FAULT CURRENT LIMITATION: RESULTS OF THE GRID FIELD-TESTING AND 3-PHASE FAULT EVENT ON THE FIRST ITALIAN SUPERCONDUCTING FAULT CURRENT LIMITER

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ABSTRACT

Present trends are leading towards more meshed distribution grids, thus implying higher short-circuit currents. Ricerca sul Sistema Energetico-RSE S.p.A. is engaged in a more than five years long project for the development and field-testing of Superconducting Fault Current Limiters (SFCL). The final result is a 3-phase resistive-type SFCL device 9kV/3.4MVA entirely developed by RSE and installed in a MV substation in the Milan distribution grid belonging to the utility A2A Reti Elettriche S.p.A. The SFCL was commissioned in March 2012 and field-tested until June 2014. In May 2014 the SFCL device limited a real severe 3-phase fault event: this is the first time in Italy, and one of the first worldwide, that a SFCL is installed in a real grid and performs a limiting action during a severe fault event. This paper reports on the major findings from the in-field activity and anticipates some details about the next steps.

INTRODUCTION

It is already known that Superconducting Fault Current Limiter (SFCL) may be highly desirable devices for utilities [1],[2] because they strongly support distribution system operators in the management of the ever-increasing short-circuit currents. The historical trend of SFCL designs and applications was already summarized in several works [3]-[7], therefore we hereby focus our attention on the experimental results from the first Italian SFCL device successfully installed in a real distribution grid. This activity has been carried-out by Ricerca sul Sistema Energetico-RSE S.p.A. in the framework of a R&D national project financed by the Research Fund for the Italian Electrical System: the main goal of the project was to develop a first generation BSCCO-based resistive-type SFCL for MV distribution grids. The main outcome consists in a 9kV/3.4MVA 3-phase SFCL device installed as a single-feeder fault protection in the Milano S.Dionigi substation belonging to A2A Reti Elettriche S.p.A. (A2A), the second largest Italian utility [4]. This SFCL prototype has been coping with the real grid conditions (9kV) for more than two years since March 2012, providing a large amount of experimental data and a significant experience in the operation and management of superconductive devices. This paper summarizes the main steps of this project, from the first design and laboratory testing to the final live-grid installation and field-testing [6],[8]. Great emphasis has been devoted to the effective limitation of a real 3-phase fault event occurred in the Milan distribution grid [9],[10]. Finally, some details of the new upgraded SFCL device to be installed in the Milan distribution grid are also anticipated.

SFCL BASIC ASPECTS

As far as a SFCL installation is considered, one of the most important specification is the Limitation Factor (LF), i.e. the ratio between the prospective short-circuit current I_{SC} and the limited short-circuit current I_{Lim} peak values. In the present case, A2A requested a LF comprised between 1.7 and 2. Table I reports on the network requirements characterizing the installation site and provides also a comparison with the short-circuit tests parameters. The High Temperature Superconductor (HTS) material used is a BSCCO-2223 tape featuring a self-field end-to-end critical current I_C at 77K of about 180A, and the amount of HTS tape used for the 3-phase SFCL device is 1800m (a small amount considering the absence of any circuit-breaker and the fault duration of 400ms). In our design each SFCL phase is constituted by three series connected HTS windings coaxially arranged and each winding is realized by two HTS layers anti-inductively wound in order to almost annihilate the magnetic self-field [11]. Finally, each phase is shunted by an air-core reactor of 0.4Ω with power factor *cosφ* of 0.1. A commercial closed-circuit Liquid Nitrogen re-liquefier is used for the refrigeration. In Fig. 1 and Fig. 2 are shown, respectively, a sketch of the system main components, and a picture of the real SFCL system at the A2A substation.

