DEVELOPMENT AND TESTING OF INNOVATIVE FAULT CURRENT LIMITERS FOR DISTRIBUTION SYSTEM APPLICATIONS

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ABSTRACT

Owing to the profound transformation of transmission and especially distribution networks, there is a need for efficient innovative components able to allow short-circuit current limitation. In this work we report on fault simulations and development of a 1-phase superconducting fault current limiter device for MV applications, that were successfully short-circuit tested in the high-power laboratory.

INTRODUCTION

The superconducting current limiter, often identified with SFCL (Superconducting Fault Current Limiter), is an innovative device that, when properly designed and placed in appropriate positions in an electrical grid, is able to limit the short-circuit current I_{SC} to values compatible with safety and reliability of the installed network components [1, 2]. By exploiting their intrinsic properties, High Temperature Superconductors (HTS) have characteristics that make them particularly suitable for use in resistive-type FCL devices. In fact, their electrical resistivity is significantly increased when they are carrying currents whose instant value exceeds a threshold called "critical current" (**Ic**), conventionally defined by using the electric field criterion of 1μV/cm.

A SFCL device combines unique features such as transparency in the network under normal conditions, quick response and recovery without external intervention.

In this work we report on the development of SFCL devices for MV applications, performed in the framework of an Italian RTD project. The main results reported in this paper are related to the comparison of network simulation studies with short-circuit testing on a single-phase SFCL unit that has been developed and successfully tested in the high-power laboratory.

SFCL DEVICES FOR MV APPLICATIONS

A2A already experienced high fault current level at different position within its MV grid and identified a few very suitable locations in its 23 kV and 9 kV networks where a SFCL device could be efficiently installed.

According to the considered grid location and associated protection scheme, for three-phase faults the maximum steady-state I_{SC} can be as high as 12 kA_{rms} corresponding to peak I_{SC} up to 28 kA_p with a fault duration of 300 ms. In this case, a SFCL device enabling a limiting factor LF=1.7÷2, being this value the ratio between the prospective I_{SC} in the absence of SFCL and the limited current I_{Lim} in the presence of the SFCL device - **LF** = I_{SC}/I_{Lim} - is highly desirable.

In the past, RSE developed MVA-class single- and three-phase SFCL prototypes with solenoid winding design, constituted by HTS layers anti-inductively wound on fibreglass cylinders [3-5]. In our design the resistive-type SFCL device includes the following components:

- Three series connected HTS windings per phase;
- A cryostat containing the HTS windings immersed in a liquid nitrogen pool at 65 – 77 K;
- The cryostat top flange with the MV bushings, the feed through for instrumentation wiring and a safety valve;
- A closed-loop refrigeration system and a data acquisition, control and communication system, suitable for remote long-term operation.

Available HTS conductors

The selection of the type of the HTS conductor for a SFCL device must be seeking the following main features:

- High value of Ic at operating temperature, to use the minimum possible number of conductors in parallel;
- Mechanical and thermal properties such as to withstand thermal and electrodynamic stresses that occur during fault transients;
- Dielectric properties compatible with the application voltage level;
- Commercial availability in useful quantities, piece length and at affordable cost.

Among the available HTS conductors, both first and second generation have been considered in the SFCL design:

- First generation (1G) multifilamentary BSCCO-2223 tapes (Tc of 110 K), having a silver matrix. The 1G tapes used in this work are 4.6 mm wide and 0.35 mm thick, have a self-field critical current of about 180 A at 77 K, two stainless steel reinforcement strips and are isolated by Kapton overlapped ribbons [6];
- Second generation (2G) conductors (Tc of about 92 K), made by a 1.1 mm thick HTS film deposited on a metallic substrate. The 2G YBCO-based conductors used in this work are 12 mm wide and approximately 110 μm thick (with a 100 μm thick Hastelloy C276 substrate), have self-field critical current of about 380A at 77 K and a 1-4 μm thick silver coating layer [7].

Figure 1 shows the comparison between the experimental critical current measurements for 1G and 2G HTS conductors at 65 and 77.3 K.

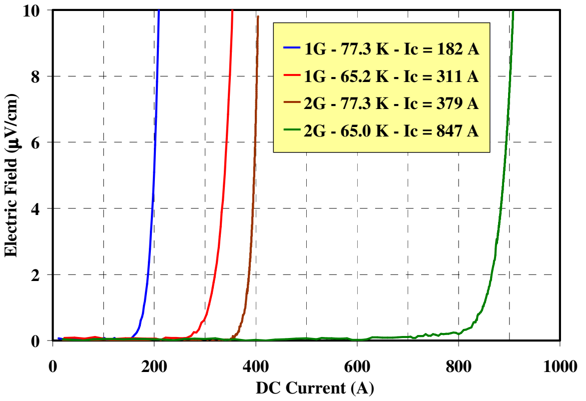


Fig. 1. Experimental measurements of electric field as a function of current for 1G and 2G HTS conductors.

