Status and Progress of a Fault Current Limiting HTS Cable To Be Installed In The Consolidated Edison Grid

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Outline

• Hydra Project Overview
  - Specification
  - Team roles and responsibility
  - Main goals and objectives

• Fault Current Limiting Cable Operation Principle

• FCL Cable System Components

• 3m & 25m Prototype Cable Test Results

• Refrigeration System

• Conclusions
HYDRA Project Overview

- Consolidated Edison’s Substations
- Electrical Characteristics
  - Design Voltage/Current – 13.8kV, 4,000 amp ~96MVA
  - Design Fault Current – 40kA @ 67ms
- Physical Characteristics
  - Length ~ 170m
  - HTS Conductor Length ~50km
  - Cold Dielectric, Triax Design
- Hardware Deliverables
  - One ~170m Long, 3 Phase HTS Cable
  - Two 13.8kV Outdoor Terminations
  - One Refrigeration System
- Commissioning – Summer 2014

World’s First FCL Distribution Cable to be Installed in Operating Grid
Team Roles and Responsibilities

DHS Science & Technology Directorate

AMSC Prime Contractor

- AMSC
  - System Design
  - Wire Development
  - Project Management
  - Wire Manufacturing
  - Technical Oversight
  - System Hardware Development

- Altran Solutions
  - Site Design

- Consolidated Edison
  - Utility Requirements
  - Construction Management
  - Permitting
  - Civil Work
  - System Planning

- DH Industries
  - Cooling System
  - Installation Support
  - O&M Contract

- Ultera
  - Cable & Accessory Design
  - Cable Manufacturing
  - Cable & Accessory Installation

- ORNL Test Agency
  - 25m Prototype Cable Test Site
  - Technical Support

Solutions
HYDRA Project Main Objectives

• Demonstrate High Temperature Superconductor Fault Current Limiting Link Between Substations

• Demonstrate Feasibility of an Installation of a Fault Current Limiting HTS System in Population-Condensed Urban Area

• Demonstrate an Installation and Operation of a Reliable Cryogenic System
**Fault Current Limiting Cable**

**Operation Principal**

- **Superconductor** wire has zero resistance up to the “critical” current

- AMSC supplies a superconductor wire that instantly introduces high resistance above the critical current

- Immediate limitation of fault current magnitudes

- Insertion of resistance decreases $X/R$ and fault asymmetry

Allows the construction of fault current limiting cables
Paralleling Urban Buses: The Appeal

Advantages of Paralleled Substations – Simple Case

- Connect additional load without additional transformers or new substations
- Increases transformer asset utilization
- Reduces cost of N-1 contingency planning; only 1 transformer required versus 2
- Increased interconnectivity protects vulnerable, critical loads in the event of a catastrophic failure
Main Components of HTS Cable Systems

- HTS Cable
- Cryostat
- Terminations
- Cryogenic Cooling System
Components of the HTS Cable System

- Superconducting Cable System
  - Cable Core
    - Transport the current
    - Limit the fault current
    - Withstand the voltage
  - Cryostat
    - Insulate thermally – keep the cable cold
    - Transport the liquid nitrogen
  - Termination
    - Connect the system to the grid
    - Manage the transition between cold temperature and room temperature
    - Provide connection to the cooling system
**Cable Design - Triax® by Southwire**

Phase 1 Superconductor

Phase 2 Superconductor

Phase 3 Superconductor

Dielectric

Dielectric

Dielectric

Copper Neutral

Former

Supply LN2

Cryostat

Photo courtesy of Ultera

Triax is a trademark of Southwire
HYDRA Project  Status and Progress

System Specs

Wire Development

3m Prototype Cable

25m Prototype Cable

Final Installation Cable

Wire Bulk Properties
Temperature Rise Verification
Over-current Behavior Verification

Operating Current 4kA Verification
Manufacturability Verification
Cryogenic Requirements Verified

Fault Current Limiting Verified
Thermal Stability Verified
Manufacturability Verified
System Operating Parameters Verified
Operating Capacity Verified
Dielectric Performance Verified
3m Cable FCL Test Setup

• Open Bath Test
3m cable FCL Tests

Voltage and Current, 32 V_{EMF} 140 ms
3m Cable Let-Through Tests

• Three 9.1kA 270ms shots
  - ~20min apart
  - Three faults within one hour

• Results
  - Cable is superconducting throughout the current surge
  - No evident heating observed
3m Cable FCL Test Conclusions

