Investigation of HTS Materials for Electric Power Equipment

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Topics

• Wire requirements and operating conditions by application
• Overview and status of HTS wire producers (1G and 1G) and selected power equipment projects
• Summary
HTS addressable device portfolio is broad and varied

<table>
<thead>
<tr>
<th>Energy</th>
<th>Defense</th>
<th>Transportation</th>
<th>Industrial</th>
<th>Medical</th>
<th>Science/Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>• FCL</td>
<td>• Motors</td>
<td>• Maglev</td>
<td>• Motors</td>
<td>• Current leads</td>
<td>• HF magnets</td>
</tr>
<tr>
<td>• Cable</td>
<td>• Cables</td>
<td></td>
<td>• Generators</td>
<td>• NMR</td>
<td>• Space exploration</td>
</tr>
<tr>
<td>• Generators</td>
<td>• Directed energy weapons</td>
<td>• Induction heaters</td>
<td>• Induction heaters</td>
<td>• MRI</td>
<td>• High energy physics</td>
</tr>
<tr>
<td>• Transformers, incl. FCL</td>
<td>• Rail engines</td>
<td>• Magnetic separation</td>
<td>• Magnetic separation</td>
<td>• SQUIDS</td>
<td>• Electronics</td>
</tr>
<tr>
<td>• Storage</td>
<td>• Motors</td>
<td>• Bearsings</td>
<td>• Bearings</td>
<td>• MR</td>
<td>• Cell tower base station filters</td>
</tr>
<tr>
<td>– SMES</td>
<td>• Generators</td>
<td>• Magnetic separation</td>
<td>• Induction heaters</td>
<td>• Current leads</td>
<td></td>
</tr>
<tr>
<td>– Flywheels</td>
<td>• Induction heaters</td>
<td>• Magnetic separation</td>
<td>• Induction heaters</td>
<td>• NMR</td>
<td></td>
</tr>
</tbody>
</table>

Key:
• Near-Term addressable: 1-5 years
• Mid-Term: 3-7 years
• Longer term: 5-10 years

Courtesy of LS Cable
Courtesy of Waukesha
Courtesy of Oswald

CIGRE Paris 2012  August 29, 2012
Key wire characteristics for HTS power equipment vary in importance

<table>
<thead>
<tr>
<th>Application</th>
<th>Ic</th>
<th>Ic Uniformity</th>
<th>AC Loss</th>
<th>C-axis strength</th>
<th>Stiffness</th>
<th>Wide wire</th>
<th>Production Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Cables</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>○</td>
<td>●</td>
<td>○</td>
<td>●</td>
</tr>
<tr>
<td>FCL Cables</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>○</td>
<td>●</td>
<td>○</td>
<td>●</td>
</tr>
<tr>
<td>DC Cables</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>○</td>
<td>●</td>
<td>○</td>
<td>●</td>
</tr>
<tr>
<td>Resistive FCL</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>○</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Generators and Motors</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>SMES</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Transformers</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

Source: AMSC

CIGRE Paris 2012  August 29, 2012
HTS applications have a broad range of operating conditions and wire requirements

<table>
<thead>
<tr>
<th>Application</th>
<th>Operating Field (Tesla)</th>
<th>Operating Temp. (K)</th>
<th>Key requirements</th>
<th>Wire needed per device (kA-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cables</td>
<td>0.01 to 0.1 (ac)</td>
<td>70 to 77</td>
<td>Low ac losses (ac)</td>
<td>40,000 to 2,500,000</td>
</tr>
<tr>
<td></td>
<td>0.1 to 1 (dc)</td>
<td></td>
<td>High currents (dc)</td>
<td></td>
</tr>
<tr>
<td>Motors and Generators</td>
<td>1 to 3</td>
<td>30 to 65</td>
<td>Low ac losses</td>
<td>1,000 to 10,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>In-field $I_c$</td>
<td></td>
</tr>
<tr>
<td>Transformers</td>
<td>0.1</td>
<td>65 to 77</td>
<td>Low ac losses</td>
<td>2,000 to 3,000</td>
</tr>
<tr>
<td>FCL</td>
<td>0.1</td>
<td>65 to 77</td>
<td>Thermal recovery</td>
<td>500 to 10,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>High volts/cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Uniform $I_c$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bandwidth</td>
<td></td>
</tr>
<tr>
<td>SMES</td>
<td>2 to 30 T</td>
<td>4 to 50</td>
<td>In-field $I_c$</td>
<td>2,000 to 3,000</td>
</tr>
</tbody>
</table>

Source: SuperPower
The HTS market is served by multiple suppliers, taking a variety of technical and business approaches

