Logical coordination between LV compensation devices to provide different PQ levels in the distribution network

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***Abstract*—The increasing use of grid connected power electronic systems generates a set of interference phenomena between those devices and distribution grids. Power electronic systems are both sensitive to voltage disturbances and sources of disturbances, such as current harmonic distortion, voltages unbalance and flicker. Such phenomena motivated the study of a system named Open Unified Power Quality Conditioner, based on power electronic converters, used for the improvement of the Power Quality level in low voltage distribution grids. The study, mainly theoretical, has addressed the issue of compensators coordination under different operating conditions.**

***Index Terms*—Power quality, series compensator, shunt compensator, coordination, distribution networks**

I. INTRODUCTION

The activities reported in the paper are part of a collaborative agreement with Unareti s.p.a. and are based on these main issues:

- power electronics devices are, disturbing elements for the quality of supply, especially for the high absorption/generation of harmonic currents. On the other hand, they are often sensitive to network disturbances, such as voltage variations, voltage dips or over-voltages;
- the increasing number of sensitive loads drives Distributor System Operators (DSO) to address the issue of ensuring adequate service quality, also in response to the need for continuous improvement of the Power Quality (PQ) level set by the Italian Regulator;
- the PQ level to be guaranteed in the network is often customized according to the specific needs of sensitive users. The DSOs have to be able to guarantee different levels of PQs, for example, with "quality contracts".

The scope of this activity, evolution of what has been described in [1], [2], [3] and [4], is the study through digital simulations of the possibilities of simultaneous use in the network of PQ compensation devices based on power electronics and their coordination (solution identified as Open Unified Power Quality Conditioner - UPQC) in order to improve PQ of Low Voltage (LV) distribution networks.

II. POWER QUALITY COMPENSATOR DEVICES

The PQ compensator devices, based on power electronic converters, considered in this study are "series" and "shunt" compensator. The main data of these devices are listed in TABLE I.

TABLE I. MAIN DATA OF THE DEVICES

Device		Series	Shunt
LV network voltage	$V_{network}$	230 V	230 V
Rated power	A_N	90 kVA	9 kVA
Transformer connection		Y/y	D/y
Primary voltage transformer	V_{ac}	152 V	400 V
Secondary voltage transformer (inverter side)	V_{ac_inv}	152 V	214 V
DC rated voltage	V_{CCN}	800 V	600 V
Inverter reactance	X_{ccind}	16,5% Z_N	16,5% Z_N
Transformer reactance	$X_{cctransf}$	3% Z_N	3% Z_N
Main ac filter	Q_N	10% A_N	10% A_N

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A. *Series compensator*

The scheme considered of the "series" compensator is shown in Figure 1. The device works independently on each electrical phase; the injected controlled voltage (V_S) is added to the grid voltage (V_G) in order to guarantee a phase-to-neutral voltage without perturbation to the downstream load (V_L):

$$V_S = V_G - V_L \tag{1}$$

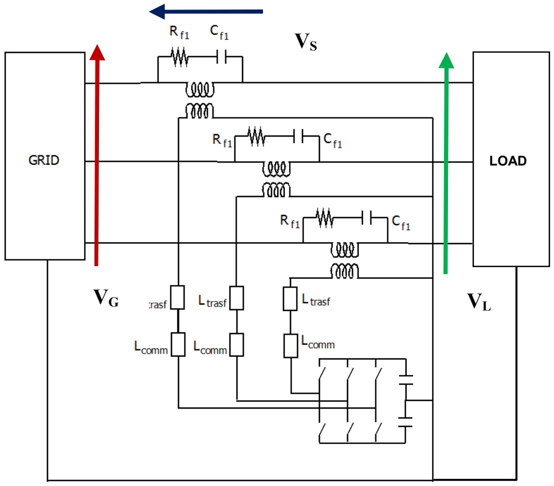

Figure 1. Series compensator scheme.

The device is able to: (i) supply rated network voltages at sensitive/privileged loads in case of mains voltage disturbances (surges, voltage dips, flicker and unbalances); (ii) limit the currents in case of a load failure, ensuring fault currents compliant with protections settings.

