2LX04

2G HTS Conductors for Fault Current Limiter Applications

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HTS Solutions for a New Dimension in Power

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Outline

Introduction

- Development of proprototype MFCL based on MCP-BSSCO
- Potential of 2G HTS conductors in SFCL applications

Low-power tests to evaluate the performance of individual wires

- Current limiting performance;
- Recovery Under No-Load Condition.

High-power tests to verify the suitability for high voltage and high current applications

Summary

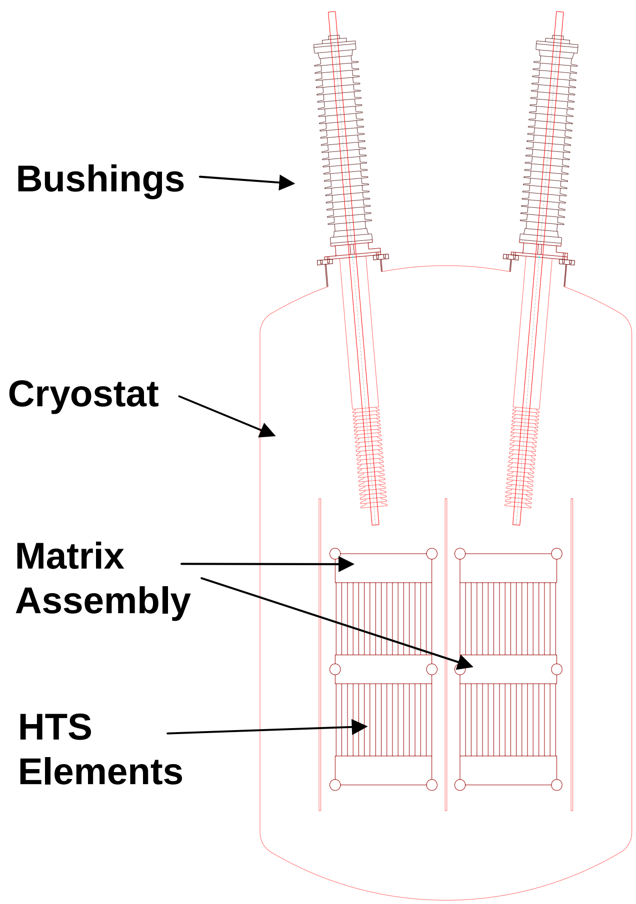
Preprototype Superconducting Matrix Fault Current Limiter (MFCL) was demonstrated by SuperPower in July 2004

Single Phase SFCL

High Voltage Insulation System
- Bushings
- Cryostat insulation system
- Matrix internal insulation

Matrix Assembly
- HTS Elements
- Connections of HTS elements and current limiting coils

Cryogenic System
- Vessels to provide stable pressurized sub-cooled environment
- Cryogens and cryo-coolers



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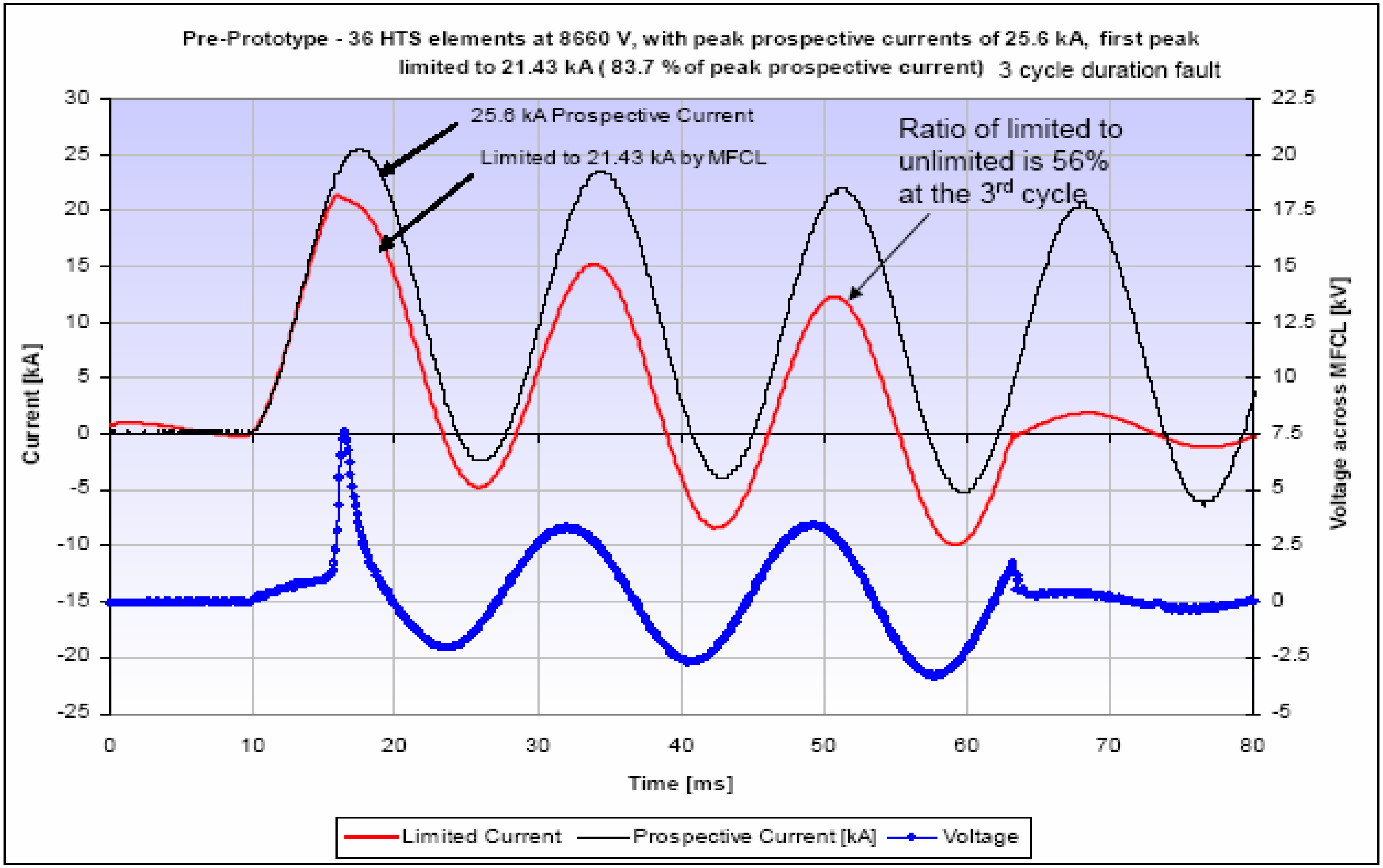
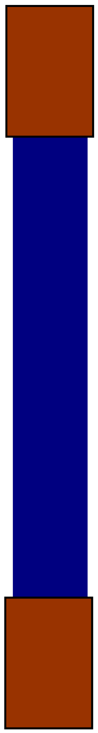


