

Progress in HTS 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 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 1G, and the mechanical properties are also superior. Scale-up of manufacturing is proceeding rapidly, with several companies already supplying of order 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 $\text{YBa}_2\text{Cu}_3\text{O}_7$ (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 U. S., 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. 2nd 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-5at%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 microns thick. A thin buffer stack is then deposited epitaxially by high-rate reactive sputtering. To achieve adequate suppression of nickel diffusion into the HTS layer and oxygen diffusion into the underlying substrate, as well as to provide a stable, lattice-matched surface for growing the HTS layer,

the buffer stack consists of three layers, each 75 nm thick, of Y_2O_3 , yttria-stabilized zirconia, and CeO_2 . Although reactive sputtering is a physical vapor deposition (PVD) process and requires expensive vacuum equipment, the layers are thin and deposition rate so fast that the cost per meter 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 onto the template by means of another low-cost process: metal-organic deposition (MOD)[1,2]. This starts with the slot-die coating of trifluoroacetate-based precursors bearing the stoichiometric proportions of cations for forming YBCO. The coating is dried and then decomposed to remove carbon-containing material, leaving a mixture of yttrium-barium-oxyfluoride, yttria and copper oxides. This film is subsequently reacted at temperatures in the range of 800°C to form YBCO via an ex-situ epitaxial growth process. A several-micron-thick silver passivation layer is then deposited, followed by an oxygen anneal to optimise YBCO performance. The coating and decomposition processes can be repeated multiple times to achieve thicker layers, though at a cost of increased process time and equipment usage. With a single coat, it has been possible to achieve 0.8 micron effective thickness (corresponding to approximately 1 micron actual thickness including porosity) carrying a minimum of 275 A/cm-width or 3.4 MA/cm² (77 K, self field), as shown for a 70 m long wire in Fig. 1. Triple coat short R+D samples have attained 560 A/cm-width.

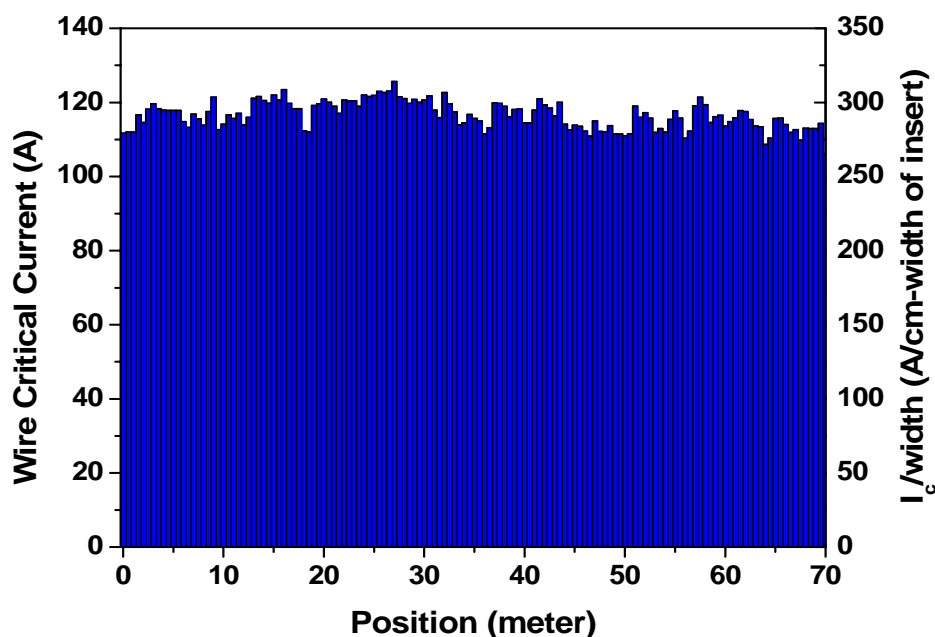


Fig. 1. Current vs. position in a 70 m long single coat 344 superconductors (4.4 mm wide laminated wire – see Fig. 3) with an effective YBCO thickness of 0.8 microns

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 Fig. 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 width 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 nonuniformities. 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.



Fig. 2. (left) 4 cm wide strip of silver-coated HTS strip roll-slitted to ten 4 mm wide wires. The outer two are discarded because of edge non-uniformities in the original MOD coating process. (right) Roll slitting apparatus

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 Fig. 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.