Voltage regulation/compensation functionalities are “always on” and they don’t need any identification algorithms to be activated, avoiding possible delay in the nominal voltage restoration at “protected” loads[1]. The short circuit current limitation is instead activated only when a downstream fault is detected through the simultaneous measurements of compensator currents (grid side) and downstream grid voltages [3].

B. *Shunt compensator*

The scheme of the considered "shunt" compensator is shown in Figure 2. The device is based on a common three phase IGBT bridge. The DC side of the bridge is connected to two capacitors connected in series, whose central point is used as neutral point for the circuit. An adaptive hysteresis current band modulation with fixed switching frequency has been considered [1], [2] and [4].

This device is able to satisfy the following compensations: (i) active load filtering, reactive and active power variations compensation, (ii) island operation of sensitive loads, after the detection of a PQ event in the grid and thanks to the static switch operation and a battery storage system, connected to the DC side of the converter.

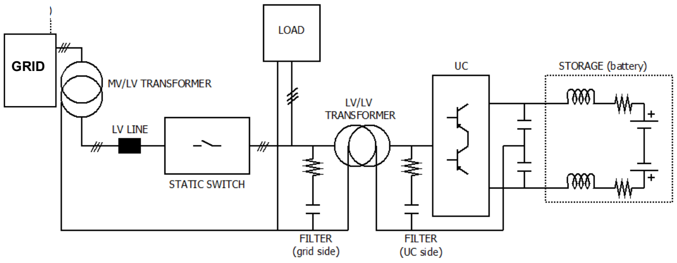

Figure 2. Shunt compensator scheme.

III. DEVICES COORDINATION

The idea of this study is evaluate the opportunity to use both of these devices connected to the same network and operating in an "autonomous" way based on local measurements, but which, if necessary, can be coordinated other through appropriate communication channels to develop the configuration of the Open UPQC system [5], [6], [7] in order to guarantee a higher PQ level in the LV distribution grid.

The coordination of the compensation devices can be based on:

- local controls: each device is controlled independently and implements only its specific compensation functions;
- local controls and information exchange among devices, in order to implement auxiliary support functions, i.e. in case of temporary overloads, resizing the possible availability of active/reactive power of the less loaded devices. Communications can be coordinated by a central controller or by the series compensator itself.

In order to evaluate the behavior and the performance of the Open UPQC system during steady state and in case of transients and network disturbances, the network model of Figure 3 was analyzed through digital simulations in the ATPDraw environment.

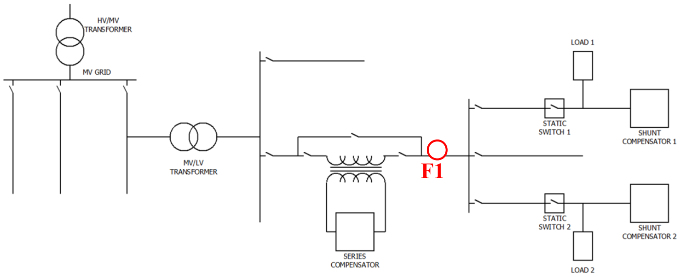

Figure 3. Grid reference model.

In particular for the coordination action, both the options have been considered and simulated. For the first approach all compensation functions were verified when both devices are connected to the same LV grid. For the second option (Figure 4), an overload of the series compensator was simulated. The

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[1] For all the considered control approaches, it was supposed that an external power converter, with its own control, manages the recharge of the DC side capacitors directly from the grid voltages.

series compensator, assumed as master device, requires to the shunt compensators for some support function.

