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Analysis and Realization of a New Device for Power Quality and Custom Power Improvement: Open UPQC

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[1]ex A2A Reti SpA

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I dedicate this thesis to my Mother and Father
who have dedicated all their lives growing me up
and teaching me true thinking.

تقدیم به پدر و مادر نازنینم که همه زندگی شان را صرف من کردند.

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Abstract

Power Quality (PQ) in Low Voltage (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 providing regulated power to the end user within standard definition. In other hand, for different reasons, customer may need or require customized power which may not fit into standard definition. PQ and Custom Power may follow the same patch or possibly those may contradict each other going in opposite directions. Therefore, it is not an easy task for Distribution System Operator (DSO) to respect both standard PQ definitions and custom power requirements.

Several solutions have been introduced by electrical power engineers in order to perform PQ compensation tasks and provide custom power requirements. Among those, Uninterruptible Power Supply (UPS) is the most interesting and prosperous solution which is able to provide both PQ and custom power requirements of a customer. However a UPS system is quite an expensive solution and several alternatives are proposed in order to decrease solution expenses in the cost of reducing its functionality and flexibility. Series and Shunt conditioners with different topologies have been studied and those can furnish the grid with their voltage and current compensation capabilities however, a series or shunt conditioner alone, is an incomplete solution due to their compensation and service restrictions. To deal with series and shunt conditioners shortcomings, a combination of series and shunt conditioner is introduced by Akagi [32] which is able to tackle both voltage and current impureness and it is called Unified Power Quality Conditioner (UPQC).

Although UPQC looks a well designed solution to manage PQ and custom power requirements, however ever increasing renewable energy types, Distributed Genera-

tion (DG) and storage integration into power system and especially at LV level, have changed the PQ conditioners paradigm into new era. By introducing bidirectional power flow in newly introduced modern and Smart Grid systems, DSOs started to look for system level and modular solutions which are able to operate within this modern and Smart Grid systems communicating with other active participants.

Open Unified Power Quality Conditioner (Open UPQC) [14] is a novel proposal and special design of original UPQC and it is a distributed solution which is able to provide high power quality to the installed area and provide custom power services to the end users and several auxiliary services to the DSO. The proposal is to split the UPQC series and shunt units, move the series unit to the Medium Voltage (MV)/LV substation, in order to support all the installed area, and to split the shunt unit into several units according to end user needs and install each shunt unit at front end of customer property, providing PQ and custom power improvements to the end user and different auxiliary services to the grid and DSO. The series and shunt units are able to communicate with each other within a generic Information and Communications Technology (ICT) system. The proposed Open UPQC is compatible to be easily integrated within Smart Grid systems.

This thesis discusses the working principle, hardware and controller design of Open UPQC. Working philosophy of Open UPQC is explained in detail and series and shunt units responsibilities are introduced. Series unit is meant to work with pure non-active power compensation strategy to inject compensation voltage in quadrature to the line current. This working principle is meant to reduce system losses and its realization cost. This non-active power working concept, will impose operation limits on series unit. Series unit operation limits is analyzed in deep, considering possible contribution that shunt units can have to improve series unit performance and this led to the co-operation idea between series and shunt units as happens in the UPQC.

Series and shunt units should be able to work independently so, both units controller should be fast enough in order to deal with transient events. Series unit is designed to work as self-supported Dynamic Voltage Restorer (DVR) system in order to compensate both fast and slow voltage variation of the grid. In other hand, shunt unit's function is like a line interactive UPS system which is able to give some ancillary services to the grid. Beside series and shunt unit local controller, ICT based controller is also described in order to enable co-operation between series and shunt units.

The performance of the designed Open UPQC is verified by MATLAB based simulation and Laboratory experimental tests prior to real field tests. The whole Open UPQC has been realized as a part of Smart Domo Grid (SDG) project and it has been

installed and tested in a real LV distribution network in the city of Brescia, north of Italy.

This thesis presents several original and innovative concepts to the research area. A common solution to answer both PQ and *Custom Power* issues are investigated. Open UPQC as a unique and innovative distributed solution is proposed to be implemented in distribution LV Smart Grid. Working principle is analyzed in detail and especially series unit operation limits is addressed and continuous operation is verified by simulation and experimental tests. Based on best knowledge of author, for first time Open UPQC is realized and the only worldwide available prototype, has been installed and tested in real LV network. PQ and custom power conditioning has been perform in LV distribution network and several scenarios have been defined and tested within Smart Grid system.

keywords:

Power Quality, Custom Power, Smart Grid, Shunt Conditioners, Series Conditioners, UPQC, Open UPQC, LV Distribution, Distributed Generation, Storage, Renewable Energies.

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CHAPTER 1

Introduction

Power Quality and *Custom Power* are two different terms in electric power system. PQ is the definition of a unique standard which the system operators should respect precisely. However the custom needs can be not satisfied respecting this standard. Custom Power requirements in some senses could be in contrary with standard PQ definition and in some cases these two area could find common needs and challenges. This chapter presents PQ standard definition and limits for LV system and later it talks about commonly used custom power definition and requirements in order to find out where these two area can be along each other. In so doing, the chapter discusses possible PQ and custom power solutions. Finally the proposed Open UPQC is introduced and described in detail. The necessity of electronic device is investigated as well and the concept of *Smart Grid* is explained.

1.1 Power Quality Standard

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 equipments of user can work properly. Standard gives the minimum boundary limits on different power quality phenomena.

These International and National Regulations require 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 [2] and European standard EN 50160 [58], have been taken as reference in this thesis. Two standards in principle are the same in their fundamental however, in some detail there are some small differences and for those cases both standard considerations are 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 0.9-1.1 p.u., where the per unit should be calculated referring to the standard phase to neutral nominal voltage, V_n and for European LV network standard defines it as; V_n=230 V. According to this PQ definition, $\pm 10\%$ variation is allowed within distribution LV network. As a mater of the frequency, the system frequency should be kept within 50 Hz $\pm$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 effect on the equipments 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 $= \frac{|V_{neg}|}{|V_{pos}|}$. Outside theses conditions the system is out of PQ standard and the DSO need to make proper intervention in order to compensate the PQ problems and move the system inside the standard. Common PQ phenomena are addressed in Table 1.1.

	Spectra	**Duration**	**Magnitude range**
Transients	kHz-MHz	ms - µs	0-4 p.u.
Short duration rms variation (sag/swell)	–	0.5-30 cycle	0.1-0.9 p.u. & 1.1-1.4 p.u. Table 1.5
Long duration rms variation	–	> 1 min	0.8-0.9 p.u. & 1.1-1.2 p.u.
Power frequency variation	–	< 10 s	$\pm$ 0.50 Hz
Imbalance	–	steady state	> 2%

Table 1.1: *Power Quality phenomena according to EN 50160 and IEEE 1159 standards.*

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 according to IEEE recommended standard are reported in Table 1.2. These steady-state limits on system voltage and current Total Demand Distortion (TDD) and Total

Harmonic Distortion (THD) are extensively explained in IEEE recommended standard [4]. TheTDD and THD definitions are addressed as well. It concerns quality of power that is to be provided at the 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"*. Voltage and current harmonics has coupling effect 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 [36].

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 the characteristic of the supply voltage at PCC and second is the limits on the connected load current characteristic. The limits are defined for THD and also the limits for each individual harmonic order magnitude. The limits are shown in Table 1.2, generally for LV system the voltage THD level should be less than 8% however, the standard defines limits on each individual harmonic as well. Table 1.2 is completed with Table 1.3 where detail consideration on each individual harmonic order is shown up to 25^{th} harmonic order according to standard because the magnitude of higher order are usually very small although some standards give limits for higher orders as well.

Bus voltage V at PCC	**Individual harmonic (%)**	**Total harmonic distortion THD (%)**
$V \leqslant 1.0$kV	Table 1.3	8.0
1kV $< V \leqslant$ 60kV	3.0	5.0
69kV $< V \leqslant$ 161kV	1.5	2.5
161kV $< V$	1.0	1.5^{a}

[a] High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

Table 1.2: *Voltage distortion limits as expressed by IEEE std 519.*

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 120 V to 69 kV. According to standard at the PCC, users should limit their harmonic currents as reported in Table 1.4. Where I_{sc} and I_L are defined in standard as:

- I_{sc} = maximum short-circuit current at PCC
- I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

A customer with high current distortion should limit its disturbances to avoid har-

Odd harmonics				Even Harmonics	
Not multiples of 3		Multiples of 3			
order h	relative amplitude u_h	**order h**	relative amplitude u_h	**order h**	relative amplitude u_h
5	6.0 %	3	5.0 %	2	2.0 %
7	5.0 %	9	1.5 %	4	1.0 %
11	3.5 %	15	1.5 %	6 to 24	0.5 %
13	3.0 %	21	0.5 %		
17	2.0 %				
19	1.5 %				
23	1.5 %				
25	1.5 %				

Table 1.3: *Individual harmonic order (up to 25) voltage values at PCC in percentage of fundamental voltage, defined by EN 50160.*

monic propagation thorough the network. This harmonic injection affects other users and may flow through their site and damage their equipment. In this case, either its the end user responsibility to limit its harmonic injection through the network or the DSO will intervene harmonic compensation action and charge the user for the compensation costs.

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)^{a,b}						
I_{sc}/I_L	$3 \leqslant h < 11$	$11 \leqslant h < 17$	$17 \leqslant h < 23$	$23 \leqslant h < 35$	$35 \leqslant h \leqslant 50$	TDD
$< 20^c$	4.0	2.0	1.5	0.6	0.3	5.0
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

[a] Even harmonics are limited to 25% of the odd harmonic limits above.
[b] Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.
[c] All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.

Table 1.4: *Current distortion limits for systems rated 120 V through 69 kV as expressed by IEEE std 519.*

Concerning PQ, the focus is often on the short-duration RMS variations, also known as voltage dips/swells, since it has the most relevant impact over the Quality of Service (QoS) after voltage interruptions.

EN 50160 standard describes the distribution of dips by considering its duration t and residual voltage u [1], proposing the clustering reported in Table 1.5. 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 [59] and EN 61000-4-34 [60], defining the testing and measurement techniques to determine the immunity level of LV connected equipment to voltage dips. Background colors, used in Table 1.5, are the mapping of immunity classes – as defined in [59] and [60] – upon the clustering proposed in [58]:

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

Event No.	t(ms)				
u (%)	10$\leqslant t \leqslant$200	200$< t \leqslant$500	500$< t \leqslant$1000	1000$< t \leqslant$5000	5000$< t \leqslant$6000
$90 > u \geqslant 80$					
$80 > u \geqslant 70$					
$70 > u \geqslant 40$					
$40 > u \geqslant 5$					
$5 > u$					

Table 1.5: *Voltage dip distribution as expressed by EN 50160.*

- Class 2 including light gray cells;
- Class 3 including dark and light gray cells.

According to the standard definition; *Class 2* refers to the PCC and internal PCC (IPCC) in an industrial environment and *Class 3* refers to IPCC in an industrial environment. Indeed *Class 1* which does not fit in any of the cells in Table 1.5 refers to protected supply systems and its compatibility level is lower than in public supply network and usually highly sensitive loads go within this class and those need extra protection by means of PQ or custom power improvement devices. In this case the load needs a power supply with quality level more rigid or different than the standard one. Figure 1.1 is represents how the PQ and Custom Power defined regions can coincide to each other or the load needs can exceed this limit.

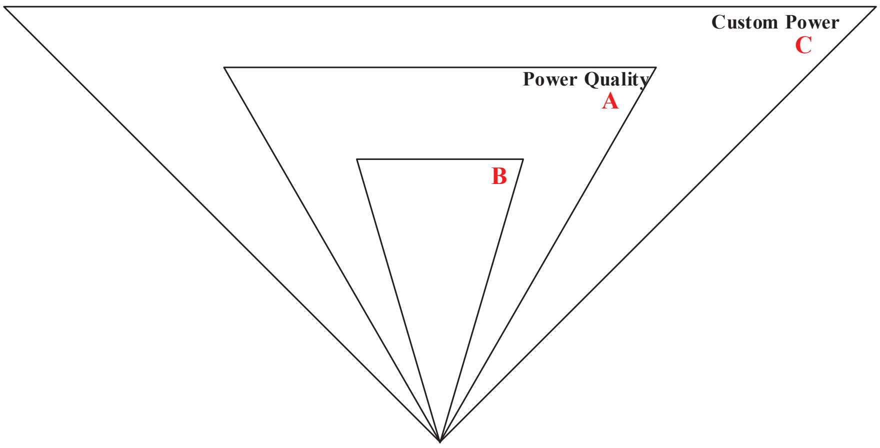

Figure 1.1: *Power Quality and Custom Power regions representation.*

The standards define a safe working region for the loads which is shown with green dotted and dashed area (*region B*) in Figure 1.1. 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 A*) in Figure 1.1, it is the DSO responsibility to properly intervene to improve the PQ level of the system and move it inside the standard safe area shown with B. In other hand, an special user may require a power level outside the standard which is shown in Figure 1.1 as custom power (*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 an specially designed electronic device to comply its needs and also to be able to respect to the standards and be connected to the grid.

1.2 Custom Power

As it is illustrated in Figure 1.1, sensitive loads may need more rigid power supply and this can stay outside standard PQ definition. Due to different reasons several industrial and domestic users require customized electric power or in other world custom power devices at their company or property. Different reasons can be mentioned as why customers want custom power 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 be more efficient. Some common reasons why customers require custom power are listed below;

- To manage their energy demand
- To maintain their production line
- They require different voltage level than the network one
- They require different frequency than the network one
- 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 an especial custom power devices based on the customer requirement and order. 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 customers 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 power quality level so, it is common to have several custom power devices in site. Research laboratories and academic works also need customized power supply system to run their tests and research. Several other industry and governmental sectors also require custom power devices.

Therefore, the Custom Power area is very wide and in some cases it is in contrary to PQ standard. So, it is necessary to investigate PQ standards with Custom Power requirements in order to find possible common working regions to introduce solution which meets both side requirements and limits.

1.3 Power Quality and Custom Power

Although principally PQ conditioners and custom power devices have different missions at installation point or network, in most solutions, their topology or task follow the same structure. In most common cases the device component and topology 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 withing a network.

IEEE 1409 guide, application of power electronics for power quality improvement on distribution systems, explains the custom power and PQ solutions for 1kV through 38kV systems [3]. 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. Table 6 of the standard is reflected as Table 1.6 where the available common solutions for power providers and customers are moved to an extra column. This means that the forth column reflects common solutions for both DSO and customers and those solutions can be repeated in second and third columns as well, but to save the space, those are not repeated. Table 1.6 suggests possible solutions for different PQ phenomena both at system providers (DSO) side and also customer side. The terminology used in the Table 1.6 is defined in detail inside the standard [3] and it is avoided to be repeated here. The custom side devices are excluded the special requirements, those need very different voltage level or variable frequency range which are very difficult to be matched with DSO side standard. The Table 1.6 is used as conjunction between DSO side solutions and customer side ones.

It can be understood from Table 1.6 that the forth column lists more recent and modern solutions and those work for both PQ and custom power improvement however, considering the second column, the solutions are mostly include *modification*, *sectionalizing* over sizing and designation of the system and those are mostly traditional and old solutions for PQ issues.

Power quality phenomena	Solutions available to power providers (DSO)	Solutions available to customers	Solutions available in common for DSO and customers
Voltage sag and swells	• line reactor • modification of protection scheme, line sectionalizing • tree trimming	• "hold-in" coil ridethrough device for motor contactors • constant voltage (ferroresonant) transformer • line conditioner • reprogramming of controls of sensitive device • voltage regulator	• static or hybrid transfer switch • static series compensation • static voltage regulator • backup stored energy system
Voltage interruptions	• modification of protection scheme, line sectionalizing • tree trimming	• coil ridethrough device for motor contactors • line conditioner	• backup stored energy system • static or hybrid transfer switch
Impulsive and oscillatory transients	• high energy surge arrester • preinsertion resistors and inductors • synchronous closing	• line conditioner • surge arrester • line reactor	
Harmonic distortion		• line conditioner	• passive filters and active filters • static shunt compensation with harmonic cancellation algorithm
Noise		• grounding and shielding • filter • line conditioner	
Flicker	• construction of new/upgraded feeder • construction of new substation • distribution series capacitors • connection to bus with higher short-circuit capacity		• static var compensation • static shunt compensator (distribution STATCOM)
Protection of nonlinear load			• combination series and shunt compensation

Table 1.6: *Available solutions for PQ and custom power according to [3].*

Referring to Table 1.6 common solutions for PQ and custom power 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.

Considering the PQ and custom power issues and modern systems in the main power network, for improvement of the PQ in LV electrical network towards the customer, variety of configuration with electronic interface between network and loads have been introduced to electrical power system [33, 6]. The interest and focus of this work is to explore the solutions those meet custom power and PQ requirements together. Referring to Table 1.6 and [3] available common solutions for PQ and custom power are summarized in next section.

1.4 Possible Solutions for Power Quality and Custom Power

In order to deal with PQ issues and meet custom power requirements, several power electronics devices have been introduced and studied [33]. In the following a summery on common devices for PQ and custom power are reported.

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

1.4.1 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 [34]. Different topologies and configurations have been proposed and practiced for UPS systems so, a UPS system can be considered a series conditioner system if *Online* UPS is taken into account. In other hand the *Line interactive* or *Offline* UPS systems are categorized as shunt conditioner. The system equipped with storage system to guarantee power continuity to the load therefore, following the standard [3] it is categorized as *backup stored energy system*.

The most reliable, popular and widely used configuration, is Online UPS system. The configuration is shown in Figure 1.2, [43]. Principally it is placed between AC source and the load. In this device the main power supply is first converted to DC by converter (1) and then reconverted to AC by means of inverter (2); the battery (3) is connected to DC link through the DC-DC converter (4) and it supplies the system in case of mains failure. The DC-DC converter (4) can be necessary for optimum designation of storage system size and ratio because usually the inverter requires DC link voltage about 1.2 times the peak AC side voltage and without a bidirectional DC-DC converter the battery should be chosen to have the required voltage on its terminal. Practically it is preferred to interface the storage battery to the inverter DC link voltage by means of a bidirectional DC-DC converter.

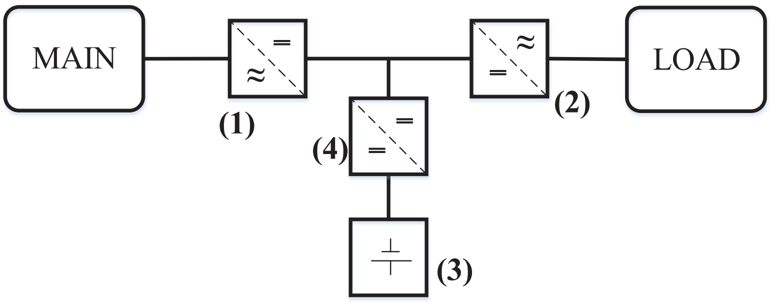

Figure 1.2: *Schematic of a double conversion online UPS system.*

This device can be inserted between the load and the main power supply and for this reason it makes the double conversion continuously even when the main power supply works normally. An amount of energy of the main supply is absorbed to charge the storage batteries, so the storage system is always ready to start properly. The energy performance of the device is low due to the total losses across the two converters on the way to supply the load.

When a failure in the main supply voltage has occurred, the converter (1) does not supply the DC section anymore, therefore, the load takes its energy from the storage batteries through the inverter (2). The situation does not change until the main voltage returns within nominal limits. This solution is widely used in different areas to protect critical load in work places, laboratories, data centers and etc.

The Online UPS is very interesting solution because it provide variable voltage and also frequency at the load side. In other hand the grid side converter (1), can be designed to set grid side power factor to unity and avoid any disturbances to the grid. Having all these options, the Online UPS is one of the best choices for both system provider aspects and also customer needs.

Line interactive and Offline UPS systems are less popular because those introduce limited controllability on voltage and on frequency control during normal operation mode because during normal operation mode the voltage and frequency are set by grid and UPS is charging the storage battery and it can work as a shunt connected PQ conditioner. If any severe disturbance is happen in grid side or in the time of voltage interruption, the UPS is ready to take over the load, disconnecting the load from grid.

Table 1.7 shows a summary of UPS performance as PQ and custom power conditioner. The statements are done according to *"Excellent - Very good - Good - Fair - Poor"* for compensation capability, *"Very high - High - Medium - Low"* for losses and cost classification and finally *"Yes - NO"* to indicate either the system is able to give the continuity option to the load or not.

Voltage PQ	**Current PQ**	**Continuity**	**Frequency PQ**	**Losses**	**cost**
Excellent	Excellent	Yes	Very good	High	Very high

Table 1.7: *UPS summary on PQ conditioning and its performance.*

1.4.2 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. Regarding voltage PQ issues several standards are defined. PQ in Europe refers to the EN 50160 [58] defining the key features of the voltage supplied by public distribution infrastructures to final customers, both in MV and LV. To deal with voltage disturbances, usually a series connected power electronic device is installed in series to the line between the distorted power supply and the load.

Considering the PQ standard and issues on supply voltage, this kind of devices can be a cost effective and suitable solution for DSO rather than the end user because it can be installed at MV level and supply a large area.

Generally speaking, DVC is a well-known series connected power electronics device, able to compensate voltage sags/swells, flickers and long term voltage drifts. It can be considered as a cost effective PQ solution that can support an area. Several compensation methods have been introduced and different topologies have been practiced and tested in the real field [53]. Among those, active power injection can be considered as the simplest and most effective method to compensate voltage disturbances, however it needs a large storage system integrated to the DC bus of the inverter. To be able to manage long term voltage compensation and regulation, quadrature to the line current voltage injection is required to decrease the storage system size and system losses [40]. The device schema is shown in Figure 1.3. DVC is placed series to the line, between grid and the load by means of coupling transformer (1). The inverter

(2) works as voltage source and injects required voltage series to the line. The storage system (3) can be included to the system or alternatively for reactive injection instead of storage system, a set of capacitors can be used.

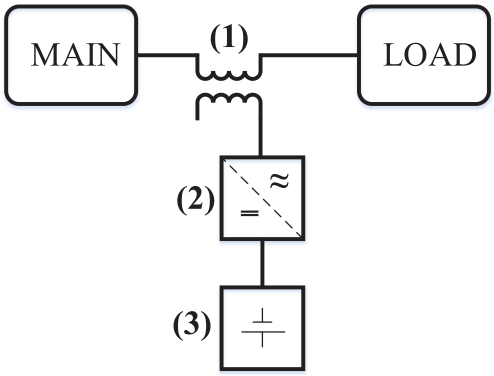

Figure 1.3: *Schematic of a DVC system.*

DVC is a PQ solution to compensate voltage issues and provide regulated voltage to the load. Different functionalities can be defined to the device. So, depend on the topology and the tasks assigned to the DVC, system can perform different functionalities in the system. With storage system the DVC can support wide range of voltage disturbance compensation, however it will increase the system cost and losses. Without any storage system, although the initial cost will be decreased but, it necessitates precise control method and it is subjected to compensation limits. Over all, since the system is placed between grid and the load, all the load current passes through it, and this will increase the losses in the system.

Table 1.8 shows a summary of DVC performance as PQ and custom power conditioner.

Voltage PQ	Current PQ	Continuity	Frequency PQ	Losses	cost
Excellent	Poor	NO	NO	High	Medium

Table 1.8: *Series conditioner summary on PQ actions and its performance.*

1.4.3 Shunt Conditioner

Due to the huge advances in electronic devices and power systems, in todays power grid, frequency deviations rarely happen and in most developed countries even the voltage magnitude is often within standard limit. As a result, it is going to be pretty common that instead of an expensive Online UPS system, the system operators and also end users prefer to have a shunt connected PQ conditioner.

As its name represents, 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. It can work as Static Synchronous Compensator (STATCOM) and Static Var Compensators (SVCs) [36, 37] to compensate reactive power of the load. It can work as Active Power Filter (APF) [61] to compensate load harmonic components and avoid these harmonic components to propagate to the grid and improve system efficiency. 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 [34].

The generic configuration is shown in Figure 1.4; it is comprised of a reversible inverter (1) that is the interface between the main and the DC link, energy storage (2) and a static switch (4). The inverter (1) is able to dispatch the energy produced by the distributed generator to the point of interconnection (3) and supplies the load with a high quality level (in this solution the frequency is fixed by the grid and the conditioner can not regulate the frequency independent from the grid one). Moreover, using a single converter, it is possible to obtain consisting economic benefit. When the main supply is present and voltage value is close to the nominal one, the load takes power from the grid, in this condition the inverter (1) maintains the grid current with a high quality level. When the main supply deviates from nominal voltage value, the static switch opens the circuit in order to avoid the power transferring to the main. In this case the load is supplied by the inverter that takes energy from the storage batteries. This changing to islanding operation mode happens without interruption of load power continuity.

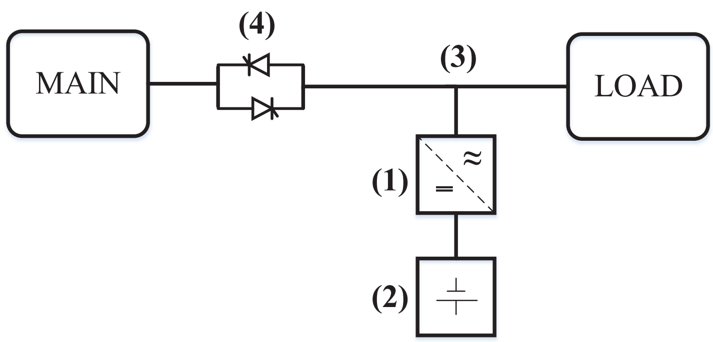

Figure 1.4: *Generic schema of shunt connected conditioner.*

The pro of this device is the high energy performance in the normal operation mode, because only a part of load power is under single conversion. In other hand, the power factor of the main is not controlled and depends on the load and the main voltage.

If instead of a 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 [7, 8, 9]. The generic schema is shown in figure 1.5 and it is comprised of a reversible inverter (1) which is connected to the PCC (3) and a set of capacitors as DC bus (2).

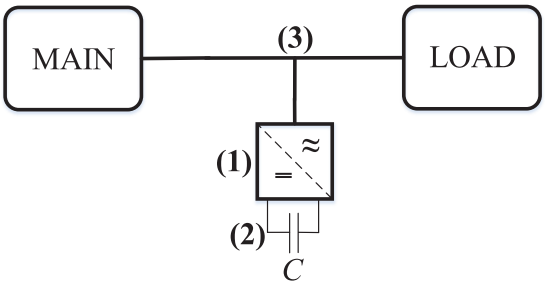

Figure 1.5: *Generic schema of STATCOM and APF.*

Since this topology has not any storage, there is no any active power exchange between inverter and the grid despite the small amount of active power that inverter requires to compensate switching losses and keep DC link voltage quite constant on capacitor. This device works as current generator to absorb/inject reactive and harmonic current components to compensate any reactive and harmonic components of the load. Although the device cost stays in low level (one inverter and there is no storage) and its losses are minor (only one conversion stage), its capabilities are limited.

Table 1.9 shows a summary of shunt conditioners performance as PQ and custom power conditioner. As it can be noticed the shunt conditioners can do nothing about the voltage PQ, instead those have very good performance on current compensation. Some topologies with storage system have the ability to supply the system during voltage interruption but without storage system a shunt conditioner lose this capability. Depends on system components the cost level can stay in medium or low level.

Voltage PQ	Current PQ	Continuity	Frequency PQ	Losses	Cost
Poor	Excellent/Very good	Yes/NO	NO	Medium/Low	Medium/Low

Table 1.9: *Shunt conditioners summary on PQ actions and their performance.*

1.4.4 Combination of Series and Shunt Conditioners

Basic configuration for a combination of series and shunt conditioners is shown in Figure 1.6. In this case the series action has been preformed by an passive element, link inductance (1), it also consists of an inverter (2) equipped with storage system (3) and connected to the line in PCC (4). In normal operation, the load is supplied by grid through coupling inductance, the inverter operates as voltage source to regulate the voltage on PCC although the capability of inverter to regulate PCC voltage is limited due to synchronous connection. In the case of main voltage interruption, the static switch (5) disconnects the system from grid, and the inverter supplies the load dissipating the energy stored in the storage system.

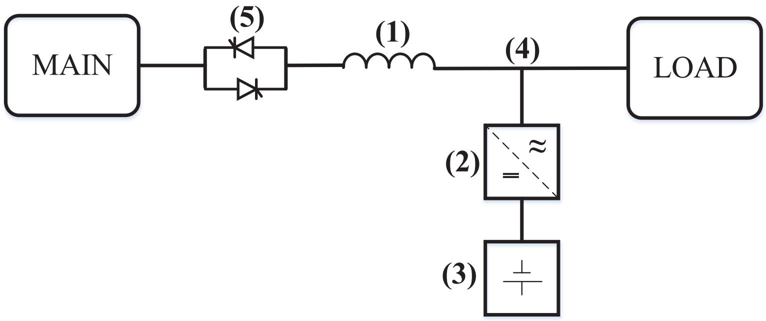

Figure 1.6: *Schematic of basic series and shunt elements as power conditioner.*

The evolution of the Figure 1.6 configuration can lead to interesting solutions capabale to deal with both voltage and current issues and provide high PQ service to the load. With an active element for both series and shunt actions, the configuration leads to the solution which is shown in Figure 1.7 and it is called UPQC. The generic idea was introduced by Akagi [32]. In this solution a static switch (1), a storage DC-DC converter (2) for a storage system (3) are represented. The UPQC is also provided by two inverters, which one is connected in series (4) with main through a coupling transformer (5) and another one is connected in parallel (6) to the load. The converter (4) behaves as an ideal voltage generator, and the converter (6) behaves as an ideal current generator. In basic UPQC configuration, series converter and shunt converter are sharing common DC link (7). The configuration can include/exclude the storage system. Without storage, the system initial cost is decreased in the cost of losing some functionalities of the device and one of the inverter, either (4) or (6) can be responsible of DC bus regulation. Shunt and Series inverter connections can be swapped. This will change device performance and its functionality [53]. With storage system presence, when a main interruption happens, the static switch (1) disconnects the system in order to avoid power flow towards the main, so the load is supplied by parallel inverter (6). Therefore, inverter (6) rating has to be designed according to the nominal power of the load. During island operation mode the series inverter (4) is stalled. During the normal operation mode, when the static switch (1) connects the load to the network, the inverter (4) can absorb the desired active power from the main supply in order to stabilize the DC voltage and stabilize the load voltage while the inverter (6) filters out any impureness of the load current.

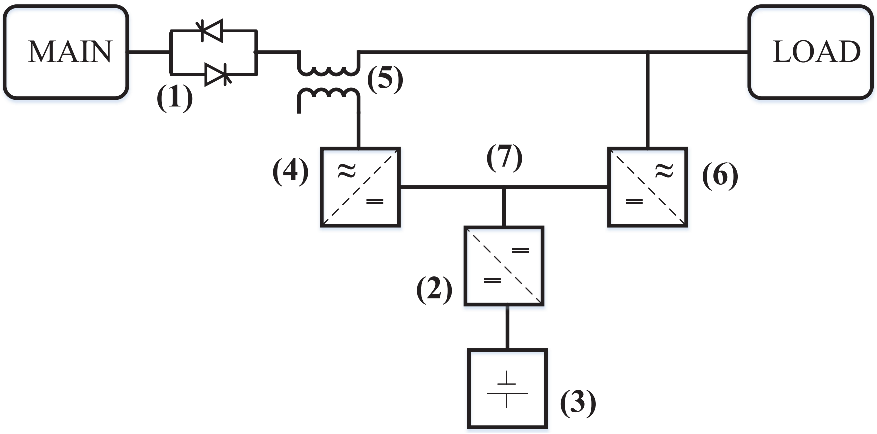

Figure 1.7: *Generic schema of series and shunt conditioners as UPQC.*

Moreover, this configuration allows a high power factor close to the unity and low current harmonic distortion. This solution introduces some amount of losses (in the normal operation mode the power exchange to the load does not convert totally), and a considerable average cost for the converters design. Obviously, as all interactive devices with the network, this configuration is not able to stabilize the load frequency.

Voltage PQ	Current PQ	Continuity	Frequency PQ	Losses	Cost
Very good/Good	Excellent/Fair	Yes/NO	NO	High/Medium	Very high/High

Table 1.10: *Combination of series and shunt conditioners, summary on PQ actions and their performance.*

Table 1.10 summarized the performance of these systems. With active elements as both series and shunt units, those can have very good performance on voltage and current PQ improvement however, a configuration as it is shown in Figure 1.6 has limited capability on voltage and current control actions. With storage system included, a UPQC can provide continuity to the load. The losses and cost of the system is also stays at High and Very high level because the series unit need to pass all the load current. Also shunt unit need to designed according to load nominal power to provide continuity.

1.4.5 Open Unified Power Quality Conditioner (Open UPQC)

For what pertains the PQ improvements as it is summarized, the technology involved is mainly based on power electronics equipment [29, 30] and mostly to increase the functionality and introduce flexibility to the distribution network, a storage system also is integrated to the PQ conditioning device. All the devices and solutions that are introduced, are usually have their own advantages and disadvantages regarding PQ actions and also considering their losses and cost. At distribution level, UPQC is an attractive and effective solution to tackle both voltage and current disturbances at a certain point of the network. Several topologies and control methods have been introduced and tested [62]. The device can comply most of the PQ improvement actions however the associated losses and design cost are the prevailing shortcoming of the solution.

Custom power solutions, and mainly the most effective and popular one UPS, is very expensive for most of the end users to equip their property with it and also to deal with its maintenance business. From the end users point of view, they prefer to receive an offer from service provider to have a custom power device at their property, although with limited functionality, which can give services to both end user and grid together and the service provider take over its maintenance and control actions. Such a solution would be a combination of power conditioner and custom power device which can improve the PQ level of the installed network and also give economic and quality services to the involved end users.

An interesting proposed device which allows to improve the PQ within the installed network and gives variety of services to the grid and the load (end user) is Open UPQC, [13, 14, 17, 19, 20]. The proposal splits out traditional UPQC shunt and series units. The series unit is moved to MV/LV substation to improve the overall PQ level of the installed area. The Shunt unit is split out again to several units, depending on end user contractual power and needs. Open UPQC single phase schema is shown in Figure 1.8. Series unit as it is shown in Figure 1.8, is installed in MV/LV substation after the distribution transformer. It consists of a coupling transformer (1), inverter (2) and a set of capacitor bank as DC bus (3). If the series unit has not any storage system integrated in, its working principle should be based on pure reactive power compensation which is explained in Chapter 2. Alternatively, if the storage system is included to the series unit, its working limit can be extended in the cost of increasing expenses and its complexity. Series unit fundamental task is to regulate PCC (4) voltage.

The shunt unit is installed close to end user. Figure 1.8 shows one shunt unit connected to LOAD_1 which is representative of controlled loads. Shunt unit consists of a *Static Switch* (5), AC-DC converter (6) and it is equipped with storage battery system (7). The number of shunt units basically correspond to end user need and request. It also can be computed depend on design parameters and installed feeder requirement, even if the system is modular and shunt units can be added to the network in time. LOAD_2 represents uncontrolled loads and in Figure 1.8 those are shown in integrated form and are directly connected to PCC without shunt unit.

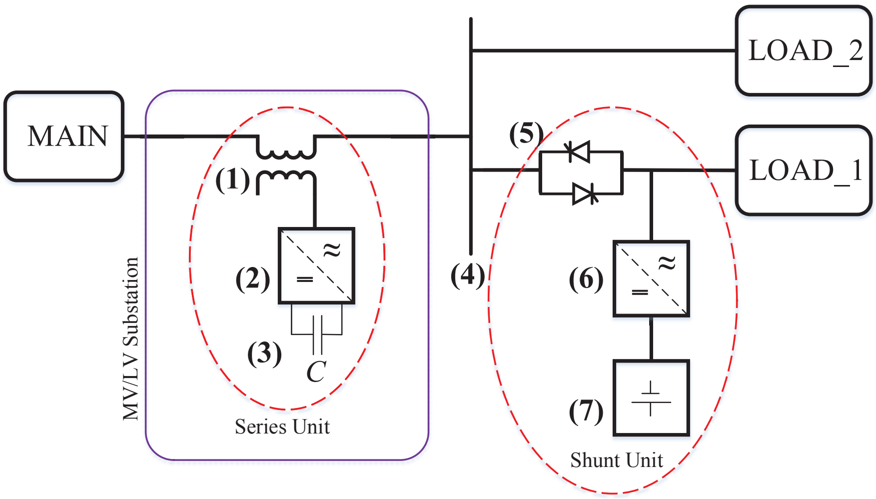

Figure 1.8: *Simplified schematic of the Open UPQC system.*

This 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), giving custom power services to the involved end users equipped with shunt unit. Therefore, to summarize, 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 distributed among the LV network, such as placed at the customer premises and capable to implement Volt/VAr control actions, too.

There are two different operation modes in function of the main voltage RMS:

- ***Online***: when the PCC voltage is within its operation limits (from 0.9 to 1.1 of the nominal load voltage defined by standards), the *Static Switch*s 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 action. 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 into the grid. In this condition each shunt unit can work as reactive power manager, active filter and peak shaving device. If there is no need to do peak shaving and there is no reactive power request, active and reactive power produced by shunt unit are equal to:

$$P_{shunt} = P_{batterycharging} + P_{losses}$$
$$Q_{shunt} = -Q_{load} \tag{1.1}$$

This means the shunt unit absorbs the power to charge the batteries and also the active power to compensate its losses in order to keep DC bus voltage constant. Additionally, it supplies load reactive power in order to set grid side PF to unity. During peak shaving and reactive power request, active power and reactive power are equal to:

$$P_{load} = P_{threshold} + P_{shunt}$$
$$Q_{request} = Q_{load} + Q_{shunt} \tag{1.2}$$

The load absorbs constant power from grid $P_{threshold}$ and the rest of load power P_{load}, is supplied by the shunt unit, P_{shunt}. The equivalent reactive power seen by grid is equal to the requested one $Q_{request}$, which is the summation of load reactive power Q_{load} and the reactive power provided by shunt unit, Q_{shunt}.

- ***Island***: when the PCC voltage is outside of its operation limits, each shunt unit *Static Switch* 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. End users equipped with shunt unit with its abilities (peak shaving, islanding and etc.) can be seen as very flexible *Smart Load* within smart grid systems [46]. In this state, the Open UPQC shunt unit reacts as line interactive UPS system, [34] and it supplies all active and reactive power of load. The power exchange is as it is shown in Equation 1.3.

$$P_{shunt} = P_{load}$$
$$Q_{shunt} = Q_{load} \tag{1.3}$$

Open UPQC is an cost effective PQ conditioner for DSO. Series unit is an voltage PQ conditioner device which supplies all the installed feeder. It can compensate all the sag/swells, under/over voltage, flickers and voltage fluctuations at the connected area. By optimal designation, series unit can give PQ service to a wide area. Meanwhile, shunt units work as STATCOM or SVC system to compensate reactive power, improving power factor and PQ level of the installed area. Moreover, shunt units with their peak shaving functionality provide continuity and economic benefits to the end user. Also shunt unit with its storage and proper battery charge and discharge management system can give further economic benefit to the connected end user. It can be managed to charge the battery storage system when the network tariff is low and instead supply part of the load or all the load when the network tariff is high in order to save part of the end user bill cost. Additionally the shunt unit islanding option, makes it a very interesting UPS like custom power device for the end users. It can guarantee their power supply in the case of line interruption and protect their property from over/under voltage and faulty condition. Beside above mentioned pros for Open UPQC, intrinsically it has some shortcoming over other devices. One disadvantage is that, the series unit is installed in series to the line so, all the load current passes through the series unit. Consequently, the series unit needs to be designed according to the nominal line current rating and this increases the design cost and system losses. Another critical design criteria is to decide whether to include storage system into series unit or not. With storage system, the series unit could have wider control limits in the cost of increasing the initial cost, make system bulky and add maintenance complexity. In other hand, without storage system, the system will have narrower control limit and also it will require more complex control strategy. The disadvantages associated with shunt unit are one; its losses due to the bidirectional DC to ac power conversion and two; its load protection restricts because it works as synchronous custom power device and it has not the capability to regulate load frequency and voltage magnitude.