Current Limiting Performance Test Results in Cryostat @ 8660VAC, 74 K, 1 atm

X. Yuan, *et al*., ASC 2004, Jacksonville, FL.

HTS Elements

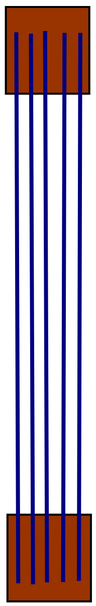
A High Risk Challenge Using BSSCO Bulk in Alpha Prototype (138 KV, 1ϕ)



- Low n-value (8-12) – the quench current is much higher than the critical current, it requires higher current to quench, in the order of >10*I_c. This increases the total material volume needed in SFCL.
- Large number of elements required. Number of elements determines device size (along with high voltage), steady state losses (connections) and rating of device cryogenic system – Keep number per phase to a manageable level. Must develop longer elements with high individual energy level to minimize total number of parts
- Reliability needs improvement - Loss of elements has negative impact on heat load and introduces debris that could compromise high voltage
- Slow return to superconducting state while carrying load current - Recovery Under Load (RUL). Bulk material with limited cooling surface area.

L. Kovalsky, *et al*., Superconductivity for Electric Systems 2005 Annual Review

Advantages of using 2G HTS Conductor for SFCL



- High n-value (20-40) – the 2G conductor quenches at around 2 – 3 times Ic, it limits fault current faster and to lower level;
- 2G conductors in 100+ m length and good uniformity are already available. (World-record performance by high throughput IBAD-MgO/ MOCVD at SuperPower)
- Superior electro-mechanical properties have been shown in SuperPower's 2G conductor – Reduce the chance for mechanical failure and increase the flexibility of element configuration/design.
- Elements with larger cooling surface area – Faster recovery
- Several structural features of 2G conductors can be tuned to optimize SFCL element performance. (2G conductor structure)
- An additional advantage of using IBAD-based 2G is the ability to use various types of substrates. The substrate currently used in SuperPower's 2G conductor is Hastelloy which has a high resistivity which is preferable for FCL applications.

2G SFCL
Preliminary Test at SuperPower

Objectives

- **Test 2G conductors for current limiting performance, including**
  - Quench speed - related to quench time and quench current
  - Current transfer speed to external shunt
  - Failure mechanism and life expectancy of the 2G tapes
  - Dynamic resistance development
- **Evaluate the advantages and disadvantages of 2G conductors for SFCL**

Test Setup

Voltage supply

- Isolating transformer, primary 208 V, Secondary 5V, 10V, 20V and 40V;
- Short circuit current could vary up to 7000 A peak.
- Thyristor switch to control the impulses
- Line frequency – 60 Hz