Fig. 3. Cross section of 344 superconductors: a 2G HTS wire with a substrate, thin buffer/HTS/Ag layers and two copper laminates.

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 centimeter 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 Sept. 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[4]. 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 cm to 10 cm wide processing, which will increase throughput by approximately 2.5, bringing the gross production level to close to 2 million meters/year.

A critical issue for low-cost high-volume manufacturing is to achieve high process rates, which enhance capacity for a given piece of equipment. A summary of the capacities for the major process steps is shown in Fig. 4, based on the assumption of 4 cm wide strips and a double-coat HTS process. In this scenario, the slowest rates are the texture anneal (recrystallization) process for the substrate, the HTS precursor decomposition and the silver deposition. R+D process optimisation has led to significant improvements as indicated by the purple bars, well exceeding the target 720 km/year capacity. As these improvements are brought into production, the same equipment should be capable of close to 1000 km/year. The slowest process step, decomposition, when extrapolated to the 10 cm processing, will operate an effective rate of over 300 m/hour for 4 mm wide wire for double coat processing, and other processes such as PVD for the buffer layers will operate at over 700 m/hour.

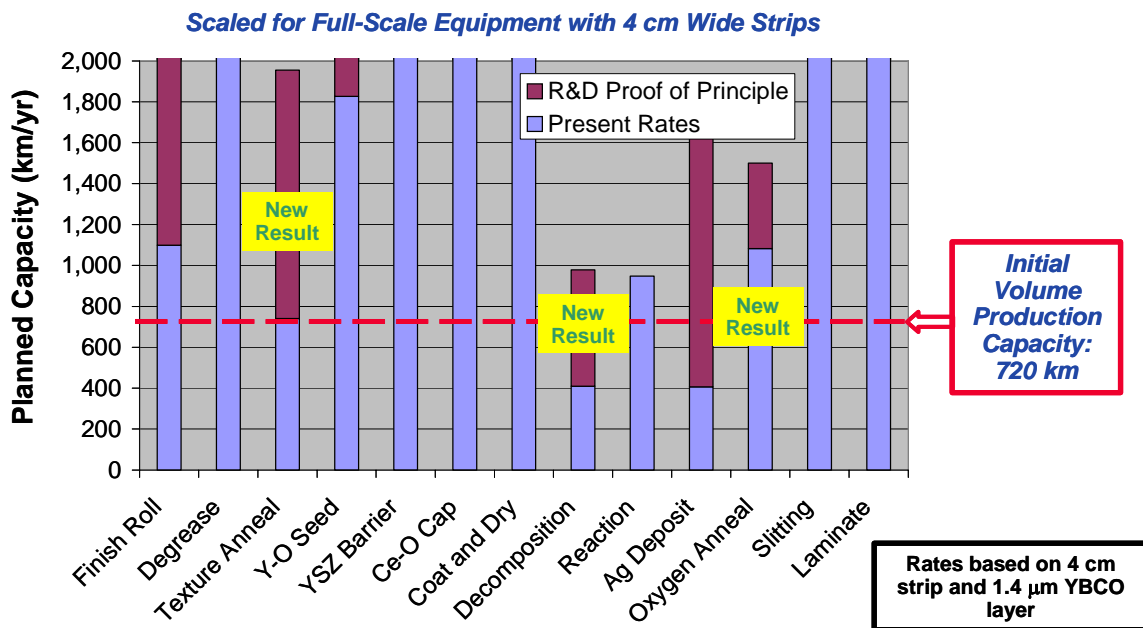


Fig. 4. Planned capacity in km/year for the steps of the 2G HTS wire RABiTS/MOD/slitting/lamination fabrication process.

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 Fig. 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”[5]. 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 perpendicular to the sample plane[5]. 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 Fig. 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 which are roughly double those of the radial stray fields at the ends of the coil; optimised wire then requires higher current density in the plane of the tape.

