THE ECCOFLOW PROJECT: DESIGN AND SIMULATIONS RESULTS OF A SUPERCONDUCTING FAULT CURRENT LIMITER FOR OPERATION IN ELECTRICITY NETWORKS

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ABSTRACT

The European project ECCOFLOW is aimed at developing and testing a 24 kV-1kA Superconducting Fault Current Limiter (SFCL) able to satisfy the specifications of two different grid installation sites. In this work we report on short-circuit simulation results that were used to develop the conceptual design of the SFCL device. These studies along with measurements will fix the detailed design.

INTRODUCTION

Superconducting fault current limiters (SFCL) are unique, innovative and attractive devices in power systems because they offer at fault conditions a fast and effective current limitation with automatic recovery and negligible impedance at normal operation [1]. The same features cannot be reached with conventional devices and therefore there is worldwide a great interest in developing SFCL devices based on High Temperature Superconductors (HTS). In fact, from the utilities' point of view the SFCL is highly attractive, as it provides not only a solution to deal with the growing level and incidence of fault currents, but also facilitates innovative planning of electricity grids [2, 3]. The significant improvements with respect to the new device will result in reduced reinvestment needs and an optimized usage of existing grids and therefore lower investment and operating cost. Accordingly, the introduction of a SFCL would enhance the performance, stability and efficiency of energy networks, and it would improve power quality and security of supply.
In this work we report on the design and simulations results of a SFCL (24 kV, 1 kA) for operation in electricity networks, obtained within the European FP7 project "ECCOFLOW — *Development and field test of an efficient YBCO Coated Conductor based Fault Current Limiter for Operation in Electricity Networks*". The main objective of the ECCOFLOW project is to develop, test, install and operate a medium voltage resistive-type SFCL.
Three-phase short-circuit transients of different duration have been numerically simulated by mathematical models able to fully describe the limiting performance of a SFCL device made by means of the state-of-the-art commercially available second generation (2G) YBCO coated conductors, at nominal and limiting conditions [4].
According to the specifications provided by two distribution hosting utilities, time evolution of limited current and other important characteristics during three-phase faults have been simulated and deeply analyzed. Simulation results showed that in case of a fault the SFCL significantly reduces the peak short-circuit current (I_{sc}) at the very first current rise. In fact, in the presence of the SFCL in a few milliseconds a prospective peak I_{SC} of about 26 kA is effectively reduced down to 10 kA or to even lower values. Short-circuit simulation results have then been used to develop the conceptual design of the ECCOFLOW SFCL device. A summary of the SFCL conceptual design and of the HTS modules layout are reported and discussed.

THE ECCOFLOW FP7 EU-PROJECT

The ECCOFLOW project (www.eccoflow.org), has been officially launched in January 2010 and is aimed at developing and testing an SFCL based on an improved HTS material: the coated conductor YBCO tape (YBCO CC) which is just now available with a suitable performance.
In comparison to other similar R&D initiatives, this project has several outstanding and unique features; in fact, for the first time ever the SFCL device has:

- To fit in two installation sites with different specifications
- To withstand subsequent field testing performed under very different application conditions, and
- To become the first permanent grid installation.

The ECCOFLOW project consortium is coordinated by Nexans France and includes 14 participants among which are several important distribution companies (ENDESA, VSE, RWE, Vattenfall, A2A) from five different European countries, thus ascertaining the broad interest for this kind of innovative devices.

INSTALLATION SITES AND SPECIFICATIONS

After the high-power laboratory testing, the SFCL device to be developed within the ECCOFLOW project will be installed at the two following very different locations:

Site 1 : Palma de Mallorca (Spain)

ENDESA will install the SFCL as a bus-bar coupling application at the *San Juan de Dios* substation which is located in the municipality of Palma de Mallorca and it transforms electrical energy from 66 to 15 kV. The single

line diagram of this substation is shown in Fig. 1. There are two bus-bars with one coupling circuit breaker, which is open in normal operation, due to the high short-circuit current in the 15 kV bus-bar when both buses are connected (first peak prospective I_{sc} around 16 kA).
The SFCL will be located such that an operation of bus bars being connected with each other is enabled. This application is expected to yield the following **main benefits**:

- The paralleled transformers contribute to a lower system impedance (i.e., higher short-circuit power) and improved voltage regulation;
- Excess capacity of each bus is available to both buses, thus making better use of the transformers rating;
- During a fault, the large voltage drop across the limiter maintains the voltage level on the unfaulted bus;
- Separate buses can be tied together without a large increase in the fault duty on either bus.

