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Progress in high temperature superconductor coated conductors and their applications

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Abstract

Second generation (2G) high temperature superconductor (HTS) wires are based on a coated conductor technology. They follow on from a first generation (1G) HTS wire consisting of a composite multifilamentary wire architecture. During the last couple of years, rapid progress has been made in the development of 2G HTS wire, which is now displacing 1G HTS wire for most if not all applications. The engineering critical current density of these wires matches or exceeds that of 1G wire, and the mechanical properties are also superior. Scale-up of manufacturing is proceeding rapidly, with several companies already supplying the order of 10 km annually for test and demonstration. Coils of increasing sophistication are being demonstrated. One especially attractive application, that relies on the specific properties of 2G HTS wire, is fault current limitation. By incorporating a high resistivity stabilizer in the coated conductor, one can achieve high resistance in a quenched state during a fault event and at the same time provide significant heat capacity to limit the temperature rise. A test of a 2.25 MVA single phase system at 7.5 kV employing such wire by the Siemens/AMSC team has demonstrated all the key features required for a cost-effective commercial system. A novel approach to providing fault current limiting functionality in HTS cables has also been introduced.

1. Introduction

This paper reviews progress made at American Superconductor Corporation (AMSC) in scaling up a second generation (2G) high temperature superconductor (HTS) wire based on a coated conductor technology and the YBa2Cu3O7 (YBCO) superconductor. Significant progress in these areas is also being made at a number of other industrial organizations around the world, including SuperPower in the US, Fujikura, Sumitomo, Furukawa and Showa in Japan, and EHTS in Germany, but this work is reviewed elsewhere at this conference. In addition, the paper reviews the first applications of 2G HTS wire, in particular a fault current limiter developed in collaboration with Siemens AG and a novel fault current limiting cable concept.

2. Second generation HTS wire process

As described in earlier reports [1, 2], American Superconductor has selected a process for its second generation wire with the goal of low-cost, large-volume manufacturing, coupled with high electrical and mechanical performance. A Ni–5 at.%W substrate is cube-textured through a low-cost process of rolling and recrystallization annealing and is prepared in the form of a flexible strip typically 75 μm thick. The x-ray full-width half-maximum (FWHM) in-plane texture Δφ is typically 6.5°. After a plasma cleaning and sulfurization to create a sulfur 2 × 2 superstructure on the nickel surface, a 75 nm Y2O3 layer is deposited by high rate reactive sputtering. Then two more layers, 75 nm of yttria-stabilized zirconia and 75 nm of CeO2, are deposited epitaxially by high-rate reactive sputtering, yielding texture typically 1° better than the metal surface.
These layers suppress nickel diffusion into the HTS layer and oxygen diffusion into the underlying substrate, as well as providing a stable, lattice-matched surface for growing the HTS layer. Although reactive sputtering is a physical vapor deposition (PVD) process and requires expensive vacuum equipment, the layers are thin and the deposition rate so fast that the cost per metre is very low. Altogether, the substrate/buffer combination forming the template is an application of the RABiTS™ process first proposed by Goyal et al at Oak Ridge National Laboratory [3].

The YBCO HTS layer is deposited by an ex situ process onto the template by means of another low-cost process: metal–organic deposition (MOD) [1, 2, 4]. This starts with the slot-die coating of a trifluoroacetate-based precursor bearing the stoichiometric proportions of cations for forming YBCO. The coating is dried and then decomposed at temperatures below 600°C to remove carbon-containing material, leaving a mixture of yttrium–barium–oxyfluoride, yttria and copper oxides. Careful control of the decomposition temperature profile, including a slower ramp in the 200–300°C temperature range, is utilized to prevent cracking of the film, which is 15–20 μm thick as it enters the decomposition process. This film is subsequently reacted at temperatures in the range of 700–800°C in an O₂–H₂O environment to form YBCO via an ex situ epitaxial growth process. A silver passivation layer several microns thick is then deposited by dc magnetron sputtering, followed by an oxygen anneal to optimize the YBCO performance. The coating and decomposition processes can be repeated multiple times to achieve thicker layers, though at the cost of increased process time and equipment usage. With a single coat, it has been possible to achieve 0.8 μm effective YBCO thickness (corresponding to approximately 1 μm actual thickness including porosity and secondary phases) carrying a minimum of 275 A per cm width or 3.4 MA cm⁻² (77 K, self field), as shown for a 70 m long wire in figure 1. It is remarkable that in spite of almost 20% porosity and secondary phases, very high current density is achieved, indicating very good connectivity around the pores. Double coat samples reach 1.4 μm in effective thickness and carried 350 A per cm width in a 94 m long wire. Triple coat, short R + D samples have attained a critical current of 560 A per cm width.

