NEXANS' SUPERCONDUCTING FAULT CURRENT LIMITERS FOR MEDIUM VOLTAGE APPLICATIONS – STATUS AND PROSPECTS

Joachim BOCK
Nexans SuperConductors – Germany
joachim.bock@nexans.com

Achim HOBL
Nexans SuperConductors – Germany
achim.hobl@nexans.com

Simon KRÄMER
Nexans SuperConductors – Germany
simon.kraemer@nexans.com

Markus BLUDAU
Nexans SuperConductors – Germany
markus.bludau@nexans.com

Judith SCHRAMM
Nexans SuperConductors – Germany
judith.schramm@nexans.com

Christian JÄNKE
Nexans SuperConductors – Germany
christian.jaenke@nexans.com

Mark RIKEL
Nexans SuperConductors – Germany
mark.rikel@nexans.com

Steffen ELSCHNER
University of Applied Science, Mannheim – Germany
s.elschner@hs-mannheim.de

ABSTRACT

The present changes in electricity networks like the ramp-up of distributed generation and the stronger need for interconnection result in an increasing demand for protection against high short-circuit currents. Superconducting fault-current limiters (SFCL) provide a completely new and efficient approach to the reliable handling of such faults. The technology has already been tested in applications like busbar couplings and in-line protection in local networks as they exist e.g. in the house load of power plants and industrial or chemical parks. The installation of a SFCL also leads to additional benefits like savings in switchgear equipment and reduction in hazard potential.

INTRODUCTION

This paper describes the current status and potential of SFCLs and their role in the deployment of future electrical networks such as the so called "Smart Grids". An excellent overview about all aspects of development and application of SFCLs is given in /1/ and references therein. Nexans SuperConductors (NSC) has designed, built, tested and installed a number of SFCL systems in different areas and application cases that differ in requirements and specifications from DNOs or power generation industry. Prospective short-circuit currents in the order of 50 kA have been limited to below 10 kA according to the design of the limiter. The limiters have shown reliable operation during about one year long field tests. Prior to field installation all systems were intensively tested at an independent and certified test lab.

All installed systems have superconducting components based on bulk melt cast processed (MCP) $Bi_2Sr_2CaCu_2O_{8+x}$ (BSCCO-2212) material. NSC masters the full product chain for the entire limiter starting from raw materials via HTS tubes /2/, FCL components /3/ and modules to the complete system. In parallel to the development of limiters based on the internally produced superconducting material, NSC now is leading two funded projects that aim at developing FCL systems based on coated conductor superconducting tapes.

DELIVERED SYSTEMS

Superconducting Components

The requirements on the limiters delivered up to now were very different dependent on the particular application cases and ratings, leading to different component designs, see Fig. 1. However, in all cases the superconducting elements were mono- or bifilar coils made from MCP BSCCO-22212 tubes (typically 50 mm outer, 42 mm inner diameter, 370 mm length) optimized to yield a material with a critical temperature $T_c \approx 94$ K, a critical current density $j_c \approx 1$ kA/cm^2 (77 K, self field) and a room temperature resistivity $\rho_n \approx 5$ mOhm·cm /4/.

The choice of the operation temperature is a trade-off between several technical aspects. On the one hand, the critical current of MCP BSCCO-2212 increases by a factor of four when cooled from 77 K to 65 K, which reduces the necessary amount of superconducting material in the same proportion. On the other hand a lower operation temperature increases the temperature gap to T_c of the superconductor. As the transition to the normal state is not always homogeneous, the risk of hot-spot formation in the superconductor in principle increases. The operation temperature

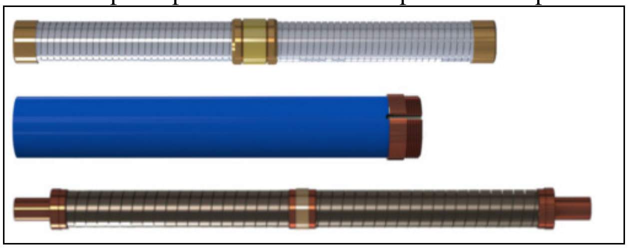

Figure 1: Components for the three systems (see Table I)