Network requirements

The network requirements for the design of the SFCL device are as follows:

- Rated voltage V_{nom} = 9.3 kV;
- Rated current I_{nom} = 220 A;
- Power factor at nominal conditions cosϕ = 0.92;
- Permanent short-circuit current I_{sc} = 12.3 kA_{rms} without SFCL (maximum prospective I_{SC} peak = 32 kA_p);
- Power factor of short-circuit current I_{SC} without SFCL cosϕ = 0.1;
- Ungrounded three-phase fault duration t_{fault} = 400 ms;
- Limiting factor LF = 1.7÷2.

SFCL DESIGN: GENERAL CRITERIA AND METHODOLOGIES

The main parameters to be defined for the optimized design of a SFCL device are:

- The HTS operating temperature under nominal condition - the lower the value the higher the Ic of the HTS conductor and then the lower the AC losses at the same current rating; but a lower operating temperature decreases the refrigeration system cooling capacity;
- The ratio between the peak value of the rated current and the HTS Ic value - the increase of that amount increases the AC losses per unit length, but decreases the amount of tape needed to carry the rated current;
- The maximum allowable temperature of the HTS conductor at the end of a fault event - this value determines the thermal stress undergone by the SFCL.

Normally it is appropriate, given the significant increase of the critical current value of HTS conductors as the temperature decreases, to work at the lowest possible temperature according to the refrigeration system capabilities. As regards the increase in the allowable maximum temperature for 1G HTS it has been estimated an upper limit value of T=280 K to preserve its integrity.

As it will be shown in the following, the two most important design parameters, whose variation leads to significant changes in the limiting factor and in the temperature of the HTS at the end of fault, are:

- The length of HTS conductor for each phase-winding of the SFCL device;
- The impedance value of the air core reactor placed in parallel to each SFCL winding phase.

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

NUMERICAL SIMULATIONS TO SUPPORT SFCL DESIGN CHOICES

Figure 2 shows the single-phase scheme of the equivalent electrical circuit used for short-circuit numerical simulations. This scheme shows the air core reactor which is placed in parallel to the HTS windings to achieve the desired limiting factor and to significantly reduce the HTS winding length and final temperature.

Three-phase short-circuit numerical simulations have been performed by taking into account the network requirements, the actual property of considered 1G and 2G HTS conductors, the operating temperature of 65 K, and a warm air-core reactor, often called shunt, placed in parallel to each SFCL phase. The simulation program allows to determine the time evolution of the prospective I_{SC} and limited current I_{Lim} values, of the temperature reached by the HTS windings at the end of the fault transient and hence allow to estimate the needed HTS conductor length. The simulations make also available other important information such as the SFCL resistance and the dissipated energy during the fault transient as function of air core "shunt impedance" values, thus allowing the preliminary design of the SFCL device for the considered network installation.

A large number of numerical simulation runs for three-phase short-circuit transients have been performed for both 1G and 2G HTS conductors. For the sake of brevity only a selection of simulation results related to the 1G HTS conductors that have been actually used to build up the single-phase SFCL unit, are reported in the following. Simulations on 1G HTS conductors spanned from 500 to 700 m of HTS length per phase and from 0.3 to 0.5 Ω for the shunt impedance value in parallel to the SFCL phases.

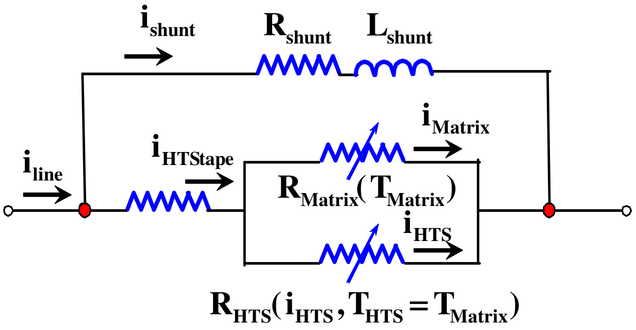


Fig. 2. Equivalent circuit used for the numerical simulations to represent 1-Phase SFCL with air coil reactor in parallel.