Increasing the process rates for all these steps is critical for a cost-effective product. Recent work has optimized the temperature and gas environments of the texture anneal, decomposition and oxygen anneal steps to significantly accelerate the rates, as shown in figure 4.

A key advantage of the RABiTS/MOD process described above is that all process steps can be carried out in a reel-to-reel configuration that provides a deposition of the buffer and superconductor layers across wide strips which can subsequently be slit to the desired dimension, as illustrated in figure 2, using a low-cost roll-slitting process. The slit wire is called the ‘insert’ for reasons to be discussed below. Early work at AMSC started with a strip width of 1 cm, but the process has been extended to a 4 cm width for regular production, with plans to increase the width to 10 cm as a next step in scale-up. The advantage of the wide strip is that (W/w) – 2 wires of width w can be slit from a W wide substrate, where 2 represents the edge strips which are discarded because of coating non-uniformities. Thus a single pass through the deposition process can produce eight 4 mm wide wires from a 4 cm wide strip, or 23 from a 10 cm wide strip, with the final wire cost reduced approximately in inverse proportion to the number of wires produced in the slitting process.

The final step of the wire manufacturing process is to laminate stabilizer strips on either side of the insert wire using a reel-to-reel wave-soldering process. By choosing stabilizers slightly wider than the 4 mm insert, for example 4.4 mm, a 0.2 mm fillet is formed on either edge, as shown in figure 3. In combination with the laminates on either side, these fillets form a hermetic seal for the superconductor material, in addition to providing mechanical strength and electrical stabilization. A variety of different materials can be used as stabilizer, including copper, brass and stainless steel. The higher conductivity material is useful for stabilizing conduction-cooled magnets, while the higher resistivity material is useful for fault current limiter applications, as discussed further below.

This 3-ply structure with a 4.4 mm width is called 344 superconductors. The architecture has flexibility in the width of the wire as well as type of stabilization,
allowing customization for particular application needs. For example, cable applications typically require wire widths of order 4.4 mm to accommodate the strains associated with helical winding around several centimetre diameter formers. However, many magnet or coil-based applications can be conveniently configured with wider wires to reduce the cost of winding multiple pancakes. It is also possible to put multiple inserts in the wire, creating a ‘444’ structure, for example.

3. Scale-up of 344 superconductors

AMSC began regular ‘pre-pilot’ production of 344 superconductors in September 2005, using R + D equipment adapted for 4 cm strips up to 100 m long. AMSC shipped 11.5 km of wire to customers from the pre-pilot operation during its 2007 fiscal year (ending in March 2007).

To increase the manufacturing capacity further, AMSC embarked on a plan to set up a full pilot operation by bringing in full-scale production equipment for each of the process steps, capable of 1000 m lengths and 10 cm wide processing [5]. Certain equipment was acquired early and has been operating successfully in the pre-pilot operation for two years, including the reactive sputtering apparatus for two of the three buffer layers and the final reaction furnace. However, throughput and length of the wire remain limited by R + D equipment for other steps of the process.

As of September 2007, all the full-scale manufacturing equipment has been designed and acquired, and final process qualification is underway, with the objective of starting the full pilot line by the end of 2007 with a gross capacity of 720 km/year. Initial operation is targeted at a strip width of 4 cm, and lengths from 250 to 500 m. Once the pilot operation is established and demand is confirmed, the plan is to transition from 4 to 10 cm wide processing, which will increase throughput by approximately 2.5, bringing the gross production level to close to 2 million m/year.

4. R + D progress

Significant performance improvements are also being achieved through ongoing R + D. The critical current performance of 2G HTS wire is complex, varying with the angle of the applied magnetic field, as shown in the left side of figure 5. Significant enhancement, particularly in the field orientation perpendicular to the sample plane, can be achieved by non-stoichiometric addition of a rare earth such as dysprosium, which precipitates during the HTS reaction process to form nanosized spherical rare-earth-oxide precipitates which have been called ‘nanodots’ [6]. These are visible in the SEM micrograph on the right. It has been found that a different type of defect, a 124 intergrowth or stacking fault, generates the prominent peak for the applied magnetic field oriented parallel to the sample plane [6]. Since the rare-earth-based nanodots tend to suppress the intergrowths, a hybrid process has been developed using two coatings, one with and the other without rare earth addition. As shown in the top curve on the left of figure 5, this gives enhanced critical current at all angles of the applied magnetic field. The presence of the large peak in the parallel orientation is in fact favourable for magnet design because typical solenoidal coils have axial fields along their interior roughly double those of the stray radial fields at the ends of the coil. Thus a tape-shaped wire optimized for use in a...
solenoidal coil requires the same critical current in the presence of an in-plane field as in a perpendicular field that is roughly half the strength. Such behaviour can be deduced from a set of function-of-angle curves at different fields of the type shown in figure 5.