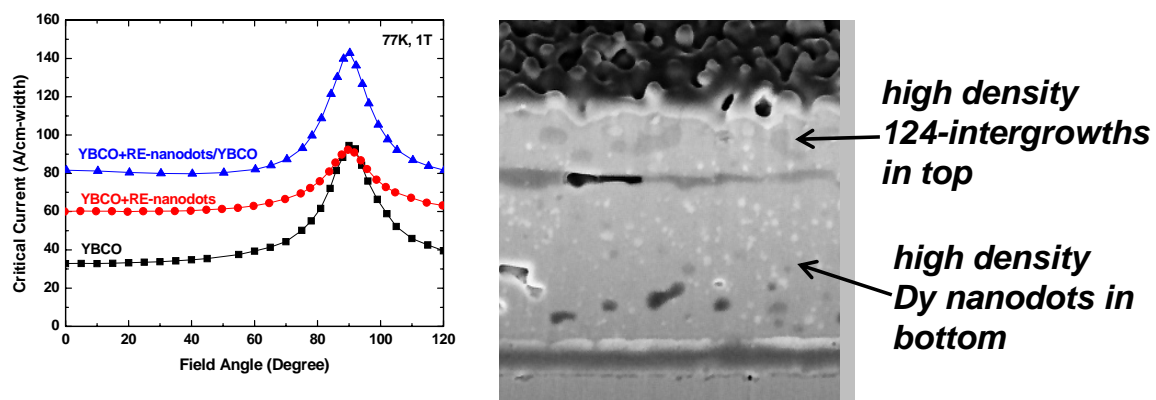


Fig. 5. (left) Critical current field-angle dependence for single-coat YBCO in a textured wire (bottom), for single-coat with nanodot-doped YBCO (middle), and for hybrid double-coat with a first layer of nanodot-doped YBCO and a second layer of YBCO specially processed to enhance the presence of 124 intergrowths. (right) SEM micrograph showing the two layers in cross-section.

This hybrid double-coat process has also enabled critical current density improvements in self-field, as shown in Fig. 6. At 400 A/cm-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/cm² current density at 77 K in single-coat wire with effective thickness 0.8 μm, on a NiW substrate with an optimal texture of 6.8° Δφ average in-plane and 6.6° Δω out-of-plane. These results compare with a maximum of 3.8 MA/cm² at 77 K in the same HTS layer on a more typical textured NiW substrate with 7.3° Δφ average in-plane texture and 7.1° Δω out-of-plane texture, and a maximum of 5.4 MA/cm² at 77 K in the same 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 critical current density with only a modest improvement in substrate texture.

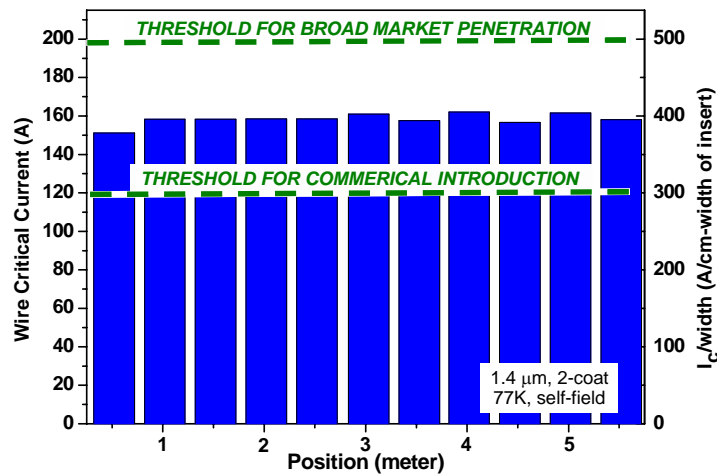


Fig. 6. Critical current in a double-coat wire, compared to threshold levels for commercial introduction or broad market penetration.

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 centered on standalone resistive FCLs based on AMSC's HTS wire laminated with 25 μm of stainless steel on either side, a wire called 344S superconductors, with an architecture similar to that shown in Fig. 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[6]. Here we focus on another prototype demonstrated by Siemens Corporate Technology, resulting from a strategic alliance with AMSC and also using 344S superconductors[7,8]. This single-phase standalone unit, illustrated in Fig. 7, had a nominal rating of 2.25 MVA, operating 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 Fig. 7, which were connected in series and parallel to form a switching module[5] meeting current and voltage requirements. The reversal of current in neighboring windings leads to a cancellation of local magnetic fields, reducing inductance as well as ac losses which otherwise 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, resistance rises within a millisecond, limiting the height of the current surge. An example of this behaviour is shown in Fig. 8, obtained in tests conducted by Siemens at IPH in Berlin.

