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High-Performance 2G HTS Wire for Efficient and Reliable Electricity Supply

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Second-generation (2G) high-temperature superconducting (HTS) wire, i.e., REBa2Cu3O7-δ (RE-123) coated conductor, holds enormous promise for the efficient and reliable supply of electricity. 2G HTS has been demonstrated in many real world applications such as electric power cables, fault current limiters (FCL), motors, generators, transformers and superconducting magnetic energy storage systems (SMES). SuperPower, Inc. developed an industrial-scale, high-throughput IBAD-MgO based process for textured buffer and an MOCVD process for RE-123 coating, and has successfully fabricated wires up to 1.5 kilometer in length for these applications. A number of prototype devices incorporating SuperPower's products have demonstrated excellent performance, and there is an increasing demand for 2G HTS wire. Standardizing manufacturing processes and implementing constant improvements in productivity and reduced variation, SuperPower is routinely producing high quality, long length wire to meet the current and future market demands. Meanwhile, we maintain a strong R&D focus to further the development of high performance wires, high efficiency processes and advanced conductor architectures to address future needs of 2G HTS technology. Our latest progress in those areas will be reported.

Index Terms—High-temperature superconductors, Coated conductors, (RE)BCO, MOCVD, superconducting power cables, fault current limiters, SMES

I. INTRODUCTION

SUPERCONDUCTING wire has been an enabling technology for many advanced applications, opening opportunities for advancements in condensed matter physics, biology, chemistry, material sciences, magnetic resonance, particle accelerators, colliders and fusion devices [1-5]. In particular, second generation high temperature superconducting (2G – HTS) RE-123 based wire holds enormous promise for the efficient and reliable supply of electricity in applications such as electric power cables, fault current limiters (FCL), motors, generators, transformers and superconducting magnetic energy storage systems (SMES) [6-10]. The performance offered by 2G-HTS wire leads to a number of system advantages including smaller footprint (weight, volume) and high power density allowing more freedom in the configuration of the rest of the device.

Today, the routine manufacture of high performance 2G HTS wire is underway. The fabrication technologies for 2G HTS materials have been progressing dramatically in the past few years [11-14] with remarkable advancements in the metrics of critical current, wire length (km+), in-magnetic-field performance and production throughput and costs..

This paper will highlight recent developments in the fabrication of 2G HTS wire and prototype devices at SuperPower Inc.(SP), including Zr:GdYBCO based wires with high in-field-critical-currents.

II. 2G HTS WIRE FOR EFFICIENT AND RELIABLE ELECTRICITY SUPPLY

The applicability of a superconducting wire for electricity supply applications is principally determined by its electrical current-carrying capability (current density) and mechanical properties to handle the stresses encountered during fabrication, cooldown and operation of electricity supply related devices. In addition, long lengths of wire are needed for the various applications at competitive pricing.

A. Structure of the SuperPower 2G HTS Wire

SuperPower 2G HTS wire is offered in multiple configurations with a typical architecture (SCS4050) illustrated below in Figure 1 consisting of a 50 micron substrate, ~0.2 micron buffer stack, ~1 micron YBCO layer, ~2 microns of Ag with 40 microns total thickness of surround copper stabilizer (SCS).

The substrate serves two purposes: it provides the mechanical backbone of the conductor and is the base for growing the subsequent layers. The nickel alloy substrate (typically Hastelloy® C276) is either 50 or 100 microns thick. The thin substrate thickness enables a high engineering current density (J_e) in the final tape that is critical for many applications. It is electrochemically polished (EP) to a surface roughness of less than 2nm and is smooth enough for ion beam assisted deposition (IBAD) of a textured MgO-based

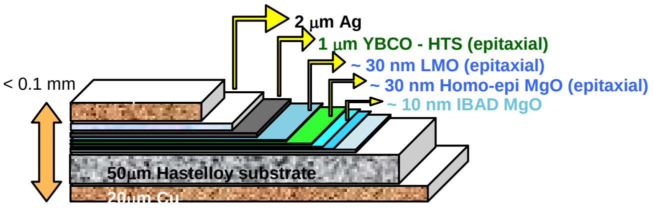

Fig. 1. Schematic of SuperPower's 2G HTS Conductor Architecture

buffer stack that serves several functions including diffusion barrier, lattice matching and as the critical aligned template for growing the current carrying HTS film. Metal organic chemical vapor deposition (MOCVD) is used to grow the YBCO HTS film. The advantages of the MOCVD method include its extremely high deposition rate, ~0.7 µm/min, and ability to extend its deposition area resulting in very high throughput. The YBCO HTS film is then capped by a thin Ag layer to provide good electrical contact. When required, stabilization of the conductor is provided by an electroplated copper layer that surrounds the entire structure. The thickness of the copper layer can be varied to meet the operational requirements of the wire in a specific application.

