Georgia Tech College of Engineering

National Electric Energy Testing Research & Applications Center
NEETRAC
A Research Center in the School of Electrical and Computer Engineering at the Georgia Institute of Technology

Superconducting Fault Current Limiter Test Program Development

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Georgia Tech / NEETRAC

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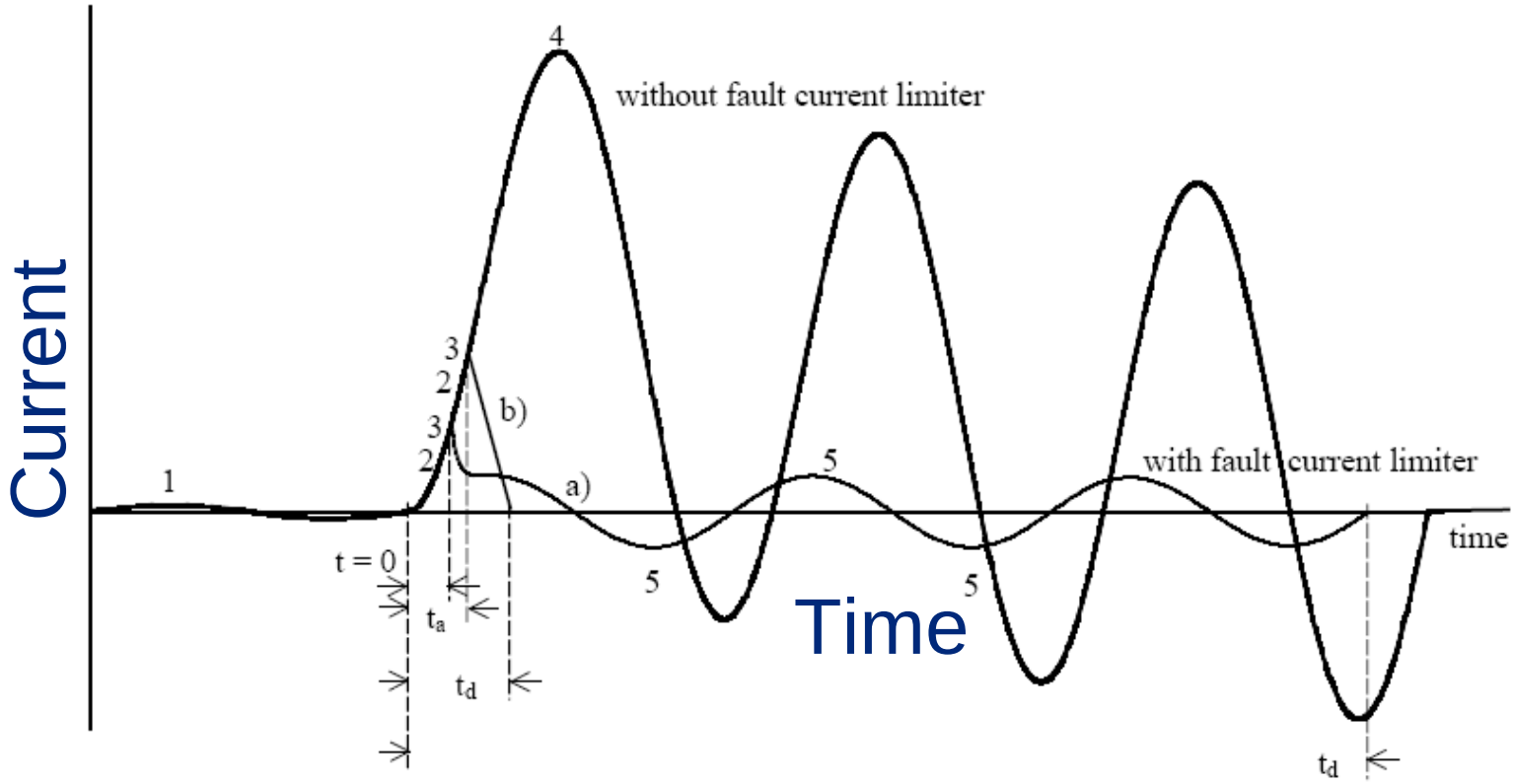
Fault Current Limiters



a) SFCL

1 – Nominal Current

2 – Minimum Initiating Current

3 – Maximum Limited Current (SFCL)

b) Pyrotechnic FCL

4 – Peak Current w/o FCL

5 – Peak of the Follow Current

Fault Current Limiters

- Active Fault Current Limiters exhibit a small impedance at nominal load with rapid increase of impedance at fault.
- Active FCLs differ from circuit breakers, reactors, and transformers.
- An International Standard has not been developed for testing active FCLs.
- Test requirements need to be compatible with existing standards, taking into account the unique characteristics of the FCL.
- CIGRE Working Group A3.10 published recommendations in December 2003 for Testing FCLs in Medium and High Voltage Systems.

