Investigation of YBCO Coated Conductor for Application in Resistive Superconducting Fault Current Limiters

Andrej Kudymow, Mathias Noe, Christian Schacherer, Helmut Kinder, Werner Prusseit

Abstract—**These R&D of YBCO coated conductor wire is progressing very fast. The manufacturing lengths for a single wire have reached up to several hundred meters with high quality. Due to its promising cost predictions, YBCO coated conductor (CC) material might considerably increase the economic feasibility of superconducting power devices (cables, transformers, machines, current limiters and energy storage) in near future. The main requirement for YBCO wire in resistive superconducting fault current limiters (SCFCLs) is quench safety for various short-circuit conditions. Up to now, only a few authors report on this subject. This paper presents experimental quench test results with short and medium length samples of YBCO coated conductor wire for different test conditions. The experimental results confirm the feasibility of YBCO coated conductor wire for application in resistive SCFCLs. Short samples showed fast and effective limitation up to an electrical field of 2.7 V/cm for a short-circuit time of 100 ms without material degradation. Even relatively inhomogeneous short samples showed a non-destructive quench. The tests clearly demonstrate that a good contact between the cap layer and the substrate is mandatory to avoid hot spots during quench.**

Index Terms—**coated conductor, DyBCO, fault current limiter, quench, YBCO**

I. INTRODUCTION

PROTECTION of the power transmission and distribution network from damage by fault current is an important task. At present, there exists no conventional electrical device to limit fault currents for high voltage levels. Since the short-circuit capacity of present circuit breakers cannot be increased considerably, there is a need to develop fault current limiting devices especially for modern highly interconnected power systems [1].

The development of coated conductors, often called the second generation or 2G wire, is progressing very fast. Its application in SCFCLs seems very attractive because of the following benefits:

1. Low production costs
2. Low AC-loss
3. Low magnet field dependency [2]
4. Short recovery time [3]
5. Flexible wire
6. Simple contact to normal conductors

One of the key properties of superconducting wires in resistive SCFCLs is the transition from the superconducting state to the normal conducting state, the so-called quench. It is well known that coated conductors can offer a fast and reliable quench without material degradation. High resistive substrate material is required to improve the switching capacity of coated conductors.

The electrical and mechanical stabilisation of the coated conductor is crucial for the application in resistive SCFCLs. A new and simple method for this stabilisation is shown in [3]. The main advantage of this method in comparison to other conductor architectures is that a higher electrical field during limitation can be achieved.

The main purpose of this paper is to confirm the feasibility of this coated conductor for the application in resistive SCFCLs. Therefore, a number of different quench tests have been performed with conductor samples of up to 1 m length and with different short-circuit conditions.

This paper describes shortly the architecture of the coated conductors and the test setup used for the experiment. The main part of this paper deals with a detailed description of the different tests, focusing on quench propagation in relation to material homogeneity. The main objective is to find a degradation limit.

II. DYBCO COATED CONDUCTORS

A. *Specification of coated conductor*

The coated conductor used in the tests [4],[5] is 10 mm wide. The substrate is non-magnetic Hastelloy® C276. The Hastelloy® is the best choice for resistive SCFCL due to its high resistivity of 130 μΩcm at room temperature and due to its low positive temperature coefficient (PTC).

Manuscript received August 29, 2006.

Andrej Kudymow, Mathias Noe, Christian Schacherer are with the Institute for technical Physics at Forschungszentrum Karlsruhe, D 76021 Karlsruhe, Germany Germany (telephone: +49 7247 82 4198; fax: +49 7247 2849; e-mail: andrej.kudymow@itp.fzk.de).

Helmut Kinder, Werner Prusseit are with THEVA Dünnschichttechnik GmbH, D 85737 Ismanung, Germany

Bi-axially oriented MgO buffer layer was manufactured by inclined substrate deposition (ISD). DyBCO layer with 1.6 µm is deposited by electron beam evaporation over buffer.

The silver layer covered SC is relative thin - 500 nm - to keep the effective resistance of the cap layer higher than that of the substrate.

So, the coated conductor, coming from series production, is perfectly designated for SCFCL application thanks to its Hastelloy® substrate and relative thin DyBCO and Ag-cover layers.

