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Power Quality Conditioning in LV Distribution Networks: Results by Field Demonstration

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Abstract--**Power quality in LV distribution networks is already a concern in many European Countries especially where there is a strong presence of renewable energy generation. Therefore there is a growing interest in new solutions able to improve the power quality level of such a system. Among them, an interesting solution is represented by the Open Unified Power Quality Conditioner (Open UPQC) proposed within the present work. The system consists of a single or three-phase AC/DC power converter installed at customer's premises and a main single or three-phase AC/DC power converter in the MV/LV substation. The paper discusses the design, simulation and implementation phases related to an Open UPQC installed in a real LV distribution grid in the city of Brescia (Italy) within the Smart Domo Grid project, co-funded by the Italian Ministry of Economic Development. Results from the field installation show the effectiveness of the proposed solution to face power quality issues in Distribution Networks.**

Index Terms--**Power quality, smart grid, Open UPQC, unified power quality conditioner.**

I. INTRODUCTION

International and National Regulations require Distribution System Operators (DSOs) to monitor Power Quality (PQ) and to appropriately intervene in order to deliver energy to customers characterized by quality levels maintained within appropriate ranges. At the same time, the deepening penetration of Distributed Generation (DG) systems within Distribution Networks (DNs) is making more complex the management of the grid [1], affecting the quality of the energy provided by DSOs [2] and making more difficult to meet those Quality of Service (QoS) standards. Thus, DSOs are starting to find out new tools and devices to cope with the compensation of such PQ problems on time.

Looking at PQ related work, Farzanehrafat has formulated new PQ estimator for three phase distribution grids [3]. A novel reactive power sharing algorithm has been developed in [4] to improve complex power management in microgrids. A day-ahead load shifting technique to demonstrate the effectiveness of Demand Side Management (DSM) to face PQ issues in a smart grid has been presented in [5]. Indeed, DSM has been proved to be an effective strategy which offers economic benefits for costumers to manage their consumption and helps DSOs to reduce the peak load demand, reshape the load profile and improve QoS.

The performance of Smart Loads (SL) on improving mains frequency by focusing on primarily reactive compensators has been analyzed in [6]. Authors of [7] have observed that an ideal mix of different resources and SLs with a proper Information Technology architectural framework lead to a flatter net demand and consequently enhance reliability and PQ in DNs. Thus, DGs, flexible loads and storage have been proved to play an important role and to offer several services and flexibility to the grid [8].

For what pertains the PQ control, past approaches were mainly focused on passive filters [9]. More recently, alternate solutions have been proposed, taking into account control capabilities of DG systems connected to the network by means of power electronic interfaces [10], or the introduction of offline, online and hybrid Uninterruptible Power Supply (UPS) systems. The latter approach concerns the installation of UPS devices at the customer premises [11] and could not be controlled by DSOs. Thus, DSOs have started to develop and install electronic devices such as Distribution Flexible AC Transmission Systems (D-FACTS) within their DNs. This device category represents a very interesting solution to furnish both PQ and reactive power support services in DNs [12], [13], particularly in the case of Unified PQ Conditioners (UPQCs). A UPQC is usually constituted by a shunt and a series unit inverter, in which the series unit is used to mitigate voltage related issues (e.g. sags and swells), while the shunt unit is managed in order to provide reactive power and/or harmonic pollution compensation by means of a shunt current injection at the load level. Concerning the various UPQC topologies and control strategies, single level [14] and multilevel [15] solutions, as well as Dual UPQC configurations [16], have been proposed. In particular, Dual UPQC, differently from the traditional UPQC configuration, presents the series unit controlled as a current source and the shunt unit acting as a voltage source converter.

The paper proposes a novel UPQC configuration for LV DNs – called Open UPQC – that is a distributed solution able to improve PQ in the installed area (instead of the typical UPQC, which consists of a single device able to improve PQ at only its connection point). The Open UPQC consists of a system level solution constituted by: (i) a series unit installed within the MV/LV substation to compensate voltage dips or to follow a specific reference voltage; (ii) several shunt units

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distributed among the LV network, such as placed at the customer premises and capable to implement Volt/VAr control actions, too. The whole system has been developed as part of the Smart Domo Grid (SDG) project [17], co-funded by the Italian Ministry of Economic Development (Ministero dello Sviluppo Economico - MiSE), and it has been tested on a real MV/LV substation and LV Network located in the city of Brescia (Italy). The system performance proves the effectiveness of the proposed solution to avoid the infringement of PQ limits and to allow the customers to have an advanced "UPS like" system available. The huge diffusion of electronic devices to mitigate/manage the voltage and the load current is due to the effective cost benefit that characterizes this device, as reported in [18]. The Open UPQC can introduce economic benefits to the costumers, enabling them to follow the DSM strategies of the DSO, and to the DSO too, allowing it to reduce the investment cost for PQ improvement within its DN. Moreover, single phase implementation is a novel system solution more compatible with DN needs where there are lots of single-phase costumers, because it permits to the DSO to be flexible by shifting all the problematic single-phase loads on the phase of a specific feeder where the proposed Open UPQC is installed, splitting the investment cost on time.

Within the paper, Section II introduces an overview concerning PQ requirements and the overall general structure of the proposed solution, Section III deals with the field demonstrator description, Section IV outlines the Open UPQC design, introducing some simulation results. Section V shows experimental results from the field testing of the proposed solution. Finally, conclusion remarks are given in Section VI.

II. STATE OF THE ART

A. International Regulation and Power Quality Devices

Concerning International regulations, the IEEE 1159-2009 [19] standard classifies PQ phenomena in: Transients; Short-duration Root-Mean-Square (RMS) variations; Long duration RMS variations; Interruption; Imbalance; Waveform distortion; Voltage fluctuations; Power frequency variations.

