# ELECTRICAL TESTING OF 1 MVA-CLASS THREE-PHASE SUPERCONDUCTING FAULT CURRENT LIMITER PROTOTYPES

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## *ABSTRACT*

*The Superconducting Fault Current Limiter (SFCL) is a novel component that will efficiently address the problems due to the increasing level of short-circuit currents in distribution networks. In this paper we summarize the short-circuit test results on a 1.2 MVA SFCL prototype and on a 200 kVA demonstrator, now installed in a test facility.*

## INTRODUCTION

The emerging trends in energy markets and the increasing power quality requirements implicate a profound transformation of transmission and especially distribution electric networks. Continuous growth of electrical energy generation, connection of independent power producers, high penetration of distributed generation (DG), and increased networks interconnection are some of the major revolutionizing changes in nowadays electric networks. It is worth to underline that these factors lead to higher short-circuit current values which were not considered in previous network planning studies. Therefore, the problem of excessive short-circuit currents has become an important issue for power system operators.

Moreover, the introduction of DG implies that electric distribution networks will lose their passive character, generating new challenges and opportunities for the operation of these systems. For the above reasons, DG has been a paramount subject in power systems' research in recent years and pushes utilities and manufacturers to develop new strategies and technologies for distribution networks.

The Superconducting Fault Current Limiter (SFCL) is a novel type of system component that will efficiently address the problems due to the increasing level of short-circuit currents in MV and also in HV networks [1, 2]. The use of fault current limiters will allow equipment to remain in service even if the prospective short-circuit current exceeds its rated peak and short-time withstand current and hence there are clear indications for a growing interest in devices which are capable of limiting fault currents. It should be noticed that other practical solutions to limit fault currents may have a negative impact on system performance. For example, splitting the substation bus reduces availability and power quality of the system, whereas less expensive solutions such as current limiting reactors produce voltage drops, energy loss and even worsen the system stability.

In this paper we report on the results of our R&D activity toward SFCL application in power distribution systems related to the following:

i) Design and electrical testing of 1 MVA-class 3-phase resistive-type SFCL prototypes based on High Temperature Superconductors (HTS). In particular, silver-sheathed BSCCO-2223 (with $T_C = 110$ K) tape conductors have been purchased, fully characterized and utilized to manufacture the SFCL prototypes. Short-circuit testing of 1 MVA-class 3-phase SFCL prototypes has been carried out up to 3.2 kV to evaluate their current-limiting performances and hence to ascertain the potential of SFCL devices.

ii) As a further step, the design, proof testing, installation and field experimentation of a 400 V/200 kVA 3-phase SFCL demonstrator in the CESI RICERCA test facility for distributed generation (DG test facility).

As a consequence, at present the DG test facility is submitted to an experimental activity aimed to verify the possibility to generate voltage dips of different severity (up to 100%) and duration. Afterward, the SFCL demonstrator will be connected to the grid to experimentally check its:

- short-circuit current limiting capability;
- grid disconnection ability;
- impact on the existing protection system and possible overcoming techniques.

## CESI RICERCA TEST FACILITY FOR DISTRIBUTED GENERATION

The CESI RICERCA test facility consists of renewable energy generators, co-generation plants, energy storage systems and controllable loads that can be connected at different points of an automated low voltage grid working in radial, ring and meshed configurations [3].

The main goals of this multipurpose test facility are:

- to assess and evaluate new DG technologies in terms of performances, power quality and safety;
- to test the dynamic response of DG systems to sudden load changes, voltage dips and phase unbalance or loss of phase conditions;
- to test autonomous micro-grid operation, including islanding and reconnection to the main grid;
- to develop and test supervision, central and local controllers functions finalized to optimize the micro-grid operation in islanding and grid connected conditions;
- to support utilities and final users in development and improvement of pilot DG micro-grids.