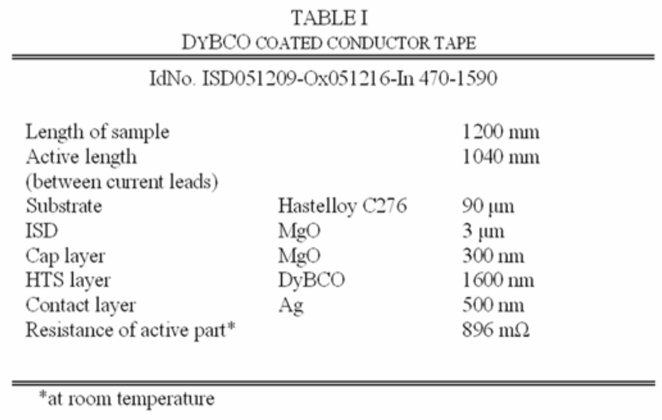

TABLE I
DyBCO COATED CONDUCTOR TAPE

IdNo. ISD051209-Ox051216-In 470-1590

Length of sample		1200 mm
Active length (between current leads)		1040 mm
Substrate	Hastelloy C276	90 µm
ISD	MgO	3 µm
Cap layer	MgO	300 nm
HTS layer	DyBCO	1600 nm
Contact layer	Ag	500 nm
Resistance of active part*		896 mΩ

*at room temperature

The stabilization of the conductor consists basically of an edge contact [6] soldered with Indium by a special apparatus that keeps the deposit thickness constant. This soldered connection joins the cover and the substrate at the edge and affects marginally the longitudinal resistance.

The longitudinal critical current distribution has been measured two times by using TAPESTAR® [7] for non-contacting critical current evaluation based on continuous Hall-probe scans. The measurements before and after the soldering were nearly identical. This demonstrates that the superconductor layer is not affected by the soldering method.

Fig. 1 shows the scan of the critical current I_c (A) measured by the manufacturer. The critical current is varying between 60 A and 190 A. So the sample is very inhomogeneous. Generally, it is expected that such non-uniformity creates hot spots and material degradation during quench.

B. *Tape preparation for switching experiment*

The 120 cm length sample was edgewise horizontally mounted in an open liquid nitrogen Dewar.

In order to contact the current leads to both sides of the conductor (substrate and cover) we have mechanically detached the oxide film from Hastelloy® and pressed the sample for 2.5 cm length between two overlapping 0.4 mm thin Indium foils. So, each contact has been connected on both sides on a length of 25 mm and has been provided with improved edge contact due to the crimped Indium.

The contacts have been fixed, but the holders along the length are still flexible to avoid a buckling under thermal stress of quench.

In order to evaluate the longitudinally quench propagation seven voltage taps have been soldered to the indium-plated edge to monitor the voltage drop along the tape. Fig. 2 shows the dimension of prepared coated conductor.

III. TEST CIRCUIT

A low impedance transformer is used to simulate the electrical grid. The transformer was fed by an AC power supply of 230 V/ 400 V, 50 Hz.

The thyristor-switch has been connected in series with the primary winding to define the pulse duration. The thyristor switch is able to vary the phase-angle and the number of half-waves.

The secondary winding of 1000 V has voltage taps from 50 V in 50 V steps. The resistance R_{ser} has been connected in series with the test sample to adjust the prospective current.

The resistance R_{par} has been connected in parallel to the test sample to vary the voltage along the sample.

The 16-channel transient recorder, triggered by fault current pulse was used to monitor the transient voltage signals and the current waveform.

Fig. 3 shows the test circuit used for the switching experiments.

IV. EXPERIMENTS

The pulse duration was varied from 20 to 100 milliseconds in the experiments. The ignition phase-angle has been fixed to 180° (non-cut first half-wave of pulse). To avoid the saturation of the transformer only even-numbers of half-waves

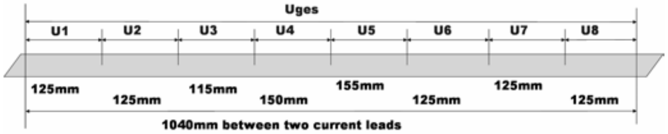

Fig. 2. Dimensions of prepared CC tape equipped with voltage taps. Left and rights are two current leads. In the middle are the voltage taps to measure the quench propagation of the figure in the caption.