- AMSC
- Bruker Energy and Supercon Technologies
- InnoST/Innopower
- Sumitomo Electric Industries
- SuNAM
- Superconductor Technologies Inc.
- SuperPower Inc

With thanks to: Greg Snitchler, AMSC; Alexander Usoskin, Bruker; Ying Xin, Innopower; Ken-ichi Sato, SEI; Soon Hwang, SuNAM; and Adam Shelton, STI
AMSC Wire Development Plan
Drive to improve critical performance characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Status</th>
<th>Improvements in Process</th>
<th>Time Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ic</td>
<td>Competitive</td>
<td>Yes</td>
<td>2013</td>
</tr>
<tr>
<td>Ic Uniformity</td>
<td>Best in class</td>
<td>Yes</td>
<td>Ongoing</td>
</tr>
<tr>
<td>AC Loss</td>
<td>Competitive</td>
<td>Yes</td>
<td>2013-2014</td>
</tr>
<tr>
<td>C-Axis strength</td>
<td>Best in class</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Stiffness</td>
<td>Best in class</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Width</td>
<td>Best in class</td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>

* Current laminated, wide-web process allows for customization of these parameters

AMSC targeting best in class performance for all major power equipment applications
Production Capacity is Key

Volume production required to support commercialization of HTS power equipment

AMSC is committed to COMMERCIAL production
100% On-Time Delivery Performance

Coated wide-web process with customized mechanicals via lamination

Stabilizer flexibility by lamination
Bruker’s YBCO coated conductors: HTS production chain

2012:
- Polishing, Cleaning
  - batch/ RtR 250m
- ABAD YSZ buffer
  - RtR >1000m
- HR-PLD CeO2 YBCO
  - batch/helix 250m
- Metallization
  - RtR >1000m
- O2-Loading
  - RtR >1000m
- Cu plating
  - RtR 100m
- Ic measurements
  - RtR >1000m

Next step: RtR >1000m

CIGRE Paris 2012  August 29, 2012
Bruker’s product spectrum and status

**Thickness:**
- Substrate: 50µm 100µm
- Cu plating: 10µm 50µm
- PEEK insulation: 30µm

**Width:**
- R&D pilot prod.
  - 4mm 12mm 40mm

**Critical current:**
- **Target:**
  - (77K, SF)

<table>
<thead>
<tr>
<th>R&amp;D</th>
<th>250-500 A/cm-w</th>
<th>Motors / Generators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot production</td>
<td>180-300 A/cm-w</td>
<td>SFCL / iSFCL</td>
</tr>
</tbody>
</table>
Bruker’s Coated Conductors and FCL Modules

- Bruker HTS coated conductors (CC) based on stainless steel substrate tape processed via HR-PLD, ABAD and deposition of shunt layer with minimized thickness are employed in superconducting fault current limiter (SFCL) development.

- In both cases of resistive and inductive SFCL the CCs are assembled in a modular structure that allows independent pre-characterization of particular HTS elements.

- Within each module the CCs are assembled in parallel/series connected internal electrical net in order to optimize transient and quasi-stationary performance during quench event.
• Project: 35kV/90MVA HTS FCL
• Year of Start/Accomplish: 2005/2007
• Project Team: InnoPower
• Installation: Puji Substation, Yunnan
• Current Status: in operation since Jan. 2008

35kV FCL DC coil

<table>
<thead>
<tr>
<th>Conductor</th>
<th>Bi2223-tape from SEI &amp; INNOST</th>
</tr>
</thead>
<tbody>
<tr>
<td>In/out dia.</td>
<td>1,280/1,340 mm</td>
</tr>
<tr>
<td>Rated current</td>
<td>300 A</td>
</tr>
<tr>
<td>Mag. capacity</td>
<td>141,000 A•turn</td>
</tr>
</tbody>
</table>
• Project: 220kV/300MVA HTS FCL
• Year of Start/Accomplish: 2007/2012
• Project Team leader: Innopower
• Installation: Shigezhuang substation, Tianjin
• Current Status: Trial operation

220 kV FCL DC coil

<table>
<thead>
<tr>
<th>Conductor</th>
<th>Bi2223-tape from SEI &amp; INNOST</th>
</tr>
</thead>
<tbody>
<tr>
<td>In/out dia.</td>
<td>1,920/2080 mm</td>
</tr>
<tr>
<td>Rated current</td>
<td>300 A</td>
</tr>
<tr>
<td>Mag. capacity</td>
<td>176,500 A•turn</td>
</tr>
</tbody>
</table>

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4mm-wide DI-BSCCO can carry 200A over 1km length

