LA-UR- 00-5093

Approved for public release; distribution is unlimited.

Title: PROPERTIES OF A PROTOTYPE BI-BASED HTS COMPOSITE WITH A HIGH RESISTIVITY SHEATH FOR RESISTIVE FAULT CURRENT LIMITING APPLICATIONS

Author(s): Robert C. Diehl, Steven Fleshler, Ralph Mason, Craig Christopherson, Ken DeMoranville, Richard Harnois, Alex Otto, Gilbert N. Riley Jr., American Superconductor Corporation, Etienne Serres, Electricite de France, Jeff O. Willis, MST-STC

Submitted to: Presented at the Applied Superconductivity Conference, ASC 2000, Virginia Beach, VA, 9/17-22, 2000, submitted to the IEEE Transactions on Applied Superconductivity

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Properties of a Prototype Bi-Based HTS Composite with a High Resistivity Sheath for Resistive Fault Current Limiting Applications

Robert C. Diehl, Steven Fleshler, Ralph Mason, Craig Christopherson, Ken DeMoranville, Richard Harnois, Alex Otto, Gilbert N. Riley, Jr., Etienne Serres, Jeffrey O. Willis, Heinrich J. Boenig, and Josef B. Schillig

Abstract— **Prototype Bi-2223 based composite conductors have been fabricated to provide inherent passive fault current limiting functionality in devices. An HTS insert strand possessing a high resistivity sheath (HRS) was laminated to two metallic strips to provide additional capacity to absorb the heat generated during a fault. Sheath resistivities up to 45 times that of pure Ag were achieved. We summarize the electrical response of 10 to 100 cm straight sections of conductor to pulsed dc and ac currents several times the critical current. DC pulsed I-V characteristics have been obtained over 7 to 8 orders of magnitude of voltage. For electric field levels around 10 V/m, the I-V curves demonstrate the advantage of the HRS conductor in facilitating fault current limiting over the conventional Ag-sheathed Bi-2223 approach. The recovery time for ac faults of 10 V/m was mapped out for various fault hold times. Instantaneous operational recovery was observed for fault hold times up to 3 seconds.**

Index Terms—**current limiters, superconductors (high temperature), fault currents**

I. Introduction

GROWTH in demand for electrical power and the prospect for increased fault currents coupled with the development of practical high temperature superconducting (HTS) materials has stimulated renewed interest in superconducting fault current limiters (FCL's). Several stand-alone HTS FCL prototypes have been demonstrated recently [1]-[3]. In one general class of superconducting FCL designs, referred to as the resistive FCL, the rapid rise in resistance that accompanies the transition from the superconducting state to the normal state when the current exceeds the critical current is used as the mechanism to limit fault currents. To prevent the development of hot spots at local inhomogeneities and avoid catastrophic failure at over-currents, superconducting conductors designed for resistive FCL's are fabricated with a direct electrical connection to a normal metal(s) to provide a current shunt. The application of material in contact with the superconductor is also desirable to provide additional heat capacity and thereby restrict the temperature rise experienced by the conductor during the fault. Limiting the temperature rise below the superconducting critical temperature, T_c, can facilitate operation at rated current immediately following the fault; this feature called instantaneous operational recovery is highly desirable in many device environments. The engineering challenge in designing a cost-effective conductor for a resistive FCL is to maximize the resistance of the conductor while providing sufficient current shunting around defects and thermal stabilization to enable instantaneous operational recovery.

HTS composites often contain a noble metal alloy sheath, matrix and/or substrate electrically connected to the superconductor that serve as parallel current paths. To attain a high equivalent resistance per unit length of the metallic component(s), R_m, the resistivity of the noble metal component(s) must be increased to ensure that they do not provide a low bypass resistance for fault currents. In this paper, we describe the properties of a conductor containing a Bi2223 ($Bi_2Sr_2Ca_2Cu_3O_x$) based composite fabricated for resistive FCL applications, in particular its enhanced electrical response for currents several times the critical current (I_c). Incorporating such a conductor into a power device such as a transformer could provide it with built-in current limiting functionality and potentially eliminate the necessity for additional fault protection in the section of the power grid serviced by the device [4],[5].

