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Physica C 372–376 (2002) 1657–1663

PHYSICA C

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6.4 MVA resitive fault current limiter based on Bi-2212 superconductor

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Abstract

ABB has recently successfully developed and tested a single phase 6.4 MVA superconducting fault current limiter (SCFCL) demonstrator, which is based on a novel conductor design and innovative Bi-2212 ceramic fabrication technology. At present, it represents the highest rated power reported for HTS based SCFCL. The employed SCFCL component is a composite consisting of layers of bulk Bi-2212 ceramic, resistive metallic electrical bypass and fibre reinforced plastic (FRP). The Bi-2212 conductor is fabricated in sheets with an area of 30×40 cm^2 by using a modified partial melt process and is subsequently structured into long length meanders. The as-processed Bi-2212 is non-textured and exhibits a uniform j_c in the range of 3000–5000 A/cm^2. The employment of a robust bypass facilitates a uniform quench in the SCFCL component during a fault event. Depending on the level of prospective fault current, a fault current is typically reduced to around 10 times nominal current in the first current peak and further to 2–5 times after 50 ms into the fault. Test and simulation results of the 6.4 MVA demonstrator, together with the application prospects of such Bi-2212 based SCFCL are presented and discussed.

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Keywords: Fault current limiter; HTS; Bi-2212; Power application; Superconductivity

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1. Introduction

It has been an old dream of electrical engineers to have a fault current limiter, which will enable reduced mechanical and thermal stresses on electric equipment in a power system by reducing short-circuit currents in the event of a fault. Any reduction of these currents can lead to significant cost savings. Among all current limiting devices, superconducting fault current limiters (SCFCLs) offer ideal performance, namely, in normal operation the SCFCL has negligible impedance as it is in the superconducting state and, in the event of a fault, the transition into the normal conducting state passively limits the fault current [1].

Different HTS materials, like YBCO films, Bi-2223 wires or Bi-2212 ($Bi_2Sr_2CaCu_2O_{8+\delta}$) bulk are being developed for SCFCL application, where various demonstrators have been reported [2–4]. However, the realisation of robust HTS components for fault current limitation is still challenged by the materials engineering of these ceramics

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PII: S0921-4534(02)01096-1

which are brittle and prone to hot-spot (excessive heating of the conductor during a fault process which can lead to burn-through of the HTS). Nevertheless, such components are essential for the design of SCFCL and its full commercial exploitation.

In 1996 the first ever SCFCL demonstrator was installed in a Swiss hydropower plant [2]. The 1.2 MVA device developed at ABB is of the "shielded core" type, which is based on tubes of Bi-2212 bulk material. A one-year-endurance test has demonstrated the feasibility of the SCFCL application in power system.

Recently, a more compact "resistive" SCFCL has been developed, based on large area flat Bi-2212 plates (panels) [3,5]. In this work, the basic conductor design, the development and characterisation of Bi-2212 composite conductor, prototype test and possible applications are described.

2. Basic design aspects

SCFCL passively limits a fault current by intrinsically developing resistance under over-current. The rated power of a SCFCL is defined by [1],

$$P = I_N U_N,$$

where I_N is the nominal current (current in normal operation) and U_N is the voltage of the system protected by SCFCL, which approximates the total voltage developed across the conductor during a fault. I_N is given by $Aj_c/\sqrt{2}$, with A being the cross-section of HTS and j_c its critical current density. U_N is given by $LE_{max}/\sqrt{2}$, where L is the length of HTS and E_{max} is the designed maximum electric field. Power application is most practically realised both by a high E_{max} and a long length L. As a practical approach, long length can be achieved by structuring a plate into a long meander. For YBCO thin film, an E_{max} value of around 25 V/cm has been reported [6]. However, in reality a much more compromised value is taken because designs with high E_{max} are more prone to hot spot. SCFCL with distinctively different limitation behaviours can be tailored by simply varying the E_{max} [1].

For economical HTS conductors, a current carrying capability, expressed as Ampere per width, higher than 100 A/cm would be required. This can be achieved either by high j_c and/or large cross-section. The exploitation of cross-section, A, has its limitation firstly, because SCFCL components usually take the form of plates where a compact design calls for a minimised width and secondly, the thickness is limited because of AC-losses (see later text). For Bi-2212 with a typical j_c in the range of 1000–10,000 A/cm^2 at 77 K, sufficient current capability can be achieved with bulk conductor (thickness in millimeter range, which can still be tolerated from the AC-losses point of view).

