Superconducting Fault Current Limiter Project

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HTS Solutions for a New Dimension in Power

Superconductivity for Electric Systems – 2006 Annual DOE Peer Review

HTS Fault Current Limiters
New Technology for a Growing Problem

As new sources of generation are added, utilities are faced with the threat of higher levels of fault current

- HTS Fault Current Limiters (FCLs) address the market pull to cost-effectively correct fault current over-duty problems at the transmission voltage level of 138kV and higher
- The HTS FCLs will reduce the available fault current to a lower, safer level so existing switchgear can still protect the grid

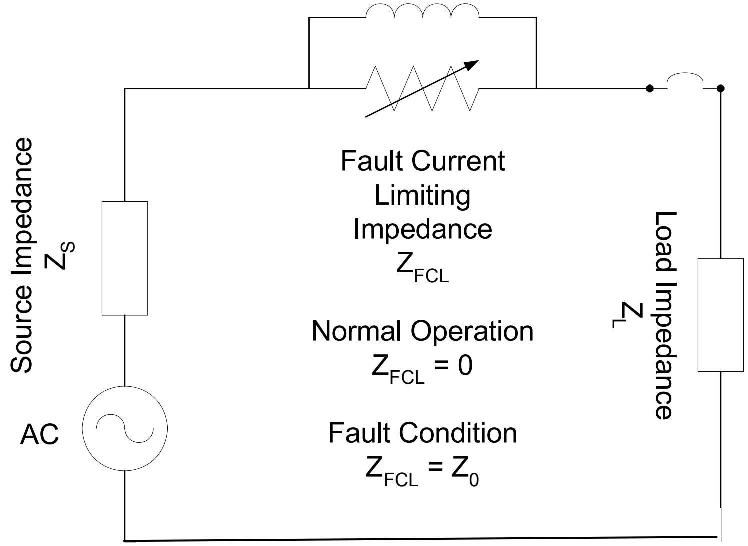
Utility market needs at the transmission level:

- Accommodate increasing fault currents due to added generation
- Avoid adverse side effects imposed by existing solutions
- Prevent breaker failures and & problems (e.g., welded contacts, bus bracing, etc.)
- Reduce "through fault" stresses on aging infrastructure
- Maintain flexibility to accommodate load growth and "open access"
- Avoid need for expensive 80kA breakers

HTS FCLs will be needed for most commercial AC HTS cable systems

Discussions with 20+ utilities have consistently validated the need!

Superconducting Fault Current Limiter (SFCL): An Alternative



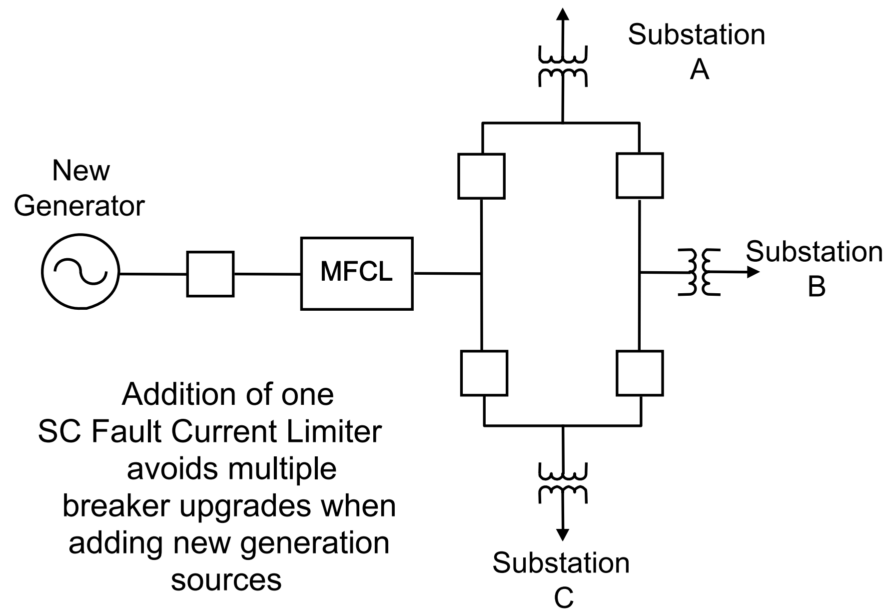
New concept with no conventional counterpart:

Passive (no active controls for insertion in system),

No Burden on system during normal operation

Modular and Scalable

Environmental benefit and no SF6



Under fault conditions critical current is exceeded and the superconductor transitions to a resistive state, introducing current limiting impedance into the grid with a parallel inductor

Project Description & Research Integration

Goal: Demonstrate SFCL feasibility at transmission level voltage – 138kV

Cost – Original $12.2M project cost estimate, with $6.1M DOE and $600K EPRI support

Now estimating project cost $23.6M, based on switch from melt cast BSCCO to 2G ($2.4M) and one year program extension (total of two years – one for RES and one to optimize 2G for application)

Schedule – Project started 6/02, original completion 6/06 – Completion now estimated to be 6/09

Project Team:

- SuperPower, Inc.: Program Lead, supply of 2G matrix material
- Sumitomo Electric Industries, Ltd. (SEI) – High voltage bushings and cryostat electrical insulation system
- The BOC Group, inc. – Cryogenic refrigeration system
- American Electric Power (AEP) – Utility host, system studies
- DOE National Labs – CRADA executed with ORNL (High voltage, cryogenics), CRADA pending with LANL (HTS element evaluation)

Research Integration (cont'd.)

Technical Advisory Board (TAB):

- Evaluate and guide project in conjunction with DOE Readiness Review
- Utility members: AEP, New York Power Authority, Southern California Edison, Con Edison, Entergy
- Academia: Rensselaer Polytechnic Institute (RPI)
- Funding sponsors: DOE and EPRI

National Electrical Energy Testing, Research And Applications Center (NEETRAC)

- Periodic reviews with 5 utilities with an interest in the project: Florida Power and Light, Exelon, Southern Company, Baltimore Gas and Electric, Entergy
- Conference calls in March, June and July 2006
- NEETRAC project manager sits on TAB

Use existing specialized facilities:

- KEMA Power Test, Chalfont, PA, for short circuit testing – 2G module tested in June 2006
- Waukesha Electric for Impulse testing up to 900kV – not this year during RES

High Voltage Working Group – SEI, RPI, AEP and ORNL

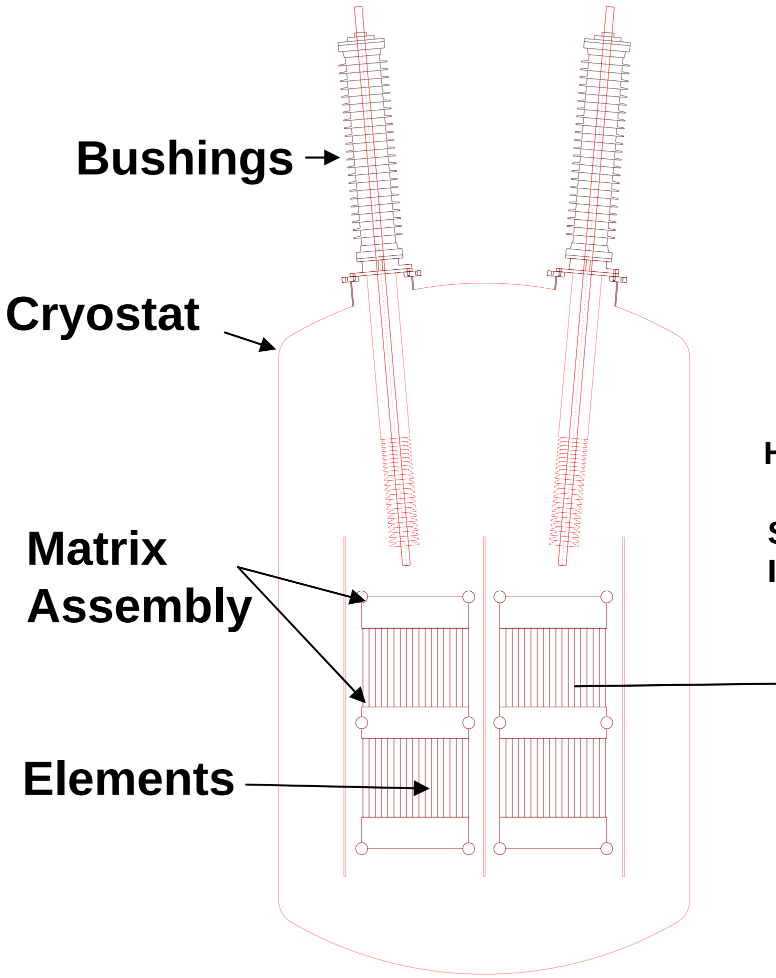
Total of 5 US patents granted on SFCL technology