II. Conductor Approach

As an approach to engineering a practical HTS FCL conductor, we have fabricated a Bi2223 monofilament with a high resistivity sheath (HRS) soldered to two stainless steel (SS) laminates for thermal stabilization. A representation of the conductor cross-section is shown in Fig. 1. The HRS monofilament insert (Bi2223 core plus sheath) was produced by the oxide powder-in-tube (OPIT) technique. In contrast to

Manuscript received September 17, 2000. This work was partially supported by the U. S. Department of Energy Superconductor Partnership Initiative. Work at Los Alamos National Laboratory was supported by the U. S. Department of Energy, Office of Power Technologies, as part of the superconductivity program for Electric Systems.

R. C. Diehl, S. Fleshler, R. Mason, C. Christopherson, K. DeMoranville, R. Harnois, A. Otto, G. N. Riley, Jr. are with the American Superconductor Corporation, Westborough, MA 01581 USA

E. Serres is with Electricité de France, R & D division, Clamart, France

J. O. Willis, H. J. Boenig and Josef B. Schillig are with the Superconductivity Technology Center, Los Alamos National Laboratory, Los Alamos, NM 87545 USA

Au-doped Ag sheaths [6], here a non-noble metal was utilized to alloy Ag and enhance the sheath resistivity. With this new alloying technique, bulk sheath resistivities of 4-9 μΩcm at 77 K have been realized to date. These values are 20-45 times that of pure Ag.

The HRS insert has a width of 3.45 mm, a thickness of 0.1 mm and a superconductor volume fraction of 0.4. The solder alloy used for lamination has a relatively high 77 K resistivity of 18 μΩcm and the solder layer thickness is roughly 12 μm. The SS laminates are 4.1 mm by 0.5 mm and possess a 77 K resistivity of 55 μΩcm. A relatively thick SS thermal stabilizer was selected to provide sufficient heat capacity to prevent the conductor from over-heating during the fault. HRS conductors have been produced with I_c's at 77 K and self-field up to 39 A over 10 m lengths.

III. High Current I-V Curves

Current-voltage characteristics of the HRS conductor were measured in self-field to currents significantly greater than I_c to elucidate the electrical behavior at levels anticipated for fault currents. The I-V curves were obtained on a 10 cm sample cut from a longer piece-length. The sample was immersed in a liquid nitrogen bath with the bath temperature varied over the range 68-100 K by regulating the vapor pressure. A standard DC four-probe transport technique was employed to measure the I-V curve for currents near I_c. Short duration half-sine current pulses were applied to the conductor to mitigate Joule heating and the associated temperature rise for currents well above I_c. The high current portions of the I-V curves were constructed from captured current and voltage waveform pairs by extracting the voltage at peak current only (for which the inductive contribution is zero). Thus, each current and voltage waveform pair produced a single data point for the I-V curve and the curve was mapped out by varying the amplitude of the current pulses.

The inset of Fig. 2 shows the highest current pulse applied to the conductor at 68 K and the corresponding voltage waveform. The displayed pulse has a rise time of 130 μs to a peak current of 633 A (approximately 13 times I_c at 68 K). The corresponding electric field at this high level of current is

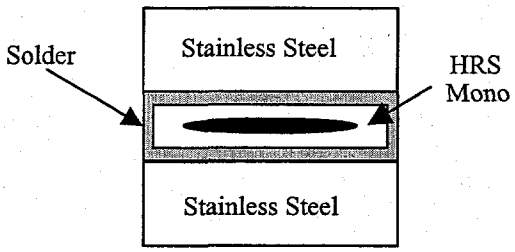

Fig. 1. A depiction of the HRS conductor containing the HRS Bi2223 insert, the SS laminates for thermal stabilization and the intermediary high resistivity solder.

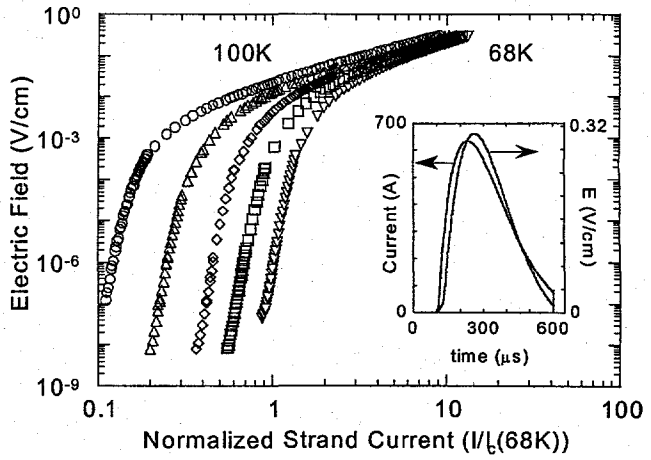

Fig. 2. I-V curves with the current axis normalized to I_c(68K, SF) for the conductor taken at bath temperatures 68, 77, 84, 92 and 100 K with the temperature decreasing from left to right. The inset shows a pulsed current waveform with the corresponding electric field response used to generate a single point on the I-V curve for currents much greater than the critical current.