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 [14]. The Open UPQC can introduce economic benefits to the costumers, enabling them to follow the Demand Side Management (DSM) strategies of the DSO, and to the DSO too, allowing it to reduce the investment cost for PQ improvement within its Distribution Network (DN).

Voltage PQ	**Current PQ**	**Continuity**	**Frequency PQ**	**Losses**	**Cost**
Very good	Very good/Poor	Yes/NO	NO	Medium/low	High/Medium

Table 1.11: *Open UPQC summary on PQ actions and its performance.*

As previous cases, Table 1.11 summarized the Open UPQC performance comparing to other solutions. It can supply the all area improving voltage PQ, the current PQ actions can be very good where there is the shunt unit available and can be considered poor or unavailable for the loads without shunt unit. The continuity same as current

PQ actions, depends on shunt unit availability, for the users with shunt unit there is and for the user without shunt unit there is not. From the losses and cost point of view, it has the advantages over other solutions because the DSO can decide where it is necessary to install series unit. On other hand, the users can decide either to have or not the shunt unit in their property. So, the cost can be spited between DSO and end user.

1.5 Electronic Device in the LV Network (Smart Grid)

This section talks about modern power systems and necessity of *Electronic Device* integration into power system which finally with proper ICT leads to *Smart Grid* Concept.

The traditional electricity grid was the consequence of progressive growth of fast and unavoidable urbanization, domestic and industrial loads distribution in cities and country sides during past decades. This traditional electricity grid was a strictly hierarchical system where power generation plants were responsible to generate required power of the domestic and industrial customers' loads. So, the system had basically a unidirectional power flow and the grid and transmission lines must be over-sized to ensure maximum demand during peak demand period [25, 31]. In most cases the grid should be sized almost twice the average load consumption ratio to be able to supply peak demand which occurs less than 20% of the time. So, for the rest of the time this over rated generation and transmission system is useless and in most cases it introduces losses to the system. A simplified schema of the traditional grid is shown in Figure 1.9. As it was explained, it shows that the power is generated in centralized power stations. The generated power is transmitted and distributed through transmission and distribution lines and the power flow as it is depicted, is one direction from the grid to the user chain.

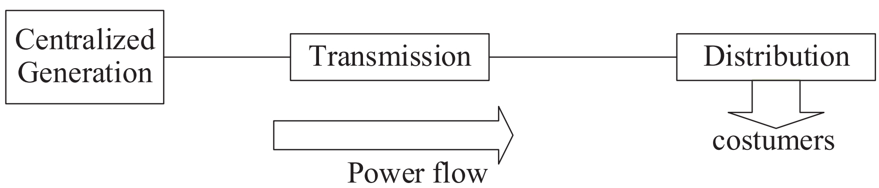

Figure 1.9: *Simplified traditional grid system structure.*

Based on the population increment rate, the electric energy consumption and electric load power demand is expected to double by 2050 [57]. The problems to supply such a demand are; first, to have proper energy source and adding new power generation plants to the grid, second, the transmission lines should be able to carry the generated power to the distribution system and eventually to the end user. Adding new transmission lines to the current network in most places are quite impossible. So, the system operators need better solutions to increase the power system efficiency and use the current network optimally.

Increasing global warming along with above mentioned energy consumption demand, made it unavoidable to look for new energy sources and system level solutions to deal with environmental problems and also supply demanded electricity power [12]. The rapid increase in the fossil fuels cost has accelerated this road and it is coupled with the utility companies' limits to expand their generation capacity. Theses changes along with the rising demand for electricity, were the major issues that traditional grid should face with. In other hand in most large and old cities, it is not any more possible to add new distribution lines to the existed network. So, even if the generation and transmission problems have been solved, still there are limits in distribution level toward the end user.

To deal with all above mentioned issues, green and Renewable Energy Source (RES) have attracted considerable attention in recent decades due to their clean and sustainable nature, in which power electronics play an important role [12]. RESs spread around and are available locally thus, these Distributed energy Resources should be tackled locally wherever those are available by utilizing the proper device. Thus far, DGs and Microgrid (μ-grid) have came into the picture and are desirable for proper utilization of RESs in either grid tied or islanded operational modes. Adding these DG types enabled bidirectional power flow within power system. However, to inject RES and DG power to the grid, system operators need another layer of infrastructure.

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 the load. Basically Supervisory Control and Data Acquisition (SCADA) system is meant to answer these requirement 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 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 DN, transition toward *Smart Grid* need to be triggered at the bottom of the chain, in the distribution system [31]. This is more desirable for end users because they need/want to control their consumption to manage their own property in order to gain economic benefits.

As explained above, traditional electricity grid was basically a 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 [31]. Moreover, considerable amount of the energy, almost 8% [31], was lost during transmission and distribution level. The new paradigm *Smart Grid* in contrast to the old system, by means of RES and DGs, provides bidirectional power flow within the system. This integration and adaption is done in distribution and LV level. Beside the bidirectional power flow, *Smart Grid* need two-way communication system as well. Table 1.12 gives a summarized comparison between the traditional grid and the *Smart Grid*.

	Traditional Grid	**Smart Grid**
Protection and Breaker	Electromechanical	Digital
Communication	One-Way	Two-Way
Generation	Centralized	Distributed
Configuration	Hierarchical	Network
Visibility	Few Sensors	Sensors Throughout
Fault detection	Blind	Self-Monitoring
Restoration	Manual	Self-Healing
Fault clearance	Failures and Blackouts	Adaptive and Islanding
Check and Test	Manual	Remote
Control	Limited	Pervasive
Customer Choices	Few	Many

Table 1.12: *Brief comparison between the traditional grid and the Smart Grid [31].*

Considering the Table 1.12, it can be understood that the *Smart Grid* by its concept, is the combination of different layer technologies both in power systems and also ICT systems. It is accommodated to include wide variety of generation options, e.g. centralized generation, distributed, intermittent and mobile generation [31].

In essence, the *Smart Grid* needs to provide the utility companies and especially DSO full visibility and flexibility to interact with end users in order to deliver full functionality. The paper [25] defines *Smart Grid* as *"a convergence of information technology and communication technology with power system engineering"*. It requires several high technological participant and one key player is power electronics devices those are able to send their data to the supervisory control system and also receive back the control action and properly react to the received command.

All these new technologies, such as renewable energy power plants and power electronics devices included in different equipment, can cause PQ and voltage problems at different levels, even if they are installed respecting connection rules [1]. At the same time, modern systems, like *Smart Grid*s and μ-grid, are also requiring autonomous voltage and current PQ conditioners. So, the *Smart Grid* as favorite system level solution for power system, especially in LV DNs accordingly will require system level PQ conditioner capable to speard toward the DN system and carry out several tasks within *Smart Grid* concept including PQ conditioning.

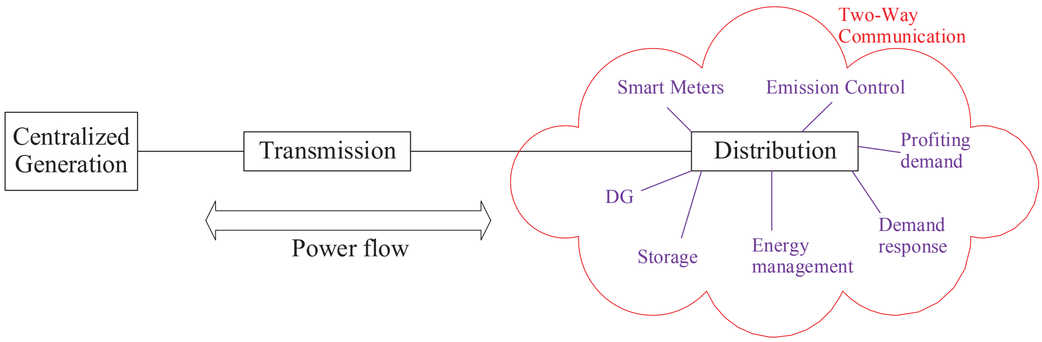

Figure 1.10: *Simplified Smart Grid system structure integrated in distribution level.*

Figure 1.10 is depicted a simplified schema of described *Smart Grid* paradigm. Several functions can be defined within this structure [6, 41]. Based on literatures, it can be categorized in three classes [25]:

- 1) Infrastructure
  As infrastructure, the so defined *Smart Grid* requires two-way communication system with high technological power electronics devices that could actively participate in system level actions to act and react within the system. Also Smart Meters are required to gather several measurement through the system.

- 2) Management System
  Load management system need to be implemented. This is like the brain of the system. It should collect all the data within the network or supported area, make proper decision and send commands to the all active participants. Cost efficiency to the end user and profits for DSO, reshaping the network profile in order to give flexibility to the system, demand side control actions, emission control and many other scenario can be included.

- 3) Protection
  Such big data and active system need intelligent and powerful protection system as well to guarantee end user privacy and power continuity and also system stability.

As a key active participant within *Smart Grid* system, power electronic devices play crucial rule in realization of such a infrastructure. In one hand, the power electronics devices interface storage and DG types to the grid and based on the communication system, those can react very fast to the received commands. In other hand, all this integration with coupled effect on each other will cause PQ issues in the installed area. So, beside the benefits, the system has disadvantages in its nature. Again thanks to the technological development, this power electronics active participants can/should deal with PQ phenomena within the installed area as well. The capability of this power electronic devices can be improved effectively within the system if the decision making system optimizes their functionalities based on the collected data through the system.

CHAPTER 2

Open UPQC Working Principle

This chapter explains the working principle of Open UPQC in ideal condition in order to demonstrate its operation concept and working limits. All the simulation in this chapter are conducted in ideal condition to explain the device working logic. Practical consideration on real device realization will be addressed in next chapters. The chapter is split into different sections in order to cover series and shunt units working principle independently and also to describe co-operation between series and shunt units within a distribution network.

The series unit is simulated as ideal voltage source which injects the required voltage in series to the connected line to compensate any voltage drop or swell. The series unit works with pure reactive power so, the injected voltage should be in quadrature to the line current. The shunt unit is modeled as current source capable to inject reactive power to the network up to rated VA, perform peak shaving action or operate in *Island* mode working as voltage source. Operation limits and co-operation between shunt and series units have been analyzed, always in ideal condition, at the end of the chapter.

2.1 Series Unit

Open UPQC series unit is a series connected power electronics device, able to compensate voltage sags/swells, flickers and other voltage disturbances. It works as self-supported DVC and several compensation methods have been introduced [56] and different topologies have been practiced and tested in field [53] mostly to reduced the storage system and the device losses. Principally the series unit is designed to work with pure reactive power to compensate voltage problems and regulate PCC voltage at nominal/set value. It is important to note that the power absorbed by the loads and the shunt units, influence the series unit injected voltage and also the performance of whole Open UPQC.

Following analysis have been done under the assumption that the main voltages are sinusoidal and are constituted of only the positive sequence component in the different network buses and also the currents are sinusoidal and distortion free. Therefore the system voltage V_s is within *Normal* operation mode. The maximum voltage drop in a LV lines is less than 5% to maintain low power loss. Indeed, if the voltage in the PCC is at its nominal value (100%), the load voltage value will be at least 95% of the nominal voltage. This result allows an improvement of the supply quality. Therefore, the series unit of the Open UPQC works to stabilize the nominal voltage at the PCC.

Figure 2.1 demonstrates the system's model where the Open UPQC series unit is modeled as ideal voltage sources. V_s and I_s stand for grid side voltage and current respectively. V_x is Open UPQC series unit injected voltage and it is perpendicular to the I_s to provide pure reactive power injection. V_{PCC} is the voltage at PCC. $U1$ and $U2$ are the loads in its generic mode. V_{U1}, V_{U2}, I_{U1} and I_{U2} are loads voltages and currents and Z_{Line} stands for distribution line impedance and it can be different for each section.

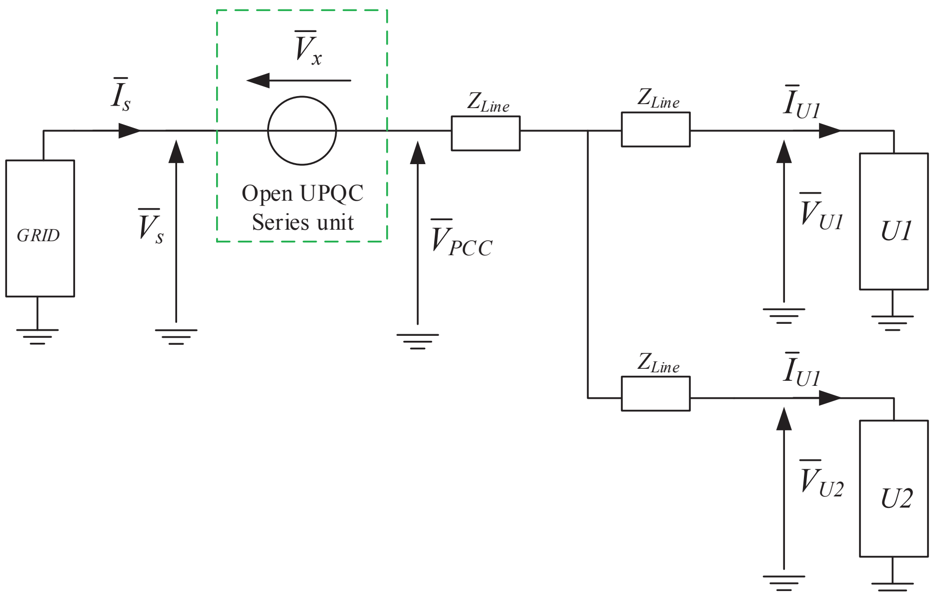

Figure 2.1: *Open UPQC Series unit system model with ideal voltage source.*

The Open UPQC series unit should inject a proper V_x in order to keep V_{PCC} constant therefore at any time KVL of Equation 2.1 should be respected.

$$V_{PCC} = V_s - V_x \tag{2.1}$$

Theoretically this can be achieved by pure reactive injection if the injected voltage V_x is always managed to be perpendicular to the line current I_s. Figure 2.2 shows the series unit reactive compensation principle. The system should inject proper V_x in quadrature to the line current in order to keep V_{PCC} at set value.

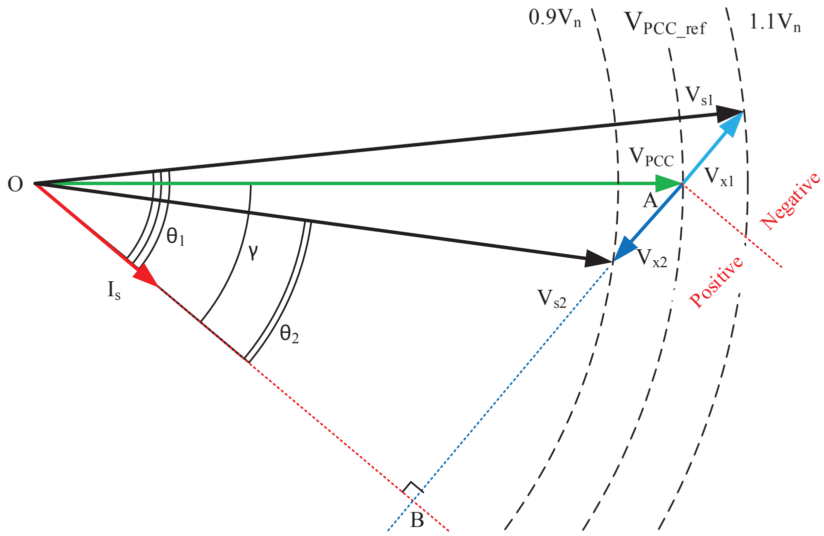

Figure 2.2: *Open UPQC series unit reactive operation principle.*

From Figure 2.2, using trigonometric equations in right triangle OAB, the injected voltage magnitude can be calculated as Equation 2.2. At Equation 2.2, i can be either 1 or 2, depend on which compensation state the system is and the γ is the phase difference between PCC voltage and line current. θ_i is the phase difference between network voltage and line current for different load conditions. V_{xi} is the calculated injected voltage magnitude. As it can be noticed from Figure 2.2 and Equation 2.2, the formula gives negative and positive values for V_{xi} in different compensation scenarios.

$$V_{xi} = V_{PCC\_ref} \cdot sin(\gamma) - V_s \cdot sin(\theta_i) \tag{2.2}$$

Equation 2.2 gives the magnitude of series unit injected voltage. This value should be injected perpendicular to the line current. So, the angular frequency of line current should be moved 90° to get the injected voltage angular frequency. Detail procedure to get the sinusoidal reference value for series unit inverter is presented in Chapter 3.

This pure reactive voltage injection, although gives the system operators the possibility to have continuous regulation on PCC voltage and the compensator designation without bulky and expensive storage system, however it has some shortcomings and may introduce some problems to the network. The major problem associated with reactive compensation is the frequency variation that the series unit can introduce to the system during transient. This frequency variation happens due to the perpendicular voltage injection.

Suppose the system is working without any voltage deviation and suddenly due to any reason a 15% voltage drop is occurred in the grid voltage. The series unit calculates the required perpendicular injecting voltage and applies it to the system immediately. So, in first half cycle after the voltage drop, the PCC voltage sees faster zero crossing and consequentially a frequency boost. Figure 2.3 shows this frequency deviation with arrows on zero crossing. Before t=0.5s, the grid voltage and PCC voltage were the same, at t=0.5s and after on, 15% voltage drop is simulated. The PCC voltage frequency variation is shown in Figure 2.4 (a) along with grid and PCC rms voltages in Figure 2.4 (b). As it can be noticed, although the grid voltage frequency is almost constant, for a short transient time during voltage drop, the PCC voltage tolerates a short frequency increment due to series unit reactive voltage injection. The frequency increases during transient because the zero crossings are shifted to left and occur faster.

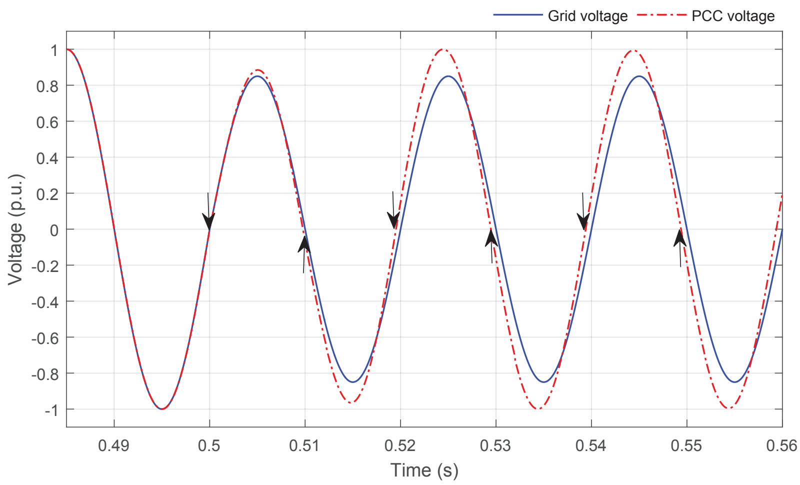

Figure 2.3: *Open UPQC series unit frequency deviation problem during under voltage.*

The same scenario happens if the grid voltage sees an over voltage for any reason. Figure 2.5 demonstrates this phenomena for 30% over voltage at grid side voltage. The grid was with no voltage problem before t=0.5s, and at t=0.5s an immediate over voltage is simulated at grid voltage. Open UPQC series unit has compensated the over voltage and due to the reactive voltage injection, the PCC voltage experience frequency variation. The phenomena can be far from realistic problem, but here the simulation is meant to explain the concept. As it can be noticed, in this case the

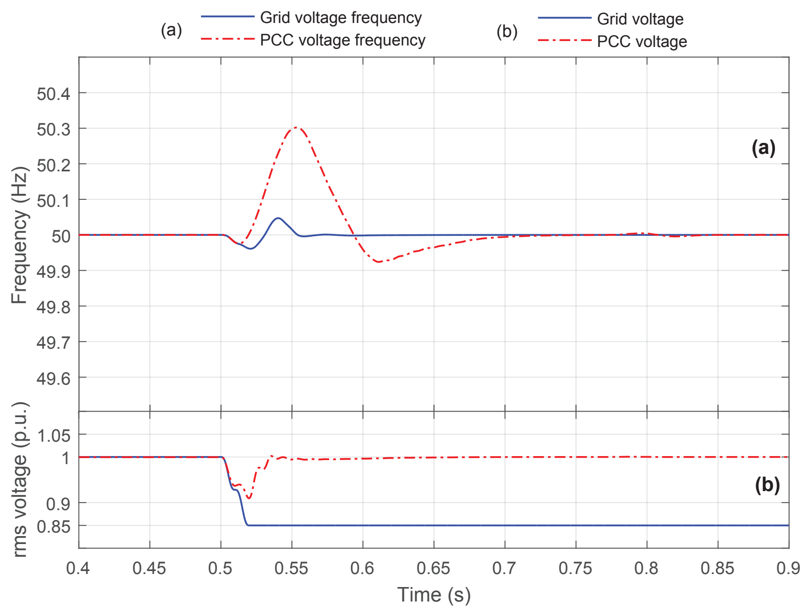

Figure 2.4: *Open UPQC series unit (a) frequency variation during under voltage transient (b) rms voltages.*

zero crossing points are shifted to the right, so the PCC should experience a drop in its frequency. Figure 2.6 (a) illustrates frequency deviation during this event and the rms voltages are shown in Figure 2.6 (b). The PCC voltage frequency drops for short transient indeed the grid frequency is almost constant. Depends on voltage drop deep and load power factor, the frequency variation can be varied. Here an example is simulated to demonstrate the problem.

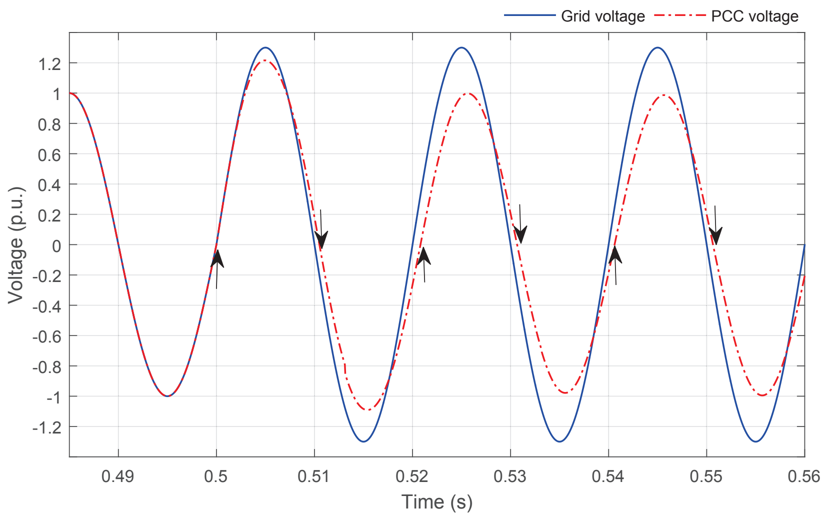

Figure 2.5: *Open UPQC series unit frequency deviation problem during over voltage.*

This frequency variation caused by series unit, can affect electronic devices' functionality those are connected downstream the Open UPQC series unit. For example

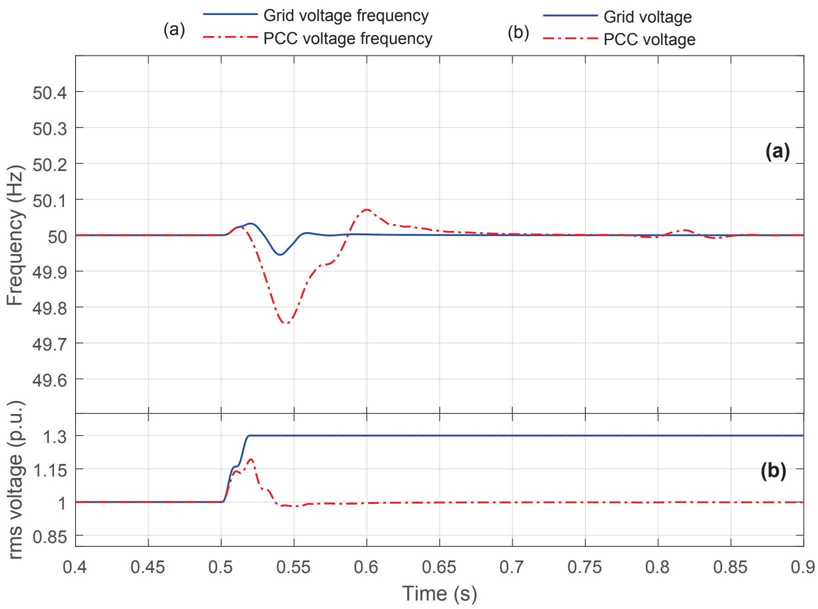

Figure 2.6: *Open UPQC series unit (a) frequency variation during over voltage transient (b) rms voltages.*

solar inverters are very sensitive to frequency variation and even very short frequency variation can send them to fault condition, activating their protection system and stop their functionality.

In other hand, another shortcoming of the reactive voltage injection compensation strategy, is the device working limits. The limits are discussed in next subsection in detail.

2.1.1 Series Unit Operation Limits

The Open UPQC series unit, depends on device nominal voltage ($|V_{x,max}|$), load power angle (γ) and requested reference voltage ($|V_{PCC\_ref}|$), has upper and lower compensation limits on V_s. Figure 2.7 shows these limits for two different load conditions considering two different load currents and corresponding load power angles I_L, γ and I'_L, γ' respectively. It can be noticed that based on V_s value independent of the load condition, there are two cases; over voltage *Case 1* and under voltage *Case 2*. Both cases limit is evaluated in the following.

Case 1) Over Voltage

In this case, the inverter nominal voltage, $V_{x,max}$ imposes limits on compensation range as shown in Figure 2.7. Triangle OAC or OAC' can be used to evaluate the upper limit in two different load conditions. The maximum value of over voltage that can be compensated with reactive voltage injection only, proportional to the segment OC or OC', can be found by Equation 2.3 for the first load condition. This is the maxi-

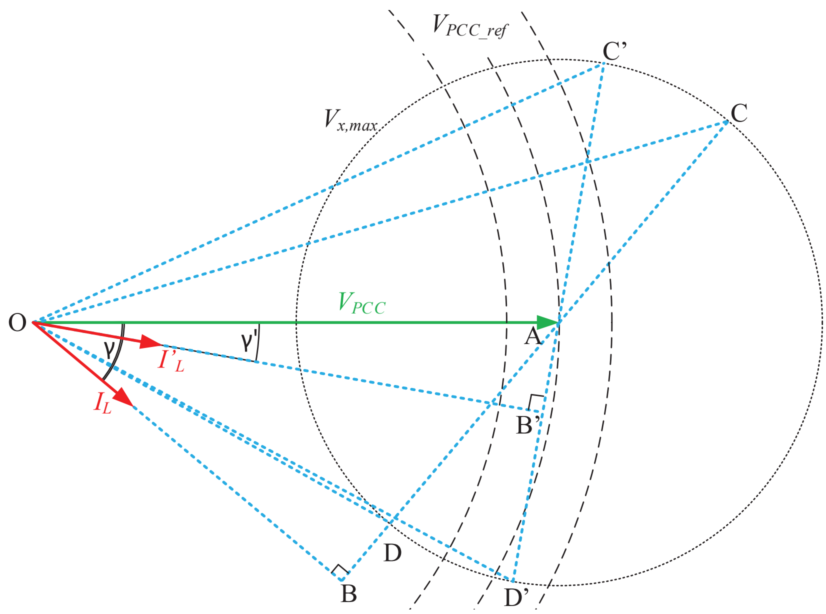

Figure 2.7: *Open UPQC series unit operation, voltage compensation limits.*

mum grid voltage that can be compensated with reactive power only and it is required to get the nominal V_{PCC} voltage for *Case 1*.

$$\overline{OC} \equiv |V_{s,max}| = \sqrt{|V_{x,max} + V_{PCC\_ref} \cdot sin(\gamma)|^2 + |V_{PCC\_ref} \cdot cos(\gamma)|^2} \qquad (2.3)$$

Considering $V_{PCC\_ref} = 1$ p.u., it is possible to discover that $V_{s,max}$ depends on $V_{x,max}$ and γ, doing so, Figure 2.8 shows the maximum V_s variation versus $V_{x,max}$ variation from zero to per unit and load power angle γ variation from pure capacitive load to pure resistive ($\gamma = 0$) and to positive values also till pure inductive load. Although $V_{s,max}$ is basically limited by inverter maximum voltage ratio, $V_{x,max}$ but, as it can be noticed from Figure 2.8, with larger power angle (either positive or negative) the Open UPQC series unit working limit is broaden.

Figure 2.9 illustrates the $V_{s,max}$ variation with different values of fixed $V_{x,max}$ versus load power angle (γ) variation. Figure 2.9 is the left side two dimensional view of Figure 2.8 for three different fixed $V_{x,max}$ values. As it can be noticed, with fixed power angle (γ), increasing the $V_{x,max}$ shifts the $V_{s,max}$ curve upward and expends the system limits.

Case 2) Under voltage

In this condition, series unit has two different limits and it is necessary to evaluate both of them and finally decide on the effective limit that should be considered.

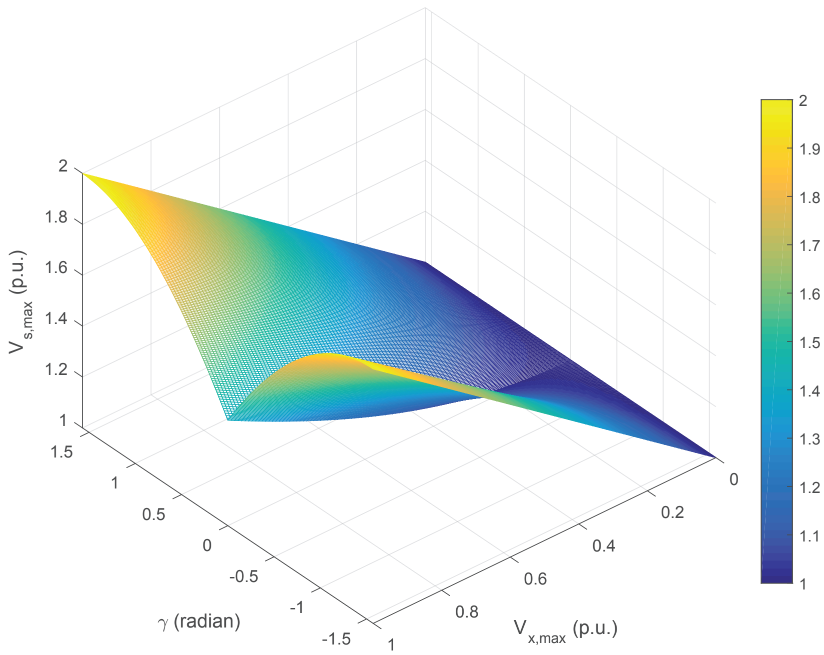

Figure 2.8: *Maximum V_s variation versus inverter rating voltage and γ variation.*

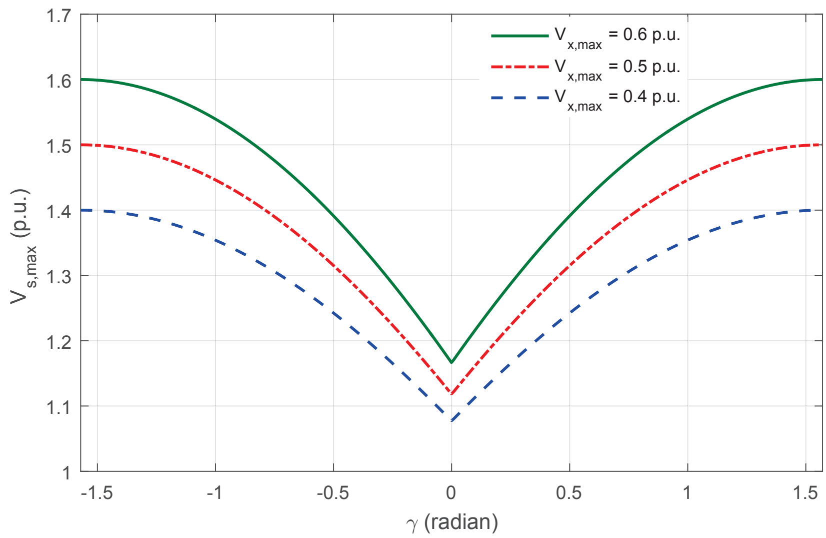

Figure 2.9: *Maximum V_s variation versus γ variation with fixed $V_{x,max}$.*

a) Limit due to $V_{x,max}$:

From Figure 2.7, the inverter nominal voltage, $V_{x,max}$ imposes limits on compensation range that can be evaluated by the triangle OAD or OAD'. The segment OD or OD' represent the limit in two different load conditions so, the minimum V_s that can be compensated with reactive voltage injection, can be found by Equation 2.4 for the first load condition:

$$\overline{OD} \equiv |V_{s,min\_a}| = \sqrt{|V_{PCC\_ref} \cdot sin(\gamma) - V_{x,max}|^2 + |V_{PCC\_ref} \cdot cos(\gamma)|^2} \quad (2.4)$$

b) Limit on Power Angle γ :

From Figure 2.7, the load power angle, γ, imposes limits on compensation ranges that can be evaluated by the triangle OAB or OAB'. The segment OB or OB' represent the limit in two different load conditions so, the minimum V_s that can be compensated with reactive power, can be found by Equation 2.5 for the first load condition:

$$\overline{OB} \equiv |V_{s,min\_b}| = |V_{PCC\_ref} \cdot cos(\gamma)| \quad (2.5)$$

Depends on the system condition either Equation 2.4 or 2.5 has to be considered the control limit for *Case 2* as if $V_{x,max} > V_{PCC} \cdot sin(\gamma)$ the $V_{s,min}$ has to be evaluated by Equation 2.5 else by Equation 2.4. When $V_{x,max} = V_{PCC} \cdot sin(\gamma)$, Equation 2.4 and Equation 2.5 give the same results. This value has to be used as the minimum grid voltage required to get the nominal V_{PCC} voltage.

Figure 2.10 shows the minimum V_s variation regarding both γ and $V_{x,max}$ variation. It can be seen that when the $V_{x,max}$ equals to zero the system limit stays on unity line and series unit has no compensation limit. Increasing the $V_{x,max}$ moves the $V_{s,min}$ downward which means an increase on compensation limits. After a certain limit the Equation 2.5 became dominant and so the variation surface has sinusoidal like shape. When the γ is equal to zero, or in other worlds the load has unit power factor, the $V_{s,min}$ is equal to unity and the device has no compensation limit. In this case the γ variation is dominant and has higher effect on device operation limits rather than $V_{x,max}$ variations.

Figure 2.11 shows the side view of $V_{s,min}$ versus γ variation for three different fixed $V_{x,max}$. As it can be noticed, after certain point, when γ is around zero, all three curves coincide because the minimum limit of Equation 2.5 became dominant and the value of $V_{x,max}$ does not affect the limit on $V_{s,min}$. In contrast, with larger γ, the limits of Equation 2.4 should be considered and the minimum value depends on $V_{x,max}$ rather than γ. Ultimately, increasing the $V_{x,max}$ and γ, the minimum V_s decreases which means that the series unit is able to compensate wider under voltage.

During operation, if the V_s is less than minimum or more than maximum value, the $|V_{PCC\_ref}|$ has to be updated to the limit value that can be achieved by the series unit. Indeed if the network voltage exceeds this limit, the series unit is not able to reach the reference value without active power to control the DC bus voltage and avoid system fail. So it is possible to update the $|V_{PCC\_ref}|$ to the new value that can be achieved.

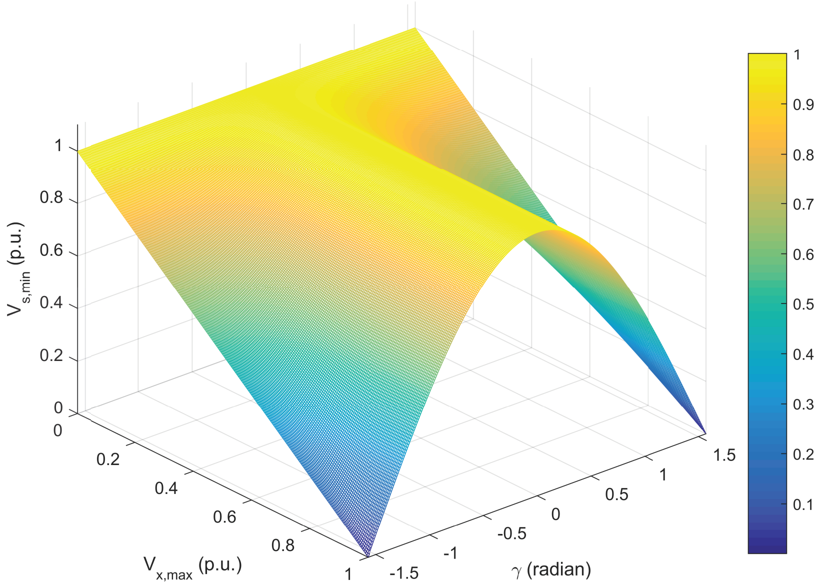

Figure 2.10: *Minimum V_s variation versus inverter rating voltage and γ variation.*

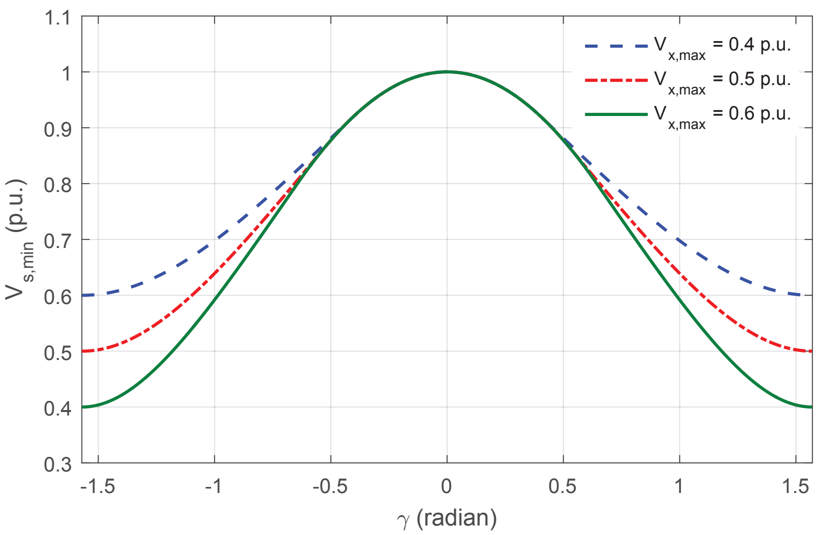

Figure 2.11: *Minimum V_s variation versus γ variation with fixed $V_{x,max}$.*

To update the new reference value, reverse calculation of Equation 2.3, Equation 2.4 and Equation 2.5 has to be done with respect to V_{PCC_ref}. As before, based on V_s value, there are always two cases; over voltage *Case 1-update* and under voltage *Case 2-update*, as it is described before. Both updating cases are described in the following.