Milestone Driven Program

Major Milestone	Objectives	Completion Date
Concept Feasibility & Application Studies	• Complete Conceptual Design • Study application requirements and perform power system studies	Completed June 2003
Proof-of-Concept Demonstration	• Scaled hardware non-grid demonstration of matrix concept	Completed July 2004
Alpha Prototype	• Focus: Scale up for non-grid demonstration at high voltage • Rating: 138kV, single phase, AEP application requirements	ON HOLD
Beta Prototype	• Focus: In-grid demonstration for specific utility application • Rating: 138kV, three phase, AEP Sporn Application	ON HOLD

Fabrication of full scale prototypes on hold in July 2005 pending further developments in focus areas:
1. High Voltage
&
2. HTS elements

Alpha Prototype Development - Main Components

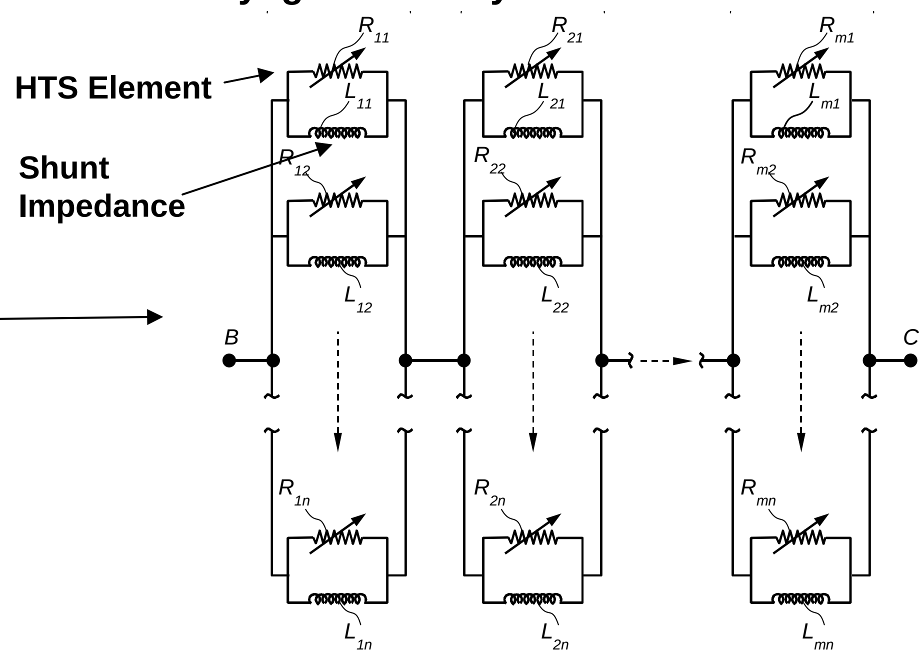


Single Phase of Alpha

High Voltage Insulation System – 1. Bushings, 2. Cryostat insulation system, 3. Matrix internal insulation

Matrix Assembly – 1. HTS Elements, 2. Connections of HTS elements and current limiting coils

Cryostat System – 1. Vessels to provide stable pressurized sub-cooled environment, 2. Cryogens and cryocoolers



Simplified Matrix Assembly Schematic

Program Status

- **At last year's Peer Review it was announced that the SFCL Program was being placed on hold (Alpha prototype design) due to:**
  - Concerns about the reliability of the melt cast BSCCO-2212 elements*
  - Need for a partner with high voltage expertise*
  - Escalating program cost

  * Both areas were identified at the 6/28/05 DOE Readiness Review as needing more priority

- **Shortly thereafter (September) stakeholders were informed that the program would be placed on Reduced Effort Status (RES) while SuperPower**
  - Investigated the feasibility of utilizing 2G material in the SFCL application
  - Obtained an industrial partner with high voltage expertise who is willing to share in the financial risk of the program
  - RES to last no later than 6/30/06
    - Reengage the program at full speed, or
    - Terminate the program

Program Status (cont'd.)