Table I. Grid requirements and short-circuit test parameters

Parameter	A2A Requirements	Short-Circuit Test
Rated voltage V_{nom}	9 kV_{rms}	10.2 kV_{rms}
Rated current I_{nom}	220 A_{rms}	220 A_{rms}
Prospective fault current I_{SC}	12.3 kA_{rms}	12.3 kA_{rms}
Max. prosp. fault current I_{SCP}	30 kA_p	33.2 kA_p
Ungrounded fault duration t_{fault}	400 ms	300 ms
Limitation factor LF	1.7 - 2	1.83

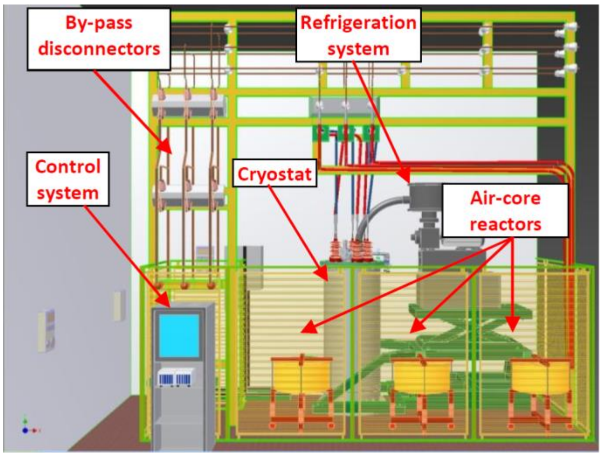

Fig. 1. General sketch of the SFCL grid installation

Fig. 2. Picture of the real installation at the S.Dionigi substation

IN-FIELD ACTIVITY

General overview

The SFCL device was installed on December 2011 and, after having successfully completed this first preliminary live-grid test, it was switched-off to make the final assembly ready for the continuous long-term in-field operation. The SFCL device was officially energized in March 2012, launching a more than two years long in-field testing activity with the SFCL device operated coping with the real conditions of the Milan distribution grid and protecting a single feeder. RSE and A2A teams monitored the SFCL behaviour throughout the whole field test duration. For remote control purposes, a dedicated software has been developed to manage data of every relevant variable and a suitable graphic interface allows the technical staff to check the SFCL status whenever it is needed, for example: the nitrogen bath temperature at three different levels, liquid nitrogen bath level and pressure inside the cryostat, time-behaviour of currents (both total currents and currents through the superconducting windings), and voltage drop across each SFCL phase. Operators were kept informed about the SFCL status in real-time, by means of e-mail messages sent at three different times per day. At the end of June 2013, due to the achievement of the maximum amount of operational hours foreseen by the manufacturer the routine maintenance of the SFCL refrigeration system became mandatory, and therefore the SFCL device was switched-off. This temporary outage offered the chance to improve at the same time some features of the acquisition system, hence the SFCL was re-energized in the beginning of October 2013 for other nine months of uninterrupted in-field testing activity. The in-field activity has been officially completed in June 2014, after more than two years of SFCL service under the operating conditions of Milan distribution grid. The major outcome has been the effective limitation of a real 3-phase fault event, that represents the first case in Italy and one of the first worldwide [12] and therefore a dedicated paragraph has been devoted to its discussion. Further to this first successful installation, the hosting utility A2A is considering to install in the same substation a new SFCL prototype protecting four feeders at 9kV, therefore implying a SFCL device upgrading up to 9kV/15.6MVA. The new SFCL device is very challenging and its design and development has already been initiated.