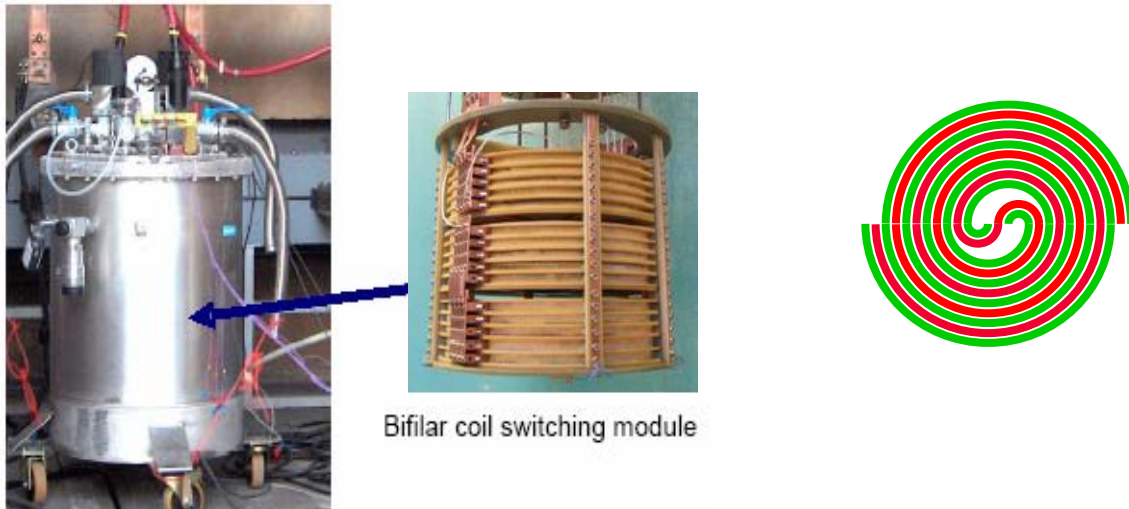


Fig. 7. (left) Single-phase 2.25 MVA rated FCL consisting of a module (center) of 15 stacked bifilar coils, 3 in series and 5 in parallel, immersed in liquid nitrogen at atmospheric pressure. (right) Schematic bifilar coil with wire in red and insulation in green.

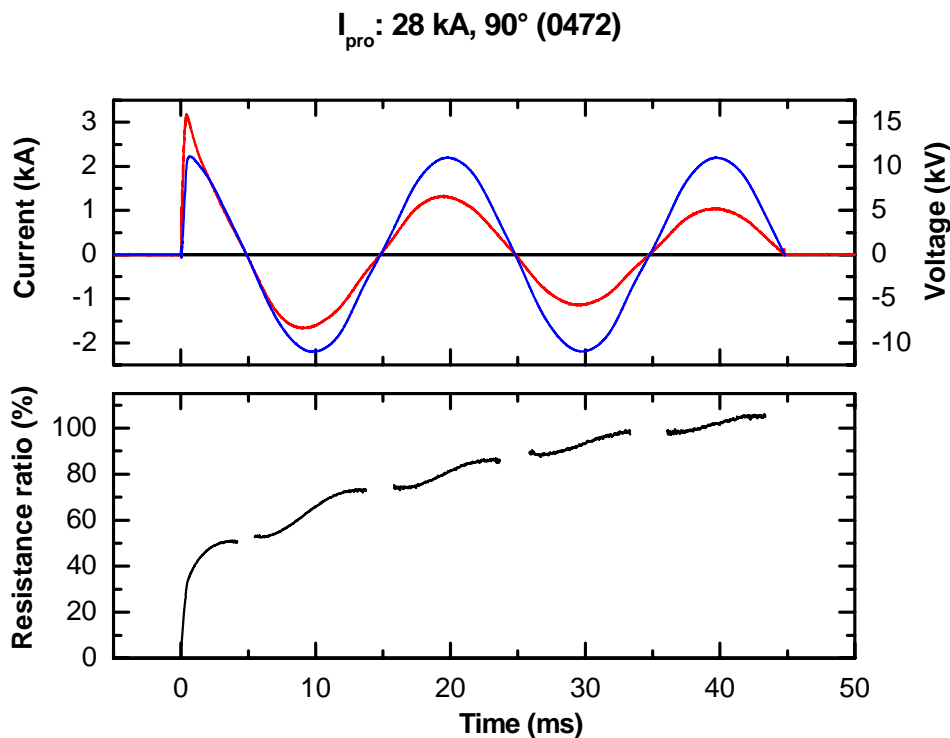


Fig. 8. (top) Current and voltage vs. time of 2.25 MVA FCL module under application of a $7.8 \text{ kV}_{\text{rms}}$ voltage pulse, at a phase of 90° with respect to the zero crossing, in a circuit with $\sim 0.3 \Omega$ source impedance which, without the fault current limiter, would give a prospective current of $28 \text{ kA}_{\text{rms}}$. (bottom) Resistance increase vs. time (relative to the value at 300 K)

