DESIGN ASPECTS OF HIGH TEMPERATURE SUPERCONDUCTING FAULT CURRENT LIMITERS

F J Mumford
ALSTOM Research and Technology Centre
PO Box 30, Lichfield Road, Stafford, ST17 4LN, England

INTRODUCTION

Increased demand for electricity and/or reorganisation of the power transmission system may lead to the need to reinforce the system. This may be achieved through interconnection of networks or increased transmission line voltage but can lead to fault current levels above the capability of existing switchgear. To replace all circuit breakers in regions of high fault risk by higher rated devices is generally not considered acceptable for three reasons. These are:

i) high estimated cost
ii) system reliability would be greatly reduced during the necessary long periods of construction
iii) breakers available today for replacement may themselves become inadequate

One possible solution is to install a current limiting device which offers a low impedance to load current and high impedance to fault current.

The requirements for such a device are that it should be faster in operation, and have the potential to keep fault currents lower than obtainable using existing switchgear. Furthermore, there is a need for the current limiter to recover rapidly from system transients under normal and fault conditions.

Potential benefits include alleviation of the need for over-design of power transmission cables, switchgear, transformers and generators (either conventional or superconducting), and up-rating of existing power transmission systems.

Superconducting-type fault current limiters (SCFCL) meet the requirements outlined above and offer additional benefits: they are self-regulating in the event of a fault and are fail-safe (a loss of superconductivity would result in the automatic introduction of a high impedance into the system). The four most promising SCFCL designs that have received the most attention are the resistive, saturated inductive, shielded inductive, and hybrid (electronic/inductive) types.

Since their discovery in 1986, superconducting metal oxides, so-called high temperature superconductors (HTS), offer even greater technical and economic benefits for current limiting. Conventional metallic superconductors, now referred to as low temperature superconductors (LTS) need to be expensively cooled with liquid helium at 4.2K and therefore have an operating cost penalty. HTS material superconducts at the temperature 85K and above, and therefore can be operated in liquid nitrogen (77K), which is cheap and readily available.

ALSTOM is in the process of investigating the performance of a model demonstrator HTS shielded inductive current limiter with a nominal rating of several kVA. The main aim of this investigation is to demonstrate the rapid limiting during, and recovery time after a short circuit fault.

These different current limiter types are discussed below together with a brief report on the initial results of the ALSTOM model demonstrator.

RESISTIVE SCFCL

Superconductors have the unique property that they may be switched rapidly from a superconducting state to a normal resistive state. This may be achieved either through the application of a transport current greater than the superconductor critical current I_c, using a magnetic field to enhance the transition through the creation of screening currents, or application of heat energy to raise the temperature of the material above its critical temperature. This quick switching property has long been used for d.c. resistive SCFCLs. However, it was not until 1983, when low a.c. loss NbTi/CuNi low temperature superconducting wires became commercially available, that serious consideration could be given to exploiting this property in SCFCL devices for a.c. applications. (see Fig 1).

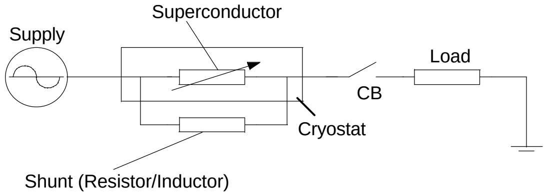

Fig 1: Resistive SCFCL with protective Shunt

Operation is based on the principle that if a fault occurs causing $I \geq I_c$, normal state resistivity is established and current limiting occurs (this process is referred to as a "quench"). Because of the high levels of current density in superconductors, there is a danger of over-heating and therefore careful attention must be given to protection of the current limiter. Inhomogeneity in the superconductor may result in localised normal state resistance being established during the onset of fault current and heating will occur. To prevent burn-out it is important that this localised normal zone rapidly propagates throughout the superconductor, thereby limiting the fault current and temperature rise. Normal zone propagation velocity is dependent on the electrical and thermal properties of the superconductor and surrounding materials. In LTS resistive type limiters the problem has been solved by careful design and several successful SCFCL demonstrators have been made, notably in France (GEC ALSTHOM, EdF, Alcatel Alsthom Recherche) and in Japan (Tokyo Electric Power Co. & Toshiba Corporation). However, SCFCLs operating at 4.2K are burdened with the technology and operating costs associated with using liquid helium.