Power Quality was addressed for the first time in Europe by the European Energy Regulators (CEER), in 2001. In [20] CEER reports a comparison among standards and regulation strategies for the electricity distribution in several European countries. The benchmark about the quality of electricity supply [21] – released in 2011 – reports that in several EU Countries (among them Czech Republic, Hungary, The Netherlands, Portugal, …) the DSO is mandated to perform a PQ assessment. Different phenomena are monitored, however the EN 50160 [22] is used as a reference in most cases. The monitoring action is performed mainly in permanent locations at HV and MV levels; the LV is monitored as well in some cases. The focus is often on the short-duration RMS variations, also known as voltage dips, since it has a most relevant impact over the QoS after voltage interruptions.

For example, the Italian Regulatory Authority for Electricity Gas and Water (AEEGSI), with the resolution 198/11 [23] introduced for some required DSOs to monitor the PQ on MV busbars in primary substations with devices compliant with EN 61000-4-30 standard [24].

For any MV dip, the PQ Meter (PQM) has to record:

- the residual voltage as a percentage with respect to the nominal value;
- the timestamp of the event, with a resolution of 10 ms;
- the duration of the event, with a resolution of 10 ms.

Voltage dips [22] describe the distribution of dips by considering its duration t and residual voltage[1] u, proposing the clustering reported in TABLE I. Each cell of the table contains the number of events. A further contribution to the description of voltage dips is provided by EN 61000-4-11 [25] and EN 61000-4-34 [26], defining the testing and measurement techniques to determine the immunity level of LV connected equipment to voltage dips. Here, the concept of immunity class is introduced. Background colors, used in TABLE I, are the mapping of immunity classes – as defined in [25] and [26] – upon the clustering proposed in [22]:

- Class 2 including light gray cells;
- Class 2 including dark and light gray cells.

TABLE I. VOLTAGE DIP DISTRIBUTION AS EXPRESSED BY EN 50160

Events No.	**t (ms)**				
u (%)	$10 \leq t \leq 200$	$200 < t \leq 500$	$500 < t \leq 1000$	$1000 < t \leq 5000$	$5000 < t \leq 60000$
$90 > u \geq 80$	░	░	▓	▓	
$80 > u \geq 70$	░	░			
$70 > u \geq 40$	▓				
$40 > u \geq 5$					
$5 > u$					

B. Open UPQC Description

At distribution level, UPQC is an attractive and effective solution to tackle both voltage and current disturbances at a certain point of the network. The original UPQC has been introduced by Akagi combining series and shunt Active Power Filters (APF) [27]. Several topologies and control methods have been introduced and tested [1].

The Open UPQC proposed by authors splits out shunt and series units of the original UPQC [18]. The series unit is moved to the MV/LV substation in order to support an area, while the shunt unit is split out again into several units and designed according to the corresponding end user contractual needs. Thus, it consists of: a series power electronic device installed in the MV/LV substation that works as voltage regulator and several shunt units installed at the front end of customer homes to give different PQ services to each end user.

Considering that all the domestic users interested by the project investigation are characterized by a single phase connection to the grid, the series unit has been designed and realized in single phase topology. It consists of a coupling Transformer (TR) with the secondary circuit connected in series with the LV line and a primary one connected to the reversible AC/DC power converter. The functionality is like a single-phase self-supported Dynamic Voltage Restorer (DVR)

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[1] Residual voltage u is the minimum value of the RMS expressed as a percentage of the reference voltage.

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[28], [29]. The operation principle is to compensate most network voltage PQ issues, more than 95 % [18], by injecting pure reactive power only. Thus, it is controlled to act as a purely reactive inductor when it is within specific limits. Outside the limits it will send reactive power request to shunt units in order to move the network current angle to be able to implement the required compensation.

Each shunt unit consists of a single-phase bidirectional converter connected to an energy storage system and a set of Static Switches (SSs) [30]. There are two different operation modes in function of the main voltage RMS:

1) *Compensator:* when the Point of Common Coupling (PCC) voltage is within its operation limits (from 0.9 to 1.1 of the nominal load voltage defined by standards), the SSs are closed, the series unit works as voltage generator and the shunt units work as current generators with several functions. During *Online* operation mode, the shunt unit, depending on batteries' State of Charge (SOC), can charge the storage system. It can also take over a part of the load and perform peak shaving actions. Furthermore, it can compensate reactive power of the load, improving LV network Power Factor (PF). To improve series unit performance, all the shunt units can provide inductive/capacitive reactive power.
2) *Back-up:* when the PCC voltage is outside of its operation limits, each shunt unit SS is open, decoupling the network by the load. The shunt unit supplies the connected load working as ideal voltage source by means of stored energy in batteries. Shunt unit with it abilities (peak shaving, islanding and etc.) can be seen as very flexible SL within smart grid systems [31].

III. FIELD DEMONSTRATOR DESCRIPTION

A. Network Description

The complete system has been tested in a LV network supplied by a MV/LV substation located in the city of Brescia (Italy). This grid is composed by eight LV feeders, characterized by three-phase LV backbones and single-phase connection to residential customers. The whole monitoring system and some further metrology details are reported in [32]. Fig. 1 focuses on the LV feeder number 7, where the Open UPQC has been installed. This feeder has been selected because of the high PhotoVoltaic (PV) penetration level, which is above the 30 % of the peak demand. All the 45 single phase customers involved have a contractual power of 4.5 kW, for a total nominal power of about 200 kW. 43 over 45 customers have a 1.3 kWp PV plant installed over their rooftops. Several customers have a second PV plant with variable sizes.

The costumers were supplied on the three phases A, B, C of the same feeder. Therefore, 15 costumers were supplied by phase B and 5 of them were equipped with an Open UPQC shunt unit having a nominal range of 3 kVA. In the secondary substation – on the line B of same feeder – a 50 kVA single phase Open UPQC series unit was installed. Both the shunt and the series units were equipped to provide measurement at their connection points.

