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First Commercial Medium Voltage Superconducting Fault-Current Limiters – Production, Test and Installation

R. Dommerque[1], S. Krämer[1], A. Hobl[1], R. Böhm[1], M. Bludau[1], J. Bock[1], D. Klaus[2], H. Piereder[2], A. Wilson[2], T. Krüger[3], G. Pfeiffer[4], K. Pfeiffer[4], S. Elschner[5]

[1] Nexans SuperConductors GmbH, Hürth, Germany
[2] Applied Superconductor Ltd, Blyth, UK
[3] Vattenfall Europe Generation AG, Cottbus, Germany
[4] Brandenburgische Technische Universität, Cottbus, Germany
[5] University of Applied Science, Mannheim, Germany

Achim.Hobl@nexans.com

Abstract. In 2008/09 Nexans SuperConductors GmbH made the step from R&D activities to the production of the first non-publicly funded fault-current limiter units. In close cooperation with two customers, Applied Superconductor Limited (ASL, UK) and Vattenfall (Germany), Nexans was able to design, produce and deliver two resistive superconducting limiter devices. Both devices are designed for the medium voltage grid and were tested at the high-voltage and high-power lab IPH in Berlin. The superconducting components of both limiters, coils of bulk MCP BSCCO-2212, have been designed and produced by Nexans.

1. Introduction

Resistive superconducting current limiters [1-3] are expected to be one of the first technically and economically viable applications of high temperature superconductors. Nexans SuperConductors GmbH has already reported about several developments and different types of HTS-components on the basis of BSCCO-2212 [3-6]. The main objective was the development and manufacturing of a superconducting component especially designed for the use in resistive fault-current limiters (FCL).

The design of the component has to be both, very flexible to allow an easy adaptation to the specific requirements of each particular application, and very robust to enable building a reliable system from a larger number of such components. Therefore it is necessary to produce superconducting components at a larger production rate and a high quality standard with reproducible properties.

On the basis of the successful project CURL 10 [3] two commercial projects for electric utilities could be realized, entire 3-phase medium voltage fault-current limiters, which were designed, manufactured, successfully tested and commissioned. In the following they are referred to as “Project 1” and “Project 2”.

For the first project, Nexans provided the cryostat, superconducting circuits, current leads and sensors for condition monitoring. The cooling system, auxiliary circuit-breaker, voltage transformers and protection, control and monitoring equipment were provided, assembled and tested by ASL.

In Project 2 the Nexans scope of supply included the entire auxiliary equipment together with the control and protection system, cooling system and weather-proof container for straightforward installation into the grid under the strict requirements for medium voltage power equipment in a power station.

2. Requirements and Specifications

Superconducting fault-current limiters can be used for different applications [7,8] in medium and high voltage networks. The most attractive applications are busbar couplings [8] and in-line connections. With classical means it is difficult to couple busbars, because the short circuits of the coupled busbars add up in case of a fault in one of the circuits. Due to such high short-circuit currents the ratings of other equipment used can easily be exceeded. By introducing a fault-current limiter the current in the coupling can be restricted to the ratings of the limiter. When connecting the fault-current limiter in-line, the rating of surrounding equipment can be reduced with respect to the unlimited case, leading to substantial cost-reduction potential. Project 1 is a busbar configuration, whereas project 2 is an application with in-line connection.

2.1. Requirements and Specifications of Project 1

Project 1 is installed at a site where a recent upgrade of transformers led to fault current levels above the capacities of existing circuit breakers. This problem was solved by introducing new switchgear equipment, but the site is since then ideal to test the FCL designed to maintain all fault levels below the ratings of the former equipment.

This project was undertaken at the request of Applied Superconductor Ltd. (ASL) and its partners CE Electric UK, Electricity North West and Scottish Power Energy Networks.

The SFCL, which is deployed in a bus-section configuration, effectively in parallel with the existing bus-section circuit-breaker (which will be left open during the trial) must limit the fault contribution, from the healthy to the faulted busbar when a fault occurs on an outgoing circuit. This contribution, together with the contribution from the transformer directly feeding the faulted bar, must not exceed 95% of the rating of the old switchgear, as shown in the figure 1 below.