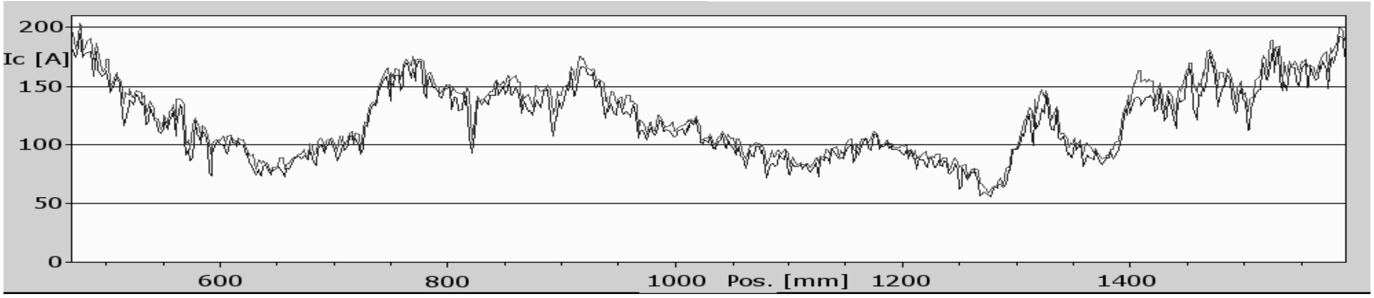

Fig. 1. Graph of critical current distribution measured by manufacturer using TAPESTAR® non-contacting measurement method based on continuous Hall-array scans. Y-Scale is a critical Ic (A) , X-scale is a length coordinate Position (mm).

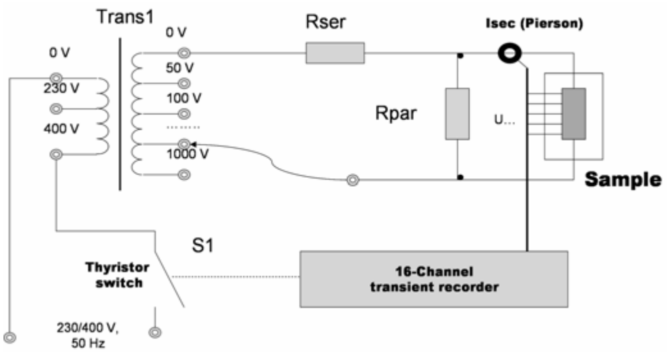

Fig. 3. Test circuit. The thyristor switch is triggered by transient-recorder. R_{ser} limits the prospective current to avoid the damaging of test circuit.

have been used. We repeated the measurements several times to approve the repeatability. The active length between two current leads (Fig. 2) was always 104 cm.

A. Quench propagation at low voltage source of 35 V $_{RMS}$ for two half-waves.

This switching experiment shows in Fig. 4 the current through CC tape, I_{sec} (A) and the voltage drop on full active length of sample, U_{total} (V). The current is inverted in the plots for better visibility. The voltage drop was able to obtain 35 V $_{RMS.}$ The prospective current was adjusted to 2100 A, which is more than 10 times higher than the critical current of the conductor. Figure 4 shows that the current is limited to 240 A in the first half-wave and to 146 A in the second.

For better comparison of the quench propagation we calculated the longitudinal electrical field as potential drop per length. It has to be kept in mind that the resistivity of the substrate does not depend very much on the temperature in the respective temperature range. The high positive temperature coefficient of the thin Ag-cover does not affect the resistance of sample significantly on account of its film thickness. The electrical field is non-uniform, so the superconductor is only partially in the normal state that is shown Fig. 5. Even with this non-homogenous voltage distribution no material deterioration was observed.

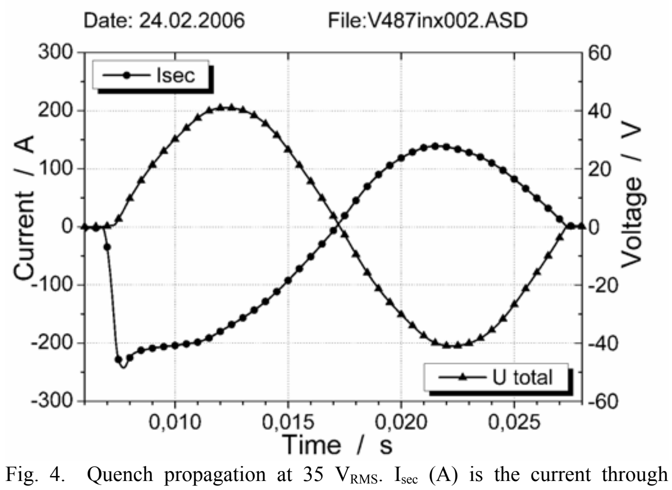

Fig. 4. Quench propagation at 35 V_{RMS}. I_{sec} (A) is the current through superconductor. U_{total} is the potential drop on full length.

