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Live-grid installation and field testing of the first Italian Superconducting Fault Current Limiter

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***Abstract*— Since 2009 Ricerca sul Sistema Energetico S.p.A. has been involved in the development of a resistive-type Superconducting Fault Current Limiter (SFCL) for MV applications to be installed in the A2A Reti Elettriche S.p.A. distribution grid in the Milano area. The project started with simulations, design and testing activities for a single-phase device; this first step paved the way for developing, testing and live-grid installation at the hosting utility site of the final three-phase SFCL prototype. The result of this research activity is a resistive-type 9 kV/3.4 MVA SFCL device, based on first generation (1G) BSCCO tapes, nowadays permanently installed as a single-feeder fault protection. This device is the first SFCL successfully installed in Italy. In this paper we report on installation of the three-phase device and field-testing activity. Additional information about the future evolution of the Italian R&D project and the use of a SFCL second unit (9 kV/15.6 MVA) as transformer protection in the same A2A substation in the Milano area, is also anticipated.**

***Index Terms*—BSCCO tape, Fault Current Limiter, High Temperature Superconductors, Short-Circuit Current.**

I. INTRODUCTION

IN transmission and distribution electricity grids there is the need to provide effective and reliable protection to cables, transformers, switches, and other equipment against over current faults. The ideal protection device presents zero impedance at nominal current and high impedance to limit the short-circuit current in the system, during the fault transients.

This device has been already conceived and it is known as Superconducting Fault Current Limiter or SFCL [1] - [3].

Among all different types of SFCL nowadays under study, resistive-type SFCL are expected to be one of the first technically and economically viable applications of High Temperature Superconductors (HTS) [4], [5]. By exploiting their intrinsic properties, HTS have characteristics that make them particularly suitable for this type of device. Silver-alloy sheathed BSCCO-2223 tapes, first generation (1G) conductors, are historically the most applicable solution for usage at liquid nitrogen (LN) temperatures [6]; nevertheless, many applications of second generation (2G) YBCO coated conductors, are nowadays in course of study [7] - [9]. Usually the latter option (2G wires) is the most common when resistive-type SFCL are developed, on the contrary Ricerca sul Sistema Energetico S.p.A. (RSE) decided to aim at conceiving a BSCCO-based resistive-type SFCL and this choice make this project unique in the superconductivity SFCL applications landscape.

The use of SFCL devices could allow utilities to avoid or delay the upgrading of existing circuit breakers to handle increasingly higher electrical surges with a consequent costs reduction. Moreover, the SFCL will improve power quality by allowing interconnection of grids with reduced capital investment and environmental impact, and by enhancing the stability of the grid. For what aforesaid, the SFCL is extremely attractive from utilities point of view [10], [11].

A2A Reti Elettriche S.p.A. (A2A), the second largest Italian utility, is planning in advance how to efficiently overcome the rising problem associated to high short-circuit current I_{SC}. This is the reason why A2A and RSE decided to team up, initially focusing on the design and then on construction, installation and field test of a SFCL prototype for the 9 kV MV grid.

The result of this research activity is a resistive-type 9 kV/3.4 MVA SFCL device, based on 1G BSCCO tapes, developed by RSE in the framework of a R&D national project and nowadays permanently installed as a single-feeder fault protection. The project started with simulations, design and testing activities for a single-phase device; this first step paved the way for developing, testing and live-grid installation at the hosting utility of the final three-phase SFCL prototype. The results related to developing and simulation of the three-phase device was already described as well as the laboratory testing activity that qualified the SFCL to be ready for its grid installation [10], [12].

This paper deals with the field-testing activity carried out at the A2A S. Dionigi MV substation located in the Milano area. During the field-testing activity, many data were logged and elaborated to study the behavior of the SFCL device under real network conditions. In addition, further details about the future evolution of the Italian R&D project and the use of a SFCL second unit (9 kV/15.6 MVA) as transformer protection in the same A2A substation is also anticipated.

II. SFCL BASIC DESIGN ASPECTS

According to the considered grid location (see Table I), a SFCL device enabling a limitation 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, is highly desirable [13].

The SFCL device is made up by means of a HTS tape total

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length equal to 1880 m. The HTS material used is a commercial multifilamentary stainless steel reinforced silver–alloy sheathed BSCCO-2223 tape insulated by a helicoidally wound Kapton layer with a 50% overlapping and thickness of 12.5 µm. The 1G HTS tape overall cross-sectional dimensions are 4.65 mm x 0.37 mm (including insulation). The self-field end-to-end critical current $I_C > 180$ A at 77 K. Each phase is constituted by three series-connected HTS windings coaxially arranged, moreover each phase is shunted by an air-reactor of 0.4 Ω with power factor *cosφ* equal to about 0.1. Each winding is realized by two HTS layers anti-inductively wound on fiberglass cylinders and between the two layers a supplementary insulation Kapton layer (125 µm thick) is added [3].