All the customers already had an electronic meter mainly used for billing purposes. For the sake of the project, 11 customers, including the ones having the shunt units installed, were equipped with a second generation smart meter installed to monitor the power exchange between the customer and the grid and the power produced by PV panels in real time. Phase voltage, current, active and reactive power, PF and RMS values were collected on a 1 minute base. Active and reactive energies were collected on a 5 minutes base. Data coming from smart meters, from the series unit and shunt units where stored into a database to perform cross analysis, such as those reported later on. This database was a part of a PC platform – called STS (Secondary Transformer Substation). The dataflow is depicted in Fig. 2. Through the STS, the DSO was able to send voltage and P/Q set-points to the series and shunt units respectively.

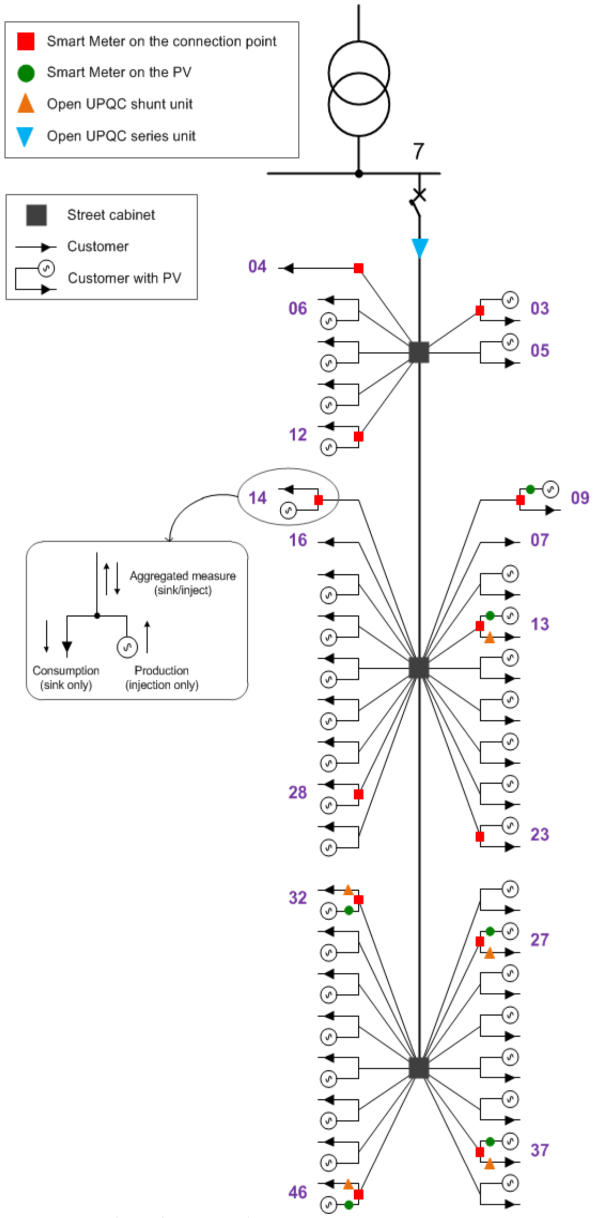

Fig. 1. Scheme of LV feeder 7 of the test network.

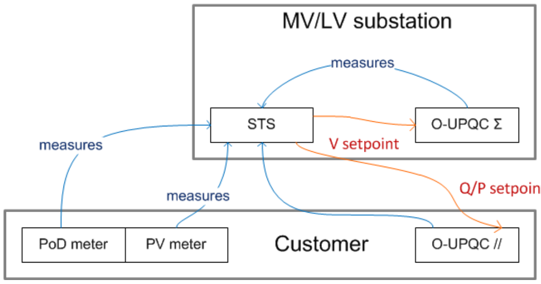

Fig. 2. Simplified scheme of the architecture of the project, illustrating data flows for the coordinated Volt/VAr regulation.

B. Power Quality Analysis

The Open UPQC can deal both with fast voltage events – such as voltage dips – and with slow phenomena like RMS voltage drift. A complete analysis of the voltage quality was done by examining the data coming from high-quality PQ meters – installed on the MV network – and from smart meters installed at LV level.

The MV busbar feeding the area involved in the project was monitored by a PQ meter compliant with the EN 50160 standard. The statistic of voltage dips – in terms of duration and residual voltage (i.e. the minimum value of the RMS expressed as a percentage of the reference voltage) is depicted in Fig. 3. It is worth to note that the voltage dips are very short. These data were used to design the Open UPQC.

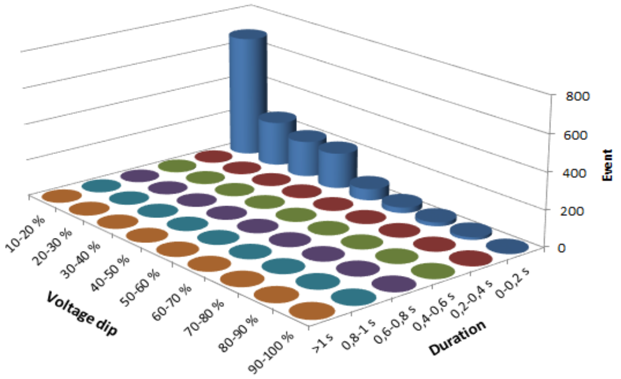

Fig. 3. Distribution of voltage dips in the city of Brescia. Data refer to the whole year 2014.

Data collected on the LV network by the new smart metering system described above were used to analyze how the RMS voltage was distributed, taking into consideration that – from a regulation perspective – the European Standard EN 50160 mandates a phase-to-ground voltage in the range of ± 10 % of the nominal value (230 V).

So the DSO has to manage the voltage on the secondary side of the MV/LV transformer, as shown in Fig.4 that report the RMS voltage of six days measured. As can be noted, an abrupt transition from the average value of 223 to 231 was logged. This effect was due to the action of the voltage regulator of the on-load tap changer located in the primary substation.

