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Power Quality improvement in LV smart grid by using the Open UPQC device

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Abstract. This paper presents the application of the Open Unified Power Quality Conditioner as a tool to improve the power quality in low voltage distribution grids. This system consists of a single or three-phase AC/DC power converter installed at customer's premises and a main three-phase AC/DC power converter in the MV/LV substation. *O-UPQC* will be installed and tested in the city of Brescia (north of Italy) within Smart Domo Grid, a project co-funded by the Italian Ministry of Economic Development. A preliminary analysis of the power quality and the load distribution of the test area will be used as input for the design of the system.

Keywords: Power Quality, Smart Grid, Smart Domo Grid project, Open UPQC.

1. Introduction

The service offered by Distribution System Operators (DSOs) is characterized by regulatory pressures aimed at improving the quality of service. In the case of Italy, the Authority of Electrical Energy and Gas (AEEG) released in 2011 a new resolution [1] upgrading the target for the continuity of service (progressively reduction of the number and the length of disconnections per customer) and mandates to monitor the Power Quality (PQ) on the distribution grid starting from MV busbars in primary substation (PS), before 2015. The focus is on voltage dips. It is reasonable to believe that in the next years, a more wide spread monitoring will be required and a remuneration/penalization mechanisms for the power quality will be introduced, as is today for the continuity. At the very same time European programs, aimed at protecting the environment – such as the European "20-20-20" directive [2] – are vigorously promoting and rewarding customers who install distributed generation (DG). The growing complexity, brought about by DG, will make more difficult to meet those quality of service standards. DSOs have to start immediately to analyze the PQ of their grid and to find out new tools to cope with the compensation of voltage dips in time. Some initiatives have been already launched. Among them, the Smart Domo Grid (SDG) project is co-funded by the Italian Ministry of Economic Development (Ministero dello Sviluppo Economico) and deals with two main topics:

- Demand Response aimed at the shaving of the peak power demand in order to reduce investments for new network infrastructures and the customers' bill [3];
- the PQ improvement on the LV grid [4],[5] by means of power electronics equipment called *O-UPQC* (Open Unified Power Quality Conditioner) including distributed energy storage (DDES).

This project will be carried out in a real DSO environment in the city of Brescia (North of Italy).

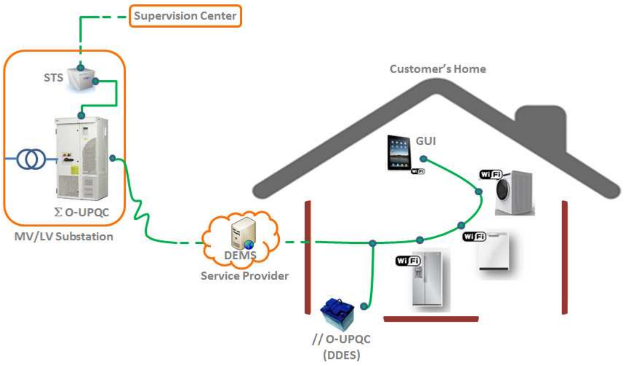

Fig. 1. SDG logical system architecture of SDG.

Fig. 1 shows the logical architecture proposed by SDG. It is a distributed intelligence system, consisting of:

- a central intelligence which supervise the entire architecture and dispatching needs of peak shaving and real-time tariff to every STS.
- an intelligent unit installed in MV/LV substations (Smart Transformer secondary Substation unit – STS), which measures the status of the grid, controls the *O-UPQC* and issues peak-shaving requests via a real-time tariff;
- a Domestic Energy Management System – DEMS – an from a service provider, receiving the total consumption and the local generation (if any – e.g. PV plants); receiving a real-time price information; controlling smart appliances and a Domestic Energy Storage (DDES, the storage part of the *// O-UPQC*

system);

Section 2 describes more in detail the *O-UPQC* structure – the system used to improve the PQ. Section 3 and 4 reports the distribution of voltage dips in the city of Brescia and the distribution of energy delivered as a function of the contractual power for LV customers. Section 5 describes the limits of *O-UPQC* architecture in function of its size.

