Power Quality and Custom Power

Seeking for a Common Solution in LV Distribution Network

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***Abstract*— Power Quality (PQ) and Custom Power (CP) are two different terms in electric power system. PQ is the definition of a unique standard which the distribution system operators (DSO) should respect precisely. The DSO can manage its network to address the PQ issues but the result could satisfy only some end users requirements while others could need to improve their voltage profile. Therefore, the custom needs can be not completely satisfied by this standard and with the term CP we define the end user needs. This paper presents PQ and CP definitions and tries to find a possible common solution for DSO and final users in a contest where power electronics play an important role. Indeed in this new concept of distribution electricity network, as application in smart grid, there is a huge diffusion of renewable energy sources and storage systems. In this contest a solution able to provide economic benefits to DSO and end users needs to be found.**

Keywords—Power Quality; Custom Power; Distribution Network; Power Electronics; Smart Grid.

I. INTRODUCTION

Power Quality (PQ) and Custom Power (CP) are two different terms in electric power system. PQ is the definition of a unique standard which the system operators should respect precisely. However, sometimes the custom needs can be not satisfied respecting this standard. CP requirements in some senses could be in contrary with standard PQ definition and in some cases these two requirements could find common needs and challenges.

Several solutions have been studied in literature to improve the PQ and CP through final user [1]. Uninterruptible Power Supply (UPS) systems [2], parallel connected Active Power Filters (APF) and STATCOM systems [3], [4], series connected conditioners like Dynamic Voltage Restorer (DVR) or Dynamic Voltage Conditioners (DVC) [5] and finally combination of parallel and series connected power conditioners like Unified Power Quality Conditioner (UPQC) [6] and even novel topologies, Open Unified Power Quality Conditioner (Open UPQC) [7].

More recently the PQ and CP conditioner devices are moved to new era and distributed solutions attracted most of leading research centers and groups in the field [7]. Different solutions like Distributed STATCOM (DTATCOM) [8] and UPQC [9] have been analyzed so far. The introduced solutions are along with Smart Grid movement which is an important progression in power system [10].

This paper presents PQ standard definition and limits for LV system and it talks about commonly used CP definition and requirements in order to find out where these two area can be along each other. The necessity of electronic devices is investigated as well and the concept of Smart Grid and PQ conditioners devices' contribution is explained. In so doing, the paper discusses possible PQ and CP solutions in the modern distribution electricity network.

II. POWER QUALITY AND CUSTOM POWER

Nowadays in power systems, the PQ is an important topic from several point of views. Improving the PQ in an electrical grid, will decrease the system losses and increase transmission and distribution systems capability. So, the standard defines appropriate working condition where the grid and electrical equipment of user can work properly. Standard gives the minimum boundary limits on different PQ phenomena.

These International and National Regulations require Distribution System Operators (DSOs) to monitor PQ and to appropriately intervene in order to deliver energy to customers characterized by these quality levels maintained within appropriate ranges. In order to define PQ limits the IEEE 1159 [11] and European standard EN 50160 [12], have been taken as reference in this study. Two standards in principle are the same however, in some details, there are some small differences and those cases both standard consideration is addressed. From the system provider point of view, the EN 50160 gives limits on supply voltage and concerning this standard, voltage PQ phenomena can be classified in: Transients; Short-duration Root Mean Square (RMS) variations; Long duration RMS variations; Interruption; Imbalance; Waveform distortion; Voltage fluctuations and Power frequency variations.

Standard defines the normal operation voltage within 0.9-1.1p.u., where the per unit should be calculated referring the phase to the neutral (V_n), for European LV network standard defines V_n=230V (during each period of one week 95% of the 10 min mean rms values of the supply voltage shall be within the range of V_n±10%, and all 10 minutes mean rms values of the supply voltage shall be within the range of V_n +10%/-15%). According to this PQ definition, ±10% variation is allowed within distributed LV network. As a matter of the

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frequency, the system frequency should be kept within 50Hz±10% limit during 99.5% time of a year. The frequency variation is much more rigid than voltage amplitude because frequency variation can have severe damage effect on the equipment and also make the power system unstable. The imbalance factor shall be less than 2% for LV network. According to the IEEE 1159, the imbalance factor is defined as the percentage of voltage negative sequence over its positive sequence, %Imbalance=$|V_{neg}|/|V_{pos}|$. Outside these conditions the system is out of PQ standard and the DSO need to make proper intervention in order to compensate the PQ phenomena and move the system inside the standard. Common PQ phenomena are addressed in TABLE I.