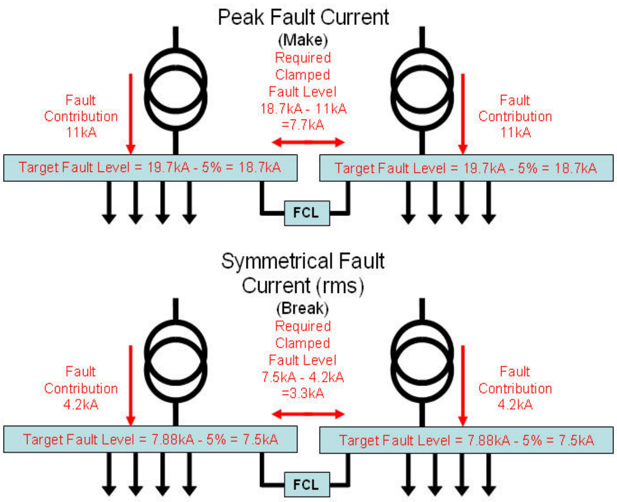

Figure 1. Schematic diagram of the Project 1 substation. The FCL in busbar configuration.

The characteristics of the FCL are given in table 1 below. It is remarkable that there are inrush currents that are a multiple of the nominal rating. The FCL must allow for 10 seconds current of up to 460 A without the initiation of a quench.

Table 1. Characteristics of Project 1 and Project 2.

Parameter	Project 1	Project 2
Rated voltage	U_r = 12 kV	U_r = 12 kV
Rated current	I_r = 100 A	I_r = 800 A
Inrush current	I = 460 A (10 s)	I = 4100 A_{peak} (50 ms) followed by1800 A_{rms} (15 s),
Prospective peak current	i_{peak} = 50 kA (R/X = 0.08)	i_{peak} = 63 kA (R/X = 0.08)
First peak limiting	i_p < 6 kA	i_p < 30 kA
Limitation time	t = 120 ms	t = 120 ms
Total loss	P = 150 W	P = 2 kW
Operating temperature	T = 73 K	T = 65 K

2.2. Requirements and Specifications of Project 2

The second project is in cooperation with Vattenfall Europe Generation AG in Cottbus, Germany. Vattenfall expects significant cost-reduction potential in using FCL in auxiliary power supply of huge power plants.

In this particular case the FCL is placed in the sub-distribution of the auxiliary power supply of the power station “Boxberg” in Saxony. In this application large electrical machines are downstream of the FCL setting demanding requirements to the limiter like high inrush currents. The placing of the limiter is shown in figure 2 below.

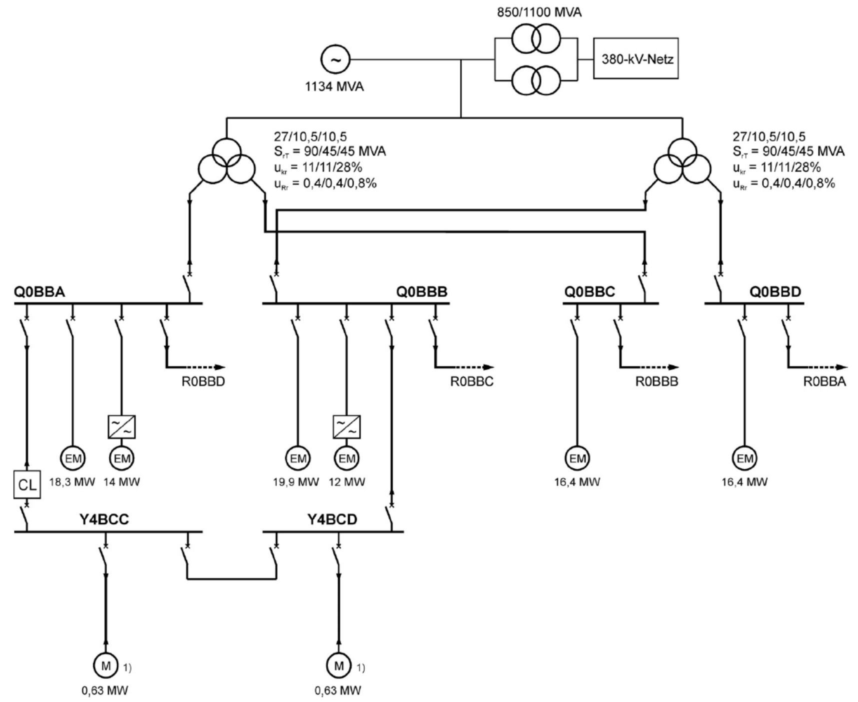

Figure 2. Project 2, schematic diagram of the power plant auxiliary supply. The FCL in in-line configuration. The limiter is represented by the [CL] box on the left side.