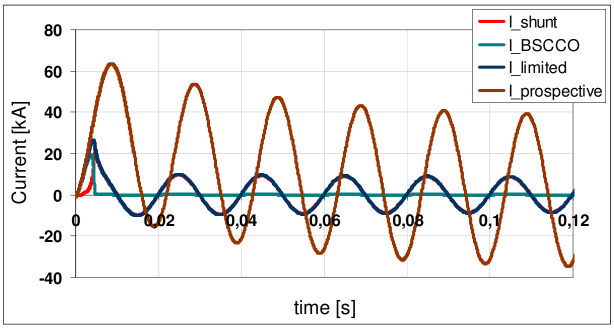

Figure 2: Computation of prospective and limited currents. The currents of superconductor and shunt are shown.

has also an influence on the economics of the cooling and the choice of the cooling concept, since AC-losses are reduced, but cooling costs increase with decreasing temperature.

A short circuit current higher than the critical current causes an immediate quench of the superconductor. The resistivity of BSCCO-2212, however, would lead to a very strong limitation of the 'follow current' which is defined as the current after the first peak, as can be seen in Fig. 2. Higher follow currents are often requested to make the detection of a fault current still possible. The follow current can be designed by an appropriate choice of a metal shunt, which is directly attached to the superconductor taking over substantial currents as soon as the voltage across the superconductor rises. After the first half-cycle, the main fraction of the limited current is carried in such a shunt. By choosing the superconductor and the shunt cross section, both the limited first peak and the follow current can be adjusted independently within certain limits and according to the specifications.

Design and Testing

The rating of a component is typically in the order of 400 A and 200 V. The system ratings are achieved by connecting components in parallel for higher currents and in series for the requested voltage. In a medium voltage limiter, the number of components is usually between 100 and 300 for the complete device. The main characteristics of three most recent SFCLs are listed in Table I. The components are assembled into a cryogenic system consisting of the liquid

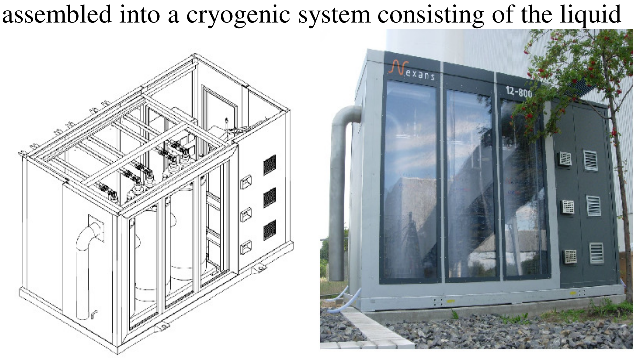

Figure 3: SFCL 12-800 installed in the power station

TABLE I. CHARACTERISTICS

Parameter	12-100[a)]	12-400	12-800
Rated Voltage U_r, kV	12	12	12
Rated Current I_r, A	100	400	800
Inrush current I, A(rms)	460	---	4100 (pk)
Prospective peak current i_{peak}, kA	50	50	63
First peak limiting i_p, kA	≈ 6	≈ 8	< 30
Limitation time, ms	120	120	120
Total loss, kW	0.2	1.0	1.5
Operating temperature, K	73	70	65
Components per phase	48	62	92

[a)] The system acronym shows operating voltage and nominal current.

nitrogen-filled cryostat with all interfaces for the cryogenic operation and the terminations for connecting the high power cables. The systems have different cooling concepts, either small cryocoolers (12-100 and 12-400) for closed-cycle operation or refill from a dewar with additional vacuum pumps to reduce the pressure above the nitrogen bath for the regulation of the operating temperature (12-800). Fig. 3 shows a view of the 12-800 limiter, installed in a brown coal power plant of Vattenfall in Boxberg, Germany.