This hybrid double-coat process has also enabled critical current density improvements in self-field, as shown in figure 6. At 400 A cm\(^{-1}\) width at 77 K, this wire has a performance (150–160 A at 77 K) comparable to earlier (and more expensive) 1G wire at a similar width. 200 A is considered a level that will enable broad market penetration for a wide variety of applications.

Another promising R + D result is 5 MA cm\(^{-2}\) current density at 77 K in single-coat wire with effective thickness 0.8 \(\mu\)m, on a RABiTS template with an average FWHM in-plane texture, \(\Delta \phi\), of 4.6\(^{\circ}\) FWHM and an average FWHM out-of-plane texture, \(\Delta \omega\), 2.3\(^{\circ}\). These results compare with a maximum of 3.8 MA cm\(^{-2}\) at 77 K in a same thickness HTS layer on a more typical RABiTS template with average \(\Delta \phi\) and \(\Delta \omega\) textures of 6.1\(^{\circ}\) and 3.7\(^{\circ}\), and a maximum of 5.4 MA cm\(^{-2}\) at 77 K in a same thickness HTS layer on a single crystal substrate. These results show that even though current density is already very high, there is significant potential to improve the critical current density \(J_c\) with only a modest improvement in substrate texture. A contributing factor to this remarkable current density is the improved out-of-plane texture of the RABiTS template resulting from a texture enhancement of the Y\(_2\)O\(_3\) seed relative to the NiW substrate [7]. This texture enhancement is believed to arise from tetragonal distortions of the Y\(_2\)O\(_3\) lattice resulting from strains induced during the deposition process. A second factor responsible for this level of \(J_c\) is believed to be the grain boundary meandering phenomenon, observed in \textit{ex situ} HTS films [6]. Increased grain boundary area from meandering both along the c-axis and in the ab-plane increases the grain boundary current density far above the classic Dimos curve of \(J_c\) versus grain boundary angle for grain boundary angles above 3\(^{\circ}\)–4\(^{\circ}\) [8]. This appears to be at least in part a geometrical effect from the increased grain boundary area.

5. Applications progress: standalone fault current limiter (FCL)

The availability of 2G wire during the last two years has spawned a number of significant prototypes for energy applications. Perhaps the greatest customer interest has centred on standalone resistive FCLs based on AMSC’s HTS wire laminated with 25 \(\mu\)m of stainless steel on either side, a wire called 344S superconductors, with an architecture similar to that shown in figure 3. In contrast to 1G wire with its silver sheath, 344S superconductors have no such high conductivity shunt and therefore achieve high resistance once the superconductivity is quenched by an overcurrent. In particular, the stainless laminates and NiW substrates have high resistivity, and even the several micron thick silver layer exhibits a resistivity much higher than pure silver resulting from alloying with the solder used to bond the laminate to the insert wire.

During the last year, Hyundai, in collaboration with Yonsei University in Korea, demonstrated a single-phase standalone FCL with a nominal rating of 8.3 MVA, operating at 13.2 kV and 630 A in liquid nitrogen, using AMSC 344S superconductors [9]. Here we focus on another prototype demonstrated by Siemens Corporate Technology, resulting from a strategic alliance with AMSC and also using 344S superconductors [10, 11]. This single-phase standalone unit, illustrated in figure 7, had a nominal rating of 2.25 MVA at 7.5 kV (equivalent to a 13 kV three-phase rating) and 300 A_{rms}.

Key to successful operation of this system were the bifilar coils, illustrated schematically in figure 7, which were connected in series and parallel to form a switching module [5] meeting current and voltage requirements. The reversal of current in neighbouring windings leads to a cancellation of local magnetic fields, reducing inductance as well as ac losses which constitute the main resistive impedance. With both inductance and resistance reduced to a minimum, the modules appear electrically invisible in the circuit under normal operating conditions, an attractive feature from the perspective of application in an electrical power grid. But when a current surge exceeds the critical current during a fault, the resistance rises within a millisecond, limiting the height
features allow for very compact and convenient installations in urban environments with crowded underground infrastructure. HTS cables also have low series inductance, opening up economic ac power flow control in conjunction with phase angle regulators. However, handling fault currents has required a significant amount of high conductivity copper in parallel with the superconductor wires, and this reduces the size and weight advantages.

