INDUCTIVE SHIELDED SUPERCONDUCTING FAULT CURRENT LIMITER – AN ENABLER OF SMARTER GRIDS

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ABSTRACT

Making future grids smarter - green fields as well as existing distribution grids - a self activating, fail safe, cost efficient solution for advanced current limitation will be a key element of the solutions portfolio.
This paper describes the showcase of the iSFCL, an inductive shielded high temperature superconducting fault current limiter based on 2G-YBCO-superconducting material. The nominal current path does not go through the cryostat, so that the cooling costs are significantly reduced. The physical behaviour of the superconducting coil in normal and quenching modes, the advanced design and the industrialization of such a design are described. In addition the paper reports on the planned 3-phase-field trial, a full scale showcase in the distribution grid of the utility Stadtwerke Augsburg in Germany.

INTRODUCTION

The distribution grid of the future will move from unidirectional power flow (Fig. 1) towards bidirectional power flow (Fig. 2). To achieve this, major challenges have to be met:
- integration of distributed generation
- highly meshed network structures
- fast disconnection and reconnection of network segments

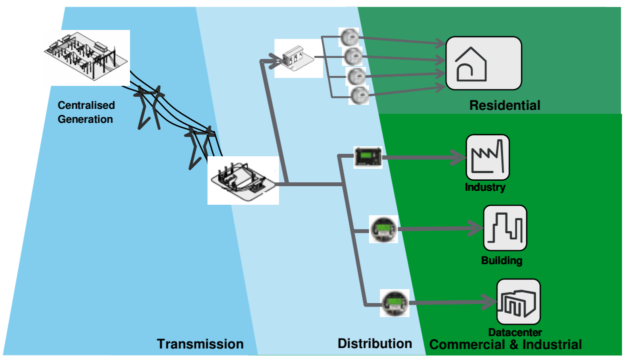


Fig. 1: Conventional Grid Structure with unidirectional power flow

These developments will lead to additional requirements of the switchgear installation which will have to be designed not only to accommodate service conditions but also failure conditions.

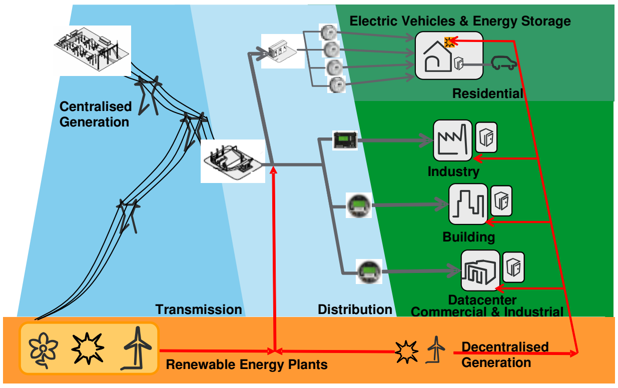


Fig. 2: Advanced Grid Structure with bidirectional power flow

One solution to this dilemma is the acceptance of increased short circuit power [1, 2] but this is directly connected with increased costs for the equipment needed. A more economic approach seems to be the search for technologies capable of limiting the short circuit current in case of a failure.

CURRENT LIMITATION

Fig. 3 shows simulated line to ground current limitation for 40 MVA distribution network with a prospective fault current of above 38kA. The current limiter is able to limit this current to 9 kA.

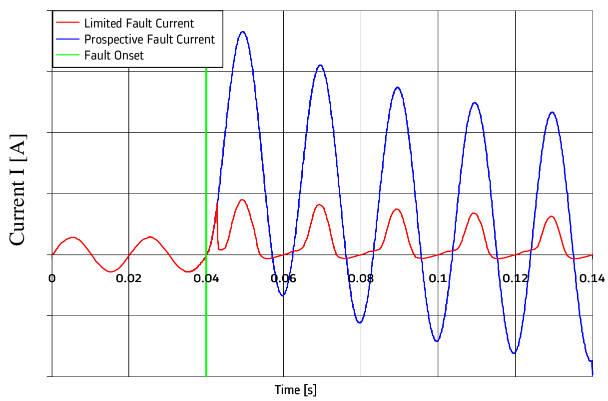


Fig. 3: Fault currents with and without an iSFCL (δ = 0º)

Fig. 3 shows line to ground current limitation for distribution networks. As seen in Fig. 3 the failure onset at 40 ms causes a prospective failure current. The current limiter is able to limit this value by a factor of 4.