3. Materials requirements

Because of its strong non-linearity (what is required for fault current limitation), HTS material is prone to the so-called "hot-spots" which could lead to burn-through of the material [5]. Improved uniformity in j_c and I_c will minimise such effect but total elimination requires good thermal stabilisation of the conductor. This can be achieved either through thermal management (e.g. by applying a heat sink) or good thermal conductor, through electrical bypass to shunt excessive current from HTS (thus to reduce heating) or through combination of both. Obviously, an electric bypass should be so selected that it itself is not prone to "hot-spot". In this study, stainless steel ($\rho = 40\ \mu\Omega\,\mathrm{cm}$ at 100 K) has been considered as electric bypass because it is a cost effective and resistive conductor with high thermal capacity. Steel sheets are electrically and mechanically joined onto the HTS with conducting join. Using stainless steel as bypass, an upper limit of the above mentioned E_{max} can be estimated to be about 2 V/cm, assuming a fault duration of 100 ms.

Furthermore, mechanically robust SCFCL component is required because during a fault current limitation process, the HTS conductor is subjected to magnetic forces and thermo-mechanic stresses. Bi-2212 ceramic demonstrated a relatively low flexural strength of 40 MPa, necessitating mechanical reinforcement, preferably with pre-stress under compression. Careful matching of mechanical and thermo-mechanical behaviour of individual component has led to the composite structure as

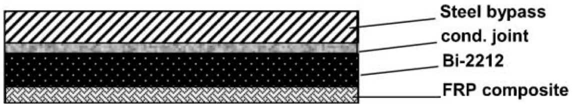

Fig. 1. Schematic cross-section of Bi-2212 based SCFCL composite.

sketched in Fig. 1. It has been shown that Bi-2212 ceramic is effectively reinforced by both stainless steel (which is needed as bypass) and glass fibre reinforced plastic composite (FRP).

For AC-applications HTS exhibits AC-losses, which should be minimised since they translate into cooling cost during normal operation. Such losses are proportional to the square of the conductor dimension, which is perpendicular to the surrounding magnetic field, i.e. the thickness for a planar conductor. From this viewpoint, the thickness should be reduced, conflicting with what is needed for high current carrying capability. Therefore, an optimal thickness has to be found. Effective reduction in AC-losses can be made possible through conductor geometry optimisation, leading to partial magnetic field compensation [7]. Practically, two planar SCFCL composite structures are joined back to back, with magnetic field compensation being achieved when the current in the two parts flows in anti-parallel directions.

The above design consideration has led to the development of a SCFCL component based on Bi-2212, as described in the following.

4. SCFCL component based on Bi-2212

4.1. Bi-2212 ceramic plate

Large Bi-2212 ceramic plates with an area of about 0.1 m^2 (30×40 cm^2) were employed in the build-up of the 6.4 MVA SCFCL demonstrator. A proprietary ceramic process has been developed at ABB, based on tape casting and partial melt process [8,9]. With such a process, large area (0.2 m^2) Bi-2212 plates with uniform thickness and smooth surface can be obtained. Bi-2212 precursor powder ($D_{90} = 20$ μm) with appropriate amount of Ag powder was first mixed with a binder system to form a slurry which was then tape cast to yield a uniform green tape up on drying. Dried Bi-2212 flexible tapes cut to large area were placed on substrate buffered with Ag and subjected to a five day heat treatment. The partial melt process involves essentially the following steps: (a) binder burn-off at slow heating rate up to 500 °C in low pO_2, (b) further heating to partial melt temperature, typically 890 °C with fast cooling to 850 °C for a 20 h dwell in pure O_2, and (c) a further dwell at 820 °C for 50 h in air before finally cooling down with atmosphere changed to pure N_2 from 700 °C.

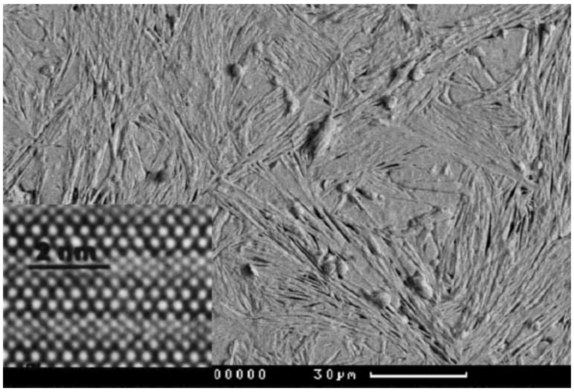

Fig. 2. SEM microstructure of bulk Bi-2212. Insert: HREM image of Bi-2212.