TABLE I POWER QUALITY PHENOMENA ACCORDING TO [11], [12]

	Spectra	Duration	Magnitude range
Transients	kHz-MHz	ms-µs	0-4p.u.
Short duration rms variation (sag/swell)	--	0.5-30 cycle	0.1-0.9p.u. 1.1-1.4p.u.
Long duration rms variation	--	> 1 min	0.8-0.9p.u. 1.1-1.2p.u.
Power freq. variation	--	< 10s	±0.5Hz
Imbalance	--	steady state	>2%

Managing harmonics in a power system is considered a joint responsibility involving both end users and system owners or operators so, harmonic limits are recommended for both voltages and currents. Harmonic voltage distortion limits are provided to reduce the potential negative effects on user and system equipment. The limits are reported in IEEE recommended standard, IEEE std 519 [13].

These steady state limits on system current and voltage Total Demand Distortion (TDD) and Total Harmonic Distortion (THD) are extensively explained in IEEE std 519 [13]. The TDD and THD definitions are addressed as well. It concerns quality of power that is to be provided at the Point of Common Coupling (PCC), where the PCC, as it is described in standard, *"is usually taken as the point in the power system closest to the user where the system owner or operator could offer service to another user"*. Current and voltage harmonics have coupling effects on each other, end users produce harmonic currents that flow through the system which lead to voltage harmonics in the voltages supplied to other users and harmonics on supply voltage can exacerbate current distortion [14].

Therefore, connecting a load with high harmonic distortion factor will propagate harmonics into the system and affect neighbor user's current and voltage profile. So, the standard defines two different restrictions; one on the characteristic of the supply voltage at PCC and the second one on the connected load current characteristic. The limits are defined for THD and also the limits for each individual harmonic order magnitude. Generally for LV system the voltage THD level should be less than 8% however, the standard defines limits on each individual harmonic as well [12], [13].

Similar limits are defined for current in different voltage ranges. The limits reported in this context is to apply to the users connected to systems where the rated voltage at the PCC is from 120V to 69kV. According to the standard at the PCC, users should limit their harmonic currents [13]. A customer with high current distortion should limit its disturbances to avoid harmonic propagation thorough the network. This harmonic injection affects other users and may flow through their site and damage their equipment. In this case it is end user responsibility to limit its harmonic injection through the network otherwise the DSO has to intervene with harmonic compensation action and charge the compensation costs to the end user.

Fig. 1 represents how the PQ and CP defined regions can coincide to each other or the load needs can exceed this limit. The standards define a safe working region for the loads which is shown with green dotted and dashed area (region A) in Fig. 1. If for any reason the quality of supply voltage at PCC falls below standard limits, for instance as it is shown with green dashed line (region B) in Fig. 1, it is the DSO responsibility to improve the PQ level of the system and move it inside the standard safe area shown with A. But a special end user may require a power level outside the standard which is shown in Fig. 1 as CP (region C). In this case, it is the end user's interest to have a supply power and voltage different than what is defined by standard, so the end user will require a specially designed electronic device to comply its needs and also to be able to respect the standards regarding grid connection.

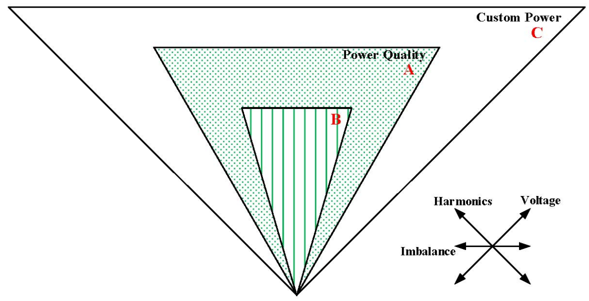

Fig. 1. Power Quality and Custom Power regions representation.

