STUDY OF UNIVERSAL POWER SMES COMPENSATOR FOR LV DISTRIBUTION GRID

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***Abstract*—The design of an interface device for interconnecting a SMES (Superconducting Magnetic Energy Storage) to a LV distribution grid is carried out, in order to demonstrate the feasibility of a SMES for achieving, with the same device, power quality and critical load protection functions. The work is developed inside a three-year research project, called DRYSMES4GRID, funded by the Italian Minister of Economic Development and sees the cooperation of five partners (companies, universities, and research institutes). The aim of the project is to demonstrate the feasibility of the SMES (500 kJ/200 kW) in the short/medium term at competitive cost based on Magnesium Diboride (MgB2). In particular, in this article, after a brief state of art of the SMES applications for the grid, the design and the control logics of the DC/DC chopper for the power modulation of the energy stored in the SMES and of the three-phase AC/DC inverter are shown. The activities are mainly based on digital simulations to evaluate the performances of this device in a LV distribution grid in presence of linear and non-linear loads, considering in particular the peak shaving function, while the device is connected to the mains, and the islanding operation condition after the detection of a voltage dip.**

Keywords—SMES; Power electronic converters; Power Quality, shunt unit.

I. INTRODUCTION

The superconducting magnetic energy storage (SMES) is an high power and low energy density electric storage system, with high number of cycles and high round trip efficiency (around the 97%). This means that it can supply a huge amount of power instantaneously, to contribute to improve the systems power quality (e.g. in case of sensitive customers, disturbing loads, stabilization of microgrids and/or vulnerable subnetworks). Thanks to the power electronic interface, the SMES can act as a peak shaving device, an active filter (thus compensating flickers, harmonic, reactive power, current unbalance, load fluctuation) and can supply loads in island operation condition, compensating network disturbances as voltage dips and interruption.

Considering these opportunities, the project DRYSMES4GRID funded by the Italian Minister of Economic Development with the cooperation of different Italian partners (Columbus Superconductors SpA, ASG SpA, University of Bologna, RSE SpA, ICAS S.C. r. l. and CNR – SPIN) have been started. The aim is to realize a demonstrator of a SMES device (500 kJ/200 kW) based on Magnesium Diboride (MgB2) superconducting material. This material has a critical temperature of 39 K, much higher than traditional superconductors, and allows a cooling technology which does not use liquids (cryogen free) thus avoiding the related issues of supply, safety and cost [1]. All engineering aspects needed of the practical development of SMES technology will be dealt with in the project, including manufacturability of cable and winding, stability of the winding during the fast charge and discharge, electrical insulation, temperature uniformity, minimization of cooling losses and converter losses during standby. Finally, the demonstrator will be tested in the test facility available at one of the partner's site. Furthermore, all aspects related to the realization of power electronic devices and controls, needed for the appropriate operation of the SMES in the distribution network, will also be dealt with. And those ones are the main core of this paper. The activity presented in the paper has also been supported by a Master degree thesis [2].

In particular in the Section II the SMES structure and the main grid applications are presented, in Section III the functions, the design and the control architecture of the Power Quality SMES device are shown. In Section IV the main results of digital simulation are discussed with the relevant conclusions.

II. SMES TECHNOLOGY AND STATE OF ART

A. SMES structure

Generally, a SMES system can be divided in three main parts (Fig. 1):

- superconducting coil: made of superconductive material, it is the effective energy storage part of the device and it can be managed in: charging, stand-by and discharging operation mode [3].
- Cooling system: bath cooling or cryogen-free [4].
- Power Conditioning System (PCS): DC/DC chopper for the power modulation of the energy stored in the SMES and three-phase AC/DC inverter for the connection to the grid.

During the charging operation mode, a DC current flows inside the coil, generating a magnetic field whose energy is described by the following formula:

$$E = \frac{1}{2} \cdot L \cdot I^2 = \frac{1}{2} \cdot \frac{vol}{\mu_0} \cdot B^2 \quad (1)$$

where L is the inductance of the coil; I is the DC current which flows in the coil; vol is the volume in which the field is stored; μ_0 is the vacuum permeability; B is the field magnetic

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induction.