The as-processed Bi-2212 shows a non-textured polycrystalline microstructure (Fig. 2) and exhibits a T_{c_onset} of 95 K and a uniform j_c of up to 5000 A/cm^2.

4.2. SCFCL modules

First of all, because of its low tensile strength (40 MPa), the large area Bi-2212 plate is reinforced by laminating and curing a sheet of FRP prepreg on to it. Then the reaction substrate Ag foil is removed from the Bi-2212 plate, a sheet of stainless steel is applied to the Bi-2212 surface with a conducting joint, forming the basic conductor composite structure, as sketched in Fig. 1. Next the plate is structured into meanders (straightforward or spiral meander) resulting in a conductor length varying between 5 and 15 m, corresponding to different meander widths. Finally, two identical meanders are mirrored together and joined with FRP

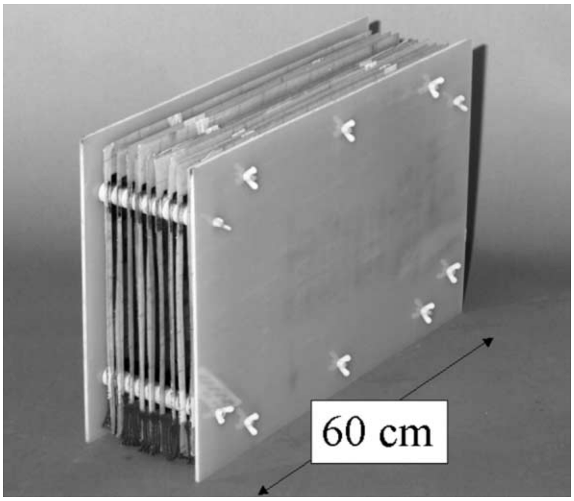

Fig. 3. Bi-2212 based SCFCL modules assembled into a stack.

prepreg. After curing the prepreg, a double meander structure is obtained, forming the basic SCFCL component, hereafter referred to as SCFCL module. Such module, being compact and mechanically robust, serve as building block, which can be built into stacks (Fig. 3) and connected in series and parallel to build up a SCFCL device.

5. Characterisation of SCFCL components

5.1. *E(j) characteristics of Bi-2212*

The most important physical property of an SCFCL is the $E(j,T)$ characteristic of the HTS [3,10]. For Bi-2212 bulk, $E(j)$ can be divided into three sub-regions [3,5] representing the superconducting state, the flux flow state and the normal conducting state, respectively. Each region can be parameterised with a different power law. Together with the thermal-diffusion equation, it forms the basis for the simulation of the fault current limiting behaviour. Fig. 4 shows the experimental $E(j, 77\ \mathrm{K})$ curves of four different Bi-2212 samples. Two regions with distinctive different power law can be clearly seen. The expected transition from the flux flow region to the normal-conducting state is beyond the reach of the experiment due to excessive heating (bending over in Fig. 4). Both power law exponents increase slightly with j_c respectively from 6 to 9 and 3 to 4 when the j_c is increased from 2000 to 5000 A/cm^2. Higher power law will lead to faster build-up in E field, resulting in a better limitation of fault current.

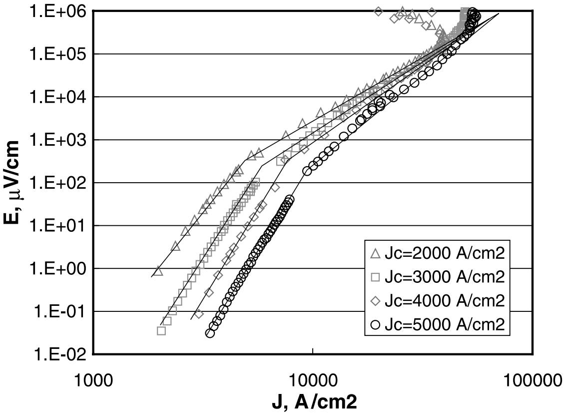

Fig. 4. $E(j)$ for different Bi-2212 samples.

5.2. *Limitation behaviour*

The effectiveness of a FCL is best described by its limitation factor, N (i.e. the ratio of the limited current to the nominal current, I_N). The initial value of the limitation factor (i.e. first peak for AC current) is determined by the prospective fault current I_{pf}, E_{max} and j_c. The value of N at the end of the fault (e.g. 50 ms) is additionally influenced by the bypass. The fault current limitation with low I_{pf}/I_N ratio is critically depending on j_c as shown in Fig. 5 (where the worst cases of limitation are presented, i.e. for first peak values from asymmetric fault and for the 50 ms values from symmetric fault). High j_c facilitates better limitation because of faster heating up, enabling application in network with $I_{pf}/I_N \geqslant 5$ for $j_c = 5000$ A/cm^2. As can be seen, SCFCL is particularly suited for application with high prospective fault current, although it could be designed to limit any type of fault current [1].