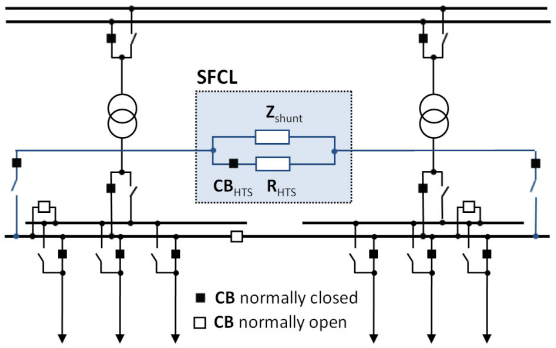

Figure 1. Bus-bar coupling SFCL installation.

Site 2 : Košice (Slovakia)

VSE (RWE group) will install the SFCL in its grid at the *ES Juh* substation which is located in Košice. This substation transforms electricity voltage from 110 to 22 kV. The SFCL will be installed on the medium voltage side of a HV/MV transformer to limit short circuit currents on the 22 kV bus-bar and outgoing feeders. The simplified single line diagram is shown in Fig. 2. The **main benefits** expected from this application are the following:

- Lower stresses: substation MV switchgear (bus-bar, circuit breakers, current transformers, voltage transformers) and Outgoing feeders;
- Prolongation of equipment lifetime, and
- Reduction of maintenance cost.

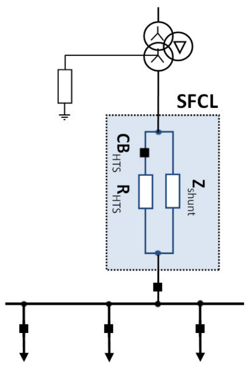

Figure 2. Incoming feeder SFCL installation.

SFCL Specifications

The following table summarizes the main specifications for both locations and shows that one SFCL design will fit both installation sites. This is possible due to the robust, flexible and modular design of a resistive-type SFCL made by second generation HTS coated conductors.

Table 1. Main specifications for both SFCL locations.

	Site 1	Site 2	Eccoflow
Nominal Voltage (kV)	16.5	24	**24**
Nominal Current (A)	1000	1005	**1005**
Short Circuit Current (kA)	21.7	25.6	**25.6**
Max. Limited first peak (kA)	10.8	17	**10.8**
Recovery Time (s)	< 30	< 30	**< 30**
AC withstand Voltage (kV)	50	50	**50**
Lightning Impulse (kV)	125	125	**125**

SIMULATION METHODOLOGY

In order to safely introduce the SFCL device into the electric power system, suitable simulation tools have been used to conveniently predict its limiting characteristics in the most severe short-circuit conditions for the two selected network sites. Within the ECCOFLOW project the simulation results have been cross-checked to experimental measurements and hence validated.
In fact, a large set of characterizations has been performed by many partners on commercially available YBCO CC having different layout and metallic matrix. Thus, the actual electrical and thermal properties of the YBCO CC as function of temperature and current value have been implemented into numerical models which are thus able to predict the behavior of HTS tapes and SFCL windings at both nominal conditions and in the limiting phase.
The amount of YBCO CC needed to develop the SFCL can be very significantly reduced by placing a shunt reactor in parallel to each SFCL phase and by means of a dedicated circuit-breaker to limit the SFCL operation down to 120 ms. Much longer fault transients will be handled by the parallel shunts. This implemented technical solution make the SFCL design more promising in terms of reduced capital cost and reliability.
Time evolution during 3-phase short-circuit fault events of the limited current (I_{Lim}) and other important quantities, as SFCL resistance, temperature and dissipated energy, have been attained, compared and deeply analyzed to study the effectiveness of the SFCL in fault current limitation.
The two most important design parameters, whose variation leads to significant changes in the fault current limiting factor and in the temperature of the HTS at the end of fault, transients are:

- The length of HTS tape for each SFCL phase;
- The value of the shunt reactor impedance placed in parallel with each phase of the SFCL.

Hence, a sensitivity analysis to identify the optimal SFCL design has been performed on these parameters.

Selected short-circuit simulation results

A very large number of simulations has been performed using the specifications reported in Tab. 1 and varying the following main parameters:

- YBCO CC properties (2 different types);
- YBCO CC length per phase (from 0.8 to 1.8 km);
- Shunt impedance value (between 1.4 and 6 Ohm);
- Shunt power factor (between 0.04 and 0.99).