Technical considerations

It is very challenging to deal with the measurements of the voltage drops across the three HTS phases, due to the large variation that affects their absolute values depending on the actual state of the HTS windings. During nominal working conditions, the current flowing through the HTS phases is lower than the critical current, therefore the voltage drop across each single HTS phase is very small, lower than $3V_{rms}$ and the related rms-value is logged by the acquisition system every 2s; in case a short-circuit occurs, the very steep enhancement of the current implies the transition of the HTS phases to the highly resistive state with an increase in the voltage drop across each single HTS phase up to $2.5kV_p$. In this case the instantaneous values of the voltage drops across the SFCL device phases, of the line currents and of the currents flowing through the HTS phases are logged by a sampling period of 10µs (100kHz). In order to properly cope with the nominal operating condition and with the short-circuit conditions, minimizing at the same time the influence of background noise, the voltage drop measurement is performed by means of voltage dividers that feature high values of accuracy (class 0.2) throughout the whole range of required voltages. It is clear that voltage dividers are adequately protected against the overvoltage in case of short-circuit and electrically insulated for the MV voltage. It is interesting to point-out that, after two-years of live-grid activity, a data base of 5 gigabyte had been constituted by the acquisition system, by recording every measurement logged during the SFCL experimental activity. Another challenging issue for the SFCL grid operations was related to the frequent voltage dips nearby the substation, that sometimes caused the temporary outage of the

refrigeration system. In this situations, the refrigeration system was manually restarted by the operators. In order to overcome this problem, a UPS rated at 30kVA was installed to supply the low voltage ancillary equipment of the SFCL device, such as the asynchronous electrical motor of the Stirling refrigeration system and the chiller devoted to the water cooling of the refrigeration system compressor. In this case, a better system reliability could be attained by using refrigeration systems able to automatically re-start in case of voltage fluctuations.
The only long duration outages of the SFCL device were due to the scheduled ordinary maintenance services and to the necessity to supersede a sensor in the Stirling machine cold head. The sensor substitution, in particular, required the cold head to be shipped to the manufacturer, therefore implying nearly one month for the successful solution of the problem.

3-phase short circuit event

The layout of the grid portion supplied by the A2A S.Dionigi substation where the field test was performed is shown in Fig. 3: $V_{Tk\ h}$ (with k=1 or 2 and h=p or s) indicates the line-to-line voltage at primary and secondary of the two transformers involved in the fault. The SFCL device is installed at the beginning of Line 2, whose end-point was identified as the section of the ungrounded clean three-phase fault. The short-circuit apparent power A_{sc} of the grid connected to the 220kV busbar it is equal to 12.53GVA (with power factor $\cos\phi_{sc}$ of 0.1). This value is so large with respect to transforms T1 and T2 ratings that the 220kV busbar voltage may be considered constant. The main parameters of transformers T1 and T2 and of lines L1 and L2 are shown in Table II. For the sake of reliability and safety, A2A chose a dedicated time slot, configured the grid and tuned the protection relays to avoid any inconveniences to customers and grid devices. Since the short-circuit event on Line 2 could cause some