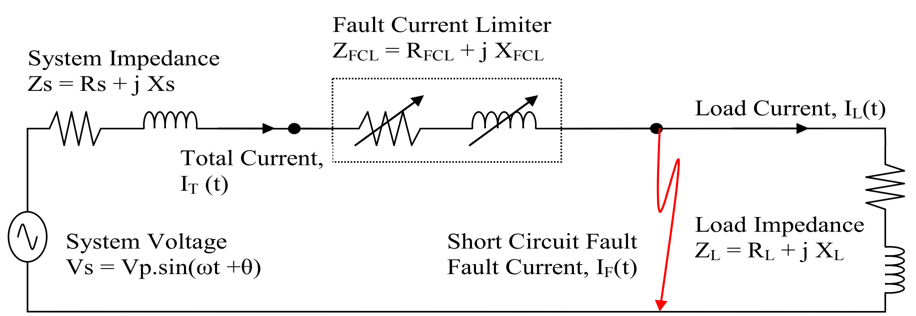


Figure 2 (a) Schematic Diagram of a single phase power system representation

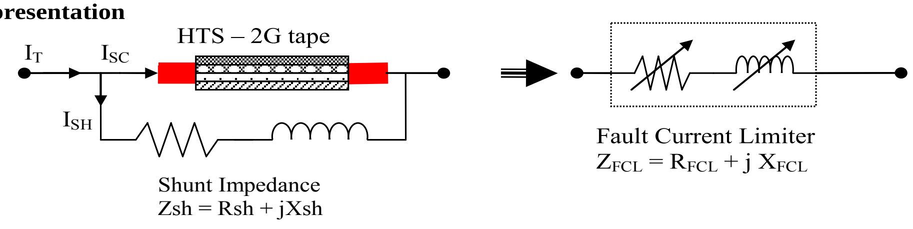


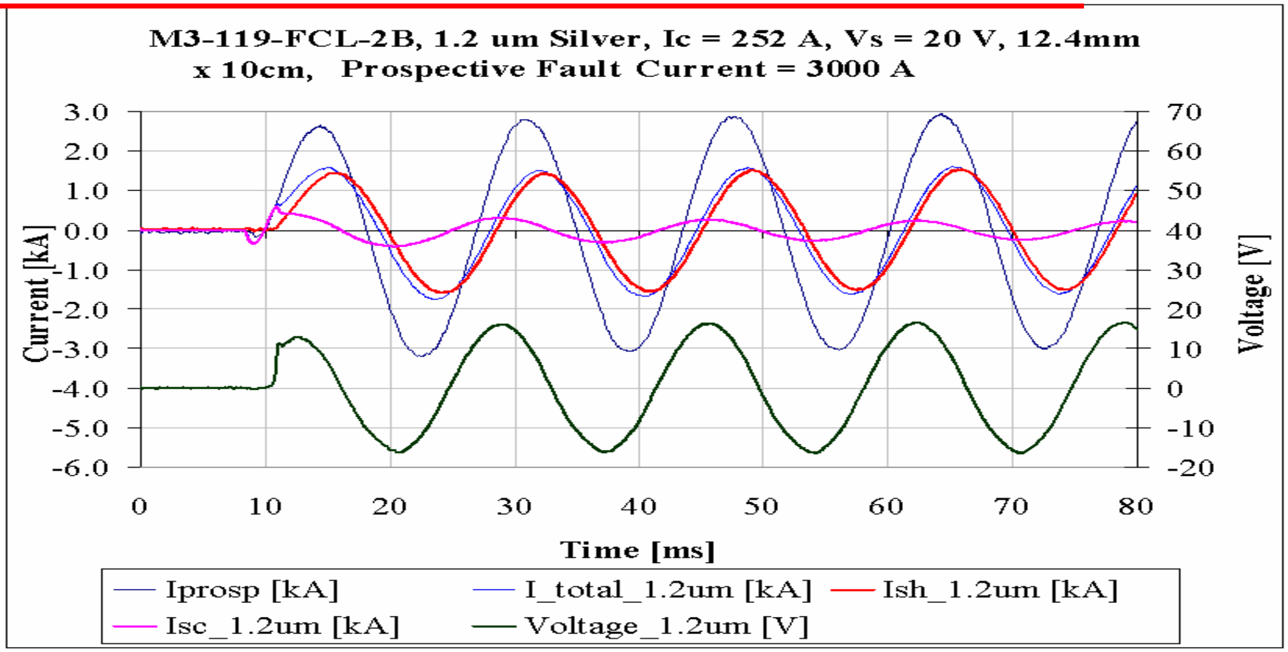
Figure 2 (b) Equivalent circuit of FCL

Performance of Single 2G Conductors

Advantage of IBAD-based conductor for FCL is use of highly resistive substrate: No need for additional stainless steel or other stabilizer!

A typical 2G conductor:

- Width: 12.4 mm;
- Length: 10 cm;
- Ic = 252 A;
- 1.2 μm metal overlayer
- Subject to a 8 cycle fault current;
- V = 20 V on the circuit.



- Multiple samples tested and all demonstrated current limiting performance, including 1st peak limitation
- Quench current under AC (60 Hz) fault current was in the range of 1.8 to 3 times critical current.
- Response time is within 1 ms.
- With shunt, the total current can be limited to half of the prospective current.

Testing 2G Conductors in Parallel Connection

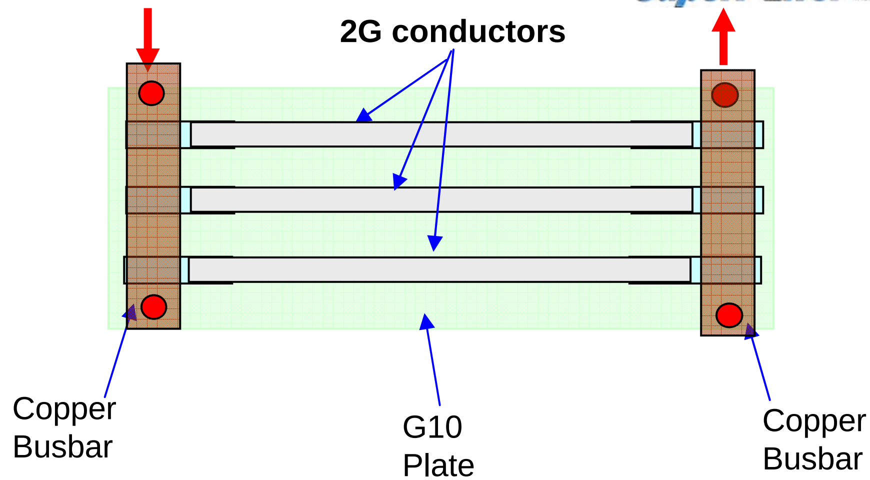
Current Limiting Performance

Three 2G conductors tested in parallel,

- Each is 20 cm long x 1.24cm wide with 2.4 μm metal layer. Ic = 277 A;