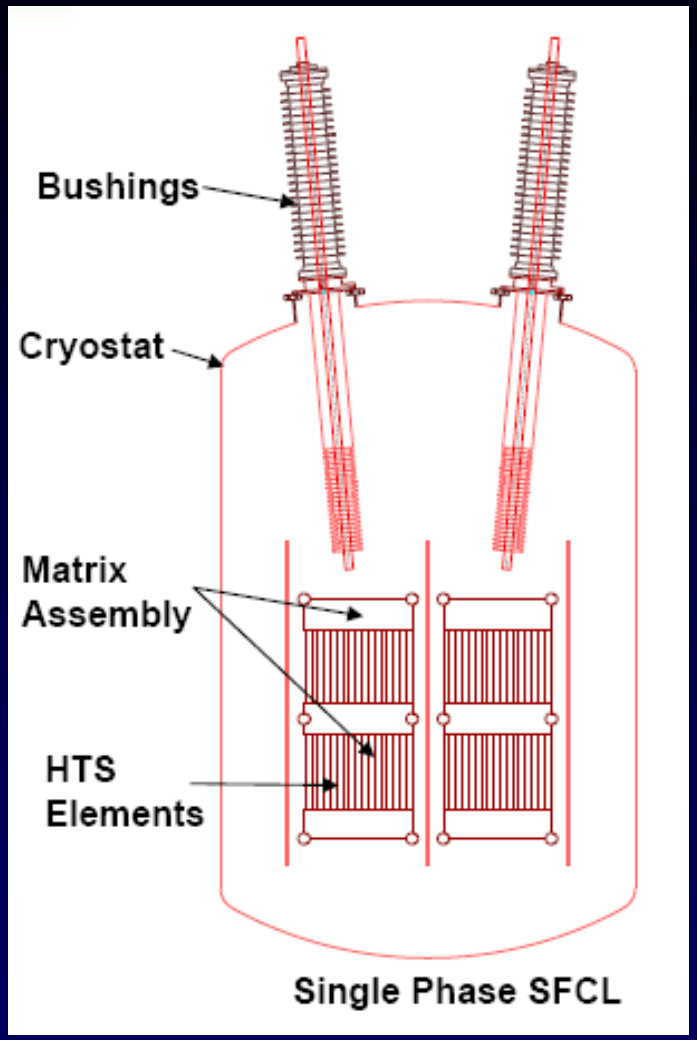
FCL – CIGRE Testing Recommendations

- Dielectric Tests
  - ac Power Frequency Withstand Voltage
  - Standard Lightning Impulse
- Temperature Rise Tests
  - Continuous Current Carrying
- Short-time (1 to 3 sec) Withstand Current Tests
  - Electrodynamic
  - Thermal capability
- Breaking / Making Tests
  - Just below minimum tripping value
  - Just above minimum tripping value
  - Maximum rated breaking current
- Endurance Tests
- EMC Tests

FCL Test Program Development - SuperPower

- Began work with SuperPower in 2003 to acquaint utilities with the new HV SFCL technologies.
- Visited with six NEETRAC member utilities during 2003 to understand potential HV SFCL applications and requirements.
- Project launched in 2004 funded by NEETRAC utilities to develop a recommended acceptance dielectric testing program for SuperPower's 138 kV SFCL.