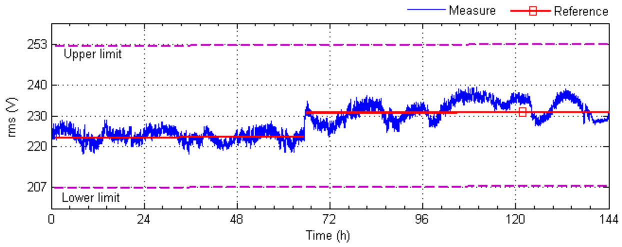

Fig.4. RMS voltage measured on the secondary side of the MV/LV transformer (two samples per min). Data refers to six days 30th June-3rd July 2015.

Moreover the voltage drop in the line influence the voltage load as shown in Fig.5 that reports the voltage trend of other six days at three different customer's connection points. It's interesting to note that the RMS value has a significant change during the day but it is lower than the previous one reaching the lower limit of the acceptable area, even if the shape of these three curves presents the same pattern. This example proves that the voltage regulation performed at the MV level and the voltage drop on the line, could cause problems on the LV grid. These changes can be effectively compensated by LV flexible resources such as the shunt and series units. These device can be used to perform specific control related to the LV network needs.

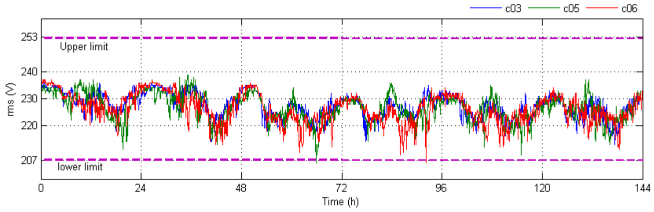

Fig.5. Voltage trend in three different nodes of the LV grid (six samples per hour). Data refers to six days 5-11th Jan., 2015.

C. Load Distribution Analysis

The design of the Open UPQC is also based on the customers' load needs. A preliminary analysis was reported in [33], where load curves of the whole city of Brescia were clustered according to the contractual power. Fig. 6 depicts the energy delivered per year in GWh as a function of the contractual power of LV customers. It can be noted that the domestic customers are usually below 6 kW. This group contains huge number of costumers and covers about the 54 % of the energy delivered. The shunt units were designed to shift 4.5 kW and 6 kW range costumers to a load pattern close to the 3 kW cluster characteristics, in order to offer economic benefits both to customers and to DSO.

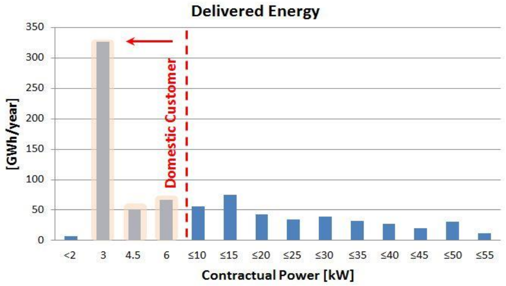

Fig. 6. Delivered energy per year as a function of power peak consumption of LV customers.

IV. OPEN UPQC DESIGN AND SIMULATION

Using the data provided in the previous section, the Open UPQC has been designed and then simulated to test its behavior in response to several PQ issues.

A. Series Unit

To develop a final three-phase device adopting a modular approach, three single-phase units have been designed to compose the series unit. Each single-phase unit rating was 50 kVA, with the full bridge voltage source inverter realized using pretty large DC bus capacitors in order to be able to damp DC voltage fluctuations and support the system during transient events.

Considering the trade-off between voltage stress on the inverter power electronic switches, nominal current flow and short circuit level, the transformer turn ratio has been selected to be 1:1.5. Since the inverter is managed as voltage source, it has been connected to the low voltage level to decrease voltage stress on switches. Being the current flow at primary (through IGBTs) high (1.5 times load current), IGBTs have been selected to have a 400 A current rating, 1.2 times over the line nominal current. The overall list of the single-phase series unit parameters are shown in TABLE II.

TABLE II. SERIES UNIT PARAMETERS

Power switches (IGBT) max. A, V	400A, 1200V
Transformer turn ratio (power), *TR*	1.5 (50kVA)
Coupling inductance *L*, A	1 mH, 300A
Inverter output and Transfromer terminal passive filter C_1, C_2, V	100 µF, 240V ac
DC bus capacitor, C_T	74.8 mF, 1000V DC
Inverter switching frequency	4 kHz

Fig. 7 depicts the series unit single-phase schema and the realized prototype. Several simulations have been performed to validate the control method performance. Four common voltage PQ issues have been studied [34]: voltage sag, swell, fluctuation and also single-phase fault.

The single-phase series unit has been managed to regulate continuously the PCC voltage to the reference value and to compensate sag and swell till a certain threshold by using pure reactive power.

Fig. 8 shows the dynamic and transient response of the series unit to a temporary voltage drop in accordance to [19]. In Fig. 8(a) it can be noted that series unit is able to maintain the V_{PCC} equal to the reference value even if the system is charging the DC bus capacitor Fig. 8(b) till first dashed line. At t=2 s a 10 % temporary voltage sag takes place and lasts till the end of simulation. Despite voltage drop on grid voltage V_s, load voltage V_{PCC}, is kept unaffected by means of series unit thanks to reactive power exchange of series unit in Fig. 8(c). Before the sag, the power exchange is around zero. After the sag occurs, there is about 1 kVAr reactive power exchanged by the series unit to compensate voltage sag. The unit absorbs around 20 W (negative within the Fig. 8) active power in order to keep constant the DC bus level. After the event, DC bus sees a slight voltage drop, rapidly has been recovered and kept constant around the set value (with a small oscillation) Fig. 8(b). Indeed, DC bus controller is much slower than the main controller in order to avoid oscillation and instability problems in control loop.