2. O-UPQC description

Concerning the PQ, SDG proposes to use an electronic device called *O-UPQC* [6]. It consists of:

- a series electronic device installed in the MV/LV substation, called *Σ O-UPQC* unit,
- parallel units installed at the customer's home, called *// O-UPQC* unit, connected to a Domestic Distributed Energy Storage (DDES).

Fig. 2 shows the multi-wire power layout of the device in a three-phase, four-wire distribution network under study.

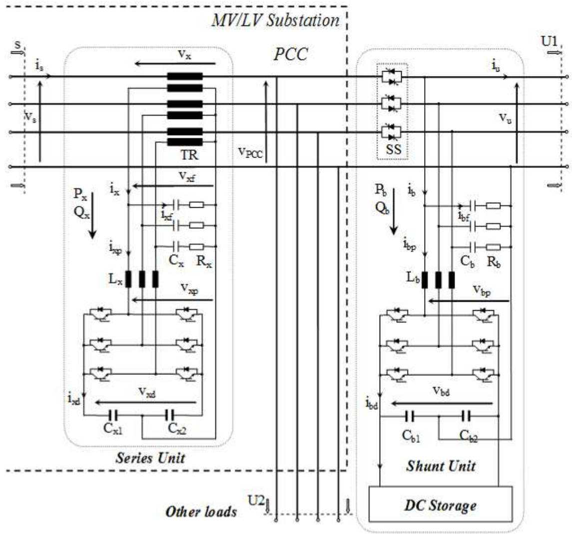

Fig. 2 – Multi-wire power diagram of the new proposed solution.

The *Σ O-UPQC* unit consists of a coupling transformer (TR), with the primary circuit connected in series with the mains line and a secondary one supplying the reversible AC/DC power converter. The output stage of the Pulse Width Modulation (PWM) voltage controlled converter contains passive RC shunt filters, to compensate for the harmonic currents at switching and multiple frequencies. Neglecting the active power to compensate the converter losses, the series unit is controlled to act as a purely reactive inductor when the supply voltage, V_S, is within its operation limits ($0.9V_n \leq V_s \leq 1.1V_n$). This fact is of fundamental importance, because in this range the loads U_1 (protected) and U_2 (not protected) must be supplied by the mains 95% of the time, as established by the IEEE Std. 1159 "IEEE Recommended Practice for Monitoring Electric Power Quality" and European EN50160; therefore, the storage system must not discharge itself. Outside of this range, active power can be used to compensate disturbances, in the same way as the usual series compensation devices [7], when a storage system is present.

The *// O-UPQC* units consist of an AC/DC power converter, similar to the one used in the *Σ O-UPQC* unit, connected to a different energy storage system and a set of static switches (SS) [8]. The parallel unit, depending on the state of the network voltage, can supply either the entire load U_1 or a part of the load U_1.

There are two different modes of *O-UPQC* operation:

- compensator: when the Point of Customer Connection (PCC) voltage is within its operation limits, the SS are closed, the series unit works as a three-phase voltage generator and the shunt units work as current generators;
- back-up: when the PCC voltage is outside of its operation limits, the SS are open, decoupling the network and the load-compensator system. Each sensitive load U_1 is supplied by its shunt unit, which acts as a sinusoidal voltage generator, using the energy stored in the storage system as an energy source.

Table I describes the main functionalities of the system.