FCL Test Program Development - SuperPower



Alpha Device

138 kV

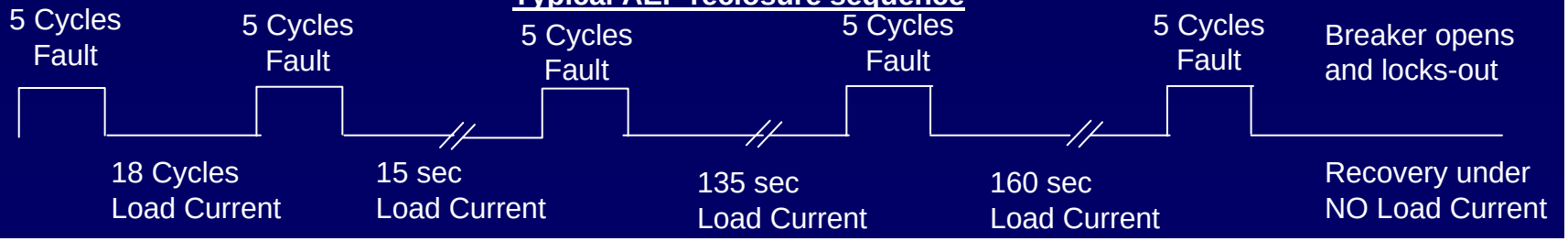
Single Phase

No Power Electronics or Aux equipment

SFCL Alpha Design Parameters	
System Parameters	
Voltage [kV rms]	80.0
Load Current [A rms]	1200.0
Short Circuit Fault Current [kA rms]	**14.0**
Short Circuit Fault Current [kA peak]	**37.0**
X/R ratio	30.0
Fault Duration [cycles]	5.0

The device is intended to handle the full reclosure sequence with a stuck breaker as the worst case condition.

Typical AEP reclosure sequence



FCL Test Program Development Process

- Review dielectric requirements of existing standards for circuit breakers, transformers, and reactors.
- Circuit Breakers ANSI/IEEE C37.06

Table 4 —Preferred dielectric withstand ratings and external Insulation (1)

Line No.	Rated Maximum Voltage kV, rms	Rating Table No.	Dielectric Withstand Test Voltages						
			Power Frequency		Impulse Test 1.2 × 50 μsec wave (a)			Switching Impulse	
			1 Minute Dry kV, rms	10 Second Wet kV, rms	Full Wave (2) Withstand kV, Peak	Chopped Wave kV, Peak Minimum Time to Sparkover		Withstand Voltage Terminal to Ground With Breaker Closed kV, Peak	Withstand Voltage Terminal to Terminal on One Phase with Circuit Breaker Open kV, Peak
						2 μsec Withstand	3 μsec Withstand		
	Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9
1	4.76	1	19	(3)	60	(3)	(3)	(3)	(3)
2	8.25	1	36	(3)	95	(3)	(3)	(3)	(3)
3	15.0	1	36	(3)	95	(3)	(3)	(3)	(3)
4	15.5	2	50	45	110	142	126	(3)	(3)
5	25.8	2	60	50	150	194	172	(3)	(3)
6	25.8 (4)	2	60	50	125	(3)	(3)	(3)	(3)
7	27.0	1	60	(3)	125	(3)	(3)	(3)	(3)
8	38.0	1	80	(3)	150	(3)	(3)	(3)	(3)
9	38.0	2	80	75	200	258	230	(3)	(3)
10	38.0 (4)	2	80	75	150	(3)	(3)	(3)	(3)
11	48.3	2	105	95	250	322	288	(3)	(3)
12	72.5	2	160	140	350	452	402	(3)	(3)
13	123	3	260	230	550	710	632	(3)	(3)
14	145	3	310	275	650	838	748	(3)	(3)

FCL Test Program Development Process

- Transformers ANSI/IEEE C57.12.00

Table 6—Dielectric insulation levels for Class II power transformers[a]

				Low frequency test levels		
Nominal system voltage (kV)	Basic lightning impulse insulation level (BIL) (kV crest)	Chopped wave level (kV crest)	Switching impulse level (BSL) (kV crest)	Induced-voltage test (phase to ground)		Applied-voltage test level (kV rms)
				One hour level (kV rms)	Enhancement level kV rms)	
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
15 and below	110	120	—	—	—	34
25	150	165	—	—	—	50
34.5	200	220	—	—	—	70
46	250	275	—	—	—	95
69	250	275	—	—	—	95
	350	385	—	—	—	140
115	350	385	280	105	120	140
	450	495	375	105	120	185
	550	605	460	105	120	230
138	450	495	375	125	145	185
	550	605	460	125	145	230
	650	715	540	125	145	275