Due to different reasons, several industrial and domestic users require customized electric power or in other word CP devices at their company or property. Different reasons can be mentioned as why customers want CP devices however, in most cases the reason originated because the costumers want to save their manufacturing and consumption costs to decrease their energy bills and/or be more efficient. Some common reasons why customers require CP are listed below:

- to manage their energy demand
- to maintain their production line
- they require different voltage level than the network
- they require different frequency than the network
- they require variable frequency
- they require flexibility on their own business
- they require controllability on their property
- they require monitoring and accessibility on their devices.

Usually the companies design and build a special CP devices based on the customer requirements. Nowadays, power electronics by means of fast turn on/turn off solid-state switches made it possible to modify the broad range of standard off the self-power supplies to meet customer specific requirements. As it was mentioned, these customizations are useful and in most cases are essential in several industrial sites. For instance, medical science needs continuity and a power supply with very rigid PQ level so, it is common to have several CP devices in site. Research laboratories and academic works also need customized power supply system to run their tests and researches. Several other industry and governmental sectors are also required CP devices.

Therefore, the CP area is very wide, and often it imposes very expensive devices, and in some cases the PQ standard cannot satisfy the end user needs. So, it is necessary to investigate PQ standards with CP requirements in order to find possible common working regions to introduce economic solution which meets both side requirements and limits.

A. PQ and CP Common Interests

Although principally PQ conditioners and CP devices have different missions at installation point or network, in most solutions, their topology or task follow the same structure. In most common topologies the device component and structure are the same and only the functionality is differ from each other. Consequently, it is possible to design a power electronic device which would be able to carry out both PQ conditioning and power customization task co-operating within a network.

IEEE 1409 guide for application of power electronics for power quality improvement on distribution systems explains the CP and PQ solutions for 1kV through 38kV systems [15]. Although the standard is for the voltage range between 1kV and 38kV systems, however as it is mention on page 7, the LV application is very similar and the guide can be adopted for LV systems as well. Several problems have been explained and different available and possible solutions are discussed in detail. Especially in Table 6 of the standard the available common solutions for power providers and customers are addressed. Table 6 of [15] suggests possible solutions for different PQ phenomena both at system providers (DSO) side and also customer side. To save paper space, the Table is avoided here. The custom side devices are developed following special requirements, those needs could be very different (as voltage level or variable frequency range) form each end users and outside the DSO standard.

Referring to Table 6 of [15], common solutions for PQ and CP compensation can be chosen. Concerning PQ improvement and voltage compensation, a suitable solution is a series connected device which can be used in both DSO and customer side. The most popular available current profile conditioning devices are the Shunt connected reactive power and harmonics compensator with or without storage. With storage system those can be considered as UPS like, "*backup stored energy system*" to supply the system in the case of voltage interruption. For critical and nonlinear loads a combination of series and shunt compensation is a practical suggestion.

The interest and focus of this work is to explore economic solutions those meet CP and PQ requirements together in the new distribution electricity network.

III. SMART GRID AND μ-GRID APPLICATIONS

Traditional electricity grid was basically an unidirectional power flow systems. Energy conversion (mostly fuel energy) is done in centralized power stations where the efficiency stands in low level, about one-third. The generation was needed to be over-sized to be able to supply peak power demand where this extra power capacity in the grid is in use during short period of the time and it was not so efficient. Moreover, considerable amount of the energy, almost 8% , was lost during transmission and distribution level.

The new paradigm Smart Grid or μ-Grid tries to optimize the traditional electricity network by managing the load profile, the Renewable Energy Resources (RES) and the Storage Systems (SSs), always more often request thanks to their clean and sustainable nature. Fig. 2 depicts a simplified schema of a *Smart Grid* structure.

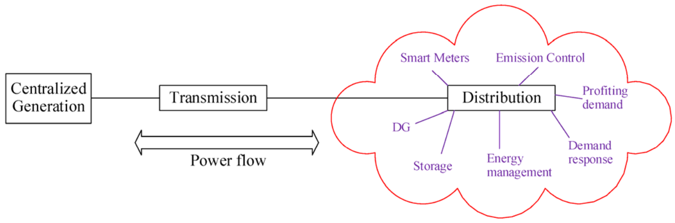

Fig. 2. Simplified distribution Smart Grid system structure.

