HTS Fault Current Limiter Design Using Continuously Transposed Cable

A General Cable Superconductors White Paper

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Introduction

HTS 2G wire[1] is currently being used to build prototype fault current limiters (FCL) for the 13.8kV distribution system. Available wire for building FCL elements is 10-12mm wide. Since the current capacity of a 10mm wide strand is limited, many elements in a series/parallel combination must be employed in such prototypes. However, a Continuously Transposed Cable (CTC) made from 2G wire with 17 strands of 5mm width could carry 1500A-rms during normal operation. This report sizes FCLs using such a CTC for a 13.8kV, 3kA distribution system. Only two CTC cables in parallel are sufficient to carry the full rated current. Four bi-filer pancake coils are needed for each phase. This greatly simplifies the construction of the FCL system, reduces its size and improves reliability by reducing the number of components. The overall dimensions of a cryostat housing coils for all 3-phases is expected to be 1.3m in diameter and 2m high (without bushings). This package is expected to be considerably smaller than for the prototypes constructed using single wires.

Discussion

In order to demonstrate the feasibility of a FCL using a CTC cable, two FCL devices were sized to the specifications in Table 1. Each FCL is sized for a 13.8kV distribution grid and it carries 3kA-rms during normal operation. During a fault (short-circuit) the grid circuit experiences a fault current of 40kA. It is desired that this fault current be limited to 30kA for a period of 0.1s. The baseline FCL concept shown in Figure 1 uses an HTS FCL device in parallel with a conventional room-temperature inductor. A fast circuit breaker is included in series with the HTS FCL element to isolate it at the end of the fault period of 0.1s and allow it to cool down to its pre-fault normal operating temperature. A CTC consisting of 17 strands, 5mm wide (17/5), is assumed in this study. Other strand configurations might be preferred in the future depending on wire current capacity.

Design Analysis

The HTS FCL is based on the following major assumptions.

1. CTC is made of AMSC and/or SuperPower 2G wires
2. Each 17/5 CTC employs 17 strands, 5mm wide. More details of each manufacturer's strands as utilized in this study are described below.
3. Key constituents of the wires as envisaged for this application are listed in Table 2.

Table 1: Specifications for a 13.8kV, 3kA Fault Current Limiter

Parameter	*Value*
Rating, MVA	72
Line voltage, kV	13.8
Line current, kA	3
Unlimited fault current, kA	40
Limited fault current, kA	30
Fault hold time, s	0.1
Conductor type	CTC
- Number of strands	17
- Strand width, mm	5

[1] Also known as YBCO Coated Conductor

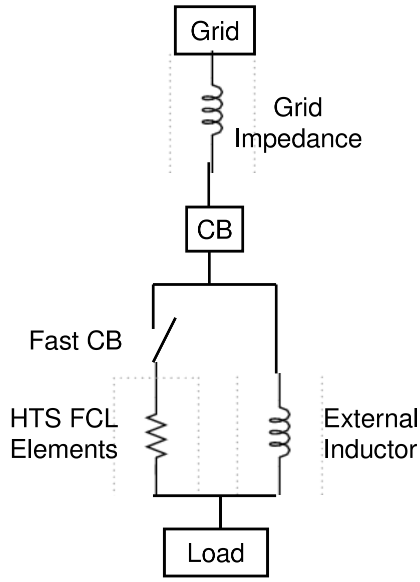

Figure 1: HTS FCL Concept with an external shunt inductor

During a fault of very short duration, it is not possible to remove significant thermal energy from the conductor surface. Due to this limitation, the analysis is based on an adiabatic temperature rise of CTC. It is further assumed that the maximum temperature of the CTC conductor be limited to 300K in order to avoid damaging the FCL coils by thermal stresses. To achieve this, it would be necessary to include additional material in the strands of the CTC.

In the case of AMSC wire, it is necessary to apply 120µm thick steel to each production wire. AMSC has developed a proprietary process in which they can sandwich their production wire between two stainless steel tapes and solder all layers together. The use of solder also requires that the maximum temperature of their wire be limited to <400K.

On the other hand, SuperPower production wire must be reinforced with a 127µm thick stainless steel tape for use in the FCL. Since SuperPower does not have a process to laminate thick stabilizer to their wire, it is necessary to develop alternative

Table 2: Details of AMSC and SuperPower Wires

Parameter	*AMSC*	*SuperPower*
Overall thickness of YBCO tape		
YBCO layer, µm	1	1
Nickel tungsten, µm	75	
Hastelloy, µm		100
Silver, µm	2.5	2
Additional material applied for FCL		
Stainless steel, µm	120	127
Solder, µm	20	
Overall strand thickness, µm	218	230

techniques. One possibility is to construct the 17/5 CTC using SuperPower bare wire and then sandwich it between two 64μm thick stainless steel tapes and wind the 3 elements together while constructing coils. This technique has been used successfully in the past. This approach could also be used for AMSC wire.