Case 1-update) Over Voltage

By Equation 2.3 a second order polynomial equation can be obtained and solving this quadratic equation for V_{PCC_ref} will give two values. Negative value will require large V_x injection so, it is not the optimal solution. The positive value as it is reported in Equation 2.6, is the new achievable reference for V_{PCC_ref} in order to update the control method and find new injection voltage (V_x).

$$V_{PCC\_ref} = -V_{x,max} \cdot sin(\gamma) + \sqrt{(V_{x,max} \cdot sin(\gamma))^2 + V_s^2 - V_{x,max}^2} \tag{2.6}$$

Case 2-update) Under Voltage

In this condition series unit has the same two different limits and it is necessary to evaluate both of them for corresponding conditions.

a-update) Limit due to $V_{x,max}$ **:**

If the limit is due to $V_{x,max}$, *case a*, solving Equation 2.4 with respect to V_{PCC_ref} will lead to a second order quadratic equation and two possible solutions can be found. Again in this case, the negative value should be ignored and the positive one, Equation 2.7, is the optimal solution.

$$V_{PCC\_ref} = V_{x,max} \cdot sin(\gamma) + \sqrt{(V_{x,max} \cdot sin(\gamma))^2 + V_s^2 - V_{x,max}^2} \tag{2.7}$$

b-update) Limit on power angle γ **:**

In this case the new achievable reference V_{PCC_ref} can be found as:

$$V_{PCC\_ref} = \frac{|V_s|}{cos(\gamma)} \tag{2.8}$$

When the upper limit is reached in order to update the PCC voltage reference value, V_{PCC_ref}, always Equation 2.6 can be used. Although, when the low limit is reached it is necessary to evaluate if $V_{x,max} > V_{PCC} \cdot sin(\gamma)$ so, the V_{PCC_ref} should be updated by Equation 2.8 otherwise by Equation 2.7. When $V_{x,max} = V_{PCC} \cdot sin(\gamma)$, Equation 2.7 and Equation 2.8 give the same result. This V_{PCC_ref} update procedure is necessary to be implemented inside series unit local control system in order to guarantee its intrinsic stability.

2.1.2 Series Unit Voltage Rating

It is essential to chose the series unit inverter maximum voltage, $V_{x,max}$, which as it can be noticed from Equations 2.3-2.5 is an important value to calculate the system limits. Figure 2.12 demonstrates how the $V_{s,max}$ changes versus $V_{x,max}$ for different typical load power factors. It can be noticed that maximum V_s is affected with $V_{x,max}$ selection however to have 10-20% over voltage compensation window, an inverter with 0.2-0.4 p.u. rating voltage can be enough.

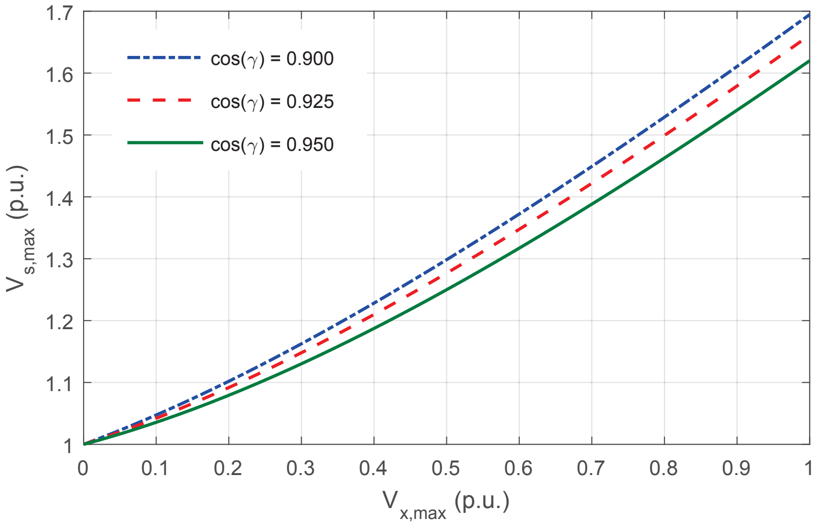

Figure 2.12: *$V_{s,max}$ variation versus $V_{x,max}$ for different fixed load power factors.*

Instead Figure 2.13 shows the $V_{s,min}$ dependency to $V_{x,max}$ variation for different fixed load power factors and it can be noticed that the minimum V_s is mostly restricted with load power factor rather than inverter rating voltage ($V_{x,max}$). In this case as it can be observed from Figure 2.13, to have 5-10% under voltage compensation window, an inverter with 0.3-0.4 p.u. rating voltage shall be designed. It is useful to mentioned that, in order to have 20% under voltage compensation capability, it would be necessary to have a load with 0.8 power factor and it that case the inverter need to be designed with rating voltage around 0.6 p.u. based on network nominal voltage.

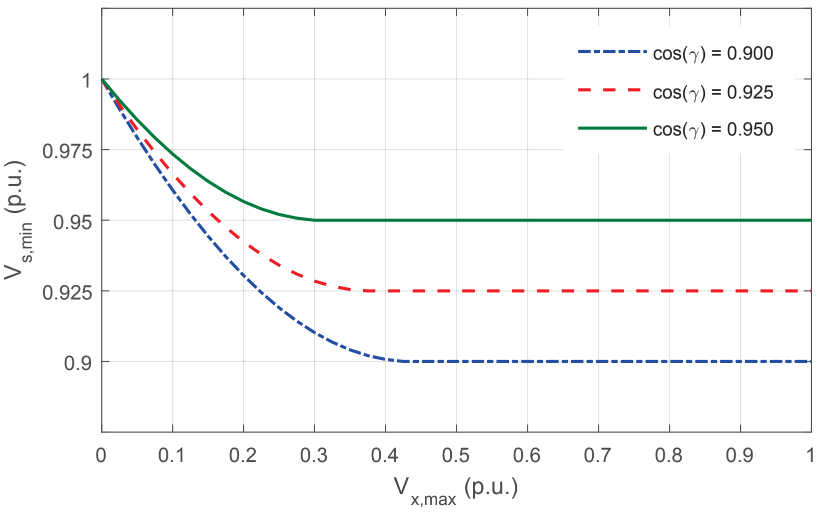

Figure 2.13: *$V_{s,min}$ variation versus $V_{x,max}$ for different fixed load power factors.*

Considering Figure 2.12 and Figure 2.13, the DSO can design proper series unit, taking into account the under investigation line typical power factor and also the over and under voltage compensation windows that is in interest taking into account its network performance.

2.2 Shunt Unit

Among all possible configurations for Open UPQC shunt unit, Figure 2.14 shows the ideal representation of the shunt unit, selected in this work, which basically includes a Static Switch (SS), a single phase full bridge inverter that is modeled with an ideal current source and a storage battery set. Inside the Figure 2.14, the *Static Switch* is represented with "SS", V_{Load} represents the voltage at the load connection point. I_{Load} and I_{shunt} are load and shunt unit injected/absorbed currents respectively.

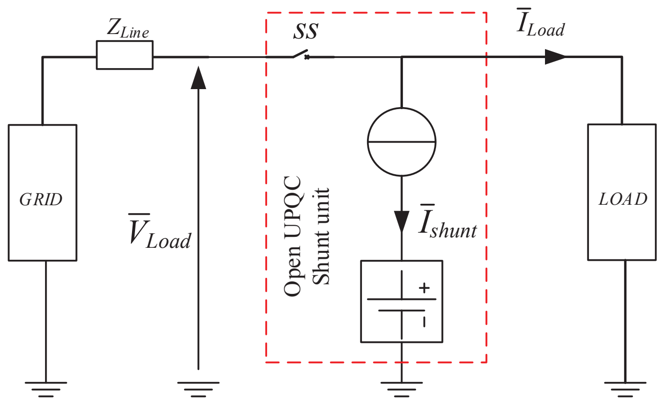

Figure 2.14: *Open UPQC selected shunt unit system model with ideal current source.*

The shunt unit, depending on the state of the network voltage, can supply either the entire load, or a part of the load. The device can work in the following two different modes:

- *Online*: when the V_{Load} is within its operation limits, the SS is closed, the shunt unit works as current generator and can give several services to the load and grid;
- *Island*: when the V_{Load} is outside of its operation limits, the SS is open, decoupling the network and the load compensator system. The load is supplied by the shunt unit, which acts as a sinusoidal voltage generator, using the energy stored in the storage system as an energy source.

So, the shunt unit as described, has two major operation modes; *Online* and *Island* operation modes. In *Online* operation mode, the shunt unit can be used by DSO to give some ancillary services to the grid. For this aim the shunt unit should be able to compensate entire reactive power of connected load or inject the required reactive power to the grid. Moreover it can manage the load profile according to DSO needs. So, during *Online* operation mode, it can give three services to the system; perform peak shaving, compensate load reactive power and harmonic current. Safe transition from *Online* to *Island* and vice versa is another function that shunt unit must be able to deal with and finally *Island* operation mode. Each function is described below in detail.

2.2.1 Peak Shaving

The peak shaving functionality has important value for customer in term of continuity. Depends of contractual power limit, each customer has its own circuit breaker to disconnect the load in cases of fault conditions, for safety reason like in the over load condition. The breaker trips by the internal digital controller of the meter in case the consumption of the customer exceeds the contractual power. Given a contractual power P_c the actual available power is 10% more, P_a=1.1P_c. While the tripping power threshold is equal to the 27% above the available power: P_t=1.27P_a. The breaker trips if the instantaneous power P deviates from these constrains:

- $P > P_t$, for more than 2 minutes,
- $P_a < P < P_t$, for more than 180 minutes.

In the case that costumer consumption exceeds the P_a, the shunt unit should supply difference between instantaneous power and P_c in order to enhance the load PQ, increase safety and give continuity of the power to the load. P_a=1.1P_c is the threshold to start the peak shaving, instead the shunt unit supplies the difference between instantaneous load power and P_c which means there is a 10% difference between control criteria and peak shaving threshold for two reasons; 1) in order to have a safe window between starting peak shaving and peak shaving threshold to avoid system oscillation when the load power consumption is close to the P_c. 2) with this consideration, the shunt unit produce at least 0.1P_c during the peak shaving and it is necessary to give to the shunt unit a considerable power to generate rather than very small or close to zero values.

Figure 2.15 demonstrates peak shaving functionality of the shunt unit. The connected load is simulated to have constant active power of 0.8P_c till t=1.5s. Between t=1.5s to t=2.5s the load active power amount is simulated to have 0.4P_c stepwise increase to the value 1.2P_c as it is shown in Figure 2.15. The load active power comes back to initial value at t=2.5s till the end of simulation. In demonstrated simulation the peak shaving threshold is set to load contractual power P_c and it starting threshold is set to 1.1P_c as it is explained above. Inside [1.5-2.5]s period, the load active power exceeds this threshold so, the shunt unit starts to do peak shaving setting the grid side active power to P_c and supplying the exceeded active power ($0.2P_c$). As it is shown in Figure 2.15 the grid side active power, outside [1.5-2.5]s period is equal to load active power and inside the [1.5-2.5]s period it is set to peak shaving threshold thanks to shunt unit. Inside [1.5-2.5]s period the shunt unit produces $0.2P_c$ active power to supply load extra power and set grid side active power to the peak shaving threshold. Indeed, outside [1.5-2.5]s period, the active power in this demonstration is equal to zero. In real prototype, device's losses or battery charging active power shall be absorbed from network during *Normal* operation mode.

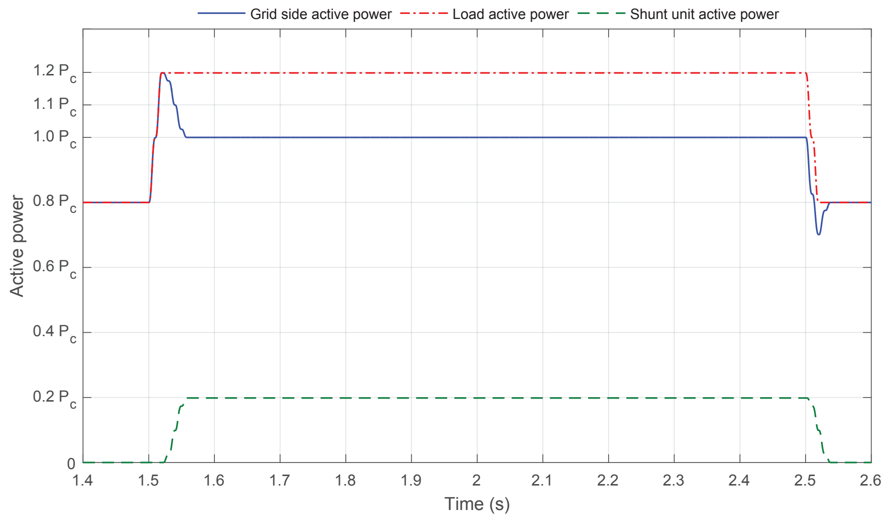

Figure 2.15: *Open UPQC shunt unit peak shaving function.*

2.2.2 Reactive Power Compensation

In *Online* operation mode the load is connected to the network through the PCC and the SS is permanently closed. In this condition the inverter is able to control the load reactive power and compensate load reactive power in order to set for example, grid side power factor to one [35]. In this mode, the PQ level of the network is increased.

Figure 2.16 is meant to illustrate this functionality. The simulation is performed with load which initially has 0.4 p.u. reactive part till t=1.5s and then an step wise 0.2 p.u. reactive power increase is simulated at t=1.5s till t=2.5s so, the load reactive power is increased to 0.6 p.u.. Then after t=2.5s the load came back to its initial value. From Figure 2.16 (a) it can be noticed that shunt unit produces all load reactive power requirement and at grid side the reactive power amount is set always close to zero. As it can be noticed from Figure 2.16 (a), during transients the grid side reactive power sees some variation due to shunt unit delay to respond load fast changes. Figure 2.16 (b) shows the load and grid side power factors. As it can be seen, it is equal to

0.9 before t= 1.5s, inside the period [1.5-2.5]s it is equal to 0.8 and after t= 2.5s it again became 0.9 as initial condition. The grid side power factor is set to unity, thanks to shunt unit reactive power compensation.

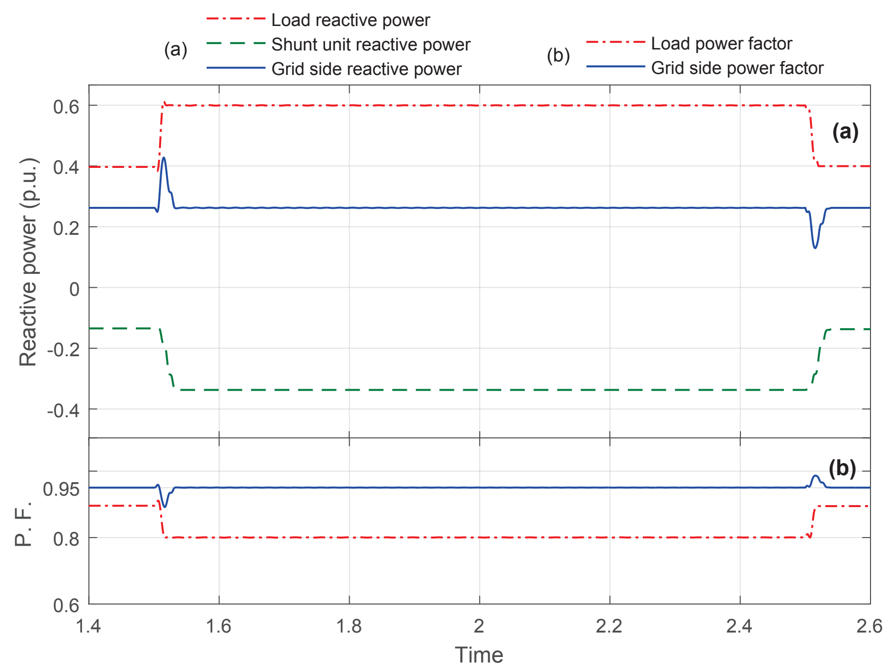

Figure 2.16: *Open UPQC shunt unit reactive power compensation function.*

Reactive power management of the shunt unit can be used as ancillary service by DSO. In this case, DSO can send the request to set the grid side power factor to another value instead of the one.

2.2.3 Harmonic Current Compensation

Shunt unit as a shunt connected power electronic device, has the capability to compensate load harmonic current up to certain harmonic order depends on its switching frequency. The principle of harmonic compensation is to first, find load current harmonic component utilizing proper calculation method. There are several instantaneous methods and also Fourier transformation based methods to extract harmonic components of the load current. After harmonic component extraction, the shunt unit task is to inject those harmonic current in right frequency with reverse magnitude to cancel out load harmonic current components and avoid harmonic propagation to the grid.

2.2.4 Transitions, *Online* to *Island* and vice versa

Figure 2.17 is meant to represent the shunt unit transition behavior. Device works in *Online* operation mode, once any interruption has occurred in main voltage, it immediately changes its operation mode to *Island* mode and works like PWM voltage generator. When the main voltage comes back within acceptable range, transition from *Island* to *Online* operation has been realized.

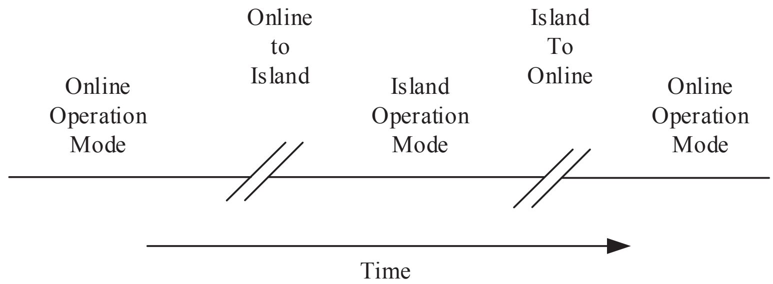

Figure 2.17: *Open UPQC shunt unit operation modes and transitions.*

When the supply voltage drops, in order to guarantee a high PQ level, the SS interrupts the circuit and the converter changes its operation mode switching from current source to voltage source. In this situation the inverter by converting storage energy, supplies the load.

Although this solution is not as adequate for special sensitive load as it is for the domestic loads; indeed, during the *Island* operation mode (when the customer network is supplied directly from the inverter) it is possible to obtain a high quality voltage waveform (amplitude and frequency control). Moreover, the opening time of SS is quite effective (normally varies between 3-4 ms), and for this reason the load will be supplied with one short interruption of voltage for each network problem. Nevertheless, the transition from *Island* to *Online* operation mode is performed without any voltage dip due to the adopted control strategy. When the supply voltage came back inside the acceptable range, frequency and magnitude synchronization will be performed by shunt unit and then the device waits next zero crossing to connect the load to the grid. With this strategy, the load will not experience any voltage dip or swell during *Island* to *Online* transition.

With *Island* operation mode, shunt unit is basically a custom power device however, the DSO, as an ancillary service, can take advantage of this islanding condition by reducing load on the defected or faulty feeder. DSO can disconnect the load deliberately and use those as load curtailment option inside distribution network.

2.2.5 Island Operation Mode

Shunt unit in *Island* operation mode is an ideal voltage generator with nominal magnitude and nominal frequency. It is decoupled from network thanks to the fast response time of SS and it shall be able to supply the load and tolerate fast load variation on its terminals supplying the load with constant magnitude and frequency always.

2.2.6 Shunt Unit Operation Limits

The shunt unit operation limit is mostly depends on its nominal VA rating. Figure 2.18 illustrates the working region of shunt unit. The shunt unit is restricted by two limits; one with device maximum VA value which is drawn with VA_{max} circle at Figure 2.18, second limit is imposed to the unit by storage battery nominal charging power (current) which is shown as P_{charge_max} limit at left side real power axes. As it can be noticed from Figure 2.18, the shunt unit is able to operate at all four quadratures of active and reactive power space. Positive and negative active power mean discharging and charging the storage battery pack respectively. The device has the potential to inject positive and negative reactive power amount to the grid so, all four quadratures can be covered by the devices. The dashed area of the Figure 2.18 shows the working region of shunt unit. Reactive power injection is an important functionality that can improve the series unit performance and it will be analyzed in the next section.

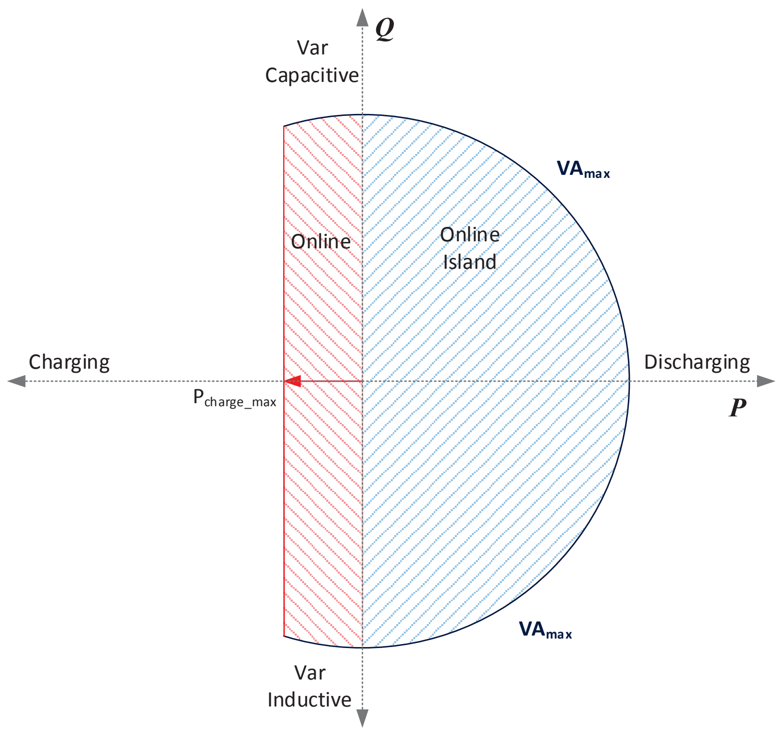

Figure 2.18: *Open UPQC shunt unit working regions.*

2.3 Series and Shunt units Co-operation

As explained before, series unit has upper and lower limits on its compensation capability. The limits are due to two factors; series unit inverter maximum voltage ($V_{x,max}$) and load power angle (γ). $V_{x,max}$ is a design criteria and the co-operation cannot influence this parameter while, γ is the total load power angle seen by series unit and the co-operation can influence this parameters, as changing this angle, series unit operation limits can be increased.

Figure 2.19 demonstrates the ideal model of Open UPQC within a distribution system, where the series and shunt units are modeled as ideal voltage and current sources respectively. V_s, I_s, V_x, V_{PCC}, I_{shunt} and Z_{Line} are the same as introduced in Figure 2.1 and Figure 2.14. $U1$ is the load without shunt unit which is called uncontrolled load and $U2$ is the load with shunt unit and here it is called controlled load. V_{U1}, I_{U1}, V_{U2} and I_{U2} are corresponding voltages and currents of controlled and uncontrolled loads.

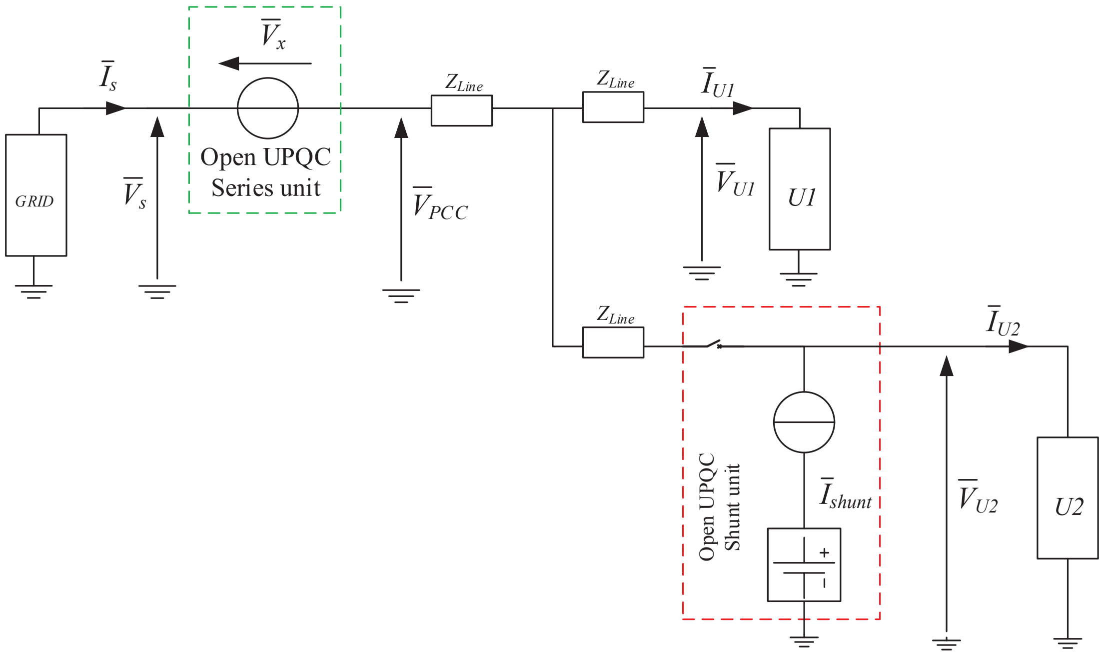

Figure 2.19: *Open UPQC system model with ideal voltage and current sources.*

In this schema, shunt unit contribution inside the system can modify the total load power angle seen by series unit. The phasor diagram of the Open UPQC is shown in Figure 2.20 where the shunt unit operation limit is also demonstrated by red dotted circle where right side is cut as it is in Figure 2.18. Considering Figure 2.20, the shunt unit effect on series unit performance can be understood. It can be seen that shunt unit by its limits can move the total load power angle γ and it can extend the series unit quadrature voltage compensation area. The gray area shows the series unit quadrature injection region. It can be noticed that changing the load power angle (γ) by means of shunt units, it is possible to broaden or lessen the series unit working limits. As described before, increasing the γ will increase the control limits of series unit so, in the Figure 2.20, point A is the maximum working condition which gives larger compensation area, correspond to the $V_{s,max-PQ}$ and $V_{s,min-PQ}$, to the series unit. In order to reach the point A, the shunt units should inject both active and reactive power to the network and the corresponding max and min limits are shown by $V_{s,max-PQ}$ and $V_{s,min-PQ}$ accordingly.

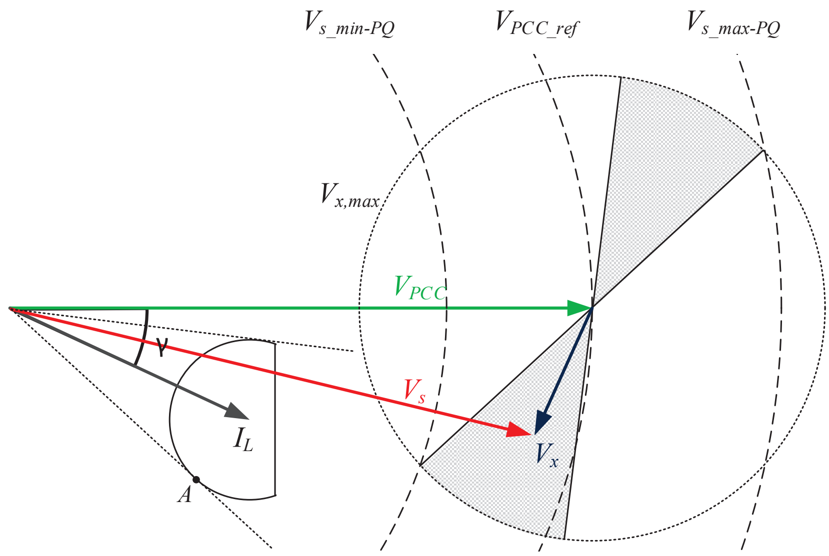

Figure 2.20: *Vector representation of series and shunt units limits for co-operation.*

Active power injection by shunt units, by increasing number of charge and discharge actions, will decrease battery set life time and also it can introduce extra losses in the system. In other hand, although the maximum point, A, is reached by both active and reactive power injection but, the active power contribution on this co-operation is limited. Figure 2.21 is meant to illustrate the active power share on this co-operation. In Figure 2.21, the dashed lines represent only reactive power injection by shunt unit. The dark gray area are the active power injection contribution on series unit control enlargement area. $V_{s,max-Q}$ and $V_{s,min-Q}$ are the limits with only reactive actions by shunt units.

It can be concluded that the effect of active power movement by shunt units is minor comparing to the reactive power movement. The point B is the maximum working condition with reactive power injection only (by shunt units) and it can be noticed that the difference between pont A and point B is very little. Therefore, instead of working on both active and reactive contribution from shunt units, which will decrease the batteries life time by increasing the number of charging and discharging of batteries, and

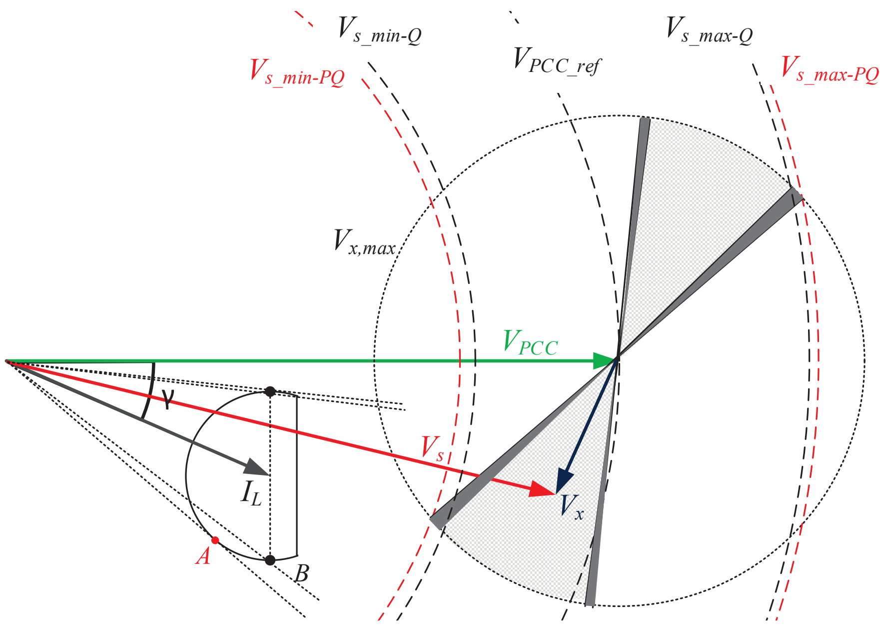

Figure 2.21: *Effect of active and reactive injection by shunt unit on co-operation mean.*

also can introduce losses to the system and increase the control complexity, only reactive injection from shunt unit can be used to get almost the same co-operation means between series and shunt units. Hereafter the $V_{s,max-Q}$ and $V_{s,min-Q}$ will be considered as upper and lower limits and for simplicity those will represent with $V_{s,max}$ and $V_{s,min}$ in generic form.

Considering above analyses, Figure 2.22 can be used as reference to represent the co-operation between series and shunt units in order to improve series unit performance. The shunt units can move the load current on the dashed line and increase or decrease the total load power angle, γ. Consequently, voltage control borders of series unit can be modified as demonstrated by gray area in Figure 2.22.

It is important to note that by properly controlling the shunt units and series unit of Open UPQC, it would be possible to have wide compensation limits for series unit which will provide high quality of power to the installed line. Such a coordinated system, needs advanced communication between series and shunt units, to give the possibility to the series and shunt units to talk to each other and choose the control action depend on system and load condition. The communication infrastructure will be described in following chapters.

In the sense of shunt units effect, their ratio and numbers in the installed distribution network is important and the percentage of controlled load with respect to the uncontrolled load as those are shown in Figure 2.19 need to be analyzed. The more the percentage of controlled loads (shunt units) the more the advantages and flexibility that the network can reach. However, each shunt unit basically is installed with a

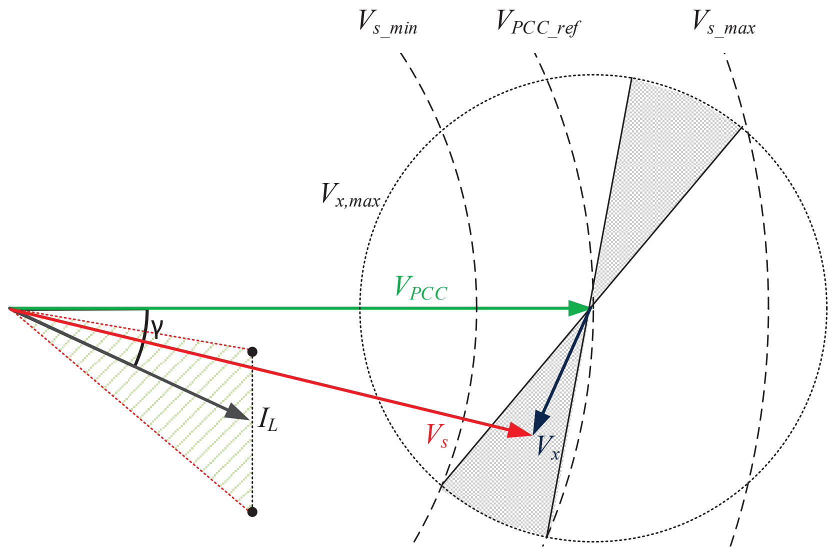

Figure 2.22: *Vector representation of series and shunt units co-operation.*

end user request and principally it depends on end user interest to have or not a shunt unit in its property. Additionally, each shunt unit means an initial cost, maintenance cost and also it introduces complexity to the installed area in terms of control and stability issues. So, the shunt units share, respect ot the installed line nominal power, is an important factor for Open UPQC successful co-operation.

The means of co-operation is to increase the series unit working region and as it is described early in this chapter, the limits on series unit control capability are due to two factors; limits due to $V_{x,max}$ and limits due to γ and since $V_{x,max}$ is a design parameter, it is not affected by co-operation so, γ is the only parameter that affects series unit operation limits.

Therefore, the shunt unit penetration percentage inside the installed network can be evaluated. For this evaluation purpose, let's define some parameters. Considering Figure 2.19 the total active power, reactive power and apparent power on the installed feeder can be regarded as summation of uncontrolled load and controlled load powers.

$$\begin{aligned} P_T &= P_{U1} + P_{U2} + P_{losses} \\ Q_T &= Q_{U1} + Q_{U2} + Q_{shunt} + Q_{losses} \\ A_T &= A_{U1} + A_{U2} + A_{losses} \end{aligned} \tag{2.9}$$

For ideal system analysis, the losses can be neglected. At Equation 2.9 the Q_{shunt} stands for aggregated shunt units reactive power inside the installed area. The A_{U2} is composed of P_{U2}, Q_{U2} and Q_{shunt} so, actually the ratio of shunt units (controlled loads) is proportional to the A_{U2} percentage inside the network. So we can define this percentage as α

$$\alpha = \frac{A_{U2}}{A_T} \times 100 \tag{2.10}$$

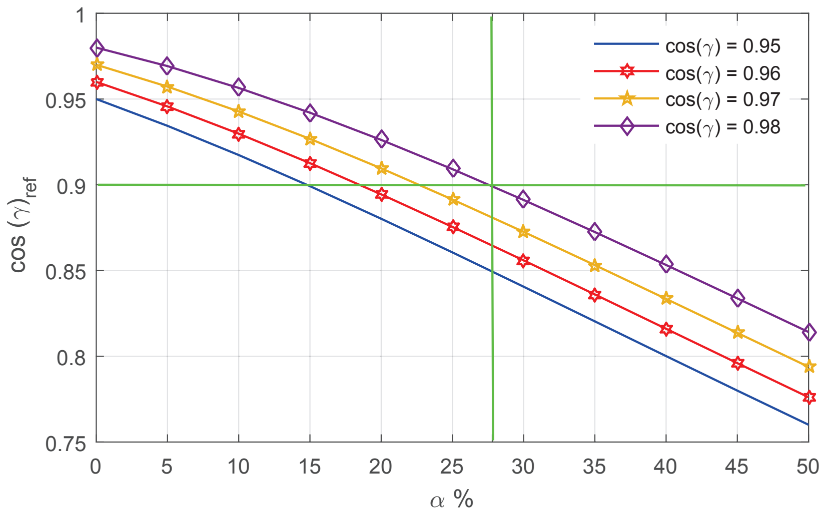

Figure 2.23: *Reference power factor variation versus α increment for different loads.*

With this definitions, we can analyze the shunt units contribution inside the network. We define the $cos(\gamma)_{ref}$ as the desired target power factor for series unit proper operation purpose, which can be set by DSO through communication. Figure 2.23 shows the $cos(\gamma)_{ref}$ variation versus α increment for different initial load power factors. In Figure 2.23 the network original load power factors were the $cos(\gamma)$ and by means the shunt unit it can be moved to $cos(\gamma)_{ref}$ to improve series unit performance. Load power factor 0.9 is shown with horizontal line because it stands for 10% under voltage compensation limit. It can be noticed that for a load with lower power factor, the shunt unit required penetration is lower as well because the load has enough reactive power itself. Instead as the load goes to be resistive, the shunt unit percentage growth as well. If we consider the 0.98 as load power factor, it can be seen that to reach to total load power factor equal to 0.9, shunt unit percentage inside network need to be around 30% or in other word, one out three of customers inside installed area need to be equipped with shunt unit.

It can be noticed also, if the target power factor is decreased, accordingly the α is increased and this means system requires higher number of shunt units penetration.

CHAPTER 3

Open UPQC Controller Design

This Chapter presents the practical control logic for the Open UPQC device and in particular for both series and shunt unit autonomous controllers and also the ICT based regulation strategy to enable co-operation between series and shunt units. Inverter controller in both series and shunt units uses MBC as current controller which is based on a full bridge inverter model so, full bridge inverter model and MBC current controller is explained and then series and shunt units individual controllers are explained. At the end, the communication based co-operative control logic is presented. Series unit and all shunt units need to be stable intrinsically without considering any communication between those so, all consideration have been made to design a stand-alone stable regulator for series and shunt units. The communication based co-operative controller is an independent control layer which will extend the series unit of Open UPQC working limits without affecting each unit local control system. It also gives DSO the possibility to improve installed area PQ level and decrease network losses.

3.1 Model Based Inverter current Controller

Control method plays an important role in power electronic devices because principally a power electronic device is made by some solid state switches and without proper control method, combination of active switches could do nothing. The inverter control still is a challenging task for engineering even for the typical full bridge topology, due to inverter intrinsic characteristics, like low-impedance and quick response [42]. Due to these characteristics, inverter current and voltage profile can change rapidly and within a fraction of cycle, those may overload, exceed the current and voltage limits and cause failure of the system [42, 62]. Thus, capability of the Open UPQC series and shunt units is affected by the control and the performance of the each unit inverter.

Several reliable and effective control methods based on classical control algorithms with Pulse Width Modulation (PWM), like conventional Voltage Oriented Control, Direct Power Control [10, 45], deadbeat control [44, 51], multiloop feedback control [49, 15], adaptive control based on bank resonant filters [50] and repetitive-based controllers [23] have been introduced and implemented to industrial applications.

Both Open UPQC series and shunt units current controller, as it is explained in [18, 21], is a Model Based Controller (MBC) adapted for inverter control. This MBC is based on the full bridge inverter model. Therefore in order to explain the MBC it is necessary to present the full bridge single phase inverter model.

3.1.1 Full Bridge Single Phase Inverter Model

Single phase full bridge inverter schema is shown in Figure 3.1. The controller is meant to manage the current on the inductance (L_{ac}). For controller design, some equations from a derived model are adopted for digital implementation so, before introducing the controller, the full bridge inverter model is described.

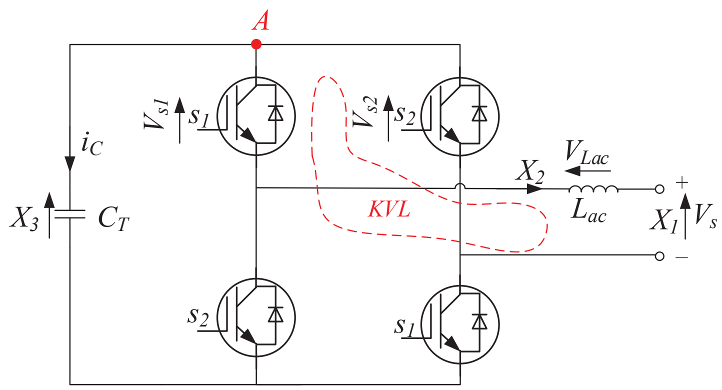

Figure 3.1: *Single phase full bridge inverter schematic.*

The schematic in Figure 3.1 from right ot left, includes the AC side inductance (L_{ac}); the full bridge single phase Voltage Source Inverter (VSI) with four controlled switches as DC to ac interface and the DC bus capacitor (C_T). In order to derive a state space model, controlled variables are shown in the Figure 3.1 where:

- X_1 stands for output voltage, or grid voltage while it is connected to the grid;

- X_2 represents the inverter current;
- X_3 is DC bus capacitor voltage;
- s_1 and s_2 are complementary gate signals to derive the IGBT bridge, and those are either zero or one;

Controlled switches gate signals, according to [37], can be modeled by continuous functions and the corresponding variables will be shown by $\hat{s}_1$ and $\hat{s}_2$. Thus, to derive the equations and the model, instead of discontinuous zero and one function, the continuous function will be used.