Table I. O-UPQC functionalities

Voltage	O-UPQC actions		Load effects
	Σ unit	**// unit**	
Black-out $V_s < 0.05V_n$	No action	P_b and Q_b injection	U_1 supplied U_2 unsupplied
Deep voltage dips $0.05V_n < V_s < 0.4V_n$	No action	P_b and Q_b injection	U_1 supplied U_2 unsupplied
Voltage dips $0.4V_n < V_s < 0.9V_n$	P_x[1] and Q_x injection[2]	Q_b injection[3]	U_1 supplied U_2 supplied
Voltage fluctuation $0.9V_n < V_s < 1.1V_n$	Q_x injection[2]	Q_b injection[3]	U_1 supplied U_2 supplied

[1] the P_x injection is possible only for few time and if it is necessary
[2] to control the voltage into PCC
[3] to increase the performance of *Σ O-UPQC*

Information about the depth and the duration of voltage dips are primarily used to evaluate a suitable size for the *Σ O-UPQC* unit. Considering to supply 60% of the LV network power and a small storage system, *Σ O-UPQC* unit can compensate for most of the voltage dips disturbances working as a Dynamic Voltage Restore [7]. It is important to underline that considering the high power respect to the energy needs the storage can be realized fruitfully by Supercapacitors [9]-[11].

Each *// O-UPQC* unit is sized in relation to its supplied loads power and energetic autonomy required by the end user, protecting its sensitive load against interruptions. The function of the *// O-UPQC* unit is similar to that of the UPS output stage [7], but it is less expensive because it only has one conversion stage and involves less power loss.

Section 3 and 4 describes the distribution of voltage dips and the distribution of the delivered energy versus the contractual power of residential customers needed to design the *O-UPQC*.

3. Analysis of voltage dips measurements

In Fig. 3 an analysis of voltage dips distribution in ca. a thousand MV/LV substation, performed by the Electric Power Research Institute, has been reported [12]. As can be seen in Fig. 3, more than 95% of voltage dips can be compensated by injecting a voltage of up to 60% of the nominal voltage, with a maximum duration of 30 cycles.

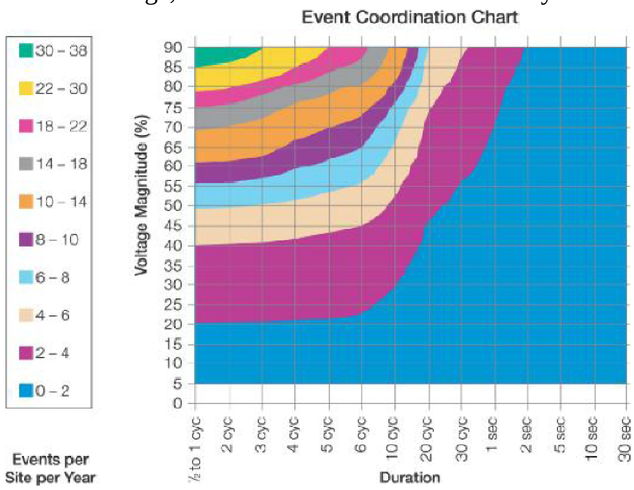

Fig. 3 - Example of distribution of voltage disturbances reported in the EPRI event coordination chart.

In order to perform a more accurate design of the *O-UPQC* system, it is important to examine the distribution of the voltage dips where the system will be installed, i.e. in the city of Brescia. In this area, managed by A2A Reti Eletriche SpA, all the MV busbars in HV/MV and MV/MV substation have been already equipped by power quality meters, since 2010. Fig. 4 shows the distribution of voltage dips as a function of duration and residual voltage[1] recorded during each voltage dip, including both single and multi-phase events. In case of multi-phase events, the worst measured value is reported (the longest duration and the lower residual voltage). Data refers to year 2011.