When the coil reaches its maximum current level, set under the critical current limit, the coil is short-circuited and it enters in the stand-by mode. This "storage" current can flow indefinitely without any significant energy loss.

The last and most important operation mode is the discharging one: in this modality, the coil is connected to the load, and it releases its energy under the form of flowing current.

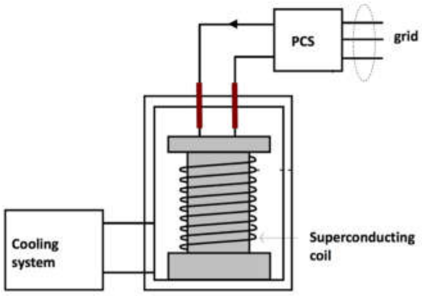

Fig. 1. General SMES Structure

B. *SMES state of art*

Basing on the SMES application state of art, it is possible to identify two main application areas: one for the protection of load against grid disturbances and the second for the protection of the grid against loads or generators disturbances.

Both of the application areas have in common a large amount energy consumption for a limited time: SMES for its nature can manage these operations. In particular the Table I summarizes some SMES applications [5] ÷ [11].

TABLE I. A SMES-POWER GRID APPLICATIONS

Power Grid Applications	SMES Functions	PCS Operation Mode
Power System Stability [5]	Active and reactive power supplier for the voltage and frequency stability	Parallel to grid
Critical Load [6]	Power supplier during a voltage dip	Islanding
Compensation of Fluctuating loads [7]	Power supplier for variable loads	Parallel to grid
Dynamic Voltage Compensator [8], Dynamic Voltage Restorer [9]	Amplitude and waveform voltage load compensator	Series to grid
Improving System Symmetry [10]	Voltage and current supplier for making symmetric the system	Series-Parallel to the grid
Tie Line Control [11]	Renewable energy power support	Series-Parallel to the grid

In particular in this study the second and third application have been considered and in the next Section the function of the device are presented with the design and the control architecture studied.

III. UNIVERSAL POWER SMES COMPENSATOR

The device is a Universal Power Compensator, designed following the strategy reported in [12]÷[15], connected in the LV distribution grid, near disturbing/sensitive loads, acting:

- in parallel with the grid as an active power compensator, able to reduce load peak shavings;
- in parallel with the grid as an universal active power filter, able to compensate current harmonics, fast active, reactive power fluctuations and reactive power compensator;
- in island operation, after a grid fault detection, able to supply sensitive loads thanks to a storage systems, connected in its DC section, and to the disconnection from the grid.

In Fig. 2 it is shown the scheme of the designed system, constituted of:

- interface device: inverter with its commutation inductances, filters, coupling transformer and static switch;
- the SMES: inductance L_{SMES} and DC/DC chopper.

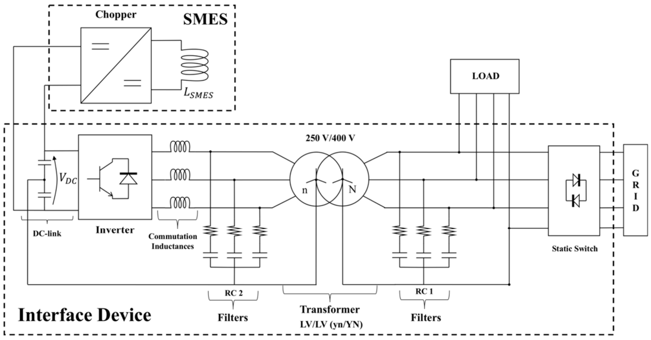

Fig. 2. General system scheme

In Table II the preliminary design parameters of the device are reported.