0.3 V/cm. Displacement of the voltage peak to later time relative to the peak of the current waveform is indicative of Joule heating as the voltage continues to rise after the current begins to descend[1].

The combined DC and pulsed I-V curves, spanning 7 to 8 orders of magnitude of voltage, are given in fig. 2. For the current region close to I_c, the I-V curves show the familiar power law behavior, $E=E_c(I/I_c)^n$, where E is the electric field and E_c is the electric field criterion for the critical current. The n values are in the range of 21-24. As current is increased significantly above I_c the curves begin to 'roll-over' to much lower n values with n = 1.0-1.7 at the highest currents applied [6]. The tendency of the I-V curves to n values between one and two for $I >> I_c$ is expected due to the presence of flux flow in the Bi2223 core. In the flux flow regime, the resistance of the Bi2223 core should be proportional to the magnetic flux density (B) and the electric field should be proportional to the product I*B. Since the conductor is in self-field, B is proportional to the current. Thus, the electric field generated in the Bi2223 core due to flux flow should have an n value of two. At successively higher currents, an increasing amount of the current flows in the HRS and SS so that the total composite n value is closer to unity. When the current is high enough such that the Bi2223 core goes fully normal, the entire conductor is ohmic and n = 1.

IV. Comparison to Ag Sheathed Conductor

To understand the impact of the HRS in altering the current-voltage response of the entire conductor, we have compared the HRS I-V results to the calculated response of a conductor containing a pure Ag sheath. First, we extracted the nonlinear resistance of the Bi2223 core from the HRS experimental data by applying a parallel resistor model to the

[1] An estimate of the temperature rise (ΔT) of the sample for this highest current pulse based on integrating the power waveform and assuming adiabatic heating suggests ΔT of 1-7 K depending on the heat capacitance assumptions.

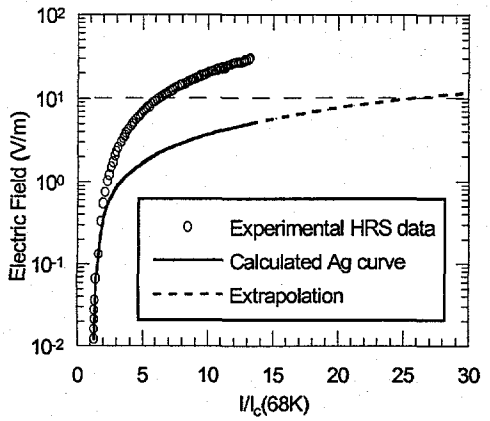

Fig. 3. I-V data for the HRS conductor (circles) and a calculated I-V curve for a conductor with a monofilament insert having an Ag sheath (solid line). The dashed line is a linear extrapolation of the high current response to an electric field of 10 V/m.

I-V curves of Fig. 2. For a given bath temperature, the value of the parallel resistance of the metallic components, R_m, was extrapolated from the normal state temperature dependence measured for this sample. The I-V curves of a laminated conductor containing a pure Ag sheath (with sheath resistivity 0.2 μΩcm at 68 K) were then constructed by reapplying the parallel circuit equations with a modified value of R_m. Fig. 3 shows the experimental I-V curve for the HRS conductor at 68 K plotted with the computed I-V curve for a conductor with Ag replacing the HRS. The curves are shown for elevated electric fields and the current axis is normalized relative to the 68 K value of I_c. The I-V curves overlap for values of current below and near I_c as the Bi2223 core dominates the current transport due to its low resistance. A substantial enhancement of the electric field for a given normalized current is observed for the HRS conductor relative to that of the conceptual Ag conductor at currents greater than roughly $2*I_c$. The effect of the sheath resistivity manifests itself once the current in the core is sufficient to drive the core resistance to values on the order of R_m.