Current Limitation Principles

Several current limitation principles are known. The most basic and effective principle is the use of an electrical fuse. A fuse can limit and switch-off a failure current. The major drawbacks are the electro-thermal losses in service and the need for a complete replacement after operation. Another technology is the use of air core reactors; here the dependency of the reactor impedance on the current through the reactor is used. A further alternative is the I_s-Limiter [3] or Pyro-Fuse. Here the fault current is electronically detected. In case of a deviation of the slope of the current, a pyro-cartridge will be fired. This explosive device will blow up a segment of the busbar and the failure current will be commutated to a parallel high rupture / high capacity fuse. Beside these industrial devices, several experimental approaches have been tested. In [4] a concept based on a current-zero-breaker with minimal moved masses and fast arc elongation is proposed. Other concepts use power-electronics. Also superconducting devices have been developed and tested [5]. The highest level of industrialisation has been reached for resistive current limiters with high temperature superconductor ceramics based on BSCCO [5, 6].

Application Requirements of Current Limiters

When considering the practical applications of current limiters, the application requirements must be defined. Firstly a current limiter must be able to limit a prospective short circuit current before it reaches the first peak. The faster the device acts, the lower the let-through-energy $E \sim I^2t$ will be. The device itself should have low impedance at normal operation, whereas in failure mode high impedance is required. Preferably the device will be self-activating, having a direct response to the fault current. In case of a failure of the limiting device itself, the distribution network should stay in operation mode. The limiter should be fail-safe. As well as having low service and maintenance costs, the device should be able to perform multiple operations.

Comparison of Different Current Limitation Principles

The following technologies are compared in Table 1:
- A: Electrical fuse
- B: Air core reactor
- C: I_s-Limiter / Pyro-Breaker
- D: Power Electronic Circuit Breaker
- E: Resistive Superconductive Fault Limiters.

Based on the results in Table 1, it can be stated that the major conflict is between costs and multiple operations. Here fuses and the I_S-Limiter technology have their major drawback. Beside the missing reclosing functionality, the operation of such devices in remote locations will have a major negative impact to outage times and the service continuity. A reset of the failed grid segment requires sending a maintenance team to the relevant switchyard.

Generally, high limitation performance is associated with high costs. In case of the I_S-Limiter this is mainly the maintenance cost of replacing a blown cartridge. The costs of resistive fault current limiters are mainly dominated by cooling costs and concerns with the complexity of cryostat design required to avoid high voltage breakdown during a current limiting scenario. Cooling costs are related to losses in the cryostat in normal service. Heat ingress into the cryostat results from thermal conduction down the resistive current leads connecting the superconducting windings at 77K with the network at a temperature of ~ 300K. Thermal conduction and Ohmic heating of the current leads will generate a significant heat load in the cryostat.

Table 1: Comparison of different current limiting technologies

Requirement	A	B	C	D	E
Limitation	+	+	+	+	+
Low operating impedance	-	-	+	-	+
High fault impedance	+	+	+	+	+
Self activation	-	+	-	-	+
Continuous operation at device failure	-	-	-	-	-
Multiple operations	-	+	-	+	+
Costs	+	+	-	-	-

THE INDUCTIVE SHIELDED SUPERCONDUCTING FAULT CURRENT LIMITER

Based on a long lasting research co-operation of Schneider-Electric and ALSTOM Grid (former AREVA T&D) with Bruker High Temperature Superconductors (Bruker HTS), the principle of the inductive shielded superconducting fault current limiter was developed, investigated and tested. After the hype of high-temperature superconductivity in the 80s and 90s, a sufficient maturity on the material technology, the cooling equipment and device design has been reached. In terms of the hype cycle (Fig. 4) we believe to climb on the “Slope of Enlightenment” and to reach the “Plateau of Productivity” within the next years.

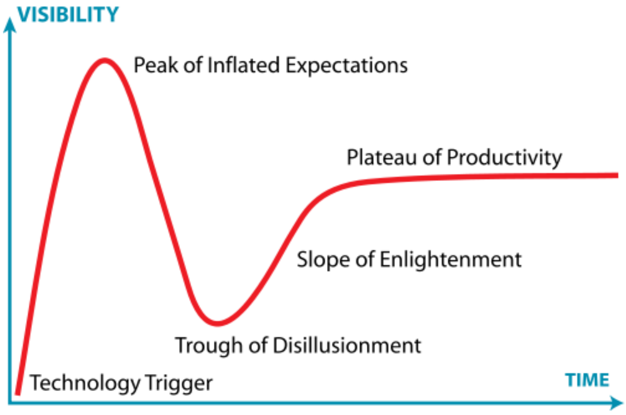
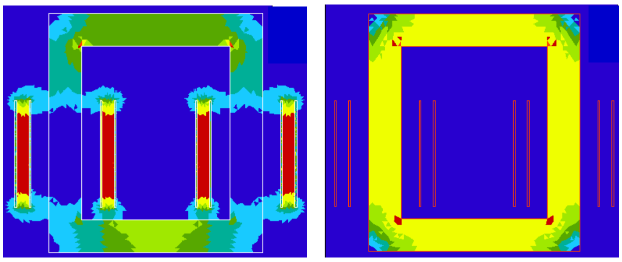


