138 kV Superconducting Fault Current Limiter (SFCL) Project

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HTS Fault Current Limiters:
New Technology (with lots of potential) 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 (~50%, possibly greater) so that 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 & associated 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

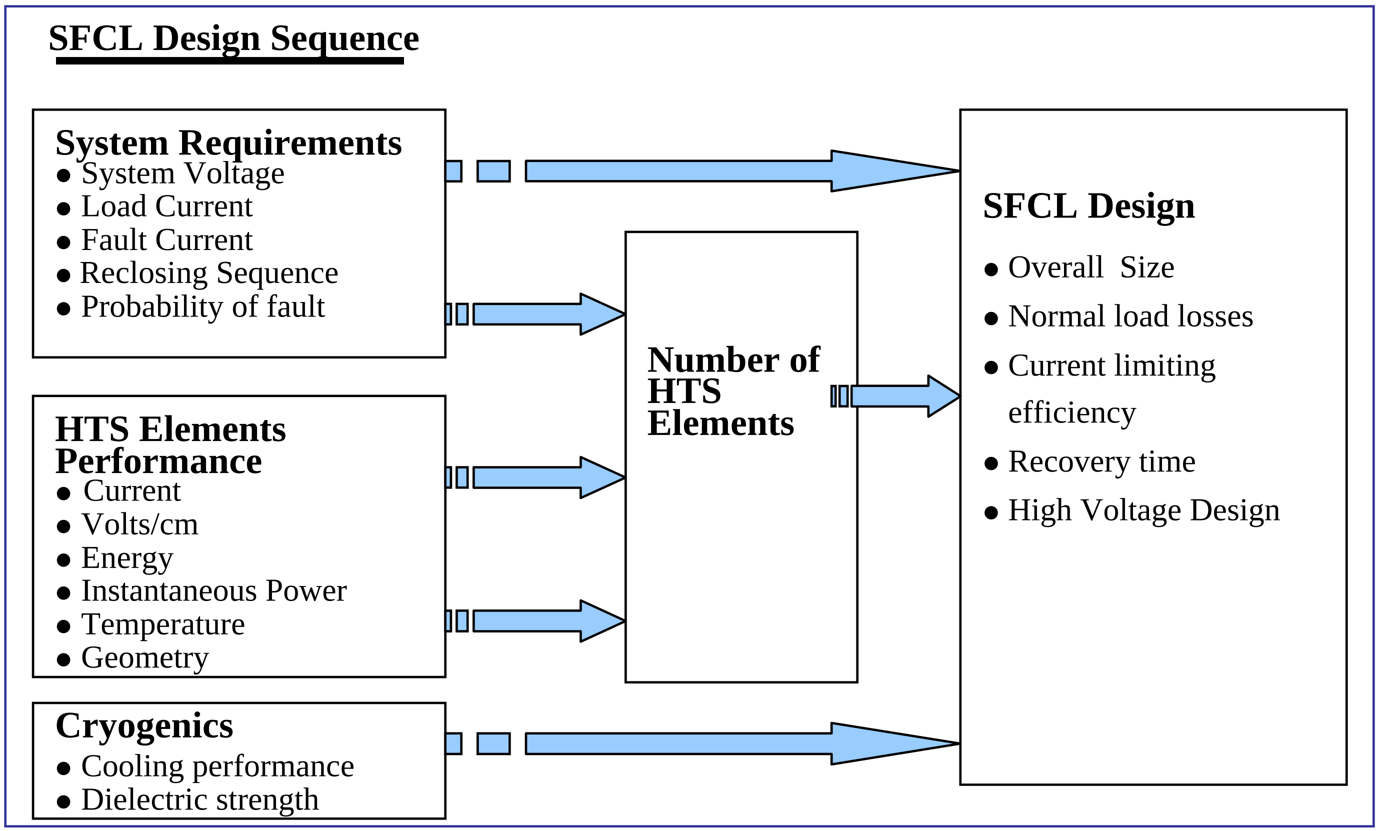
HTS FCLs are a natural compliment to AC HTS cable systems

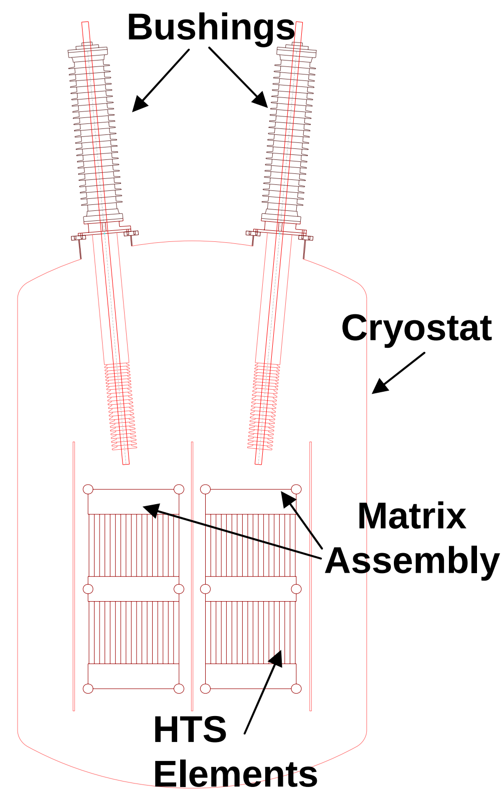
Discussions with 20+ utilities have consistently validated the need