The design details of a FCL utilizing AMSC and SuperPower wires are summarized in Appendix A. On the basis of the specifications in Table 1, the HTS FCL circuit has to generate a resistance of 0.22Ω at the end of the specified fault period of 0.1s. The impedance of the inductor in parallel with the HTS FCL circuit is 0.073Ω. The FCL assembly is assumed to have 3-phases connected in a Y-configuration. A critical current of 300A/cm (self-field, 77K) is assumed for the 2G wire. The width of a 17/5 CTC is assumed to be 12mm and the turn-to-turn insulation width is 17mm. Thickness of a CTC with stabilizer is 2.3mm for AMSC strands and 2.4mm for SuperPower strands. The thickness of a spacer between turns is 3mm. This spacer is made of crinkled paper (currently used in conventional transformers) with a total build of 3mm. A distance of 20mm is maintained between adjacent coils during stacking of pancakes next to each other, The minimum piece length of CTC used in a coil is about 48m. The coils are of bifilar construction type wherein adjacent turns carry current in opposite direction as shown in Fig. 2. The maximum piece length of a CTC could be reduced to about 24m if two pieces of CTC are joined in the bore of a coil. Total length of CTC and strands required are ~590m and ~10km, respectively.

Design Details

A FCL assembly is shown in Figure 3. It houses HTS FCL components for all 3-phases only. An external inductor is not included in this package. The diameter of the cryostat is 1320mm and it is 2000mm high. The top of the cryostat has a tight fitting foam plug that separates the cold LN_2 region from the warm top flange. The top flange also houses six 15kV bushings. These are off-the-shelf conventional bushings. The distance between the cold LN_2 region and the top flange is about 800 mm and is considered sufficient to house current leads with one end at LN_2 temperature and the other end at near room-temperature at the lower end of the bushings. The LN2 is sub-cooled using a cooling approach which has been discussed in the white paper "Superconducting Transformers Using Continuously Transposed Cable"

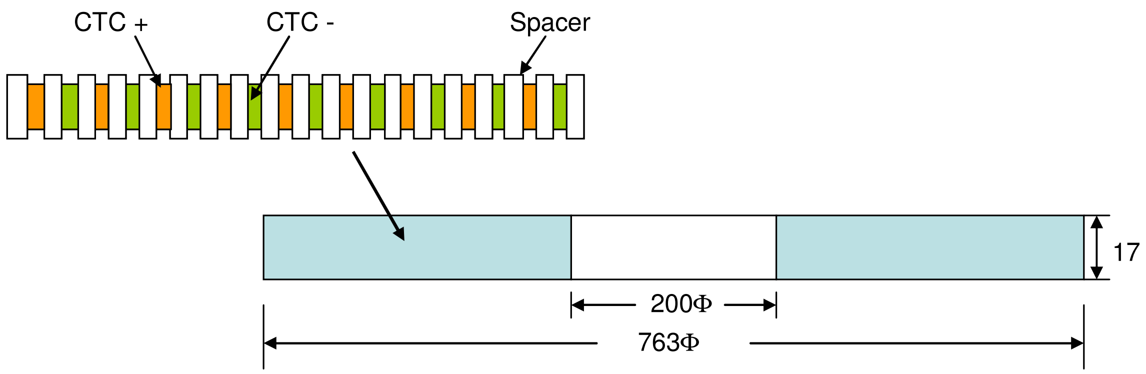

Figure 2: Cross-section of a bifilar pancake

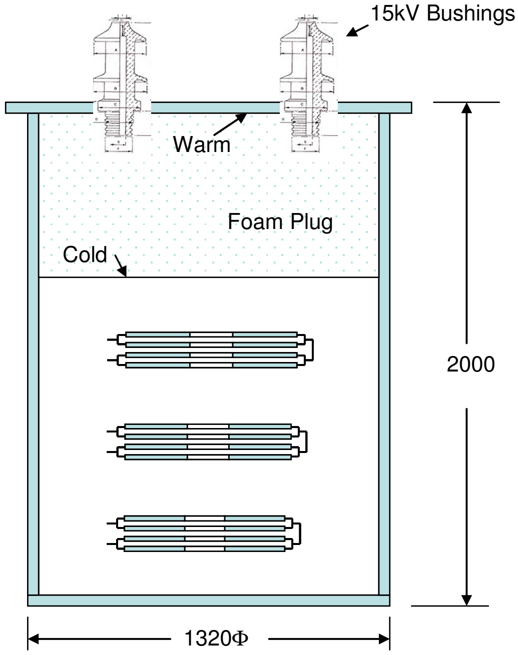

Figure 3: HTS FCL Assembly

Each phase assembly consists of 4 pancake coils; 2 in series and 2 in parallel. The connection arrangement is shown in Figure 4. Each coil is surrounded by a corona ring that has minor diameter of 31mm. A clear distance between coronal ring and the inside wall of the cryostat is 300mm, which is considered sufficient to withstand BIL voltage of 385kV.