5.3. *Normal operation*

The SCFCL component has a typical current carrying capability of 150 A/cm. The overload

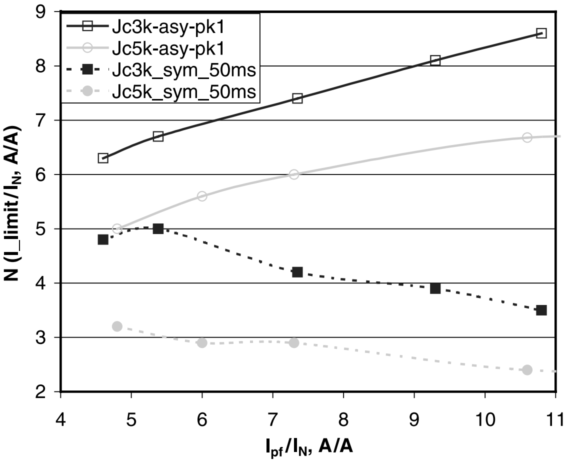

Fig. 5. Limitation behaviour of Bi-2212 vs I_{pf}/I_N for $j_c = 3000$ and 5000 A/cm^2.

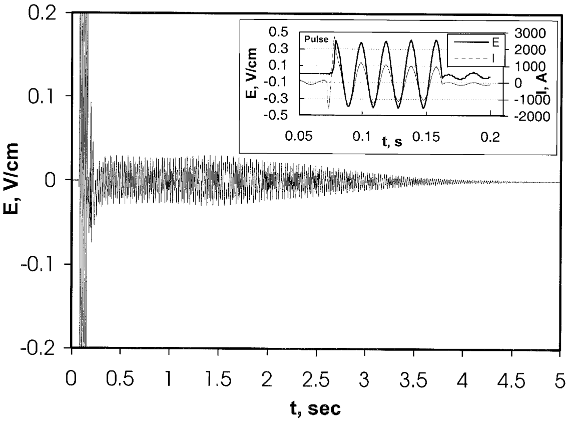

Fig. 6. Recovery of SCFCL under 50% I_N after pulsing at 0.4 V/cm for 90 ms (see insert). SCFCL returns to superconducting state (i.e. $E = 0$) in 5 s.

capability of HTS is critically influenced by the uniformity of j_c. The current SCFCL module, with a power law of around 9, can be operated at 10 μV/cm without losing stability. This corresponds to an overload capability of 30%, which is, however, accompanied by increased AC- and Joule-losses. It should be noted that a higher overload capability could be achieved for transient over-current.

SCFCL modules show much reduced AC-losses, which are typically in the range of 0.001% at I_c in good agreement with simulation [7]. Such reduction in AC-losses is only achieved through the module design with magnetic field compensation which can be further optimised for an even lower loss level.

5.4. Recovery

The recovery time of SCFCL (following the limitation process) which is an important application parameter, depends on the heat dissipated in the SCFCL component, its thermal mass and the heat exchange with LN$_2$. Recovery time is typically on the order of 3 s for SCFCL module after a fault at 0.4 V/cm for 90 ms. As shown in Fig. 6, the current design is able to recover under partial load, e.g. 50% I_N with a prolonged recovery time of 5 s. It is possible to design SCFCL which can be re-connected into the network immediately after fault limitation.

6. Test of 6.4 MVA demonstrator

A total of 100 SCFCL modules were assembled into stacks, example of which illustrated in Fig. 3. The demonstrator, consisting of SCFCL stacks connected in series and in parallel, has a nominal current, I_N of 800 A$_{rms}$ at 77 K. The SCFCL demonstrator has a very compact design, showing a total volume of less than 1 m^3 including cryostat.