TABLE II. MAIN CHARACTERISTICS DESIGN OF THE DEVICE

Measures	Symbol	Inverter	Chopper (I/V)
Rated Power	A_n	200 kVA	200 kW
DC Voltage	V_{DC}	750 V	
AC Voltage	V_{AC}	250 V	
DC Capacitor	C_{DC}	81 mF	
Commutation Frequency	f_{sw}	12.6 kHz	5 kHz
Maximum coil current	I_{max}		400 A
Minimum coil current	I_{min}		135 A
Coil inductance	L_{SMES}		4.33 H
Commutation Inductance	L_{Com}	16.50% A_N	
Transformer Inductance	Z_{tr}	3.5% A_N	
RC filter Capacitor 2	R_{f2}, C_{f2}	0.50% A_N	
RC filter Capacitor 1	R_{f1},C_{f1}	10.30% A_N	

A. *SMES design*

In the study, the inductive storage system has been considered as a simple inductance whose value is L_{SMES}; this solution is no so far from the reality since the superconductive material reaches very low resistance, operating under its critical temperature. Furthermore, the losses in the coil-chopper interconnection cables have been considered negligible.

The energy stored in the SMES is modulated by the two-quadrant chopper, whose scheme is shown in Fig. 3[1]. In the scheme, it has been also considered a dump resistor, which is activated by the control system when the DC voltage and the current in the SMES overcoming its security levels (in the real application, it is activated by the quench detector protection). Its activation opens the circuit breaker isolating the SMES from the inverter DC side. The dump resistance value is calculated in order to not overcome a maximum allowable voltage of 1 kV when the SMES is operating at the maximum current of 400 A. This implies a resistance of 2.5 Ohm and a time constant during discharge of 1.73 s.

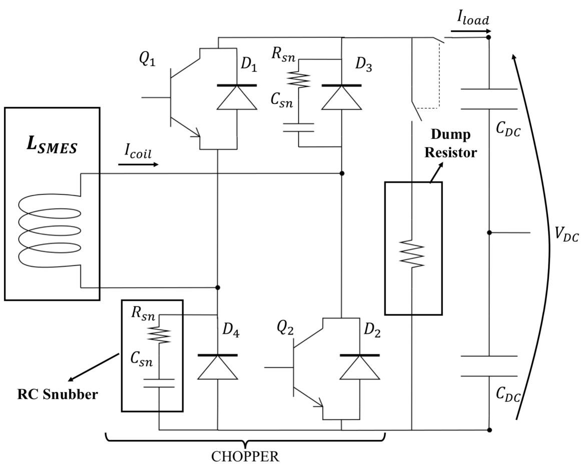

Fig. 3. SMES scheme

Considering the eq. (1) and the preliminary data in Table II, it is possible to define the maximum available energy stored in the coil as:

$$E_{av} = \frac{1}{2} \cdot L_{SMES} \cdot (I_{max} - I_{min})^2 = 307\ kJ \tag{2}$$

given E_{av}, the SMES discharge time τ_{SMES} is:

$$t_{SMES} = \frac{E_{av}}{P} \tag{3}$$

where P is the DC voltage product with the current absorbed by the load on the DC side:

$$P = V_{DC} \cdot I_{load} \tag{4}$$

Eq (4) shows an important constraint imposed by the load DC voltage, which has a direct consequence on the coil available current. I_{coil} has to be greater than I_{load} to supply the load. Considering a fixed load power absorption at the rated conditions: P = 200 kW and V_{DC} = 750 V, the resultant coil available current is 266 A. Substituting I_{min} with 266 A in (3), the useful energy becomes 154 kJ consequently the SMES, in rated condition, has an energetic autonomy of 770 ms. Using I_{min} (135 A from Table II) the SMES could supply a load of 100 kW for 3 s.

The coil SMES characteristics have been determined from the coil capability graph (Fig. 4, max coil current Imax – operating temperature T_{op}) considering an operating temperature of 22 K with a density current ratio (J/JC) equal to 0.6. In particular in the paper the results of the behaviour of the system considering the "star" point in Fig. 4 are presented in the following sections.