Figure 3 summarizes the results of many simulation runs as function of shunt impedance and HTS tape length for phase. As it can be seen, the simulation results for Z_{shunt}= 0.5 Ω show the highest limitation factor (LF = 2.13); however, at this shunt impedance value correspond the highest HTS conductor final temperatures, being the T=280 K threshold satisfy only for HTS lengths L_{HTS} > 580 m per phase.
A more appropriate shunt impedance value of Z_{shunt}= 0.4 Ω and a conservative length of HTS conductor per phase equal to 620 m, corresponding to a limiting factor equal to 1.9, as been selected for the SFCL design.

CONSTRUCTION AND CHARACTERIZATION OF A MV SINGLE-PHASE SFCL DEVICE

Figure 4 shows the single-phase SFCL components constituted by three series connected 1G HTS windings arranged in a concentric configuration.

Fabrication and experimental characterization of the HTS winding components

The three windings were made by anti-inductively wound 1G HTS layers and have been individually tested in liquid nitrogen pool. Critical current Ic measurement results at 77.3 K for the three HTS coils range from 195 A to 220 A, being Ic = 201 A for the series connected coil assembly. This assembly exhibited an Ic value as high as 339.4 A when measured at 65 K. Ac loss measurements on the three individual 1G HTS coils and on the final assembly have been performed at both 77.3 and 65 K for different 50 Hz AC currents up to I_{nom}= 250 A_{rms}. AC losses of 0.3 W/m have been measured at 65 K at the nominal current value I_{nom}=220 A_{rms} (peak value 311 A_p), being this value in line with the estimated values and compatible with the refrigeration system cooling capacity. SFCL temperature operation of 65 K is assumed in order to avoid the use of paralleled 1G HTS conductors (I_{nom} / Ic = 0.92).
The single-phase SFCL device is thus made up of three series connected 1G HTS coils, with a total HTS conductor length equal to 620 m, immersed in liquid nitrogen at 65 K.

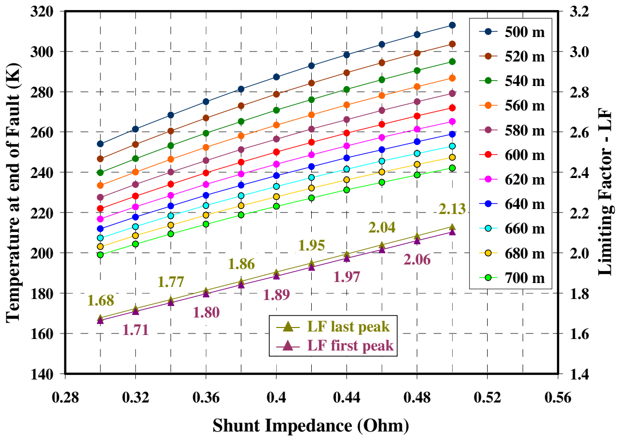


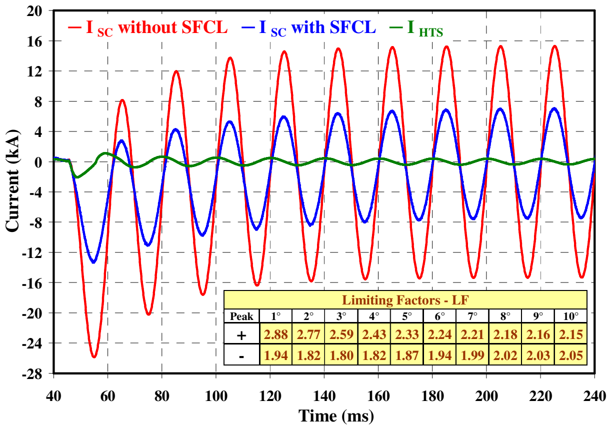
Fig. 3. Temperatures at the end of fault and limitation factors as function of air coil impedance and HTS length.

Fig. 4. Assembly of the 1-phase SFCL components with HTS coils arranged in a concentric configuration.

The complete device, constituted by the cryostat containing the single-phase SFCL and the coolant, the refrigeration system, etc, was moved to the CESI Medium Power Laboratory for carrying out short-circuit tests for qualification according to the utility technical specifications.