- **In the last year during the RES**
  - The BOC Group, Inc. joined the project with responsibility for the cryogenic system design, development and device monitoring
  - Sumitomo Electric Industries, Ltd. (SEI) joined the project as the high voltage partner with responsibility for the bushings and cryostat electrical insulation system
  - Reconfirmed AEP participation as the beta prototype host site although the previously selected Sporn substation may change
  - Reaffirmed interest of TAB and NEETRAC utility members in the SFCL
  - Retained DOE and EPRI financial support albeit at a reduced levels
  - Obtained additional DOE support via the GridWorks program to specifically address optimization of 2G for the SFCL application
  - Demonstrated through in house and KEMA Power Lab testing that 2G is feasible for the SFCL application
- **Conclusions**
  - All conditions established to reengage the program at full pace have been fulfilled
  - The use of the same industrial partner team as the Albany Cable Project will build upon the close working relationships already established by world class organizations

Melt Cast BSCCO Element Performance

- **Testing of the BSCCO tube elements @ KEMA prior to last year's Peer Review**
  - High probability of failure

  - Low N value - typically I > 10 Ic
  - Limited cooling surface area - long recovery time typically of the order of 10s of Seconds
  - Melt cast BSCCO tube length = 20 cm

2G SFCL Elements
High Current and High Voltage Test @ KEMA

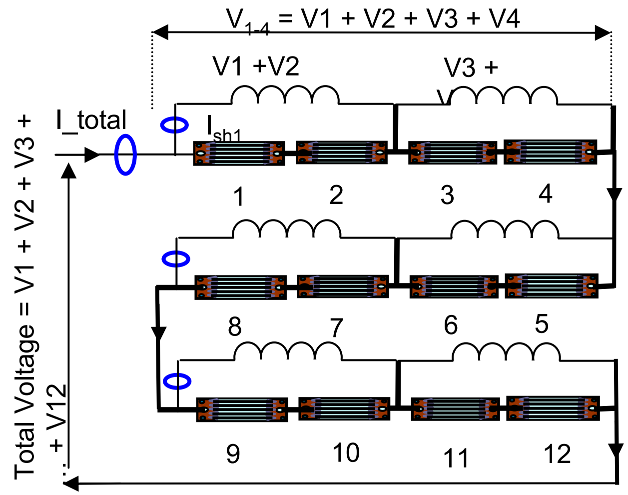
Objectives

- Demonstrate the suitability of 2G tapes for current limiting at currents and voltages comparable to utility requirements provided for alpha and beta prototype SFCLs
- Verify in-house test results at higher currents and voltages
  - Dynamic resistance of the 2G tape
  - Failure mechanisms and performance limits – maximum current, voltage, energy, volts/cm and temperature rise
  - Life expectancy of the tape
- To carry out limited design studies of SFCL modules - Shunt coil design, spacing between 2G elements

2G SFCL
12 Element Module Assembly & KEMA Test

2G SFCL – Mockup assembly components

- 12 elements, 40 cm long with 4 2G tapes in parallel per element
- 12 elements connected in series
- 2 sets of 6 shunt coils of 10 mΩ and 5 mΩ



Equivalent Circuit

Test Voltage and Current Ranges

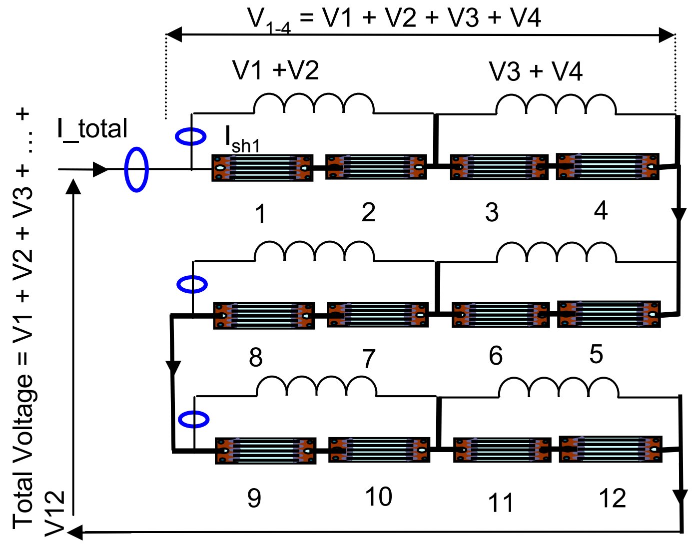
- Voltage range from 120 V_{rms} to 1200 V_{rms}
- Fault current ranges from 3 kA peak to 100 kA peak