<Bi-2223 Features>
1. Controlled-Over Pressure Sintering was introduced in 2004 → Commercial Product
2. Unit Length: up to 2,000m Uniform Property
3. Production Capacity 1,000 km/year
4. Cost/Performance
   DI-BSCCO: 10~15 → 5 Yen/Am
   Copper: 5~7 Yen/Am
5. Application
   Cables, SMES, Motors/Gene
   SFCL, Magnets, Leads

Cross-sectional View of HTS Wire
DI-BSCCO Mechanical & Ic-B-T Properties

Over 500 MPa with 3 ply

4mm-wide DI-BSCCO can carry; ~400A@20K & 5T (B ⊥),
~250A@20K & 10T (B ⊥)
Also, at 90K can carry 100A in self field
## GdBCO Performance for Model Cable

### 66kV/5kA-15m Model Cable

<table>
<thead>
<tr>
<th>Layer</th>
<th>Width of CCs</th>
<th>Number of CCs</th>
<th>( I_c ) (A / 4 mm(^w))</th>
<th>Total ( I_c ) (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor ((4\text{-layer}))</td>
<td>2 &amp; 4 mm</td>
<td>59</td>
<td>130~150</td>
<td>8300</td>
</tr>
<tr>
<td>Shield ((2\text{-layer}))</td>
<td>50</td>
<td>120~130</td>
<td></td>
<td>6100</td>
</tr>
</tbody>
</table>

### Typical long length \( I_c \)

- **2 mm\(^w\)**
- **4 mm\(^w\)**

---

**Ingenious Dynamics**
SuNAM Wire Structure
Novel RCE-DR* Process for SC layer

- High deposition rate
- Fast conversion
- Easily scalable
- Low cost for source & system

High throughput & low cost!

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Production scale-up plan

<table>
<thead>
<tr>
<th></th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (km)</td>
<td>200</td>
<td>500</td>
<td>700</td>
<td>6000**</td>
</tr>
<tr>
<td>(4 mm equivalent)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Reactive Co-evaporation – Deposition & Reaction
** Switch to 120 mm-wide tape process

http://CoatedConductor.com

SuNAM

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km length wire on both Hastelloy and Stainless Steel

Product specification (4 mm wide tape)

<table>
<thead>
<tr>
<th></th>
<th>Now</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Regular</td>
<td>On order</td>
</tr>
<tr>
<td></td>
<td>100 A / 100 m</td>
<td>200 A / 100 m</td>
</tr>
<tr>
<td></td>
<td>150 A / 100 m</td>
<td>150 A / 200 m</td>
</tr>
<tr>
<td></td>
<td>100 A / 200 m</td>
<td></td>
</tr>
</tbody>
</table>

http://CoatedConductor.com

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Benefits of Our Unique HTS Growth Technique:
- Reactive Co-evaporation Deposition and Reaction (RCE-CDR)
- Fewer deposition process steps – reduces runtime and increases yield
- Simple and repeatable template utilized
- High throughput and large HTS growth area
- Lowest cost raw materials

Conductus® 2G HTS wire manufacturing approach utilizes a simplified, layered wire architecture, with the goal to deliver high performance wire at a cost competitive with copper.

Conductus® 2G HTS Wire Product Features:
- Tape like metal substrate in designed to accommodate custom wire widths (10mm – 100mm)
- High critical current performance
- High in-field magnetic performance for motor, generator and SFCL applications
- Robust and flexible design for efficient use in cable
- Optimized for AC loss
- Designed to operate in devices from 4K to 77K
Conductus® Achieves Commercial Target
HTS Cable Applications

Conductus wire achieves - 500 A/cm @ 77K >2 micron thick HTS film in 2012
SuperPower 2G HTS wire types suitable for all electric power applications

- Robust, high-performance wire; several architectures, incl. variations of width (3 – 12 mm), substrate thickness (50 and 100 um,) stabilizer, and insulation
- Two formulations:
  - AP (Advanced Pinning) – for enhanced in-field performance in motors, generators, SMES,, high field magnets, etc.
  - CF (Cable Formulation) – for cable or FCL
- Single piece lengths of 50-300m and increasing
- High critical current: 100A standard; 110-130+ A premium (4 mm width)
- Uniform critical current over long lengths: +/- 10% standard deviation
  - Excellent 2D uniformity of critical current across width for ROEBEL cables
  - Tight bandwidth of critical current for FCL
- Excellent joints & solderability:
  - No degradation in Ic even when joint is bent over 1” diameter and thermal cycled
  - Joint resistance ~ 40 nohm-cm²
- High engineering current density
- Superior mechanical properties
  - Yield strength up to 700 MPa with superalloy-based coated conductors
- Manufacturing volume steadily increasing
SuperPower 2G HTS offers excellent performance for all electrical device operating ranges