Fig. 8 shows the evolution of current under application of a $7.8 \text{ kV}_{\text{rms}}$ 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 $28 \text{ kA}_{\text{rms}}$. 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 msec 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 [7].

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 sec was demonstrated in the 2.25 MVA unit, very close to what was achieved in isolated wires immersed in liquid nitrogen[7]. 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.

5. Applications progress: fault current limiting cable

Many HTS cables are being demonstrated around the world[9,10]. 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 environmental impact as no heat or electromagnetic fields are emitted. These unique 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 can partially neutralizes 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[11] 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 HTS cable is evident in the 3G grid that Con Edison has proposed for New York City, illustrated in Fig. 9.

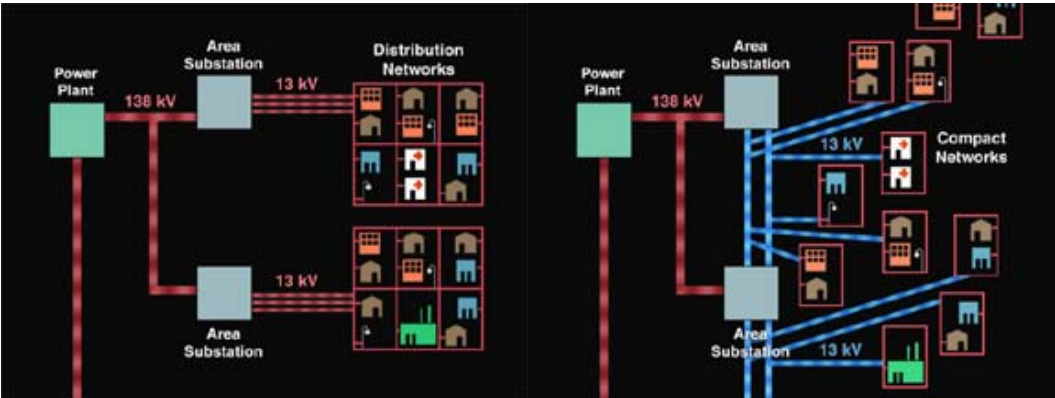


Fig. 9. Schematic New York City electric power network. (left) Present day “islanded” distribution networks fed by area substations. (right) Proposed 3G network with distribution-level interties between area substations and compact networks served by multiple sources. (Courtesy of Con Edison)

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 Fig. 9 (right), a problem in one area substation could be mitigated by power flow from a neighboring 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 2 extra inactive transformers in each area substation, as is presently done, the redundancy can be achieved through backup power flow from a neighboring 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 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 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 $\Delta E = VI_{lim}\tau$, where V is the rms system voltage, I_{lim} is the rms limited current (typically some multiple of the net superconductor critical current I_c as seen in connection with Fig. 8) and τ is the fault hold time, which for typical grid protection schemes can be 200 msec or longer. For a 13.8 kV distribution voltage, $I_{lim} = 9000 A_{rms}$ (assuming about three times a 3000 A_{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 optimised, 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, though these other connections have in general significantly higher impedance. For example, in Fig. 8, 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 Fig. 9. Furthermore, a fast breaker or switch is added in parallel to 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 dash-dotted line in Fig. 9 constitutes what AMSC has branded as its Secure Super Grids™ system. Electrically this is closely analogous to the standalone shunt FCL.