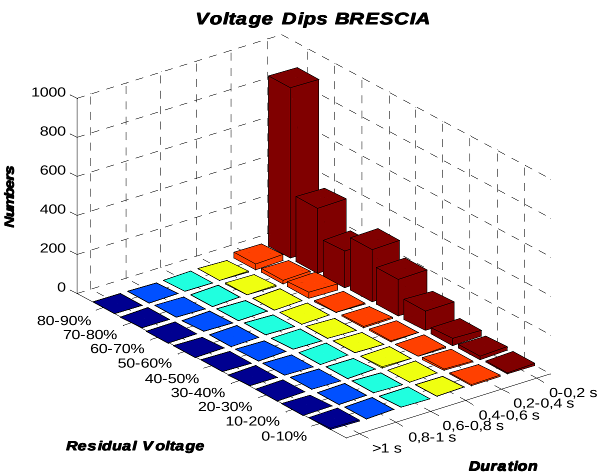

Fig. 4. Distribution of voltage dips in the city of Brescia.

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

Table II reports the number of single, double and three phases voltage dips for Brescia area.

Table II. Total number of event

Type of dip	Numbers
single phase	832
double phase	379
three phase	912
TOT	2123

Like Fig. 3, Fig. 4 suggests that the most of events last between 0 and 200 ms and in this group ca. 40% have a residual voltage dip between 80% and 90%. Fig. 5 and Table III describe the voltage dip distribution of two primary substation:

- PS-VIOLINO is a 23 kV/15 kV substation (MV/MV), it has 1 busbar and 5 MV lines,
- PS-EST is a 132 kV/15 kV (HV/MV), it has 2 busbars and 10 MV lines.

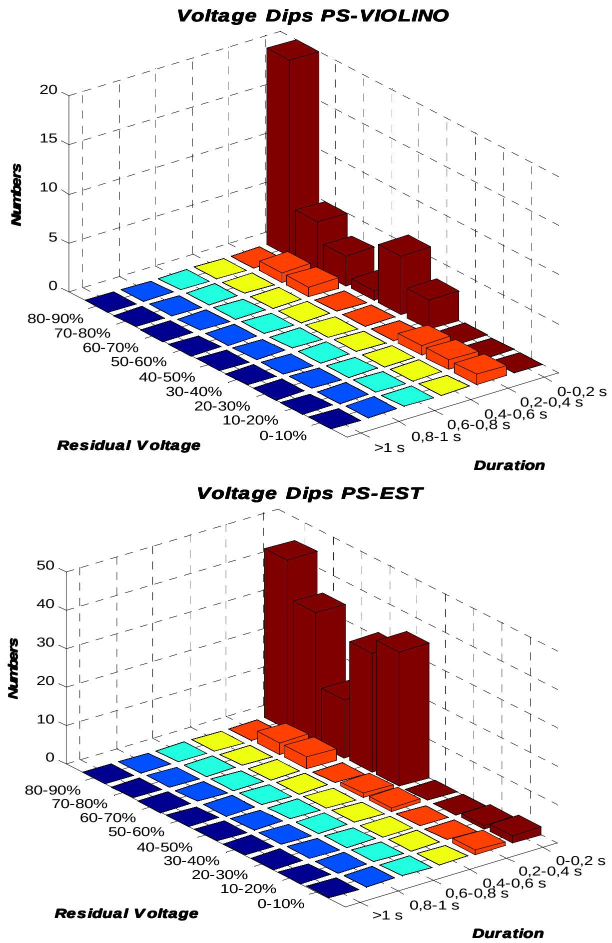

Fig. 5. Distribution of voltage dips for primary substations: (top – 5.a) PS-VIOLINO; (bottom – 5.b) PS-EST.

Table III. Number of event for two primary substations.

Type of dip	PS-Violino	PS-Est
single phase	22	52
double phase	9	17
three phase	12	102
TOT	43	171

In PS-EST, the number of deep voltage dips is higher than PS-VIOLINO. Those two examples prove that in general, the distribution of voltage dips varies according to the area considered. Together with MV busbars in PS, LV busbars in some secondary substation have been monitored. In the following, two examples will be shown. Fig. 6 and Table IV show data from SS-1056 and SS-1249 that are fed respectively by PS-VIOLINO and PS-EST.