Fig. 4: The Hype Cycle according to [7]

Operating Principle and Prototype Mock-up

The iSFCL is basically a transformer comprising an iron core, copper primary winding and a single shorted turn superconducting secondary winding housed in a cryostat. (Fig. 6, 8). In normal service and assuming a theoretical 100% coupling, the ampere-turns of the primary winding are balanced by the induced current in the superconductor which exhibits virtually no resistance. All flux generated by the primary winding is excluded from the iron core. The iSFCL thus inserts very low impedance in the circuit to be protected. During a short circuit fault, the ampere-turns of the primary winding increase to a level above which the critical current, I_c, of the superconductor is exceeded and it becomes resistive [8]. Flux enters the iron core, large impedance is inserted in to the circuit and the fault current is limited.



a) Superconducting State   b) Non-Superconducting State

Fig. 5: Operation Principle of the iSFCL, Simulation done with the software package SLIM

Fig. 5 shows the magnetic flux density distribution in an iSFCL during normal service (superconducting state) and a current limiting scenario (non- superconducting, resistive, state). The device shown has the concentric primary and secondary windings split between the two limbs of the iron core.

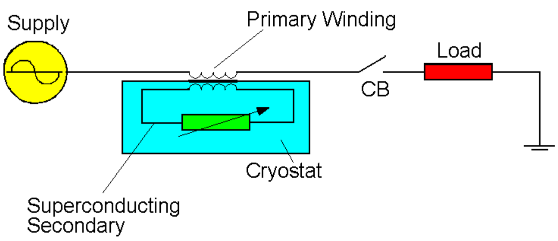


Fig. 6: Generic outline of an iSFCL with an energy source, a load and a circuit breaker

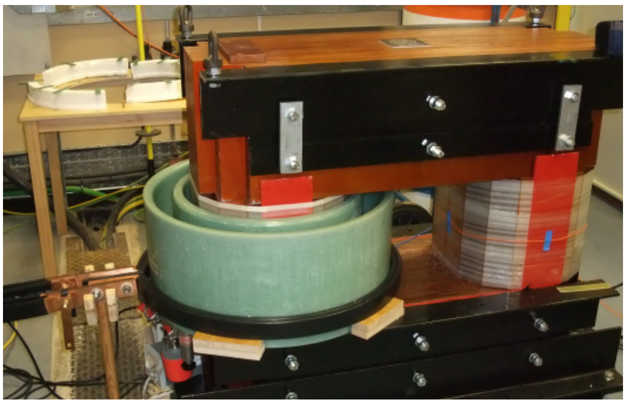


Fig. 7: iSFCL Test Module

Based on the principle of perfect ampere-turns balance between the primary and shorted secondary windings, the scheme of an iSFCL will look like Fig. 6, whereas the device, utilized for the first reference tests, is shown in Fig. 7. Fig. 8 shows the schematic outline of a single phase of an iSFCL.

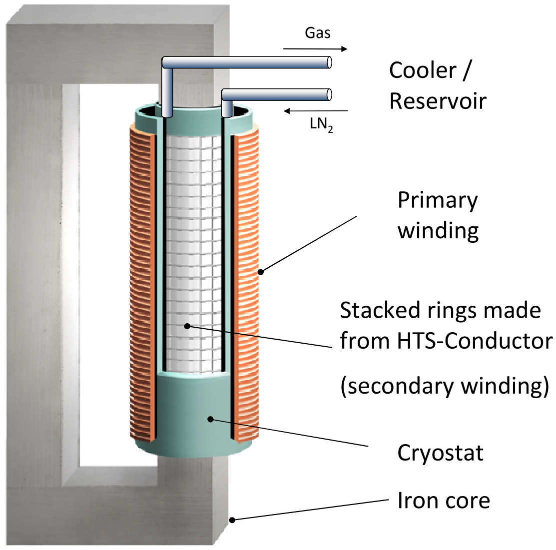


Fig. 8: Schematic outline of a single phase of an iSFCL

Results on a Single Module of a 13 MVA iSFCL

A one to one full scaled simulation circuit has been used to determine the performance of a 13 MVA (6.4kV, 2000A) rated iSFCL, see figure 8. A sequence of more than 100 short circuit events was successfully executed during these tests. Table 3 and Figure 9 shows the parameters and short circuit test result respectively for the iSFCL module (point on wave, $\delta = 0°$).