The inverter model can be driven by Kirchhoff's Voltage Law (KVL) in the shown loop and Kirchhoff's Current Law (KCL) on the DC bus capacitor current (node A), Equation 3.1 shows the KVL;

$$V_s + V_{Lac} + V_{s2} - V_{s1} = 0 \tag{3.1}$$

Where V_{s1} and V_{s2} as shown in the Figure 3.1, stand for the voltage on switches and those are equal to:

$$V_{s1} = \hat{s}_1 \cdot X_3 \tag{3.2}$$

$$V_{s2} = \hat{s}_2 \cdot X_3 \tag{3.3}$$

Equation 3.4 shows the KCL at node A:

$$i_c - \hat{s}_1 \cdot X_2 + \hat{s}_2 \cdot X_2 = 0 \tag{3.4}$$

where $\hat{s}_1 \cdot X_2$ represents the state when the s_1 is on and the inverter ac side current (X_2) flow through it and $\hat{s}_2 \cdot X_2$ represents the state when the s_2 is on. Using state space parameters and Laplace transform equation for the inductance voltage (V_{Lac}) and Equation 3.2 and 3.3, the Equation 3.1 can be rewritten to:

$$X_1 + S \cdot L_{ac} \cdot X_2 = \hat{s}_1 \cdot X_3 - \hat{s}_2 \cdot X_3 \tag{3.5}$$

and with the same procedure, using state space parameters and Laplace transform equation for the capacitor current (i_C), the Equation 3.4 can be rewritten to:

$$S \cdot C_T \cdot X_3 = \hat{s}_1 \cdot X_2 - \hat{s}_2 \cdot X_2 \tag{3.6}$$

S stands for Laplace transform parameter, and the complementary properties of $\hat{s}_1$ and $\hat{s}_2$ necessitates that: $\hat{s}_1 + \hat{s}_2 = 1$. Using this property, the inverter model can be simplified.

By equations 3.5 and 3.6 the state space model of the single phase full bridge inverter can be driven. Due to multiplication of time varying switching functions to state variables, it can be considered as Linear Time Varying (LTV) system, and the model can be solved by proper iteration method. There are two main operation modes for these inverters; working as current source in grid connected mode, in this case, the model output is X_2 (the inverter current), working as voltage source in islanded mode where the X_1 (the inverter output voltage) is considered as model output. In each case, all independent state variables are computed by continuous switching functions $\hat{s}_1$ and $\hat{s}_2$. The model is shown to understand the inverter behavior and MBC design. The complete model analysis is out of scope of this dissertation.

3.1.2 Model Based Controller (MBC)

The Model Based Controller (MBC) is designed based on Equation 3.1 or Equation 3.5. The V_s and X_3 are network voltage and DC bus voltages respectively. Inside the controller, these two variables are real measurements. The V_{Lac}, $\hat{s}_1$ and $\hat{s}_2$ are unknown so, to calculate switching functions, $\hat{s}_1$ and $\hat{s}_2$, it is necessary to estimate V_{Lac}. The traditional method to estimate voltage drop on the inductance is using Euler first order approximation for derivative. Therefore, it can be written in the discrete domain as:

$$v_L = \frac{\Delta i_L \cdot L_{ac}}{T_s} = \frac{(i_L(k) - i_L(k-1)) \cdot L_{ac}}{T_s} \tag{3.7}$$

where k is the iteration order, $i_L(k)$ and $i_L(k-1)$ are inductance currents at corresponding iterations. L_{ac} is the coupling inductance value in Henry and T_s is the iteration step (in this work, it is equal to 50 µs both in simulation and experiment). All the variables in Equation 3.7 are presented in discrete time domain. In order to control the current in the coupling inductance, it is assumed that the inverter works in a stable condition, and it follows the reference current properly. With this assumption, it is possible to consider the reference current as a prediction for the next iteration step of the inverter current and update Equation 3.7. Therefore, the current deviation on the inductance can be represented as the difference of reference current and measured current.

$$\Delta i_L = i_L(k) - i_L(k-1) = i_{ref} - i_L(k) \tag{3.8}$$

where the i_{ref} is the instantaneous reference current. With this estimation, the voltage drop on the inductance can be predicted by adopting Equation 3.9 instead of

Equation 3.7. Equation (3.9) can be replaced in Equation 3.5 for digital implementation.

$$v_L = \frac{(i_{ref} - i_L(k)) \cdot L_{ac}}{T_s} \tag{3.9}$$

Rewriting Equation 3.5 using Equation 3.9 and using the complimentary property of the inverter continues switching functions ($\hat{s}_1 + \hat{s}_2 = 1$), the continuous inverter switching function can be computed by Equation 3.10:

$$\hat{s}_1 = \frac{(v_s + v_{DC} + v_L)}{2 \cdot v_{DC}} \tag{3.10}$$

The switching function evaluated by Equation (3.10), $\hat{s}_1$ and $\hat{s}_2 = 1 - \hat{s}_1$ will be used as control voltage (v_c) to be fed to the PWM signal generator to run the IGBT drivers of inverter legs. This MBC has a fast and reliable response of the model base controller, and it also has constant switching frequency due to the PWM technique integration into the control loop.

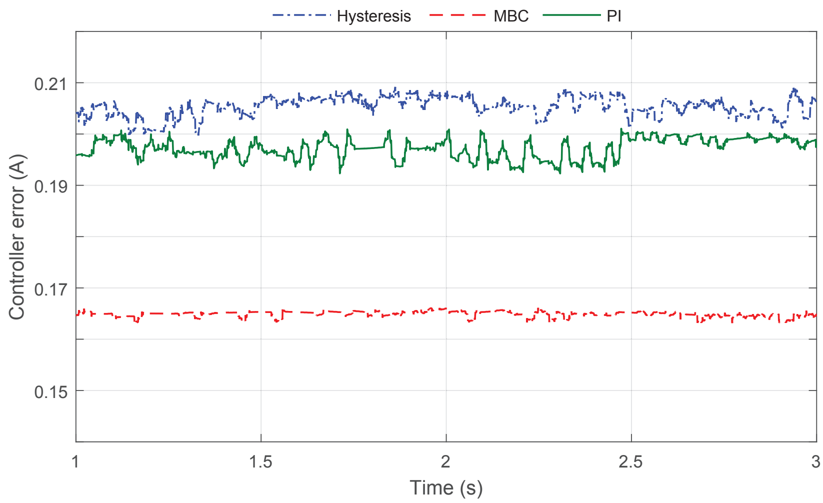

Figure 3.2: *Normal operation current error for three different controllers.*

Figure 3.2 shows the comparison results between two commonly used current controllers (Hysteresis and normal PI) again proposed MBC. Simulation has been done for a full bridge single phase inverter working as current source with three different current controllers. As it can be noticed, the proposed MBC has smallest error among the studied other controllers. The controllers' speed during transient depend on several factors as sampling time, controller gains (PI parameters and Hysteresis band setting) and also the inverter physical characteristics. So the comparison on controllers transient response time need more detail analysis which is out of scope of this work.

This MBC is the current controller which is always in loop and its proper functioning is very essential for both series and shunt units.

3.1.3 Full Bridge Inverter MBC performance

The proposed MBC is an inverter current controller so in order to verify its performance in series unit or shunt unit during *Island* operation mode (when inverter works as voltage source), there should be an outer voltage controller. Alternatively, to work as current source, the inverter need to operate in grid connected configuration which is happen during shunt unit *Online* operation mode. In grid connected mode, inverter terminal voltage is imposed by grid so in both cases, the inverter controller is responsible to follow the current reference. The performance of this MBC is verified by simulation study for both cases where the inverter works either as current source or voltage source.

Inverter as Current Source

Here in order to show the MBC performance, a full bridge inverter is simulated in grid connected mode. The situation is like shunt unit *Online* operation mode. The simulated configuration is depicted in Figure 3.3. A single phase inverter is connected in parallel to the grid and load. As inverter DC bus, a DC voltage source with constant voltage is used in order to remove DC bus control effects in reported results.

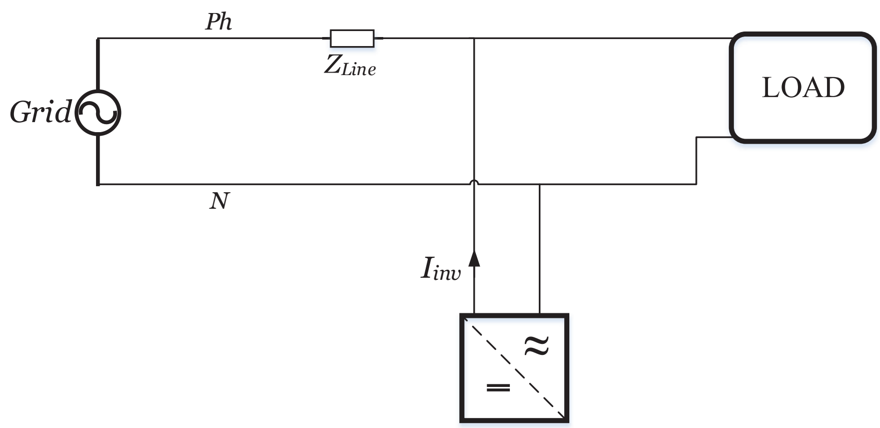

Figure 3.3: *Simulation schema - grid connected single phase inverter.*

Two different scenarios are defined to show the controller performance. As first test, a step wise change in reference current is simulated. The controller response is shown in Figure 3.4. The inverter is connected in parallel to the grid, so the inverter ac side terminal voltage is fixed by grid voltage and inverter works as current source. The system initially was working with zero current reference till t=1.5s. At t=1.5s, a step change is triggered and reference current is set to a sinusoidal current with rms 15A. In Figure 3.4 the reference current is completely covered by inverter current and its switching ripples. As it can be noticed from Figure 3.4, the inverter is able to follow this step change in ac current thanks to the proposed MBC.

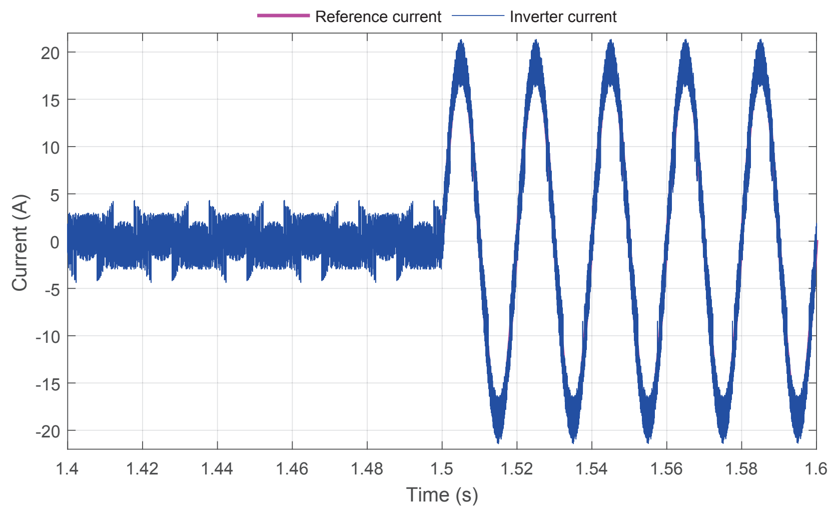

Figure 3.4: *Simulation - single phase inverter MBC performance on current step change.*

Step change is one important test in these kind of application however, in both cases of Open UPQC shunt unit, another interesting scenario is slower ramp like transition. Figure 3.5 shows the MBC controller response to the ramp like slow change in reference current. Same as previous scenario, the system was working with zero reference current till t=1.5s. At t=1.5s, the inverter started to inject active power to the grid and its reference current is increasing with constant slop till t=2s from initial zero value to final 15A rms. Proposed MBC shows satisfactory response for ramp like change in reference current.

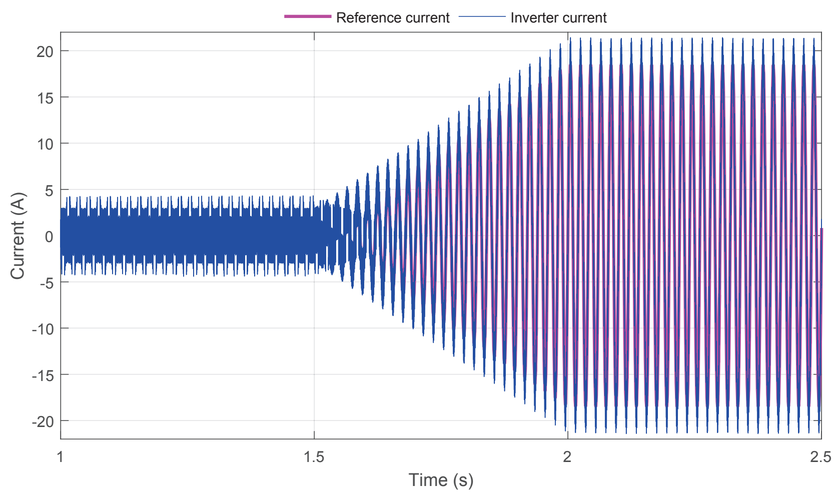

Figure 3.5: *Simulation - single phase inverter MBC performance on current ramp change.*

Inverter as Voltage Source

As a voltage source, the inverter main responsibility is to keep voltage at its ac side terminal regulated with constant magnitude and frequency. In the case of Open UPQC both series and shunt units, the outer voltage controller is accomplished with inner current controller which is the proposed MBC. Therefore, at any working condition the MBC is always in loop and it is the last controller which runs IGBTs PWM module.

In order to verify MBC performance while the inverter works as voltage source, two possible scenarios are taken into account as those are shown in Figure 3.6 (a) and (b). In both cases the possible scenario to have fast changes on load current is load variation and usually load variation happens instantaneously in step like manner. Therefore in both cases a step wise change on load current is simulated. Outer voltage controller is managed to be stiff enough so, the inner MBC behavior can be verified.

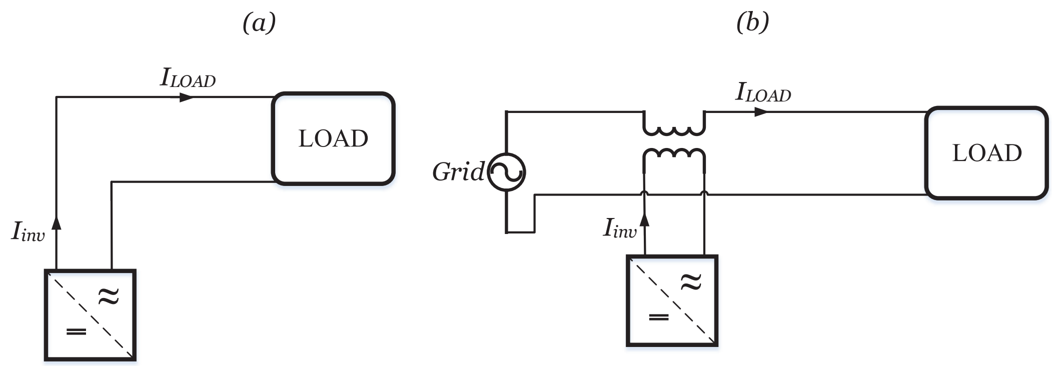

Figure 3.6: *Simulation schema - single phase inverter as voltage source, (a) Island operation mode (b) series connected configuration.*

In order to verify the controller response during *Island* operation mode, configuration of Figure 3.6 (a) is simulated. System was simulated to work with no load till t=3s. Figure 3.7 shows the inverter behavior. The small amount of current before t=3s is due to inverter output low-pass filter current. At t=3s, 2.5kW load is connected to system which with 230V voltage absorbs about 12A rms current. Proposed MBC response to this step change at load current is demonstrated in Figure 3.7. It can be seen that the controller has fast and reliable behavior under this critical load variation.

To verify the proposed MBC performance within series unit control system, series connected voltage source inverter, the configuration of Figure 3.6 (b) is simulated. For the series connected device it is essential to have a load current at any working condition because the adopted control logic needs load current angular frequency and also load power angle in order to injected required compensation voltage. Therefore, as it is shown in Figure 3.8, system was working with constant load 1kW + 1.2kVar till t=3s. At t=3s, 3kW + 1.5kVar load is added to the system. Figure 3.8 shows the

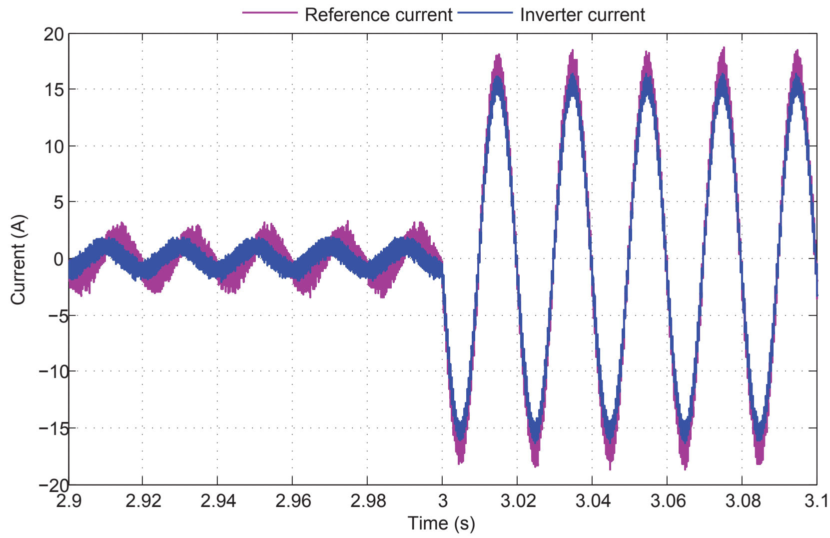

Figure 3.7: *Simulation - single phase inverter works as voltage source in island mode, MBC performance on load current step change.*

controller response to this fast load variation. As it can be noticed, after connecting the load, system sees a small over current for half period, however proposed MBC is able to react to this fast load change and follow reference current perfectly. The over current is comes from outer controller and as it can be noticed that MBC follows the reference current at any moment. Reference current in Figure 3.8 is covered by inverter current which has switching ripples.

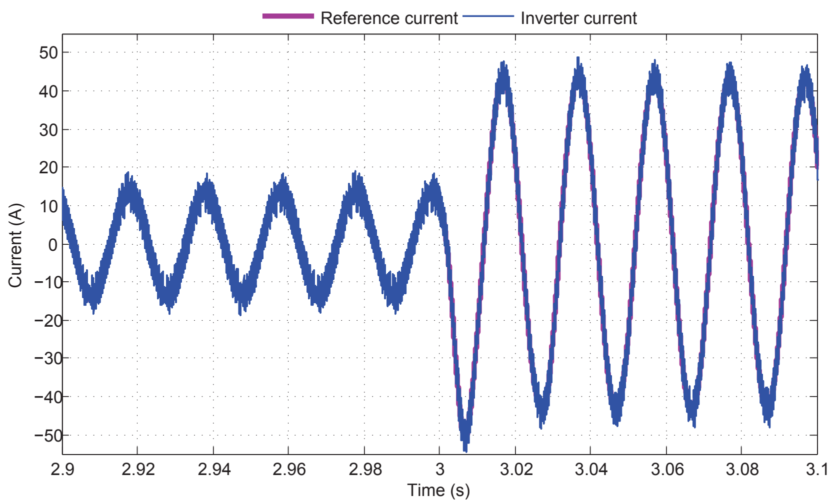

Figure 3.8: *Simulation - single phase inverter works as voltage source in series connected configuration, MBC performance on load current step change.*

3.2 Series Unit Controller

Open UPQC series unit is a series connected device, so the whole load current passes through it and it has to be a voltage generator that need to pass the load current with minimum distortion. This makes its control more complex and difficult. Furthermore, this series connected device is coupled to the system by means of a transformer. The power electronics converter is connected at secondary side and the primary is connected in series to the power line. This configuration with converter, LC filter at inverter output and transformer, is highly vulnerable to instability and resonant problems. Another consideration is the series unit continuous functionality because, in literature, these kind of series conditioners and associated controller is usually equipped with a detection algorithm to activate the device in the case of sag/swell, under or over voltage in the system. Rest of the time the series connected device is bypassed and does nothing. So, this continuous operation is not well analyzed in literature. Knowing that the Open UPQC series unit is a DVC that is able to regulate continuously voltage at PCC and be able to tolerate wide range and fast load variations, it can be interesting for DSOs and also several applications within power systems. However this kind of device needs very precise control method.

Series connected conditioners usually are designed for MV level and three phase systems [47]. For the three phase system the reference voltage generation is based on synchronous frame d-q transformation and the controller deals with DC signals. However, the Open UPQC, in this work is meant to be implemented within an LV distribution network where most of the end users have single phase connection. The series unit is designed to be realized as three single phase units. Therefore, it can be concluded that the Open UPQC series and shunt units are designed as single phase units to make it possible to be installed on one phase of the selected feeder and also with three phase series unit. For the series unit, each single phase unit configuration and associated controller will make DC bus control more difficult and the whole controller more complex because the controller should deal with ac signals as well. consequently for the controller design and rest of the work single phase configuration is considered, although it is possible to build a three phase system realizing three different single phase devices.

Figure 3.9 shows the single phase Open UPQC series unit configuration within a distribution network. It consists of a full bridge inverter equipped with capacitor as DC bus storage, switching inductance, coupling transformer and a bypass switch that can manage inverter function, bypassing the unit in the case of inverter failure or any fault on load or grid side. In Figure 3.9, V_s is the grid voltage, V_x is the injected voltage by series unit, I_L is the load/line current and V_{PCC} is the voltage at PCC. X_{Line} and R_{Line} represent distribution line parameters.

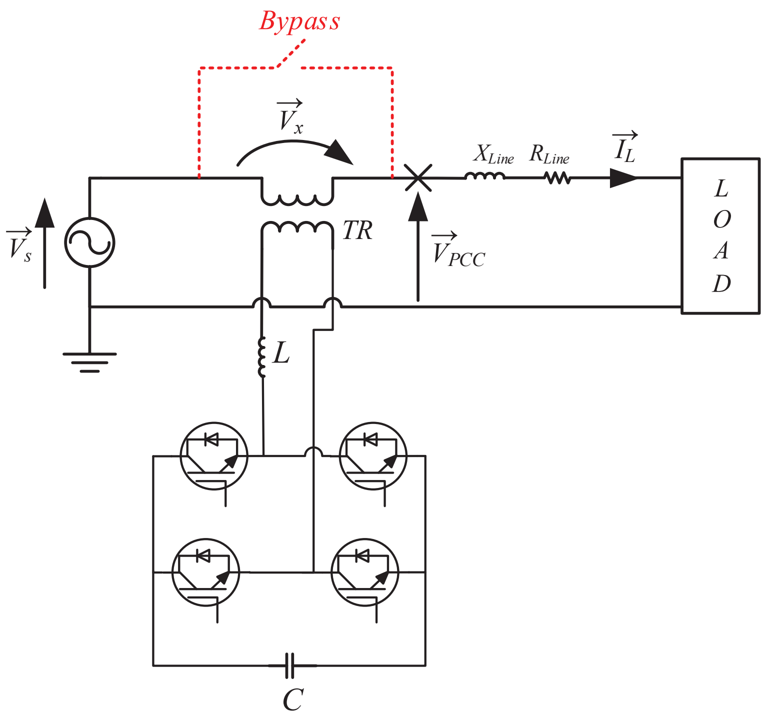

Figure 3.9: *Open UPQC series unit single-phase configuration.*

Theoretically PCC voltage regulation can be achieved by pure reactive injection if the injected voltage V_x is always managed to be perpendicular to the line current I_L. The magnitude of V_x can be computed as it is shown in Equation 2.2 as it is repeated in Equation 3.11.

$$V_{x\_cal} = V_{xi} = V_{PCC\_ref} \cdot sin(\gamma) - V_s \cdot sin(\theta_i) \tag{3.11}$$

However, system (transformer and switching) losses need to be compensated to keep DC bus voltage constant. So the calculated V_{x_cal} should be injected not exactly in perpendicular but with proper phase shift in order to enable the system to absorb a suitable amount of active power from the network to regulate DC bus voltage.

Several control strategies for series connected compensator are proposed in literature, like single loop voltage control, voltage control with feedforward signal and double loop control with outer voltage control and inner current loop [55, 47]. The double loop control method has been found more suitable for Open UPQC series unit, due to its capability to manage wide load current variation and avoid current distortion during transient [47]. The proposed controller needs instantaneous voltage reference to be followed by series unit inverter. Therefore, the sinusoidal $v_x(t)$ signal need to be generated, as reference for inverter voltage controller. As explained before, the reference voltage has to be injected perpendicular to the line current in order to meet non active power injection. Equation 3.12 is adopted in order to calculate sinusoidal $v_x(t)$ reference value.

$$v_x(t) = \sqrt{2} \cdot V_x \cdot sin(\omega_{I_L} \cdot t \pm \frac{\pi}{2}) \tag{3.12}$$

In Equation 3.12, the V_x is the rms value of the series unit injected voltage, ω_{I_L} is the line current angular frequency, $\pm\pi/2$ is due to the nature of the load (if inductive $\pi/2$ is subtracted from the line current angular frequency, while if the load is capacitive $\pi/2$ should be added) so positive or negative sign in Equation 3.12, is for capacitive and inductive loads respectively. In order to generate Equation 3.12, it is important to take into account the system limits as explained in Chapter 2. So, before going deep into ac signal generation, the strategy to implement system limit is described in next subsection.

3.2.1 Operation Limits Implementation

In order to compute Equation 3.12, it is necessary to consider the limits and use the achievable PCC voltage reference value. Without going in detail, the system limits and V_{PCC_ref} update equations are repeated here to make the document more easier to be followed.

$$V_{s,max} = \sqrt{|V_{x,max} + V_{PCC\_ref} \cdot sin(\gamma)|^2 + |V_{PCC\_ref} \cdot cos(\gamma)|^2} \tag{3.13}$$

$$V_{s,min\_a} = \sqrt{|V_{PCC\_ref} \cdot sin(\gamma) - V_{x,max}|^2 + |V_{PCC\_ref} \cdot cos(\gamma)|^2} \tag{3.14}$$

$$V_{s,min\_b} = |V_{PCC\_ref} \cdot cos(\gamma)| \tag{3.15}$$

$$V_{PCC\_ref\_1} = -V_{x,max} \cdot sin(\gamma) + \sqrt{(V_{x,max} \cdot sin(\gamma))^2 + V_s^2 - V_{x,max}^2} \tag{3.16}$$

$$V_{PCC\_ref\_2a} = V_{x,max} \cdot sin(\gamma) + \sqrt{(V_{x,max} \cdot sin(\gamma))^2 + V_s^2 - V_{x,max}^2} \tag{3.17}$$

$$V_{PCC\_ref\_2b} = \frac{|V_s|}{cos(\gamma)} \tag{3.18}$$

Considering limits from previous chapter, complete flowchart to update the V_{PCC_ref} to calculate V_x is shown in Figure 3.10. The flowchart in Figure 3.10 is implemented following the same concept as the limits of the system were extracted in Chapter 2. First the measured V_s voltage is compared with V_{PCC} in order to understand in which case (*Case 1* or *Case 2*) the system is, then, by checking corresponding equation, it has been evaluated that either the system exceeded the system limits or not. If the system exceeds the corresponding limit, the V_{PCC_ref} need to be updated otherwise, the system is inside the limits and can continue operating with nominal or V_{PCC_ref} set value. The only point is when the system is in *Case 2*, under voltage condition, where it is important to understand which limit should be considered, limit due to $V_{x,max}$ or limit due to γ. To do so, $V_{x,max}$ is compared with $V_{PCC} \cdot sin(\gamma)$ instantaneous value in order to make right decision on either $V_{x,max}$ limit or limit due to γ, need to be used. If it is necessary, the V_{PCC_ref} value should be updated and the new value should be used in Equation 3.11 to find the V_x (signed rms) for $v_x(t)$ calculation.

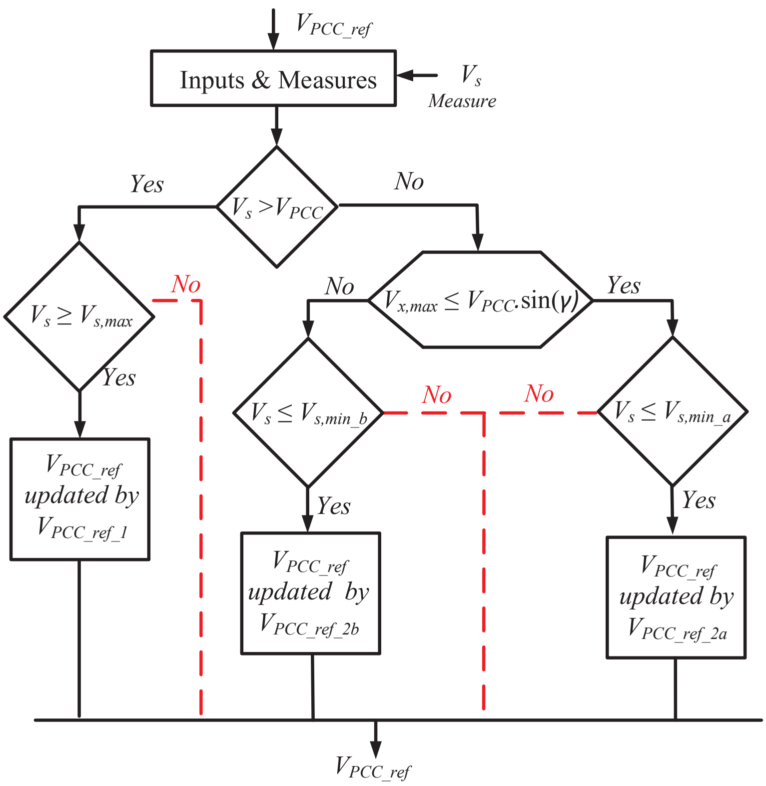

Figure 3.10: *Open UPQC series unit PCC reference voltage update flowchart for V_x calculation.*

The situations shown by dashed red lines in Figure 3.10 are for the conditions where the system is inside its compensation range and V_{PCC_ref} does not need to be updated. So, depends on system operational condition, either original V_{PCC_ref} or the updated one, will be used as V_{PCC_ref} to generate $v_x(t)$ for inverter voltage controller. Implementing this strategy, the system can continue to operate even if the load power angle and grid voltage are not enough to guarantee the nominal/set V_{PCC_ref}. Instead the reference value will be updated, series unit will do its best and the system can avoid any instability and failure. This update approach is necessary to guarantee series unit local stability.

3.2.2 Voltage Reference Generation

The controller limits block implemented in Figure 3.10, can update V_{PCC_ref} if it is necessary. With V_{PCC_ref} it is possible to evaluate V_{x_cal} by Equation 3.11 and the V_{x_cal} can be used in Equation 3.12 to generate the required injection voltage instantaneous signal. To have better control on PCC voltage, an extra PI controller is also used and the output is added to the calculated value in Equation 3.11 as shown in Figure 3.11 and the output is considered as V_x to generate the reference voltage signal. Load current angular frequency is extracted from I_L and it is used to generate proper $v_x(t)$ signal as shown in Figure 3.11. It is important to underline that the series unit injects this voltage by means of coupling transformer to stabilize the PCC voltage. During the work period, the series unit has some losses and it is necessary to compensate these losses. This can be obtained by changing the voltage injection phase of the angle δ, that can compensate the device active losses and manage the DC bus voltage constant. Doing so, the Equation 3.12 change in the Equation 3.19. DC bus controller has been put in evidence in red inside Figure 3.11.

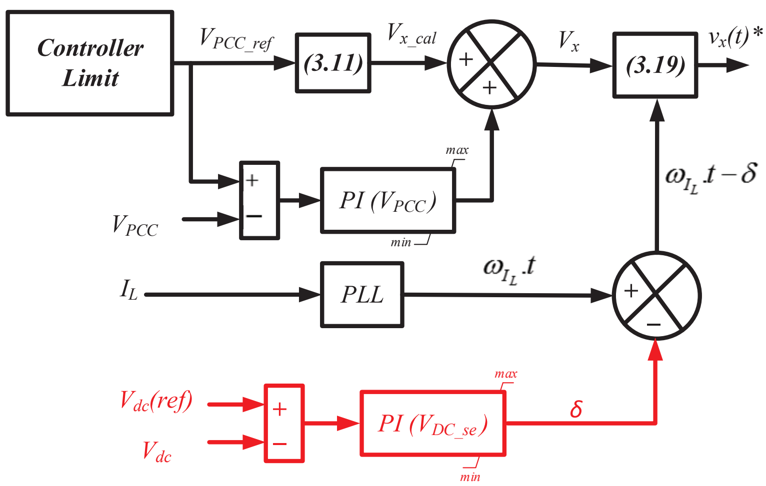

Figure 3.11: *Open UPQC series unit reference voltage generation block diagram.*

$$v_x(t)^* = \sqrt{2} \cdot V_x \cdot sin(\omega_{I_L} \cdot t \pm \frac{\pi}{2} - \delta) \quad (3.19)$$

DC bus PI controller (shown with red in Figure 3.11) is designed much slower than main controllers, in order to avoid side effects on voltage compensation performance. The reference voltage is fed to voltage source inverter. Double loop controller is used as inverter voltage controller to have better performance during transient [21, 47].

3.2.3 Series Unit Double Loop Inverter Controller

In the previous section the instantaneous reference voltage $v_x(t)^*$ calculation strategy is presented. This reference value is fed to the inverter controller. The series unit inverter, is working as ac voltage generator and it should be able to follow this reference. Inverter double loop controller is illustrated in Figure 3.12.

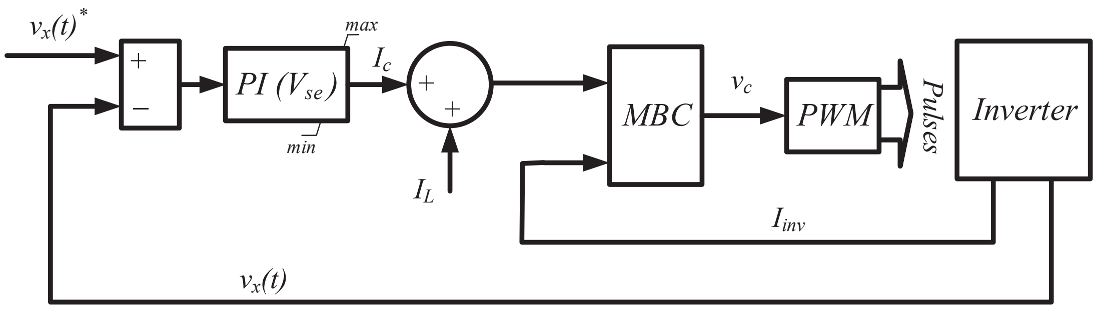

Figure 3.12: *Open UPQC series unit double loop controller.*

This double loop inverter controller is meant to force the inverter to produce the requested reference voltage on inverter ac terminals. As outer voltage controller normal PI controller is used inside inverter controller loop. The transfer function of the PI controller is reported in Equation 3.20.

$$H_{PI}(s) = k_p + \frac{k_i}{s} \quad (3.20)$$

PI output is considered as control current I_c and it is added to measured line current I_L to produce the reference current for inverter current controller. So, as it can be noticed the PI controller is responsible to produce just the small control current which is added to the line current.

The last controller in loop is the MBC as it was explained at the beginning of this Chapter. The series unit inverter is a single phase full bridge inverter and all the equations derived in the Section 3.1 are applicable for it. With described MBC and configuration of Figure 3.12 the inverter switching frequency will be kept constant (by means of constant frequency PWM strategy) and it can avoid problems associated to the variable switching frequency methods. The pulse signals will be sent to inverter. Feedbacks of the system are inverter current (I_{inv}) and inverter voltage ($v_x(t)$) measurements as it is shown in Figure 3.12.

3.2.4 Series Unit Controllers Setting

Table 3.1 shows the controllers set parameters of series unit. For each controller the PI output parameters with corresponding limits are shown also. V_{PCC} PI output, generates series unit injected voltage, so it is saturated according to series inverter maximum voltage injection capability. The DC bus voltage controller, generates δ and it is limited to $\pm 30°$ and the series inverter voltage PI controller as its output, generates the control current (I_c) for current controller and it is limited according to the series unit switching inductance maximum current.

	k_p	k_i	**Output saturation**		
			Item	**Max**	**Min**
$PI(V_{PCC})$	0.20	4.00	V_x (V)	+150	-150
$PI(V_{DC\_se})$	0.04	0.30	δ (radian)	+π/6	-π/6
$PI(V_{se})$	0.25	330.00	I_c (A)	+300	-300

Table 3.1: *Series unit controllers parameters.*

Several computer based simulation studies have been performed to verify designed controller behavior before series unit hardware design and starting laboratory work. The logical steps are followed to design the controller and then realize the real prototypes however in this dissertation all the results are introduced in Chapter 6 in order to be able to compare simulation based results with experimental ones.

3.3 Shunt Unit Controller

Intrinsically Open UPQC shunt unit is a UPS like bidirectional converter which is able to manage a storage system [6, 19]. So, basically shunt unit control is the same as a bidirectional converter management equipped with a storage battery set.

Therefore device control includes inverter controller and chopper controller where these two parts are linked to each other by means of inverter DC bus. Shunt unit controller is a Model Based Controller (MBC) adapted for inverter control and a simple, but yet reliable, PI controller for chopper control. Same as it was explained for series unit control, first the reference voltage and current generation procedure will be explained and then the inverter and chopper control logics will be introduced.

3.3.1 Current and Voltage Reference Generation

While the device is connected to the grid (*Online* operation mode) it has several functionalities and all the functions are managed by changing the reference current because during *Online* operation mode, the shunt unit works as current source. So, it needs a reference current to follow. While during *Island* operation, the shunt unit is a voltage source to supply the load and it will need an sinusoidal voltage as reference. Most of the functionalities are defined in *Online* operation mode and it is achieved by different current references.

Online Operation Mode

The reference current generation algorithm for Open UPQC shunt unit *Online* operation mode is shown in Figure 3.13. It is composed of several components. I_{ref-DC} is the reference current component to keep DC link constant and it has been generated by using a PI controller. The difference between reference value and measured DC bus capacitor voltage fed to a PI controller as the error. The PI controller output has been multiplied to the *sin(ωt)* in order to be in phase with grid voltage which means active power exchange. The *sin(ωt)* and *cos(ωt)* functions are extracted from grid voltage (V_s) by using a Phase Lock Loop (PLL) system which calculates the grid voltage frequency f_s and angular frequency ω, comparing zero crossing points. The output of the DC bus PI controller, is the active component sinusoidal current, which is required to regulate DC bus voltage in set value and it is added up to the inverter reference current. Although this component is not always in loop because during peak shaving action the chopper leg carries out DC bus voltage control.