The DG test facility is continuously updated implementing different innovative components and at present includes a 10kW hybrid photovoltaic (PV) system, a 14kW PV field, a 10kW solar thermal dish Stirling (named Eurodish), a 10kW biomass CHP plant, a 105kW micro-turbine CHP plant, a 3kW PEM fuel cell, 42kW / 2 hours Vanadium Redox and 100kW / 1 hour Lead batteries, a 100kW / 30 seconds flywheel for Power Quality, a 64kW / 30 minutes high temperature "Zebra" battery, a remotely controllable resistive-inductive three-phase load of 100kW plus 70kVAR, a 150kVAR capacitive load and several R/L loads with local control.
The DG test facility is equipped with a supervision and data acquisition system in order to record and analyze the experimental data derived from the field tests, to monitor power quality and electrical transients. The DG test facility is also used to experiment dispatcher and control system, which exploits power line and wireless communication technologies, suitable for distribution networks with high penetration of distributed generation.

## SFCL Installation aimed at Field Testing

A 3-phase SFCL prototype is ready to be field tested in the CESI Ricerca test facility for Distributed Generation (DG) to study the actual fault current limiting performances of this new protection device. The SFCL demonstrator will be tested for a 3-month period experimentally reproducing most of the typical MV perturbations.
The SFCL will improve the power quality and the system reliability since it doesn't introduce voltage drop during normal operation and instantaneously limits the short-circuit current peak ($I_{SC}$) for transitory and permanent faults.
The SFCL installation site was selected after a careful analysis of the micro-grid topology of the DG Test Facility which has been modeled by means of the commercial software DIgSILENT. Short-circuit analysis have been performed by this SW taking into account the actual electrical characteristics of the micro-grid and the rating values of its main components.
The short-circuit simulation results have been used to identify the most critical system site, i.e. the position where, in case of a fault event, the SFCL could best exhibit its limitation capabilities. According to the simulation results it has been decided to place the SFCL immediately down stream of the secondary substation (23kV/400V, 800 kVA), that connects the MV public electric grid to the DG test facility, see Figure 1. At this location, owing to the connection to the public grid (having, in this context, infinite power), we reach the highest prospective short-circuit current peak $I_{SC}$ value that can be as high as 15 kA. Moreover, being this site a connection point, it is ideal to test the ability of SFCL to effectively electrically separate two grids, during a fault event. Owing to this very attractive SFCL capability, the healthy system can remain in operation also in case of a fault occurrence on the adjacent network.
The SFCL has been designed to introduce a high current

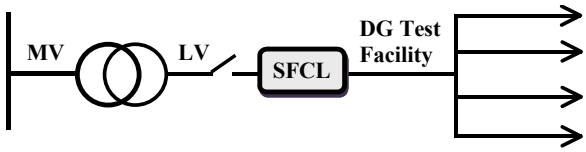


**Figure 1 Schematic drawing of the SFCL insertion in the DG test facility micro-grid.**

limiting effect, but it does not necessarily own a very short recovery time (time needed by the SFCL, after a fault, to recover its superconducting, i.e. zero impedance state), since the opening of this interconnection for few seconds can be acceptable.

## SFCL BASIC DESIGN ASPECTS

Fault current limiters employing HTS exploit the sharp transition of HTS conductors from an extremely low resistance during normal grid operation to a finite resistance during a fault event. Several configurations have been considered for the SFCL; among them the resistive-type SFCL is the simplest layout. The current-carrying element of the SFCL is designed so that during normal operation the current in the HTS is below its critical current, resulting in a negligible impedance. During fault events, the current will largely exceed the critical value, causing the SFCL device to become, within a few milliseconds, highly resistive.

## Resistive-type SFCL prototypes: basic layout

The developed SFCL prototypes have a solenoid winding design, constituted by four HTS layers in BSCCO-2223, anti-inductively wound on glass-fiber G10 cylinders [4, 5]. For the 3-phase SFCL prototypes the HTS windings have been then assembled in Y or coaxial configuration.
The HTS windings have been immersed in a liquid nitrogen ($LN_2$) bath and kept cooled by a re-liquefying Stirling machine with a cooling power of 700 W at 65 K. A closed-circuit cooling system has been used in order to reduce refrigeration costs in view of the field testing and long term operation. The top flange of the SFCL cryostat allows the feed trough of current leads, for powering of the SFCL, of instrumentation wiring and is equipped with a pressure gauge and a safety valve. The normal operating pressure inside the cryostat ranges between 130 mbar and 1 bar, but the SFCL can be safely operated up to 4 bar.