Introducing fault current limiting functionality directly into an HTS cable can have major benefits in reducing the necessity for this excess copper and in controlling system-wide fault currents without the introduction of standalone fault current limiters, saving on space and cost. This idea was first explored in the European SuperPOLI program [14] but proved to be very challenging with either the solid rods or early 2G HTS wire available at that time.

Now this idea is being developed with a more practical solution in a program being undertaken by AMSC with Con Edison and Southwire, and sponsored by the US Department of Homeland Security. The security value of a current limiting solution in a program being undertaken by AMSC with Con Edison and Southwire, and sponsored by the US Department of Homeland Security. The security value of a current limiting solution in the 3G grid that Con Edison has proposed for New York City, illustrated in figure 9.

In Con Edison’s present day configuration, a disturbance in an area substation can blackout an entire network. However, if multiple area substations could be connected at the 13 kV distribution level as shown in figure 9 (right), a problem in one area substation could be mitigated by power flow from a neighbouring connected substation. This configuration also raises the possibility of significant savings in the number of transformers required for the ‘$N - 2$’ redundancy which Con Edison requires for its network. Instead of having two extra inactive transformers in each area substation, as is presently done, the redundancy can be achieved through backup power flow from a neighbouring substation.

The challenge in doing this is two-fold. (1) The connections require high current, which in turn would require multiple conventional cables installed under crowded city streets. High power and environmentally benign HTS cables solve this problem. (2) The connections increase fault current by providing additional paths for current flow. This is where FCL functionality becomes critical, since fault currents in Con Edison’s grids are already reaching a level beyond which wholesale replacement of breakers and other equipment would be required. Taking advantage of the existing superconductor

of the current surge. An example of this behaviour is shown in figure 8, obtained in tests conducted by Siemens at IPH in Berlin.

Figure 8 shows the evolution of current under application of a 7.8 kV rms voltage, with an initial surge of current limited by the transition to the resistive state. Without the fault current limiter and with a source impedance of $\sim 0.3 \ \Omega$, the prospective fault current would have been 28 kA rms. As energy is absorbed adiabatically by the resistive wires with their laminates, the temperature and correspondingly the resistance increase, and the current amplitude accordingly drops. The peak current at the end of the 45 ms fault hold time is 1 kA, a factor of 2.3 times the critical current of the module. Siemens has carried out tests at a variety of phases and prospective fault currents, as well as in a shunt configuration with a parallel inductor, as described in more detail in [10].

Another key requirement for successful FCL operation is rapid recovery to the superconducting state. This is ensured by spacing the windings of the bifilar coil by several millimetres. Recovery within 2.4 s was demonstrated in the 2.25 MVA unit, very close to what was achieved in isolated wires immersed in liquid nitrogen [10]. All in all, the Siemens tests of the 2.25 MVA unit have been important in confirming practical current limitation based on switching of 344S superconductors.

6. Applications progress: fault current limiting cable

Many HTS cables are being demonstrated around the world [12, 13]. They bring significant advantages including their ability to carry up to ten times greater current and power capacity per cross section than corresponding conventional copper cables, leading to reduced system weight and size. Additionally these systems reduce the environmental impact as no heat or electromagnetic fields are emitted. These unique features allow for very compact and convenient installations in
wires in the cables for fault current limiting, rather than introducing standalone fault current limiters for this purpose, saves valuable space in crowded substations and reduces the cost substantially.

2G HTS wire with a thick, high resistance stabilizer like AMSC’s 344S superconductors is key to enabling such a fault current limiting cable. But even in this case, the energy dumped into the cable during a fault can be very substantial; it is given by \( \Delta E = V I_{\text{lim}} \tau \), where \( V \) is the rms system voltage, \( I_{\text{lim}} \) is the rms limited current (typically some multiple of the metal superconductor critical current \( I_c \) as seen in connection with figure 8) and \( \tau \) is the fault hold time, which for typical grid protection schemes can be 200 ms or longer. For a 13.8 kV distribution voltage, \( I_{\text{lim}} = 9000 \text{ A}_{\text{rms}} \) (assuming about three times a 3000 A_{\text{rms}} nominal current), this corresponds to 24 MJ, which, even if distributed over a kilometre-length cable, causes substantial heating. In contrast to the case of the standalone fault current limiter, where cooling by liquid nitrogen can be optimized, the process of flushing out heat from a kilometre-length cable can take hours, making the recovery time unacceptably long.