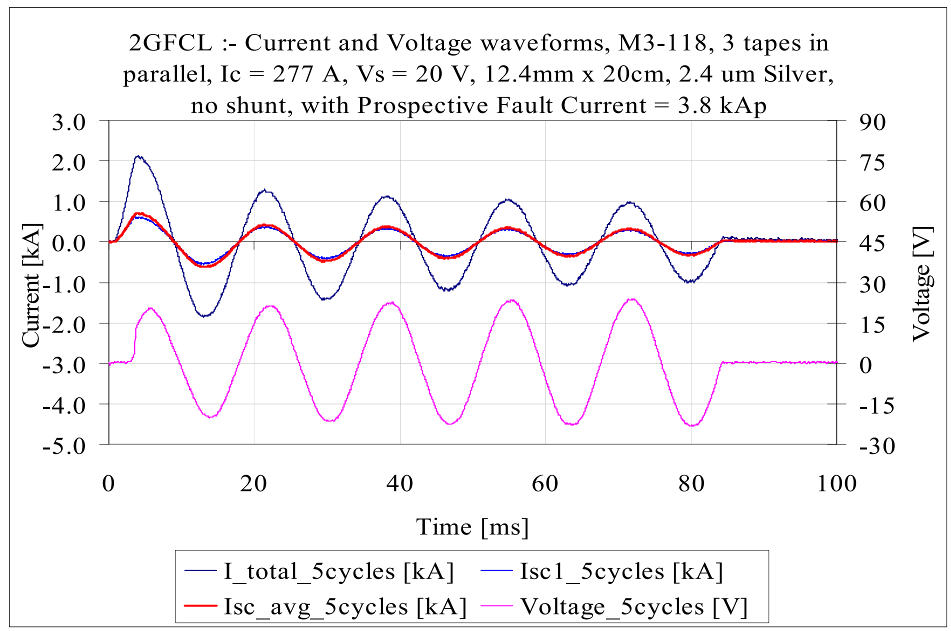
Test procedure:

- Apply fault currents with prospective fault current of 442 A, 705A, 1140A, 1360A, 1650A, 2320A, and 3800A at 20 V. No shunt.
- Fault duration from 5 cycles up to 12 cycles



Test results:

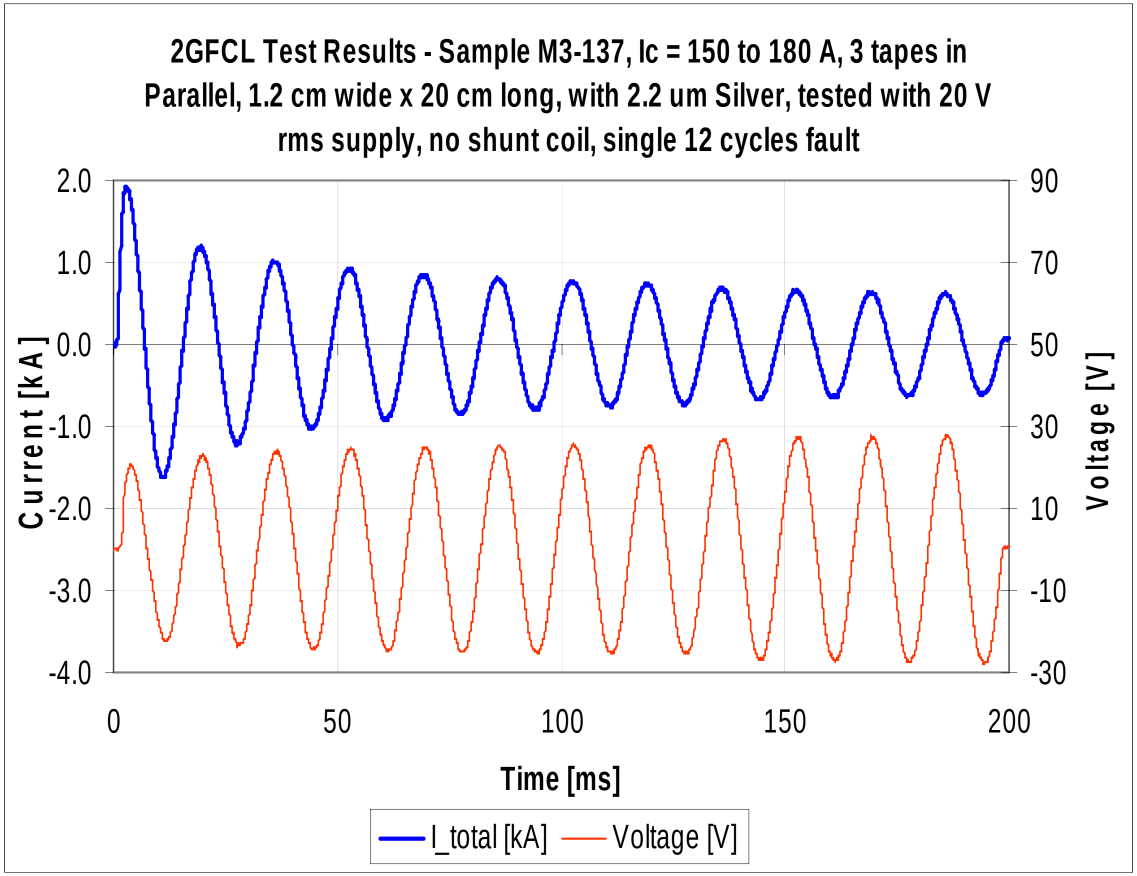
- At 3.8 KA prospective fault current, first peak current was 600 - 700 A for each wire.
- Two samples failed at the same time during 11 cycles test at same_energy level; The 3rd sample failed during the next 12 cycles test.
- Failure of parallel conductors close to each other means small variation and good predictability of life expectancy



Testing 2G conductors in parallel connection
Recovery Performance

A different set of three 2G conductors tested in parallel:

- Each is 20 cm long x 1.24cm wide with 2.2 μm metal layer. Ic ~ 180 A;
- Survived single 12 cycles faults at the same energy density level as for single tapes;
- Current decreases and voltage increases with time during fault, implying accumulative heating to the tapes and temperature rise.