To assess the impact of the HRS on current limiting in a device operating with a stiff voltage, we compare the normalized currents at which each conductor reaches the same fixed electric field. As a benchmark we choose an electric field of 10 V/m and extrapolate the nearly linear behavior of the I-V response of the Ag-based conductor to this value. The current at which the HRS conductor reaches 10 V/m is $6.3*I_c$ and is approximately four times lower than that for the Ag-based conductor, illustrating the advantages of the HRS conductor for current limiting applications.

V. AC Fault Response and Recovery

AC faults were applied to lengths of conductor in a separate testing apparatus developed at Los Alamos National Lab. A representation of the circuit designed to drive the faults is shown in Fig. 4. The load resistor on the secondary of the transformer was short-circuited by activating the

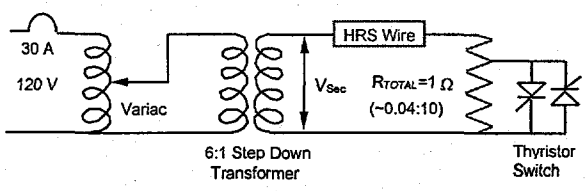

Fig. 4. Schematic of the circuit utilized to induce ac fault currents to the HRS conductor by short-circuiting the 1Ω resistor with the thyristor switch.

thyristor switch. Conductor lengths of 0.8 m were subjected to faults on the order of 0.1 V/cm for durations (hold-times) varying up to 240 power-line-cycles at 60 Hz (PLC's). The conductor was immersed in liquid nitrogen that was pumped to 68 K.

Fig. 5 exhibits the current and voltage waveforms during the fault and the recovery phase for a 30 PLC hold-time. The voltage drop per unit length measured across the HRS conductor sample increased from well below 1.0 μV/cm at the nominal current of about 20 A, to about 0.1 V/cm at fault currents of about 200 A. The factor of ten increase in current during the fault corresponds to a voltage drop increase by a factor greater than 10^5. Even in the high impedance test circuit, looking much like a current source to the sample, this resulted in a 30% decrease of the fault current as compared to the fault current with the HRS conductor sample shorted using a copper shorting strap. In a lower impedance environment, the fault current reduction would be very much greater. The ratio of the 200 A fault current (at 0.1 V/cm) to

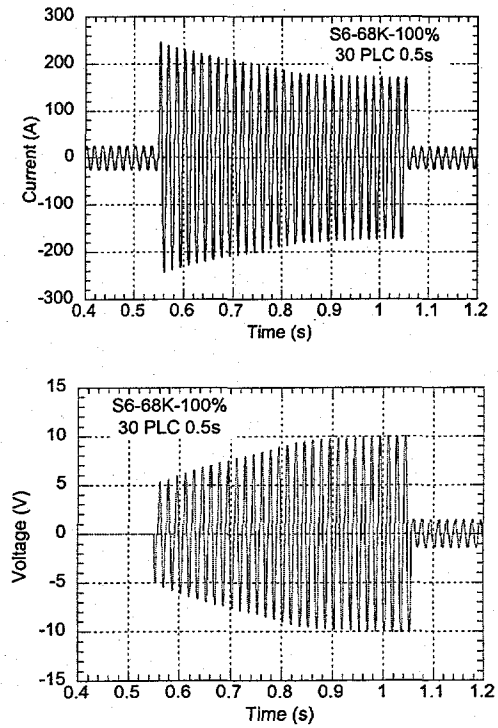

Fig. 5. The top panel shows the fault current applied to the HRS conductor and the bottom panel exhibits the corresponding waveform. These results were obtained in self-field with the sample was cooled to 68 K.

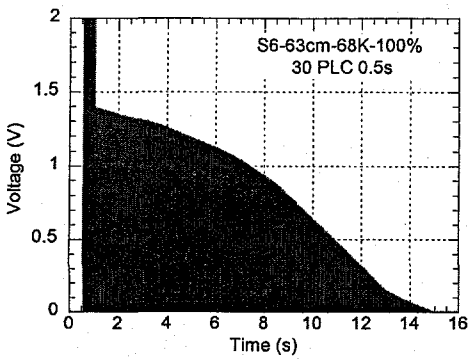

Fig. 6. The time evolution of the voltage after the fault while the current is maintained at its initial pre-fault value. Only the envelope of the peaks is discernible as the 60 Hz sinusoids are too dense to be resolved.

the designed conductor operating current of 30 A is 6.7. This value is in close agreement with results obtained for dc pulsed currents.