SFCL System Design

Objectives

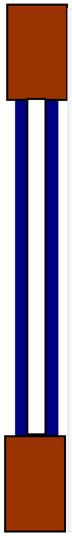
- Alpha SFCL Design - a 138 kV, 650 kV BIL transmission line Fault Current Limiter
- Limits fault currents to < 60% of the steady state prospective fault current





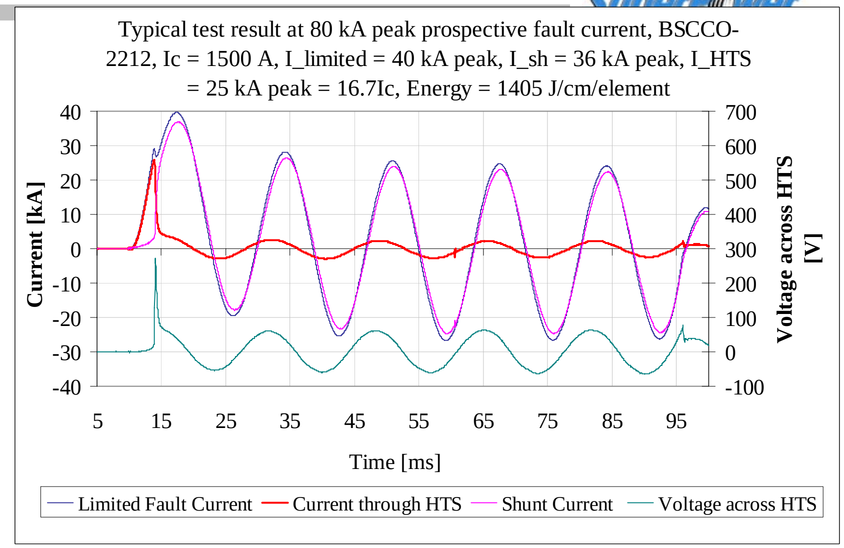
Single Phase SFCL

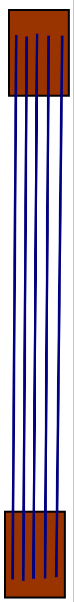
2G FCL – Compared with BSCCO-2212



BSCCO-2212

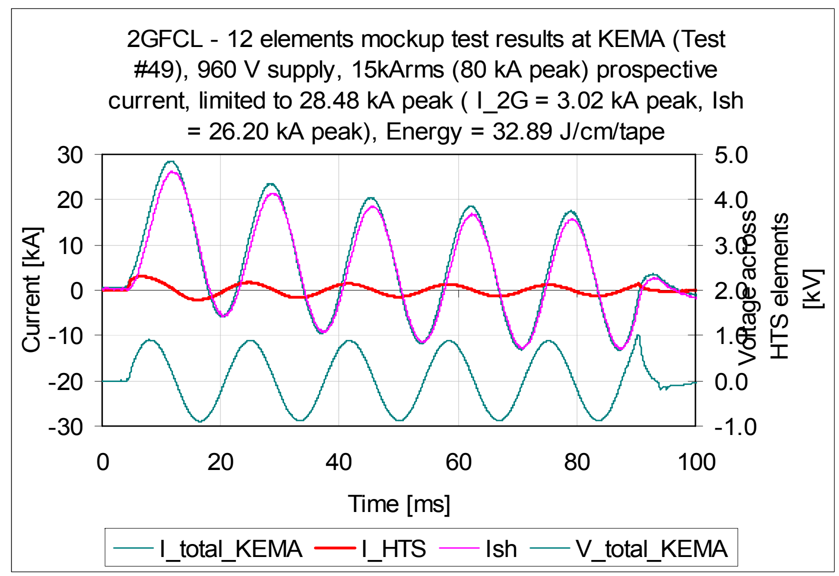
- Bulk BSCCO – Ceramic with no substrate is more fragile
- Low n-value (8-12) – the quench current is much higher than the critical current, in the order of >10Ic
- Producing longer elements is a big challenge – 20 cm long elements and connection losses is high
- Using short elements increases number of parts – reduced reliability
- 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

- The SC part is a small fraction of the tape – mostly metallic substrates and stabilizers increase mechanical strength
- High n-value (20-40) – the YBCO tape quenches at around 2 – 3 times Ic, it limits fault current faster
- Overall mass of 2G is less than BSCCO for same current
- Manufacturing longer elements or continuous conductors is less challenging – significant reduction in connection losses
- Elements with larger cooling surface area – Faster recovery
- 2G tape, length = 40 cm, Cross-sectional area ≈ 0.012 cm^2, Volume ≈ 0.48 cm^3