## EXPERIMENTAL DETAILS

Short-circuit currents with a power factor $\cos\varphi_{SC}$=0.1 lagging have been chosen in order to take into account the inductive nature of the large majority of faults on MV grids. In particular, prospective peak short circuit currents up to 15.5 kA have been applied for 30-100 ms on SFCL prototypes. Typical testing cycles simulating characteristic O-C-O duty cycles have been repeatedly applied to the SFCL prototypes continuously monitoring, with a 20 kHz sampling rate, temperature, current and voltage across the

test object. Moreover, the effective limitation capacity of SFCL devices has been tested under several typical fault conditions: line-to-ground and inter-phase short-circuits with and without earth connection. Other important experimental data as HTS temperature at different locations, gas pressure inside the cryostat and all cooling system functioning information have been collected by means of a 24-channel multiplexer and real time displayed.

## SHORT-CIRCUIT TEST RESULTS

### 1.2 MVA 3-phase SFCL Prototype

Figure 2 shows the time dependence of current and SFCL resistance during a 3-phase short-circuit test performed at 350 $V_{rms}$ with peak short-circuit current $I_{SC}$ = 15440 A. It can be noticed that $I_{SC}$ is effectively reduced to much lower limited current $I_{Lim}$ values (+1720 A, -1590 A and +1500 A at the first peak for the S, R and T-phase, respectively), further greatly reduced at the subsequent cycles because of the HTS tape heating. Indeed, the calculated resistance exhibits peak values that increase for the whole fault duration and start to decrease after the fault clearing, as a result of temperature lowering due to the heat exchange with the cryogenic bath. The final 3-phase prototype (made by 450 m of HTS tape) has been submitted to intensive testing sessions with no degradation, lasting several days with the SFCL kept at selected temperatures (65 K<T<78 K) by the closed-circuit refrigeration system, without any need for liquid nitrogen refill. A picture of the 1.2 MVA 3-phase SFCL demonstrator and the related refrigeration system for $LN_2$ during the short-circuit testing is shown in Figure 3a. This SFCL demonstrator exhibited a purely inductive (L=23.8 μH) negligible impedance, lower than 7.5 mΩ, for nominal currents $I_{Nom}$ exceeding 250 $A_{rms}$ at 65 K.

Figure 3b shows the current and voltage evolution for a 50ms short-circuit test at 3.2 $kV_{rms}$ on the 1.2 MVA SFCL prototype: peak $I_{Nom}$= 304 A, peak $I_{SC}$ = 15440 A. It can be noticed that $I_{SC}$ is efficiently reduced to a $I_{Lim}$ peak value of 3045 A at the first cycle i.e., a $I_{SC}$ reduction of 80.3% with 10 p.u. of $I_{Nom}$ ($I_{Lim}$=610 $A_P$ after 40 ms from first cycle).