Prior to installation all systems have undergone rigorous testing at the certified test lab IPH (Berlin, Germany). The devices were subjected to high voltage, partial discharge and lightning inrush tests (1.2/50 µsec) according to IEC 62271-200. The test parameters are listed in Table II. All tests were performed under inspection of the respective customers for the devices and were successfully completed.

Electrical Behaviour in the Grid

The 12-100 and 12-800 limiters have already performed a field test for up to 12 months. The systems have shown the reliable operation of the superconductor, though no full 3-phase short-circuit event happened at both sites. The first system 12-100 was installed in a substation at Bamber Bridge (UK), in the network of ENW (Electricity North West) carrying load currents for several months. The device is now disassembled and subjected to several after-operation tests.

TABLE II. TEST PARAMETERS

Test Parameter	12-100	12-400	12-800
Withstand voltage U_w (1 min), kV	28	28	28
Partial discharge P, pC	< 5	< 5	< 5
Lightning impulse, kV (15 repetitions)	±95	±95	±75
Prospective peak current i_{peak}, kA	50	50	63
Tests with fraction F of i_{peak},			
100%: 3-phase, 3 shots	X	X	X
100%: 2-phase, 2 shots			X
60%: 3-phase, 3 shots	X	X	
30%: 3-phase, 3 shots	X	X	
10%: 3-phase, 3 shots	X	X	

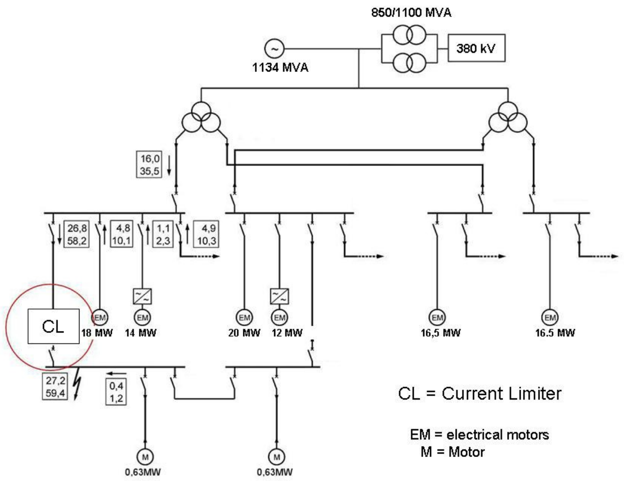

Figure 4: SFCL 12-800 single-line diagram in the power station

The limiter 12-400 is at present ready for installation at the dedicated site, a busbar coupling within the grid of Scottish Power in the Liverpool area (UK), where the networks are mesh connected and short circuit events during the projected one-year field test are very likely. The installation of NSC´s limiters at the DNO sites in the UK is handled by Applied Superconductors Ltd (ASL). Installation and commissioning of SFCL 12-800 at the Vattenfall power station were performed by NSC. The SFCL system was installed in the auxiliary supply of the power plant as schematically shown in Fig. 4.

A typical operating current curve for the three phase currents is given in Fig. 5. The average current is smaller than the rated current, but the peaks in the curve show inrush currents of large MW class motors with correspondingly higher amplitudes. During the 12-800 field test an almost simultaneous failure of two vacuum pumps inside the cooling system resulted in a shut down. This experience will be taken into account in future systems by either choosing other pumps or changing the cooling concept. The successful high power and field tests showed that the SFCL 12-800 system withstands high inrush currents – more than two times the nominal current for 15 s – and high follow currents that were requested by the protection relays without the addition of an external shunt. The ability to handle high inrush currents without quenching is a particular advantage

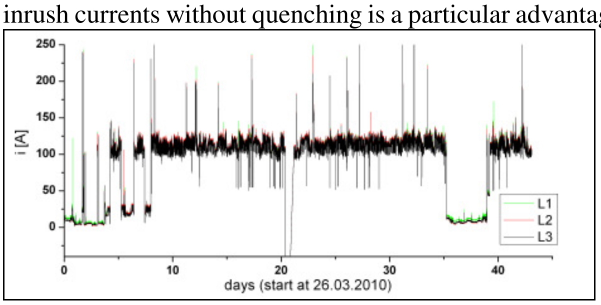

Figure 5: SFCL 12-800 operating current

of MCP BSCCO-2212 superconductor that has a moderate n-value and high thermal capacity. A prospective current of 25 kA is reliably limited to 6.6 kA.