• The cable is superconducting after the tests
• No change in temperature seen in 9.1kArms 270ms thru fault tests
• Less than 1K in temperature rise in 7.2kArms 2000ms thru fault tests.
• Current limiting capability is evident
  - Prospective current of 60kArms limited to 30kArms
  - Cable voltage is $8V_{\text{peak}} / \text{m}$ at first cycle and $11V_{\text{peak}} / \text{m}$ at last cycle
25m Prototype Cable Test Setup

Termination

Refrigeration system

25m HTS Triax® Cable
25m Cable Test LN2 Flow Diagram
25m Cable Test Plan

25m Prototype Cable Tests

- Performance Characteristics
  - Cable Resistance
  - DC Critical Current
  - AC Loss
  - FCL Low Voltage
  - FCL High Voltage

- Thermal Tests
  - Thermal Stability

- Dielectric Tests
  - Voltage Soak
  - Partial Discharge
  - AC Withstand
  - Lightning Impulse

- Other Tests
  - Leak Check
  - Post-BIL
    - Partial Discharge
    - AC Withstand
    - Post BIL & FCL DC Ic
    - Post Thermal Cycle DC Ic
25-m HTS Cable $I_c$ Tests

25-m Cable $I_c$

Critical Current (A)

Temperature (K)

Requirements of phase conductor $I_c$ at 77.3K

Phase 1
Phase 2
Phase 3
Stability Test

![Graph showing temperature and cable pressure over time](graph.png)

- Refrigerator return temperature
- Refrigerator supply temperature
- Cable pressure

4000 Arms was applied
AC Loss

![AC Loss Graph]

3 phase AC loss (W/m) vs Current (Arms)

- Current (Arms): 0, 1000, 2000, 3000, 4000, 5000
- 3 phase AC loss (W/m): 0.00, 1.00, 2.00, 3.00, 4.00, 5.00, 6.00, 7.00, 8.00, 9.00

Data point: 72K
FCL Test

Measured versus Simulated Results
Symmetrical Fault

Current (kA)
Time (S)

Measured Limited Current (kA)
Meas Unlimited Current
Simulated Limited Current (kA)
Measured & Simulated Limited Current
Unlimited Fault Current
Cable and Termination Dielectric Test

- 25m Cable type tests have been completed to a test requirement that was discussed and agreed to by the Team
  - Three phase voltage soak test 15.2kV, 60 minutes
  - Partial discharge measurement in accordance with Southwire’s HTS cable standard
  - AC withstand test – 37 kV, 5 minutes
  - Lightning impulse voltage test – 110 kV ±10 shots
  - Post BIL partial discharge test
  - Post BIL AC withstand 37.5kV, 5 minutes

Cable has passed all type tests listed above
Cryogenic System Requirements

- Cryogenic specification
  - 6.2 kW @ 72 K
  - ~1kW @ 72 K (Additional load for LN$_2$ pumps and thermal leaks from cooling system)
  - 90L/min LN2 Flow Rate
  - Pressure drop less than 3 bar

- Multiple technological solutions have been investigated
  - Gifford-McMahon Cryocooler
  - Stirling Cryo-generator
  - Reverse Brayton
Refrigeration Cycle chosen is Stirling Cryo-generator
- Modulated design (3 x 4kW @ 77K)
- Best return on specific efficiency (We/Wc) vs. capital cost

Flexibility Requirement:
- 80% of time at 50% heat load on HTS cable

Reliability
- Redundancy accomplished at component level, pumps
- No 1st order single point of failure allowed

Capacity Margin
- Current design has 20% safety margin to the expected losses
Refrigeration System Diagram

- Estimated foot print size & weight
  - 11.6 m x 9 m (38’ x 30’) + outdoor water chiller
  - ~ 15 000 kg (33 000 lbs) empty
  - Fits within available space
Accomplishments to Date

The key invention has been demonstrated

- Demonstration of the Fault Current Limiting aspects of 2G wire and the cable design
- Exceptionally good agreement between Fault Current Limiting model predictions and measured performance in 25 meter cable demonstration
- The HTS FCL Cable successfully passed all the qualification tests for installation in the power grid
Conclusions

- American Superconductor and the project team are demonstrating significant progress toward the development of a long length fault current limiting superconducting cable for integration into the Consolidated Edison grid.
- Short cable tests demonstrated the current limiting capability
- 25m cable and termination type tests have been successfully completed.
- Cable manufacturing process has been approved
- A 170m long HTS cable with fault current limiting functionality is planned to connect two of Con Edison’s substations in late 2014.
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