Testing of 2G conductor has confirmed its superiority for FCL applications

- **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;**
- **<u>Low-power tests:</u>**
  - **Demonstrated 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 w/ up to 6 repetitive faults of 12 cycles.**
- **<u>High-power tests:</u>**
  - **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.**
- **Good performance with 'stock' material, but we are confident we can do even better…**

2G Optimization

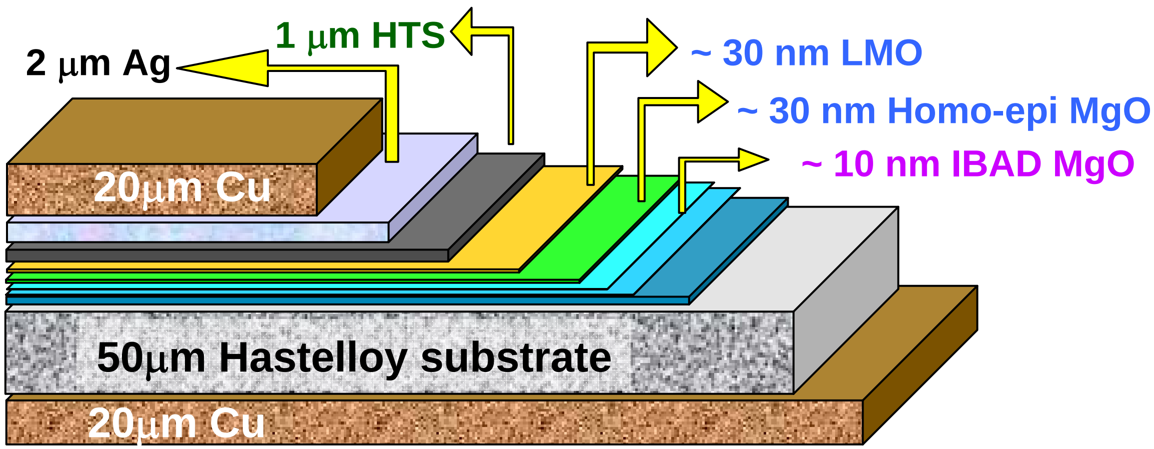
Main Areas for Optimization

- Substrate & Stabilizer thickness and composition
- Critical current
- Enhanced heat transfer to cryogen bath
- Tape layout, side stabilizer coverage and end termination

Each of these areas has tradeoffs

- More mass (constant current) is better for minimizing temperature rise
- Lower resistance leads to higher current sharing with fixed shunt impedance
- Shunt impedance variation limited by system requirements

Recovery under load (RUL) performance optimization is key



SFCL – Recovery of 2G tape

Recovery Test – Design of Experiments

Objectives

- To determine the recovery under load performance of the 2G tapes
- To determine the number of parallel tapes for 1200 A rms load current
- To determine the shunt impedance in order to optimize the 2G materials requirement and fault limiting performance

Input Variables

- X1 = Load Current
- X2 = Shunt impedance
- X3 = Energy
- X4 = Critical Current
- X5 = Substrate thickness
- X6 = Cooling efficiency
- X7 = Repetition of fault

Output Variables

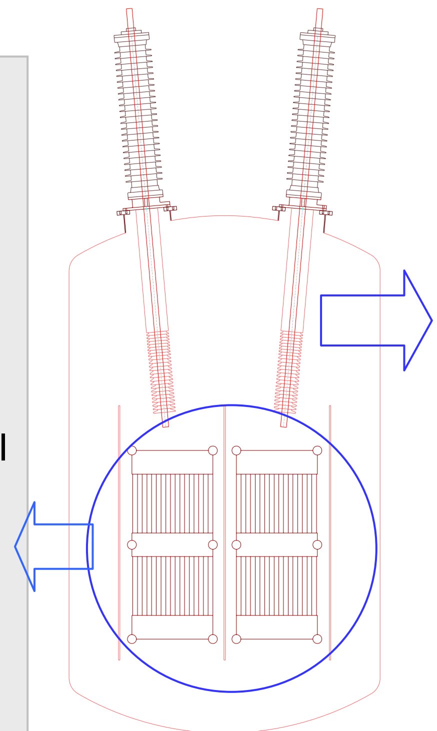
- Y1 = Recovery time
- Y2 = Cooling performance [uniformity, thermal diffusion]
- Y3 = ratio of Load current to critical current of tapes for optimum recovery under load

Cryogenic System – Transient Heat Loads - Fault

Transient heat load impact short term RUL of HTS & long term system recovery - Fault current energy (fault current & number of cycles) drives transient heat load

Short Term Recovery Under Load

- HTS elements re-cool to superconducting state
- Value of shunt impedance impacts RUL
- HTS element temperature based on total energy deposition
- HTS elements directly cooled by LN2 bath – Impact of external cooling is minimal
- Recovery time driven by heat transfer from elements to LN2 bath
    - Heat transfer aided by higher operating pressure
    - Higher pressure suppresses visible bubble formation with improved dielectric performance
- Unit is functional as HTS elements recover



Longer Term System Recovery

- System recovers to baseline operating level
- Cooling by external cooling system
- Driven by total energy deposited in the LN2 bath
- Unit is operational as system recovers, up to a finite energy deposition level