The specifications of the FCL are given in table 1 above.

3. Design of the Components

The superconducting components limit the fault current by transition to the resistive state. While resistive, the component acts like a normal resistor and is heated during the limitation time – 120 ms in this case – reaching high temperatures that also result in mechanical stress for the component, which is a composite of several materials selected for their mechanical and electrical properties. To avoid damage to the materials, only a limited amount of energy can be absorbed. Since the FCL is voltage-driven during limitation, the energy constraint leads to a maximum electrical field value. Given an operating voltage of the FCL, the maximum electrical field value of the superconductor directly leads to the required length of superconducting material. The operating current needs to be carried by the superconductor safely without any local transition to the resistive state. Knowing the critical current density of the superconductor, which is a function of temperature and magnetic field density, this immediately gives the superconductor cross section needed for the limiter. Starting with metal oxide raw material powder Nexans produces melt cast processed BSCCO 2212 bulk superconducting tubes [9]. For these tubes Nexans has developed a technique to cut them into a helix, with the possibility to adjust the superconducting cross section according to the specifications (typically 0.1-1 cm^2). In contrast to the anterior project CURL 10 [3] a monofilar instead of a bifilar coil design was chosen because of high voltage aspects. The additional inductance resulting from this design could easily be accepted by the customers in both projects.

A metal shunt (CuNi, $\rho = 77\mu\text{Ohm*cm}$) is applied to the superconducting coils for two reasons: The resistance of the pure superconductor is too high for the required forward current in limiting mode. A certain current is required by the network operator to monitor the short circuit and to use circuit breakers at different safety levels. The metallic shunt can perfectly be tailored in material and cross section to the specific current requirement. The second advantage of the shunt is the protection with respect to hot spots in the superconductor [5]. Therefore it has to be contacted continuously over the whole superconducting length. The BSCCO components are mechanically stabilized and insulated by fibre-reinforced plastic, thus forming a rigid compound.

In both projects the components had an outer diameter of 50mm and a length of about 40 cm with electrical contacts at the ends. To reduce the overall length needed for connections, Nexans has developed a screw socket that connects two components to a double-component with minimum additional length, see figure 3.

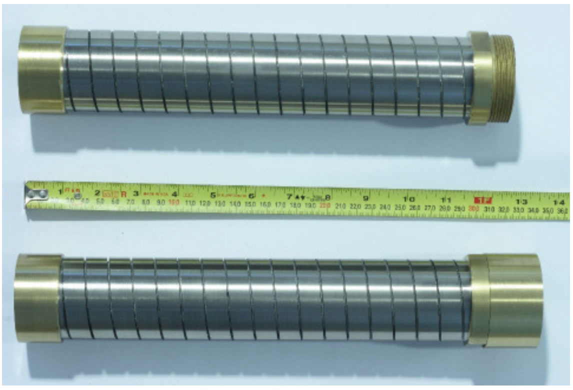

Figure 3. Double-component, the screw socket is on the right side of the lower component.

In Project 2, two double-components each are connected in parallel to obtain the inrush current of 1800 A over 15 s.

As a basis of the design the limitation behaviour of the component is calculated incorporating the E(j) characteristics of the superconductor as well as all thermal and electrical properties of the materials involved. The simulation for the entire system is given in figure 4:

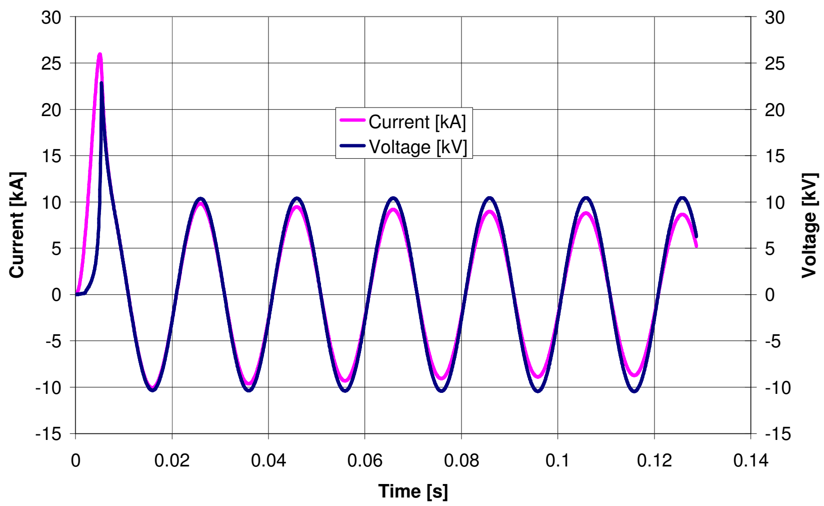

Figure 4. Simulated limitation behaviour of Project 2.