Therefore, in contrast to the old system, in the new LV distribution electricity network the power can be produced reducing the amount of generation and transmission power but so doing bidirectional power flow within the main are possible and need to be managed.

In this contest the increasing demand and diffusion of DG, RESs and SSs is changing the management of the network and also the PQ and CP device evolutionary paradigm [16].

In order to optimal employment of existed network, apply demand response, energy conservation and reduction of the industry's overall carbon footprint, traditional grid need information from load side to be able to manage loads, RESs and SSs. To manage RES or SS and use these systems' inverter to give some ancillary services to the grid, the system operators need at least a new layer of infrastructure.

Basically Supervisory Control and Data Acquisition (SCADA) system is meant to answer these requirements however, this communication system has its own restrictions and mostly it is applied to generation, HV and MV transmission units and basically in a large LV system it is not applicable.

Although system operators in small units are able to actively control their system by means of SCADA but, the need to manage most problematic part of the grid is still alive. Since up to 90% of the grid failures and disturbances come from LV distribution network, transition toward Smart Grid need to be triggered at the bottom of the chain, in the distribution system [10].

Therefore in a Smart Grid different technological layers both in power systems and also ICT systems are necessary.

In the power system layer new power electronic technologies, for example for renewable energy power plants, can cause PQ and voltage problems at different levels, even if they are installed respecting connection rules [11].

In the ICT system layer, the Smart Grid needs to provide the utility companies full visibility and flexibility to interact with end users in order to deliver full functionality. It requires several high technological participants and a group of key player in this system is, power electronics devices those can send their data to the supervisory control system and also receive back the control action and properly react to the received command.

At the same time, modern systems, like Smart Grids and µ-grid, are also requiring autonomous voltage and current PQ conditioners.

Therefore power electronic devices play a crucial rule in a Smart Grid or a µ-Grid. The interface power electronic devices; need to be based on a communication system and they need to react very fast to the network variation and to the received commands avoiding PQ problems in the installed area.

So considering that both:

- RESs spread around and are available locally, these distributed energy resources should be tackled locally wherever those are available by utilizing proper device;
- SSs are distributed in the network and generally connected close to the end users by utilizing proper device,

and in the future thanks to the technological development, these power electronics active participants can/should deal with PQ and CP phenomena within the installed area as well.

IV. POSSIBLE COMMON SULOTIONS

Based on the problem definition and system configuration, possible solutions can be categorized into two generic conditioners; *Series Conditioner*, which is located in series to the line and can be support an area of the network or a single load and *Shunt Conditioner*, those connected parallel to the grid and usually in front end of the final load or costumer. Beyond these two generic classification, the most popular and widely used device is Uninterruptible Power Supply (UPS) system which is capable to protect critical loads or an important line or feeder.

A. Uninterruptible Power Supply (UPS) System

Among the power electronics devices for PQ and custom power improvement, the widely used and most accepted solution in medical, defense, telecom and several other industries, without doubt, is UPS systems. Fig. 3 shows the Online UPS system configuration. Principally it is placed between ac source and the load. In this device the main power supply is first converted to DC by an ac/DC converter and then reconverted to ac by means of DC/ac inverter, the battery is connected to DC link through the DC-DC converter and it supplies the system in case of mains failure. RESs can be connected by a dedicated converter to the DC link also.

The Online UPS is very interesting solution because it provides variable voltage and also frequency at the load side. In other hand the grid side converter, can be designed to set grid side power factor to unity and avoid any disturbances to the grid. This solution can meet requirements of region C as represented in Fig. 1.

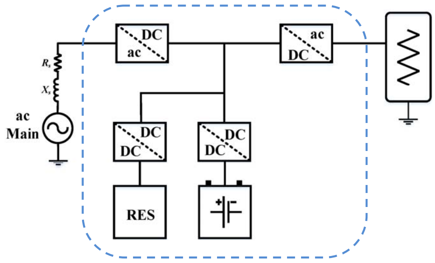

Fig. 3. Schematic of a double conversion online UPS system.