B. Current-Carrying Capabilities of 2G HTS Wire

The applicability of a superconducting wire is mainly driven by its electrical current-carrying capability under wide ranging operating conditions. Applications such as power cables, transformers and fault current limiters typically would operate in liquid nitrogen (64K – 77K) at low magnetic fields of 0.1 to 0.3 Tesla. HTS rotating machinery in general will operate in the temperature range of 20 – 50 K in magnetic fields of 2-5 Tesla. The current-carrying capability of a wire is characterized by the critical current (I_c) as a function of the operating temperature and the magnetic field seen by the conductor. Typical I_c(B,T) data on standard production SCS4050 wire is shown below in Figure 2. A typical reference critical current for this wire at 77K, self field is 100 A at a 1.0 microvolt/cm criterion for a 4 mm wide tape. The high current-carrying capability of SuperPower's 2G HTS wire, combined with its low cross-sectional area results in high engineering critical current density (J_e) values for magnet based applications where high J_e is a critical factor.

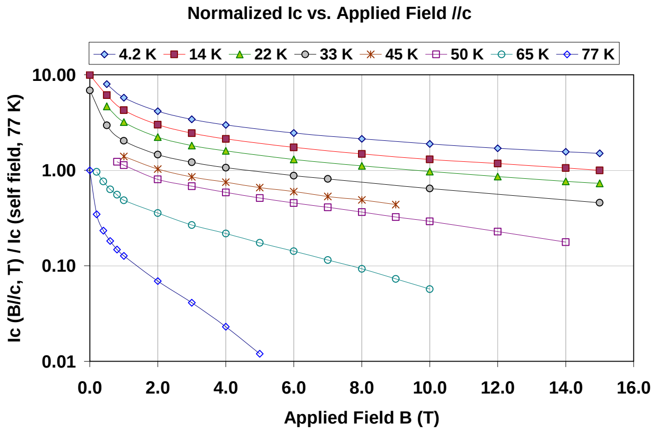

Fig. 2. Typical Ic(B,T) / Ic (self field, 77K) plot for standard SuperPower 2G HTS wire with the field perpendicular (//c) to the tape surface.

The performance of the 2G HTS material in field, including the field orientation with respect to the tape, is of critical importance. Recently, improvements have been made in the I_c vs. magnetic field angle performance of the 2G HTS wire with the inclusion of Zr into the (RE)BCO structure. Figure 3 is a plot of 77K, 1 Tesla critical current vs. field orientation for wires with varying compositions. In this plot, undoped wire is represented by the lower (0%-blue) line. Other compositions show the impact of Zr doping on the critical current performance. In power cable applications, the performance of the 2G HTS wire is determined by the critical current in magnetic fields parallel (90°, 270°) to the tape surface while other applications are driven more by magnetic fields at intermediate angles. The 2G HTS wire can thus be tailored to meet the operational requirements of specific applications for reliable electricity supply.

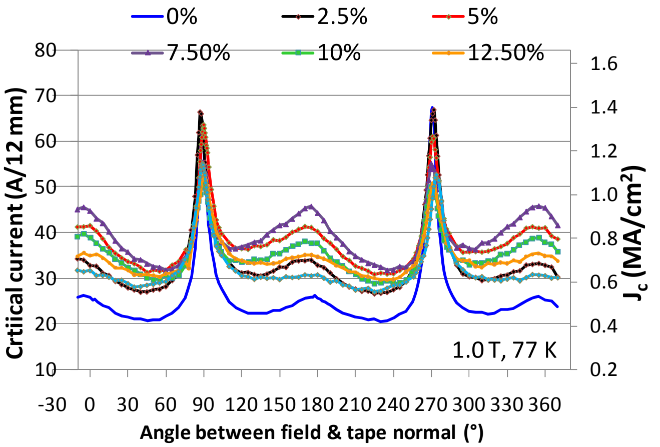

Fig. 3. Critical current as a function of angle between magnetic field and film surface at 77 K, 1 T for 12 mm wide samples with same film thickness but different film compositions. The lower blue line is representative of undoped 2G HTS wire. The upper lines are representative of improved conductors with Zr substitution into the (RE)BCO structure.