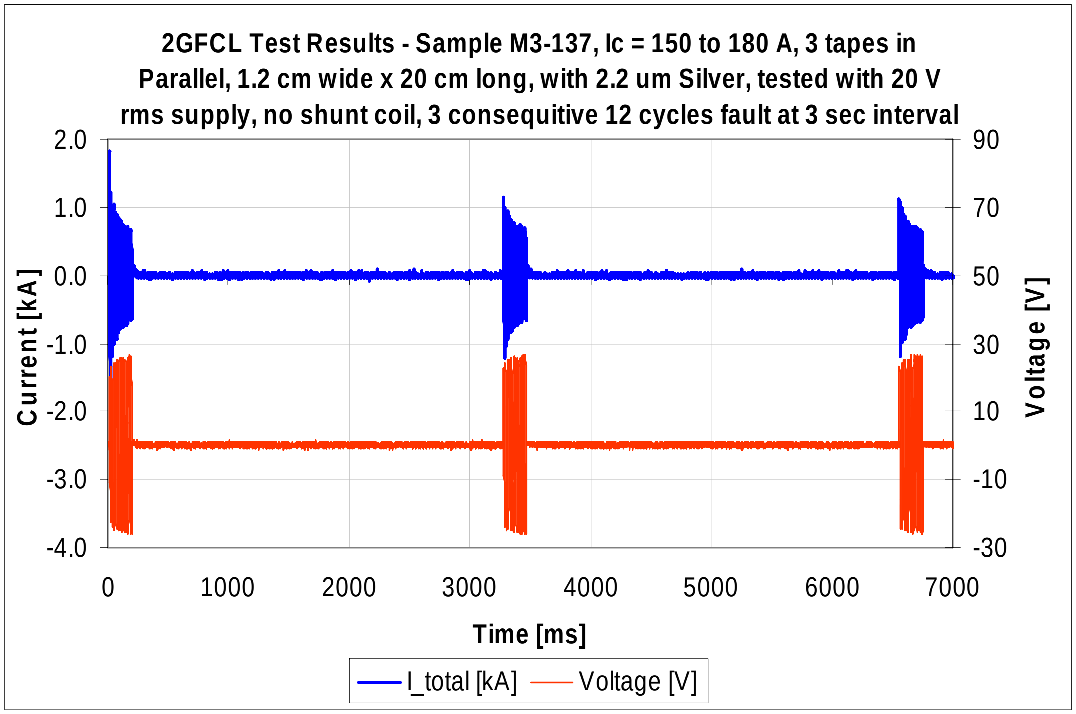


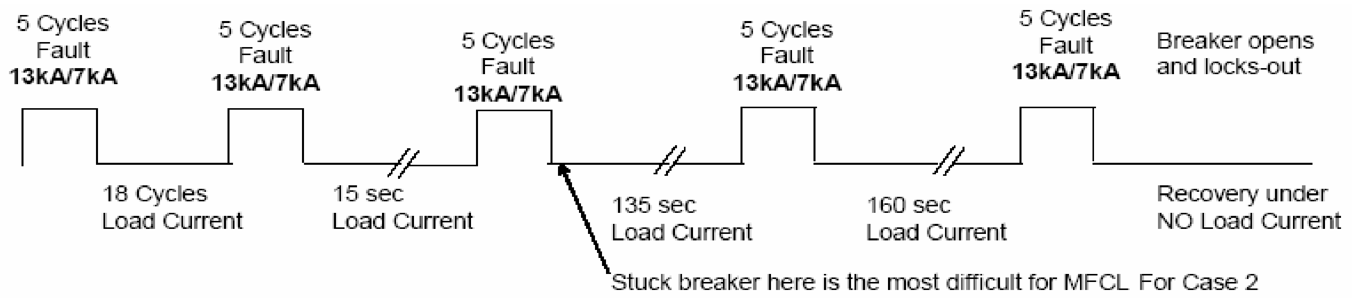
Testing 2G Conductors in Parallel Connection

Recovery Performance

Repetitive fault performance – Recovery under no load test

- Simple estimation of recovery time based on LN_2 bubble activities showed that conductors recover within 4 to 6 seconds.
- Up to 6 repetitive faults of 12 cycles at an approximately 3 seconds interval were applied. 3 repetitive faults of 12 cycles shown in the chart.
- Large surface area is beneficial to recovery. RUL performance needs to be tested under different breaker switching sequence scenarios. For example, the worst case.





2G FCL
High Current and High Voltage Test

SuperPower Inc.