FCL Test Program Development Process

- Reactors ANSI/IEEE C57.16

Table 5—Insulation test levels for dry-type air-core series reactors

Nominal system voltage (kV)	Applied voltage test (kV) rms	Turn-to-Turn overvoltage		BIL and full wave (kV) crest	Chopped-Wave (kV) crest	Time to flashover (μs)	Switching impulse (kV) crest
		Indoor (kV) rms	Outdoor (kV) rms				
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8
1.2	10	10	13	45	50	1.25	—
2.5	19	19	25	60	66	1.5	—
5.0	26	26	35	75	83	1.6	—
8.7	36	36	48	95	105	1.8	—
15.0	50	50	67	110	120	2.0	—
25.0	70	70	93	150	165	3.0	—
34.5	95	95	127	200	220	3.0	—
46.0	120	—	—	250	275	3.0	—
69.0	120	—	—	250	275	3.0	—
	175	—	—	350	385	3.0	—
115.0	175	—	—	350	385	3.0	280
	—	—	—	450	495	3.0	375
	280	—	—	550	605	3.0	460
138.0	—	—	—	450	495	3.0	375
	280	—	—	550	605	3.0	460
	335	—	—	650	715	3.0	540

138 kV Class ac Tests - SuperPower

Conditions	Values			
	Breakers C37.06, Table 4	Transformer C57.12.00, Table 6	Reactor C57.16, Table 5	Proposed SFCL
1 minute withstand (dry)	310 kV			310 kV
10 second withstand (wet)	275 kV			275 kV
Applied Voltage		275 kV	335 kV	
Induced Voltage Partial Discharge		125 kV for 1 hour, 145 kV for 120 s, 125 kV for 1 hour		125 kV for 1 hour, 145 kV for 120 s, 125 kV for 1 hour

138 kV Class BIL Tests (Lightning) - SuperPower

Conditions	Values			
	Breakers C37.06, Table 4	Transformer C57.12.00, Table 6	Reactor C57.16, Table 5	Proposed SFCL
1.2x 50µs	650 kV 3(+) & 3(-)	650 kV	650 kV 1 reduced & 3(+)	1 reduced full (650 kV), 2 chopped (715 kV- 3µs chop), 1 full (650 kV) (-) polarity
2µs chop	838 kV 3(+) & 3(-)			
3µs chop	748 kV 3(+) & 3(-)			
3µs chop		715 kV, 1 reduced full, 2 chopped, 1 full (-) polarity	715 kV, 1 reduced full, 1 full, 1 reduced chopped, 2 chopped, 2 full (+) polarity	

138 kV Class BIL Tests (Switching) - SuperPower

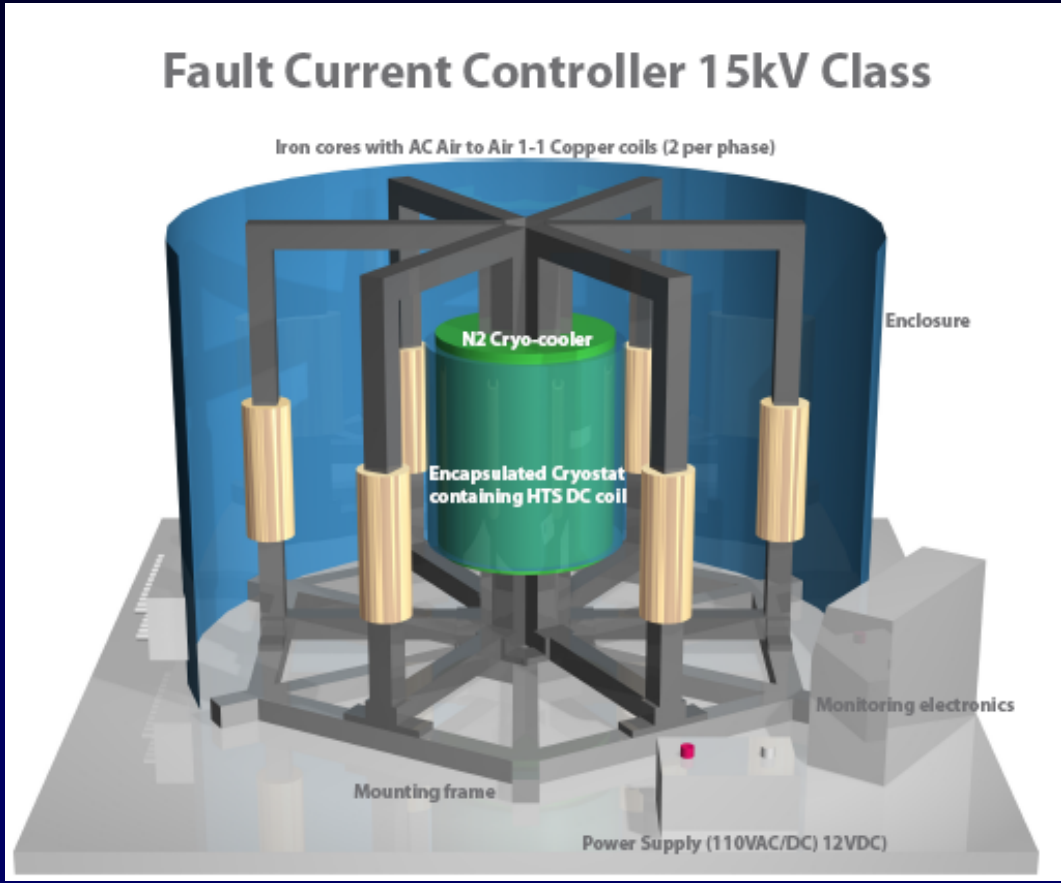
Conditions	Values			
	Breakers C37.06, Table 4	Transformer C57.12.00, Table 6	Reactor C57.16, Table 5	Proposed SFCL
250 x 2500μs	N/A	540kV 1 reduced, 2 full either (+) or (-)	540kV 1 reduced, 15 full (+) (2 disruptive discharges are allowed)	540kV 1 reduced, 2 full (+) 1 reduced, 2 full (-)