I_{ref-Q} is the reactive component of the reference current which can have different values. With no command from DSO the shunt unit is meant to compensate all load side reactive power so Q_{ref} is set to zero otherwise with any command from DSO the Q_{ref} will be updated and shunt unit will fix grid side reactive power to the requested value. In order to comply the reactive power request, the error between reference value and the measured value is fed to a slow and simple digital repetitive controller. The implemented repetitive controller works as it is explained in Equation 3.21:

$$\begin{aligned} if(error > 0) &\Rightarrow I_q = I_q + const. \\ else\_if(error < 0) &\Rightarrow I_q = I_q - const. \\ else\_if(error = 0) &\Rightarrow N.O. \end{aligned} \tag{3.21}$$

For each iteration step, if the error between reference reactive power and the mea-

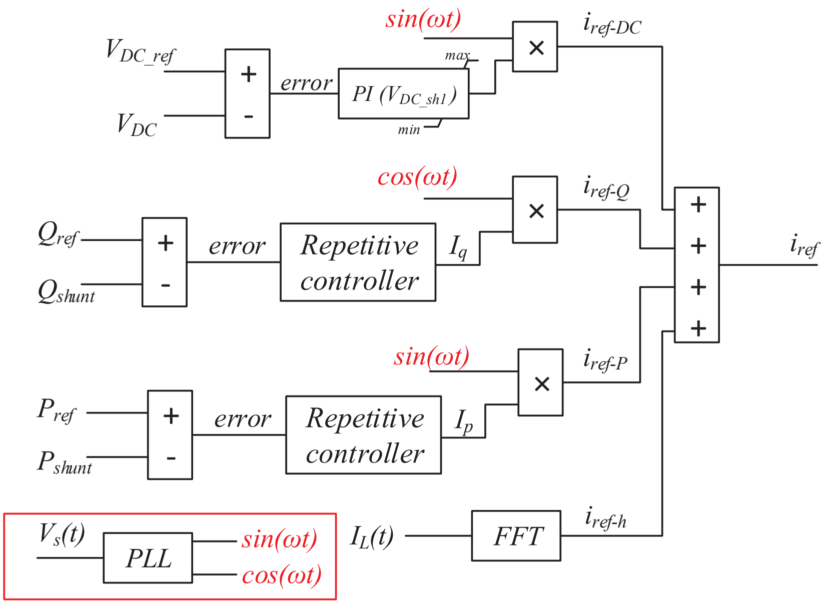

Figure 3.13: *Reference current generation algorithm for shunt unit Online operation mode.*

sured reactive power is positive, a small constant value is added to the I_q otherwise if the error is negative, the constant value should be subtracted. If the error was equal to zero, No Operation (N.O.) need to be performed.

I_{ref-P} is another active component of the reference current which is activated once the peak shaving threshold has been exceeded and shunt unit is required to do peak shaving so, normally the P_{ref} is set to zero but if the load power exceeds peak shaving threshold, the exceeded active power $(P_{load} - P_{threshold})$ is updated into P_{ref}. Similar to reactive power control, a simple repetitive controller is utilized to carry out peak shaving. The controller is described in Equation 3.22. For both reactive and active power control the dynamics of the shunt unit can be designed by modifying the constant value which will increase or decrease the controller speed. Due to the communication delay, the shunt unit is not required to have a fast response time for reactive power request. Also the thermal breakers normally can tolerate exceeded rated power around 1s so, both reactive and active power repetitive controllers can be slow (around *1s* response time) respect to the inverter controller (around *ms* response time).

$$
\begin{aligned}
if(error > 0) &\Rightarrow I_p = I_p + const. \\
else\_if(error < 0) &\Rightarrow I_p = I_p - const. \\
else\_if(error = 0) &\Rightarrow N.O.
\end{aligned}
\tag{3.22}
$$

And the last component of the reference current is the load harmonic compensation current. The load current passes through Fast Fourier Transform (FFT) block and harmonic components are extracted and compensated by shunt unit. In practice the shunt unit inverter switching frequency is 20 kHz and it has the possibility to compensate up to eleventh harmonic component of fundamental signal.

Island Operation Mode

During *Island* operation, the shunt unit need an ideal sinusoidal voltage reference. Nominal frequency and voltage magnitude is considered to generate an ideal fundamental component voltage reference. In order to avoid phase jump and any sag/swell on load voltage, the last information of the grid voltage magnitude and phase is considered and used to generate the *Island* operation mode voltage reference.

3.3.2 Inverter Control Method

Inverter control also has two states. When the inverter is connected in parallel to the grid, the inverter terminal voltage is imposed by the grid so the inverter needs to work as a current source. Instead, when the inverter is disconnected from the grid, it should be able to keep its terminal voltage with constant frequency and magnitude under wide load variation. Both states will be discussed below in detail. Both operation modes controllers use described MBC current controller as the latest controller in their loop. The focus of this section is to manage the inverter properly, so the Open UPQC shunt unit will be able to follow any current and voltage reference.

Online Operation Mode

During *Online* operation mode, the shunt unit should manage to keep capacitor DC bus voltage constant to charge the storage, if it is necessary. Depending on status, the shunt unit can also be responsible for several tasks like reactive power compensation, harmonic elimination, peak shaving, and so on. During the *Online* operation mode, the device has to work as current source and needs to properly follow a reference current. Figure 3.14 shows the *Online* operation mode controller block diagram, which is the described MBC that needs reference current and inverter current measure. The MBC produce control voltage (v_c), and it is fed to the PWM module of microcontroller to control the power electronic switches.

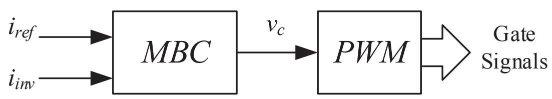

Figure 3.14: *Shunt unit Online operation mode controller block diagram.*

It is important to mention that during *Online* operation mode, it is either the inverter that is responsible to control the inverter DC bus voltage or the chopper leg. When the system works to charge the storage, inverter is responsible to keep DC bus voltage regulated by means of V_{DC_sh1} *PI* controller. During the peak shaving or the *Island* operation mode, it is the chopper leg responsibility to regulate the inverter DC bus voltage using the energy stored inside the battery set.

Therefore, *Online* operation mode controller is only a MBC current controller and all the functionalities of the system are managed by changing the reference current.

Island Mode

During *Island* operation mode, the inverter terminal voltage frequency and magnitude should be controlled by shunt unit inverter. Therefore, the inverter voltage PI controller is added in the front end of the described MBC to design the *Island* operation mode PI Model Base Controller (PI-MBC) controller. Since inverter current measurement is used for the MBC inverter current controller, the same measure can therefore be used in the island voltage controller. A control method, based on cascade controller with load current feedback, is implemented in order to avoid voltage drop under load variation for *Island* operation mode [48]. The implemented controller is shown in Figure 3.15.

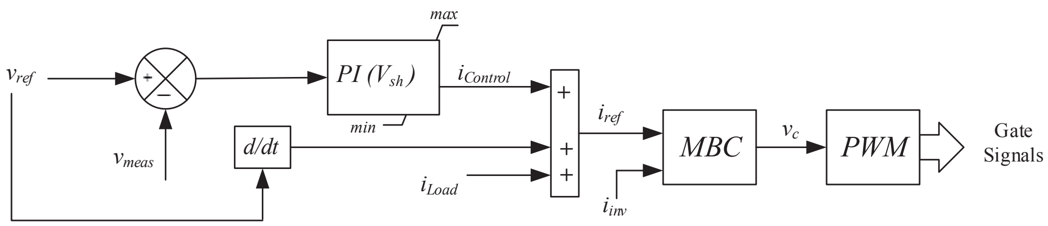

Figure 3.15: *Shunt unit island mode controller block diagram—PI-MBC, inverter.*

An ideal sinusoidal waveform with nominal frequency and peak value is considered as the voltage reference, it is compared instantaneously with inverter AC terminal voltage, and the error is fed to a PI controller. The $PI(V_{sh})$ output is considered as the control current, and $i_{Control}$ is added to the current reference for the inverter current controller. The PI controller output limit is set according to AC side inductance current ratio. $i_{Control}$ is added to the load current feedback and the estimated output filter capacitor current, which uses the reference voltage and basic capacitor equation in order to estimate capacitor current. The sum is considered as the reference current. The generated reference current is fed to the inverter MBC that is explained in previous section.

In *Island* operation mode the inverter DC bus voltage regulation is being carrying out by DC chopper leg discharging the energy inside storage battery system. The chopper control logic is described in following section.

3.3.3 DC leg Chopper Control

DC leg Chopper can be managed either to charge the storage or to discharge the storage in order to supply the load in *Island* operation mode and also during peak shaving. Figure 3.16 shows the complete single phase schema of the shunt unit with inverter and chopper leg. The inverter and chopper leg are linked together through DC bus capacitor. In Figure 3.16 the chopper leg components from right to left, L_{DC} is the DC side inductance, V_{Ldc} is the voltage on it and rest of the parameters are the same as explained before. Other variables are as below:

- X_4 is the DC storage current;
- V_B is the storage system voltage, to derive the model for simplicity, it is considered constant;
- D_{Buck} and D_{Boost} are not complementary gate signals; to derive the chopper leg, those are either zero or one.

As it is seen, the battery management leg has two IGBTs, where the midpoint is connected to the batteries' positive terminal through an inductance. Considering antiparallel diodes of the IGBTs by blocking the low-side switch and controlling the high-side switch, it becomes *Buck* converter, which can charge the batteries using voltage on DC bus capacitor and the power is supplied from network. Likewise, blocking the high-side switch and controlling the low-side switch, it works as *Boost* converter. In *Boost* mode the chopper leg can discharge the battery to provide required power of the inverter in order to supply part of the load in peak shaving or all the load in *Island* operation mode.

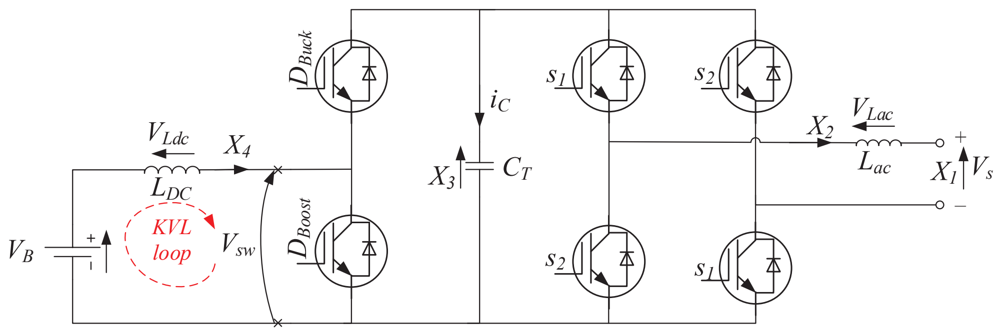

Figure 3.16: *Shunt unit complete schema with inverter and chopper leg.*

Thus, the DC chopper leg can work as *Buck* and *Boost* converters. Adopted controller for chopper leg is also a Model Based controller so first of all chopper leg state space model is derived. In the model, both modes of operations have been considered. For each operation mode, specific equations have to be used. Using the same notation, we can write the KVL of *KVL loop* for chopper leg as Equation 3.23.

$$V_B - V_{Ldc} - V_{sw} = 0 \tag{3.23}$$

where V_{sw} is defined as switch side equivalent voltage for either *Boost* and *Buck* conditions as those are shown in Equation 3.24. Replacing the *Boost* and *Buck* voltage, Equations 3.23 and 3.24 can be rewritten for two different operation modes as reported in Equation 3.25. Using Laplace transform for inductance voltage, Equation 3.25 leads to Equation 3.26 and applying *Boost* and *Buck* converter equation, the current balance can be written as reported in Equation 3.27, where i_C is the current through the DC link capacitor. Therefore, voltage and current equations for *Boost* and *Buck* converters can be extracted as those are reported in Equation 3.26 and 3.27.

Boost	*Buck*	
$V_{sw} = (1 - \hat{D}_{Boost}) \cdot X_3$	$V_{sw} = \hat{D}_{Buck} \cdot X_3$	(3.24)
$V_B - V_{Ldc} - (1 - \hat{D}_{Boost}) \cdot X_3 = 0$	$V_B - V_{Ldc} - \hat{D}_{Buck} \cdot X_3 = 0$	(3.25)
$V_B - S \cdot L_{dc} \cdot X_4 - (1 - \hat{D}_{Boost}) \cdot X_3 = 0$	$V_B - S \cdot L_{dc} \cdot X_4 - \hat{D}_{Buck} \cdot X_3 = 0$	(3.26)
$i_c = S \cdot C_T \cdot X_3 = (1 - \hat{D}_{Boost}) \cdot i_{DC}$	$S \cdot C_T \cdot X_3 = \hat{D}_{Buck} \cdot i_{DC}$	(3.27)

By Equations 3.26 and 3.27, the state space model of the chopper leg can be driven. Due to multiplication of time varying duty cycle functions to state variables, it can be considered as LTV system, and the model can be solved by a proper iteration or linearization methods. Equation 3.26-*Buck* will be used as current controller during charging state for *Buck* converter.

Charging Mode

Standard Lead-Acid battery charging method is applied in order to charge the batteries, which is called Constant Current Constant Voltage (CCCV) method. This technique of battery charging has two modes of charging that depend on batteries' state of charges; constant current and constant voltage [16] as it is shown in Figure 3.17. It charges the batteries until near nominal voltage by inserting constant current. Then, it uses constant voltage, charges the batteries keeping the voltage constant, meanwhile the current goes to zero slowly [16]. Normally the "constant voltage" mode duration is about double the "constant current" one as it is shown in Figure 3.17. Consequently the battery charging control has two working modes; *Constant current* and *Constant voltage*.

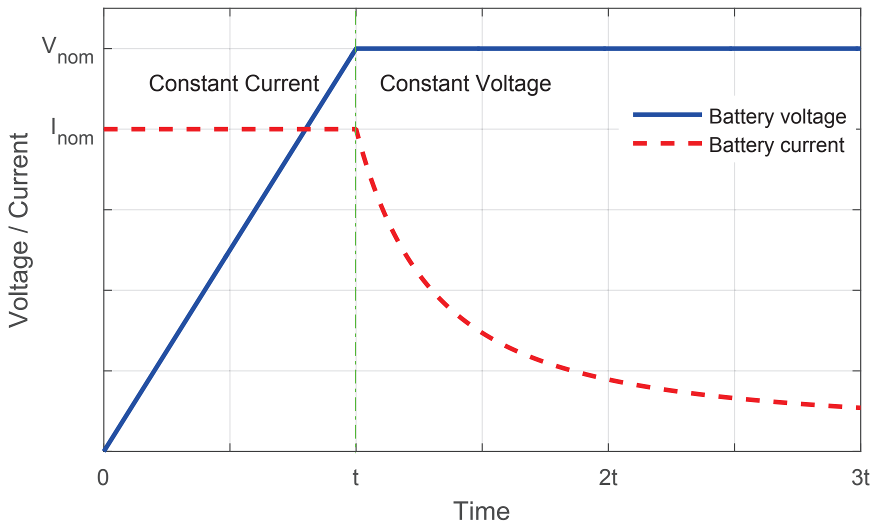

Figure 3.17: *Lead acid battery charging procedure.*

For the constant current mode by using the basic principle of *Buck* converter operation [52], considering the Equation 3.26-*Buck* part and using Euler first order approximation instead of Laplace transfer function for the derivative, the voltage balance on inductance for one switching period can be achieved by rewriting Equation 3.26-*Buck*. Therefore, the duty cycle can be evaluated by the Equation (3.28).

$$D_{Buck} = \frac{(-\frac{\Delta iLDC \cdot L_{DC}}{T_s} + V_B)}{V_{DC}} = \frac{(-\frac{(i_{LDC}(k) - i_{LDC}(k-1)) \cdot L_{DC}}{T_s} + V_B)}{V_{DC}} \tag{3.28}$$

where i_{LDC} is the DC side inductance current in ampere and $\Delta iLDC$ is the current variation on the inductance; k is the number related to time step; L_{DC} is the DC side inductance value in Henry; V_B is the instantaneous overall battery voltage in volt; V_{DC} is the inverter DC bus voltage; T_s is the controller sampling time in second, and D_{Buck} is the calculated duty cycle in p.u.. Considering the adopted MBC for the inverter control, with the same approach, Δi_{LDC} can be replaced with the difference between reference current (the batteries' nominal charge current) and measured current. So doing, equation (3.28) changes to equation (3.29). The generated duty cycle runs the high-side switch of the chopper leg:

$$D_{Buck} = \frac{(-\frac{(i_{ref}-i_{LDC}(k))\cdot L_{DC}}{T_s} + V_B)}{V_{DC}} \tag{3.29}$$

For constant voltage charging control, since the batteries' voltage is near nominal, the duty cycle can be considered as *Buck* converter voltage equation 3.24; however, in order to have better control on the absorbed current, a cascade controller is used. The controller schema is shown in Figure 3.18.

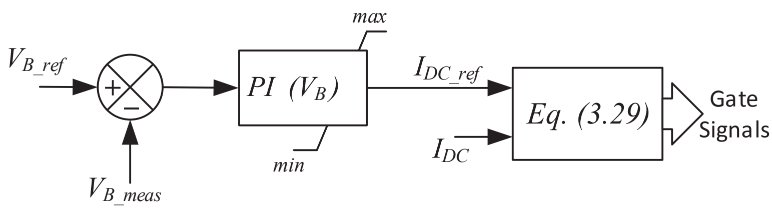

Figure 3.18: *Constant voltage chopper charging controller—PI-MBC, chopper.*

The difference between nominal voltage value and measured voltage is fed to a PI controller, and the output is considered as the current reference, which is used as reference to the constant current controller of equation (3.29). In order to have control over the absorbed current, $PI(V_B)$ output is limited with upper and lower limits. It is considered as batteries' charging current, so the max is cut to the batteries nominal charging current. Switching and sampling time of charging mode for DC chopper leg IGBTs are the same as the inverter switching frequency.

Discharging Mode

The batteries have been discharged in two working state. During *Island* operation mode and peak shaving. In both these working state, the DC bus voltage is controlled by DC chopper leg instead the inverter absorbs the power from DC side and it is no more able to regulate DC bus voltage. In the discharge mode, the high-side switch of the DC chopper leg is blocked, and by running the low-side switch and means of the antiparallel diode, it works as a *Boost* converter. During discharging mode, the batteries' voltage is boosted to a higher value and keeps DC bus voltage constant for inverter functioning to supply the load. During discharging mode, in order to decrease losses and keep the converter at Discontinuous Current operation Mode (DCM), the switching frequency is considered much lower than the inverter one. Control approach is based on cascade PI controller with outer voltage control and inner current controller. The schema is shown in Figure 3.19.

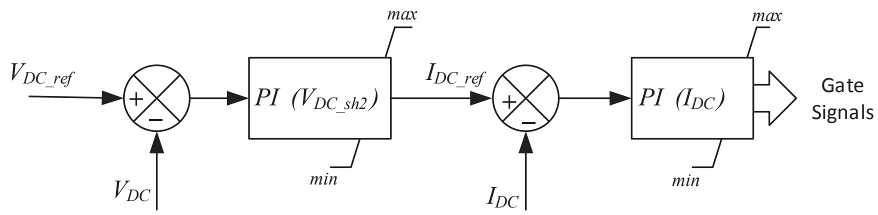

Figure 3.19: *Chopper Discharging controller.*

The second PI output is considered as the duty cycle to run the corresponding switch. First PI, $PI(V_{DC\_sh2})$ output is the reference DC current for battery discharging mode. During discharge mode, the battery current can be high and the limit is set according to DC inductance rated value to avoid inductance saturation. $PI(I_{DC})$ output is the duty cycle for the PWM module, so it is limited to stay below one.

3.3.4 Shunt Unit Controllers Setting

Table 3.2 shows the parameters for the shunt unit controllers. In each case the corresponding output signal means and the associated saturation limits are also presented. The $PI(V_{DC\_sh1})$ output will lead to an AC signal to charge or discharge the inverter DC bus for regulation purpose so it can have both positive and negative values. $PI(V_{sh})$ is the inverter voltage controller and the output is the control current for the inverter current controller and it is limited according to inverter ac side switching inductance. $PI(V_B)$ output is the current reference to charge the batteries and the batteries' nominal current is 3 A so $PI(V_B)$ output will be a one direction DC current and it is limited between zero and three. $PI(V_{DC\_sh2})$ output is the reference current to discharge the batteries and the discharging current can be much higher than the charging one so, it is limited according to the DC chopper switching inductance. The $PI(I_{DC})$ output is fed to the IGBT driver to run the IGBTs so, the $PI(I_{DC})$ output is duty cycle and should be limited between zero and one however, to avoid over modulation problems it is limited between zero and 0.95.

	k_p	k_i	**Output saturation**		
			Item	**Max**	**Min**
$PI(V_{DC\_sh1})$	0.01	0.10	I_{ref} (A)	+10	-10
$PI(V_{sh})$	0.74	3000.00	$I_{Control}$ (A)	+35	-35
$PI(V_B)$	0.50	35.00	I_{DC_ref} (A)	+3	0
$PI(V_{DC\_sh2})$	3.00	25.00	I_{DC_ref} (A)	+45	0
$PI(I_{DC})$	12.00	50.00	Duty cycle	0.95	0

Table 3.2: *Shunt unit controller parameters.*

Same as series unit procedure, several computer based simulation studies have been performed to verify designed controller behavior before shunt unit hardware design and starting laboratory work however to make it easy to follow the work and compare simulation based results with experimental ones, all the results are reported in Chapter 6.

3.3.5 Transitions

The Open UPQC shunt unit should be able to detect any under/over voltage of grid as fast as it can, in order to do proper control action especially to change its operation mode from *Online* to *Island*. Electromechanical breakers has quite long delay to carry out such a task so, a set of *Static Switch* (SS) is used to couple and decouple the shunt unit in appropriate time. Here the SS control logic is described for transitions from *Online* to *Island* operation mode and vice versa.

Transition from *Online* to *Island* Operation Mode

The SS control strategy adopted in the device is based only on the verification of the real RMS value of the main voltage. Therefore, it has been realized a software able to evaluate the effective RMS of the main voltage with the mobile window technique (evaluated in an half period). The implemented method is intrinsically "slow" because it is necessary at least an half-cycle in order to evaluate the new main voltage. This characteristic can be seen as a negative aspect (it operates with delay) or as a positive aspect (it operates independently from disturbances). For this reason, it is always possible to guarantee the network separation in less than half cycle.

However the implemented digital control strategy notices very quickly wide variations of the RMS voltage value. Also thanks to available very fast switches that in case of supply interruption or deep voltage sags, transitions is realized in the order of few milliseconds. The implemented control strategy is realized with 20 kHz acquisition frequency. Figure 3.20 shows the minimum detection time in function of the variation depth of the network voltage for different values of starting main voltage (values comprised between 0.9 p.u. and 1.1 p.u.). It also shows the minimum detection time in case of over voltages [22].

It is important to observe that this control strategy does not take into account the "quality" of the voltage waveform (that could be non-sinusoidal) and the frequency of the supply voltage. In the case of supply voltage interruption, connection between the network and the PCC should be opened (through the SS). So while the device works in parallel to the network (*Online* operation mode) once the supply voltage of PCC interrupts, the static switches opens the line and consequently after few milliseconds (i.e. 3-4 ms) the device passes into *Island* operation mode, generating the voltage in "phase" with the previous network voltage. Transition from *Online* to *Island* operation

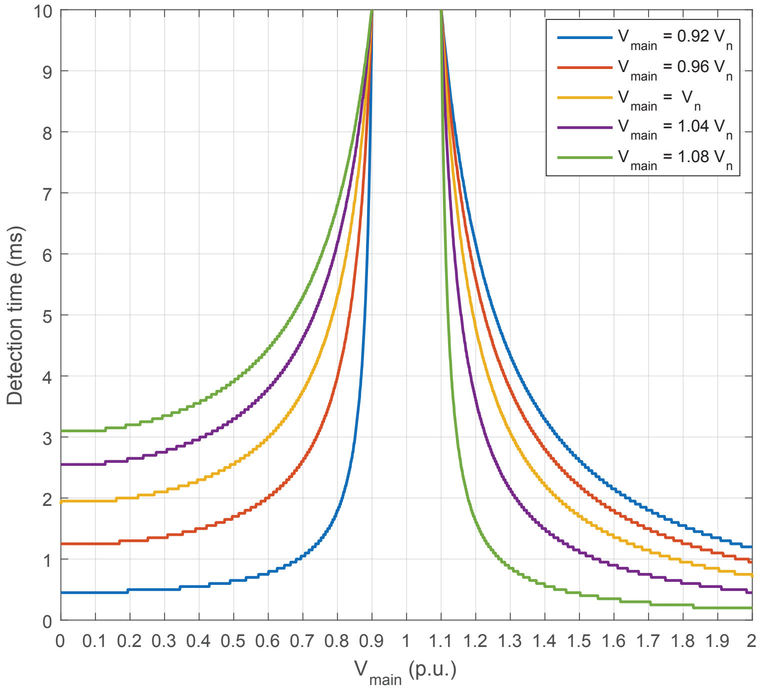

Figure 3.20: *Time detection delay with different p.u. value of main voltage, in mobile window acquisition case. (the minimum detection time is equal to 0.05ms).*

mode should be done instantaneously with as less as impress on voltage characteristics of load. There can be very short duration voltage drop or over voltage because of rapid changes on RMS inverter current ($I_{inverter}$) passing through *Online* to *Island* operation mode.

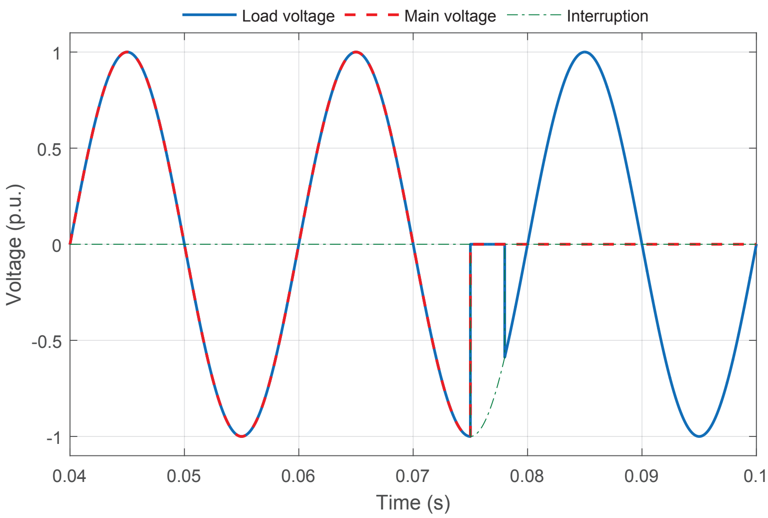

Figure 3.21: *Shunt unit Online to Island transition example.*

Figure 3.21 shows an example of shunt unit transition from *Online* to *Island* operation mode in ideal condition. The main voltage interruption is simulated at t=0.075 s.

As it can be noticed before the interruption, the load was supplying from the main and the load and main voltage are the same. There is less than half a cycle interruption on load voltage and then the shunt unit inverter takes over the load and supplies the load by means of stored energy on batteries.

Transition from Island to Online Operation Mode

In the case of transition from *Island* to *Online* operation mode, the connection between the network and the PCC should be closed. When the control strategy that described before, verified that the RMS value of the main voltage is inside the standard limits after that, the microprocessor starts the resynchronization phase; changing the load voltage phase and amplitude and commands the closing of the static switch when the generated voltage is synchronized with the network voltage. When the RMS value of the main voltage returns inside the standard limits, the voltage generated during the *Island* operation mode changes initially its frequency and then its amplitude in order to obtain the perfect waveform for the load. In order to appropriate reconnection, the phase and amplitude resynchronization is realized every time that the current goes through the zero value (zero crossing) and a maximum step size for frequency variation (i.e. $\Delta f = 0.1\ Hz$) also a maximum voltage step size variation (i.e. $\Delta v = 0.02\ p.u.$) are considered. It is important to take into account the voltage variation transitory on the static switches due to the phase and amplitude difference between the V_{load} and the V_{main} during the transition. It is essential that in the moment of commutation, perfect synchronization of the two voltages has been done and this voltage stress has been minimized.

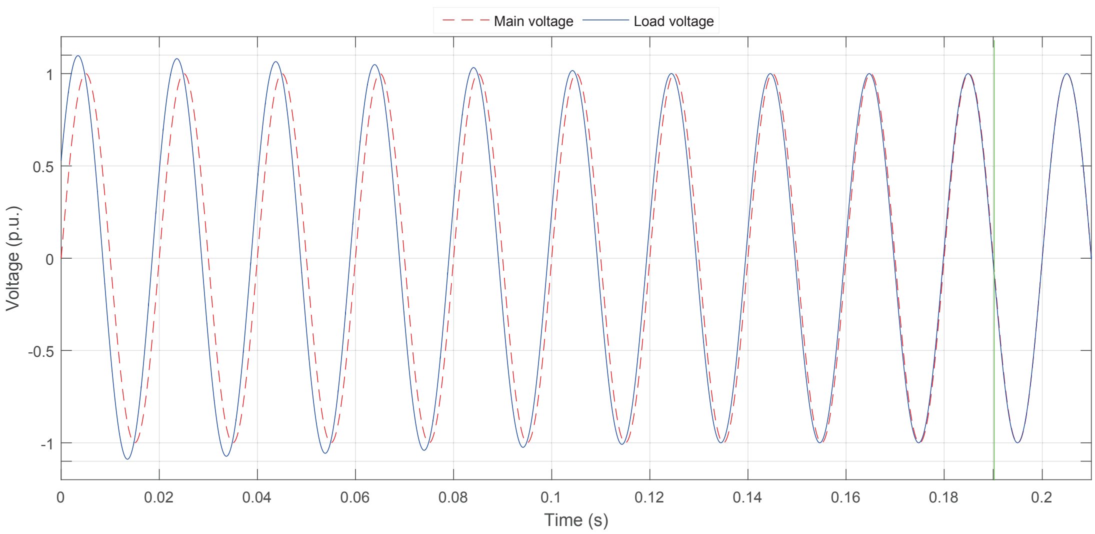

Figure 3.22: *An example of shunt unit magnitude and phase synchronization for Island to Online transition.*

Figure 3.22 illustrates an example of magnitude and phase synchronization before reconnecting the load to the main. The example is simulated to show the magnitude and phase difference between shunt unit generated voltage and main voltage at the beginning of the simulation. Device starts with magnitude and phase synchronization, once the perfect synchronization is achieved, it waits for the next zero crossing to command the *SS* reconnecting the load to the main and change the shunt unit operation mode.

3.4 Series and Shunt Units Co-operation

The Open UPQC series and shunt units can operate independently. Nevertheless, during the SDG project they were located in a more general architecture which allow those to coordinate the series and shunt units. This will enable a more effective control strategy to communicate with an Energy Management System to do *Peak Shaving* [6] by shunt units and also reactive power generation to improve series unit performance. As explained before, this reactive power injection is essential to enlarge series unit working region. So, Volt/Var control is one possible action that co-operation can mean to do. With shunt unit reactive power control, the DSO can follow different approaches. It can increase the feeder total reactive power to enlarge series unit compensation limits or conversely, the DSO can decide to set the overall reactive power on the feeder to zero, compensate all the reactive power to decrease current and consequently the losses on the feeder. Another option for the DSO, can be to perform Voltage Optimization actions to reduce the system losses and improve the load performance. Voltage Optimization is out of scope of this work and it will not address in this Thesis.

This section describes the ICT based controller for co-operation between series and shunt units of Open UPQC. Considering Figure 3.23, which is a simplified ideal model of Open UPQC in the installed area, the co-operation control logic can be explained. This controller will generate the total required reactive power Q_{T_ref}, depends on the strategy that DSO wants to follow, and will send this request to the Distributed Energy Management System (DEMS) to be sent to the available shunt units. DEMS will share the Q_{T_ref} amount among the available shunt units and for each shunt unit a Q_{ref} will be sent to be used for its internal *Online* mode operation controller.

3.4.1 Reference Calculation

First of all required total reactive power should be computed depending on the interested control action. Here three different strategy will be considered; 1) Decrease

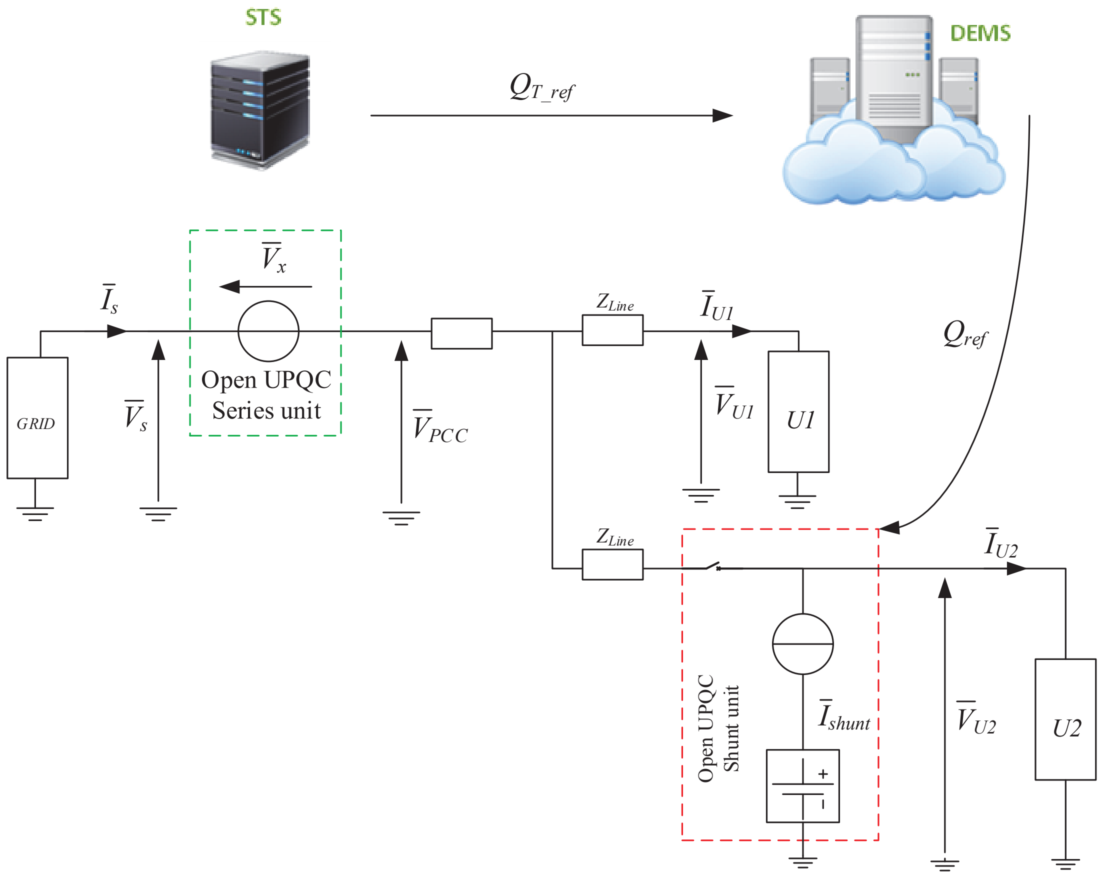

Figure 3.23: *Open UPQC system model with ideal voltage and current sources.*

feeder losses 2) Increase over voltage compensation limits and 3) Increase under voltage compensation limits.

The series unit microcontroller has all voltages, currents and phase measurements, required for these calculation. The measurement data is sent to the STS control computer where this control system is running. Finally the calculated required total reactive power Q_{T_ref} will send to the DEMS to be shared among shunt units. DEMS will collect all the shunt units data and depend on their availability and status, it will send Q_{ref} to each shunt unit. Each scenario will be described in detail.

Decrease Feeder Losses

The DSO depend on its network status and several consideration that can be performed, can decide to decrease the feeder looses by means of shunt units. In this case the total reactive power of the load seen by series unit (Q_{load}) can be calculated and need to be compensated. The load reactive power can be computed as follow:

$$Q_{load} = V_{PCC} \cdot I_L \cdot sin(\gamma) \tag{3.30}$$

Hereafter, V_{PCC} stands for PCC voltage measured value and V_{PCC_ref} for its set reference value. Total value should be compensated completely and so, the target reactive power for the DSO Q_{target}, shall be set to zero. Therefore the requested reactive power to be sent to shunt units is calculated by Equation 3.31. In this case the load side reactive power can be set to zero.

$$Q_{T\_ref} = Q_{target} - Q_{load} = 0 - V_{PCC} \cdot I_L \cdot sin(\gamma) \tag{3.31}$$

Increase Over Voltage Compensation Limits

The DSO for several reasons can decide to increase the series unit over voltage compensation limits. For example, for a specific period, it can predict some probable over voltage events on the feeder so, it can act to increase series unit over voltage limits. The maximum main voltage ($V_{s,max}$) as it was explained in Chapter 2, can be calculated with Equation 3.32.

$$|V_{s,max}| = \sqrt{|V_{x,max} + V_{PCC\_ref} \cdot sin(\gamma)|^2 + |V_{PCC\_ref} \cdot cos(\gamma)|^2} \tag{3.32}$$

In this equation, $V_{x,max}$ is a known parameter and depends on series unit design parameter. V_{PCC_ref} is also a known parameter and it is set by DSO itself. So, if the DSO set the required maximum over voltage compensation limit to the $V_{s,max}$, it is possible to find the corresponding γ and $sin(\gamma)$ values by reverse calculation. The calculated values will be considered as γ_{ref} and $sin(\gamma_{ref})$ and those stand for DSO new request values. By reverse calculation from Equation 3.32, the $sin(\gamma_{ref})$ can be calculated as Equation 3.33.

$$sin(\gamma_{ref}) = |\frac{V_s^2 - V_x^2 - V_{PCC\_ref}^2}{2 \cdot V_{x,max} \cdot V_{PCC\_ref}}| \tag{3.33}$$

It is important to mention that, the γ_{ref} need to be at the same direction that the load power angle (γ) is. That means, to calculate $sin(\gamma_{ref})$ the sign of the γ should be considered as well so, the Equation 3.33 has to be updated to the Equation 3.34.

$$sin(\gamma_{ref}) = |\frac{V_s^2 - V_x^2 - V_{PCC\_ref}^2}{2 \cdot V_{x,max} \cdot V_{PCC\_ref}}| \times sign(\gamma) \tag{3.34}$$

Therefore in this case, the DSO target reactive power can be set to:

$$Q_{target} = V_{PCC} \cdot I_L \cdot sin(\gamma_{ref}) \tag{3.35}$$

The requested reactive power to be sent to shunt units can be calculated by Equation 3.36. With this procedure the DSO can ask the shunt units the required reactive power to increase series unit over voltage compensation limit.

$$Q_{T\_ref} = Q_{target} - Q_{load} \tag{3.36}$$

Increase Under Voltage Compensation Limits

As explained for over voltage case, for several reasons the DSO can decide to increase the series unit under voltage compensation limits. For example it can predict some probable under voltage events on the feeder so, it can act to increase series unit under voltage limits. The minimum main voltage ($V_{s,min}$) as it was explained in Chapter 2, can be calculated for both cases if the limit is due to the $V_{x,max}$ or γ with Equations 3.37 and 3.38 respectively.

$$|V_{s,min\_a}| = \sqrt{|V_{PCC\_ref} \cdot sin(\gamma) - V_{x,max}|^2 + |V_{PCC\_ref} \cdot cos(\gamma)|^2} \tag{3.37}$$

$$|V_{s,min\_b}| = |V_{PCC\_ref} \cdot cos(\gamma)| \tag{3.38}$$

In this case, despite the over voltage case, the DSO should consider both limits. If the limit is due to the $V_{x,max}$, the co-operation can do nothing with that but if the limits are because of the γ, the Equation 3.38 can be used for reverse calculation to find required γ_{ref} and target reactive power. In Equation 3.38, the V_{PCC_ref} is a known parameter and if the required under voltage limit is set to the V_{s,min_b} the corresponding γ can be found with reverse calculation and like previous case it can be considered γ_{ref}. Again, in order not to lose the reactive power direction (inductive or capacitive), the computed $sin(\gamma_{ref})$ shall be multiplied by sign(γ) as it is reported in Equation 3.39 and 3.40.

$$cos(\gamma_{ref}) = \frac{V_{s,min\_b}}{V_{PCC\_ref}} \tag{3.39}$$

$$sin(\gamma_{ref}) = (\sqrt{1 - cos^2(\gamma_{ref})}) \cdot sign(\gamma) \tag{3.40}$$

The load reactive power can be computed always by Equation 3.30 and DSO target reactive power is equal to

$$Q_{target} = V_{PCC} \cdot I_L \cdot sin(\gamma_{ref}) \tag{3.41}$$

So the reactive power request to be fed to the ICT based controller is equal to;

$$Q_{T\_ref} = Q_{target} - Q_{load} \tag{3.42}$$

Q_{T_ref} from Equation 3.31 or Equation 3.36 or Equation 3.42 is the command that is continuously updating and send to ICT based controller thought communication system. To get stability point within control loop, the reference update rate should be slower than control loop speed.