Device Short Circuit Tests

- Start with the lowest fault current setup (5kA_{rms} at 480 V_{rms}) and lowest supply voltage setting, 120 V_{rms}, and gradually step the voltage up to a maximum of 1200 V_{rms}
- Repeat the above procedure with the 10 kA_{rms} and 15 kA_{rms} prospective fault currents
- Record voltage and current waveforms

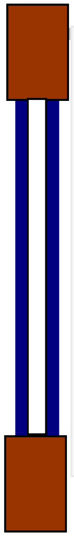
2G Material Element Test Summary

- **Testing of non optimized 2G material elements @ SuperPower & KEMA this year**



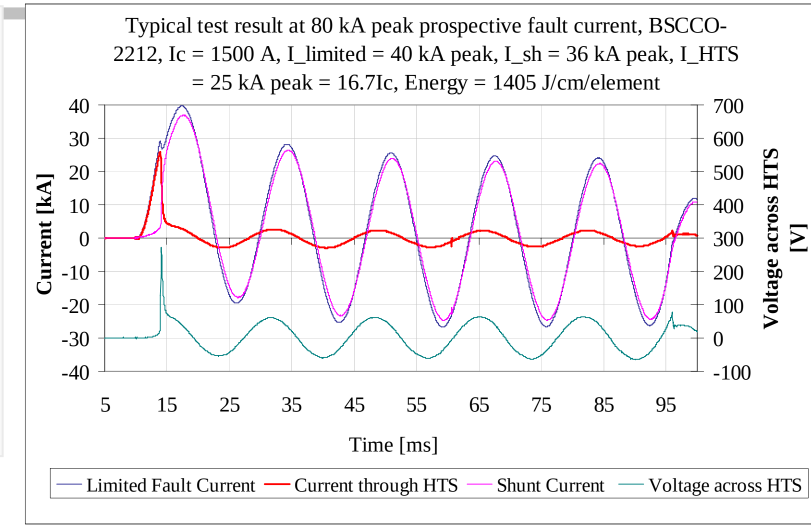
- High N value means Iquench = 2 - 3 Ic
- High cooling surface area means shorter recovery time, ~ 4 – 6 seconds
- Tested 2G elements are 40 cm long, this will be extended to ~ 1 m
- Flexibility to optimize

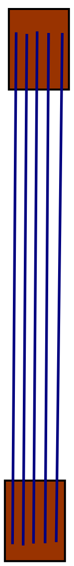
Melt Cast BSCCO vs. 2G Summary



Melt Cast BSCCO - 2212

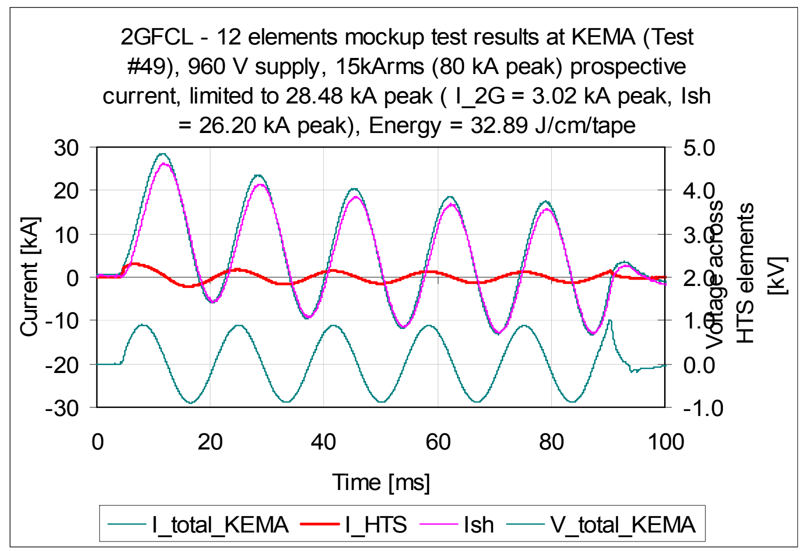
- Ceramic with no substrate is more fragile
- Low n-value (8-12) – quench current is much higher than the critical current, > 10 x Ic
- Producing elements longer than 20 cm is a big challenge
- Using short elements increases number of parts – reduced reliability, increased complexity & cost
- Bulk material with limited cooling surface area
- BSCCO tubes, length = 20 cm, Cross-sectional area = 1.20 cm^2, Volume = 24 cm^3