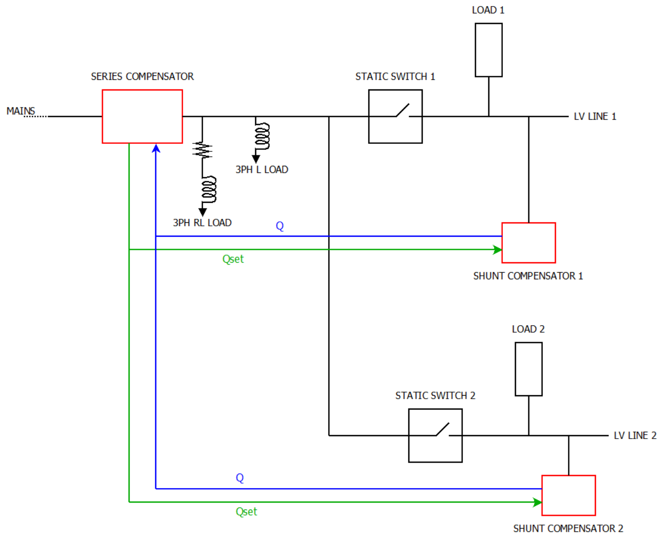

Figure 4. Scheme of information exchange among compensators for the support of the overloaded series devices by additional reactive power contribution from shunt compensators.

IV. SIMULATION RESULTS

In this section the main simulation results are shown; in the study different types of network failure were simulated, both in the upstream network of the series compensator and in the downstream. Furthermore, failures of the compensators themselves were considered. The ability of the compensation system to cope with all types of disturbances was proved, both on the basis of "local" machine controls only and in cooperation with other devices, thanks to a communication channel. Finally, simulations of internal failures of the devices and the procedures for their deactivation have been hypothesized and implemented in simulation models.

In particular in the following the scope of the simulation was to verify the behavior of the system in case of: a coordination strategy between the devices through a communication channel, (i) under over-load of the series device condition and (ii) in case of fault upstream and downstream in the LV grid.

A. *Over-load of the series device*

In this example, the series compensator is overloaded by the high current demand of downstream loads, so it requires supplementary reactive power to the shunt compensators. This condition has been simulated with the connection of a linear inductive three-phase load ($Q = 6$ kVAr, L_{load}=85 mH).

Simulation results are reported in Figure 3[2] and in particular:

a) line to line voltages in MV grid;
b) line to four wire voltages in LV grid;
c) line to four wire voltages of the single phase load (LOAD 2) during the fault in the LV grid;
d) line to four wire voltages of the disturbing (LOAD 1) during the fault in the LV grid;
e) series compensator currents;
f) single phase load (blue), shunt compensator (red) and grid (green) active power;
g) single phase load (blue), shunt compensator (red) and grid (green) reactive power;
h) disturbing load (blue), shunt compensator (red) and grid (green) active power;
i) disturbing load (blue), shunt compensator (red) and grid (green) reactive power;
j) active (red) and reactive (green) power of the series compensator.

At simulation time t=0,1 s a fault occurs in the MV grid (Figure 3a), and the voltage dip shows a residual voltage of 45% V_N, while the series compensator is overloaded (Figure 3e). The series compensator restores the downstream voltage to rated value (Figure 3b). At t= 0,8 s the series compensator imposes to shunt compensators to supply an additional reactive power contribution (+5 kVAr each) for reducing its overall current (Figure 3e, Figure 3j). Meanwhile, shunt compensators continue to compensate disturbing currents of their loads (Figure 3g, Figure 3i, Figure 3f, Figure 3h). At t = 1,1 s a fault in the grid section protected by the shunt compensator related to the single phase load was simulated, in order to verify the ability of the system to restore a “clean” voltage for all other loads. At the fault occurrence, a voltage dip occurs in the LV grid downstream the series compensator (Figure 3c, Figure 3d). Both shunt compensators disconnect from the mains for supplying their privileged loads in island operation. The shunt compensator 2 (supplying the single phase loads) starts to limit current, due to the presence of the grid fault in the associated network section. After 100 ms, the compensator shuts down and stops to supply the fault (Figure 3d, Figure 3h, Figure 3i). The shunt compensator 1 supplies the disturbing load in island mode for 100 ms and then it starts to synchronize island voltages to the main ones in order to have a reconnection to the mains without significant transients to loads (Figure 3c, Figure 3f, Figure 3g).

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[2] In the graph there are the logic signal to detect the voltage dip in the grid (pink signal up means there is the fault) and the logic signal of the static switch of the compensator 2 near the single phase load (brown curve).