3.4.2 ICT Based Controller

Q_{target} is the reference for the controller and as it is explained, considering feeder status, DSO can decide which strategy shall be followed and corresponding value can be computed. But, it is essential to continuously calculate Q_{load} in order to find the difference between Q_{target} and Q_{load} which gives the needed reactive power to be generated by shunt units. Therefore, a close loop controller must be implemented. ICT infrastructure of the SDG project is used as platform to implement a PI controller to enable co-operation between series and shunt units. The reactive power control loop can be schematized as Figure 3.24. The difference between Q_{target} and Q_{load} is considered as error signal and it is sent to a PI controller and the output is used as command to be sent to shunt units. PI output is saturated according to the installed shunt units overall maximum ratio. There is time delay and then actuator which decides each unit's share on the reactive power, considering Q_i and P_i, in order to avoid total VA (3 kVA) over load issue on shunt units. The actuator and decision making system is realized inside DEMS which has information about all shunt units.

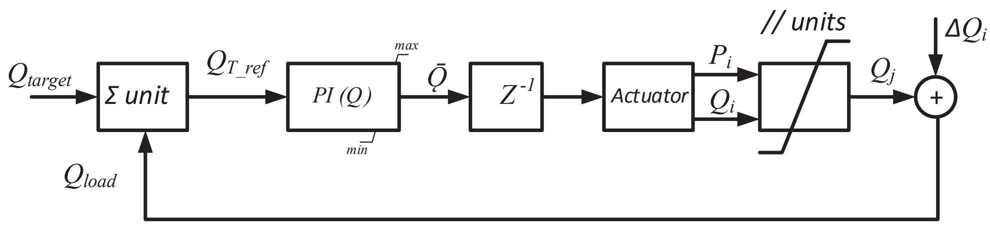

Figure 3.24: *Open UPQC ICT based Var controller block diagram.*

Q_j is the command to shunt units and ΔQ_i is the each controlled ($U2$) load reactive power that is considered as disturbance in this control loop. PI controller can be designed considering time delay of the communication loop. The PI controller transfer function is:

$$H_r(s) = \frac{k_p \cdot s + k_i}{s} \tag{3.43}$$

So the close loop transfer function became:

$$H(s) = \frac{1 + s \cdot T_1}{1 + s \cdot T_2} \tag{3.44}$$

Where T_1 and T_2 are equal to $T_1 = k_p/k_i$ and $T_2 = (1 + k_p)/k_i$. The control loop, in field test realization, is discrete-time with a period of about few minutes. Therefore, the time constant of the feedback system T_2 can be set to 1 min and if the k_p is set to 1, the k_i can be computed. Considering this design procedure the controller parameters can be computed as:

$$\begin{aligned} k_p &= 1 \\ k_i &= 0.0333 \end{aligned} \tag{3.45}$$

Here the control loop delay is considered 1 min which can be a little faster than the real Internet based communication system of SDG project however, with this design procedure the controller gains can be computed for a system with any delay time in communication system.

CHAPTER 4

Smart Domo Grid and Test Field Demonstration

This chapter introduces the Smart Domo Grid (SDG) project [6], co-funded by the Italian Ministry of Economic Development (Ministero dello Sviluppo Economico - MiSE), as main framework in order to evaluate several aspects of Smart Grid concept and especially the test field which hosts the Open UPQC. The Open UPQC has been developed as part of the project and it has been tested in a real MV/LV substation and LV Network located in the city of Brescia (Italy). Therefore, to understand Open UPQC functionalities, the whole project has been introduced briefly then the field network has been described and some preliminary analysis of the network have been reported in order to understand the right size of the Open UPQC series and shunt units.

4.1 Smart Domo Grid Project

This section gives general description and information about Smart Domo Grid project and its different technological layers.
Basically the project has three major action places;

1. Costumer houses where Open UPQC shunt units are installed
2. Smart MV/LV substation where Open UPQC series unit is installed
3. DSO control center and ICT Architecture.

These parts are interacting to each other by means of Internet based communication. So, in this chapter these three action places based on required ICT infrastructure are explained.

4.1.1 General Description of the Project

The Smart Domo Grid (SDG) project has been developed by A2A Reti Elettriche SpA[1], Smart Grid Projects Department, Whirlpool Corporation and Politecnico di Milano Energy Department. SDG project has been tested in a real MV/LV substation and LV Network located in the city of Brescia, north of Italy. The project is meant to introduce high PQ and economic benefits to the end users beside several advantages to the DSO. Objectives of the project are:

- Improve the management and exploitation of the electricity within distribution LV network with two main aims
  - Implementation of Demand Response Business and Techniques
  - Voltage Power Quality control
- Demonstrate Smart Grid concept through interactions between various actors

The requirements for such objectives are to build and test a system capable to remotely control smart appliances in order to implement the Demand Response scenarios in hourly rates. It will give the capability to the DSOs to manage the needs of electrical networks in terms of network congestion, quality of service and reduction of the failure time of the systems. The outcome will be to demonstrate that an intelligent use of energy can provide economic benefits to the consumers without impact on quality of their life. Also it will show how the consumer aware of their consumption, may change their habits. An overview of the SDG host field existed network where the the project is demonstrated, is shown in Figure 4.1 where dashed lines stand for communication connection and solid lines are for power connection.

As it can be noticed, three action places of the project are shown. The substation was equipped with network analyzer and system data was monitored. The substation is equipped with PC where all the data is being storing and it will be used during project as well and it is called Smart Transformer Substation (STS). The DSO had these information through existed IEC 61850 communication platform. The customer with PV module is also shown in Figure 4.1. As it can be noticed, the only information about end user consumption is on its total consumption by means of installed smart meter. Indeed, during SDG project, the network is updated as it is depicted in Figure 4.2. The newly added communication connections are shown with green dashed lines.

In this system inside costumer's house, refrigerator, dishwasher and washing machine will be connected to the Internet and they are called *Smart Applaiances* within

[1]Starting from April 2016 the name of company has been changed to Unareti SpA.

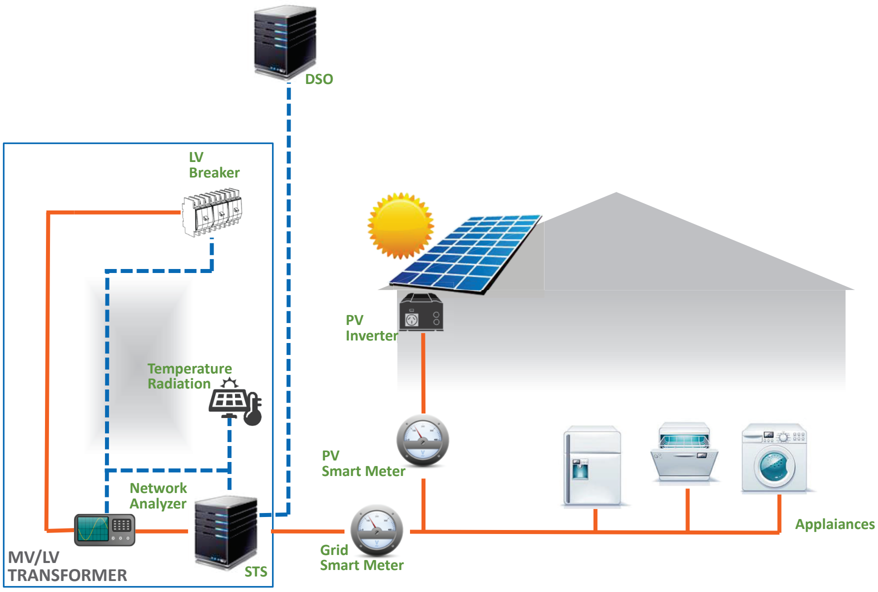

Figure 4.1: *Overview of the Smart Domo Grid project, the old existed network.*

the project. The Open UPQC shunt unit is connected at the front end of the costumer's house. By means of communication system and its battery storage system, shunt unit will work as Distributed Energy Storage System (DESS) within DN. The Shunt unit is able to supply the load in *Island* mode, in the case of grid power interruption or distortion. Costumers with Shunt unit have PV system installed in their rooftop and they are equipped with separate PV smart meter and grid smart meter.

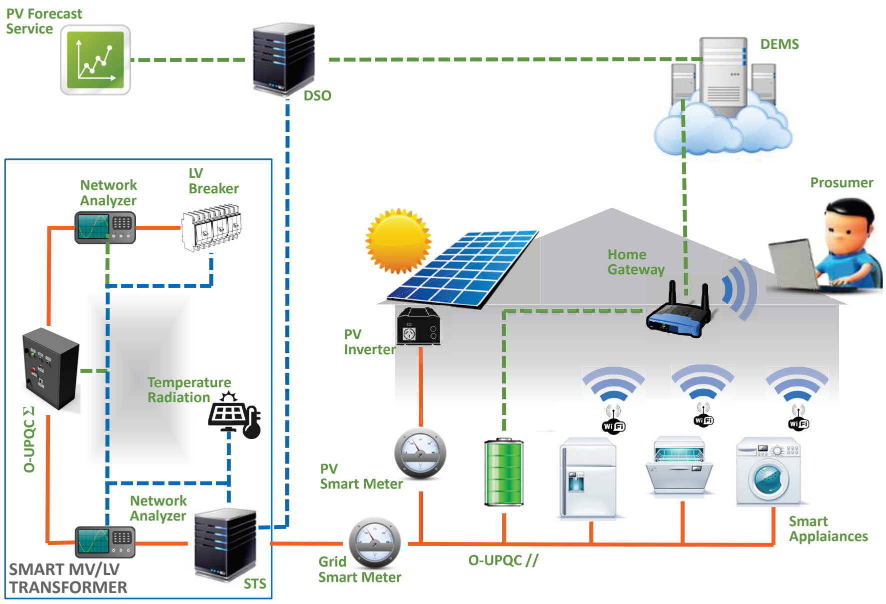

Figure 4.2: *Overview of the Smart Domo Grid project, the new ICT based project network.*

At the MV/LV substation after and before the Open UPQC series unit, two network analyzers are installed in order to monitor the PQ level before the series unit (grid side) and also after series unit (PCC). All the data are collected thanks to ICT system, and those are stored inside the STS. STS sends and receives data/commands to/from DSO control center and the DSO control center communicates with DEMS to manage the Open UPQC shunt unit and connected consumer house.

In such network, the required technological chain for DSO to install Open UPQC series and shunt units and test the concept of SDG project are:

- Measure energy flows
- Calculate the consumer and prosumer absorptions
- Implement the government tariff and logic
- Implement the control actions of the loads

So, the network will need a Internet based communication system to collect all the data, and also different participants of the project could communicate to each other and interact properly. PV forecast system is also integrated into the management system (DEMS), so the forecasted solar irradiance and consequently the PV production is a part of system data. The PV forecast is also sent to DSO control center as well and the information is processed in the control center in order to define new tariff or understand when a congestion in the network can happen.

4.1.2 Project Action Places

The SDG project is consist of several parts and several research groups and parties are involved within the project. Describing all parts of the project is out of the scope of this dissertation however different parts of the project are described here shortly to help the reader in order to understand the overall performance of the project and especially Open UPQC series and shunt units functioning within the SDG project. The descriptions are divided into different subsections based of location and technological layer.

Consumer House without or Equipped with Shunt Unit

The customer house with communication between smart appliances and its DEMS, also equipped with shunt unit, is called Active costumer within SDG project. Each customer has its own DEMS inside general DEMS. The required technological chain for the costumer house (End User) in order to participate within the described scenarios can be summarized as bellow:

- To know its electrical consumption or production

- To plan and manage their appliances remotely
- To know the best economical period to consume energy

As it can be understand from Figure 4.2, the customer house has to have the Internet connection for the *Smart Appliances* and also if present, the shunt unit can be connected too. Each Customer has their iPad with a *interface application* capable to remotely control their refrigerator, dishwasher and washing machine and also to monitor the PV plant power and the shunt unit status. Through the Internet and iPad *interface application* the customers will receive different economical offers from DSO control center to manage their consumption and their appliances' usage.

Two separate communication layer can help to explain the functionality. The consumers have received an iPad with the Beta version of the application to control all the appliances as shown in Figure 4.3. The customer receives economical offers from DEMS according to network power flow condition, electricity tariff and possible PV forecast information. All network information is gathered in DSO control center and in this control center new scheduling is performed and new incentives are sent to the DEMS and from each DEMS to its corresponding costumer.

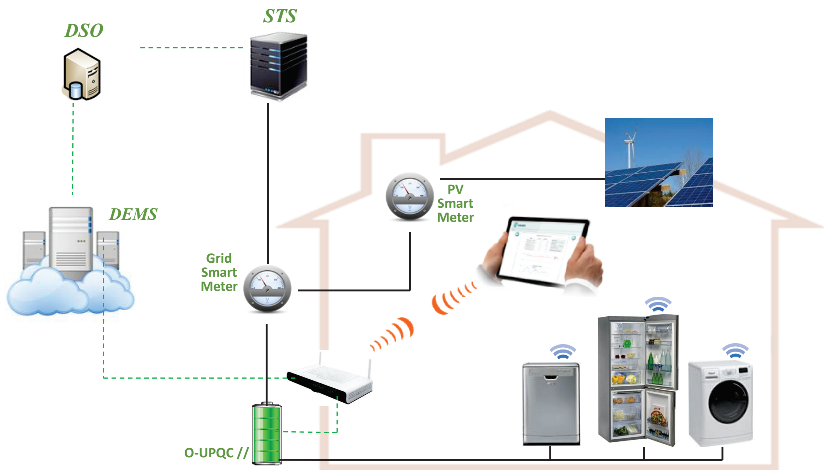

Figure 4.3: *Interactive costumer receives economical offers from DSO through GUI iPad.*

So, through the iPad the customer receives these information and by means of the application, users are able to:

- Remotely schedule their appliances
- Check the appliances' status
- Schedule their appliances to use up to future 48 hours
- Get information about timetables energy costs

- Receive real-time estimate of their cost per cycle

This means, they are free to either accept the received economical offer and plan their energy usage accordingly or not. With this means of communication the costumer get information about energy costs timetables and their real-time estimate of the energy cost per cycle. Indeed it has control action on the smart appliances.

Some customers are equipped with another communication and control action between Open UPQC shunt unit and their DEMS. The shunt unit is equipped with *Raspberry Pi* embedded PC [54] and it is able to send its information to its corresponding DEMS and receives control commands from it. Shunt unit has its Internet connection by conecting to the costumer house Internet router. A remote screen shot of the shunt unit commander is shown in Figure 4.4 which was meant during the project in order to test shunt unit and DEMS communication and send/receive commands to/from shunt unit. This consul has the possibility to read each shunt unit status as; battery State of Charge (SoC), reactive power (Var), active power (Watt) and its operation mode (*Online* or *Island*).

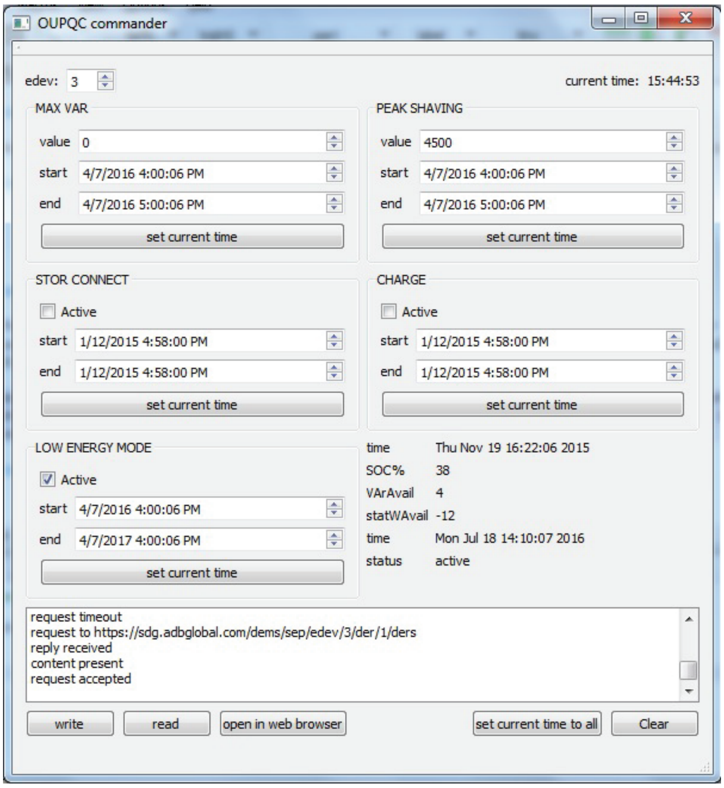

Figure 4.4: *Screen shot of the Open UPQC shunt unit test commander consul.*

With this consul several control actions have been simulated and tested as during the real time operation of the project DSO will take charge of those:

- To set the requested reactive power injection of the shunt unit and its effective time period
- To set the peak shaving threshold of the shunt unit and its effective time period
- To send the shunt unit into the *Island* operation mode with its effective time period
- To set the shunt unit battery charging mode with its effective time period. The DSO can set three different charging modes (which is possible to be tested by developed consul as well):
  - Stop charging
  - Slow charging mode
  - Fast charging mode

So, these communication level and control actions are meant to give possibility to the DSO to control the Open UPQC shunt unit and specially its storage battery to introduce benefits to the end users and also to the grid. Although the Active customers receives PQ services and economic benefits by means of shunt unit and its storage battery, but they have no direct control on it. They may interact with DSO to make any control action on their shunt unit.

Smart MV/LV Substation Equipped with STS and Series Unit

The MV/LV substation where the Open UPQC series unit and STS are installed is called Smart MV/LV Substation. The data collected from series unit by STS, is sent to the DSO control center through IEC 61850 communication. STS receives voltage set point from DSO control center and transfers it to the series unit.

Series unit communication is realized by the same *Raspberry Pi* embedded PC used for Open UPQC shunt unit communication. Same as shunt unit, the data from series unit microcontroller is sent to the *Raspberry Pi* embedded PC by means of Modbus serial communication protocol and the *Raspberry Pi* embedded PC communicates with STS by means of conversion from Ethernet connection to IEC 61850 protocol and it is the STS that talks with rest of the project participants. The smart MV/LV substation of the SDG project and the installed STS and LV breakers inside are shown in Figure 4.5.

ICT Architecture and DSO Control Center

A simplified scheme of the data flows and ICT of the project for different coordinated regulation actions are depicted in Figure 4.6. Series unit parameters together with Active costumers' (equipped with shunt unit, smart appliances and PV inverter) data are sent to DSO control center by means of STS. These information include, requested

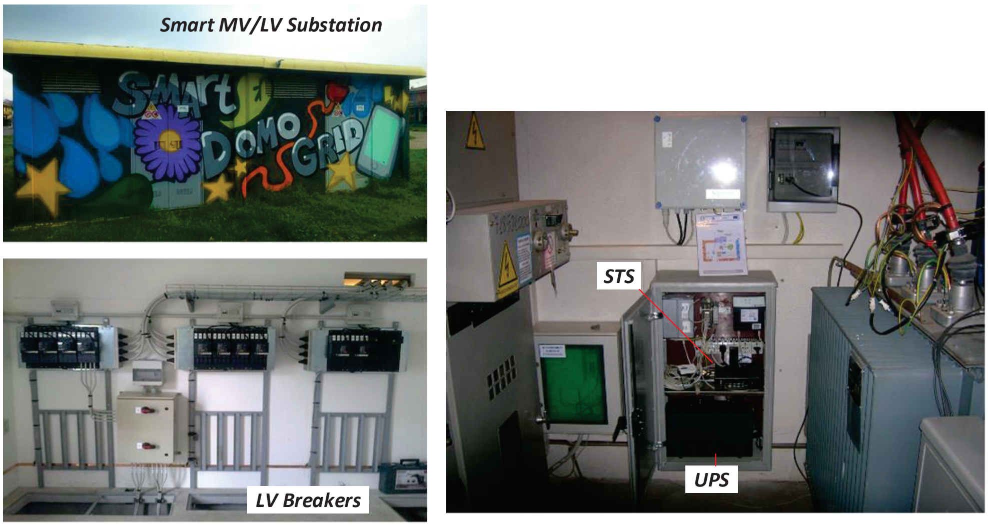

Figure 4.5: *SDG project, Smart MV/LV Substation with STS and LV breakers inside.*

reactive power ($Q_{request}$) by series unit, in order to enable co-operation between series and shunt units.

The DSO control center is driven by DSO and several important decisions are made inside. As it was explained, voltage set point for series unit come from control center and it is sent to the STS and from STS to the Open UPQC series unit. Instead requested reactive power from the series units ($Q_{request}$), follow reverse direction, it comes from series unit to STS and from STS to the DSO control center. The $Q_{request}$ goes to DEMS and DEMS decides how to share the total amount within available shunt units. The allocated reactive power is sent to each shunt unit by it own DEMS and in this way the control loop is completed and series unit reactive power request is provided.

Different functionalities of shunt units can be set by each unit corresponding DEMS through Internet, like; turn ON/OFF the device, peak shaving threshold level and batteries' charging mode. Data and status of each shunt units are also stored in each unit DEMS.

There are different layers for the communication and management through the ICT system. The information is collected in DSO control center and it schedules the incentive plan. Each customer's DEMS receives the scheduling info from DSO control center and since it has all the information from PV forecast service, consumer power consumption, shunt unit status and the PV inverter situation, it manages the load and send incentives to the end user via Graphical User Interface (GUI) application. Finally the end user, locally has control on his appliances and also informations about shunt unit and PV inverter system. Speaking more detail about ICT system is beyond the focus of this thesis since the communication part of the project is done by another

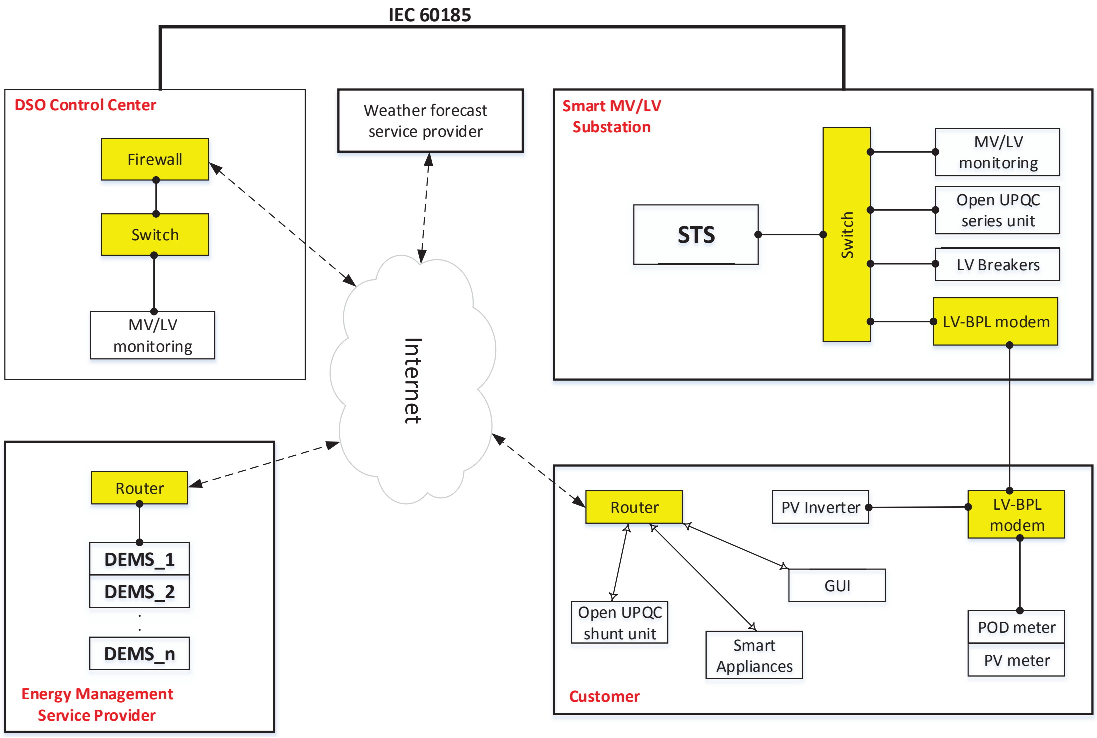

Figure 4.6: *Simplified scheme of the architecture of the project. Data flows for the coordinated regulation actions were depicted.*

research group.

4.2 Test Network Description

The area selected for the SDG project field test is a LV network connected to a MV/LV substation located in the city of Brescia. Scheme of the test area is shown in Figure 4.7. Figure 4.7 highlights customers equipped with a Smart Meter (SM), with a real time measurement capability collecting RMS values: phase voltage, current, active and reactive power (P, Q) and power factor (PF). Data are store in a database located in the secondary substation (STS according to Figure 4.6 as it is described in previous section).

The LV feeders fed by a MV/LV substation are partially equipped with a new smart meter (SM) to monitor in real time the power exchange between the customer and the grid and the power produced by PV panels. This area has been selected because of the high PhotoVoltaic (PV) penetration, which is about 30% of the peak demand and because it is monitored by second generation of smart meters. This grid is composed of eight LV feeders. LV backbones are three-phase, while the connection to the residential customers is single phase. Three types of installations can be found:

- Passive customers, with no PV generation

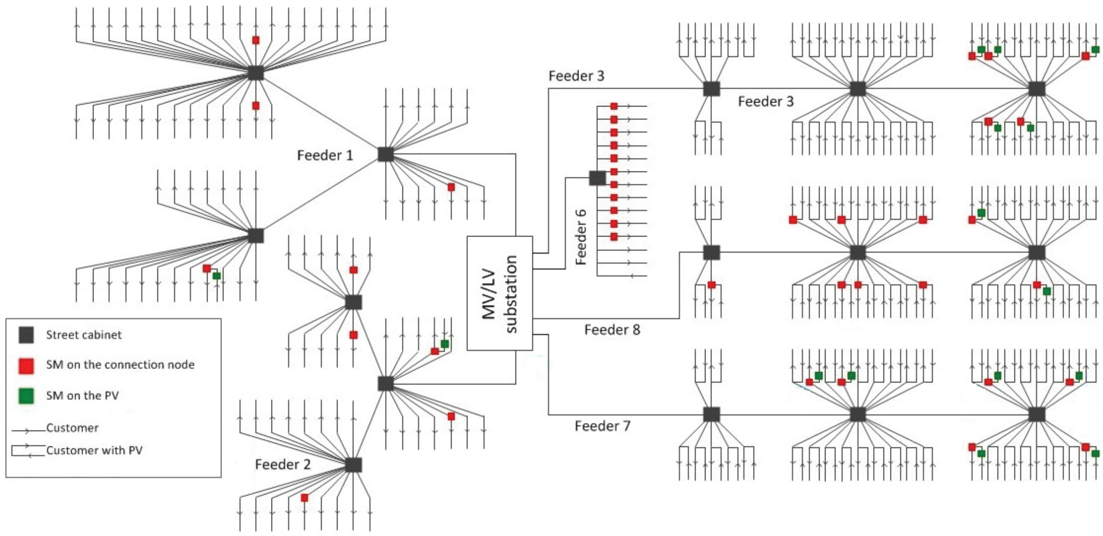

Figure 4.7: *Scheme of the Open UPQC test network - SDG project.*

- Active customers with a PV plant
- Active customers with a PV plant and an Open UPQC shunt unit.

Figure 4.8 focuses on the LV feeder number 7, where the Open UPQC has been installed. 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 indeed, those are not depicted in Figure 4.8.

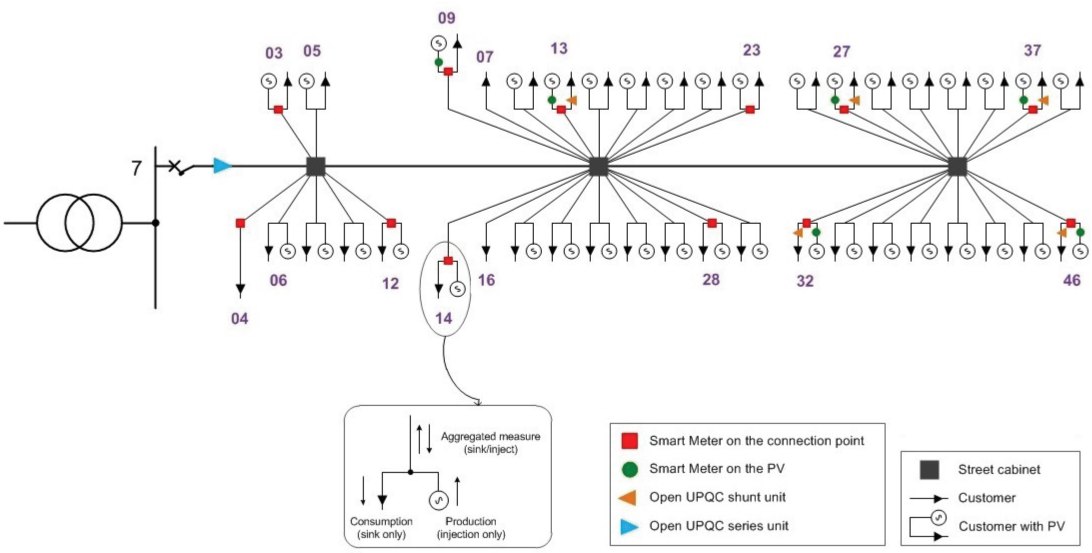

Figure 4.8: *Scheme of feeder 7 of the Open UPQC test network - SDG project.*

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

The size of the Open UPQC series and shunt units are defined after power quality analysis of the area [6], as it is reported in the following.

4.2.1 Test Field Power Quality Analysis

The Open UPQC series unit can deal both with fast voltage events – such as voltage dips/swells – 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 in the STS. 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[2] is depicted in Figure 4.9. It is worth to note that the voltage dips are very short. Open UPQC series unit is designed based on these data.

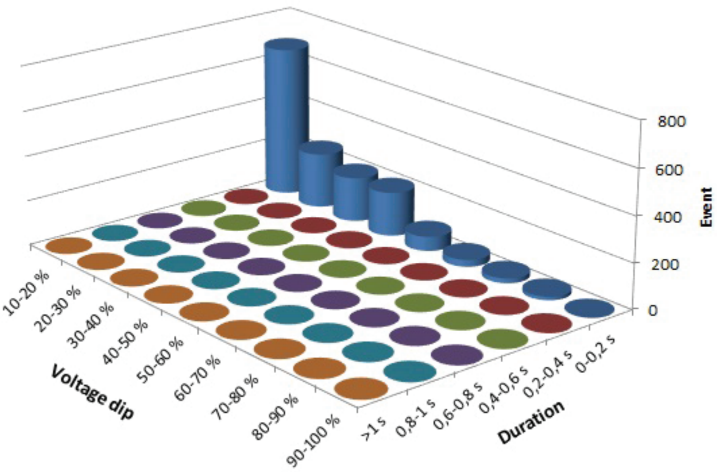

Figure 4.9: *Distribution of voltage dips in the city of Brescia. Data refer to the whole year 2014.*

The LV side – on the other hand – was monitored with the new smart meters described before. The nominal phase to ground voltage is 230V and the system is monitored in order to get statistic reports of standard deviation, min, max and jitter[3] about the voltage of all the feeders under test, grouped per phase. As it can be seen in Table 4.1, even if the voltage is always within the range mandates by the European Standard EN 50160 [58], in some cases it is closer to these lower boundary during the acquisition period.

[2]the minimum value of the RMS expressed as a percentage of the reference voltage
[3]defined as the maximum voltage variation during the observation

Feeder	Phase	Mean (V)	Std (V)	Min (V)	Max (V)	Jitter (V)
FD01	3	228.14	3.91	208	240	34
FD02	1	229.06	3.94	209	241	32
FD02	3	228.28	3.62	211	240	29
FD02	2	231.22	3.60	218	246	28
FD07	2	230.55	3.22	215	242	27
FD03	2	230.60	3.23	216	242	26
FD08	2	230.96	3.10	217	243	26
FD03	3	229.74	3.16	217	242	25
FD08	1	230.93	3.16	216	241	25
FD01	2	230.65	3.29	218	242	24
FD07	3	230.81	3.06	218	241	23
FD03	1	231.59	3.18	218	241	23
FD07	1	230.51	3.26	218	240	22
FD08	3	230.50	2.94	218	240	22
FD06	2	230.77	2.43	222	240	18
FD06	3	230.71	2.49	222	239	17
FD06	3	230.99	2.54	223	240	17

Table 4.1: *Minimum, maximum, mean values, jitter and standard deviation of the voltage measured in the test area, grouped per feeder and per phase.*

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

So the DSO has to manage the voltage on the secondary side of the MV/LV transformer, as shown in Figure 4.10 that reports the measured RMS voltage of six days. As it can be noticed, an abrupt transition from the average value of 223 V to 231 V was logged. This effect was due to the action of the voltage regulator of the on-load tap changer located in the primary substation.

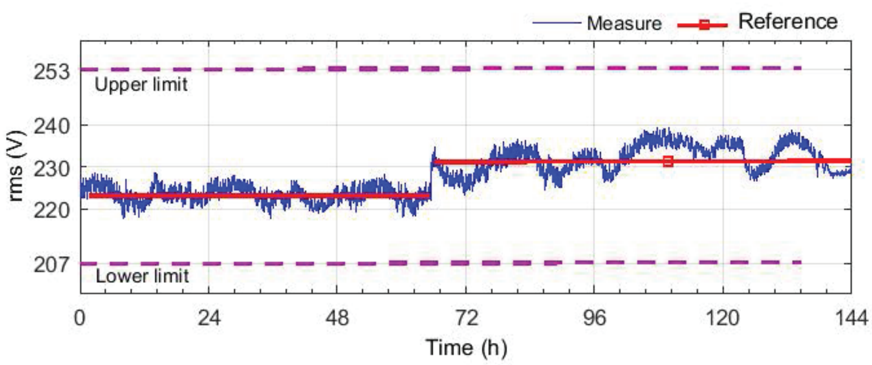

Figure 4.10: *RMS voltage measured on the secondary side of the MV/LV transformer (two samples per min). Data refers to six days 30th June-3rd July 2015.*

Moreover the voltage drop in the line, influences the voltage load as shown in

Figure 4.11 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.

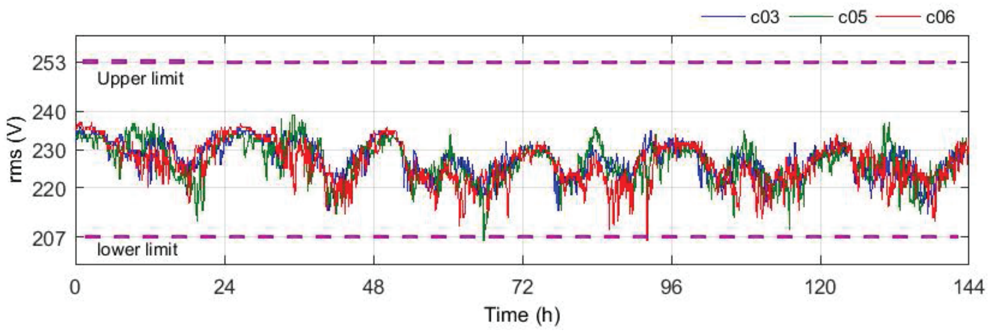

Figure 4.11: *Voltage trend in three different nodes of the LV grid (six samples per hour). Data refers to six days 5-11th Jan., 2015.*

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 Open UPQC shunt and series units. This device can be used to perform specific control related to the LV network needs.

To size Open UPQC shunt unit, it is important to observe the load profile of end users. Figure 4.12 reports the daily mean of domestic customers' load profile, in July 2011. This is therefore, the group of customers to take into account for the sizing of the system.

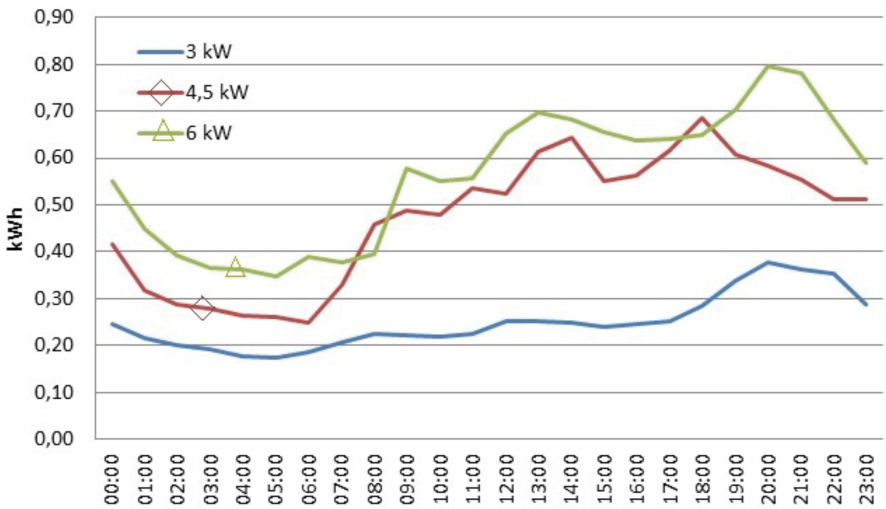

Figure 4.12: *Daily mean of domestic customer's load profile – July 2011.*

As it can be noticed, the average power in all cases, stays below 1kWh even if it should be noted that instantaneous consumption can vary significantly. But, this average load profile is used to design Open UPQC shunt unit size especially the storage system which is one of the most expensive and bulky parts of the shunt unit and need to be selected and sized carefully.

4.2.2 Load Distribution Analysis

The design of the Open UPQC is also based on the customers' load needs. A preliminary analysis was reported in [5], where load curves of the whole city of Brescia were clustered according to the contractual power.

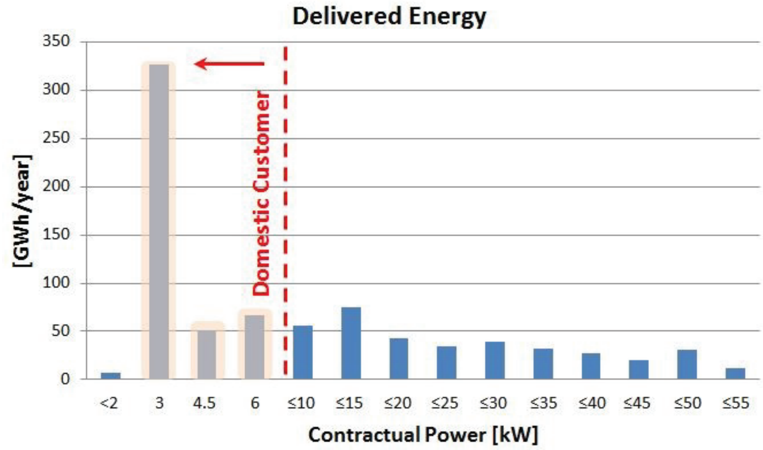

Figure 4.13: *Delivered energy per year as a function of power peak consumption of LV customers.*

Figure 4.13 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 in Italy are usually below 6 kW. This group contains huge number of costumers and covers about the 54% of the all delivered energy. 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.