Compared to other limiting devices a resistive type SCFCL using HTS material should in principle be simpler in design and operation, require less material and have a normal operating voltage drop of <1% of rated line voltage. However, the following comments are made:

- The current limiter conductor should not be sheathed with high electrical conducting metal (such as silver) as this would reduce the effective current limiting resistance per unit length.

- Thermal propagation velocities in HTS at 77K are very small in relation to LTS (due to a 2000 fold increase in specific heat at 77K over that at 4.2K) and could make switching to the normal state slow and difficult so that a lower operating temperature may be necessary.

- Control of superconducting tape or filament thickness will also be of particular importance in order to reduce the risk of localised normal zones.

- A critical current density $\geq 10^9 \mathrm{Am}^{-2}$ appears desirable to provide adequate switching times and reduced conductor volume but problems with overheating must be addressed. To prevent excessive heating of the superconductor when transporting a fault current, a circuit breaker must be opened within several cycles of the occurrence of the fault.

Heat ingress into the cryostat due to I^2R heating and thermal conduction in the current leads will lead to a significant refrigeration load even during normal passive operation of the SCFCL. However, refrigeration operating costs can be reduced by as much as a factor of 25 for an SCFCL operating at 77K compared with a device operating at 4.2K.

- Loss will be present in HTS wires (which should be non-inductively wound), but by careful design should be acceptably low.

- A resistive/reactive shunt will possibly be required to relieve heat load in the cryostat during fault limiting conditions.

- Finally, although resistive type HTS fault current limiter models with adequate switching times have been successfully demonstrated, many problems have to be overcome in the design and fabrication of HTS if they are to be used in power devices for current limiting. LTS, incorporating HTS current leads to reduce heat ingress to the cryostat, appear at present to be more suitable for resistive type SCFCLs.

SATURATED INDUCTIVE SCFCL

The saturated inductive superconducting fault current limiter, (Fig 2) operates on the principle that, as an inductive device goes into or out of saturation, its impedance changes by a significant amount.

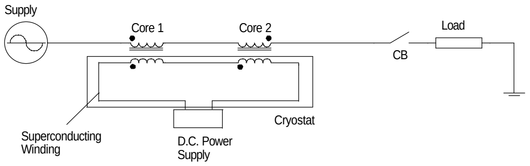

Fig 2: Saturated Inductive SCFCL

In order to achieve current limiting in both halves of a cycle, two inductive devices (inductors) are required per phase. These are driven into saturation by a d.c. bias field supplied by a superconducting coil. The a.c. line to be protected is therefore wound around two inductor cores. When a fault current flows, the large m.m.f. produced by the a.c. winding drives the core out of saturation on one half cycle, automatically inserting a large impedance and limiting the magnitude of the fault current. Limiting on the reverse half-cycle is achieved by the use of the second inductor connected in series with the first and is saturated by current in the opposite direction. To protect all three phases, six inductors are required.

The saturated inductive design is attractive because the superconducting component (the field winding) is external to the circuit being protected, the field winding current is d.c. and transition from normal to fault operation and vice versa is gradual and without interruption of the superconducting state of the winding.

Opening of a circuit breaker to protect the superconductor is not a requirement of this design which is therefore particularly attractive for overhead transmission networks when it is desirable to have automatic re-closing after faults. A successful prototype of this device, operating with an LTS field winding (4.2K) was built and tested by IRD Co. Ltd. and Parsons Peebles Power Transformers in 1982.

This device did not, however, reach the market place for several possible reasons including: high costs, requirement of a large volume of iron, and concerns including reliability and maintenance requirements associated with liquid helium refrigeration.

Replacement of the LTS wire with HTS wire would potentially result in both technical and economic benefits.

However, the following should be borne in mind:

- A large volume of iron and copper would still be required.
- Normal operating voltage across the limiter is ~4% of the normal rated line voltage so in normal operation the saturated iron core will have a relative permeability of about 5.
- The superconducting d.c. field winding will probably need to be protected against the electromagnetic fields of the a.c. windings so an electromagnetic screen will be required which will be a source of energy loss.
- Due to the large m.m.f. required to saturate the iron cores, the d.c. bias field at the superconducting field winding will be relatively high (2-3 Tesla). Because of the susceptibility to high magnetic fields of present HTS wires (BSCCO) at 77K, lower operating temperatures (20-30K) will be required.

HYBRID (ELECTRONIC/INDUCTIVE) SCFCL

This hybrid type of fault current limiter involves the use of fast power electronics to automatically switch an HTS inductive coil into the circuit to be protected at the onset of a short-circuit fault, see (Fig 3). The reactance of the coil limits the fault current to a predetermined level.