While 2G HTS piece lengths of several hundred meters are routinely manufactured, splice joints between segments will be needed in the foreseeable future for most applications. These joints are routinely fabricated using a simple lap joint technology which has recently been automated. The lowest resistance joints are made with the (RE)BCO sides facing each other using a thin intermediate solder layer. For example, 100 mm solder lap joints between two 4 mm wide SCS4050 wires have typical joint resistances on the order of 20 nano-ohms. In a wire carrying 100 A of operating current, this results in local heating at the joint of 0.2 mW which can be readily handled by the cooling system, particularly if higher (20K and above) operating temperatures are used.

C. Mechanical Properties of 2G HTS Wire

In order to function properly over the lifetime of the application, the 2G HTS wire must maintain its current-carrying capability under the fabrication, thermal and operational stresses the coil experiences during fabrication and operation. The 2G HTS wire fabricated by SuperPower has the inherent advantage of a built-in structural element with its Hastelloy® C276 substrate, often eliminating the need for added external reinforcement. In uniaxial tension, the 2G HTS conductor can tolerate stresses on the order of 700 MPa without I_c degradation. The material has been shown to tolerate fatigue cycling (100,000 cycles) up to the 700 MPa limit without degradation [15].

Thermal stresses are developed during the cool down of the tape as well as any thermal transients that may be experienced during fault or quench situations. SuperPower 2G HTS wire has thermal expansion characteristics well suited for inclusion with typical structural materials that would be used in the different applications as shown below in Figure 4.

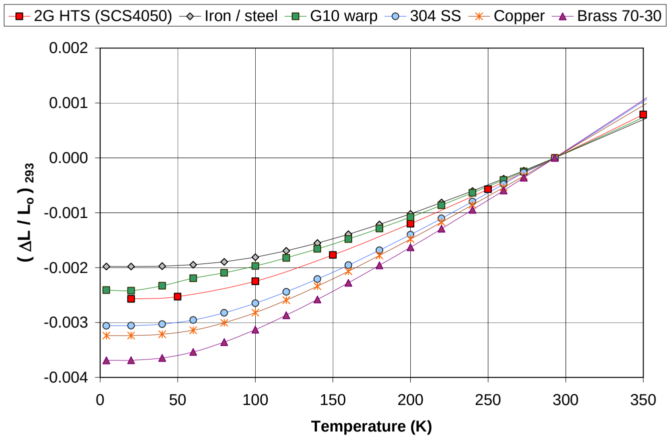

Fig. 4. Thermal expansion of standard production (SCS4050) SuperPower 2G HTS wire compared with other common magnet construction materials.

D. Other Considerations for Using 2G HTS Wire in Electricity Supply Applications

For most electricity supply applications, long lengths of wire are required to reduce the number of splices in the system. Continuous piece lengths of up to 1300 m have been fabricated of the 2G HTS material. Piece lengths of several hundred meters typically show very uniform I_c properties and high n-values of ~30.

Since most electricity supply applications operate in an ac environment, low ac loss conductor is highly desirable in order to reduce the heat load on the cryogenic system. This is an active area of ongoing research since reduction of ac losses is a critical step in reducing the cost of superconducting systems. One technique for addressing the ac loss in a conductor is the fabrication of multifilamentary wire with channels cut along the length of the wire to produce discrete filaments (Figure 5). With these types of structures, the 2G HTS wires see a hysteretic ac loss reduction on the order of 5 times or more in the 50 – 100 Hz range. The eddy current loss in the wire is negligible since the Hastelloy® C276 has a very high resistivity of ~ 125 µohm –cm.

