Magnetic Field Assisted Quench Propagation as a New Concept for Resistive Current Limiting Devices

S Elschner², F Breuer¹, H Walter¹ and J Bock¹

¹ Nexans SuperConductors, D 50351 Huerth, Germany
² University of Applied Science, D 68163 Mannheim, Germany

s.elschner@fh-mannheim.de, frank.breuer@nexans.com,
heribert.walter@nexans.com, joachim.bock@nexans.com

Abstract. We present a superconducting current limiter concept based on Melt Cast Processed (MCP)-BSCCO 2212 bulk material. Key feature is a novel protection technique using the strong magnetic field dependence of critical current density of the BSCCO material. A coil is physically wound around a superconducting tube and electrically connected in parallel. If hot spots develop, a part of the current shunts on the coil and the resulting magnetic field brings the superconductor to a rapid and homogeneous quench. Experimental evidence is shown, that superconducting tubes (normal operating current: 1000 A at 77K) are protected effectively, also in the particularly dangerous small load regime and if several components are connected in series. Electric fields up to 2.5 V/cm were achieved without damaging the samples. As a consequence the required superconducting length and with it the AC-losses under normal operation conditions are strongly reduced compared to the usual resistive shunt concepts.

1. Introduction
Fault current limiters are at present the most mature application of high temperature superconductors in power electronics. Especially resistive concepts based on bulk material seem to have excellent chances for economical and technical viability. This was shown, up to 10 kV/10 MVA, e.g. within the successful German limiter project CURL 10 [1]. However, in all resistive concepts the stabilisation against hot spot formation is so far made with a metal shunt contacted continuously over the whole superconducting length. This shunt, due to its low resistivity, restricts the applicable voltage in the short circuit case to fields below 0.5 V/cm. As a consequence, and especially in high voltage grids (>100 kV), a prohibitively large superconducting length is required.

This contribution presents a novel protection concept based on the strong magnetic field dependence of critical current density in (MCP)-BSCCO 2212. The single component consists of a normalconducting coil wound around a superconducting tube and electrically connected in parallel. If a voltage occurs, a part of the current is shunted on the coil and the resulting magnetic field drives the superconducting material into a rapid and homogeneous quench. A similar concept with a however much more complex triggering mechanism but based on the same material has already been proposed [2]. Since the electric field in the short circuit case is now limited by the much larger (normalconducting) resistivity of the superconducting ceramic the required length can be reduced by up to one order of magnitude. We expect, that our new concept helps to fully exploit the excellent limiting properties of MCP BSCCO 2212 and will lead to a more efficient use of the material. In addition the cooling effort for operation of the FCL device will be reduced.
2. Influence of magnetic field on superconducting properties

Manufacturing, contacting and characterisation of MCP BSCCO 2212 is described elsewhere in detail [3]. We use tube shaped samples with a length of 200 mm, an OD of 25mm and a wall thickness of 1.6mm. The critical current at $T = 77$K and $T = 65$ K typically is 1500 A r.s. 4500 A, i.e. 1360 A/cm² and 4100 A/cm² with a scatter of about 5% within a sample and between different samples.

Basic idea of the investigated protection concept is the strong dependence of critical current density and U(I)-characteristics on the magnetic field. Indeed this field dependence in a transverse magnetic field is well known for BSCCO 2212 at 77K and the usual 1µV/cm-criterium [4]. In small fields it can roughly be described by an exponential decay $j(H) = j_0 \cdot \exp(-H / H_0)$ with $H_0$ near 20 mT.

We have extended these experiments to the samples foreseen in our limiter concept and with the magnetic field parallel to the tube axis. To this purpose a coil was wound around the sample and fed with a DC current. The U(I) characteristics were measured at different temperatures and fields with a pulsed technique up to a current of 500 A. In figure 1 the results at $T=77$K are shown. Especially the result at $H=0$ fits well elder data on 5mm rods [5] (squares in figure 1). The measured field and temperature dependences U(I,H,T) were parameterised with simple expressions. These were then successfully used to calculate the resulting quench behaviour [6].

3. Magnetic field triggered current limitation

The main challenge in the design of resistive current limiters remains the control of hot spots. Our concept is based on the idea that with the beginning of the quench, i.e. in the flux-flow state or in a hot zone situation, the parallel coil sees a voltage. The current caused by this voltage creates a field and, with the field-effects described in sec. 2, brings the sample to a homogeneous quench. To confirm the viability of this concept we have made a couple of experiments for comparison: In a first experiment the coil was connected in parallel and wound around the tube, in a second experiment the same coil was again connected in parallel but placed approximately 20cm away from the sample, so that field effects on the superconducting transition can be neglected.

The copper coil (mean diameter: 45mm, 23 windings, cross section of the conductor: 25mm²) was designed to be nearly inductive ($R(77K) = 0.3 \ \text{mOhm}, \ \text{XL} = 2 \ \text{mOhm}$). However it is not clear up to now, to which extent the inductance in the beginning of the quench is reduced by shielding effects.

In both experiments the same short circuit was applied using an 1.8 MVA transformer. The series impedance was chosen to yield a symmetric prospective short circuit of 16 kApeak. This corresponds to a (particularly dangerous) medium load. The duration of the short circuits was limited to 20 ms. In order to monitor the limiting behaviour, the voltage was measured with equidistant voltage pads.