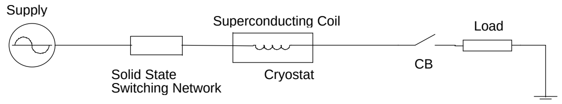

Fig 3: Hybrid (Electronic/Inductive) SCFCL

This device is being developed in the United States by a team consisting of Lockheed Martin, Southern California Edison, Intermagnetics General, and Los Alamos National Laboratory.

Operation is effected using a patented thyristor switch design (behaving as a diode bridge circuit under non-fault conditions) which is activated at a pre-set current threshold and passes the fault current through the superconducting coil. The device is activated within half a cycle of the onset of a fault occurring and the limited current may be sustained for an arbitrary length of time or switched off at the first current zero crossing.

The coil remains superconducting during steady-state and fault limiting conditions with little rise in temperature (several degrees K).

Cooling of the coil is achieved using helium (liquid/gas) which reduces the temperature to about 30K or less. This is necessary because the critical transport current of present HTS (BSCCO) wires and tapes is degraded in the presence of magnetic fields at temperatures above about 30K.

SHIELDED INDUCTIVE SCFCL

This device, (Fig 4), consists of an iron core, a primary copper winding in series with the circuit to be protected, and a shorted turn superconducting secondary (cylinder) housed in a non-conducting (to avoid eddy current heating) annular cryostat.

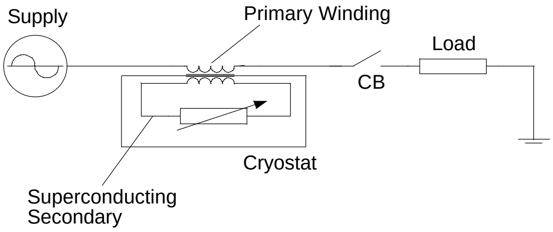

Fig 4: Shielded Inductive SCFCL

Because the primary winding in this device is usually wound over the superconducting cylinder, the superconductor is commonly referred to as a magnetic shield or screen, preventing primary winding flux from entering the iron. It may also be visualised as a transformer with a shorted secondary winding with a single turn. For normal operation, the ampere-turns in the coil are balanced by the induced current in the superconductor and the SCFCL behaves as a low impedance device. During a fault situation the ampere-turns balance is destroyed, flux enters the iron and a high impedance is inserted in the circuit to be protected. In accordance with transformer theory, the relative magnitude of the superconductor resistance will determine whether the limiter impedance is predominantly reactive or resistive.

The shielded inductive design requires superconducting properties that can be achieved today with HTS materials operating at 77K.

Current may also be limited to near the maximum nominal value allowed and hence switchgear ratings could be substantially reduced. Also of importance, the transient process of current limiting and recovery time to the superconducting state may be completed within the time taken for a circuit breaker to open and reclose (i.e. ~0.3 seconds). This would enable existing outage times due to a momentary fault to be maintained.

By design, the voltage generated by leakage flux can be kept below 1% of the nominal rated line voltage.

The quality of performance of superconducting material for a shielded type SCFCL may be expressed in terms of the resistivity ρ, and the product $J_c t$, where J_c is the critical current density of the superconductor and t is its thickness. ρ is important for controlling the impedance of the SCFCL during current limiting. A relatively substantial secondary winding resistance is required to destroy the ampere turns balance. The $J_c t$ product determines the level of shielding (ampere turns balance/unit length of the superconducting cylinder). J_c is a property of the superconductor, hence t is the main variable for controlling B_P (the peak value of external flux density for which flux just penetrates the material thickness).

Using bulk HTS cylinders, thicknesses of the order of tens of millimetres are possible. However, the material's thickness will influence heat transfer rate and the recuperation time of the superconductor after a fault has been cleared; during current limiting the superconductor will be in a resistive state and the heat generated must be dissipated quickly if overheating is to be avoided. This problem has been evident in most SCFCL models operating with bulk cylinders demonstrated to date and it has been necessary to remove the fault current after several cycles in order to avoid possible burn-out. Furthermore, bulk HTS cylinders are inherently brittle and would be particularly fragile given that large diameters will be required for large power applications. Thick film HTS coated onto a cylindrical substrate such as yttria stabilised zirconia (YSZ) or MgO would improve the mechanical integrity and provide better control of the superconductor resistance during limiting. A thick film of superconductor <1mm will substantially improve the heat transfer characteristic and enable the temperature to be maintained at a controlled level.