Faults of 0.1s duration are simulated using the circuit configuration of Figure 1. Integration is performed as a function of time. Circuit currents and the HTS coil temperature are calculated. The temperature rise of the HTS coils is shown as a function of time in Figure 5 for AMSC and SuperPower wires. In both cases the peak temperature reached at the end of the fault period is 300K. Any cooling effect over this period will slightly lower the final temperature.

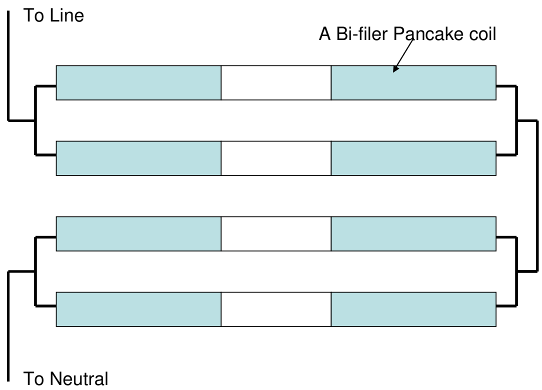

Figure 4: FCL HTS coil assembly for one phase

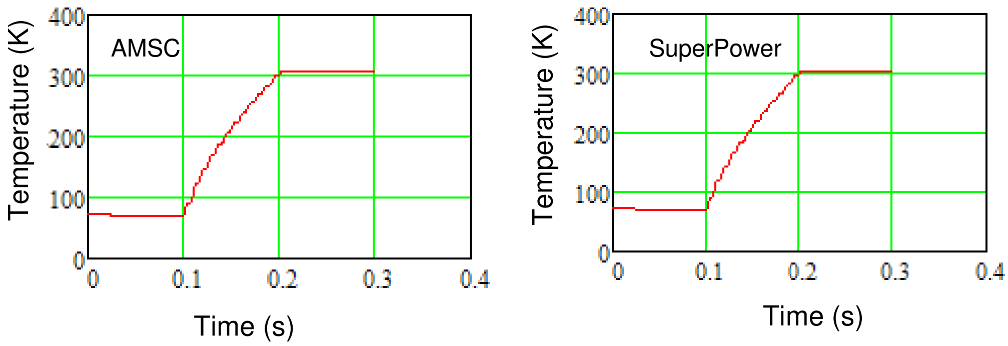

Figure 5: Temperature rise of HTS FCL coils during a 0.1s long fault
AMSC wire on left and SuperPower wire on right

Conclusions

CTC manufactured from 2G wire is an excellent choice for building fault current limiters. It reduces the number of individual coils to be built and thereby reduces the total package size. Utilities are particularly sensitive to the overall FCL assembly as it must fit in a restricted space in a substation. This FCL is designed for a distribution grid and is significantly smaller than others proposed. However, the most attractive application is at the sub-transmission and transmission levels (>138kV), where CTC based FCL will be most attractive. Alternative approaches will yield oversize devices which would be impractical to house in substations and will be very costly.

Appendix A: Design and Performance Parameters for CTC based HTS FCLs

HTS CTC - FCL, 13.8kV, 3kA	**AMSC**	**SuperPower**
Line Voltage, kV-rms	13.8	13.8
Normal current, kA-rms	3.0	3.0
System Impedance, ohm	0.075	0.075
Unlimited Fault Current, kA	40	40
Limited Fault Current, kA	9.6	9.6
Basis Insulation Level (BIL), kV	385	385
FCL Impedance at End of Fault, ohm	0.22	0.22
Fault Hold Time, s	0.1	0.1
Operating Temperature, K	72	72
Temperature at End of Fault, K	306	304
Wire Critical Current at 77K (A/cm), A	150	150
Wire (strand) Width, mm	5	5
Wire Layers		
HTS Layer Thickness, µm	1	1
NiW Thickness, µm	75	100
Silver Thickness, µm	2.5	2
Solder Thickness, µm	20	0.1
Stainless steel Stabilizer Thickness, µm	120	127
Maximum temperature limit at end of fault period, K	300	300
Effective Resistance of Non-HTS at Tmax, ohm/m	0.07	0.08
CTC Cable Specification		
Strand width, mm	5	5
Number of strands	17	17
Cable width, mm	12	12
Cable thickness, mm	2.3	2.4
Pancake Coil ID, mm	200	200
Pancake Coil OD, mm	604	591
Turns/pancake	38	36
Wire Length in a Pancake, m	48	45
Wire Length/phase, km	3.3	3.0
Wire Length/3-phase, km	9.8	9.1
Number of pancakes/ph	4	4
Width of a pancake coil, mm	17	17
Separation between pancakes, mm	20	20
Axial length of pancake stack/ph, mm	148	148
Voltage drop across a pancake, kV	1.04	1.04
Pancake in series/phase	2	2
Pancakes in parallel/phase	2	2
FCL Resistance at End of Fault, ohm	0.22	0.22
Shunt Current		
Just before the HTS coil is disconnected, kA-rms	28.0	28.0
After HTS coil is disconnected, kA-rms	29.3	29.3
Energy Dissipated/Phase, MJ	2.4	2.3