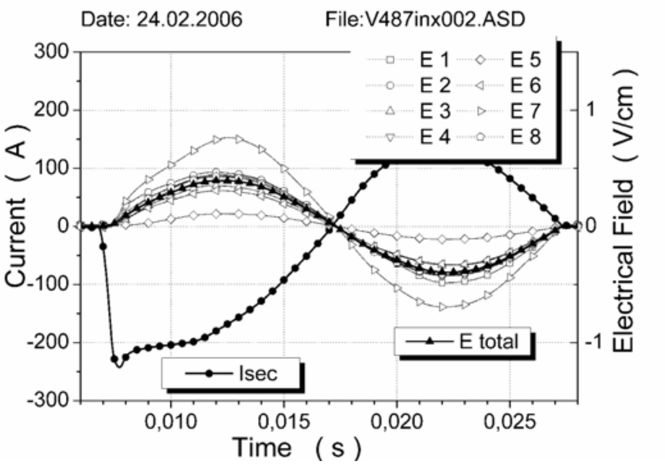

Fig. 5. Quench propagation at 35 V_{RMS}. I_{sec} (A) is the current through superconductor. E $_{total}$ (V/cm) is the average electrical field of full length. E $_n$ are electrical fields of each individual segments. The coated conductor is only partially quenched.

So, with a low electrical field applied, the segments with lowest critical current are quenching first and limiting the current, keeping it under critical current of segments with higher Ic. The superconductor is only partially quenched under low longitudinal electrical field conditions.

B. Quench propagation high voltage source of 230 V $_{RMS}$ for eight half-waves

Figure 6 shows the total voltage and the current for a relatively high voltage.

The current is limited to 310 A in the first half-wave and to 218 A in the last (eighth) half-wave. The peak voltage in the last half-waves achieved 283 V. Fig. 7 shows the quench propagation with up-scaled time coordinate for the first half-wave and electrical fields. The average electrical field E $_{total}$ increases from 2.4 V/cm in the first to more than 2.6 V/cm in the eighth half-wave. The quench starts non-uniform and propagates through the full length within 2.5 milliseconds.

The longitudinal electrical field distribution shown in Fig. 7 after the quench propagation is very homogeneous compared to the previously discussed low field condition in Fig. 5.

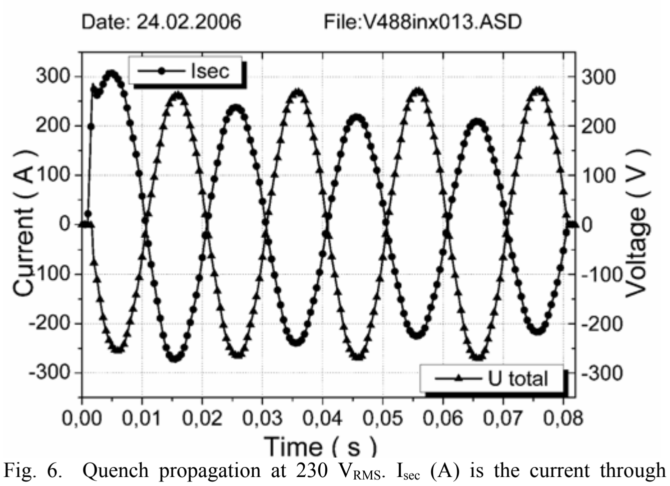

Fig. 6. Quench propagation at 230 V_{RMS}. I_{sec} (A) is the current through superconductor. U_{ges} is the potential drop on the full length.

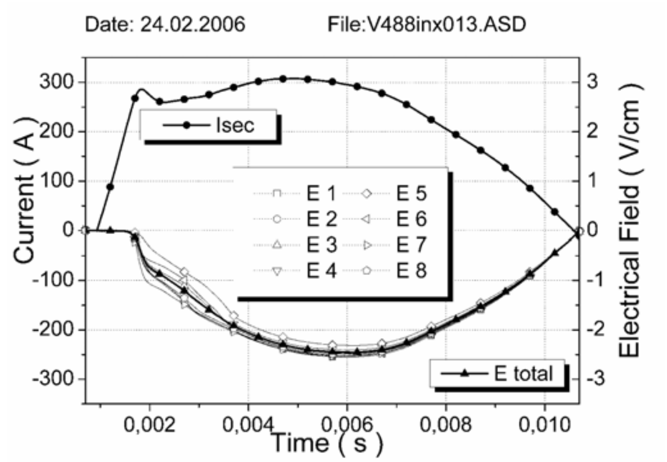

Fig. 7. Quench propagation at 230 V_{RMS}. I_{sec} (A) is the current through superconductor. The E_n are the electrical fields of each segments. Up-scaled time X-axis to demonstrate quench propagation at full length within 2.5 milliseconds.

The further increase of the pulse duration to 100 milliseconds leads to a superconductor degradation.

Fig. 8 shows the I-U graph for the transient curve in Fig. 6. The soft switching operation within the first half-wave and the slow increase of substrate resistance seems to be optimal for current limiting. The resistance is voltage divided by current. We can define a current resistance value as an angle between the X-axis and the vector from origin to current time position in the graph.