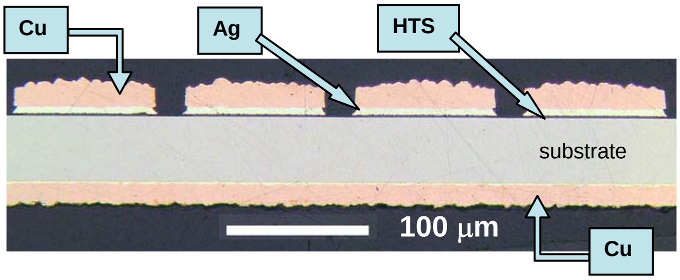

Fig. 5. Cross-section of an experimental SuperPower multifilamentary wire with ~ 100 micron wide filaments and ~ 20 micron wide channels for effectively reducing hysteretic ac losses in the 2G HTS wire.

In order to reduce the coupling loss in a winding constructed with 2G HTS wire, a Roebel cable construction can be used. This also allows for higher operating currents while lowering the induction of the device while providing the transposition required to lower the coupling ac loss in the wire. An example of a Roebel cable construction fabricated by the Karlsruhe Institute of Technology (KIT) using SuperPower 2G wire is shown below in Figure 6.

Fig. 6. A section of Roebel cable constructed by KIT using SP 2G HTS wire providing the transposition required for lowering the coupling loss component of the ac losses. Total width of the cable is 12 mm.

III. ELECTRICITY SUPPLY DEVICE DEMONSTRATIONS

Several device demonstrations have been successfully completed using SuperPower 2G HTS wire and additional demonstrations are ongoing.

A. Albany Cable Project

In 2008, SuperPower, in partnership with Sumitomo Electric (SEI), Linde, National Grid and financial support from DOE and NYSERDA, completed testing of an underground superconducting power cable located on-grid in Albany, NY on National Grid's network. The 350 m long cable included a 30 m section fabricated using SuperPower's 2G HTS wire. Figure 7 shows a cutaway section of the 2G HTS cable section.

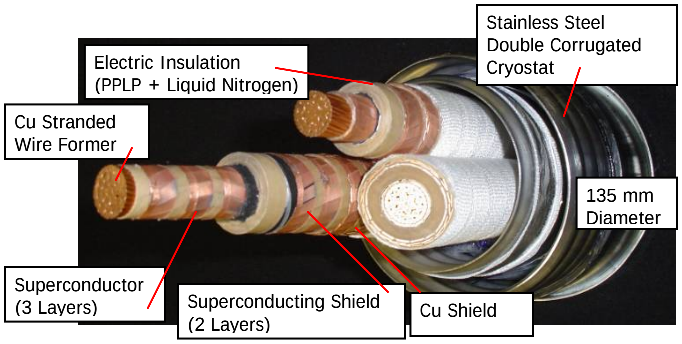

Fig. 7. Cutaway of the 3 phase-in-1 cryostat cable section using SuperPower 2G HTS wire. Cable fabricated by Sumitomo Electric.

Each of the three phases consisted of a central stranded copper former used for both structural support and for current overload conditions. Three superconducting layers were used per phase. Dielectric insulation was provided by PPLP and liquid nitrogen. The three phases were all contained in a nominal 135 mm diameter, double wall vacuum insulated cryostat.

B. Superconducting Fault Current Limiter (SFCL) Demonstrations

Superconducting fault current limiters are a promising application for 2G HTS. As new sources of generation are added, utilities are faced with the threat of higher levels of fault currents. SFCL devices address the market need to cost-effectively correct fault current over-duty problems at both the transmission and distribution level. By injecting impedance into the line during the fault transient, HTS SFCLs reduce the fault current to a lower, safer level (20%-50% reduction), so that existing switchgear can still protect the grid, preventing breaker failures & associated problems while maintaining flexibility to accommodate load growth and avoiding the need for expensive breaker upgrades.

There are several approaches to using 2G HTS in fault current limiters [xx-zz]. SuperPower has focused on the resistive type SFCL approach and has successfully tested prototype resistive SFCL demonstration modules highlighting the performance of the tape in this application. A pair of SFCL test modules in a test cryostat is shown below in Figure 8. Each module contains a meander path of parallel 2G HTS tapes. The number of tapes is selected based on the current capability of the module while the length of the tapes determines the voltage capability of the module. A parallel shunt is often used to provide added impedance during the quenched state of the superconductor.