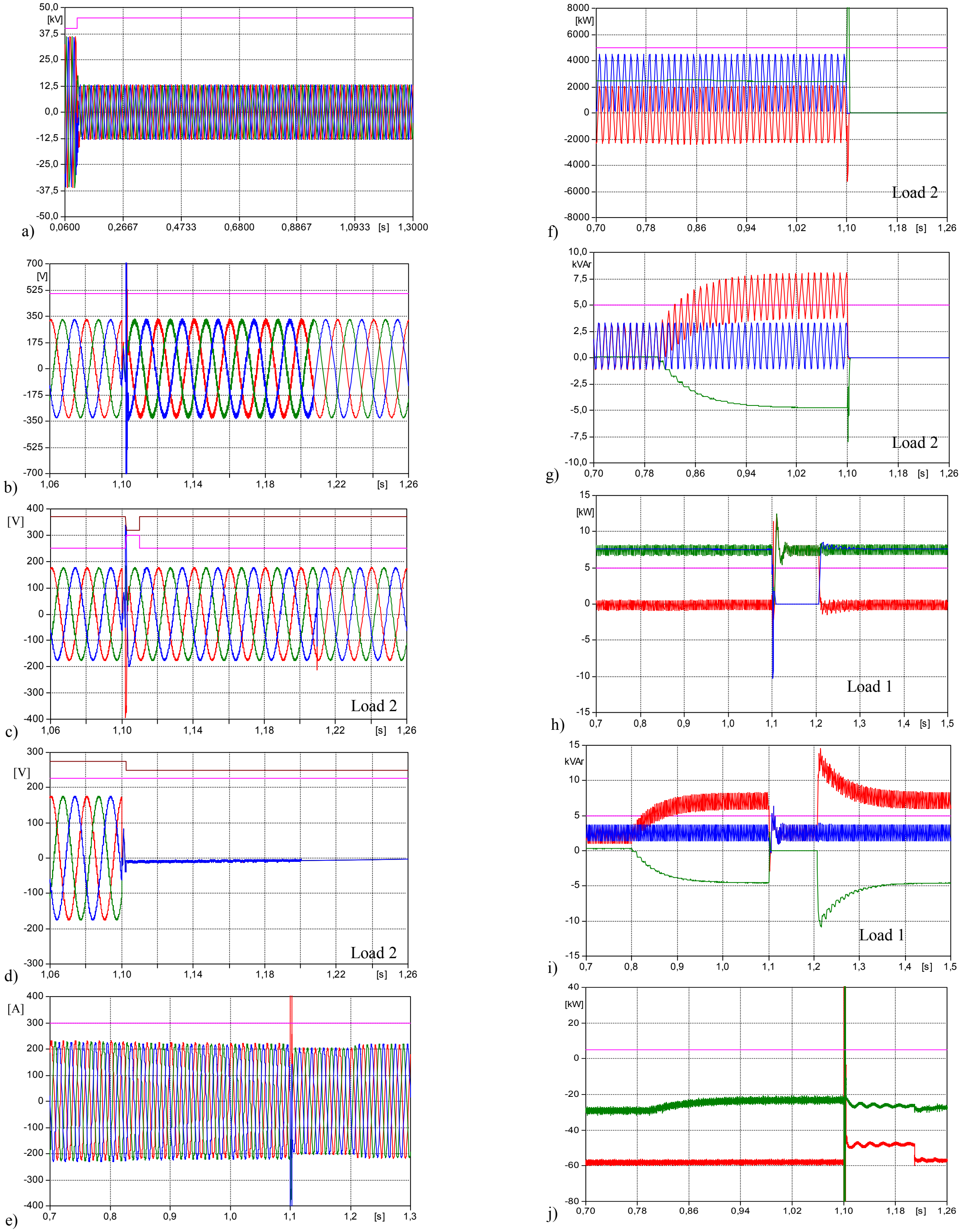

Figure 5. Scheme of information exchange among compensators for the support of the overloaded series devices by additional reactive power contribution from shunt compensators.

B. Low Voltage grid fault

In the following the simulation results for a LV downstream fault (F1 in Figure 3.) are presented. The fault occurs at t = 1 s and lasts 300 ms[3].