The three HTS phases are immersed in a liquid nitrogen bath inside a cryostat 1800 mm high with an internal diameter of 600 mm. A closed-circuit Stirling LN liquefier, with cooling power of 1000 W at 77 K (700 W at 65 K) is used for the SFCL refrigeration.

TABLE I HERE

III. QUALIFICATION AND ACCEPTANCE TESTS

Critical current measurements at 65 K and 77 K for each HTS winding of the three-phase device were carried out, moreover the windings underwent the experimental procedure for the evaluation of AC losses. Finally, qualification tests (partial discharge test, short-duration power-frequency withstand voltage test, basic impulse insulation level test) and acceptance tests (short-circuit current test) validated the readiness of the SFCL for the grid installation (see Fig. 1).

The aforesaid steps were already described in [13], therefore this paper is aimed at drawing the attention to the main outcomes from the real installation and the in-field experimental activity.

FIG. 1 HERE

IV. SFCL INSTALLATION

In December 2011 the SFCL device was moved to the A2A S. Dionigi substation. The transportation from RSE superconductivity laboratory to the substation was rather delicate because the device is made up of different parts. Among the several parts composing the SFCL, the most important ones are listed below:

- Three-phase SFCL prototype
- Nitrogen re-liquefying Stirling machine
- No. 3 shunt reactors
- Chiller
- Stirling machine control panel
- Rack for the housing of acquisition and control system

The SFCL device was commissioned for the first time on December 22nd ; temporary electrical connections to the grid were fixed and the device was finally switched-on and fed by the distribution grid. The SFCL device run coping with the real conditions of the Milan distribution grid and protecting a single feeder; RSE and A2A teams monitored the SFCL behavior throughout the whole test duration, logging current values up to 143 A_{rms}. Upon successfully completing this first site-test, the SFCL was switched-off to make the final assembly ready for the continuous SFCL long-term operation.

Fig. 2 shows a picture of the SFCL prototype taken at the installation site (the A2A S. Dionigi substation) and ready for starting the in-field experimental activity.

FIG. 2 HERE

Fig. 3 and Fig. 4 show respectively, a schematic overall view of the SFCL installation and a general description of the main SFCL system components.

FIG. 3 HERE

FIG. 4 HERE

For remote control purposes, the SFCL device is provided with a control and acquisition system able to log electrical and thermal magnitudes every three seconds that keeps operators informed by means of e-mail messages that are sent three times per day (7:06 AM - 1:06 PM - 9:06 PM). In case of an abnormality occurs, the control system sends a warning e-mail to operators so that they can quickly analyze the situation and implement a solution. The graphic interface allows the visualization of all the relevant data from the installation, for example the nitrogen bath temperature at three different levels, liquid nitrogen bath level and pressure inside the cryostat, time-behavior of currents (both total currents and currents through the superconducting windings), and voltage drop across each SFCL phase.

Fig. 5 shows an example of the interface outputs provided by the control system during the in-field activity.

FIG. 5 HERE

Once the last adjustments at the substation site were completed, the SFCL officially started running in March 2012 so that the in-field activity was definitely launched.

This installation allows gathering important data about the device behavior facing the everyday network conditions and acting as a single feeder protection. In-field activity started in a conservative way; in fact, initially the load on the feeder was very small (about 45 A_{rms}) and this allows evaluating the device by a sort of initial training. Afterwards, once the proper SFCL behavior against small currents was verified, by reconfiguring the grid the load enhanced up to about 150 A_{rms}.

V. IN-FIELD ACTIVITY AND RESULTS

The present section reports on the main achievements and results related to the experimental in-field activity. The SFCL device has been working since March 2012 under the typical conditions characterizing the Milan MV distribution grid to verify that the SFCL properly behaves in agreement with simulations and experimental tests.

Fig. 6 refers to a period of field testing activity of about three weeks (from March 30th until April 23rd). It shows the typical daily load cycles of the urban feeder to be protected by the SFCL device, with maximum phase currents that progressively increased from an initial value of approximately 60 A_{rms} up to a maximum value of about 120 A_{rms}.

Fig. 7 allows to look in more detail to the SFCL behavior within one single day; this graph shows the time evolution of

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the three SFCL phase currents (respectively phase *R*, *S* and *T*) over a twenty-four hours period and in particular from 7 AM of April 19th until 7 AM of April 20th. It represents the load current cycle for a typical day, with a maximum value of about 120 A_{rms} . This is typical for inverted power flow purposes in highly meshed networks and for 30-year old cables as urban feeders in the Milano downtown area.