A key step to solve this problem is to recognize that, in most cases, in complex meshed city grids, there will be multiple conventional connections between the city nodes to be connected by an HTS cable, through these other connections have in general significantly higher impedance. For example, in figure 9, such a conventional connection arises through the transformers and high voltage interconnections. In the case where such parallel connections do not exist, a parallel conventional cable of relatively low capacity and high impedance \( Z_R \) can be installed in parallel to the HTS cable, as shown schematically in figure 10. Furthermore, a fast breaker or switch is added in series with the fault current limiting cable, and a reactor can be added to the conventional cable path to tune the system impedance for the given utility protection scheme. Altogether, the area outlined by the dashed–dotted line in figure 10 constitutes what AMSC has branded as its Secure Super Grids™ system. Electrically this is closely analogous to the standalone shunt FCL.

The system operates as follows: under normal operating conditions, the impedance of the superconductor cable, \( Z_F \), is on the order of 1/6 or less compared to that of the shunt conventional cable (and optionally its series reactor), so that the dominant portion of the current flows through the high capacity superconductor cable. No voltage sag arises from the conventional cable or its series reactor. When a fault occurs, the superconductor cable switches immediately to a resistive state, limiting the fault current, just as in the standalone FCL.

The superconductor cable with its HTS wire is designed so that the resistance is large compared to the impedance of the conventional cable, so that the remaining fault current is diverted to the conventional cable (and its series inductor) and is finally limited by the total shunt impedance \( Z_R \) of this parallel path once the fast switch opens.

The fast switch is designed to open after a fault hold time of four cycles (67 ms in the US), limiting the energy dumped into the superconductor wire by a factor of three compared to the case of conventional circuit breakers which may open after 200 ms or more. A second major factor limiting the energy dumped comes from the fact that, during the fault hold time, the conventional parallel cable connection, in conjunction with the source impedance \( Z_S \), acts like a voltage divider, reducing the voltage \( V \) over the fault current limiting cable to \( U_0 Z_N/(Z_S + Z_N) \), where \( Z_N = (Z_F^{-1} + Z_R^{-1})^{-1} \) is the net impedance of the parallel superconductor and conventional branches of the Secure Super Grids system. In these formulas, all calculations must be done vectorially to account for the predominantly inductive source and conventional impedances \( Z_S \) and \( Z_R \), and resistive impedance \( Z_F \) of the fault current limiting cable. Now the fault current reduction factor \( f \) coming from the introduction of the Secure Super Grids connection is just \( Z_N/(Z_S + Z_N) \). Thus one finds simply \( V = U_0 f \). For example, a 25% reduction in fault current, obtained by adjusting the shunt impedance in the above formulas, implies a factor of four decrease in voltage over the fault current limiting cable. This remarkable effect, in combination with the use of the fast switch, enables a reduction in the energy dumped by a factor of more than ten. A more complete treatment including the nonlinear resistance of the cable and a full vectorial analysis modifies this estimate, but only modestly, given typical system parameters.

Under these conditions, it becomes practical to design cables whose superconductor wires will heat to a very limited degree and thermalize within minutes with the local liquid nitrogen, giving a net temperature rise of only a few degrees and enabling fast recovery to the superconducting state. Then it becomes possible to design a cable system that can withstand several fault events in rapid succession without significant temperature rise, provided that an hour can then be allotted to flush the heat out of the cable length and recover the original base operating temperature.

Note that after the fast switch opens, and before downstream breakers activate, the conventional cable carries power based on its overload rating, allowing standard operation of the utility’s protection circuitry. After a few minutes’ initial recovery time, the superconductor cable is reconnected to the circuit by closing the fast switch, and it again picks up the majority of the power flow. This allows the parallel conventional cable to operate only in overload mode, enabling the use of a far smaller and lighter cable than would be necessary for operation at nominal rating. If the fault does not clear during the initial recovery time, the system circuit breaker opens to initiate the utilities’ standard protection operating procedure.
These novel operating principles are the basis for a proposed laboratory test and then installation in the New York City grid under the recently announced project.

7. Conclusion

344 superconductors—2G HTS wires based on coated conductor technology—are making rapid progress on many fronts. Critical current performance is increasing rapidly and low-cost deposition techniques have been developed. The wire has become commercially available and a major scale-up in production capacity and wire length is underway. The first applications have already been demonstrated, particularly resistive fault current limiters, where a prototype by the Siemens/AMSC team has confirmed the key properties required for a practical FCL. A new concept for a fault current limiting cable system has also been introduced which will provide significant economic and performance advantages for cases where new HTS cable connections need to be made with fault current limiting functionality.

References