2G Tape - YBCO

- HTS is a small fraction of the tape – mostly metallic substrates & stabilizers increase mechanical strength
- High n-value (20-40) – quench current is around 2 – 3 x Ic, limiting fault current faster
- Overall mass of 2G < BSCCO for same current
- Manufacturing longer elements or continuous conductors is less challenging – significant reduction in connection losses
- Larger cooling surface area – faster recovery
- 2G tape, length = 40 cm, Cross-sectional area ≈ 0.012 cm^2, Volume ≈ 0.48 cm^3

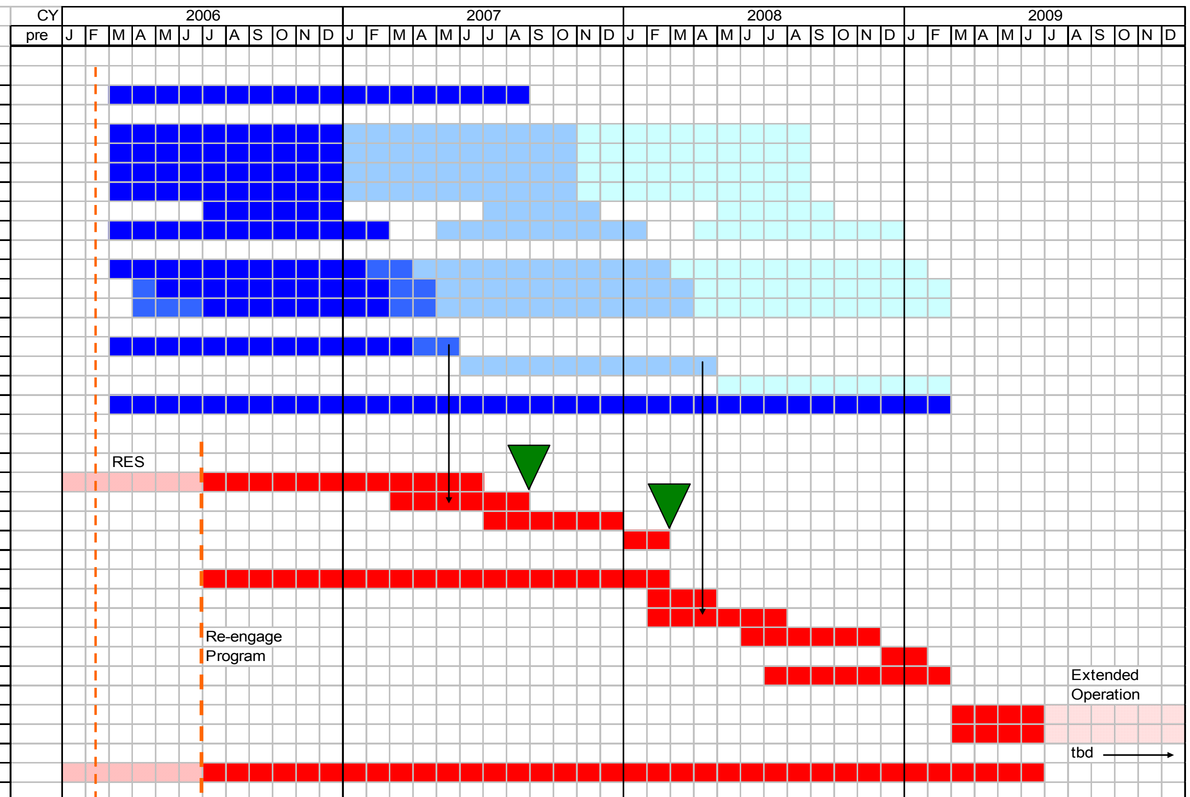


Optimization of 2G for The SFCL

- **2G by its very nature is adaptable to the SFCL application**
  - Reduced metal content – substrate and stabilizer thickness
  - Addition of a thermal heat sink
  - Increased surface area – reduced conductor width or patterning
  - Increased Ic conductor – thick film multilayers
- **SuperPower has received an award to perform this optimization under DOE's GridWorks program**
- **GridWorks and SPI are complementary programs and fully integrated**
  - GridWorks develops optimized 2G matrix elements and elements for the SFCL
  - SPI designs, builds and tests 2G 1ϕ Alpha and 3ϕ Beta prototypes and installs and tests the beta prototype on the AEP grid