CURRENT PROJECTS

During the last years, a dramatic progress has been made in the development of YBCO coated conductor (CC) tapes, which have J_c(77 K, sf) > 1 MA/cm^2 in 1-2 µm thick superconductor layers. CC tapes with performance of > 200 A/cm-width are now available in kilometric lengths and have a clear prospective of becoming commercially attractive within a few years. Compared to BSCCO-2212 bulk, the use of CC tapes in SFCLs leads to a stronger limitation of the first peak and reduced AC losses as well as to potentially faster recovery times /5/. However, these conductors are more delicate in handling and contacting and are less tolerant to short term over-currents. The SFCL systems based on CC tapes are the subject of two running projects ENSYTROB and ECCOFLOW, the characteristics of which are given in Table III.

ENSYSTROB

NSC is a project leader of the nationally funded project “ENSYSTROB” aiming at the development of a SFCL for the application in the auxiliary supply of a power station. Partners are the Karlsruhe Institute of Technology (KIT), University of Dortmund and the Technical University of Brandenburg, Cottbus. Within this project the BSCCO-2212 based superconducting components of system 12-800 will be replaced by components made using CC tape, while the cryostat and other auxiliary equipment will be maintained. Therefore the project with the included field test will allow the direct comparison between the bulk and the coated conductor components. First pre-prototype components have already been tested successfully /6/.

ECCOFLOW

The European “ECCOFLOW” project – also co-ordinated by Nexans – aims at developing a resistive SFCL which will serve two installation sites of two different utilities. Even though one site operates at 16 kV as a bus bar coupling in the grid of Endesa and another at 24 kV as a transformer feeder (see Fig. 6) in the grid of VSE, it was possible to find

TABLE III. CHARACTERISTICS OF SFCL SYSTEMS BASED ON CC TAPES

Parameter	**ENSYSTROB 12-800**	**ECCOFLOW 24-1000**
Rated Voltage U_r, kV	12	24
Rated Current I_r, A	800	1005
Inrush current I, A(rms)	4100	---
Prospective peak current i_{peak}, kA	63	26
First peak limiting i_p, kA	< 30	< 10,8
Limitation time, ms	120	1000
Total loss, kW	1.0	0.8
Operating temperature, K	77	77

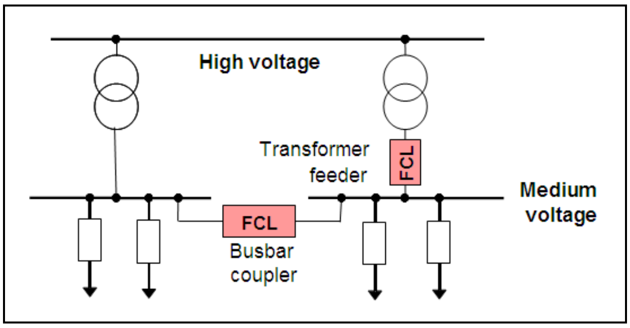

Figure 6: SFCL as busbar coupler or transformer feeder

a common design. There are 15 partners from industry and research in the project including utilities (RWE, Endesa, VSE, Vattenfall, A2A) from five different countries. For the application in the grid of Endesa an extension of the limitation time to 1 s is needed. Since this is not possible or would be too costly with the presently existing CC tapes, a system using an additional parallel impedance plus a circuit breaker will be applied, see Fig. 7. The parallel circuit of the impedance (resistor or reactor) and the SFCL limits any high short-circuit current to a pre-set value. A considerable amount of energy is deposited in the SFCL. To limit the temperature rise of the superconductor, a circuit breaker in line with the SFCL is introduced which opens after about 100 ms. This circuit breaker needs only the rating of the limited current flowing through the SFCL and can therefore be much smaller and less expensive than the conventional solution. With the impedance still in line the limitation is maintained. After the fault is cleared and the limiter is cooled back to operating conditions, the breaker can be reclosed and the SFCL system is back to normal operation with the superconductor by-passing the impedance. Dependent on the size and rating of the impedance, it would be technically feasible to stay connected continuously albeit with reduced supply voltage as long as the SFCL series circuit breaker is opened.