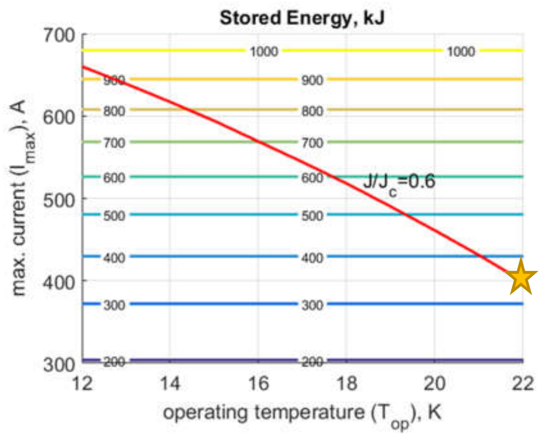

Fig. 4. Coil SMES capability

B. *Control System Architecture*

In order to perform all the functions, it is designed a control system based on an open loop control with broad range harmonic analysis using the sinusoidal Pulse Width Modulation (PWM) technique. Fig. 5 shows the general control system blocks scheme; the scheme varies its topology depending on the following two operation modes:

- in grid connected mode: the relevant function block in Fig. 4 is active and its algorithms, implemented inside it, provides the reference compensative error e_{comp};
- in island mode: the relevant function block in Fig. 5 is activated after the voltage dip detection[2] and its algorithms, implemented inside it, provide all the current e_{UPS}, necessary to protect the load.

In both of the cases the reference errors, e_{comp} and e_{UPS}, are processed by the same current regulator which determines the reference voltage (V_{reg}). After subtracting to V_{reg} the grid voltage (as a feedforward action) and the voltage error of the capacitors central point (e_{cen}), the resultant voltage V_{mod} becomes the reference voltage for the PWM modulation. The preliminary set of parameters for the control block are reported in Table III. Current and Voltage regulators are resonant (PIR), while DC voltage regulator is a simple Proportional-Integral (PI) type.

[1] The RC snubber is designed in parallel with each diode D_3 and D_4, this solution is necessary in order to guarantee the simulation stability by providing a fixed voltage across the diodes and by filtering the commutation spikes of the IGBT. The value of the capacitor is chosen minimizing the commutation power losses which are directly proportional to the capacity of the snubber and to the commutation frequency.

[2] The voltage dip detection acts in two ways: calculating r.m.s grid voltage, on 1⁄4 of its period [16], or measuring the value of the rectified voltage. The voltage dip detector provides the logic signal (0/1) in order to communicate the voltage dip occurrence, to the control system.

TABLE III. AC/DC INVERTER CONTROL BLOCK PERFORMANCES

	I	V_{DC}	V_{AC}
	PIR	PI	PIR
cut-off frequency [Hz]	800	5	300
phase margin	75°	85°	85°

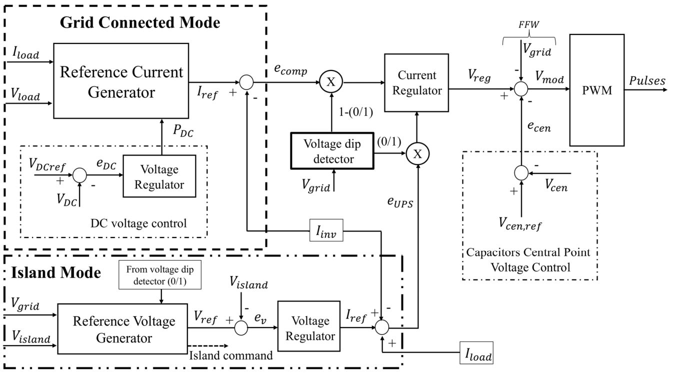

Fig. 5. General control system blocks scheme

To allow the control of the charge/discharge and stand-by of the SMES, a chopper control scheme has been implemented as shown in Fig. 6: the step-response analysis suggests a cut-off frequency $\omega_{cut} = 720$ Hz and a phase margin $\omega_{cut} = 64°$.