To assess the economic benefit, a real example in reference to the actual Italian tariffs [24] has been studied, comparing two different customers, with same average power consumption and energy cost but with different contractual power. Installing the Open UPQC shunt unit, with a nominal power of 3 kW and 1.5 kW for first and second users, thus respectively updating the contract at 3 kW for both, a consistent saving is possible. The economic benefits are summarized in Table 4.2. For this evaluation it is assumed that, due to device losses, the power consumption is increased as portion of additional power (10% for the consumer with 4.5 kW initial contractual power, 20% for the consumer with 6 kW initial contractual power). As it can be noticed from Table 4.2, shunt unit installation can introduce considerable economic benefits for customer with both contractual limits 6 and 4.5 kW.

Customer contractual power [kW]	4.5	**6**.0
Open UPQC shunt unit power size [kW]	1.5	3.0
Contractual Power Reduction [kW]	1.50	3.00
Average power consumption [kWh]	440.00	480.00
Total Cost [€]	51.40+VAT	55.80+VAT
Saving [€/year]	**177.12 + VAT**	**174.24 + VAT**

Table 4.2: *Possible energy saving by Open UPQC shunt unit application in LV customers.*

CHAPTER 5

Open UPQC Hardware Design

This chapter introduces the hardware design and specifications of both series and shunt units of Open UPQC. Series unit is like a DVR and the common application for these kind of devices is in MV level or substations with mostly three phase configuration. So, the initial design had been done based on three phase system. In other hand, within LV distribution level and with mostly single phase users as domestic ones, a cost effective and practical design for the series unit is three single phase devices. This configuration can reduce the maximum current on power electronic switches also. Additionally, three single phase configuration will make it possible to realize final three phase system with three single phase units to be able to test Open UPQC final device functionalities both with single phase series unit or a three phase one.

The device is going to be tested in LV network and in LV distribution network where most of the domestic, commercial and some industrial loads are single phase. The shunt units will be installed close to the domestic end users and those need to be designed in single phase configuration.

Therefore, as the controller has been designed, series and shunt units are also designed in single phase configuration although three single phase series units can be joint together to build the three phase series unit. With single phase configuration, Open UPQC can give to the DSO the possibility to move all problematic loads on specific phase of the feeder equipped with the device, reducing installation cost. Therefore, although for series unit the final device can be three phase but it constitutes of three single phase units so, for both series and shunt units single phase devices have been designed and realized.

5.1 Series Unit

In order to respect three phase configuration and also to increase the nominal power of the series unit, as it is mentioned before, instead of a three phase inverter, series unit can be realized by properly coordinated three single phase inverters. Series unit three phase design schema is sketched in Figure 5.1. As it can be noticed, it has been composed of three single phase units. Each unit has its own single phase inverter and coupling transformer. With this solution, although the number of power electronic switches will be increased (12 switches rather than 6), instead it allows to design device at twice power with same current capability of switches, or at nominal power with switches that have half current capability. So, in other word, this configuration can increase the nominal power of the total device.

Each unit has a DC bus realized by the Capacitor Bank modules ($CB_{1,2,3}$). DC bus of all three units are connected to each other to make the DC bus control smoother. As it can be seen form Figure 5.1, each single phase unit has its own Microcontroller (*MC*) although for final three phase schema, one of the *MC*s should be used as master controller in order to manage the synchronization between the units and also DC bus regulation because, at any moment only one inverter shall take care of DC bus control.

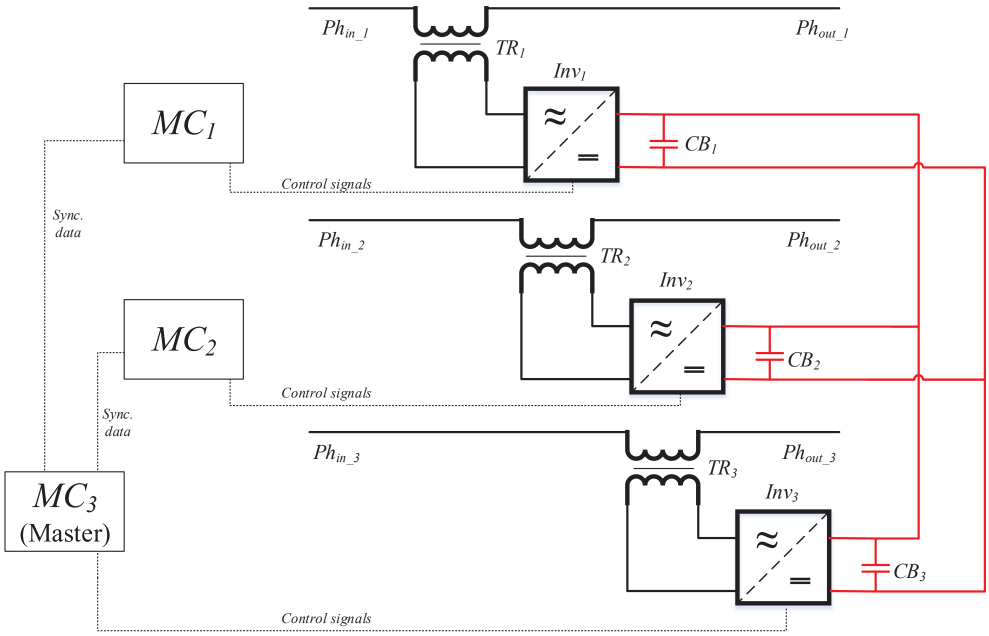

Figure 5.1: *Open UPQC series unit three phase design schema.*

Each phase of the units in Figure 5.1 are realized as a separate single phase units and here a single phase unit design procedure will be addressed. Each unit consists of a coupling Transformer (TR) with the primary circuit connected in series with the LV line and a secondary one connected to the reversible AC/DC power converter. The functionality is like a single-phase self-supported DVC [53, 55] because there is not any storage system to provide active power for DC bus and the DC bus should be controlled by inverter itself. Passive capacitor filters C_f are connected to both primary and secondary sides of the transformer to mitigate switching ripples of the inverter. Full bridge inverter is realized by two IGBT legs (T_1 and T_2), switching inductance (*L*) and set of capacitors as DC bus (Capacitor Bank, CB). The device is equipped with bypass switch system in order to bypass the system in the case of any fault condition on the grid side or failure of the inverter. Inverter control and all other control signals are driven by a Microcontroller (*MC*) which is supplied from a 24V DC by means of a AC/DC power supply. These terminologies for the components will be used through the text. Here the design consideration for each part is introduced in detail and then all the parts are put together to build the final single phase series unit. Single phase series unit parts are listed below and those designation procedure will be reported in the same order.

- Coupling Transformer
- Series Unit Inverter
- DC bus Pre-Charge Circuit
- Microcontroller and its Power Supply
- Internet based Communication
- Bypass Circuit

5.1.1 Coupling Transformer

Figure 5.2 shows the series unit configuration putting in evidence its coupling transformer. I_L is the line or load current which passes through the transformer (*TR*) primary winding and I_{inv} is the series unit inverter current. V_x is the voltage at transformer primary and it is the injected voltage by series unit and V_{inv} is the generated voltage by the inverter. The main responsibility of the coupling transformer is to electrically decouple the power electronics part from the line and avoid direct inverter connection to the power line. The manageable power by converter and current capability of switches are function of the winding turn ratio of the transformer (*TR*). If the transformer is sized with winding turn ratio equal to a and load current flows through primary, according to ampere turns balance, secondary current can be decreased to $1/a$ of nominal value ($I_{inv} = (1/a) \times I_L$). Transformer voltage is directly proportional to the turn ratio therefore, the voltage at secondary will be a times the voltage in primary and using transformer with winding turn ratio equal to a, the inverter voltage is a times the primary voltage ($V_{inv} = a \times V_x$). By this consideration, in the case of short circuit at grid side of TR, between the phase and neutral, as it is depicted in Figure 5.2, all the network voltage supplies the primary of the transformer so, at the secondary of the transformer (inverter side) the voltage will be equal to $a \times V_n$ where V_n is the nominal grid voltage.

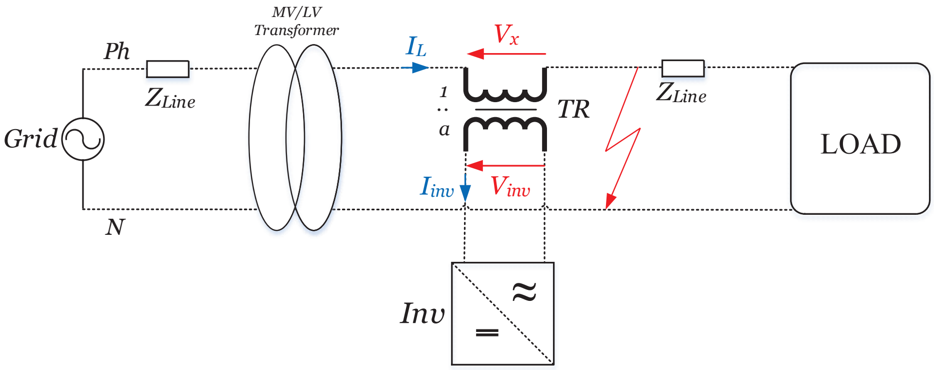

Figure 5.2: *Open UPQC series unit Coupling Transformer within the whole system.*

Principally, a transformer with turn ratio equal to one can carry out decoupling task but with $a = 1$ the inverter current will be in the same rate of the load current and the inverter should inject required compensation voltage. If the a is chosen so high, the current on the inverter IGBTs can be decreased in the cost of voltage increment on inverter side because the inverter needs to generate a times the required voltage at secondary side.

After some economical and technical evaluation, the final solution is designed with a transformer with winding turns ratio, a equal to 1.5. In this configuration, the inverter will be connected to the secondary of the transformer so it needs to generate 1.5 times the required injection voltage instead, the current through the IGBTs can be decreased by the same factor. With this schema of the system, the inverter voltage will be $V_{inv} = 1.5 \times V_x$ and its current will be $I_{inv} = (1/1.5) \times I_L$. So doing, maximum voltage in inverter DC link in the case of fault, will be $1.1 \times V_n \times \sqrt{2} \times 1.5$ and considering $V_n = 230$V it became about 540V.

The nominal power of the transformer is selected according to the total loads on the connected phase. Each single phase line supplies 15 customers and the nominal power of each customer is 4.5 kVA so considering contemporaneity coefficient[1] (*k=0.67*) the overall power became 45 kVA and the coupling transformer is selected to have 50 kVA nominal power, following these procedure.

[1] contemporaneity coefficient, *k*, gives the percentage of the load in network making simultaneous use of electric power.

5.1.2 Series unit Inverter

Figure 5.3 shows the series unit inverter connected to the secondary of the coupling transformer along with its filter capacitors. As it can be noticed, two low-pass filters are connected one at coupling transformer primary side and another one at inverter side (coupling transformer secondary). The inverter is composed of four main important components as those are listed below:

- Inverter DC bus capacitor bank (CB)
- IGBT modules, Power electronics switches (T_1 and T_2)
- Inverter switching inductance (L)
- Inverter output and transformer primary side low-pass filter capacitors (C_f)

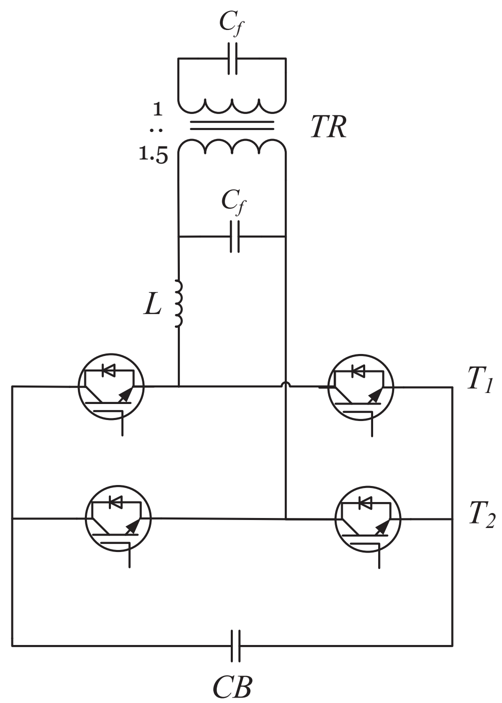

Figure 5.3: *Open UPQC series unit Inverter connected to the secondary of the coupling transformer.*

In the following the design procedure for each components of the series unit inverter is described in detail.

DC Bus Capacitor Bank (CB)

Considering voltage compensation limits and the selected coupling transformer turn ratio, the required voltage on inverter DC bus voltage can be evaluated. Single phase full bridge inverter is a boost type converter, this means the minimum voltage of the DC bus should be kept greater than the peak value of the inverter output voltage which choosing transformer with turn ratio equal to 1.5, should be 1.5 times more that the value on the primary side. Following the opposite path, to provide 200 V injection capability in the network as peak value in primary, the inverter voltage rate will be 1.5×200 = 300V and this can be provided with minimum of about 400 V on DC bus voltage. So, if the DC bus reference is set to 750 V and with variable DC bus voltage control strategy, DC bus voltage can vary between 400-750 V during transient and this stands for exploitable active power during transient and short term compensation. By considering DC bus voltage variation from 750 V to 400 V, the extractable energy from the capacitors, to ensure consistent performance during transient, can be evaluated. The energy inside the capacitor can be obtained by Equation 5.1, [26, 27].

$$E_C = \frac{1}{2} \cdot C \cdot V^2 \tag{5.1}$$

Considering 750 V as set point for series unit DC bus voltage and 400 V as the minimum, the exploitable energy and active power during transient can be calculated by using the energy difference between two voltage levels. Equation 5.2 can be used to find this difference.

$$\Delta E = \frac{1}{2} \cdot C \cdot (V_{max}^2 - V_{min}^2) \tag{5.2}$$

Replacing V_{max} =750V and V_{min} =400V, Energy variation (ΔE) can be computed and considering the relation between energy and active power ($E = P \cdot t$), this energy can be transfered to exploitable active power. In order to design series unit DC bus capacitor, since the control strategy is based on pure reactive power compensation algorithm during regime operation, series unit inverter does not require any active power and the active power is required only during short transient events. For transient events, load nominal power (50 kW) support for 300 ms is considered for series unit DC bus design so, following the reverse path as describe above the energy variation equation can be updated as:

$$\Delta E = P \cdot \Delta t = \frac{1}{2} \cdot C \cdot (V_{max}^2 - V_{min}^2) \tag{5.3}$$

Rewriting this equation for C, will give the minimum required capacitor value.

$$C_{min} = \frac{2 \cdot P \cdot \Delta t}{(V_{max}^2 - V_{min}^2)} \tag{5.4}$$

Replacing the values inside the Equation 5.4 the minimum required capacitance at DC bus can be computed equal to 75 mF.

During the voltage sags compensation, the capacitors are discharged decreasing the DC voltage nevertheless, in the case of over voltage the DC bus will be charged and DC bus voltage will be increased. The maximum voltage on DC bus capacitors is 1000 V (two capacitors with maximum 500 V in series as it will be described further) and 250 V windows is reserved for over voltage events. Again for over voltage events using Equation 5.2 and the designed DC bus capacitor value, 75 mF, the manageable energy and corresponding power and duration can be calculated. Following the same procedure, considering V_{max} =1000V and V_{min} =750V the nominal load power can be managed with chosen capacitor bank for about 300 ms. So, symmetrical up and down window is provided with V_{DC_set} =750V, upper 1000 V and lower 400 V control limits.

Capacitor Banks (CB) are realized by two set of capacitors connected in series in order to increase maximum DC bus voltage capability and indeed several parallel connections to increase overall capacitance. The capacitors with nominal 500 V have been used and for series unit DC bus, two capacitors are used in series, so the overall nominal voltage can be considered 1000 V.

To realize the designed capacitor bank, capacitors with 6800μF are used. Connecting two capacitors in series the overall capacitance became 6800μF/2 = 3400μF and to realize designed 75mF capacitor bank, 22 parallel connection is required.

$$\frac{6800\mu F}{2} \times 22 = 74.8\ mF \tag{5.5}$$

One module of the *CB* is realized as it is shown in Figure 5.4. Each module as it is shown in Figure 5.4 and with $C_{1,2,..,10}$ =6800μF has about 17 mF overall capacitance and each single phase unit has four of these *CB*s and each bank consists of 10 capacitors with 6800μF. In order to balance DC bus voltage and suppress voltage ripples due to the inverter switching, the Central Points (*C.P.*) are connected together and in final three phase unit, the *C.P.* can be connected to the Neutral.

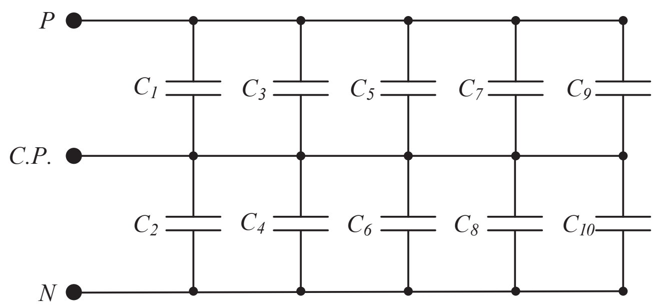

Figure 5.4: *Open UPQC series unit capacitor bank (CB), one module realization.*

As it was mentioned, the total CB can be realized by 22 parallel connections. Putting four of Figure 5.4 modules in parallel means 20 parallel connections and each inverter has two internal parallel connections (four 6800 μF capacitors in series and parallel connection). Therefore total 22 parallel connection can be reached and DC bus overall capacity is 74.8 mF following its design procedure (75 mF).

IGBT Modules (T_1 and T_2)

Power electronic switches are the most important component of an inverter so those need to be designed carefully. By doing the same analysis, as it has been done for voltage, for the current we can observe that the nominal current on inverter side is (1/1.5) times the load current and this will decrease stress and losses on IGBTs and consequently the required heatsinks size can be reduced as well.

As it has been mentioned, on the test feeder there are 15 customers with contractual power of 4.5 kVA therefore, the nominal RMS current on the feeder, considering the connected nominal load power on the test phase of the feeder and contemporaneity coefficient *k* equal to 0.75, can be computed as it is reported in Equation 5.6.

$$I_N = \frac{0.75 \times 4500VA \times 15}{230V} = 220A \tag{5.6}$$

Consequently the peak value is around 305 A. This nominal current on transformer side shall be divided by 1.5 so, at inverter side this nominal peak current is about 205 A. In order to guarantee series unit safe operation and considering switching ripples, the series unit inverter IGBTs has been chosen with 400 A nominal current ratio. This selection will guarantee series unit safe operation during transient events.

Switching Inductance (L)

The inverter switching inductance design procedure depends on several parameters as; Inverter nominal power, inverter DC bus voltage level and inverter switching frequency. The minimum inductance value can be designed using the Equation 5.7 [11].

$$L = \frac{V_{DC}}{4 \cdot f_{sw} \cdot \Delta i_L} \tag{5.7}$$

In Equation 5.7, V_{DC} is the average voltage on inverter DC bus. f_{sw} is the switching frequency of the inverter and Δi_L is the maximum current ripple on the inductance which is usually considered as 20% of the inverter nominal peak current. In order to design series unit inverter switching inductance, in Equation 5.7, the average voltage on DC bus (V_{DC}) is considered around 600 V, while the maximum inductance current ripple and switching frequency can be set according to the device nominal power. The switching frequency depends on system rating power because switching losses increases by increasing the power level so, it can be considered function of the system nominal power as well. To minimize the switching losses, the switching frequency shall be set around 4-5 kHz and the Δi_L can be replaced with 20% of the nominal peak current on inverter side (40A). Therefore the minimum inductance value can be calculated as about 1 mH. For series unit inverter switching inductance, since its power ratio is pretty high, the calculated minimum inductance value is selected. Indeed, the nominal current of the selected inductance should be about nominal peak current in order to avoid inductance overload and saturation issues. Considering the nominal current in inverter side, about 205 A, an inductance with nominal current equal to 300 A is chosen to be able to tolerate switching ripples and also to guarantee safe and proper operation during transient condition which the device may absorb higher current. Therefore, the final switching inductance is selected as 300 A, 1 mH inductance.

Filter Capacitors (C_f)

As it is shown in Figure 5.3, in order to suppress inverter switching ripples, it is necessary to design proper low-pass filters for inverter out put at coupling transformer secondary and also coupling transformer primary side. This filters are meant to filter out high frequency ripples of the inverter current. This filter design is function of inverter switching frequency because the generated disturbances are in order or multiple of switching frequency. Series unit switching frequency is set to 4 kHz so, the low-pass filter should be designed to be able to cut frequencies below this switching frequency. As it is shown in Figure 5.5, if the switching inductance and coupling transformer equivalent resistances are considered in series (R), combination of the C_f and this resistance creates a first order low-pass filter which its transfer function is reported in Equation 5.8 where "s" stands for Laplace transform variable.

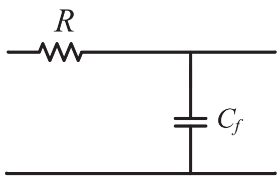

Figure 5.5: *C_f low-pass filter equivalent circuit.*

$$H(s) = \frac{1}{R \cdot C_f \cdot s + 1} \tag{5.8}$$

Considering this transfer function, and since a simple first order low-pass filter with cut-off frequency below 4 kHz is required, the C_f value can be designed. For this evaluation the R resistance value is set to one in order to relax its effect on filter design procedure even thought, one ohm is a rational estimation about overall coupling transformer and rest of the circuit's equivalent resistance. Choosing the C_f the transfer function can be driven and the bode diagram can be drawn as it is shown in Figure 5.6 for four different C_f values.

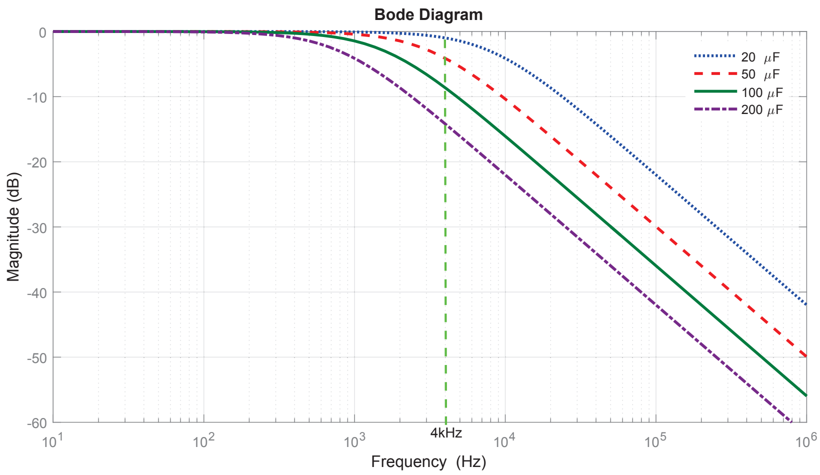

Figure 5.6: *Series unit passive low-pass filter Bode diagram.*

As it can be seen from Figure 5.6 Bode diagram, for $C_f = 20\mu$F and $C_f = 50\mu$F the cut-off frequency is close to the inverter switching frequency (4 kHz). The filter with $C_f = 100\mu$F shows acceptable performance to properly filter out switching ripples and it is enough far from network nominal frequency (50 Hz) however the low-pass filter characteristic in the case when $C_f = 200\mu$F can not be used because the cut-off frequency is very close to the network voltage frequency. With above evaluation, low-pass filter is designed with $C_f = 100\mu$F and it is connected at both primary and secondary sides of coupling transformer.

5.1.3 DC Bus Pre-Charge Circuit

DC bus capacitor bank need to be charged before starting the series unit. A simple diode bridge can be used for this purpose, however with nominal network voltage (230 V), the rectifier DC voltage is equal to ac side voltage peak value which is about 325 V and as it is reported in inverter DC bus design section, this voltage is below series unit inverter DC bus minimum set value so, this voltage is not sufficient for series unit to start its operation. Therefore, a power transformer with turn ratio equal to 2 is used which is able to double the voltage at its secondary so the rectifier DC side voltage can be reached to about 650 V. The DC bus pre-charge circuit schema is shown in Figure 5.7. The resistor R is used in series to the circuit in order to limit high instantaneous initial current with completely discharged capacitors. A circuit breaker B_1 is used in order to disconnect the circuit after charging the DC bus and avoid possible power flow from grid to the inverter. Although the DC bus set value

(750 V) is higher than the rectifier DC bus voltage (650 V) and rectifier diode bridge will automatically block this power flow.

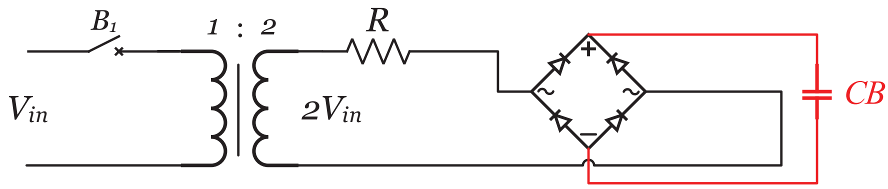

Figure 5.7: *Series unit DC bus Pre-Charge circuit schema.*

5.1.4 Microcontroller and its Power Supply

According to Open UPQC series unit controller design in Chapter 3, to manage one single phase unit, four voltages and two currents measurement is required so a Microcontroller (MC) with at least six Analog to Digital Conversion (ADC) ports is required for control purposes. Two PWM ports are needed to run the inverter IGBT modules (one port for each leg). Also several contactors need to be managed by MC. For communication purpose, the MC need to have Modbus connection port. Taking into account all the requirements, Texas Instrument (TI) *TMS320F28335* Microcontroller is selected as main MC cpu.

In order to supply the series unit MC, an AC/DC power supply is used with 24V DC at its output as it is shown in Figure 5.8. A 24V, 3A power supply is used to supply the MC and also provide required DC voltage for the used contactors inside the unit. All the control logic has been programmed using C++ programming language within the selected *TMS320F28335* main Microcontroller and the gate signals for IGBT modules and rest of the control signals are managed by this MC.

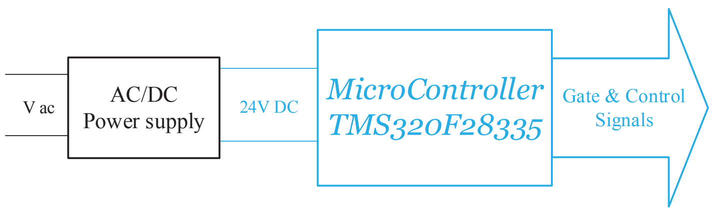

Figure 5.8: *Series unit Microcontroller and its power supply.*

5.1.5 Internet based Communication

For communication purpose, a Raspberry Pi embedded PC is integrated into series unit. The Raspberry Pi speaks through IEC 61850 communication protocol with rest of the communication system, the commands are transferred to the unit Microcontroller by means of serial port and Modbus protocol. The series unit microcontroller send back its response and information by means of Modbus using this communication means. Figure 5.9 shows the components of these communication.

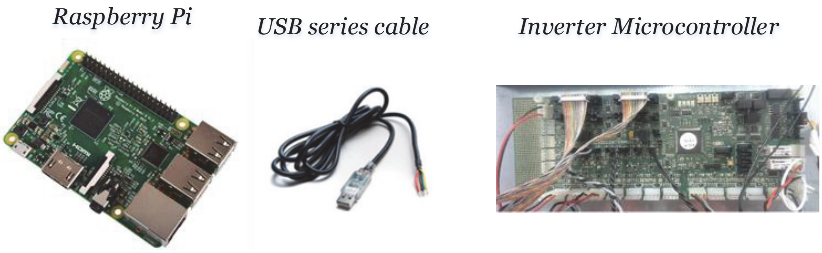

Figure 5.9: *Communication between series unit through IEC 61850 protocol.*

Table 5.1 shows the list of commands that STS can send to the series unit and list of data that series unit send back to the STS as part of communication system. Series unit has the possibility to receive V_{ref} (PCC reference voltage) from STS and it transfers back its information as listed in Table 5.1. V_{PCC} is the voltage that series unit measures at its output terminals. V_{ref} is the reference voltage that series unit follows and it can be the same as the command that it received from STS or not because as it has been explained in Chapter 2 the series unit can touch its upper or lower operation limits and in that cases, it can update its reference voltage. I_L is the line current which passes through the line where the series unit is connected. V_s is the grid voltage at input terminal of the series unit. V_x is the series unit injected voltage. All the communicated voltage and currents are the RMS values. Finally γ is the phase difference between V_{PCC} and I_L likewise θ is the phase difference between V_s and I_L.

Data from series unit to STS	Command from STS to series unit
V_{PCC} voltage, RMS	–
V_{ref} voltage, RMS	V_{ref} voltage, RMS
I_L current, RMS	–
V_s voltage, RMS	–
V_x voltage, RMS	–
γ phase, degree	–
θ phase, degree	–

Table 5.1: *Series unit communication data and command signal list.*

Series unit uses received command inside its controller instead all the data from series unit to the STS are stored for further analysis purpose.

5.1.6 Bypass Circuit

The Open UPQC series unit is equipped with a bypass switch in order to automatically bypass the device in emergency conditions. For any reason if the series unit inverter does not operate properly or goes to fault status, since the device is connected in series to the load, all the load current will pass through the series unit coupling transformer and it will cause considerable voltage drop on series unit and this will affect load voltage deeply. So, the bypass switch will guarantee trustable voltage profile for the load during series unit inverter malfunction.

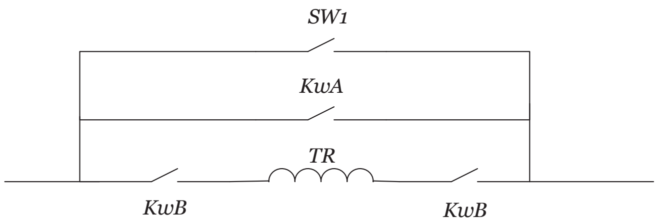

Figure 5.10: *Open UPQC series unit bypass switch design, power circuit connection.*

The series unit bypass switch power circuit connection is shown in Figure 5.10. $SW1$ is a manual switch for emergency cases instead, KwA and KwB are automatic controllable switches. The control circuit is designed in order to manage KwA and KwB properly as it is shown in Figure 5.11 (a) and (b) where series unit bypass switch control circuit and its electrical connection are shown respectively.

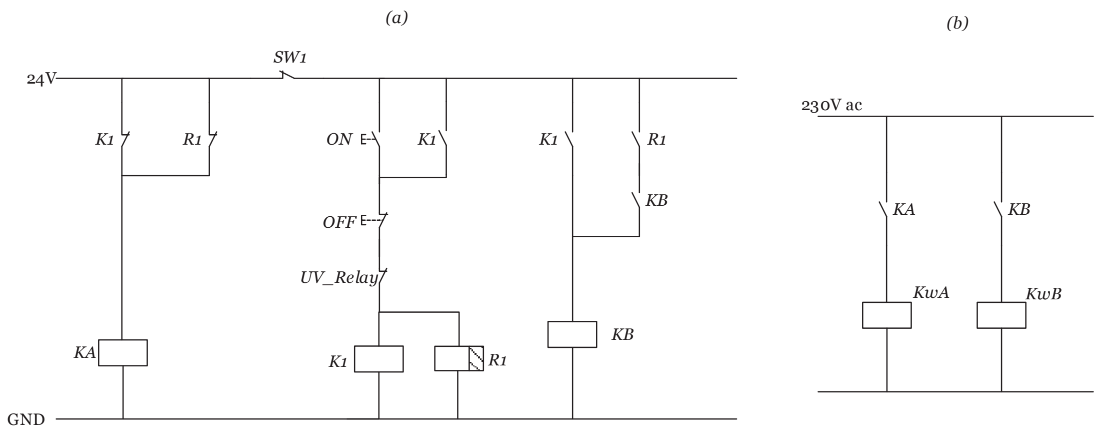

Figure 5.11: *Open UPQC series unit bypass switch design, (a) control circuit, (b) electrical connection.*

KA and KB are corresponding contactors to derive KwA and KwB respectively as it is shown in Figure 5.11 (b). $K1$ is a contactor, $R1$ is a relay with delay and UV_Relay is a *Under Voltage* relay which can detect under voltage and automatically send series unit in bypass mode. ON and OFF are push buttons to manage the bypass circuit.

From Figure 5.11(a), while the device is bypassed by manual switch ($SW1$), its auxiliary normally closed contact is open and disconnects right side of the control circuit and it is not possible to manage the bypass circuit with push buttons. The KA

is supplied before the $SW1$ auxiliary contact so, the KwA is closed in this situation.

When the manual switch is open, its auxiliary contact is closed, so it is possible to manage the bypass circuit by push buttons. Turning ON and turning OFF operations are explained below.

Turning ON

Turning on the bypass circuit means to put the series unit in online mode while it was bypassed. Therefore the initial condition for this operation is:

- KwBs open
- KwA close

Therefore, for any reason the series unit was bypassed and if the fault is removed and device was ready, by pushing the ON button the system can go to online condition. Pushing the ON button will powered $K1$ and $R1$, so KB will be commanded immediately and then KwB will be closed and for a short period (depends on $R1$ delay which in real test field is set to about 100 ms) both KwA and KwB will be closed. In this short period the inverter terminal voltage should be set to zero. After $R1$ delay, the KwA will be opened and series unit will be connected series to the line.

Turning OFF

Three possible reasons can bypass the series unit; 1) UV_Relay operation, 2) pushing OFF button and 3) closing manual bypass $SW1$ which will open its auxiliary contact. All actions has the same effect since the signals are in series in control circuit, Figure 5.11 (a). In this condition $K1$ and $R1$ will be disconnected so, KwA will be commanded immediately but KB is not disconnected due to $R1$. So, again for a short period due to $R1$, both KwA and KwB are close. By means of auxiliary contact, series unit inverter microcontroller senses this condition and set its injected voltage to zero. After $R1$ delay, the KwB will be commanded to open the circuit so, the device will go to bypass mode.

It should be noted that, opening the KwB breakers, the series unit microcontroller will loss the voltage on the series unit terminals. The series unit inverter microcontroller is programmed to go to idle condition if it lost its input terminal voltage measure. In this idle condition, it does nothing and waits the grid side voltage measurement in order to restart its normal operation.

5.1.7 Series Unit Design Parameters

After explaining all the series unit components design procedure, it is time to put together all the elements and build up single phase series unit. The Open UPQC series unit simplified single phase schema is shown in Figure 5.12 and Table 5.2 shows list of its components with detail information. Figure 5.12 represents major components, since the detail explanation of each part is introduced at their own specific section. Coupling transformer primary is connected series to the line, at the secondary of the coupling transformer the inverter is connected as it was explained before. The inverter DC bus pre-charge circuit is meant to charge the DC bus before inverter start up. Microcontroller is the device's main brain and it is supplied by means of a AC/DC power supply and finally as it is explained in detail, the device is equipped with bypass switch in order to bypass the series unit in the case of any interruption at main voltage or series unit inverter fault. Table 5.2 presents one individual capacitor specification used in capacitor bank. As it is reported, this is one capacitor which is used to realize a unit as it is shown in Figure 5.4 and finally to build the total capacitor bank (CB).

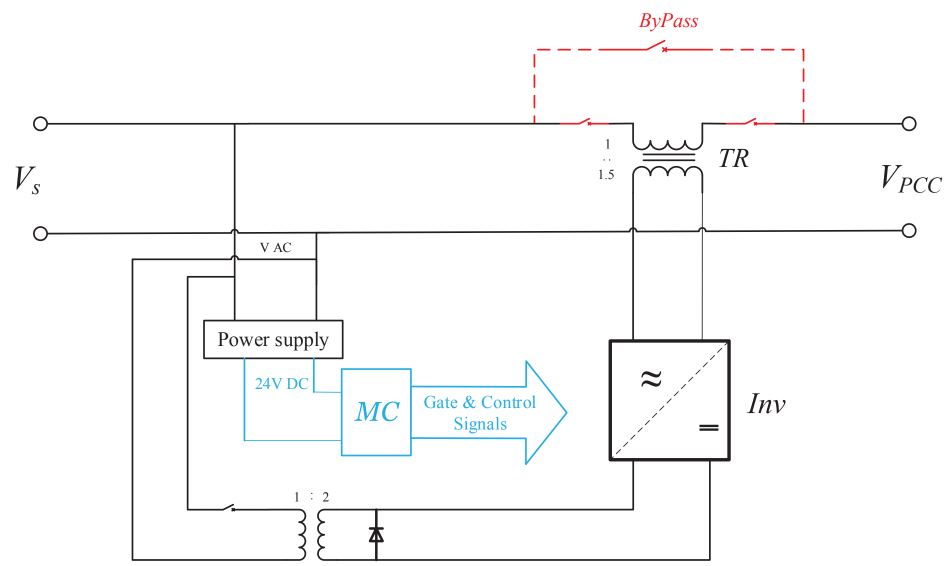

Figure 5.12: *Open UPQC series unit single phase schema.*

symbol	Object	Specification
T_1, T_2	IGBT modules	SKM400GB12T4, 400 A, 1200 V
TR	Coupling transformer	Turn ration 1.5, nominal power 50 kVA
C_n	DC bus capacitors	AYX-HR, electrolyte 6800 μF, 500 V
CB	Total inverter DC bus	$(C_n/2) \times 22$ = 74.8 mF, 50 kW - 300 ms
L	Coupling inductance	1 mH, 300 A
f_{sw}	Inverter switching frequency	4 kHz
C_f	Passive filter capacitor	100 μF, 480 V ac
MC	Microcontroller	TI, TMS320F28335 cpu
IT	Internet communication module	Raspberry Pi

Table 5.2: *Single-phase series unit components parameters.*

Indeed Figure 5.13 depicts the series unit single phase realized prototype putting in evidence each components. It should be noted that the capacitor bank is mounted behind the front plate and those are not visible in Figure 5.13 and also bypass switch and all its relevant control circuit is realize in another cabinet not included in Figure 5.13. Similar to microcontroller power supply, the Raspberry Pi power supply adapter is supplied form main grid as it can be seen from Figure 5.13.

As it can be seen from Figure 5.13, the heavy and bulky parts of the unit are; switching inductance (*L*), coupling transformer (*TR*) and also two missing parts in Figure 5.13 capacitor bank (*CB*) and bypass switch. This study is meant to demonstrate the device performance within Smart Grid and it was not focused to optimize the prototype component design however, with proper design consideration the device weight and cost can be optimized.

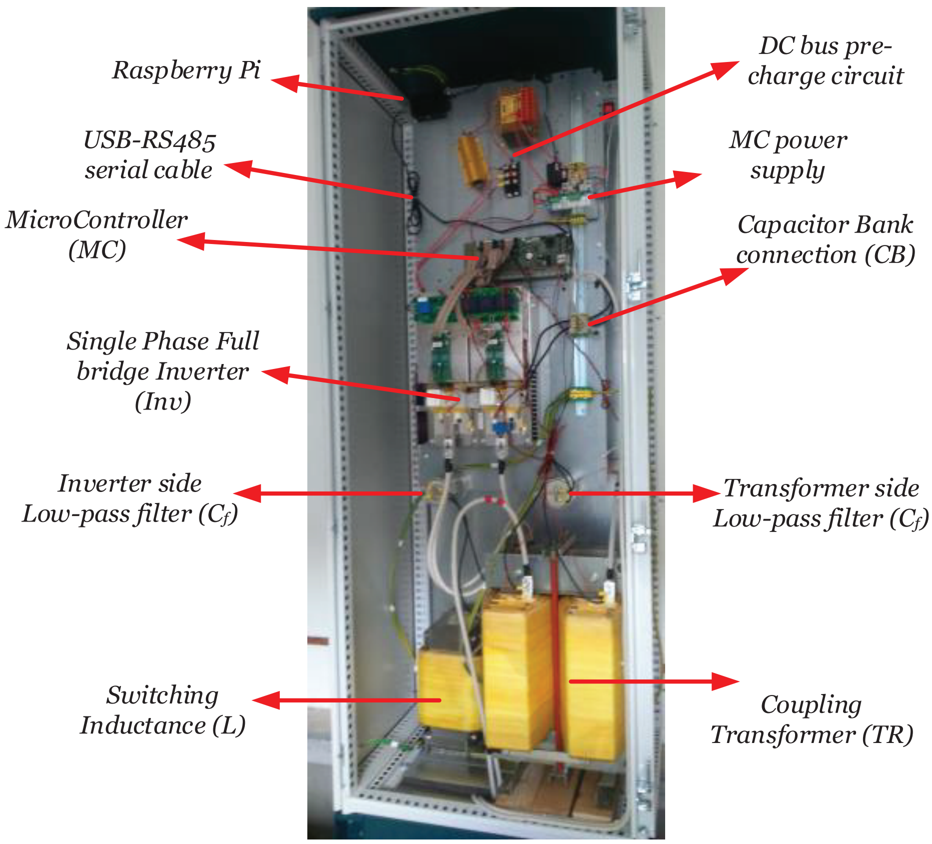

Figure 5.13: *Open UPQC series unit single phase realized unit.*

5.2 Shunt Unit

Open UPQC shunt unit is realized as a single phase device because it will be connected in front end of customer house which has single phase connection. Almost all the design parameters of the shunt unit are tied up together and those are function of each other. Changing one parameter can change all the design values. The usual practice for this kind of application is to set/select one parameter in desired value and find the other parameters accordingly.