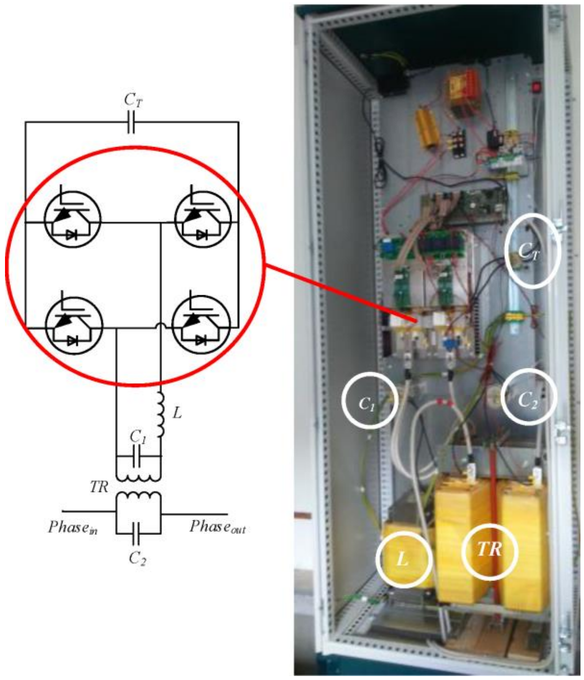

Fig. 7. Series unit single phase designed schema and realized unit.

Fig. 8(d) represents transient behaviors of the series unit, which is able to recover the load voltage in less than half period of the line waveform.

Series unit response to voltage swell is similar to the sag one. To avoid repeating similar figures, results concerning voltage swell obtained by field tests are described in Section V.

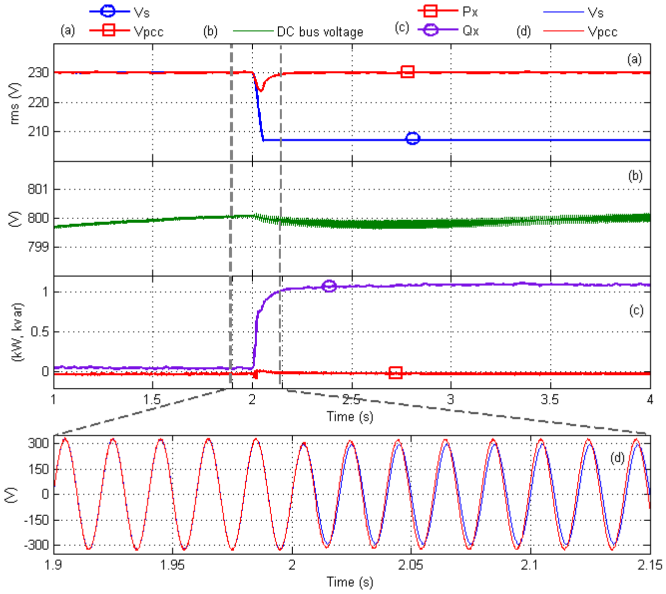

Fig. 8. Series unit response to 10 % voltage drop: (a) Grid voltage and PCC voltage, (b) DC bus voltage, (c) Series unit active and reactive power, (d) transient, grid voltage and PCC voltage.

B. *Shunt Unit*

Shunt unit, according to contractual rating of the end costumers, has been designed as a 3 kVA rated power device even if capable to work for few seconds till 18 kW, to guarantee the right short circuit protection breaking capability. Power switches (IGBTs) have been selected to have 195 A nominal current in order to be able to tolerate switching ripples. A full bridge inverter has been realized with an extra DC chopper leg. The DC leg midpoint has been connected through an inductance to the batteries, which, by proper control on up/down switch, will act as a *Buck*/*Boost* converter to manage the batteries' charge and discharge working conditions [30]. Shunt unit single phase parameters are listed in TABLE III.

TABLE III. SHUNT UNIT REALIZATION PARAMETERS

Power switches (IGBT) max. A, V	195A, 1200V
Batteries	12V, 12Ah, Sealed Lead-Acid
Static switch, *SS*	75A for continous operation
DC bus capacitor C_1, V	3 parallel 6800 µF, 500V DC
DC switching inductance L_{dc}, A	1mH, 50 A
ac switching inductance L_{ac}, A	1mH, 30 A
Inverter output filter C_f, V	10 µF, 240V ac
Inverter switching frequency	20 kHz
Chopper leg switching frequency	Charging 20 kHz, Discharging 4.5 kHz

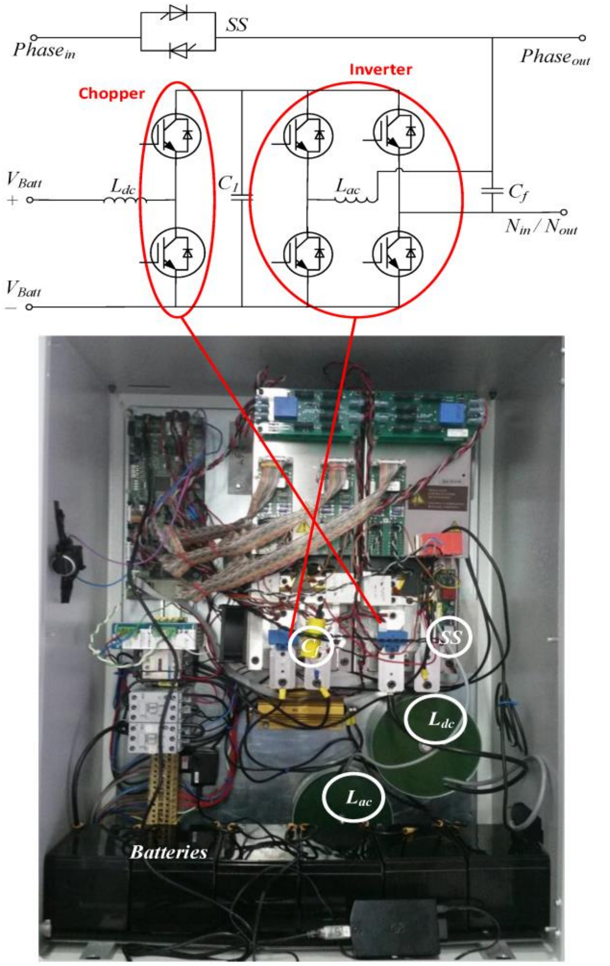

Fig.9. Shunt unit single phase design schema and realized unit.