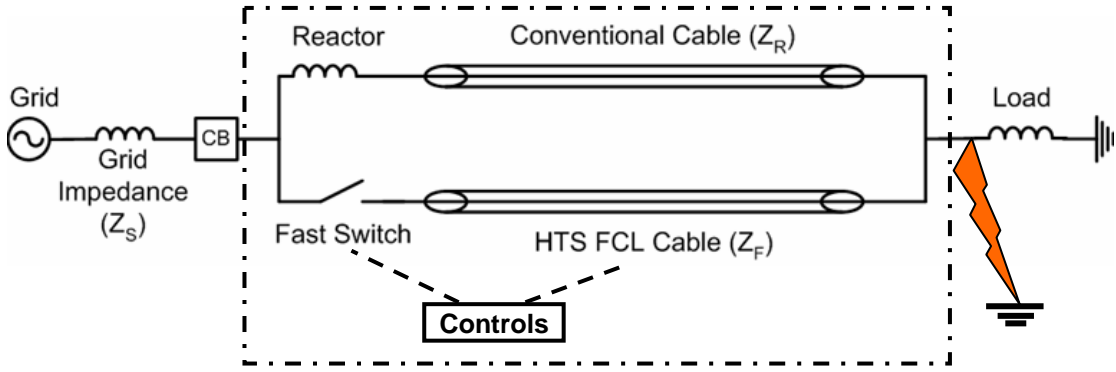


Fig. 9. Schematic utility grid with the Secure Super Grids system consisting of a fault current limiting cable in series with a fast switch and in parallel with a conventional cable and optional reactor.

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 msec 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 msec 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 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 more than a factor of ten.

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 lab test and then installation in the New York City grid under the recently announced project.

6. Conclusion

344 superconductors - 2G HTS wire 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

- [1] Rupich M, Schoop U, Verebelyi D, Thieme C, Buczek D, Li X, Zhang W, Kodenkandath T, Huang Y, Siegal E, Carter W, Nguyen N, Schreiber J, Prasova M, Lynch J, Tucker D, Harnois R, King C, Aized D 2007, *IEEE Trans. on Applied Superconductivity* vol 17, No. 2, 3379-82
- [2] Malozemoff A P, Annavarapu S, Fritzsche L, Li Q, Prunier V, Rupich M, Thieme C, Zhang W, Goyal A, Paranthaman M, Lee D F 2000, *IOP Conference Series #167* (Institute of Physics, London), 307-312; *Superconductor Science and Technology* **13**, 473-476.
- [3] Goyal A, Norton D P, Kroeger D M, Christen D K, Paranthaman M, Specht E D, Budai J D, He Q, Saffian B, List F A, Lee D F, Hatfield E, Klabunde C E and Martin P M 1997, *J. Materials Research* **12**, 2924-40
- [4] Fleshler S, Rupich M and Malozemoff A P 2007, *DOE Peer Review 2007*, Arlington VA, Aug. 709, CD to be published
- [5] Holesinger T, Civale L, Maiorov B, Feldmann M, Coulter Y, Miller D, Maroni V, Chen Z, Larbalestier D, Feenstra R, Li X, Huang Y, Kodenkandath T, Zhang W, Rupich M, Malozemoff A P 2007, *Advanced Materials*, to be published.
- [6] Seok E Y, Lee C J, Kang H K, Nam K W, Yoon Y S and Ko T K, Development of a 32 kV, 630 A (8.3 MVA) High Temperature Superconducting Fault Current Limiter, Paper 1A03, Magnet Technology Conference, Philadelphia PA Aug. 27-30, 2007, to be published.
- [7] Kraemer H-P, Schmidt W, Wohlfart M, Neumueller H-W, Otto A, Verebelyi D, Schoop U and Malozemoff A P 2007 *Journal of Physics: Conference Series*, to be published
- [8] Schmidt W, Kraemer H-P, Neumueller H-W, Schoop U, Verebelyi D and Malozemoff A P 2007 *IEEE Trans. on Applied Superconductivity* vol 17 no 2 pp 3471-74
- [9] Demko J A, Sauers I, James D R, Gouge M J, Lindsay D, Roden M, Tolbert J, Willen D, Traeholt C and Nielsen C T 2007 *IEEE Trans. on Applied Superconductivity* vol 17, No. 2, 2047-50
- [10] Masuda T, Yumura H, Watanabe M, Takigawa H, Ashibe Y, Suzawa C, Ito H, Hirose M, Sato K, Isojima S, Weber C, Lee R and Moscovic J 2007, *IEEE Trans. on Applied Superconductivity* vol 17, No. 2, 1648-51
- [11] Paasi J, Lehtonen J, Verhaege T and Herrmann P F, 2001, *IEEE Trans. on Applied Superconductivity* vol 11 no 1, pp 1928-31