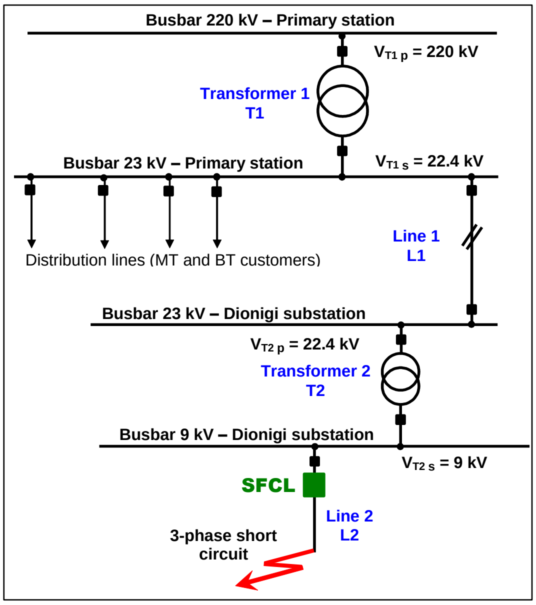

Fig. 3. Grid layout for the 3-phase fault event

Table II. Main parameters of transformers T1, T2 and lines L1, L2

Symbol	Quantity	T1	T2
A_n	Nominal power (MVA)	73	15.7
V_{Pn}	Primary nominal voltage (kV)	220	23.5
V_{Sn}	Secondary nominal voltage (kV)	23.8	9.43
v_{sc}%	Short-circuit voltage % V_n	12.3	5.5
p_{sc}%	Short-circuit power % A_n	0.32	0.38
z_{sc}%	Short-circuit impedance % Z_n	7.06	3.17
r_{sc}%	Short-circuit resistance % Z_n	0.19	0.22
x_{sc}%	Short-circuit reactance % Z_n	7.06	3.17
Symbol	**Quantity**	**L1**	**L2**
L_{line}	Line length (km)	3.2	0.29
N_{line}	Number of lines in parallel	2	1
R_{puL}	Line resistance per unit length (Ω/km)	0.15	0.2
X_{puL}	Line reactance per unit length (Ω/km)	0.12	0.1

inconveniences to both 9kV and 23kV customers, it was decided to differently supply those customers shifting them to other busbars connected to the same substation. The short-circuit event has been created by applying a suitable procedure that was agreed by A2A and RSE. It is important mentioning that the feeder protected by the SFCL (L2) links the S.Dionigi substation to the final end customers through a distribution cabinet. Therefore the first preparatory step consisted in shifting every load from the L2 feeder. Afterwards, the procedure included the following steps: (1) the feeder starting disconnector (at S.Dionigi substation) and the end-point disconnector of the same cable were opened; (2) the end-point disconnector was earthed; (3) the disconnector at S.Dionigi substation was closed. The above steps created a short-circuit event that, starting from an open-circuit condition, made the feeder protected by the SFCL suddenly fed by the full nominal voltage (9kV), thereby causing a three-phase fault at the feeder end-point. Absolute value and phase of the sinusoidal steady-state prospective short-circuit current were evaluated using the grid layout reported in Fig. 3 but without the SFCL device. In these conditions, also the short-circuit current instantaneous values were calculated by means of numerical simulations of the electromagnetic transient, taking into consideration the same initial conditions that the electrical variables had at the inception of the real short-circuit event. Table III reports on the resistance and reactance values (referred to the 9kV voltage level, i.e., the line-to-line busbar voltage before the fault inception) for each grid branch involved in the fault. The rms-value of the steady-state prospective short-circuit current, its power factor and the maximum prospective peak absolute value, calculated as functions of the reactance and resistance values reported in Table III, are shown in Table IV.

Table III. Equivalent resistances and reactances referred to 9kV

Grid part	R (mΩ)	X (mΩ)	Z (mΩ)
HV grid upstream the 220kV busbar	0.65	6.43	6.46
Transformer 1	3.61	135.6	135.65
Line 1	39.38	30.12	49.58
Transformer 2	21.63	310.5	311.26
Line 2	56.84	29	63.81
Short-circuit resistance, reactance and overall impedance	122.11	511.65	526.02

Table IV. Prospective short-circuit current: calculated values

Symbol	Variable	Value
I_{SCss}	Steady-state rms value (kA_{rms})	9.88
$\cos\theta_{SC}$	Steady-state power factor	0.232
I_{SCp}	Maximum-peak absolute value (kA)	20.86

The maximum-peak absolute value arises when the short-circuit inception coincides with the zero-crossing of the phase voltage, that is considered as the forcer input in the equivalent grid representing the short-circuit.
The short-circuit event took place on May 17th 2014 at 7:52AM: the fault lasted 70ms and the acquisition system logged the electric variables in fast mode for 400ms (i.e., about 50,000 samples for each variable).
Fig. 4 shows time behaviour of prospective short-circuit current (I_{SC}) and of the limited current (I_{LIM}). The data analysis shows that the SFCL device limited the short-circuit current with peak Limitation Factors ($LF=I_{SC}/I_{LIM}$) comprised between 1.76 and 2.48.
Table V reports I_{SC} and I_{LIM} peaks, the current fraction flowing through the HTS windings (I_{HTS}) and the featured LF. In particular at the first peak, the current values of phase R were limited from 16.07kA down to 8.43kA, hence performing LF=1.91; similarly, for phase S from 5.63kA down to 2.63kA (LF=2.14), and for phase T from 20.84kA down to 11.87kA (LF =1.76).