Objectives

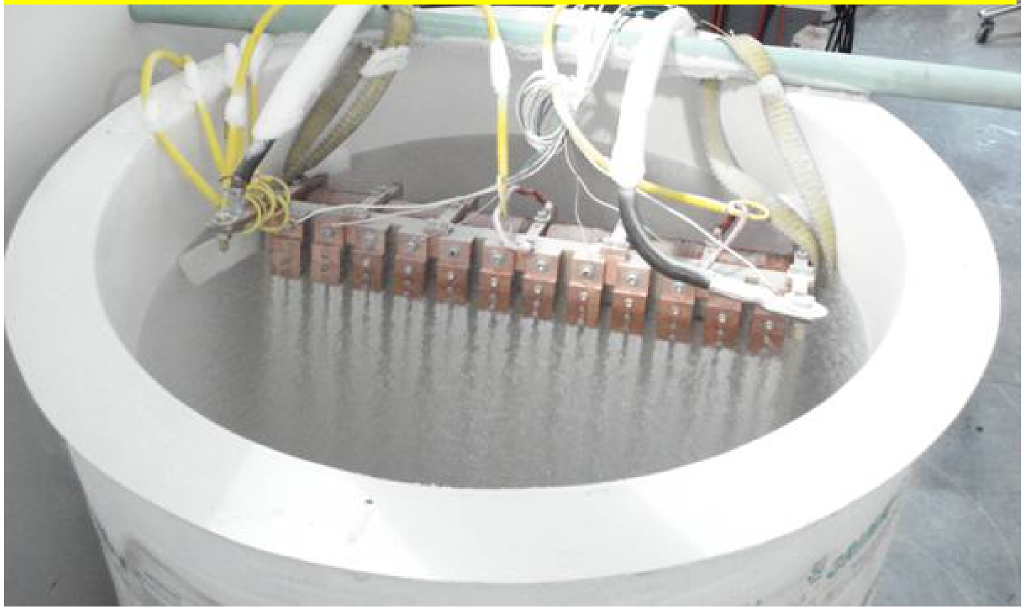
- To verify in-house test results at higher currents and voltages
- To demonstrate the suitability of 2G tapes for current limiting application at higher currents and voltages comparable to utility requirements provided for alpha MFCL

2G FCL – 12 Elements Mockup Assembly

2G FCL – mockup assembly components

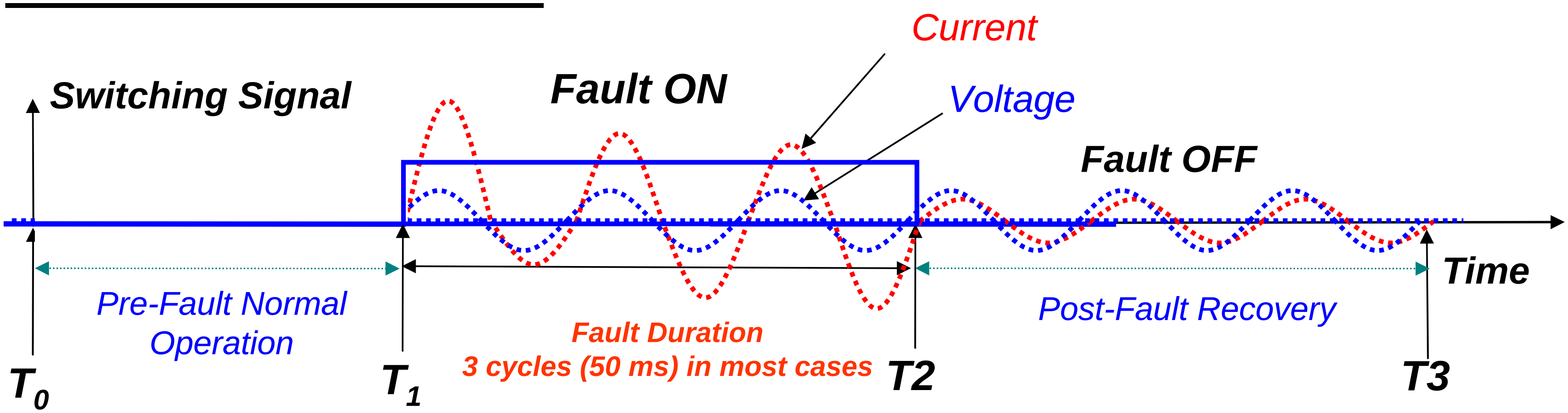
- 12 elements; 40 cm long with four 2G tapes in parallel per element;
- At least three voltage and three current measurement probes