FIG. 6 HERE

FIG. 7 HERE

The Stirling re-liquefier is charged with the duty to keep the temperature stable inside the liquid nitrogen bath. In order to achieve this goal, among other operational conditions, its electric motor works in the range between 900 - 1500 rpm being the higher value associated to a larger cooling power.

Fig. 8 shows the phase currents and the motor speed of the refrigeration system as function of time for the SFCL device throughout 24 hours during the first week of October 2012: it is quite straightforward that the motor speed follows the current time evolution.

In fact, the higher are the SFCL phase current values, higher are the losses and the associated heat deposited inside the cryostat; therefore, faster has the electric motor to run in order to keep stable - the pressure inside the cryostat and hence the temperature of the liquid nitrogen bath.

FIG. 8 HERE

VI. CONCLUSIONS

In this work we reported on the installation and field testing activity of a three-phase 9 kV/3.4 MVA Superconducting Fault Current Limiter prototype for MV applications, developed in the framework of an Italian R&D project.

In particular, firstly we briefly summarized the distribution network requirements, the criteria and methodologies that have been used in the optimization of the SFCL design and the results of its acceptance tests.

Secondly, we reported on the important milestone of our project, i.e. the SFCL system final installation within the Milan distribution network as a single-feeder protection and the related in-field activity. This is an extremely relevant result for us, since the device is the first SFCL installed in Italy. The device is foreseen to stay in operation for another six-month period to gain additional knowledge about its behaviour and also maintenance procedures, till a new SFCL device with higher rating will be installed.

In fact, next step of the R&D activity will consist in the design of a three-phase SFCL demonstrator with current rating of 1 kA to be installed at the same substation in an incoming feeder to limit the contribution of this feeder to the total short-circuit current of the network. Being this application very demanding in terms of SFCL reliability and availability, but also the most interesting one for the A2A hosting utility needs.

ACKNOWLEDGMENTS

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TABLE I
NETWORK REQUIREMENTS

Parameter	**A2A Requirements**	**Qualification Tests**
Rated voltage V_{nom}	10 kV	12 kV
Rated current I_{nom}	220 A_{rms}	220 A_{rms}
Prospective short-circuit current I_{SC}	12.3 kA_{rms}	12.3 kA_{rms}
Prospective short-circuit current peak I_{SC}	30 kA_p	33.2 kA_p
Prospective short-circuit power factor $cos\varphi_{SC}$	0.1	0.08
Ungrounded short-circuit duration t_{fault}	400 ms	300 ms
Limitation factor $LF = (I_{SC} / I_{Lim})$	1.7 - 2	1.83

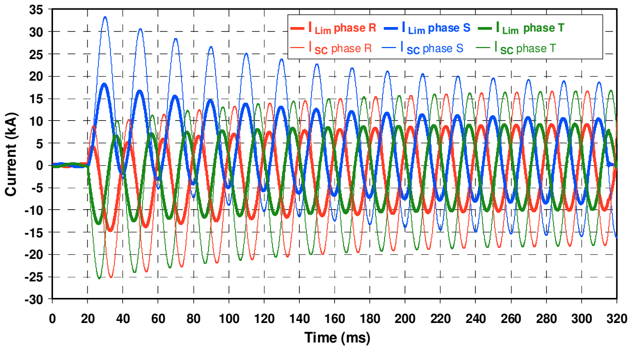

Fig. 1. Short-circuit laboratory test at 10.2 kV: comparison between prospective (I_{SC}) and limited (I_{LIM}) current