FCL Test Program Development – SC Power Systems

- Project launched in 2006 funded by NEETRAC members to develop a recommended acceptance testing program for SC Power's 15 kV SFCC.

- SC Power Systems saturable core FCC design will have dry type ac windings similar to a dry type transformer with porcelain external bushings in a NEMA 3R enclosure.

FCL Test Program Development – SC Power Systems



12.47 kV, three-phase ac device

BIL of 110 kV

Nominal current rating of 1,200A

FCL Test Program Development – SC Power Systems

- Transformers ANSI/IEEE C57.12.01

Table 5— Dielectric insulation levels for dry-type transformers used on systems with BIL ratings 200 kV BIL and below

Nominal L-L system voltages	Low-frequency voltage insulation level[a]	Basic lightning impulse insulation levels (BIL ratings) in common use kV crest[b,c] (1.2 × 50 μs)									
(kV)	(kV rms)	10	20	30	45	60	95	110	125	150	200
0.25	2.5	None									
0.6	3	S[d]	1[e]	1							
1.2	4	S	1	1							
2.5	10		S	1	1						
5.0	12			S	1	1					
8.7	19				S	1	1				
15.0	34					S	1	1			

15 kV Class Dielectric Tests – SC Power Systems

Test	Conditions	Values	
		Transformer C57.12.01, Table 5	Proposed SFCC
Applied Voltage	60 Hz	34 kV	34 kV
BIL Lightning Impulse	1.2x 50μs	110 kV (+)	110 kV (+)
Chopped Wave		110 kV, 1 reduced full, 2 chopped (1.8μs chop), 1 full (+) polarity	110 kV, 1 reduced full, 2 chopped (1.8μs chop), 1 full (+) polarity

Dielectric tests for the HTS coil are under consideration.

Temperature Rise Tests – SC Power Systems

- Thermocouples will be installed in the core and coil assembly to measure hot spot temperatures.
- Low voltage tests will be used to circulate full load current (1,200A) through the ac coils and measure corresponding temperature rise values.
- High voltage load tests will be performed at no load, 50A and 100A to check for model validation.

Fault Tests – SC Power Systems

- The FCC will undergo the following test sequence:
  1. Energized at 12.47 kV, no load
  2. 1,200A load applied for 20 cycles
  3. 10 kA prospective fault applied at V = 0 to obtain maximum asymmetry
- A one hour recovery time is required to allow the power laboratory load resistors to cool before the next fault with this I^2t.
- A three axis Hall probe (frequency response of 10 kHz) will be used to measure the fields at various locations under different loading and fault conditions. The probe data will be used to validate the finite element model.

Audible Noise Tests – SC Power Systems

- Measurements will be made with the FCC energized and under load to assess its audible noise performance.

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