SFCL performance during limitation

Each SFCL phase is shunted by an air-core reactor featuring a resistance of 0.011Ω and a reactance of 0.395Ω. During nominal conditions, the current flowing through the reactors is negligible because they are short-circuited by the HTS windings (being the HTS resistance practically zero), whereas during short-circuit conditions it carries about 90% of the total current. Indeed, Fig. 5 shows that during the short-circuit transient the currents flowing through the HTS windings are significantly smaller than those circulating through the air-core reactors, moreover they are shifted by π/2, being the air-core reactors impedance almost completely inductive.

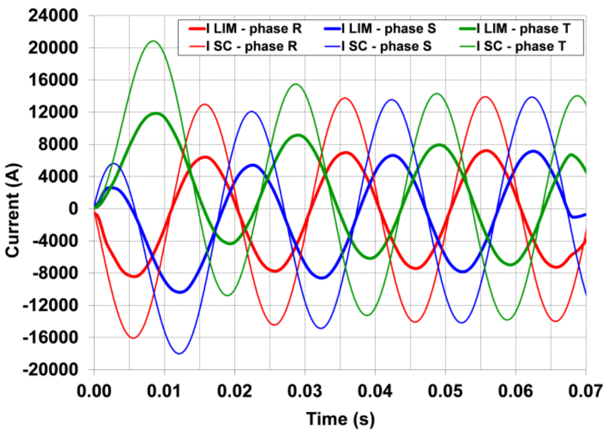

Fig. 4. Time behaviour of the prospective fault current without SFCL (I_{SC}) and of the fault current as limited by the SFCL device (I_{LIM}).

Table V. Short-circuit current peak values in kA with (I_{LIM}) and without SFCL (I_{SC}), in HTS windings (I_{HTS}), and Limitation Factors LF

Peak no.	1st	2nd	3rd	4th	5th	6th	7th
Phase R							
I_{SC}	-16.07	12.98	-14.44	13.75	-14.07	13.92	-13.99
I_{LIM}	-8.43	6.43	-7.76	7.00	-7.43	7.23	-7.27
I_{HTS}	-1.88	1.30	-0.82	0.64	-0.59	0.56	-0.53
LF	1.91	2.02	1.86	1.97	1.89	1.92	1.92
Phase S							
I_{SC}	5.63	-18.01	12.08	-14.87	13.55	-14.17	13.88
I_{LIM}	2.63	-10.38	5.42	-8.62	6.63	-7.84	7.15
I_{HTS}	1.47	-1.55	1.13	-0.64	0.62	-0.57	0.55
LF	2.14	1.73	2.23	1.73	2.04	1.81	1.94
Phase T							
I_{SC}	20.84	-10.79	15.49	-13.26	14.31	-13.81	14.05
I_{LIM}	11.87	-4.35	9.15	-6.18	7.94	-6.98	6.72
I_{HTS}	1.63	-1.23	0.64	-0.63	0.57	-0.55	0.52
LF	1.76	2.48	1.69	2.15	1.80	1.98	2.09

The pure resistance inserted by the SFCL during the fault is function of the actual current and temperature and it is approximately equal to 5.9Ω at the end of the fault.
Fig. 6 shows the instantaneous values of the resistance that each HTS winding inserts in the grid during the short-circuit, along with the dissipated energy in the HTS windings and in the air-core reactors. The HTS winding of phase R, S, and T dissipated respectively 81.0, 75.2 and 78.3kJ during the 66ms-long short-circuit (i.e., 1.23, 1.14, and 1.19MW in terms of mean power). Numerical elaborations where performed to purify the voltage drop measurements from external disturbances and the small inductive component due to HTS windings residual inductance (about 8μH). This approach allowed to get the resistance time-behavior ($R_{HTS}=V_{HTS}/I_{HTS}$) shown in Fig. 6. Devices devoted to protection against short-circuits have to meet the following requirements:

(a) Rated short-circuit "breaking" current exceeding the prospective short-circuit current;
(b) Switching time compatible with the max allowed temperature increase of cables (protections have to guarantee that the temperature increase does not exceed the temperature limit of installed cables).

