Development of CORC® power transmission and fault current limiting cable systems

Jeremy Weiss & Danko van der Laan
Advanced Conductor Technologies & University of Colorado, Boulder, Colorado, USA

Chul Kim & Sastry Pamidi
Center for Advanced Power Systems, Florida State University, Tallahassee, Florida, USA

Lukas Graber
Georgia Institute of Technology, Georgia, USA

This work was in part supported by the US Navy under agreements N00024-14-C-4065, N00024-16-P-4071, and N68335-18-C-0151
**Conductor on Round Core (CORC®)**

**CORC® cable principle based on strain management**
Winding many high-temperature superconducting REBCO coated conductors in a helical fashion with the REBCO under compression around a small former to obtain high conductor currents.

**Benefits of CORC® cables and wires**
- Very high currents and current densities
- Mechanically very strong
- Very flexible
- High level of conductor transposition
We are developing high-current power transmission systems for operation in helium gas at 50 K
  • Currents up to 10 kA/phase at 50 K
  • Voltage rating of 1-12 kV

**Typical CORC® wire**
  • 3.6 mm diameter with 29 tapes
  • $I_c$ (77 K) = 2,000 A
    • $J_e$ (77 K) = 200 A/mm²
  • $I_c$ (50 K) = 8,000 A
    • $J_e$ (50 K) = 800 A/mm²

**Typical CORC® cable**
  • 7.5 mm diameter with 42 tapes
  • $I_c$ (77 K) = 4,500 A,
    • $J_e$ (77 K) = 100 A/mm²
  • $I_c$ (50 K) = 18,000 A,
    • $J_e$ (50 K) = 400 A/mm²
Winding of long CORC® cables with custom cable machine
- Accurate control of cable layout
- Long cable lengths possible (> 100 meters)
- $I_c$ retention after winding 95-100 %

First commercial sale (CERN)
- 12 meter CORC® cable (38 tapes)
- Cable for detector magnets
- Delivered August 2014

Many commercial orders followed
Over 400 meters of CORC® cable and wire sold thus far to various customers
   CORC® wires and cables for accelerator magnets including Canted Cosine Theta magnets and Common Coil magnets

   CORC® cable for fusion magnets, cable joints, and terminations for fusion magnets

3. Navy
   CORC® power transmission, fault current limiting cables, and Dielectrics for CORC® power transmission
CORC® power transmission cables for the US Navy

CORC® power cables in collaboration with Center for Advanced Power Systems
• Operation in helium gas at 50 K
• DC and AC cables
• 3-10 kA per phase
• 1-20 kV operation
• Fault current limiting capabilities

Potential applications for 1 – 100 MW power transmission
• Navy ships
• Electric aircraft
• Data centers

Challenges of power transmission in confined spaces
• Operating voltage is relatively low: 270 V (Air Force) – 12,000 V (Navy)
• High operating currents are required to reach high power rating
• Tight bends require flexible cables
• Asphyxiation hazards may prevent use of liquid cryogens in some cases
Development of a demonstrator 10-meter 2-pole DC CORC® power transmission system
10-meter 2-pole CORC® DC power system

Goal

- 2-Pole DC CORC® power transmission cable
- 10 meter long twisted pair cable layout
- Operating current 4,000 A (50 K)
- Cooled with 2 MPa helium gas

---

- LN₂ 77 K
- Helium gas 50-65 K
- LN₂ 77 K
- Current leads
- 10 meter CORC® power cables
- Current leads

---

- Nexans cryostat
- Cryostat end cap
- Current lead
- Helium line

- CORC® cables
- Nexans cryostat
10-meter 2-pole CORC® system test

Test procedure

• Cool-down to 64 K inlet, and 72 K outlet
• Test each phase individually
• Test phases connected in series

- Individual cable tests $I_{\text{quench}}$ (Phase 1) = 4,560 A, $I_{\text{quench}}$ (Phase 2) = 4,670 A
- Series connected cable tests $I_{\text{quench}}$ (Phase 1) = 4,530 A, $I_{\text{quench}}$ (Phase 2) = 4,360 A
- Results suggest that $I_{\text{quench}}$ at 50 K would be > 10,000 A
Fault Current Limiting Test

- Current to 6,000 A
- 10 V supply voltage

- Current was limited to 2,000 A after 2 seconds
- Voltage over each pole was 5 V
- Maximum power dissipation: 43.4 kW
- Total energy dissipated: 53.7 kJ
CORC® power cable performance verification

Recovery and performance verification
• Maximum helium temperature 200 K
• Recovery time > 20 minutes

- CORC® power cable performance unchanged after FCL test
- Dissipation within helium gas needs to be limited during FCL event
  => use of hybrid FCL cable with fast acting switch as solution
CORC® power transmission system shipped to Navy
CORC® power transmission cables: Additional progress
Increasing the voltage rating on CORC® cables

Investigating wrapped (unsealed) dielectrics and sealed dielectrics

- Partial Discharge (PD) and Break Down (BD) measurements
- Cables measured in 2 MPa helium gas at 77 K

- Partial discharge for sealed dielectric is much lower than for wrapped dielectric
- Preventing helium gas penetration significantly reduces the partial discharge
- Breakdown voltage depends on cable insulation thickness
**CORC® cable terminations**

- Very compact
- Capable of injecting large currents
- $R$ (77 K) = 5 to 50 nΩ

**CORC® cable Joints**

15 cm long simple double terminal joint

$R$ (77 K) $\sim$ 100 nΩ

20 cm long praying hands demountable joint

$R$ (77 K) $< 200$ nΩ

Courtesy of Xiaorong Wang
CORC® for fault current limiting (FCL) applications
Background: resistive fault current limiting

- When a fault develops, the superconductor quenches, its resistance rises and current is diverted to a parallel circuit with the desired higher impedance.