Joule heating in the cryostat of this type of limiter is considered to be lower in normal and in fault operation than a resistive type of SCFCL.

The shielded inductive type of limiter, like the saturated inductive SCFCL, requires a relatively large volume of iron. With careful design optimisation this can be minimised.

PRELIMINARY RESULTS FOR THE ALSTOM MODEL DEMONSTRATOR

ALSTOM's philosophy for a fault current limiter is that it should protect power transmission systems and circuit-breakers by rapidly limiting fault currents to a safe level; that the limiting process and recovery time of the device, should be within the time taken for a circuit-breaker to open and reclose following a momentary fault. The materials used to make a limiter must be robust and cost effective.

ALSTOM considers that the shielded inductive type of SCFCL offers the potential to achieve these requirements and has constructed a small model demonstrator for investigation. Fig 5 is a schematic diagram showing the main components of the SCFCL.

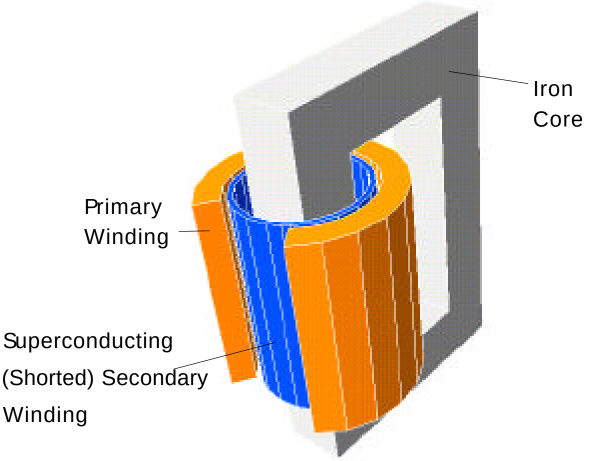

Fig 5: HTS Fault Current Limiter – Shielded Inductive Type

The shorted secondary winding comprises five cylinders of stabilised YSZ insulated substrate (125mm high, 133mm diameter and 6mm thick) coated with a 100 micron layer of yttrium-barium-copper oxide (YBCO) superconductor [1]. The conductors are cooled in liquid nitrogen at 77K.

Details regarding a preliminary test, with limiter operation at half power rating design, are given below in Fig. 6 and Table 1.

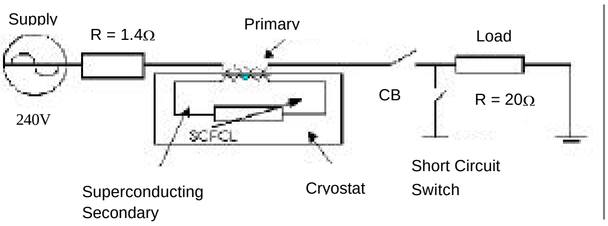

Fig 6: Fault Current Limiter Test facility – Circuit Diagram

Normal Operation	
Nominal Circuit Current I_N	11.2 $A_{r.m.s.}$
Nominal Circuit Current, $\hat{I}_N$	15.8 A_{peak}
Supply Voltage, V	240 $V_{r.m.s.}$
No. of Turns, Primary Winding	136
Secondary Winding Current (5 Superconducting Cylinders)	~1.5 $kA_{r.m.s.}$
Nominal Rating	2.7 kVA
Fault Operation	
Fault Duration	60 msec (3 cycles)
'Unlimited' Fault Current, $\hat{I}_{UN}$	242 A_{peak}
Limited Fault Current, $\hat{I}_F$	128 A_{peak} (after half cycle)
	26.6 A_{peak} (after one cycle)
	~15 A_{peak} (after three cycles)
Current Ratios, $\hat{I}_F$ / $\hat{I}_N$	8.1 (half cycle)
	1.7 (one cycle)
	~1 (three cycles)

Table 1: Operating Parameters and Results of SCFCL Test

The ability of the SCFCL to effectively limit a short-circuit fault current has been demonstrated with encouraging results.

However, with reference to Figure 7 it is evident after removal of the short-circuit and re-insertion of the load resistance, that the limiter has not fully recovered its initial state of low impedance. The line current is in a steady state and is below the nominal operating level. This implies that the superconductor is still in a resistive state and in thermal equilibrum with the liquid nitrogen. There is no evidence of thermal runaway or excessive heating in the superconductor. However, to regain the superconducting state, the current must be interrupted for a period of a few tens of milliseconds [2] - well within the reclosing time of a circuit-breaker (which opens after three cycles).