![Figure 1. Current / Voltage characteristics of MCP BSCCO 2212 tubes at $T = 77$K and different external fields parallel to the axis of the tube. Blue squares from Ref. [5]. Horizontal line: limit of resolution.](image)
(distance 5cm) on three length sections of the sample. The differences between these three voltages \( U_a, U_b, U_c \) are a measure for the inhomogeneity of the quench. Figures 2 a,b depict the current and the three voltages for both experiments, i.e. without and with field effect. Two main results are visible:

- With field the quench is about 3ms earlier than without field.
- Without field the ratio between the highest and the lowest measured voltage maximum is about a factor 9.0, in the case with field this ratio is just about 2.3. This demonstrates that the quench is strongly homogenised by the impact of the magnetic field.

Only in the case with field a small limitation is observed. This is due to the fact, that the prospective current is not sufficient for a limitation within the first period.

We have repeated the same couple of experiments with the highest prospective current possible with our set-up, i.e. 37.5 kA peak ("full load"). Here the current was limited to a peak value of 20 kA within the first half wave and to 15 kA \(_p\) after 100 ms. Also in these experiments the quench was much more homogeneous with magnetic field.

### 4. Multi component test

For an application at high voltages an important aspect of the proposed protection mechanism is its functionality with several components in series. To this purpose we conducted tests at the high current facility of IFPS in Bonn, Germany. Five superconducting tubes were connected in series. As described in section 3 a copper coil (23 turns, Cu-cross section: 25mm\(^2\)) was wound around each of the tubes and connected in parallel. The whole assembly was immersed in LN2. The asymmetric prospective current was set to a maximum peak of 80 kA within the first half wave. The current and the voltage transients of the five components were recorded simultaneously. Figure 3 depicts the prospective current and the limiting behaviour. Already in the first peak the current is reduced to 40 kA \(_p\) and after 100ms to 25 kA \(_p\). It is determined by the design of the shunt coil. The current in the superconductor was only about 2 kA \(_p\), independently measured. An integration of the heat production yields a final temperature near 230 K. The voltage is distributed homogeneously among the five components with an effective value of 46 V\(_{\text{rms}}\), i.e. 2.7 V\(_{\text{rms}}\)/cm. After multiple experiments (99 shots) with different prospective currents the samples were analysed and any degradation could be excluded.

Voltage and current are phase shifted by nearly \( \pi / 2 \) reflecting the inductive nature of the coil. This makes sure that the heat deposited in the coil and consequently in the LN2 bath remains low and vapour development can be controlled. The critical current of 1400 A/cm\(^2\) at 77 K allows a normal operation current of 1000 A\(_{\text{rms}}\) (3000A at 65K). With a voltage of 45 V\(_{\text{rms}}\) this corresponds to a protected load of 45 kVA per component.

**Figure 2.** Current (red) and voltages \( U_a, U_b, U_c \) of three adjacent length elements (blue) in the case of medium load (I\(_{\text{prosp}}\)=17 kA). Left: without magnetic field, right: with magnetic field (see text).
5. Conclusion and outlook

With respect to a commercial device at high voltages it is of crucial importance to reduce the superconducting length. Following this target we developed a novel protection mechanism based on the magnetic field dependence of critical current density. It could be shown, that this field effect indeed contributes to a homogenisation during quench thus avoiding the occurrence of hot spots.

However, the geometry of the shunt coils is still not optimised. Important criteria for the design are the accepted first peak, the desired fault current and the amount of heat deposited in the heat bath. Further a maximum field increase in the beginning of the quench is desired.

Compared to the protection concept of CURL 10 based on a parallel normalconducting shunt the electric field along the conductor can be increased from 0.4 V\(_{\text{rms}}\)/cm to at least 2.5 V\(_{\text{rms}}\)/cm. From heat capacity evaluations there are clear prospects that this field can be further pushed to 5 V/cm. In the same proportion the requested superconducting length and the AC-losses under normal operation conditions are reduced. The operation at 65 K, as in CURL 10, will increase the normal operation current by a factor of 3 so that a protected load of 150 kVA per component appears realistic. The improved economics (less material use, lower cooling investment and operating cost) will open the way to the commercial breakthrough of this FCL application.

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References

[1] J. Bock, F. Breuer, H. Walter, S. Elschner, M. Kleimaier, R. Kreutz, M. Noe, IEEE Transact. Appl. Supercond. Vol. 15, p. 1955 (Proc. ASC 2004, Jacksonville, USA), 2005
[2] X. Yuan, K. Tekletshadik, L. Kovalsky, J. Bock, F. Breuer, S. Elschner, IEEE Transact. Appl. Supercond. Vol. 15, p. 1982 (Proc. ASC 2004, Jacksonville, USA), 2005
[3] J. Bock, S. Elschner, P.F. Herrmann, IEEE Transact. Appl. Supercond., Vol. 5, Nr.2, p. 1409, (Proc. ASC 1994, Boston, USA), 1995
[4] S. Elschner, J. Bock, H. Bestgen, Supercond. Sci. Technol., 6, 413 (1993)
[5] S. Elschner, F. Breuer, A. Wolf, M. Noe, L. Cowey, J. Bock, IEEE Transact. Appl. Supercond., Vol.11, Nr.1, p 2507, (Proc. ASC 2000, Virginia Beach, USA), 2001
[6] M. Stemmler, B R Oswald, F. Breuer, S. Elschner, M. Noe, “Simulation model for a novel superconducting fault current limiter”, Proc. EUCAS 2005, submitted

Figure 3. Magnetic field assisted current limitation with five superconducting tubes in series. The measured transients of prospective current (black), limited current (red) and the five voltages (nearly identic) are depicted.