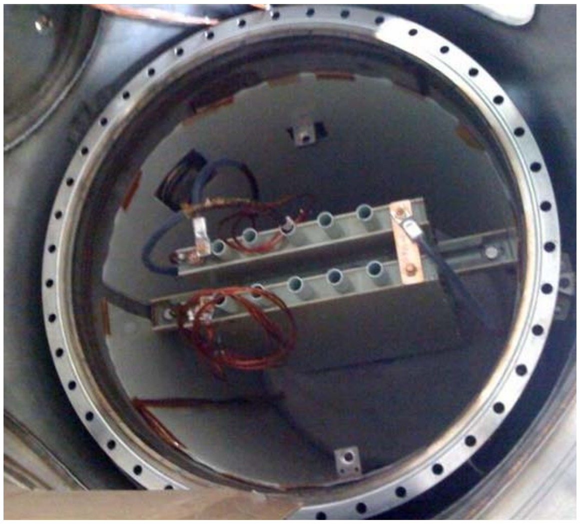

Fig. 8. View of a pair of 2G HTS based SFCL modules in a test cryostat. Operation is in LN_2.

During normal operation, the resistive SFCL is essentially invisible to the grid, providing a near zero impedance device in the network. When a fault current reaches the SFCL, the critical current of the 2G HTS elements is exceeded and the material transitions from the superconducting state to a highly resistive quenched state, also “switching in” any parallel shunt if it is provided. The high impedance of the quenched 2G HTS and shunt significantly reduce the prospective fault current to levels that can be handled by the downstream breakers and other equipment. Once the fault is cleared, the 2G HTS can then recool to the superconducting state. Figure 9 shows an example of experimental test data on a resistive fault current limiting module using SuperPower 2G HTS tape. Note the fast response time of the module (<1 ms) and the reduction of the ~25 kA prospective current to below 12 kA (>50% reduction).

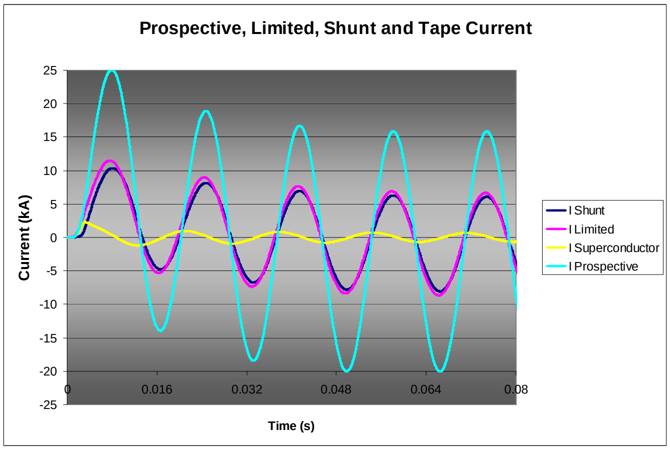

Fig. 9. Test data on SFCL modules operating in LN2 showing a response time of < 1 ms and >50% reduction in the current.

C. Other Electricity Supply Applications

In addition to distribution power cables and fault current limiters, 2G HTS conductor will be used in other electricity supply applications that can take advantage of the high power density available. Superconducting transformers can be made half the size and weight of conventional transformers and have the added advantage of being able to be run over rated capacity without loss of life and can incorporate a fault current limiting function with proper design. Long distance bulk power transmission using dc cables take advantage of the “zero resistance” of 2G HTS conductors. Superconducting magnetic energy storage (SMES) using 2G HTS can be used to help balance electrical loads on the grid, particularly with the introduction of renewable sources such and solar and wind. Superconducting generators for use in wind farms will permit the introduction of direct drive generators, eliminating the need for gearboxes, one of the high maintenance items impacting the economics of wind power generation.

IV. SUMMARY

2G HTS wires with high engineering critical current density have been developed and are being manufactured by SuperPower in long lengths. In field performance of the 2G HTS wire has been remarkably improved, particularly at higher operating temperatures, through REBCO composition adjustment, high-T_c rare-earth element substitution, Zr-doping and growth condition optimization. The electrical and mechanical properties of SuperPower’s wire are well suited for a variety of electricity supply applications.

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