- When in the resistive state, the cryogenic cooling system must be capable of removing the heat generated to restore the cable to its superconducting state in a suitable timeframe (recovery time).

- A switching component may need to be incorporated to isolate the superconducting/cryogenic component from the resistive shunt.

EPRI, 2009
Advantages of CORC® topology for FCL application

**Versatile architecture allows for tunable properties**
- Can incorporate any number of normal and superconducting tapes to tailor operating current, normal state resistivity, and thermal management
- Extremely compact package delivering 1-20 kA in a 4-8 mm outer diameter

**HTS tapes are layered and transversed**
- Direct contact between each tape and up to 8 other tapes
  - More paths for current sharing adds electrical stability
  - More thermal contacts allows proficient cooling
- Such high level of current sharing is not available in conventional HTS FCL cables that typically require laminates
Key features of our V(I) test setup:
- 13.5 kA worth of current supplies
- Ramp rates up to 1 MA/s
- Highspeed data acquisition (50 kS/s)
Two CORC® wire designs tested

SuperPower tape was chosen for the CORC® FCL wires

<table>
<thead>
<tr>
<th>Sample name</th>
<th>$I_c$ at 76 K (A)</th>
<th>$J_e$ at 76 K (A/mm$^2$)</th>
<th>Total wire diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CORC® wire 1</td>
<td>646</td>
<td>80</td>
<td>3.2</td>
</tr>
<tr>
<td>CORC® FCL wire 2</td>
<td>1124</td>
<td>99</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Key features
- Wire length between terminals = 20 cm
- CORC® wire 1 was not optimized for FCL operation
- CORC® FCL wire 2 was optimized for FCL operation
- Wires also contain several tapes of varying quality “Frankenstein’s wire”
  - Average $I_c = 72.9$ A (STDEV $\sim 8.7$)
Overcurrent response of CORC® FCL wires

CORC® FCL wires
• Fast response to overcurrent
• Voltage develops concurrent with the current-pulse rise time

Electric field over CORC® wire
20 V/m with the current pulse, and 50 V/m after 5 ms!

Applied overcurrent $I/I_c=2.5$
• CORC® FCL wire 1: 1,600 A
• CORC® FCL wire 2: 2,800 A
Overview of a hybrid CORC® FCL system

CORC® FCL wire in parallel with room temperature nonsupercconducting cable

Configuration allows current to bypass superconducting part of circuit to protect sensitive equipment and/or lesson switching requirements.

Cable can be isolated after fault, enabling faster recovery cool-down to cryogenic temperature
Overcurrent testing of a hybrid CORC® FCL system

Fault overcurrent of 320% $I_c$
- Peak current in FCL wire 2,700 A after 3 ms
- FCL voltage 10 V/m after 5 ms
- Current in FCL wire back below $I_c$ after 10 ms, while maintaining ~10 V/m over hybrid cable system
- Constant voltage suggests CORC® wire remains at constant temperature, although dissipation at ~10 kW/m
- Rapid cool down requires switch to isolate the CORC® wire

$I_c = 1124$ A
Extensive cycling did not degrade CORC® FCL conductor

Includes

- several non-controlled cool-down cycles (thrown into LN₂ bath)
- full warm-up cycles to room temperature (during 10-20 ms fault)

No degradation after more than 90 faults and several rapid thermal cycles
**Summary**

**CORC® cables and wires enable high-current density power transmission**
- Helium gas-cooled 2-pole CORC® dc power cable system demonstrated
- Current rating of 10 kA at 50 K easily realized with plenty of margin

**CORC® cables and wires can be operated as Fault Current Limiters**
- Current sharing between tapes in CORC® cables/wires allows us to produce CORC® FCL conductors without the need for laminates
- Low thermal capacity and high normal resistance allow for very fast response to fault currents
- Response time is nearly instantaneous, with voltage rise following the current ramp which takes 3-4 ms to reach $I/I_c = 2.5$
- Fast acting CORC® FCL wire demonstrated with 50 V/m after 5 ms of overcurrent in LN$_2$
- No degradation in CORC® wire performance after more than 90 faults
Recent publications

Development of CORC® cables for helium gas cooled power transmission and fault current limiting applications

Hybrid superconducting fault current limiting CORC® wires with millisecond response time

Topical Review

Status of CORC® cables and wires for use in high-field magnets and power systems a decade after their introduction