In this session we present a summary of the simulation results for one type of YBCO CC only (with fixed shunt power factor of 0.05 and fault duration of 120 ms) by considering the SFCL temperature being initially at 77 K by immersion in liquid nitrogen.
Figure 3 summarizes the results of many simulation runs and reports the limited current for L1 at the 1st peak and the SFCL temperature after 120 ms, as function of the shunt impedance. As it can be seen, for higher shunt impedance values or shorter HTS lengths, the estimated SFCL temperature at the end of the fault is higher. In the SFCL design study as a safety margin we set an upper temperature limit of T=360 K at the end of transient fault. The box in Fig. 3 encloses some of the most suitable HTS length values for the SFCL device; such values satisfy simultaneously the following criteria: T < 360 K and I_{Lim} < 10.8 kA, trying to minimize the total amount of the needed YBCO CC.
Figure 4 shows the three-phase short-circuit simulation results for the case: 1200 m of YBCO CC with Z_{shunt} =2.6 Ω per phase. As it can be noticed, the peak values of fault current I_{SC} have been strongly limited and e.g., for phase L2 have been effectively reduced from 25.57 kA to 9.85 kA. The simulation results confirm the SFCL ability to effectively limit in a few milliseconds the I_{SC} to much lower values and that the maximum temperature of the SFCL is kept within the acceptable limit of 360 K.

SFCL DEVICE CONCEPTUAL DESIGN

Knowing the type and length of superconducting tape needed as well as the number of parallel paths for the operating current, a mechanically, thermally and electro-

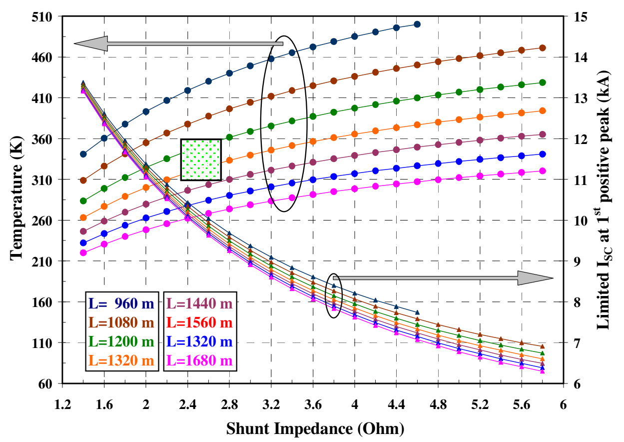

Figure 3. Simulation results: Limited current and SFCL temperature after 120 ms, as function of shunt impedance.

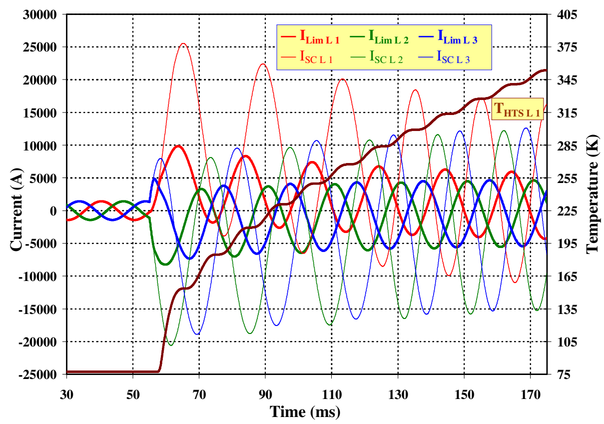

Figure 4. Simulation results for a 3-phase fault (V=24 kV, I_{nom}=1 kA, I_{SC}=12 kA_{rms}): evolution of I_{Lim} , I_{SC} and T_{HTS}.

technically stable environment for the conductor has to be established to form a reliable FCL system. The present conceptual SFCL system design consists of several major parts shown schematically in Fig. 5. The HTS components are arranged to a HTS module and this is inserted in the cryostat. The cryostat is filled with liquid nitrogen and is connected to a cooling system. On top of the cryostat the current leads and the bushings provide the connection to the room temperature part of the system. In addition, an air coil and a circuit breaker are needed to complete the SFCL system. A very crucial part of the SFCL system is the HTS component. In principle several design options (e.g. meander, monofilar coil, bifilar coil) are possible but it turned out that a bifilar coil design is the most favorable design with respect to low AC loss and low volume. Each component incorporates a parallel connection of in total 6 HTS conductors, sufficient to carry the nominal current of 1005 A and avoiding parallel connections of components. The HTS tape arrangement within a component is chosen such that the AC losses are strongly reduced by field compensation compared to the loss values of a single tape in self-field, leading to about 300 W total AC losses for the entire SFCL. While the nominal voltage of one HTS component is chosen to about 800 V, the insulation requirements on the component due to lightning inrush are considerably higher and in the order of 10 kV.