The short circuit tests were performed in ABB Power Lab. (Baden, Switzerland). The SCFCL stacks immersed in LN$_2$ were tested as single phase against a generator which has a prospective fault current of 20 kA$_{rms}$ when excited to a phase to ground voltage of 8 kV$_{rms}$. A total of 20 tests were successfully carried out at voltage level ranging from 2.5 to 8 kV$_{rms}$ with a fault duration of 100 ms. The one phase demonstrator was repeatedly tested to 8 kV$_{rms}$ with no degradation, thus demonstrating a rated power of 6.4 MVA. In all tests both symmetrical (Fig. 7) and asymmetrical faults were effectively limited. At 8 kV$_{rms}$, the SCFCL curbed a prospective fault of 20 kA$_{rms}$ to a peak value of 10.6 kA (9.5I_N) at the first peak and further to 3.2 kA$_{rms}$ (4I_N) after 20 ms and finally down to a value of 2.7 kA$_{rms}$ (3.1I_N) after 100 ms as a

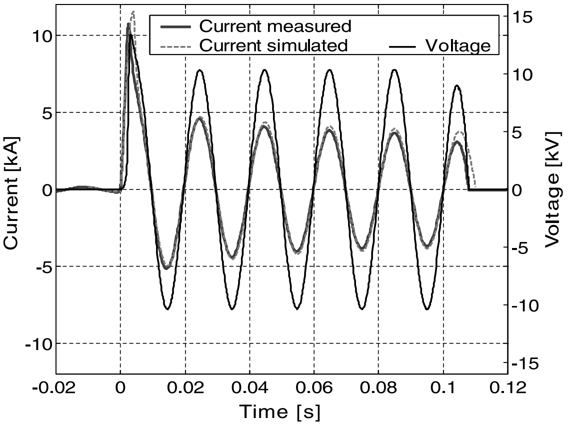

Fig. 7. Test result of 6.4 MVA single phase demonstrator ($I_{\mathrm{pf}} = 20$ kA$_{\mathrm{rms}}$).

result of warming up of SCFCL. During the fault, SCFCL developed the quench at around 5 ms into the fault, effectively limiting the first fault current peak from 25 to 9.5I_{N} and, at the same time, leading to a slight overvoltage (25%). The observed behaviour of the demonstrator is well described by the established theoretical model [5] (see also Fig. 7).

With the above tests, a single phase SCFCL demonstrator with a rated power of 6.4 MVA (0.8 kA$_{\mathrm{rms}}$/8 kV$_{\mathrm{rms}}$) is successfully demonstrated.

7. Application prospects

As discussed above, SCFCL represents an ideal fault current limiter, which is particularly suited to applications with high prospective fault current. Although it can be designed to limit low prospective fault current, application in this area could face strong competition from other technologies.

Among various applications, SCFCL can (a) bring added value to existing grids, where the I_{pf} has reached the design value of the breakers, e.g. grid-coupling, coupling of additional power source in existing grid (HV or MV) and isolating perturbing customer from high power quality network, and (b) enable design of novel power system with high short circuit power, e.g. supply of local industry on MV-level, connection of several generators to one busbar, and new grids [3,5].

Clear benefits have been demonstrated in a case study joined with the largest German utility, RWE, on grid coupling [3,5]. When coupling two symmetric grids each having a short circuit power of 5 GVA with SCFCL ($I_{\mathrm{N}} = 600$ A$_{\mathrm{rms}}$), it is shown by simulation that the contribution to the total fault current from the second grid become negligible, avoiding a doubling effect. This is because SCFCL not only reduced the fault contribution from grid 2 but also shifted its phase. Most remarkably such effect can be realised with a very relaxed limitation factor of the SCFCL, which in this case is about 15 (first current peak).

The realisation of the 6.4 MVA SCFCL further demonstrates the feasibility of the novel application, bringing this technology one step closer to the market place. It is believed that the application of SCFCL will start with niche market and large scale application will arrive only when the device can meet the technical specification at competitive cost. This will most probably be brought around with the realisation of both low cost HTS conductor and cost effective reliable cooling system.

8. Conclusion

The feasibility of fault current limitation based on HTS is further demonstrated with the test of the 6.4 MVA single phase demonstrator. With a nominal current of 800 A$_{\mathrm{rms}}$ and rated voltage of 8 kV$_{\mathrm{rms}}$, a fault current was successfully limited from 20 to 2.7I_{N} after 100 ms. The technology is based on a novel design concept and an innovative conductor process technology. The key SCFCL component is a long length planar composite consisting of layers of bulk Bi-2212 ceramic, resistive metallic electrical bypass and FRP composite. It is believed that this technology can be up-scaled to the high voltage level. The technical benefits of SCFCL have been further confirmed with simulations on grid coupling. It is strongly believed that SCFCL, as an emerging technology, will bring major added value to existing power systems and enable new and unconventional designs of power systems.

Acknowledgements

The authors gratefully acknowledge L. Widenhorn, A. Braun, W. Lanz, W. Hofbauer, D. Braun, J. Rhyner, L. Gauckler, U. Kaltenborn and M. Carlen for in-depth discussion. Solvay Barium Strontium is acknowledged as partner on Bi-2212 powder.

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