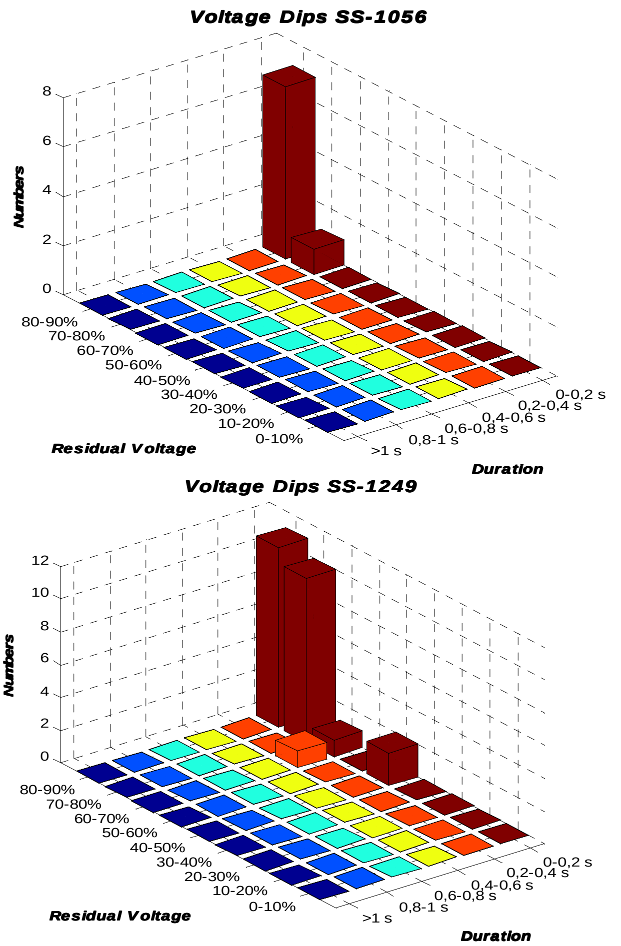

Fig. 6. Distribution of voltage dips for primary substations: (top – 6.a) SS-1056; (bottom - 6.b) SS-1249.

Table IV. Number of event for two secondary substations.

Type of dip	SS-1056	SS-1249
single phase	6	14
double phase	2	3
three phase	0	8
TOT	8	25

4. Analysis of the load distribution

A general overview of the distribution of the load for the city of Brescia is provided in Fig. 7, which depict the energy delivered per year in GWh as a function of the contractual power of LV customers. In Italy, domestic customers are usually below 6 kW. In 2011 in Brescia, the energy delivered in the cluster 3 kW – 6 kW was the 54% of the energy delivered under 55 kW LV contractual power. To size *// O-UPQC* is important to observe the load profile of end users. In Fig.8 is reported daily mean of domestic customers' load profile for example in July 2011. This is therefore, the group of customers to take into account for the sizing of the system. Fig. 8 reports the daily mean of domestic customers' load profile, in July 2011.

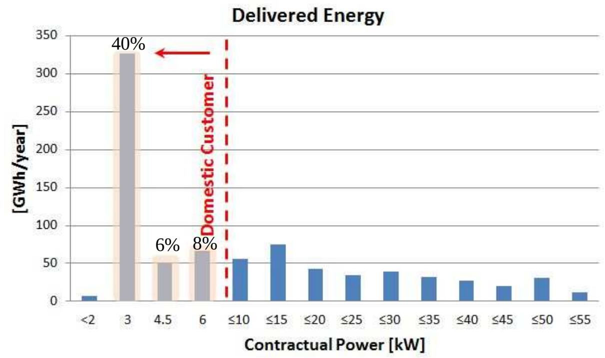

Fig. 7. Delivered energy per year as a function of power peak consumption of LV customers.