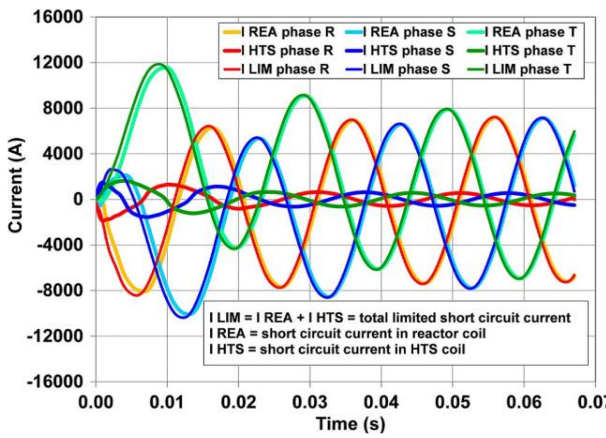

Fig. 5. Limited short-circuit current (I_{LIM}): comparison between the current flowing through the HTS windings (I_{HTS}) and the reactors (I_{REA}).

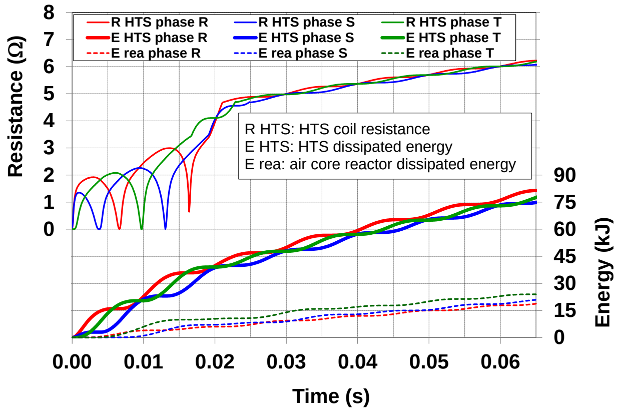

Fig. 6. HTS windings resistance and dissipated energies of air-core reactors and HTS windings during the fault transient.

As far as the requirement (a) is concerned, SFCL benefits are well described by the LF shown in Table V. Requirement (b) implies the study of the energy passing through the device during the short-circuit event. This energy is commonly represented by the expression:

$$I_{qt}(t)=\int_0^t I^2(\tau)\cdot d\tau \qquad (1)$$

The equation (1) is introduced by international standards to estimate the specific thermal energy that flows through the protection device during the fault. Remarkably, the SFCL limiting action allows a reduction of the short-circuit specific energy by a factor in the range 3.5 - 4.

CONCLUSIONS

The first Italian SFCL device has been installed in a real distribution grid. This project has been carried-out by RSE in the framework of a R&D national project and the result is a resistive-type BSCCO-based 9kV/3.4MVA SFCL installed as a single-feeder fault protection in a A2A substation of the Milan urban area. The SFCL was commissioned in March 2012, thereby launching a more than two years long field-testing activity. It is the first time in Italy, and one of the first worldwide, that a SFCL device has been successfully installed in a real distribution grid, coping with the daily grid working condition and limiting a three-phase fault in agreement with the hosting utility requirements. This first successful installation paves the way for a second in-field activity: the hosting utility A2A is considering to protect four different feeders at 9kV in the same substation by means of a new SFCL device. This means a SFCL device upgrading up to 9kV/15.6MVA. The development of the new upgraded SFCL device has already been initiated.

Acknowledgments

This work has been financed by the Research Fund for the Italian Electrical System under the Contract Agreement between RSE S.p.A. and the Ministry of Economic Development in compliance with the Decree of March 8, 2006.

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