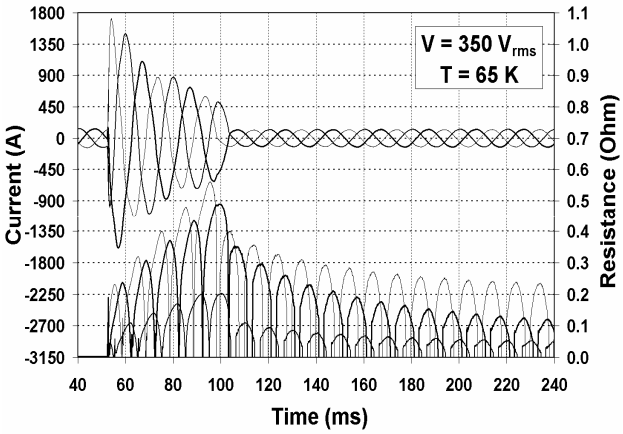


**Figure 2 Test results: time evolution of current and SFCL resistance during a short-circuit test cycle.**

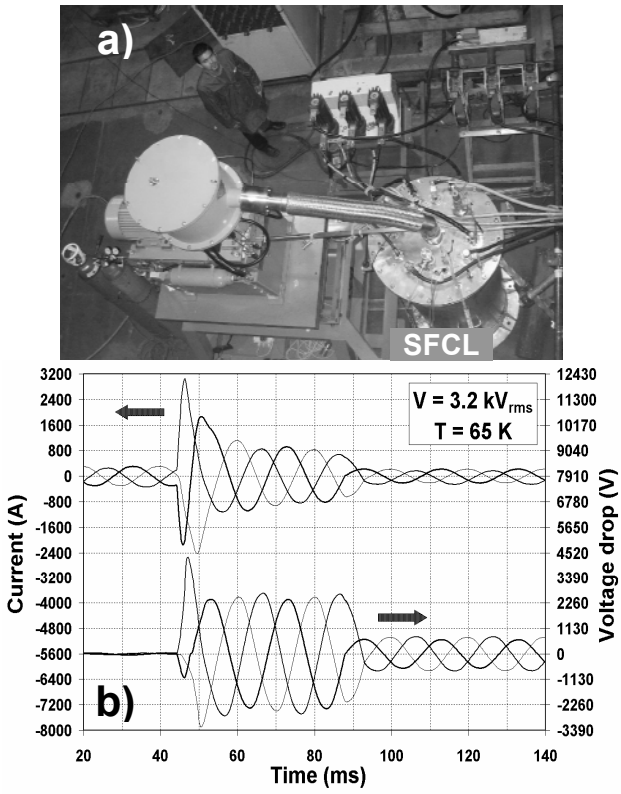


**Figure 3 (a) Picture of the 1.2 MVA SFCL prototype inside of the testing laboratory; (b) Short-circuit test results: time response of current and voltage drop across the SFCL.**

A negligible voltage can be measured across the SFCL at $I_{Nom}$ prior to the fault, whereas a large voltage appears after the fault clearing. In fact, owing to the large energy dissipated during this 50 ms fault (E= 203 kJ), the HTS temperature rise is large (ΔT>210 K) and hence, **especially because under $I_{Nom}$ condition,** the SFCL didn't completely recover. It should be pointed out that the temperature increase strongly enhances the SFCL limiting capability, as it can be seen from the reduced $I_{Lim}$ values at the subsequent peaks. However, as a drawback the risk for possible HTS degradation or even failure becomes extremely high.

### 200 kVA 3-phase SFCL Demonstrator

Since the SFCL expected benefits for the DG test facility strongly depend on the specific system position, design, manufacturing and laboratory testing of the 200 kVA SFCL demonstrator (600 m of HTS tape) reflected the electric parameters of the selected installation site. Firstly, an extensive simulation work has been performed by means of a self-developed mathematical model able to describe accurately temperature and resistance evolution of HTS windings, and hence the limiting performance of the SFCL prototype, at nominal and limiting conditions i.e., for high currents ($I>>I_C$). It should be pointed out that the simulation results were fully confirmed by the subsequent short-circuit tests. As a typical result of SFCL electrical tests, Figure 4 shows the comparison between the SFCL-limited ($I_{Lim}$) and