Integrated GridWorks/SPI Program Schedule

Task #	Task Description
1.0	SFCL Specification Development
2.0	2G Development
2.1	Modification of metal content of the conductor
2.2	Addition of high resistance heat sink
2.3	Modification of surface area of conductor
2.4	High current conductor
2.5	Long length integrated conductor
3.0	2G SFCL Matrix Development
4.0	2G Pre-prototype Matrix Assembly Design, Fabrication and Test
4.1	Design
4.2	Fabrication
4.3	Test
5.0	2G Prototype Conceptual Design
5.1	Alpha
5.2	Beta
5.3	Phase 3
6.0	2G Program Management
7.0	Alpha Prototype Development
7.1	Component design and prototyping
7.2	Detail design
7.3	Fabrication
7.4	Non-grid test and evaluation
8.0	Beta Prototype Development
8.1	System studies and specification development
8.2	Component upgrade
	Detail design
8.3	Fabrication
8.4	Non-grid qualification tests
8.5	Installation and commissioning
9.0	Beta Prototype Operation, Evaluation and Site Restoration
9.1	Operation
	Evaluation
9.2	Site Restoration
10.0	SPI Program Management



Stage gate milestone - go/no go decision point

(dark blue)	2G Project Schedule - Phase 1 (Alpha)	65 % of 2G dev effort
(light blue)	2G Project Schedule - Phase 2 (Beta)	25 % of 2G dev effort
(pale cyan)	2G Project Schedule - Phase 3	10 % of 2G dev effort
(red)	HTS FCL Project Schedule	
(pink)	Reduced Effort Status	
(light pink)	Operational Extension	

SFCL FY 07 Milestones*

1.0A	Complete AEP grid SFCL specifications	November 2006
1.0B	Identify representative U.S. utilities for study	November 2006
2.0A	Select 2G configuration for alpha prototype	December 2006
3.0A	Complete optimized 2G element configuration for alpha prototype	February 2007
4.0A	Complete optimized 2G matrix configuration for alpha prototype	April 2007
5.0A	Complete alpha prototype conceptual design	May 2007
7.1A	Complete alpha prototype cryogenic system development	June 2007
7.1B	Complete alpha prototype HV bushing and cryostat electrical insulation system development	June 2007
7.1C	Complete alpha prototype HV matrix insulation development	June 2007
7.1D	Complete overall integrated alpha prototype design review	June 2007

* Schedule subject to revision pending further review by SuperPower, SEI, BOC, AEP and DOE

SFCL FY 07 Milestones (cont'd.) *

7.2A	Complete alpha prototype HV matrix design	August 2007
7.2B	Complete alpha prototype bushing and cryostat electrical insulation system design	August 2007
7.2C	Complete alpha prototype cryogenic system design	August 2007
7.2D	Stage Gate Review – Alpha prototype design review	August 2007

* Schedule subject to revision pending further review by SuperPower, SEI, BOC, AEP and DOE

SFCL Project Roles

Partner	Project Role
SuperPower	• Overall project management • Systems integration • SFCL matrix design and development • 2G material and matrix component supply • Alpha and beta prototype design, fabrication and test
SEI	• Bushing and cryostat electrical insulation system design, development and manufacturing • Participate in prototype designs
AEP	• AEP and U.S. utility grid generalized SFCL specifications • Select beta prototype site and define specifications • Support beta prototype system studies and specification development • Substation design and engineering, procure and install beta prototype support equipment • Support beta prototype installation, commissioning, testing, data collection and analysis

SFCL Project Roles (cont'd.)

Partner	Project Role
BOC	• Cryogenic system design and development • Cryogenic system instrumentation and overall system monitoring • LN_2 supply • Support prototype assembly and testing
ORNL	• Specialized design and testing support for high voltage matrix components in a cryogenic environment • Cryogenic consulting
LANL	• Investigate methods to incorporate a heat sink and improve surface area of 2G conductor • Assist SuperPower by testing 2G elements • Support matrix testing and conceptual designs

Conclusion

SuperPower and its team are poised to restart the SFCL program at full pace with added expertise in high voltage (SEI) and cryogenics (BOC) using superior 2G material