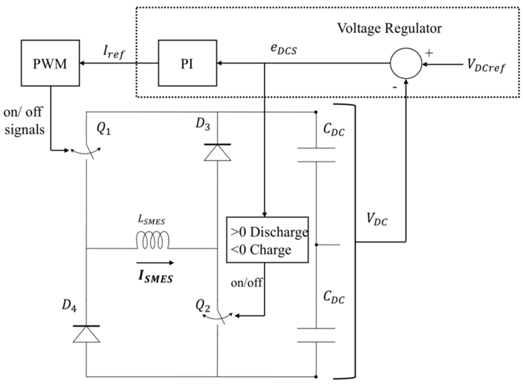

Fig. 6. Chopper General Control System

IV. SIMULATION RESULTS

In the study, in order to verify the performances of the Universal Power SMES Compensator, different kind of loads have been considered: linear three-phase balance resistive-inductive load, single-phase load and three-phase non-linear load (f.i. diode bridge). The digital simulations have been developed in ATPDraw to analyse the behaviour of the device both in grid connected operation mode and in island mode.

As an example, in the following the main results of a peak shaving compensation and an island operation condition have been shown.

A. Peak shaving and reactive power conpensation

In this case, the device operates to maintain to a defined level the power delivered from the distribution network compensates, facing to an absorption power variation of a three-phase RL load (50 kVA). Starting at t=0.3 s, the load active and reactive power vary between 200 kW-107 kvar and 100 kW-22 kvar with a frequency of 9 Hz and after 450 ms it returns to its initial steady state condition. In Fig. 7 the active powers are shown: the device (green line) generates power when the load power overcomes the reference level and it absorbs power in the dual condition. The reference grid power value is set to 150 kW (red line).

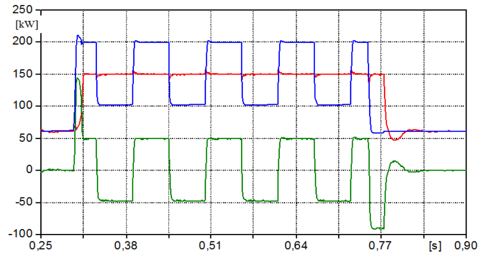

Fig. 7. Active power: load (blue), grid (red), inverter (green)

About the reactive power, as shown in Fig. 8, the device (green line) is able to compensate totally the load reactive power (blue line): the effect on the grid is a complete absence of reactive power exchange, except the spikes which are the effect of instantaneous power changes.

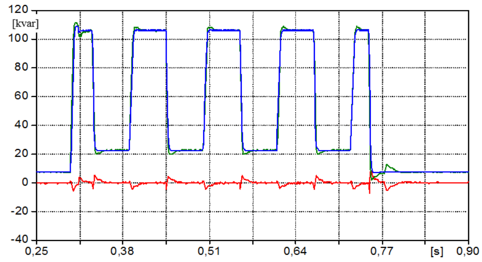

Fig. 8. Reactive power: load (blue), grid (red), inverter (green)

The compensating action of the SMES device can also be pointed out comparing the load and grids currents: against load currents (Fig. 9) abruptly changes, the grid delivers a "constant" current flow (Fig. 10).

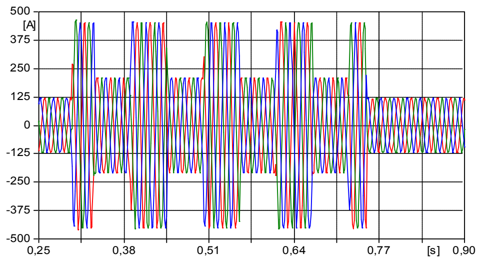

Fig. 9. Load currents

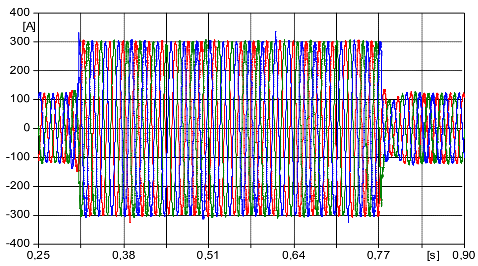

Fig. 10. Grid currents

About the DC section, in Fig. 11 the V_{DC} regulated by the chopper is shown ($V_{DCref} = 750\,V$). The sudden load power variation changes have a direct consequence on the inverter DC side, decreasing or increasing the voltage value.