4. Design of the Limiter Systems

The superconducting components are operated in boiling liquid nitrogen. The critical current of the superconductor strongly increases with decreasing temperature, therefore in both projects the temperature of the nitrogen can be set either by a closed cycle cryocooler or by reducing the pressure of the nitrogen atmosphere above the liquid.

The superconducting components together with their connectors are assembled to a module that is afterwards inserted into a cryostat vessel. Additionally all sensors and instrumentation devices are attached to the module. Dependent on the design, especially on the voltage and current levels, the components of the three phases are mounted into one or three cryostat vessels. The cryostats together with all necessary equipment for cooling, monitoring and control are placed into a container, which was especially designed by a company dedicated to industrial design, to allow safe and simple transport, handling and installation.

4.1. FCL Design of Project 1

The FCL for the UK network has the components for all three electrical phases in one module, segregated with metal plates at earth potential. All sensors are installed in the cryostat and there is an interconnection box on the outside for simple integration into the control system. The FCL nitrogen temperature is maintained at a stable level by a 300 W closed-cycle Gifford-McMahon cryocooler together with a small regulation heater. By using a cryocooler the cryostat is a closed system.

4.2. FCL Design of Project 2

The higher nominal current of Project 2 demands a larger volume of superconducting material. For practical reasons and for simplifying the high voltage insulation concept, the three phases have individual cryostat vessels with one module in each of them. This separation eliminates the risk of a phase-to-phase short. The three vessels are connected in the liquid and gaseous phase and have only one common nitrogen supply and gas relief. Due to simple availability of liquid nitrogen at this particular location, the cryostat is fed from a large nitrogen tank and vacuum pumps together with a heat exchanger are used to decrease the nitrogen temperature to 65 K. To ensure safe operation over a long period of time, all sensors are duplicated for redundancy. A quench detector measuring the differential voltage across the FCL is included. All ancillary equipment for nitrogen temperature and level regulation, monitoring and control, compressed air supply and venting and air conditioning is installed inside the container.

The cryostat and cooling machinery (pumps, valves) are designed for the losses that are estimated in table 2.

Table 2. Thermal losses in the cryostat of Project 2.

Part	Thermal loss [W]
AC loss	860
Connectors	4
Contacts	34
Screwed contacts	87
Cryostat losses	200
Current leads	240
Total	1425

5. Manufacture of the Limiters

The superconducting components for both projects are manufactured in house. After the component tests, the modules are built from the components and all necessary connectors. A typical module after fabrication is shown in figure 5. The completed FCL cryostat of Project 1 ready for connection to the auxiliary equipment is shown in figure 6.

Figure 5. Project 2 FCL module after assembly.

Figure 6. Completed FCL cryostat of Project 1.

The completed container for Project 2 including all ancillary equipment for operation, control and supply after installation in the power plant is shown in figure 7.

Figure 7. Completed FCL of Project 2 after installation in the power plant.

6. High Power Test

During manufacture all components were thoroughly tested. The full current limitation and the high voltage performance, however, can only be tested on the completed device. Only few laboratories have the capacities to perform such tests. For experience, availability and accessibility reasons the institute IPH in Berlin was chosen. For Project 1 the testing requirements were developed by Applied Superconductor in conjunction with its network operator collaborators. For both projects, the limitation is tested for different values of prospective fault current, and for one- and three-phase faults. All relevant test parameters are given in table 3.

Table 3. Test parameters.