The performance of the device is summarized in TABLE II.

TABLE II UPS PERFORMANCE SUMMARY

Voltage	Current	Freq.	Continuity	Losses	Cost	Region
Excellent	Excellent	Yes	Yes	High	Very High	C

B. Series Conditioner

A series conditioner is connected between the grid and the load. Basically it means to deal with voltage PQ problems towards the supplied area and load. Generally speaking, DVC is a well-known series connected power electronics device, able to compensate voltage sags/swells, flickers and long term voltage drifts. Several compensation methods have been introduced and different topologies have been practiced and tested in the real field [17].

The device schema is shown in Fig. 4. DVC is placed series to the line, between grid and the load by means of coupling transformer (*TR*). The DC/ac inverter works as voltage source and injects required voltage series to the line. The storage system, in this case cannot be used for RESs, can be included to the system or alternatively for reactive injection instead of storage system, a set of capacitors can be used.

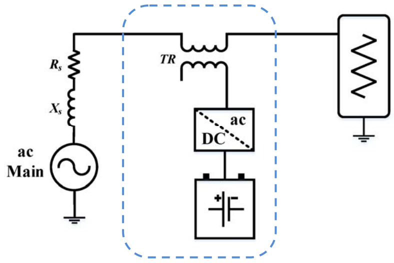

Fig. 4. Schematic of a DVC system.

The performance of series conditioner device is summarized in TABLE III. The device can meet requirements of region A.

TABLE III SEREIS CONDITIONER PERFORMANCE SUMMARY

Voltage	Current	Freq.	Continuity	Losses	Cost	Region
Excellent	Poor	No	No	High	Medium	A

C. Shunt Conditioner

A shunt conditioner is connected parallel to the grid or end user and usually works as current generator and gives PQ services to the connected point to improve network current profile. To enhance its functionalities and performance, a storage system can be integrated to the device. With storage system, this solution can be considered as Offline UPS type system [2].

The generic configuration is shown in Fig. 5; it is comprised of a reversible DC/ac inverter that is the interface between the main and the DC link, energy storage and a static switch (*SS*). The DC/ac inverter is able to dispatch the energy produced by the distributed generator or battery system to the point of interconnection and supplies the load with a high quality of power (in this solution the frequency is fixed by the grid and the conditioner cannot regulate the frequency). Moreover, using a single converter, it is possible to obtain consisting economic benefit.

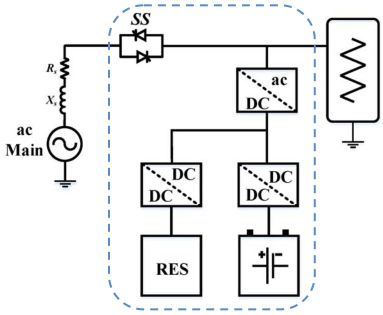

Fig. 5. Generic schema of shunt connected conditioner.

If instead of a RES or storage system, a set of capacitors is used as DC bus, the schema is changed to a popular application and depends on its mission in the system, it can be controlled as STATCOM or APF.

The performance of shunt conditioner devices' is summarized in TABLE IV. The device can meet requirements of region A giving few CP services only.

TABLE IV SHUNT CONDITIONER PERFORMANCE SUMMARY

Voltage	Current	Freq.	Continuity	Losses	Cost	Region
Poor	Excellent	No	Yes/No	Low	Low	A

D. Combination of Series and Shunt Conditioners

Combination of series and shunt conditioner system can lead to interesting solutions capable to deal with both voltage and current issues and provide high PQ service to the load. The generic configuration is shown in Fig. 6. In this solution, a static switch (*SS*) and a DC-DC converter for a storage system are represented. The UPQC is also equipped by two DC/ac inverters, which one is connected in series with main through a coupling transformer (*TR*) and another one is connected in parallel to the load. In UPQC configuration, series converter and shunt converter are sharing common DC link. The configuration can include or exclude the storage system. Without storage, the system initial cost is decreased in the cost of losing some functionalities of the device. The RES type can be integrated to the system as it is represented in Fig. 6.