12 elements, 40 cm long with four 2G tapes in parallel per element



2G FCL – High-Power Test Setup and Conditions at KEMA

Short Circuit Simulation

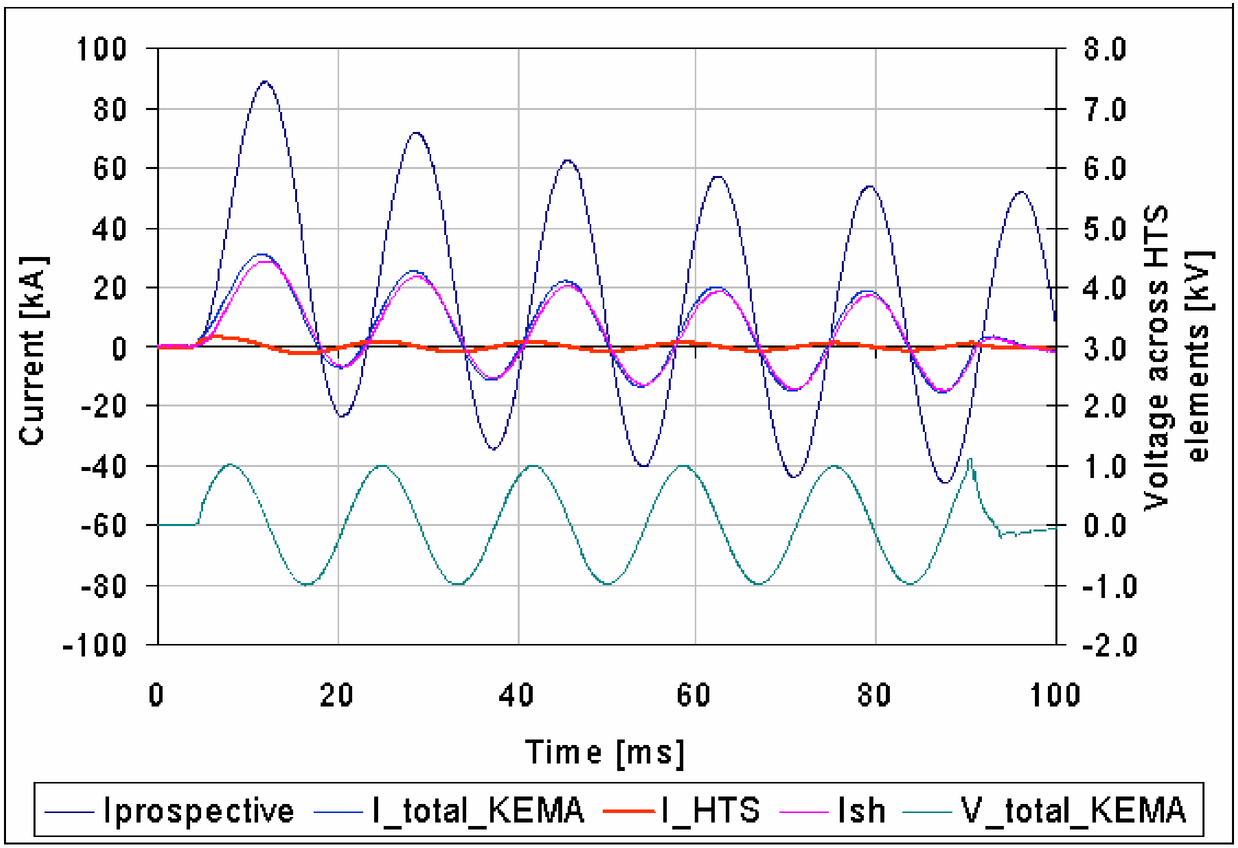


Test Voltage and Current Ranges

- Voltage range from 120 Vrms to 1200 Vrms;
- Fault current ranges from 3 kA peak to 100 kA peak;
- 51 tests on the assembly