PERSPECTIVES FOR FUTURE GRIDS

Two different superconducting material options are currently available for manufacturing resistive SFCL systems. For the BSCCO-2212 bulk material, NSC has proven the viability of SFCLs from the basic superconducting material to the complete system. The CC tape based SFCLs still need to prove their suitability also under field conditions. Time will show which material has the perspectives for a better technical and economical viability, and it is likely that different application cases may need different material options. In any case SFCLs have the unique characteristics of almost zero impedance under normal operating conditions and high impedance at fault conditions. This technology provides the exceptional possibility to design new innovative grid structures: the grid can have very low impedance, e.g. by grid coupling or low impedance equipment, but without the risk associated to high short circuit power.

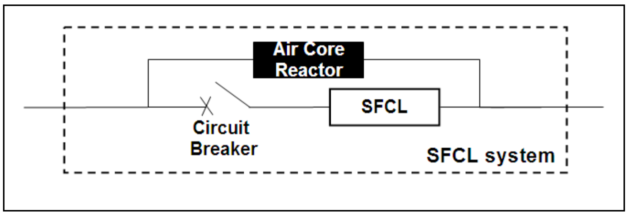

Figure 7: Principle of SFCL with parallel impedance

With a resistive SFCL in the line, the limiter minimises the phase shift between current and voltage during a short circuit, an effect which strongly reduces the stress and requirements on the circuit breakers in line, because the current and voltage are zero almost simultaneously. In any case, all circuit breakers, busses and cables downstream of a limiter can have much lower ratings and significant equipment cost can be saved. For e.g. the power plant installation this would be attractive in the case of building new blocks or extending the existing ones.

An interesting aspect of using SFCLs is also that in case of equipment loaded close to its operating limits, investment can be shifted by temporarily installing an SFCL.

ACKNOWLEDGEMENTS

The project ENSYSTROB is funded by the German government under grant 03KP102A. ECCOFLOW is funded by the EU Seventh Framework Program (FP7/2007-2013) under grant No. 241285. The authors would like to thank D. Klaus and A. Wilson, ASL, T. Krüger and D. Haake, Vattenfall, for their valuable contributions during the field tests.

REFERENCES

[1] M. Noe, M. Steurer, "High-temperature superconductor fault current limiters: concepts, applications, and development status" Supercond. Sci.Tech. 20 R15, 2007

[2] J. Bock, S. Elschner, P.F. Herrmann, "Melt-cast processed MCP-BSCCO 2212 tubes for power applications up to 10 kA", IEEE Trans. Appl. Supercond., vol. 5, No. 2, pp.1409-1413, 1995

[3] J. Bock, F. Breuer, H. Walter, S. Elschner, M. Kleimaier, R. Kreutz, M. Noe, IEEE Transact. Appl. Supercond. Vol. 15, pp. 1955-1958, 2005

[4] A. Malozemoff and J. Bock, "Status of Development and Field Test Experience with High Temperature Superconducting Power Equipment", CIGRE Report #418, June 2010

[5] W. Schmidt, B. Gamble, H.-P. Kraemer, D. Madura, A. Otto and W. Romanosky, "Design and test of current limiting modules using YBCO coated conductors", Supercond. Sci. Tech. 23, (2010) 014024 (9pp)

[6] S. Elschner, A. Kudymow, S. Fink, W. Goldacker, F. Grilli, C. Schacherer, A. Hobl, J. Bock, M. Noe, "ENSYSTROB - Resistive Fault Current Limiter based on Coated Conductors for Medium Voltage Application", IEEE Trans. Appl. Supercond., (Proc. ASC 2010), in press