Fig.9 shows the shunt unit single phase schema and the realized prototype. Several functionalities have been defined for shunt unit while the unit is *Online*, such as compensating reactive and harmonic current, charge the batteries, or using batteries energy to perform peak shaving. Peak shaving threshold and also reactive power request can be received through internet from a remote control action.

Another relevant feature associated to the proposed solution is represented by its capability to move from *Online* to *Island* operation mode. Passive islanding detection method based on measured RMS mobile window has been implemented in order to enhance reliability of the system [35], [36]. Considering that islanding detection time delay depends on sampling time, main voltage and nominal set value, to prove to performance of the proposed solution, experimental records on device's transition behavior from *Online* to *Island* and vice versa are presented in section V.

Also the *Island* operation mode control method has been verified by simulations. In this case, the battery leg IGBTs' and the inductance acted as a *Boost* converter, boosting the battery voltage to 450V on the inverter DC bus side and controlling the inverter as ideal voltage source to supply the load. Switching frequency for chopper leg has been set to 4.5 kHz, in order to run the chopper leg in Discontinuous Conduction Mode (DCM) to decrease the losses.

Peak shaving and reactive power control functionalities are shown in Fig. 10. The simulation results are just meant to show the system behavior and validate the control method. In particular, it has to be noted that the control method implemented for the experimental phaser is slower and device dynamics are smother.

The simulation starts with 1 kVAr reactive power request and load power less than peak shaving threshold. There is a small amount of load reactive power due to the inverter output passive filter. The reactive power request is 1 kVAr and after 1 s the grid side VAr amount is fixed to requested value Fig. 10(a) (in the real prototype, this time is about 10 s). Inverter provides 0.5 kVar reactive power, Fig. 10(c), which is added to the load reactive power Fig. 10(b) to set grid side Var to 1 kVar. Peak shaving threshold is set to 3 kW. Load active power initially is less than this set value till t=1.5 s so, the load and grid side active power is almost the same (the difference is due to the power to charge the batteries and inverter losses). At t=1.5 s the load power exceeds the peak shaving threshold Fig. 10(b), thus the shunt unit starts doing peak shaving and fixes the absorbed active power from grid to 3 kW Fig. 10(a). The remaining load is powered by shunt unit using the energy stored in batteries Fig. 10(c). Simulation results show that shunt unit takes over its share instantaneously once the load power exceeds the peak shaving threshold. However, in experiment, due to the control technique adopted, this transition is smother and it takes about 1 s for shunt unit to start doing peak shaving and take over its share.

In the real prototype there is a low pass filter on power measures and 300 W gap between the set value to start peak shaving and the value to stop peak shaving inside control

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method. This window is meant to avoid oscillation between two modes when the load power is close to the threshold set value.

In Fig. 10(c), shunt unit active power before t=1.5 s and after t= 2.5 s is negative. This is because it absorbs active power to charge the batteries. Inside the time span [1.5- 2.5] it is doing peak shaving and supplies part of load.

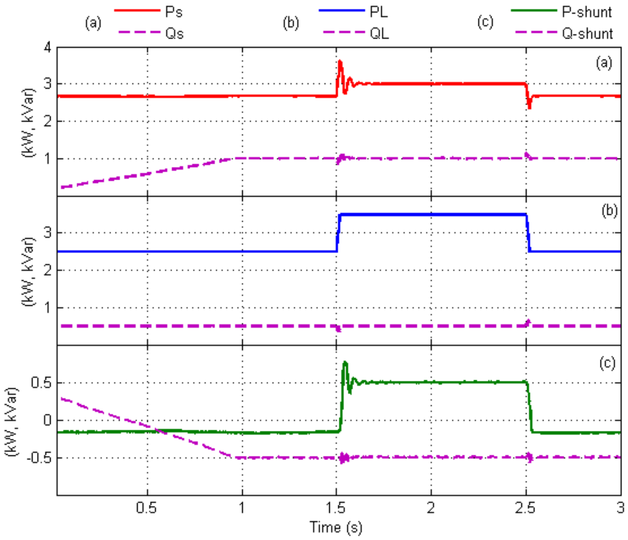

Fig. 10. Peak shaving and reactive power generation functionalities of shunt unit, (a) grid side active and reactive power, (b) load active and reactive power, (c) shunt unit active and reactive power

C. Open UPQC Functions

The several PQ services to the LV Grid and Load delivered by series/shunt units by means of different functionalities are summarized in TABLE IV and letters "G" and "L" mean the service is given to the Grid or to the Load respectively.

For instance, series unit, by implementing dynamic voltage regulation at V_{PCC}, improves voltage profile at PCC and gives PQ services to the supplied area. When the shunt units inject reactive power (Q), the series unit can improve its functionality to manage the voltage and consequently enhance the PQ level of the supplied area. When costumers with shunt units operate in *Island* mode, they are supplied by the unit and the grid can get advantage by removing some loads. This co-operation between series and shunt units is one of the essential and fundamental functions of the Open UPQC.

