL would increase, which forms the major part of the impedance, limiting the fault current. In addition even in large-scale SFCLs of this type, the magnetic flux density outside the core is much less than the flux density inside the core. i.e. the superconductor bulk is not subject to high magnetic flux densities. Due to these reasons, the possible enormous active power dissipation on the SFCL can be avoided. Furthermore, as a result of the superconductor bulk not being exposed to high magnetic flux densities, changes in the critical current density of the superconductor bulk not being exposed to high magnetic flux densities, changes in the critical current density of the superconductor bulk due to the magnetic field would be negligible and since the superconductor is deeply immersed in liquid nitrogen bath in the considered design, the superconductor heating and the resulting decrease in \( J_c \) is considered negligible, and the fault current is almost a constant value during the fault, as may be seen in Figs. 8 and 9.

The \( V-I \) characteristics of the SFCL, obtained by measurement, is shown in Fig. 10. It may be seen that at the current of approximately 3 A (the activation current, \( I_{\text{start}} \)) the slope of the curve rises considerably so the inductance starts to increase. This further verifies the results of fault current limitation.

6. Summary and conclusion

A method has been introduced for flat superconductor ring fabrication. This method eliminates the need for machining in bulk superconductors. The critical current density of the fabricated flat ring was measured based on the trapped flux density. Using these flat rings, a prototype superconducting fault current limiter has been fabricated. It has been tested in a circuit and the results have been reported. It has been shown that using flat YBCO rings, this particular type of SFCL shows satisfactory fault current limitation capability with a limitation ratio of the independent fault current to the limited current of 16 for the SFCL terminal fault and eight for the load terminal fault. The voltage–current characteristic of the SFCL was obtained by measurement which verified the current limitation results.

References