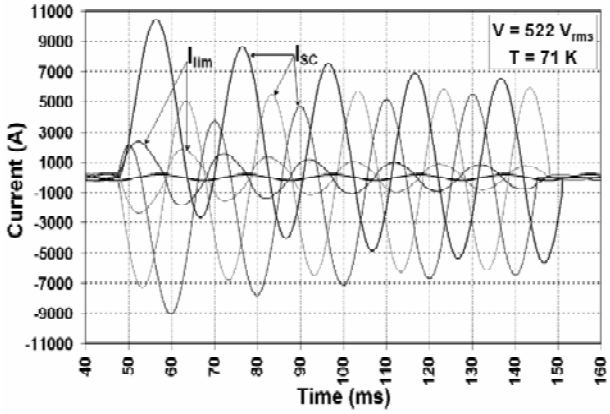


**Figure 4 Short-circuit test results: comparison between $I_{SC}$ and $I_{Lim}$ for a line-to-line fault test.**

unlimited $I_{SC}$ currents for a line-to-line short-circuit test at 522 $V_{rms}$ with: $I_{Nom}$=308 $A_P$, $I_{SC}$=10450 $A_P$, $t_{SC}$ =100 ms. It can be noticed that $I_{SC}$ is efficiently reduced to a $I_{Lim}$ value of about 2300 A at the first peak i.e., a $I_{SC}$ reduction of 78% with 7.5 p.u. of $I_{Nom}$. As it can be seen also in Figure 5, owing to the SFCL temperature rise, the height of subsequent $I_{Lim}$ peaks is continuously reduced. In addition Figure 5 shows, for the same test of Figure 4, the time evolution of SFCL resistance, calculated from instantaneous voltage and current experimental data. This graph clearly shows the following SFCL features: i) no resistance at $I_{Nom}$, ii) fast resistance development at fault inception, and iii) the resistance steadily increase during the whole short-circuit.

## CONCLUSIONS

In this work, we reported on electrical testing of specifically designed 3-phase resistive-type SFCL prototypes exploiting HTS conductors. Short-circuit test results showed the excellent current-limiting capability and fast (t ≈1 ms) action of the SFCL devices and in particular, of a 3.2 kV/1.2 MVA SFCL prototype that withstood repeated thermal and short-circuit cycling without any detectable degradation. The extensive testing sessions lasted several

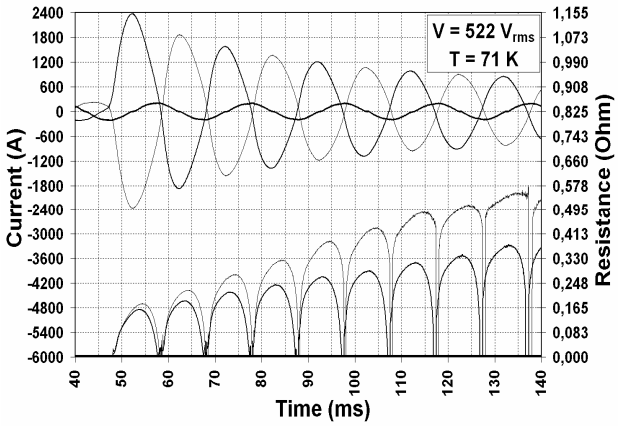


**Figure 5 Waveform of limited current $I_{Lim}$ and SFCL resistance for the same line-to-line fault test as in Figure 4.**

days with the SFCL prototype kept at nominal temperature by a closed-circuit refrigeration system, i.e., without any need for liquid nitrogen refill. Time evolution of limited current and voltage across this 3-phase SFCL prototype has been reported and deeply analyzed with respect to its scalability to higher power rating and then its actual potential for MV applications.

Moreover, as a further step of our R&D activity toward SFCL application in power distribution systems, a 3-phase SFCL demonstrator has been designed, laboratory tested and then installed in the CESI RICERCA test facility for distributed generation and, at present, is ready to be field tested.

The field testing activity will certainly give additional information about performances and reliability of resistive-type SFCL devices. It's believed that the utilization of the SFCL will contribute to enhancing the security, reliability and quality of energy supply of the CESI RICERCA test facility for DG and will also allow to control the increase of $I_{SC}$ due to possible future expansion of this facility by new generation units. This activity could hopefully give some direct contribution to the optimal integration of distributed energy resources in the EU-wide power networks.

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