TABLE IV. OPEN UPQC DIFFERENT FUNCTIONS SUMMRY

Function	Series unit	Shunt unit
Voltage regulation	G & L	-
V_{PCC} set point	G & L	-
Reactive and harmonic compensation	-	G & L
Q injection	G	G
Island	-	L
Peak shaving	-	G & L

V. EXPERIMENTAL RESULTS

An experimental characterization has been performed firstly in a laboratory environment and then on the field test-site. Several tests from both series and shunt units operation have been reported.

A. Series Unit

Series unit stand-alone functionality and also co-operation with shunt ones have been tested. Series unit functionality is always on-line and gives PQ services to the connected feeder. It is able to compensate voltage sag/swell and keep the PCC voltage constant at the set point. The tests have been performed with 4.5 kW+1 kVar load. The voltage swell has been simulated in laboratory by means of Variac transformer.

1) *10 % voltage swell*

Series unit behavior in the case of a 10 % voltage swell has been verified. Fig. 11 shows all the recorded data of this event.

Before the event the system was working with no voltage swell, with grid and PCC voltage equal to 195 V Fig. 11(a). In this condition the load current is about 20A and injected voltage V_x is around 5 V, as depicted in Fig. 11(b), while the DC bus voltage is around 427 V, Fig. 11(c).

At t=0.4 s, a 10 % voltage swell is applied to the grid voltage till t=1 s. During this event, in order to compensate the grid voltage V_s, the injected voltage V_x increases of about 18 V. Indeed, the DC bus reaches around 443 V due to the power flow through the series unit. It can be noted that the swell at the grid side is completely removed at the PCC and so the load current is quite constant.

After the swell, the grid voltage and PCC voltage are still equal to around 195 V and the DC bus recovers slowly to its reference value around 427 V in less than 4 s as shown in long representation of Fig. 11(c).

Swell management for this type of conditioners is easier because the compensation margin is wider.

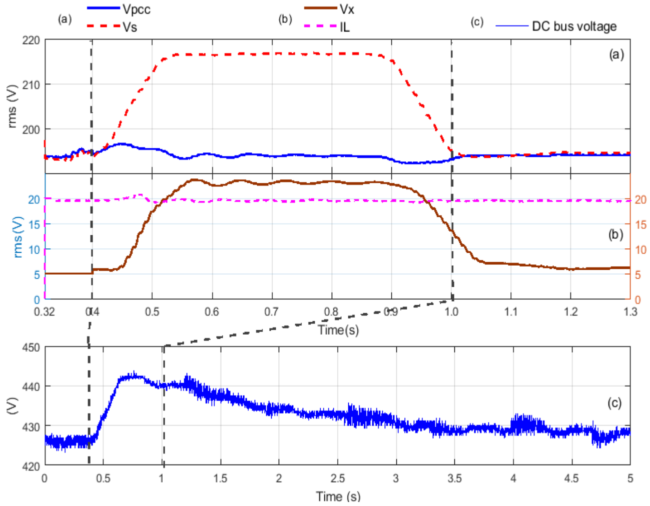

Fig. 11. Series unit response to 10% temporary voltage swell, (a) PCC voltage and Grid voltage (b) injected voltage and load current (c) DC bus voltage.

2) *Load variation*

Considering that all the load current flows through series unit, the response to load variation is very important because it require a high device robustness. In the following, about 50 % load current variation transient is considered. Rapid load change from 1 kW+0.8 kVar to 2.5 kW+0.8 kVar and vice versa has been tested. Fig. 12 shows about 50 % load increment happening at t=0.085 s - shown by arrow in Fig. 12 - with no voltage sag/swell on grid voltage. It can be noted that load increment influences a little bit the voltage profile. Fig. 13 shows about 50 % load current decrement around 0.07 s - shown by arrow in Fig. 13 - with no voltage sag/swell on grid voltage. Voltage decrement has no effect on voltage profile.

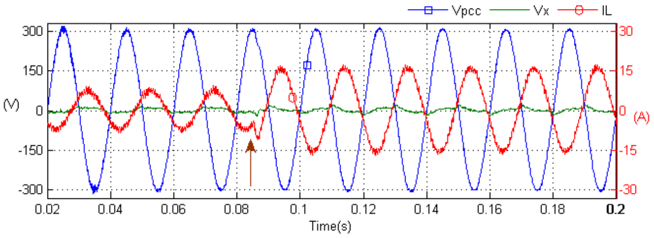

Fig. 12. Series unit transient behavior, adding 50 % load

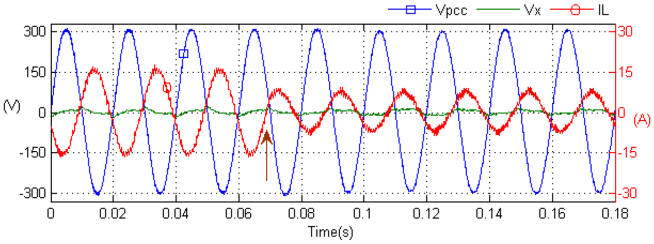

Fig. 13. Series unit transient behavior, removing 50 % load

Voltage THD analysis is done by recording data and processing them by MATLAB software. Comparison analysis depicts that introducing series unit affects 1 % voltage THD level of the system but it is always within standard [19] and acceptable range.

B. *Shunt unit*

Shunt unit has the capability to insert up to nominal VAr value to the system. Transition from -3 kVAr to +3 kVAr smooth change takes less than 30 s. Several measurements have been recorded on voltages and currents by using differential probes (30 MHz bandwidth) for voltage and clamps (100 kHz bandwidth) for currents. THD comparison analysis shows that voltage and current distortions introduced by shunt unit are always less than 1 % and within standard. Two different functionalities have been focused and presented in detail.

1) *Online to Island Transitions (1 kW load)*

Fig. 14 shows transition from *Online* to *Island* operation mode. The grid is disconnected at t=0.035 s. Transition from *Online* to *Island* inserts around quarter of cycle (4-5 ms) disturbances to voltage, depending where, on voltage profile, the sudden disconnection happens (near peak or near zero crossing). This time is the total - detection plus inverter reaction - to take over the load [36].