The cause of the observed 'residual' limiter impedance, after removal of the fault current, is related to the relative values of the secondary (superconductor) resistance, and primary and secondary inductances of current limiter. Previous experience with a smaller shielded inductive SCFCL has shown that recovery times of a (few milliseconds are possible without the need to break the circuit [3].

This work is continuing and will be reported on at a later date.

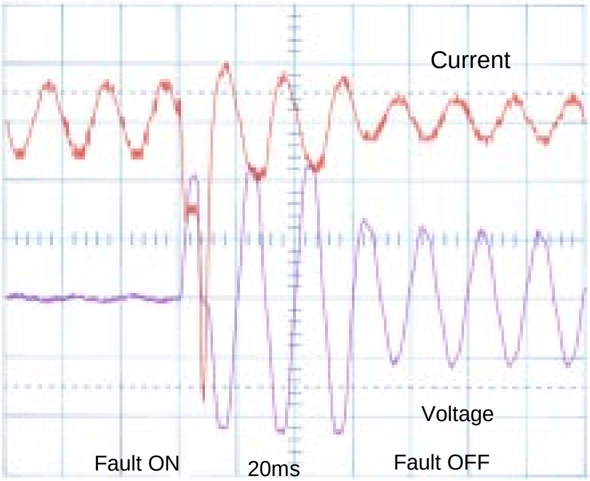

Fig. 7: Fault Current Limiter Current/Voltage Waveform

COMMENTS

Table 2 is a summary of the major parameters of the four SCFCLs discussed.

Of the four types of current limiter described, the shielded inductive type is proving to be most popular. ABB has recently demonstrated a successful 1.2MVA three phase shielded-type inductive HTS current limiter at a hydro-electric plant in Switzerland [4]; Siemens has demonstrated a single phase 100 kVA resistive type of HTS limiter [5].
The future of superconductivity to power applications looks brighter now than at any time in the past. The advent of HTS has been a major contributor to this situation. The potential to operate superconductors stably at the temperature of liquid nitrogen (77K) is particularly attractive. Being available as a thick film on substrate and in bulk monolithic form, has further extended the existing range fault current limiter designs.

Control of the current limiting process, together with the availability of suitable superconductor and substrate in terms of performance and costs, are the key requirements for the future success of SCFCLs.

ACKNOWLEDGEMENTS

ALSTOM acknowledges the support of National Grid Company for its model demonstrator current limiter investigation.

REFERENCES

1. C Meggs et al. "HTS Thick Film Components for Fault Current Limiter Applications" presented at the Applied Superconductivity Conference, Palm Desert, USA, September 1998.

2. Y Shirai et al, "Recovery Characteristics of Fault Current with Adjustable Trigger Current Level", presented at the Applied Superconductivity Conference, Palm Desert, USA, September 1998.

3. F J Mumford. "Superconducting Fault Current Limiters" Colloquium on Fault Current Limiters – A Look at Tomorrow, IEE, London, 8 June 1995.

4. W Paul et al. "Test of a 1.2MVA High-T_c Superconducting Fault Current Limiter", Proceedings of EUCAS 1997, Third European Conference on Applied Superconductivity, The Netherlands, 1997, p 1173-1178.

5. B Gromoll et al. "Resistive Fault Current Limiter with YBCO Films – 100kVA Functional Model", presented at the Applied Superconductivity Conference, Palm Desert, USA, September 1998.

	Resistive	**Saturated**	**Shielded**	**Hybrid**
Self activating	yes	yes	yes	yes
Fail safe	yes	yes	yes	yes
Operating temperature	4.2-77K	4.2-30K	77K	4.2-30K
Relative weight for same rating	0.1	1	≤1	<1
Switching-on time	≤1ms possible	no delay	<1ms possible	≤8mS
SCFCL recovery time after fault	0.5 - several seconds	no delay	1ms possible using thick film	≤800mS
Circuit breaker opening absolutely necessary	probably	no	no	no
Shunt impedance required	probably	no	no	no
Operating voltage drop SCFCL to line voltage %	<1%	~4%	<1%	<1%
Current leads required	yes	yes	no	yes
Superconductor directly connected to protected circuit	yes	no	no	yes
High voltage bushings required	yes	no	no	yes

TABLE 2 Major SCFCL Parameters