Fig. 2. SFCL ready for in-field activity

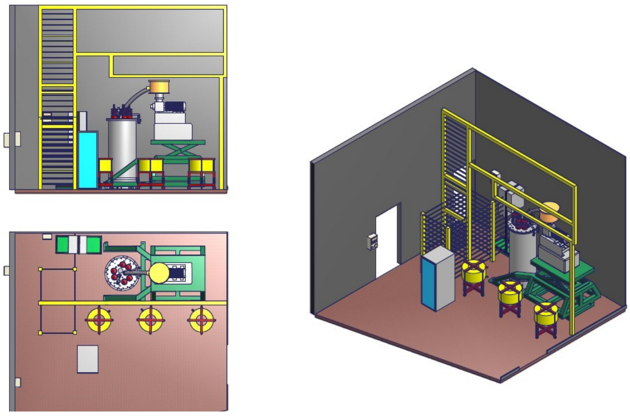

Fig. 3. 3D view of the whole installation

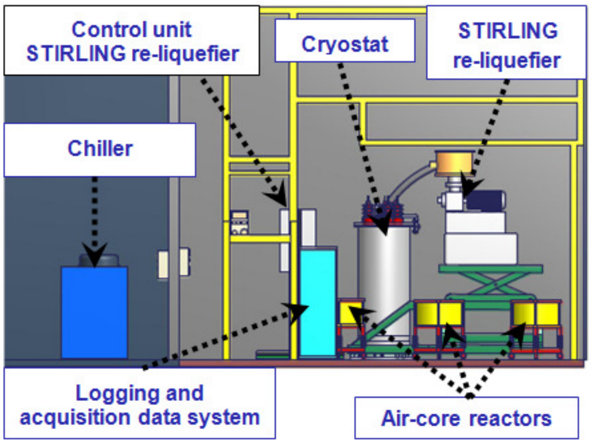

Fig. 4. Components description of the whole installation

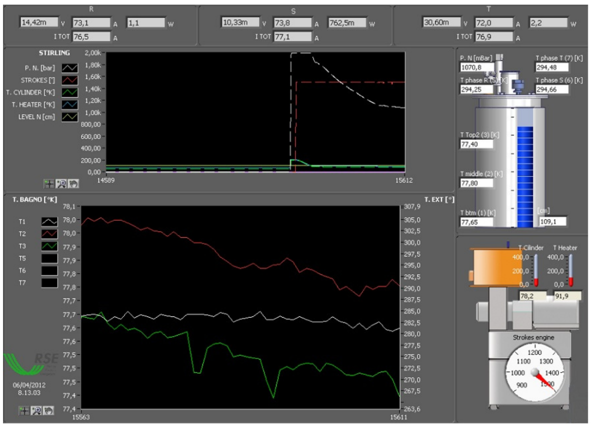

Fig. 5. Control system interface

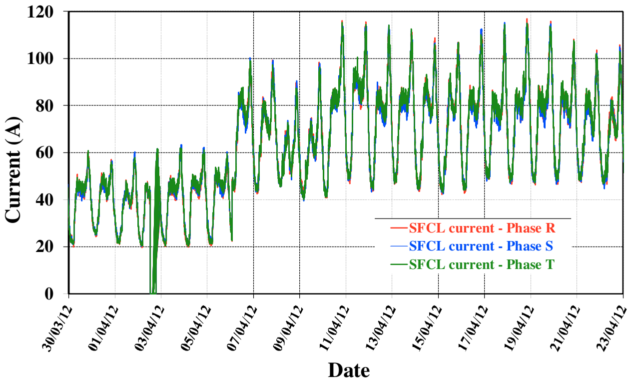

Fig. 6. SFCL phase currents throughout three weeks

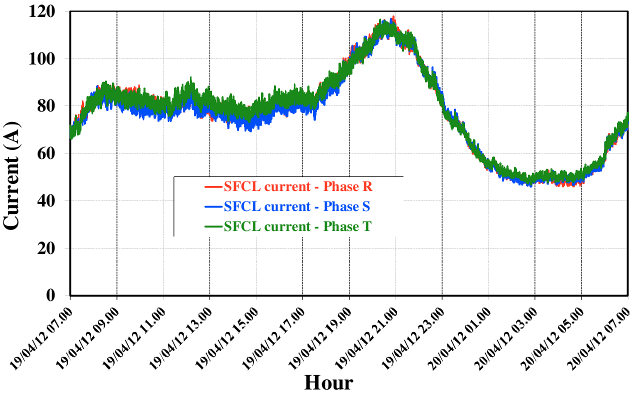

Fig. 7. SFCL phase currents vs time throughout 24 hours

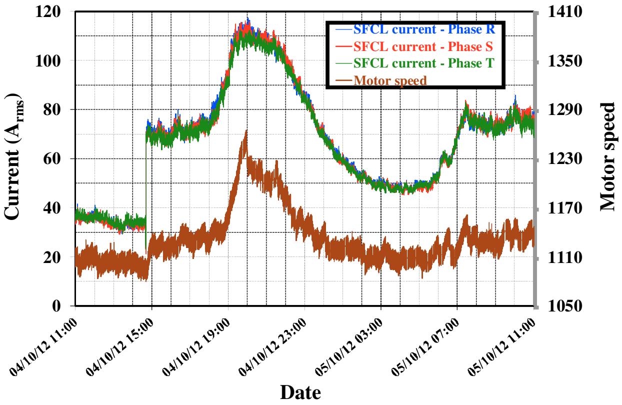

Fig. 8. Phase currents and motor speed vs time throughout 24 hours