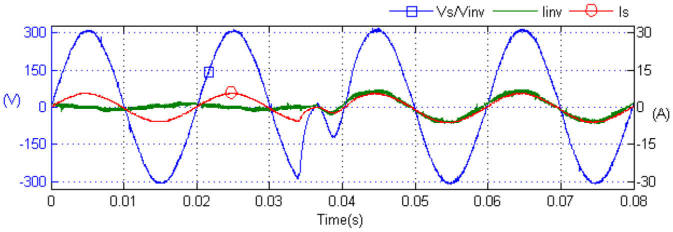

Fig. 14. Shunt unit transitions, Online to Island.

2) *Island to Online Transitions (1 kW load)*

Transition from *Island* to *Online* operation mode is shown in Fig. 15. When the grid voltage came back to standard limit, shunt unit starts doing amplitude and phase synchronizations. After amplitude and phase synchronizations are reached, it waits for the next zero crossing to reconnect the inverter to the grid. Injected distortion on voltage profile, by performing a good synchronization procedure, is negligible (it takes less than 1ms).

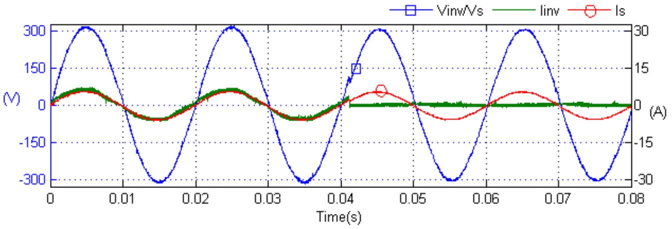

Fig. 15 Shunt unit transitions, Island to Online

C. *Co-operation of shunts and series units. Reactive power (Q) injection.*

The co-operation of shunt units and series unit can be understood by Fig. 16, that shows the effect of shunt units reactive power injection on series unit voltage control. Considering line B of the feeder 7 working with an average load, of about 19.5 kW and 4.7 kVAr, as shown in Fig. 16(a). During all the testing period the series unit tries to keep voltage at PCC (V_{PCC}) constant to 230 V regardless of grid voltage (V_s) variation, as depicted in Fig. 16(b).

As it is possible to see in Fig. 16(b), the series unit control can reach the reference value in function of absorbed load power and the network voltage, as happen often before the second vertical dashed line. If the control capability limit is reached the unit try to work as close as possible to the reference value, as happens after the second dashed line. In Fig. 16(b), the end point of the feeder (worst case) as load voltage (V_L) and the network voltage V_s are also shown.

During the time interval highlighted by the two vertical dashed lines, 2 kVAr reactive power request is sent to four shunt units (U_1, U_2, U_3, and U_4), so the 4×2 kVAr reactive power is injected in the network, as shown in Fig. 16(c). Doing so, the current in the line B of the feeder 7 increases of about 14 A (it changes from 87 A to 101 A).

Analyzing the Fig. 16(c) and (d), one can observe three different moments in which the injected voltage (V_x) depending on V_s and load, varies between:

- 40-55 V, before the first dashed line;
- 15-25 V, between the two dashed lines;
- 45-60 V, after the second dashed line.

The reason why the injected voltage (V_x) during the period shown by the two dashed lines is reduced, is due to reactive power provided by shunt units. Among this period, the cooperation between the units of the Open UPQC permits to decrease the injected voltage V_x, so the series unit can maintain easily V_{PCC} at the reference value. It can be noted that the reactive power supplied by series unit also drops from 5 kVAr to 2.5 kVAr, Fig. 16(e), reducing the stress on series unit and its losses, while its active power exchange is always almost zero.

During the Q injection, V_L in Fig. 16(b) slightly drops due to the additional Q injection (higher current on line).

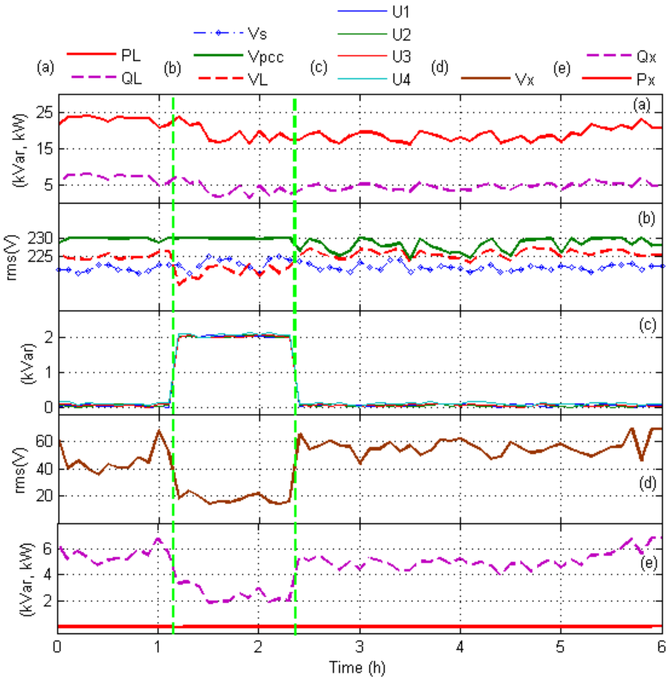

Fig. 16. Reactive power (Q) injection and effects on voltage regulation, 10 samples per hour.

VI. CONCLUSIONS

The paper has proposed a new system solution to improve the PQ level in LV distribution networks given by the use of the Open UPQC. The design of the system, relevant results obtained from the extensive simulation approach performed and meaningful measurement results obtained from its installation into a real distribution grid have been reported within the paper, highlighting the good performance of the proposed solution and its capability to offer a wide range of services to DNs, as well as economic benefits to customers.

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