KEMA Test Results

Typical Current Limiting Performance

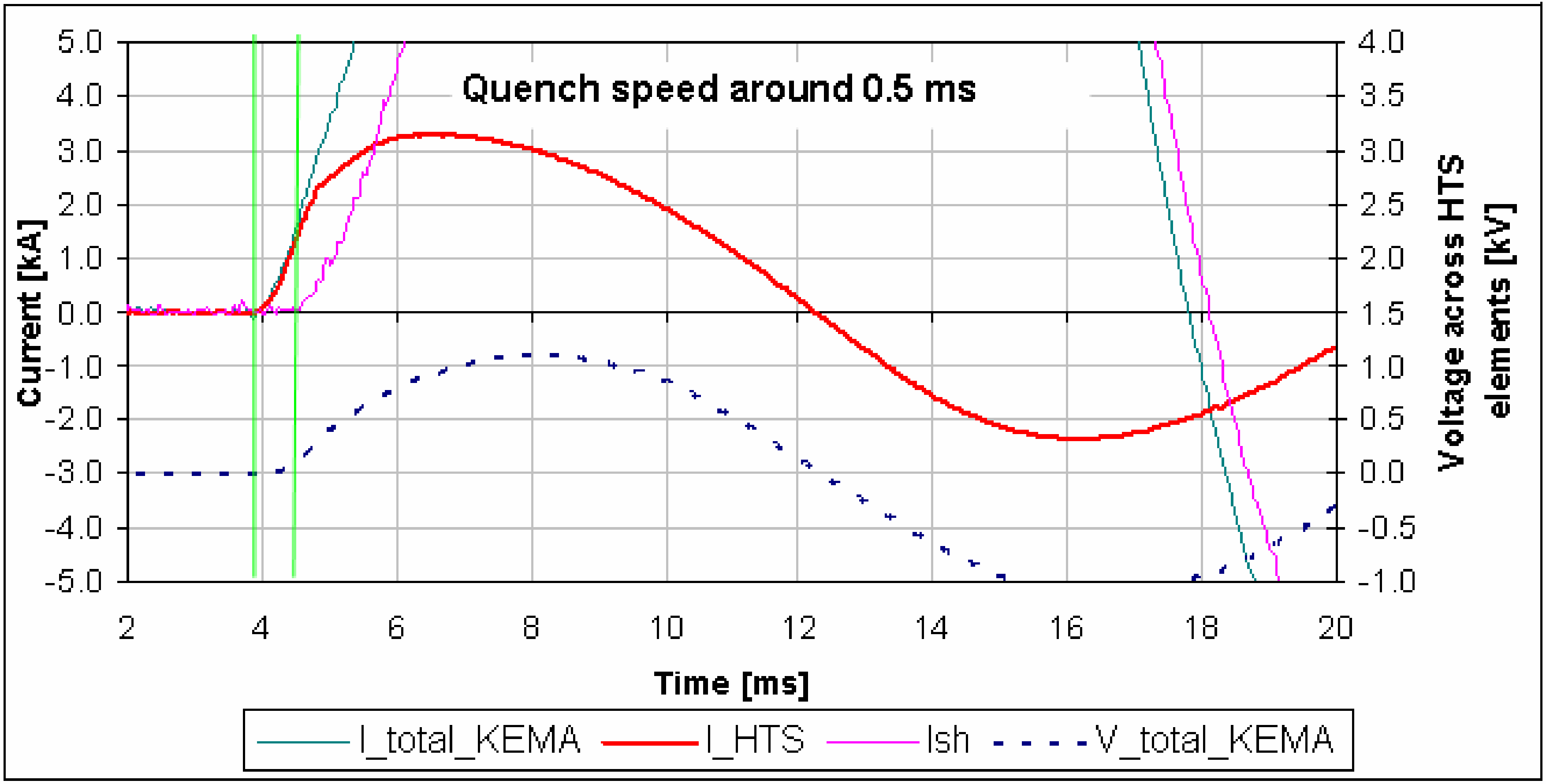


- Test result at 1080 V with prospective fault current of 33.75 kA rms (90 kA peak)
- Limited current to 31.81 kA peak ~ 35.3% of prospective fault current at 1st peak
- HTS current limited to 3.16 kA peak and shunt current to 29.10 kA peak

Full scale SFCL System design implication

- AEP's requirement of 26 kA rms (70 kA peak) fault condition is satisfied with this performance.

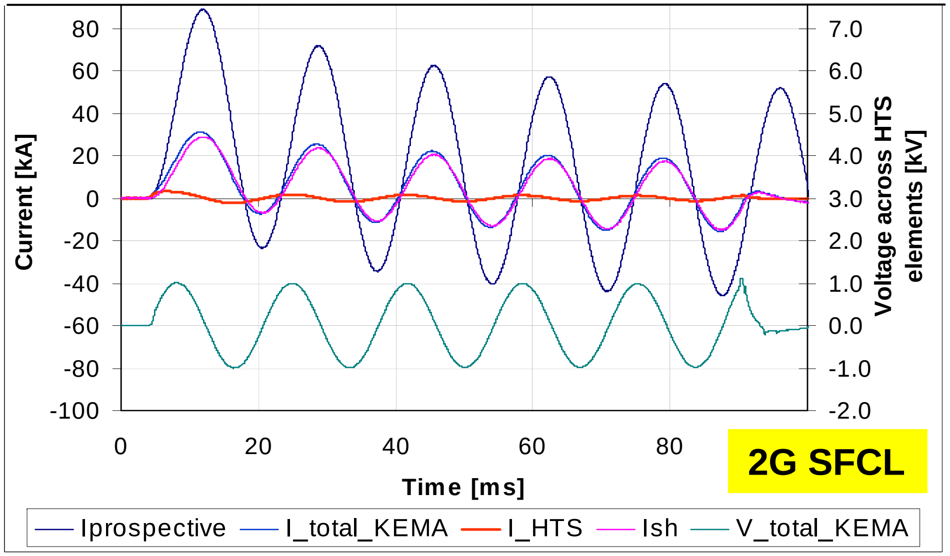
KEMA Test Results - Current Limiting Speed

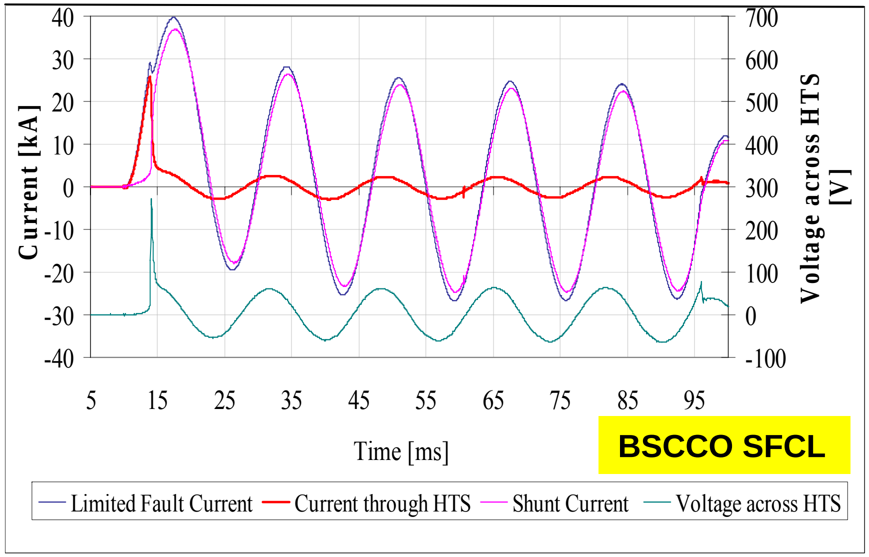


Current limiting performance

- Quench response time within 1 ms
- 2G tapes fully quenched at currents around 4 x Ic = 2350 A (Ic ~ 500 A)

2G SFCL vs. BSCCO MFCL Comparison





High-power SFCL test	2G	Melt-cast BSCCO
Prospective current	90 kA*	80 kA
Limited current	32 kA	40 kA
Current through element	3 kA	25 kA
Response time	< 1 ms	4 – 5 ms
Element quality range	Narrow	Broad

Superior performance in all respects using 2G SFCL in high-power tests

2G SFCL – Summary

- IBAD-based 2G HTS conductors showed superior performance SFCL in low-power and high-power SFCL tests. Alpha prototype can be designed using 2G FCL to AEP's requirements;
- Low-power tests:
  - Demonstrated including 1st peak limitation, fast response time (within 1 ms) and low quench current (1.8 to 3 times Ic)
  - Uniform current sharing when conductors were tested in parallel.
  - Successful tests on recovery under no load conditions up to 6 repetitive faults of 12 cycles.
- High-power tests
  - 12-element assembly demonstrated limiting perform at 1080 V supply voltage with 90 KA peak prospective fault current. The fault current was limited to ~ 35% of the prospective fault current.

THANK YOU