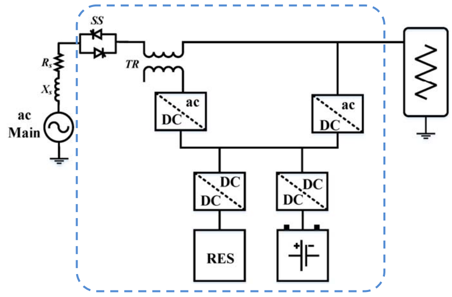

Fig. 6. Generic schema of series and shunt conditioners as UPQC.

The performance of UPQC is summarized in TABLE V.

TABLE V UPQC PERFORMANCE SUMMARY

Voltage	Current	Freq.	Continuity	Losses	Cost	Region
Very good	Very good	No	Yes/No	High	High	C

E. Distributed Solution, Open UPQC

Open UPQC is the evolution of original UPQC and it proposes to decouple series and shunt units of UPQC as it is described in [18]-[20]. So, it is the combination of distributed series and several shunt units, which introduces interesting solution applicable in modern power system contest. The series unit can be connected in the beginning of the feeder to give services to the all users. Instead several shunt units can be spread and located within the supply area. All the units of the Open UPQC are communicating to each other through internet based ICT system improving system PQ and introducing economic benefits to the DSO and end users. The general schema of Open UPQC is shown in Fig. 7 (only one shunt unit is shown).

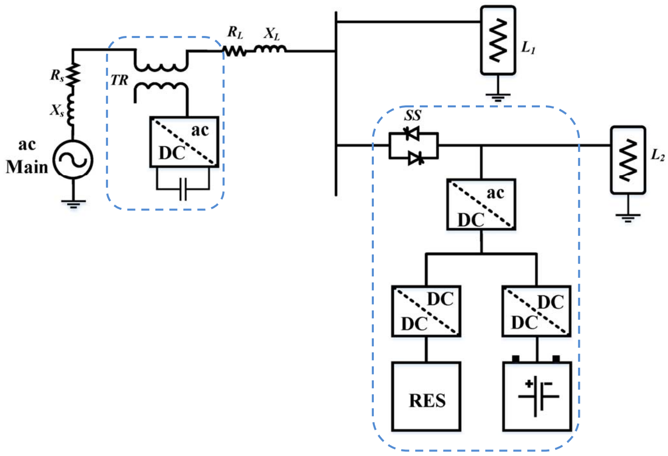

Fig. 7. Generic schema of Open UPQC.

Despite traditional solutions, Open UPQC equipped with ICT system and it is designed to work within Smart Grid systems and communication play important role in its operation and functionalities.

The performance of Open UPQC is summarized in TABLE VI. The device basically is able to meet region A requirements however, for the loads with shunt unit, the functionality can be extended to region C as it is reported.

TABLE VI OPEN UPQC PERFORMANCE SUMMARY

Voltage	Current	Freq.	Continuity	Losses	Cost	Region
Very good	Very good	No	Yes/No	Medium	Medium	A/C

V. DISCUSSIONS AND CONCLUSIONS

Considering the developments in Smart Grid and μ-Grid systems, PQ conditioning devices are moving to new paradigm and system level distribution solutions. Controllers with supervisory control possibility [21] and even reactive power management within these distributed systems are analyzed by researchers [22]. An interesting, economic and effective solution for this kind of systems, is a distributed PQ conditioner system including both series and parallel connected devices, capable to communicate to each other and perform optimized PQ conditioning actions.

Apart from this distributed solutions, modern power systems need active participants or Active Loads [23] in order to perform several predefined tasks within system. These active loads are key components to integrate RESs and SSs to the grid [24], [25]. With above definitions, new generation of PQ and CP and common solutions need to have both system level and local control strategies in order to meet modern Smart Grid system requirements [26].

In order to sum up, a common solution for PQ and CP improvement considering recent development in power systems, should have these options:

- it needs to find a distributed solution and composed of several units instead of one single unit;
- the units need to have different functions and capabilities to work in different conditions and take charge of several responsibilities within different scenarios;
- the system level solution need proper communication between different participants.

In this new concept, Open UPQC can be an interesting solution applicable within LV Smart Grid and μ-Grid systems.

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