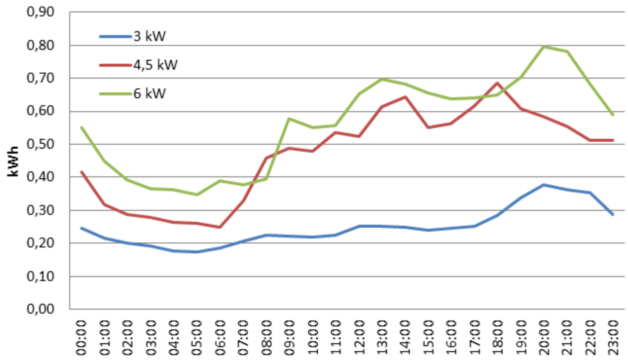

Fig. 8. Daily mean of domestic customer's load profile – July 2011

5. O-UPQC performance and sizing

This section is focused on understanding the *O-UPQC* compensation limits related to its sizing. The following analysis will be carried out under steady state conditions, defining the normal operation mode when the voltage is inside of the following range $0.9 \cdot V_n \leq V_s \leq 1.1 \cdot V_n$.

It is important to underline that the power absorbed by the loads and the *// O-UPQC* (shunt) units influences the performance of the *Σ O-UPQC* (series) unit, and therefore of the whole *O-UPQC*. Therefore, when considering a particular set of load conditions, it is possible to find operating conditions for the *// O-UPQC* units that increase the compensating limits of the *Σ O-UPQC*. Depending on whether or not storage systems and interruptible loads are present, the series, the shunt units and loads can exchange only *non-active* power or both *non-active* power and *active* power with the mains. Surely, when the supply voltage V_s is near the contractual limits (*normal operation mode*) the series converter must exchange only non-active power. In order to avoid *active* power injections, the series voltage V_x has to be in quadrature with the mains current I_s. The V_x value is reported in (1), and the grey areas in Fig. 9 indicate the field of possible V_x values.

$$\overline{V}_x = \overline{V}_{PCC} \cdot \frac{\sin\left(\left|\varphi_{PCC} - \varphi_S\right|\right)}{\cos\left(\varphi_S\right)} \qquad (1)$$

Another important aspect to underline is that the current I_s

is primarily composed of the current of unprotected loads U_2 (Fig. 2 - whose phase difference with respect to V_{PCC} cannot be varied) and the current of protected loads U_1 (Fig. 2 - whose phase difference with respect to V_{PCC} can be changed by the shunt units) as reported in (2), where $P_{U1,2}$ and $Q_{U1,2}$ are the active and reactive power of the equivalent load $U_{1,2}$, respectively, P_{losses} and Q_{losses} are the active and reactive power lines losses, respectively, and Q_b is the reactive power injected by all the shunt units.

$$\underline{I}_s = \frac{P_{U1} + P_{U2} + P_{losses} + j \cdot \left(Q_{U1} + Q_b + Q_{U2} + Q_{losses} \right)}{\overline{V}_{PCC}} \tag{2}$$

Therefore, the angle φ_{PCC} can oscillate between the upper and lower limits $\varphi_{PCC\_\max}$ and $\varphi_{PCC\_\min}$, obtained when Q_b=A_1 and Q_b=-A_1 respectively, in the area highlighted in Fig. 9 (A_1 is the size of *// O-UPQC*). Therefore, the current phasor I_s can move along the black dotted line, varying the reactive power Q_b of the shunt units.

Assuming that $V_{s\_\max}+V_{s\_\min}\approx 2\cdot V_{PCC}$, it is possible to demonstrate that the range amplitude $V_{s\_\max}$-$V_{s\_\min}$ can be obtained with equation (3).

$$V_{s\_\max} - V_{s\_\min} \approx 2 \cdot V_{x\_\max} \cdot \sin\left(\varphi_{PCC\_\max}\right) \tag{3}$$

It can be seen that the compensating range amplitude $V_{s\_\max}$-$V_{s\_\min}$ depends on the $V_{x\_\max}$ value that the series unit can inject, and on the *non-active* power Q_b.