The current in the SMES coil (Fig. 12) varies incrementing and decrementing its value following the load variations. There is not a significant variation of the current at the beginning and at the end of the event because the reference power chosen (150 kW) is positioned almost in the average of the power variations, the result is an almost symmetric charging and discharging effect of the coil.

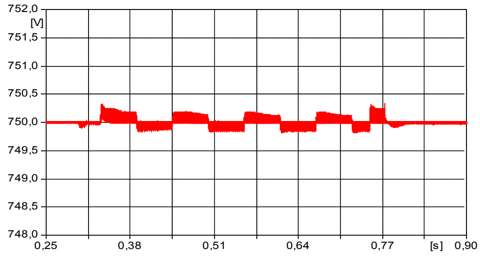

Fig. 11. DC voltage (change the figure)

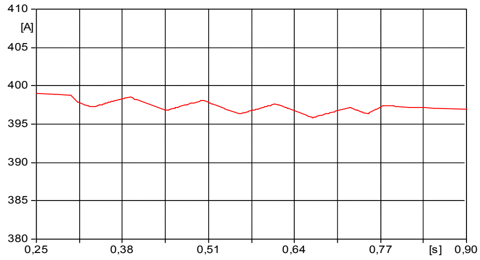

Fig. 12. Current in the SMES coil

B. *Island mode: non linear sensitive load*

In case of fault in the upstream distribution grid, the Universal Power SMES Compensator device is able to supply the sensitive load during island operation. After the detection of a voltage dip, the static switch opens and the device starts to regulate the V_{island} voltage to the load.

As an example, the main results of the simulation with a diode-bridge of 200 kVA are shown. At 0.4 s a symmetric fault occurs in the MV distribution grid which causes a voltage dip with 90% V_n depth (Fig. 13) with a 500 ms duration. Detecting the voltage dip, the interface device opens the static switch and enters in island mode (brown curve in Fig. 14).

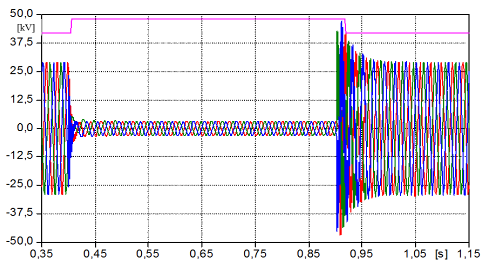

Fig. 13. Line to line MV voltages and voltage dip detection signal (magenta)

The load line voltages (Fig 14) are restored with a minor transient. The device is able to regulate the AC voltage in presence of the disturbing load: in islanding, the voltages are affected by a THD equal to 8%[3]. After the voltage dip extinction, the control system of the device recognizes the grid normal operation condition after 10 ms, but the compensation lasts 100 ms more, before starting the resynchronization and reconnection with the grid: this choice has been adopted to avoid any fast reconnection to the disturbed grid. As a direct result, the device is reconnected to the grid after 150 ms, with a total islanding duration of about 650 ms.

Before the voltage dip detection (Fig 15), the SMES device works in a grid connected mode. In the proposed test the device is filtering the load current (blue line) characterized by a THD equal to 18%, indeed the grid one (red line) shows a THD of 6%. When the fault occurs in the MV grid, the inverter current (green line) increases feeding the fault until the voltage dip is detected and the static switch opened. In the island mode, the device supplies the load and, when the fault is extinguished, the device starts to synchronize the V_{island} to the V_{grid} of the mains. When the rms, the phase and the frequency of the island voltage reach the values of the mains ones, the static switch closes and the device compensation mode get back to the pre-fault conditions (Fig 16).