Short-circuit tests on the 1-phase SFCL device

The short-circuit tests were carried out with I_{nom}=225 A_{rms} at two different voltage ratings, and with different values of fault duration and parallel shunt impedance in order to qualify the behaviour of the SFCL device. It is recalled that since the test circuit is single-phase an applied test voltage of 5.4 kV corresponds, for a 3-phase device to 9.3 kV, being this value the nominal voltage of the network where the SFCL will be finally installed.
Figure 5 shows the experimental short-circuit test results for the single-phase SFCL at 5.4 kV having a warm air-core reactor with Z_{shunt} = 0.5 Ω in parallel, after a fault initiated at t = 45 ms, lasting for 200 ms. It gives a direct comparison between the magnitude of unlimited short-circuit current I_{SC} (i.e. without SFCL) and limited current I_{Lim}. In fact, as it can be noticed, the peak values of fault current have been strongly reduced; in particular, from 26.6 kA to 13.7 kA at the first peak with a LF=1.94.
Figure 6 shows the time evolution of actual and simulated I_{SC} currents during a short-circuit event at 5.4 kV, both with and without the SFCL, and the HTS winding temperature.



Limiting Factors - LF

Peak	1°	2°	3°	4°	5°	6°	7°	8°	9°	10°
+	2.88	2.77	2.59	2.43	2.33	2.24	2.21	2.18	2.16	2.15
-	1.94	1.82	1.80	1.82	1.87	1.94	1.99	2.02	2.03	2.05

Fig. 5. Short-circuit tests on 1-phase SFCL at V_{nom}= 5.4 kV: Current with and without SFCL and I_{Lim} carried by the HTS.

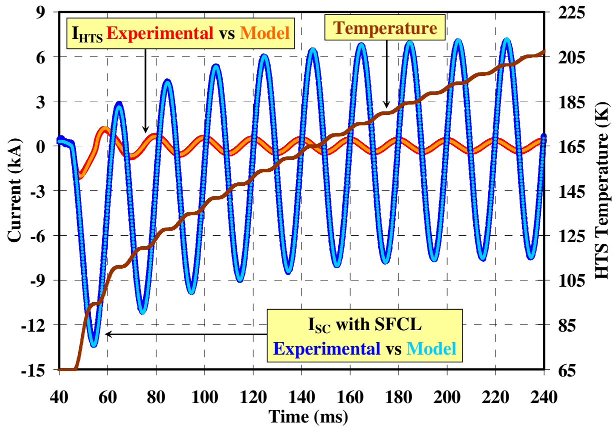


Fig. 6. Short-circuit tests on 1-phase SFCL at V_{nom}= 5.4 kV: Comparison between simulations and experimental results.

As it can be seen, there is an excellent agreement between the experimental short-circuit test results and the calculated values. During the fault transient the HTS windings calculated temperature steadily increases, being however lower than T=210 K after 200 ms at the end of fault. The HTS winding temperature has been calculated under adiabatic assumptions, i.e., neglecting the heat exchange with the surrounding liquid nitrogen bath, thus leading to a conservative HTS temperature estimation.

CONCLUSIONS

In this work we reported on the development of Superconducting Fault Current Limiter – SFCL devices for MV applications, performed in the framework of an Italian RTD project. In particular, we briefly presented the electrical properties of selected 1G and 2G HTS conductors in the 65-77 K temperature range, the A2A distribution network requirements, and the criteria and methodologies that have been used in the optimization of the SFCL design. However, the main results reported in this paper are related to the comparison of network simulation studies with short-circuit testing on single-phase SFCL unit that has been developed and successfully tested in the high-power laboratory. The simulations show an excellent agreement with the experimental short-circuit test results and fully describe the behaviour of the SFCL device in nominal and limiting conditions.

The 1-phase SFCL device, made with 620 m of 1G HTS conductor, has been short-circuit tested at 5.4 kV that corresponds, for a 3-phase device to 9.3 kV, being this value the nominal voltage of the A2A network where the 3-phase SFCL will be finally installed.

Somewhat conservative testing have been performed on this single-phase unit (in particular, fault duration of 200 ms vs 400 ms and prospective I_{SC} peak of 26.6. kA_p vs 32 kA_p) since we foreseen its integration in the final 3-phase SFCL device, which will consist of three HTS phase-windings completely analogous to that described in this paper, and successfully tested.

In the past months, our national SFCL project progressed with the construction and integration of the other two HTS phases in the final 3-phase 9 kV/3.8 MVA SFCL prototype. The 3-phase SFCL device already successfully underwent to insulation and short-circuit testing in January 2011. Owing to the positive results of these acceptance tests the 3-phase SFCL device will be installed in the A2A distribution grid in the Milano area by spring 2011, followed by a 1-year long field testing activity.

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