When the shunt units can exchange *active* and *non-active* power with the mains (than in the eq.1 appears the P_b term), the performance of the *O-UPQC* does not change a lot. Figure 9 depicts the new phasor diagram of the *O-UPQC* under the above operating conditions.

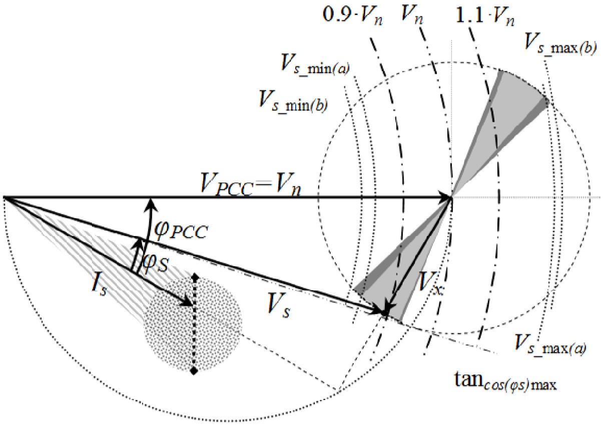

Fig. 9. Compensation limits of the *O-UPQC*: with non-active power exchange only (light grey) and with also active power exchange (dark grey) by the shunt units

In Fig. 9, the light grey areas indicate the field in which V_x can lay without *active* power exchanges by the shunt units, and the dark grey areas indicate the new possible values of V_x with *active* power exchanges by shunt units. In this case, the compensating range amplitude $V_{s\_\max}$-$V_{s\_\min}$ is greater than without *active* power exchanges, but it is important to note that the difference is very small. The phasor current I_s can move inside of the grey dotted circle, varying the *active* and *non-active* power of the shunt units (movement on the black dotted line regards only *non-active* power exchange). Therefore the loads can manage the active power without constrains. This condition could be represented as an active network into which dispersed generations are inserted. When the network is outside from the *normal operation mode* both series and shunt units inject *active power*. Given a storage system it is possible to compensate voltage disturbances in V_s that are outside of the contractual limits. At the same time in case of mains interruptions the SS of the shunt units switch off, and the loads are supplied in *back-up* mode.

Considering compensation of transient disturbances, such as voltage dips, swells, etc., various compensation strategies are available for the *O-UPQC*, including minimizing the energy required by the storage system of the series unit. The new phasor diagram of the *O-UPQC* operation is shown in Fig. 10. In the case of transient disturbances, the series unit can compensate the voltage V_s over a very large range compared with all the cases previously analysed. Indeed, the series unit can exchange active power with the mains in the dark grey areas, but this is only possible for transient disturbances due to the small size of the series unit storage system.

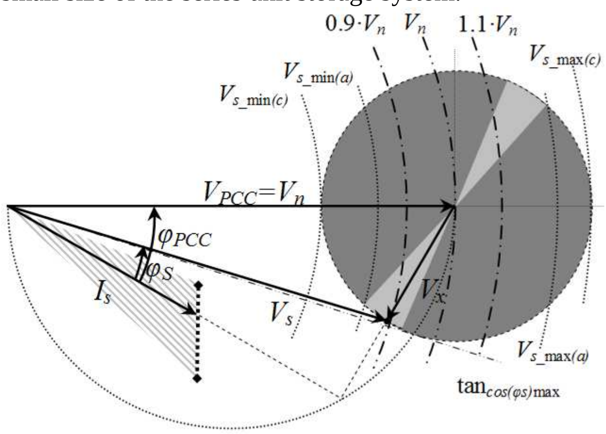

Fig. 10. Compensation limits of the OPEN UPQC: with non-active power exchange only (light grey) and with also active power exchange (dark grey) by the series unit