The black triangles on the line are current ticks, or time stamps every 500 µs.

V. CONCLUSION UND DISCUSSION

DyBCO coated conductor with soldered edge contacts has achieved electrical field of more than 2.6 V/cm (273 V at 104 cm active length) for a pulse duration of 80 milliseconds without material degradation.

The samples of up to 1 m length switched on the full length within 2.5 milliseconds.

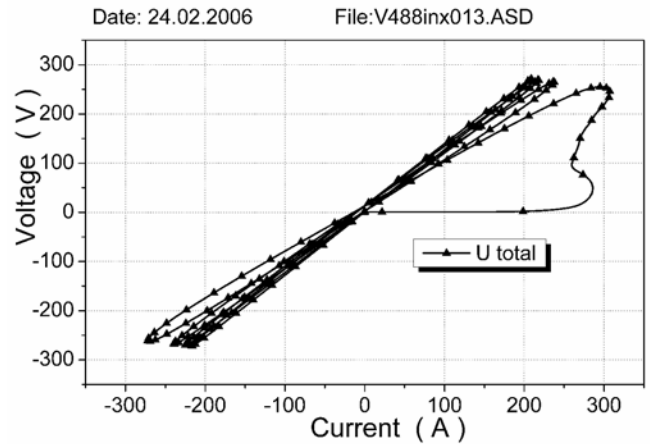

Fig. 8. Quench propagation at 230 V_{RMS}. X-axis is current through superconductor I_{sec}(A). Y-axis is the voltage drop on full active length U_{total}(V). The triangle marks are time ticks every 500 µs. Switching properties of coated conductor in a fault current limiter application are demonstrated.

The experimental results underline that the stabilization without Cu-lamination allows significantly higher electrical field and reduced heating-up effect, compared to [8].

The quench propagation (switching of FCL) is reproducible during limitation.

The next steps in this research are to investigate the parallel connection of several tapes and to scale-up the experiments to longer lengths.

REFERENCES

[1] M. Noe, A. Kudymow, S. Fink, S. Elschner, F. Breuer, J. Bock, H. Walter, M. Kleimaier, K.-H. Weck, C. Neumann, F. Merschel, B. Heyder, U. Schwing, C. Frohne, K. Schippl, M. Stemmle, “Conceptual design of a 110 kV resistive superconducting fault current limiter using MCP-BSCCO 2212 bulk material”, *IEEE Trans. Appl. Superconductivity,* to be published in this issue.

[2] A. Usoskin, A. Rutt, J. Knoke, H. Krauth, T. Arndt, “Long –length YBCO coated stainless steel tapes with high critical currents”, *IEEE Trans. Appl. Superconductivity,* 2005, vol.15, no. 2, pp. 2604-2607

[3] W. Prusseit, H. Kinder, J. Handke, M. Noe, A. Kudymov, W. Goldacker, “Switching and quench propagation in coated conductors for fault current limiters”, Presented at ISS 2005, Tsukuba, Japan, 24.-26.10.2005,
Available: http://www.theva.com/downloads/ldb/ISS2005_FCL.pdf

[4] W. Prusseit, G. Sigl, R. Nemetschek, C. Hoffmann, J. Handke, A. Lümkemann, H. Kinder, “Commercial coated conductor fabrication based on lnclined substrate deposition“,*IEEE Trans. Appl. Superconductivity,* 2005, vol.15, no. 2, pp. 2608-2610

[5] W. Prusseit, C. Hoffmann, R. Nemetschek, G. Sigl, J. Handke, A. Lümkemann, H. Kinder, „Long length coated conductor fabrication by inclined substrate deposition and evaporation”, Presented at EUCAS 2005, 12.-15.9.2005,Vienna, Austria,
Available: http://www.theva.com/downloads/ldb/EUCAS2005.pdf

[6] H. Kinder, patent number DE 10225935 B4.

[7] W. Prusseit, S. Furtner, R. Nemetschek, C. Hoffmann, “Identification of defect signatures in coated conductors by continuous Pall probe scans”, Presented at CCA 2004 in Kanagawa, Japan,
Available:
http://www.theva.com/downloads/ldb/CCA2004_Tapestar.pdf

[8] Seong Eun Yang, Min Cheol Ahn, Dong Keun Park, Dae Hee Jang , Tae Kuk Ko, “Manufacture and test of small-scale superconducting current limiter by using the bifilar winding of coated conductor”, *Journal of the Korea Institute of Applied superconductivity and cryogenics,* 2005, vol. 7, n0. 4, pp. 20-23,