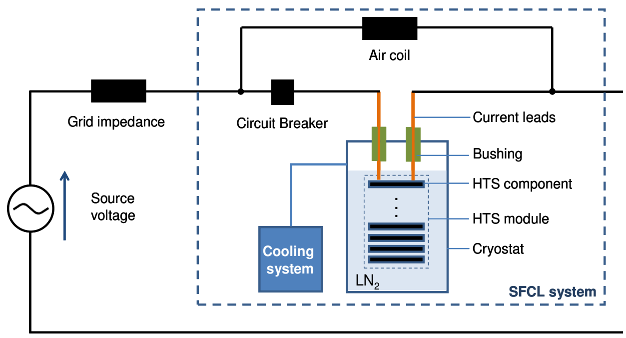

Figure 5. Conceptual sketch of the SFCL system including all major parts in a single-phase line diagram.

The nominal voltage rating of the SFCL is reached by stacking a series connection of HTS components, leading to the so called HTS module, as seen partly in Fig. 6. Within the ECCOFLOW project, a HTS module for each phase consists of a maximum of 12 HTS components connected in series. The ground insulation of the HTS module is realized by sufficient distance between the HTS module and the cryostat walls even in case of nitrogen gas forming in the liquid nitrogen filled insulation gap. A distance of 100 mm between cryostat wall and HTS component is proposed keeping in mind a maximum electrical field of 20 kV/cm and an appropriate safety margin.

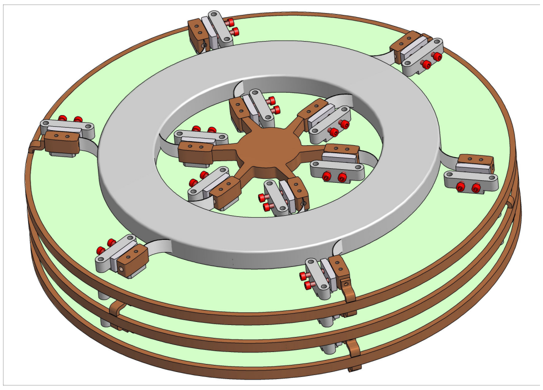

Figure 6. Conceptual arrangement of HTS module consisting of a stack of several HTS components (D = 640 mm).

This leads to a cryostat with a diameter of about 840 mm and a height of less than 2000 mm. At present one cryostat per phase is considered, with the three cryostats connected to allow one common cryogenic supply and relief. The cryostat is coupled to a cooling system; several options for the cooling system have been investigated, including cold heads, a small cryo-plant or bulk cooling from a storage dewar. On top of the SFCL cryostat, the current leads and the bushings provide the connection to the room temperature part of the system. As shown in Fig. 2, the combination of an air coil reactor and a circuit breaker enables the requested limitation time of about 1 s: 120 ms after the initiation of the short-circuit the circuit breaker, rated for the limited current flowing through the FCL, opens and the parallel air coils sustain the limitation. After the fault is cleared and the SFCL is cooled back to the nominal operating conditions, the SFCL system is back to normal operation with the HTS by-passing the air-coils.
The main components of the SFCL system are foreseen for installation into standard containers to enable safe and easy transportation to the different test and operating sites.

CONCLUSIONS

In this work, we reported on fault simulations aimed at the study and conceptual design of a resistive-type 3-phase SFCL demonstrator for distribution electrical systems for two case studies of practical interest, performed in the framework of the EU FP7 ECCOFLOW project.
The high-resistive matrix and the prospective lower cost compared to the 1G tapes, make 2G YBCO CC promising candidates for SFCL applications. However, the lack of availability of 2G HTS conductors until recently has been an impediment to realizing practical resistive-type SFCL demonstrators.
The simulations performed fully describe the behaviour of SFCL devices made by means of the state-of-the-art commercially available 2G HTS composite conductors, at nominal and limiting conditions. These results are very important to study the impact of SFCL on electric networks and to give useful hints to the design of practical SFCL devices, since a FCL with small impedance at nominal operation and very fast increase of impedance at fault conditions almost becomes a necessity to meet future power system requirements. Simulation results showed that in case of fault, the SFCL significantly reduces the peak short-circuit current at the very first current rise. In fact, in the presence of the SFCL, in few milliseconds the prospective peak short circuit current of about 26 kA is effectively reduced down to 10 kA or even lower values by selecting the appropriate reactance value of the air-core reactor placed in parallel to the SFCL device.
Within the first 12 months of the project the specification for both applications has been worked out and an appropriate conceptual design of the SFCL system has been conceived. A next major step is to complete the ongoing electrical. mechanical, and thermal measurements in order to fix the detailed SFCL design for construction.

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