Fig. 6 shows the decay of the voltage back down to its steady state operating value after the fault is removed. The conductor is observed to return to the low-dissipation state in roughly 15 seconds while the steady-state operating current is maintained at its pre-fault value. From an operational point-of-view, the conductor can handle the full load of current immediately after the fault, and is thus capable of instantaneous operational recovery. The time for the voltage to fully return to the low dissipation, steady-state operating condition increases with larger fault amplitudes and longer hold-times. For a hold-time of three seconds at the maximum amplitude studied, the full recovery time to the low dissipation operational steady state is less than one minute. The HRS conductor eventually failed mechanically at a hold-time of 240 PLC (4 s) and maximum fault amplitude. This is equivalent to a power dissipation of ~16 W/cm for 4 s or energy deposition of ~63 J/cm.

VI. CONCLUSION

We have succeeded in introducing a high resistivity sheath to OPIT monofilament strand, while maintaining a high critical current density, by alloying Ag with a non-noble metal. This HRS insert strand possesses a sheath resistivity that is 20-45 times that of pure silver. The HRS insert provides the basic superconducting element in a thermally stabilized conductor designed for current limiting and fast recovery [5]. Rollover of the I-V curves to n values between one and two was observed at high current presumably due to the onset of flux flow in the Bi2223 core. Despite the tendency for thedifferential resistance of the conductor to decrease with increasing current, sizeable electric fields in the 0.1 V/cm range were generated at current levels around six times I_c at 68 K. The conductor carried the steady-state current indefinitely immediately after faults up to three seconds were removed. Full recovery to the initial low-dissipation state took less than one minute. This HRS conductor could enable limiting fault currents to 5-10 times I_c in devices for which the short circuit electric field across the conductor is 10 V/m and provide an instantaneous operational recovery feature.

ACKNOWLEDGMENT

The authors gratefully acknowledge discussions with S. Kalsi, A. Malozemoff, G. Snitchler of American Superconductor Corporation, M Chen, M. Lakner and W. Paul of ABB Corporate Research, D. Bonmann of ABB Transformatoren, and V. R. Ramanan of ABB Power T&D Company. D. Tatelbaum contributed to the development of the pulse testing equipment.

REFERENCES

[1] W. Paul, M. Lakner, J. Rhyner, P. Unternährer, Th. Baumann, M. Chen, L. Widenhorn, A. Guérig, "Test of 1.2 MVA high-T_c superconducting fault current limiter," Proceedings of EUCAS 1997 Third European Conference on Superconductivity, 30 June-3, July 1997, Koningshof, Netherlands, Vol. 2, H. Rogalla and D. H. A. Balnk, Eds. Bristol, UK: Institute of Physics, 1997 pp. 1173-1178.

[2] B. Gromoll, G. Ries, W. Schmidt, H.-P. Kraemer, B. Seebacher, B. Utz, R. Nies and H.-W. Neumueller, E. Baltzer, S. Fischer, B. Heismann, "Resistive Fault current limiters with YBCO films – 100 kVA functional model," IEEE Trans. Appl. Supercond. Vol. 9, 656-659 (1999).

[3] J. Cave, D. Willén, R. Nadi and Y. Brissette, "Development of inductive fault current limiters up to 100 kVA class using bulk HTS materials," IEEE Trans. Appl. Supercond. Vol. 9, 1335-1338 (1999).

[4] V. R. Ramanan, Gilbert N. Riley Jr., Lawrence J. Masur and Steiner J. Dale, "A vision for applications of HTS transformers," paper submitted to Proc. of the 47th International Wire & Cable Symposium, Philadelphia, PA, November 16-20, 1998.

[5] E. Serres, C. Levillain, F.X. Camescasse, J.-F. Picard, M. Lakner, J. Rhyner, M. Chen, W. Paul, H. Zueger, J. Backes, D. Bonmann, S. Fleshler, R. Diehl, C. Christopherson, R. Mason, K. DeMoranville, J. Daniel, "Current limitation in high temperature superconducting transformers and impact on the grid," Paper submitted to CIGRE 2000.

[6] Y. Sato, S. Honjo, Y. Iwata, Y. Miyamoto, J. Fujikami, H. Mukai, K. Fujino, K. Ohmatsu, K. Hayashi, K. Sato, "Characteristics of resistance in high-Tc superconductor carrying currents above Ic," Advances in Superconductivity, Vol. 12, T. Yamashita and K. Tanabe, Eds. Tokyo: Springer, 2000, pp. 652-654.