As introduced in the previous part, in order to operate correctly, the *O-UPQC* has to be determined in each elements. These parameters depending for the series unit from the load of network supplied and for the shunt unit from the load and autonomy of the single final customer supplied. Therefore, considering that in our test, the *Σ O-UPQC* unit will be directly connected downstream to the MV/LV transformer of the secondary substation SS-1056, a nominal voltage of about 25% is more than enough to compensate all the voltage dips measured in this secondary substation, see Fig. 6.a. So doing the nominal power of the *Σ O-UPQC* unit can be of 100kVA to compensate all these kind of voltage dips at maximum supplied current. To exchange active power with the mains, a storage system connected to the DC section of the series unit is needed. The storage system size does not need to be very large, because little energy is required to compensate these disturbances. To compensate the voltage variations for 30 cycle for the maximum load condition (400 kW), an energy equal to 60 kJ is needed, corresponding to a battery capacity of about 0.4 Ah at 48 V or a capacitor or supercapacitor bank of about 0.8 F at 400 V [9]-[11]. This value can be double in order to allow bidirectional energy exchange with the mains.

The *// O-UPQC* unit sized is function of connection typology of the customer (mono-phase or three-phase), the nominal power and the autonomy required. Therefore several power sizes have to be available to satisfy customer needs. Considering the delivered energy of LV customers reported in Fig. 7, it is possible to define two main size for this unit, the first one of 2 kW and the second one of 4 kW. Depending on the customer these size are good to obtain: from one side, important economic saving (reducing the tariff profile) especially for all the customers with a nominal power of 4.5 kW and 6 kW; while from another side, power quality improvement reducing power peak absorption and back-up. It is important to underline that the transient current sizing of the *// O-UPQC* unit has to be at least double of the nominal value required in order to manage correctly the protection apparatus of the customer. To compensate the load absorption for 1 hour for an average load of 0.6 kW (Fig. 8), an energy equal to 2160 kJ is needed, corresponding to a battery capacity of about 25 Ah at 24 V.

It is necessary to underline that the control strategy of the *// O-UPQC* unit have to be made in order to filter harmonic component reducing residual ripple current in line. Therefore the values of LCL output filter of the series unit has to assure that the maximum voltage output value required to VSI to compensate the load current and provide all the active power has not to exceed the nominal DC voltage value (for mono-phase application of 500V).

An additional important aspect is to evaluate the maximum value of *reactive* power injectable by all the *// O-UPQC* units (Q_b) in *normal operation mode*. Supposing a *// O-UPQC* unit at home of about 50% of 3 kW customers and of all the 4,5 kW and 6 kW customers, the maximum *reactive* power injectable is equal to about the *reactive* power absorbed by all the end users of the LV grid in exam. This permits to adopt several compensations strategy.

6. Conclusion

PQ monitor and regulation is becoming more and more important as the penetration level of renewable sources is increasing. In the future new solutions have to be found on the power grid, to cope with the regulation. The paper first of all introduce data collected in the city of Brescia, where PQ analysers have been installed in every primary substation and in some secondary substations. The load distribution analysis shows that the most part of the energy (more than 50%) is absorbed by domestic customers with a contractual power typically in the range of 3-6kW. These kind of customer actually are not involved in network stability problems. Therefore in the Smart Domo Grid (SDG) project we focus mainly on these users trying to solve problems of quality of voltage supply of the LV network using an innovative distributed electronic power system called *O-UPQC*.

Dips voltage analysis shows that the events measured in primary substation are reflected only in part on the secondary substation and that the most of them has a short duration and a depth. During the course of SDG project we will want to demonstrate that the *Σ O-UPQC* system, sizing for 1056 secondary substation , can compensate voltage dips and in function of the number of distributed *// O-UPQC* installed in the home of the domestic end users can be able to cope with the totality of detected events, and then provide to the end user a quality of voltage supply much higher.

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