Test parameter	Project 1	Project 2
Withstand voltage, 1 minute	$U_w = 28$ kV	$U_w = 28$ kV
Partial discharge	$P < 5$ pC	$P < 5$ pC
Lightning impulse (15 repetitions)	$U = \pm 95$ kV	$U = \pm 75$ kV
Prospective peak fault current	$i_{peak} = 50$ kA	$i_{peak} = 63$ kA
Test with 100% prospective fault current	3	3
Test with 60% prospective fault current	3	-
Test with 30% prospective fault current	3	-
Test with 10% prospective fault current	3	-
Test with 100% prospective fault current, (two phase)	-	2

All tests have shown the expected results without any difficulties or problems during the test. The insulation tests were performed according to IEC 62271-200: 2003-11 and have shown no dielectrical breakdown. The partial discharge measured was < 1.8 pC.

A typical graph of the current and voltage measured at Project 2 with 100% prospective fault current, 3 phase fault is shown in figure 8. With a prospective current of 63 kA the limited current remains below the specified peak value (30 kA) in all three phases

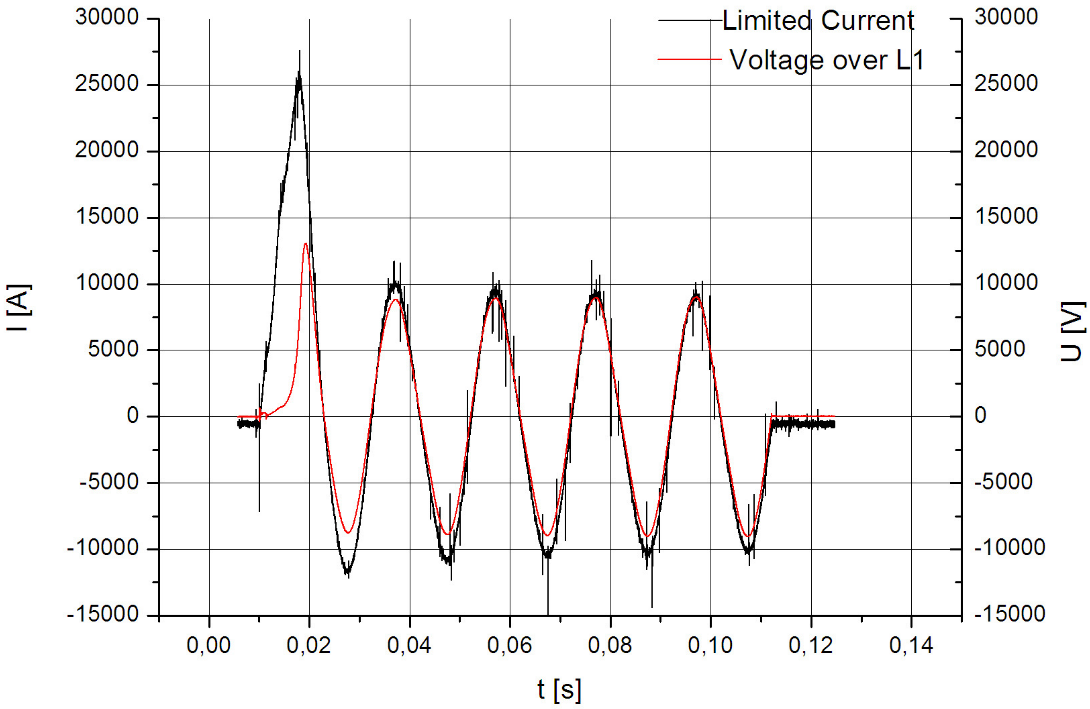

Figure 8. Limitation test of Project 2, voltage and current of phase 1. The prospective current of 63 kA is limited to 26 kA.

7. Status and Outlook

Both FCL have been delivered and commissioned, to be connected to the grid in the nearest future. "Going live" is envisaged for October 2009 for both, Project 1 and Project 2.

The specifications for Project 3 have already been developed together with ASL and the component design is almost finished. In this device bifilar components [5] for reduced AC loss will be used. The bifilar concept uses a double-helix structure for the superconducting component design instead of a single helix. This alternative results in a component that significantly reduces the magnetic field volume integral and thereby lowers both the AC losses as well as the inductance. The field installation of Project 3 is foreseen in early 2010.

In particular it could be shown that the bulk based components are very well adapted to handle safely the large inrush-currents specified in both projects. This is due to the large heat capacity of the ceramic/shunt composite. We here see a considerable advantage with respect to the coated conductor based limiter concepts [2, 10], where already a small exceeding of the critical current leads to a quench within milliseconds. Since the coated conductor concepts probably have advantages with respect to AC-losses and recovery times it might emerge that for different applications different material options are to be favoured.

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