Normalized $I_c$ vs. Applied Field $//c$

- $4.2 \text{ K}$
- $14 \text{ K}$
- $22 \text{ K}$
- $33 \text{ K}$
- $45 \text{ K}$
- $50 \text{ K}$
- $65 \text{ K}$
- $77 \text{ K}$

- **Motors, generators**
- **SMES**
- **Cables, FCLs, transformers**
Improving price/performance on two fronts: Manufacturing process and in-field performance

<table>
<thead>
<tr>
<th>Time</th>
<th>Performance at 77K, 0T *</th>
<th>Lift Factor at operating condition (30K, 2.5T)</th>
<th>Performance at operating condition</th>
<th>Wire price * ($/m)</th>
<th>Wire price ($/kA-m) at operating condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Now</td>
<td>100-130+ A</td>
<td>2</td>
<td>260 A</td>
<td>$45*</td>
<td>$175</td>
</tr>
<tr>
<td>2 years**</td>
<td>160 A</td>
<td>4</td>
<td>640 A</td>
<td>$35*</td>
<td>$ 55</td>
</tr>
<tr>
<td>4 years**</td>
<td>200 A</td>
<td>6</td>
<td>1200 A</td>
<td>$35*</td>
<td>$ 30</td>
</tr>
</tbody>
</table>

** Projections

* Average, 4 mm width

At 40K and 3T, the quantity of wire required for the device is reduced by HALF, greatly improving the economics of the device
Device demonstrations – vehicles for continuing wire development efforts

DOE Smart Grid Demonstration Program

2G Superconducting

FCL Transformer

(ac loss + wire structure improvements)

SuperPower - SPX/Waukesha - U. Houston -
Southern California Edison

ARPA-E GRIDS Program

2G SMES Project

(manufacturing approaches to improving performance)

ABB – SuperPower – Brookhaven – U.Houston

ARPA-E REACT Program

Low-cost wire for HTS wind turbine generators

(technology approaches to improving performance)

UH - SuperPower

NREL – Tai Yang -
TECO Westinghouse
## Overview of supplier approach and status

<table>
<thead>
<tr>
<th>Supplier</th>
<th>HTS Type</th>
<th>Width (mm)</th>
<th>Stabilizer</th>
<th>Piece Length</th>
<th>Current $I_c$ (4 mm)</th>
<th>Current Annual Capacity</th>
<th>Current Price $$/kA.m</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMSC</td>
<td>2G</td>
<td>4.8 +12+40</td>
<td>Cu + Brass + SS Lamination</td>
<td>1000m processing lengths; yielded unclear</td>
<td>80-100+ A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bruker</td>
<td>2G</td>
<td>4 + 12+40</td>
<td>Cu Plating</td>
<td>1000+ m</td>
<td>72-120A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>InnoST</td>
<td>1G</td>
<td>4.2</td>
<td>---</td>
<td>1000+ m</td>
<td>200A</td>
<td>1000 km</td>
<td>Now: ¥10-15/ $125-187  Target: ¥5/ $62</td>
</tr>
<tr>
<td>Sumitomo</td>
<td>1G</td>
<td>4</td>
<td>---</td>
<td>1000+ m</td>
<td>200A</td>
<td>1000 km</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2G</td>
<td>2 + 4</td>
<td>Cu clad</td>
<td>100+ m</td>
<td>120-150A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STI</td>
<td>2G</td>
<td>10 (100mm)</td>
<td>Cu Plating</td>
<td>1000m</td>
<td>200+ A</td>
<td>demonstrated</td>
<td></td>
</tr>
<tr>
<td>SuNAM</td>
<td>2G</td>
<td>4 + 12 (120mm)</td>
<td>Cu Plating Brass Lamin</td>
<td>1000m demonstrated</td>
<td>100A</td>
<td>200 km</td>
<td></td>
</tr>
<tr>
<td>SuperPower</td>
<td>2G</td>
<td>3 + 4 + 6 + 12</td>
<td>Cu Plating</td>
<td>50-300+ m routine production</td>
<td>100-150A</td>
<td></td>
<td>Now: $175-200 Target: &lt;$30</td>
</tr>
</tbody>
</table>
Summary

• Wire requirements and operating conditions vary by device application
• Suppliers addressing requirements in multiple ways
  – Alternative technology approaches
  – Alternative processing and manufacturing methods
• Flexible architectures allow customization for different requirements
• Different approaches benefit the device market
• Work continues to address areas in need of further improvement
  – Performance, piece length, price, capacity ...
• The number of suppliers is growing to address unmet requirements and growing demand
  – Not included here: Fujikura, Theva, Deutsche Nanoschicht, MetOx, Russia 2G plan, China 2G