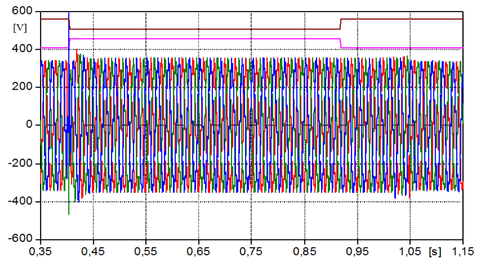

Fig. 14. Line voltages in island at the beginning of the voltage dip, for non-linear load; voltage dip detection signal (magenta); static switch trip (brown)

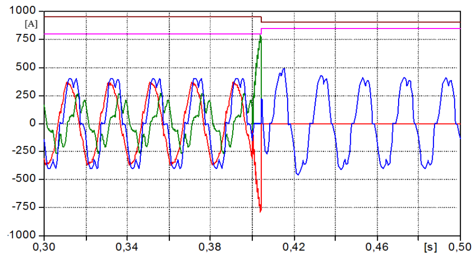

Fig. 15. Phase "c" currents at the beginning of island operation: grid (red), load (blue), inverter (green); voltage dip detection signal (magenta); static switch trip (brown)

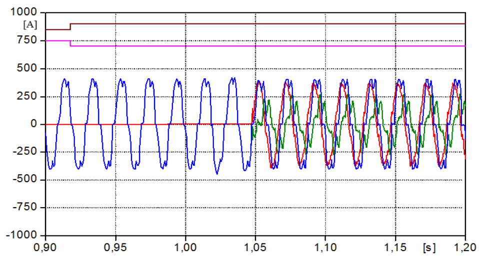

Fig. 16. Phase "c" currents at the end of island operation: grid (red), load (blue), inverter (green); voltage dip detection signal (magenta); static switch trip (brown)

[3]This value is in compliance with the CEI EN 50160 requirements.

About the DC side, the DC voltage, regulated by the chopper ($V_{DCref} = 750\ V$) is kept constant with small transient variations at the beginning and at the end of the island operation. In particular during the resynchronization it's possible to see the dynamic of the control blocks but the relevant effect is a V_{DC} variation less than 1% (Fig 17). The SMES current decreases, providing the necessary power to the load (Fig. 18). The current stored in the SMES after the islanding event (650 ms) is 315 A, comparing this result with the evaluations explained in Section III, it is possible to notice that the system cannot compensate two consecutive events with a load of 200 kVA, because the theoretic limit is fixed at 266 A: after the resynchronization to the grid the SMES has to be recharged.

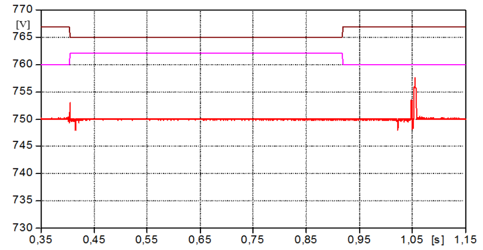

Fig. 17. DC voltage during the island operation; voltage dip detection signal (magenta); static switch trip (brown)

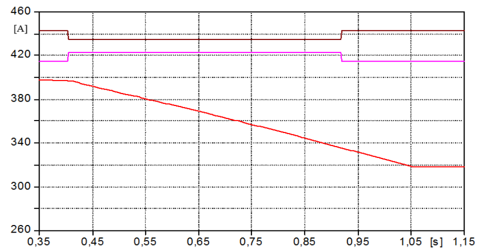

Fig. 18. SMES current trend (red) during the island operation; voltage dip detection signal (magenta); static switch trip (brown)

V. Conclusion

The paper presents the preliminary results of the study of a Universal Power Compensator connected in the LV distribution grid, characterized by a SMES storage system. In the frame of the project DRYSMES4GRID, the aim is to realize a demonstrator of a dry SMES device and to validate the functions to support the distribution grid that could be implemented by the device.

In particular, in the study it is also considered the presence of disturbing/sensitive loads, to evaluate the behaviour of the device as a PQ compensator, both when it is connected to the grid and it is supplying the sensitive load when a fault occurs in the main distribution grid. After the design of the components and of the control schemes different digital simulations have been performed.

The simulation results allow having the first validation of the expected performance in both the operation conditions. The next step, before the realization of the hardware demonstrator, is the Real Time simulation. Control Hardware in The Loop tests will be performed in order to verify the feasibility to develop the device control logic into hardware electronic boards.

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