At the fault occurrence, the series device acts as a current limiter avoiding the voltage dip upstream propagation (Figure 6. Figure 7. and Figure 8. [4]): to limit the line current at 580 A (value defined in accordance with the capability of the device and with the protection relay thresholds), the series compensator injects a voltage to obtain a downstream voltage equal to:

$$V_S = I_{\lim} Z_{fault} \,. \tag{2}$$

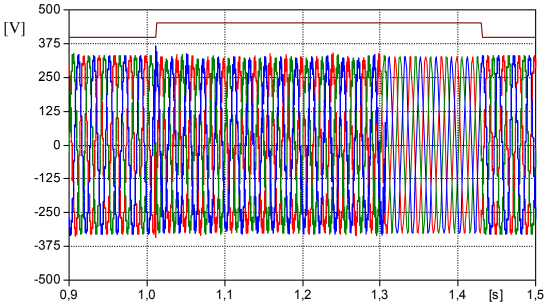

Figure 6. Upstream series devices voltages.

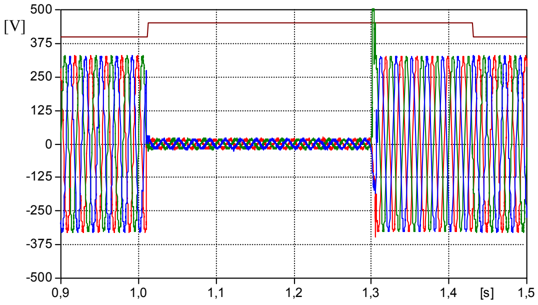

Figure 7. Downstream series devices voltages.

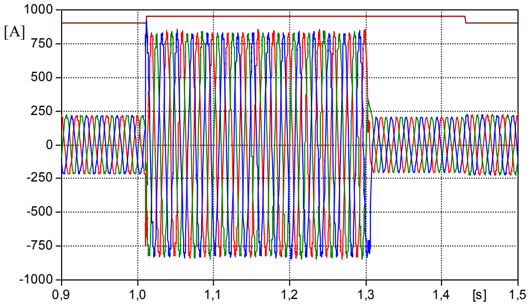

Figure 8. Limited fault line currents.

At t = 1 s, the shunt device, after the voltage dip detection (2 ms), feeds the sensitive load in islanding operation condition (Figure 9.): the shunt compensator is able to supply the load thanks to the storage connected to the DC link. When the fault is extinguished, after an intentional delay of 100 ms, the device starts to re-synchronize the island voltages to the main ones, before switching on the static switch and restoring the "pre-fault" operating condition.

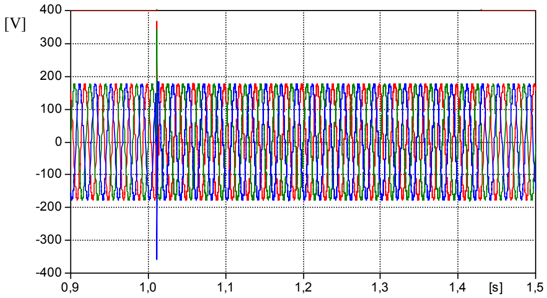

Figure 9. Load voltages during island operation condition thank to the shunt device.

V. CONCLUSION

The study and the simulation results have shown the possibility to use the series compensator together with one or more shunt compensators in a configuration of Open Unified Power Quality Conditioner (Open UPQC). The series device can be installed along a feeder or in the secondary substation to regulate the load voltages downstream; the shunt devices can be installed near sensitive or disturbances loads to compensate locally the reactive and disturbing components of the load currents or to supply them in island operation.

The devices can work independently (considering only their own local measurements), without creating interferences between themselves, as well as during transient phenomena. The right functionality of the system has been validated also during unbalanced network faults.

At the end the opportunity to coordinate the devices has been considered to support the network, based on a communication channel. In particular, the series device has been hypothesized as master in order to be able to control the reference set point of the shunt devices to regulate the reactive power to reduce the series device currents. The simulations showed the ability of the devices to cope with the different types of disturbances in each of the examined configurations.

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[3] Even if grid protections haven't been considered, the fault duration is fixed to consider the transient behavior during the network voltage restoration.

[4] The brown line refers to island operating condition.

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