Table 3: Comparison of module and full scale iSFCL

Parameter	Full Scale Device	Single Module
Primary winding N1	140	1
Secondary turns N2	1	1 (slice)
Phase Rating	13MVA – 6.4kV/2000A	13MVA/N1 = 93kVA
Operating Current	2000A	2000A
Fault voltage per turn N1 & N2	45V	45V

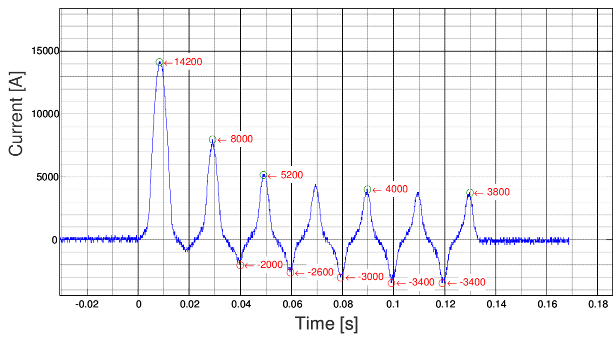


Fig. 9: Short circuit test result for the iSFCL module (point on wave, δ = 0º)

Technology Comparison

It can be stated that the iSFCL solves two key issues of the resistive SFCL. In case of a failure in the cryostat, the resistive type will cause a complete break down of the main current path. A costly solution might be given by a bypass with two full sized circuit breakers. However the iSFCL can stay in continuous service during a cryostat failure as the primary winding will not be affected. As the design-intrinsic cooling costs of the iSFCL are significantly reduced, it is sought to establish a trial project to demonstrate that the overall costs will be highly competitive as well.

Table 2: Comparison of different current limiting technologies including the iSFCL

Property	A	B	C	D	E	F
Limitation	+	+	+	+	+	+
Low operating impedance	-	-	+	-	+	+
High fault impedance	+	+	+	+	+	+
Self activation	-	+	-	-	+	+
Continuous operation at device failure	-	-	-	-	-	+
Multiple operations	-	+	-	+	+	+
Costs	+	+	-	-	-	(+)

A: Electrical fuse B: Air core reactor C: I_s-Limiter / Pyro-CB
D: Power Electronic CB E: Resistive SFCL F: iSFCL

THE AUGSBURG FIELD TRIAL

Based on the successful trials with the prototype, a next step was planned. Combining the know-how of a market leader in distribution equipment with the leading manufacturer of 2G high temperature superconductors and cryo-infrastructure will generate a setup to continue towards a full scale device of the iSFCL. Teaming up with Stadtwerke Augsburg, a local German utility, known for its affinity to new technologies lead to the field trial project.

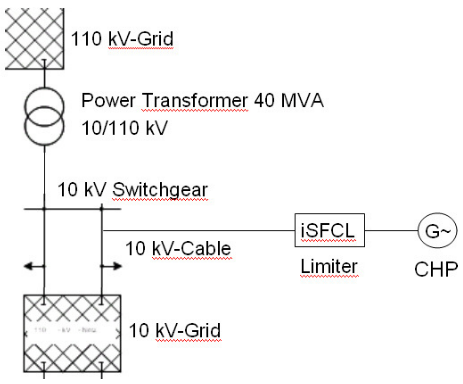


Fig. 10: Network integration of an iSFCL

The network setup combines a local industrial network with the utility network (Fig. 10). The substation of the network consists of a 110 kV incomer from the upstream transmission grid, a 40 MVA transformer (110/10 kV), and a 10 kV distribution grid. The industrial customer is serving a motor test plant for medium and large diesel and gas driven motors, generating electrical energy, feeding into the utility network, like a CHP-plant. This CHP-plant is directly connected to the 10 kV switchgear of the substation. Today an air-core-reactor is providing the protection in case of a short circuit.

This test plant will undergo a 2-step-extension in the next years. Therefore also the air core reactor needs to be changed, a good opportunity to test the new iSFCL. Utilising the iSFCL, two network scenarios are covered. In case of a failure close to the generator the iSFCL will limit the I_{SC} coming from the utility network. In case of a failure on the utility side, the iSFCL will limit the additional I_{SC} generated by the test plant. The second scenario covers one of the potential smart grid scenarios for the short circuit limitation in grids with a high energy contribution by distributed generation. The technical parameters of the targeted technical device and project requirements of the field trial device are shown in Table 3. Field testing of the new device is planned to start end of 2012.

Table 4: Technical parameters of the iSFCL for the Augsburg Field Trial

Targeted Device Ratings			
U_r	12 kV	I_r	1250 A
P_r	15 MVA	I_{SC}	25 kA
Limitation Factor		1st peak	5
		continuous	12
Project Ratings			
U_r	10 kV	I_r	817 A
P_r	15 MVA	I_{SC}	8,5 kA
Limitation Factor		1st peak	4
		continuous	4

ACKNOWLEDGEMENT

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