Principally shunt unit is a parallel connected device, but it has the capability to disconnect its load from the grid and supply it in *Island* operation mode so it needs a fast and reliable switch series connected on the way of the load so, it is equipped with a *Static Switch* (SS). It equipped with battery set to supply the load in *Island* operation mode so, a bidirectional single phase inverter and an interface chopper leg is used to manage the battery set. Shunt unit is composed of several parts and similar to the series unit, each single part design procedure will be described in this section. Shunt unit most important components can be listed as below:

- Static Switch
- Shunt Unit Inverter
- DC bus Pre-Charge Circuit
- Chopper Leg
- Battery set
- Microcontroller and its Power Supply
- Internet based Communication
- Connection plug and Bypass switch

Although all the houses inside the project has 4.5 kVA contractual power, the shunt unit is designed with 3 kVA rating power because its main responsibility is to work as peak shaving device and also giving other ancillary services to the grid and connected load. Shunt unit only in *Island* operation mode will supply all the loads and during this operation mode the end user needs to be aware of its consumption in order not to overload the shunt unit.

So, shunt unit, according to above consideration, has been designed as a 3 kVA rated power device even if it is capable to work for few seconds (2s) till 18 kW, to guarantee the right short circuit protection current by the breakers. After this brief description on overall device size and its components, the design and selection criteria on main parts are discussed in detail in the following sections.

5.2.1 Static Switch (SS)

As it was explained in Chapter 3, in order to provide fast response to network failures and guarantee safe operation mode for shunt unit and continuity to end user, instead of normal electromechanical breaker, a Static Switch (SS) is used in front end of shunt unit. Which in *Online* operation mode will connect the shunt unit parallel to the grid since all the load power pass through it. Before this SS, the Contactor_1 is placed in order to guarantee the system complete disconnection from grid in *Island* operation mode. Figure 5.14 presents this contractor and SS configuration. The contactor is placed on the way of both phase and neutral cables. During *Online* operation mode, in the case of any event, both contactor and SS will be managed by Microcontroller to open the circuit. The SS due to its intrinsic will react faster and decouple the load from the grid. Instead Contactor_1 because of its intrinsic electromechanical delay, will react slower but will disconnect both phase and neutral and completely decouples the load to the main.

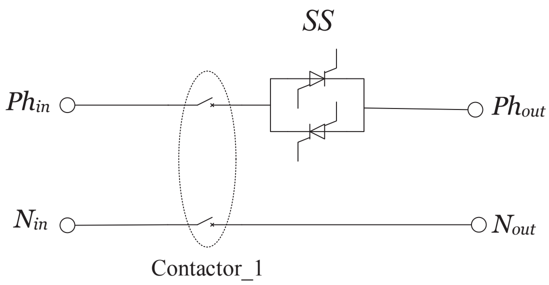

Figure 5.14: *Open UPQC shunt unit Static Switch connection schema.*

SS is on the way of the load during *Online* operation mode and all the load power passes through it. Therefore, the Static Switch is selected according to the load's rating power which is 4.5 kVA. For the continuous operation, load rating current RMS value considering 4.5 kVA as rating load power and nominal voltage 230 V, can be computed and it is around 20 A. The static switch is over rated to be able to carry switching ripples and 40 A continuous operated switch is chosen. TY 40A 1200V SKKT 42 has been used as *SS* for Open UPQC shunt unit.

SS is a solid state switch and it needs gate signals to start operation. Practically with about minimum 2 A current once it was triggered, it would start operation and it will continue to conduct until the current became zero (next zero crossing). Therefore, SS either needs continuous gate signals or gate signal at zero crossing vicinities. This switching device will introduce losses to the the device especially because it is connected in front end of the load and all the load current goes through it so, its losses is proportional to the load consumption.

5.2.2 Shunt Unit Inverter

Shunt unit inverter is a full bridge inverter and as it is shown in Figure 5.15, it consists of power electronic switches (IGBT modules), T_1 and T_2, switching inductance,

L_{ac}, DC bus capacitor where the total capacitor is represented by C_T and inverter ac terminal passive filter capacitors, C_f in order to suppress switching ripples at inverter output terminal voltage. Each component design will be addressed in detail in the next.

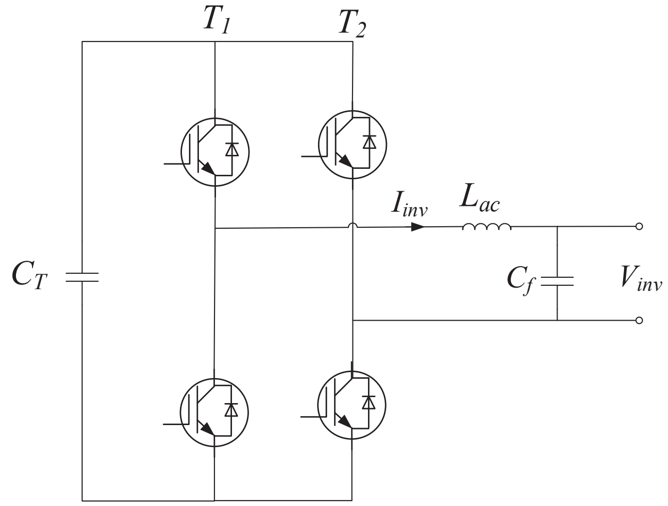

Figure 5.15: *Open UPQC shunt unit inverter schema.*

DC Bus Capacitor (C_T)

Shunt unit inverter is a boost type converter so, the DC bus capacitor voltage should be kept higher than ac terminal voltage peak value which in the case of shunt unit, is the network voltage. Considering network nominal voltage (230 V) the peak value became around 325 V and inverter DC bus voltage needs to have higher voltage level. Values about the ac terminal peak value (325 V) might send the inverter to over modulation mode so, it is better to keep DC bus voltage not close to the margin but with acceptable window higher than this peak value. Gird voltage according to standard can vary between $\pm$10% nominal value (V_n) so considering the upper limits (1.1$\times$ 230 $\times$ 1.41=357V) the DC bus shall be set to 1.1 times this maximum peak value which became about 390 V. Shun unit inverter DC bus voltage is regulated to around 400 V. Therefore as DC bus capacitor, electrolyte 500 V capacitors is used but apart its voltage ratio the capacitance should be designed properly.

The shunt unit inverter DC bus will be regulated by inverter, absorbing power from the grid, or by the chopper leg, discharging the energy inside battery set. So, practically the DC bus capacitor voltage is controlled at any moments however the capacitance should be enough in order to first of all suppress DC bus voltage fluctuations and second, to avoid high voltage drop during transients. Considering $\pm$10% voltage variation as acceptable shunt unit inverter DC bus voltage variation, the DC bus capacitance value can be designed. Considering Equation 5.9 the exploitable energy can be computed setting V_{max} and V_{min}. Using the relation between energy and power ($E = P \cdot t$) and setting nominal device power (3 kW) for one period as required exploitable power, the required energy and consequently capacitor value can be calculated by this equation.

$$\Delta E = \frac{1}{2} \cdot C \cdot (V_{max}^2 - V_{min}^2) \tag{5.9}$$

Following the same procedure as it has been done for series unit and using Equation 5.9 and 5.4, the DC link capacitor can be designed. In this case the Δt is considered five fundamental periods, 100 ms and the deliverable power, P, is equal to device nominal power. Replacing V_{max} with 10% more 440V and V_{min} with set value, 400V the required capacior value can be found. Doing so, the required minimum capacitor can be calculated to about 20 mF.

$$C_{min} = \frac{2 \times 3kW \times 100ms}{440^2 - 400^2} = 17.8mF \tag{5.10}$$

Using the same capacitors, those have been used to realize series unit inverter DC bus capacitor bank (6800 μF), to realize shunt unit inverter DC bus overall capacitor (C_T), the required value can be reached by putting three single capacitors in parallel. So, the shunt unit inverter DC bus capacitor is realized as it is shown in Figure 5.16 putting three capacitors ($C_{1,2,3}$) in parallel. Following this procedure, the total realized DC bus capacitor is equal to C_T =3× 6800μF =20.4mF.

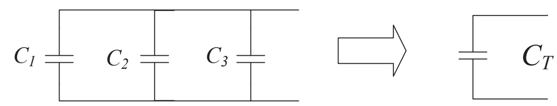

Figure 5.16: *Open UPQC shunt unit inverter DC bus capacitor realization.*

IGBT Modules (T_1 and T_2)

Inverter power electronic switches selection is one of the crucial part of inverter design procedure because the power electronic switches, if those did not designed carefully, can be the most problematic part of the device. Shunt unit IGBT modules have been designed considering the unit rating power. As it was mentioned, device nominal power is 3 kVA, so the nominal peak current is around 20 A. However the device is designed to be able to tolerate up to 18 kVA power during fault and transients (peak current 110A) in order to convey absorbed current before breaker functioning. Principally the power electronic switches shall be chosen to be able to tolerate this current however, switching ripples and possible transient instantaneous peak current need to be taken into account as well. Considering switching ripples and initial starting or inrush currents, the shunt unit IGBT modules are chosen to have 195 A nominal current. Shunt unit IGBTs are over rated in order to guarantee safe operation during its normal operation and also during its several transients events.

Switching Inductance (L)

The shunt unit switching inductance selection is performed considering Equation 5.7. For the shunt unit since its power ratio is much lower than series unit, the switching frequency (f_{sw}) is set to 20 kHz. DC bus voltage, as it was explained, is controlled around 400 V. Therefore, setting the current ripples maximum to 25% of the device nominal power (Δi_L = 0.25× 20A=5A) the minimum value for inverter switching inductance can be computed as:

$$L_{min} = \frac{400V}{4 \times 20kHz \times 5A} = 1mH \tag{5.11}$$

Therefore the minimum required inductance value is about 1 mH. Higher inductance values will decrease switching ripples in cost of increasing the losses therefore the optimum selection in this case to decrease shunt unit losses can be 1 mH. The inductance rating current is also important because it determines its volume and weight. The shunt unit is meant to work mostly in *Online* operation mode so normally its operating power is less than the connected load nominal power however, in *Island* operation mode all the load will be supplied by shunt unit so, inductance rating current shall be designed according to load nominal power, 4.5 kVA. The load nominal peak current is about 27 A so, shunt unit switching inductance is designed as 1 mH, 30 A in order to guarantee proper functioning and avoid inductance over load and saturation problems.

Filter Capacitors C_f

Shunt unit inverter ac side terminal requires a low-pass filter in order to filter out switching ripples, same as series unit inverter. So the shunt unit inverter as it is shown in Figure 5.15 is equipped with C_f low-pass filter at its ac side terminal. This Capacitor's value needs to be designed properly in order to have desired cut-off frequency. C_f and circuit resistance create a low-pass filter. The equivalent circuit and its transfer function is as those are reported in Figure 5.5 and Equation 5.8. In the case of shunt unit, the inverter switching frequency is 20 kHz so, the low-pass filter need to filter out ripples due to this switching frequency and principally the cut-off frequency needs to be below 20 kHz. Figure 5.17 shows frequency responses of filter with different C_f values with fixed R =1Ω in order to relax its effect.

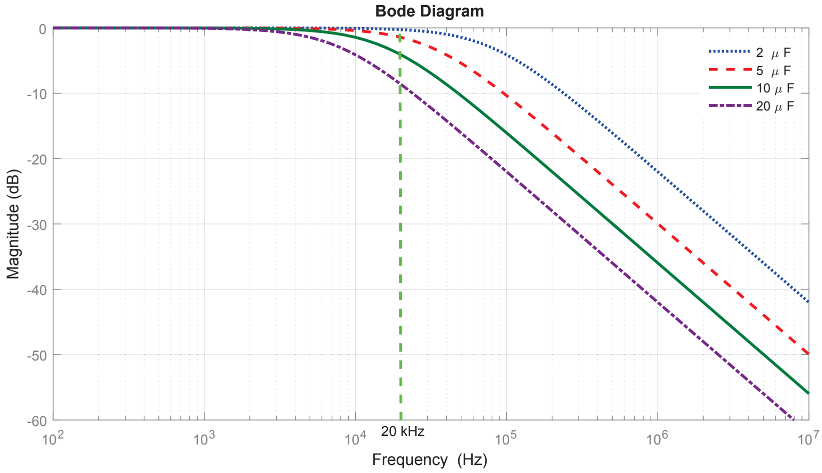

Figure 5.17: *Shunt unit low-pass filter Bode diagram.*

From Figure 5.17 it can be understood that increasing C_f moves the cut-off frequency to the left and this can improve filter performance however, higher capacitance means higher cost and bulky components. A trade off has been done in order to choose shunt unit passive filter and according to Figure 5.17, a 10 μF, 400V capacitor has been selected as passive filter which, as it can be shown in Figure 5.17, can filter out ripples due to inverter switching and its voltage ratio is selected considering inverter ac terminal nominal voltage which is the same as the network nominal value (230 V - RMS).

5.2.3 DC Bus Pre-charge Circuit

Shunt unit inverter is a parallel connected device and the voltage on its ac side terminal is imposed by grid and it is equal to the grid voltage. Once the shunt unit is connected to the grid by means of IGBTs' anti-parallel diode, the inverter circuit as it is shown in Figure 5.18, became a diode bridge between ac terminal and DC bus capacitors. During starting and if the DC bus capacitors were completely dis-charged, the circuit may absorb high instantaneous initial current which may damage the IGBT modules anti-parallel diode and also DC bus capacitors.

In order to avoid this problem, as it is shown in Figure 5.18, resistor R_0 is connected in series to the inverter during device starting state to limit the initial charging current of the inverter DC bus capacitor (C_T). Resistor R_0 is meant to limit initial DC bus charge current and protect DC bus capacitors and IGBT modules. Practically by means of diode bridge which is highlighted in Figure 5.18, the DC bus can be charged till network peak voltage (about 325 V). Once the DC bus capacitor voltage reached to its acceptable range (above 300V), the resistor R_0 is bypassed by Contactor_2.

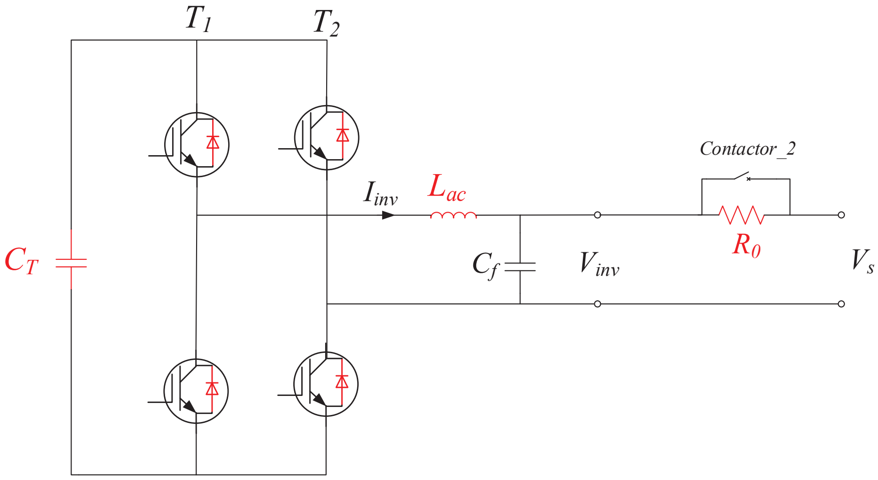

Figure 5.18: *Shunt unit DC bus Pre-Charge circuit schema.*

5.2.4 Chopper Leg

Shunt unit has been realized with an extra DC chopper leg linked to the full bridge inverter through DC bus capacitors. 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 [18, 21] as it is shown in Figure 5.19.

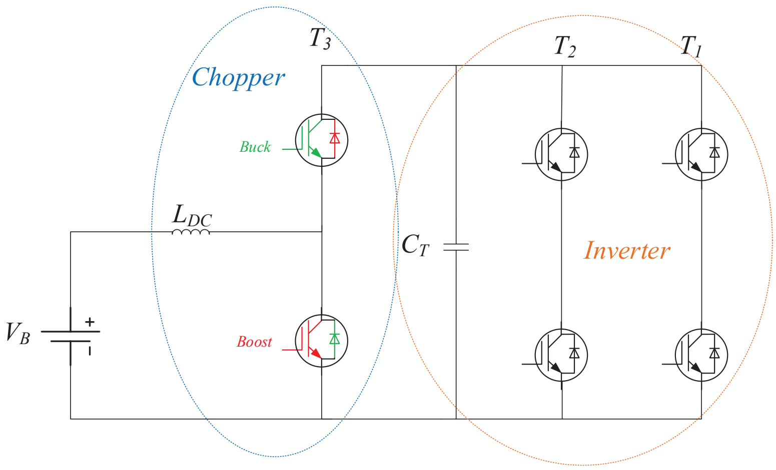

Figure 5.19: *Shunt unit inverter with chopper leg.*

Therefore, the chopper leg is composed of two main components; IGBT modules (T_3) and the DC side switching inductance (L_{DC}). Design procedure for these two parts is discussed in following.

Chopper Leg IGBT Module

DC side IGBT module is meant to manage battery charge and discharging actions. During charge mode the absorbed current is limited by batteries nominal charging current which in case of Open UPQC shunt unit battery set is equal to 3 A however, the battery set can be discharged with higher current. Considering the battery overall voltage, around 80 V, and device nominal power 3 kVA the current on DC chopper leg can be around 50 A in order to provide device nominal power. Although absorbing this much high power will decrease battery set life time but the DC leg IGBT modules needs to be sized according to this value.

In other hand, the shunt unit inverter is designed to be able to tolerate 18 kW for 2s which at DC side with 80V on battery set became minimum 225 A current because if the battery set voltage drops this current would be increased. In order to guarantee proper operation of the DC leg which due to the DC current can be most problematic part of the device and also tolerate switching ripples, the chopper leg IGBT is chosen to be the same IGBT module as inverter ones, modules with 195 A nominal power. The selected module has the capability to limit short circuit current up to six times nominal value and this can provide sufficient security during fault condition.

DC side Switching Inductance (L_{DC})

The DC link inductance selection has high importance because by means of IGBTs and anti-parallel diodes it will work as *Buck* converter during battery charging action and *Boost* converter during discharge action as it is depicted in Figure 5.20. Considering the power flow direction in *Buck* and *Boost* operation modes, the input and outputs are swapped with each other regarding each operation mode. The minimum inductance value for *Buck* and *Boost* converters can be found using the Equation 5.12 and Equation 5.13 respectively as those are reported in [38] and [39].

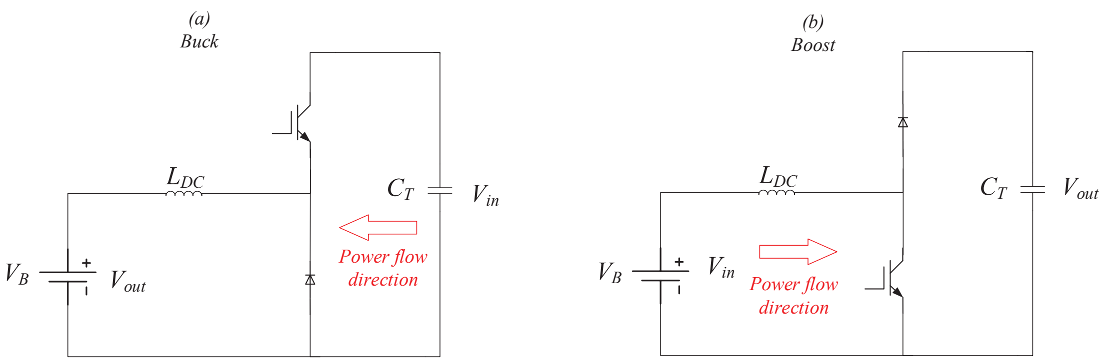

Figure 5.20: *Shunt unit chopper leg Buck and Boost converter operation modes.*

$$L_{min\_Buck} = \frac{V_{out} \cdot (V_{in} - V_{out})}{\Delta i_L \cdot f_{sw1} \cdot V_{in}} \tag{5.12}$$

$$L_{min\_Boost} = \frac{V_{in} \cdot (V_{out} - V_{in})}{\Delta i_L \cdot f_{sw2} \cdot V_{out}} \tag{5.13}$$

where

- V_{in} is typical input voltage, in *Buck* mode equal to 400V and in *Boost* equal to 80V
- V_{out} is desired output voltage, in *Buck* mode equal to 80V and in *Boost* equal to 400V
- f_{sw1} and f_{sw2} are the *Buck/Boost* converter switching frequencies, in *Buck* mode equal to 20kHz and in *Boost* equal to 4.5kHz
- Δi_L is the estimated inductor ripple current which is about 20% of nominal current

Input and output voltages are inverter DC bus voltage and battery set overall voltage and those are the same in both operation modes. The design procedure difference is due to switching frequencies, f_{sw1} and f_{sw2}, and the ripples on inductance current which depends on current on it.

As it was mentioned, during battery charge action the current is limited with battery nominal charging current and typically it is much lower than battery maximum discharge current so, the batteries can be charged with higher switching frequency than discharge switching frequency. Therefore in *Buck* operation mode the switching frequency is set to 20kHz, same as inverter switching frequency however, during *Boost* operation mode lower switching frequency is desired.

In *Buck* operation mode, replacing V_{in} with DC bus nominal value, 400 V, V_{out} to the battery set overall voltage, 80 V, switching frequency to 20kHz and maximum ripple of inductance current to about one amps, the minimum value for the chopper switching inductance can be estimated to about 3 mH. In this case the Δi_L is set to maximum 1 A because nominal charging current for the selected battery set is 3 A.

$$L_{min\_Buck} = \frac{80V \times (400V - 80V)}{1 \times 20kHz \times 400V} = 3.2mH \tag{5.14}$$

Following the same procedure to find the minimum switching inductor value for the *Boost* converter operation mode, the Equation 5.13 can be used. However during both operation mode the same inductance will be used so, the practical solution is to fix the inductance as it is calculated for *Buck* mode and instead find the switching frequency for *Bosst* operation mode. During discharging mode the maximum ripple can be estimated as about 10% of the nominal power (about 50 A) which can be set to about 5 A, setting the inductance value to 3mH the switching frequency can be calculated from Equation 5.13

$$f_{sw2} = \frac{80V \times (400V - 80V)}{5 \times 3mH \times 400V} = 4266.66Hz \tag{5.15}$$

Therefore, by setting the switching frequency to about 4.5 kHz the selected 3 mH can be used for both operation modes instead, with this lower switching frequency the chopper leg losses can be decreased because in *Boost* mode the current can be higher than *Buck* operation mode.

Therefore an inductance with value about 3 mH can be a good design value since it has to be shared in both *Buck* and *Boost* operation modes. Next step is to define the inductance current ratio. Again respecting the device nominal power during discharging mode, the maximum nominal current can be about 50 A so in order to avoid DC chopper leg switching inductance over load or saturation problems, the inductance is selected to have nominal current equal to 50 A. As a result, for the DC chopper leg switching inductance a 3 mH, 50 A inductance is chosen.

5.2.5 Battery Set

Battery set selection is performed based on two factors. The overall voltage on battery terminal and the required capacity. During the chopper leg design, battery voltage is set to 80 V. According to available commercial batteries, six Sealed Lead-Acid Battery (12 V) can be used in series as battery set inside shunt unit. Next step is to define batteries' capacity. The shunt unit battery set is meant to supply the load in the case of main voltage interruption and also provide peak shaving power. Peak shaving power is usually a portion of the load nominal power however during *Island* operation mode the shunt unit should supply all the load. This capability is defined by battery set capacity. If the device maximum power is considered as 3 kVA equal to the shunt unit designed nominal power, to be able to supply the load with nominal power for about 20 min, a storage system with about 1 kWh capacity is required. Although this capacity is achievable assuming fully charged batteries and discharging the batteries with high current. Again considering available solutions, 12Ah batteries can be selected. Therefore, the nominal power of each battery is about 12×12 = 144 Wh and the total power is about 900 Wh. Consequently, using six battery with 12 V and 12 Ah, will give the shunt unit the possibility to supply the load in nominal power (3 kW) about 20 min. This capability depends on battery State of Charge (SoC). Here the design consideration has been made for the fully charged battery set.

It should be noted that discharging the batteries with higher current will decrease the exploitable energy as well. Figure 5.21 shows the discharge characteristics for one unit cell of selected Lead-Acid batteries. It can be noticed that discharging the batteries with higher current decreases the discharge time considerably. With higher current the batteries will be discharged faster and also the exploitable energy is lessen. Therefore, although the batteries is designed for a 3 kVA device however discharging the batteries with nominal current on DC side, 50 A, will cause very fast power failure and also can damage the battery cells.

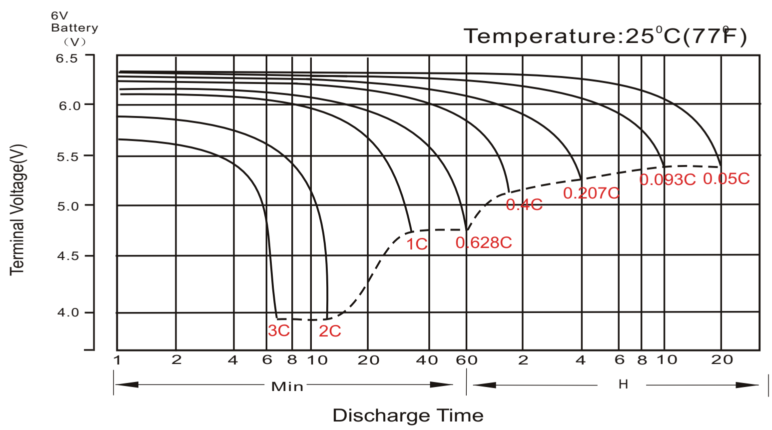

Figure 5.21: *Lead-Acid battery Discharging characteristics.*

Figure 5.22 shows the schema of shunt unit battery set and its electrical connection. C_{Batt} is used as a filter, parallel to the battery set. Contactor_3 is meant to avoid battery direct connection to the completely discharged C_{Batt} capacitor. The Contactor_3 is closed by proper control signal if the voltage on C_{Batt} capacitor is close to the battery set overall voltage.

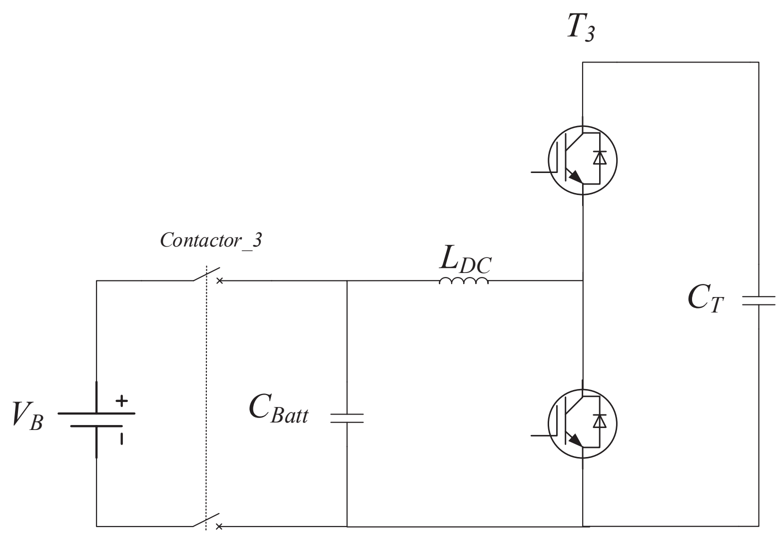

Figure 5.22: *Shunt unit battery set connection.*

Choosing the battery type, the nominal charging current of the batteries can be found from its datasheet and for the selected batteries it is 3 A. The Lead-Acid battery charging strategy as it has been described in Chapter 3 is divided into two subsections; fast charge and slow charge modes. During fast charge mode the charge current is set to battery nominal charging current (3 A) however, during slow charge mode the charging current is set to 1A.

5.2.6 Microcontroller and its Power Supply

According to Open UPQC shunt unit controller design in Chapter 3, to manage one single phase unit, three voltages and two currents measurement is required so a Microcontroller (MC) with at least five Analog to Digital Conversion (ADC) ports is required for control purposes. Three PWM ports are needed, Two ports to run the inverter IGBT modules (one port for each leg) and one port to run chopper leg. Also several contactors need to be managed by MC. For communication purpose, the MC need to have Modbus connection port. Taking into account all the requirements, same as series unit MC, Texas Instrument (TI) *TMS320F28335* Microcontroller is selected as main MC cpu.

The shunt unit MC should be supplied once the device is connected to the grid even if the power circuit is off. So the MC power supply initially need to be supplied before the SS and directly from the grid however, the MC need to be supplied during *Island* operation mode even if the grid voltage was interrupted. Therefore, the MC power supply should be managed to change its input connection from shunt unit input terminals to its output terminals after turning on the device or vice versa. Figure 5.23 shows the shunt unit MC power supply circuit connection by means of a Single Pole Double Throw (SPDT) Relay (*SPDT Relay*).

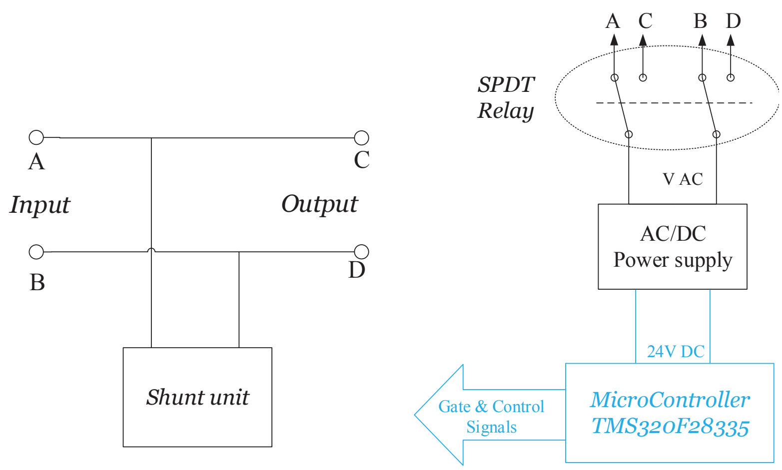

Figure 5.23: *Shunt unit Microcontroller power supply circuit.*

With this configuration, once the shunt unit is turned on, by means of SPDT *Relay*, the AC/DC power supply connection is transfered to the shunt unit output terminals in order to guarantee MC power supply even if the system goes to the *Island* operation mode.

5.2.7 Internet based Communication

For Internet based communication purpose, a Raspberry Pi embedded PC is integrated into the shunt unit, the Raspberry Pi speaks through Internet with rest of the communication system, the command is transferred to the unit microcontroller by means of serial port and Modbus protocol. The microcontroller send back its respond and information by means of Modbus and serial port to the Raspberry Pi and from Raspberry Pi through Internet to the rest of the communication system. The communication components are the same as those were depicted in Figure 5.9.

Table 5.3 lists the communication signals from shunt unit to DSO and also the commands from DSO to it. Shunt unit transfers battery SoC, its produced or consumed active and reactive powers and device working status to the DSO. Instead rather than series unit which accepts only one command from DSO, shunt unit has the capability to accept several commands from DSO. It receives reactive power command, peak shaving threshold, battery charge command in order to charge or stop charging and also fast or slow charging mode commands. Additionally the shunt unit is programmed to accept "*Low energy mode*" command which is meant to switch OFF the device while it is bypassed in order to decrease system losses associated to the device.

Data from shunt unit to DEMS	Commands from DEMS to shunt unit
SoC% battery State of Charge	±Var injection
Produced/consumed active power, Watt	Peak shaving threshold
Produced/consumed reactive power, Var	Charge or not charge the battery
Device Status, ON, OFF, *Online*, *Island*	Fast or slow charging mode
–	Low energy mode

Table 5.3: *Shunt unit communication data and commands list.*

5.2.8 Connection Plug and Bypass

The shunt unit need a connection plug equipped with bypass switch in order to provide seamless connection for customer home and bypass the device when it is required. The bypass is necessary in order to bypass the shunt unit in case of shunt unit failure, or any fault at load or grid side also during shunt unit maintenance or any other required operation on the device. The plug and bypass schema and realized unit is shown in Figure 5.24. With this plug the shunt unit can be connected in front end of customer house by putting the device in bypass mode. After turning ON the shunt unit, the bypass can be removed putting the shunt unit in *Online* operation mode parallel to the end user. As it can be depicted in Figure 5.24, the connection plug has two input terminals for input phase and neutral connections. Two output terminals for output phase and neutral. Apart from Input/Output phase and neutral, it has ground connection and bypass switch status signal. The auxiliary contact of bypass switch is meant to send bypass information to the microcontroller. There is also an extra signal to manage the connection plug LED which starts to blinking once the shunt unit is in bypass mode.

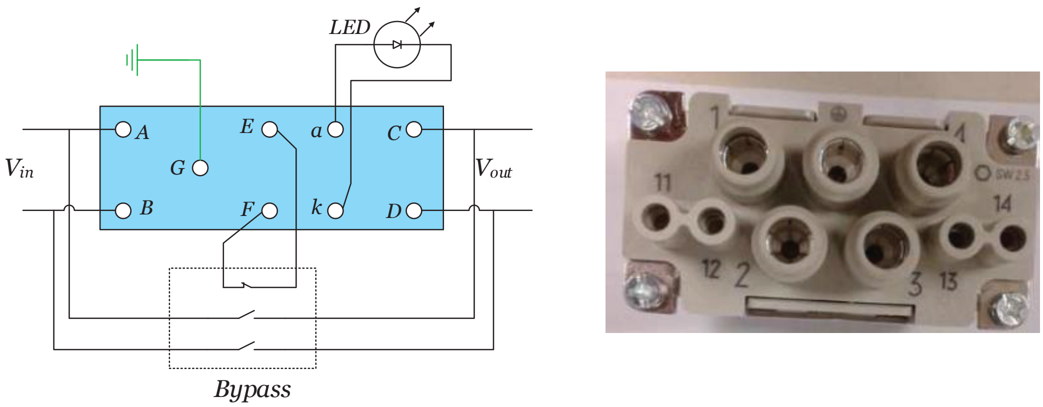

Figure 5.24: *Shunt unit connection plug schema and realized unit.*

Table 5.4 lists shunt unit connection plug descriptions. At the auxiliary contact 13 and 14 a normally close contact is connected so while the device is *Online*, the connection is closed and during bypass mode the connection is open. The LED Anode and Cathode is connected to 11 and 12 respectively.

Letter	Number	Definition
A, B	1,2	Input Phase and neutral
C, D	3, 4	Output Phase and neutral
G	5	Ground connection
E, F	13, 14	Bypass auxiliary contact
a, k	11, 12	LED signal

Table 5.4: *Shunt unit connection plug description.*

5.2.9 Shunt Unit Design Parameters

All the components of the shunt unit are explained in detail. Those parts are joint together to build the Open UPQC shunt unit as its simplified single phase schema is shown in Figure 5.25. All the gate signals to run inverter and chopper leg IGBT modules, gate signals to run the SS and commands to manage contactors are driven by shunt unit microcontroller (MC).

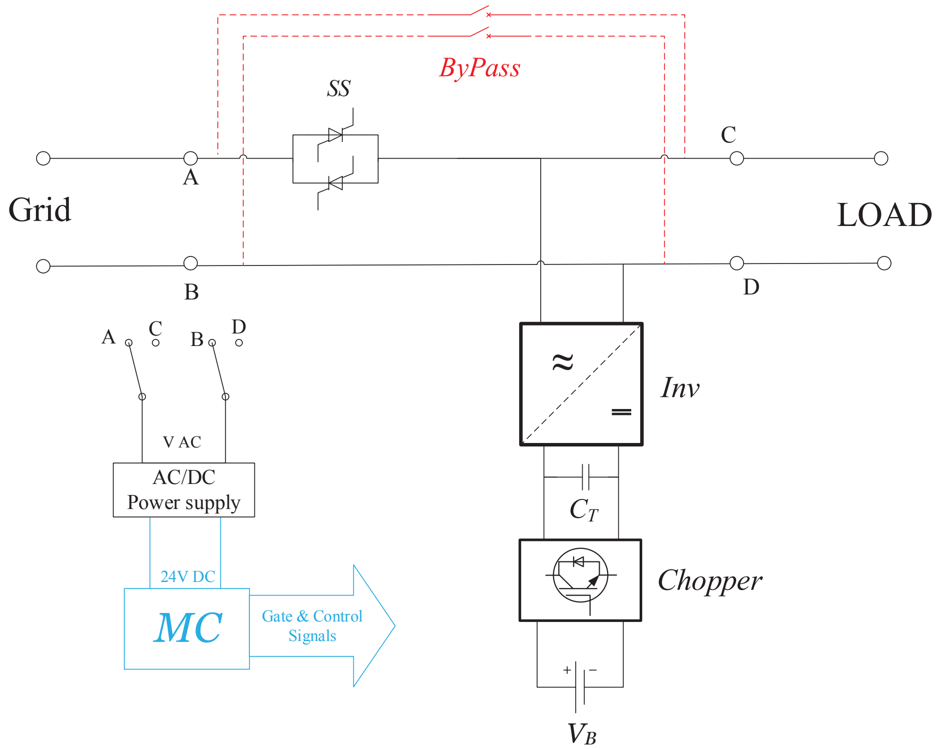

Figure 5.25: *Open UPQC shunt unit single phase schema.*

symbol	Object	Specification
SS	Static Switch	TY 40A 1200V SKKT 42
T_1, T_2 , T_3	IGBT modules	SKM195GB066D , 195 A, 600 V
C_T, C_{Batt}	DC bus capacitors	AYX-HR, electrolyte 6800 μF, 500 V
L_{ac}	ac side coupling inductance	1 mH, 30 A
f_{sw}	Inverter switching frequency	20 kHz
C_f	Capacitor passive filter	10 μF, 400 V ac
L_{DC}	DC side coupling inductance	3 mH, 50 A
f_{sw1}	Buck mode switching frequency	20 kHz
f_{sw2}	Boost mode switching frequency	4.5 kHz
V_B	Battery set	12 V, 12 Ah, Sealed Lead-Acid
MC	Microcontroller	TI, TMS320F28335 cpu
IT	Internet communication module	Raspberry Pi

Table 5.5: *Single phase series unit components parameters.*

Shunt unit single phase parameters are listed in TABLE 5.5 and Figure 5.26 shows the shunt unit single phase realized prototype. Shunt unit intrinsically is a UPS like custom power device which is able to guarantee load power supply in the case of main interruption. Meanwhile, by means of adopted communication system, it has the capability to give several ancillary services to the connected feeder and DSO. As it was mentioned before, six batteries are used in series as storage system (V_B). Parallel to the batteries, a capacitor (C_{Batt}) is connected and it works as a passive filter between batteries and chopper leg. In order to derive the SS same as IGBT driver system, a PWM output port of MC is used with proper driver circuit. In order to realize inverter DC bus, three AYX-HR, electrolyte capacitors are used in parallel and one of the same capacitors is used for C_{Batt}.

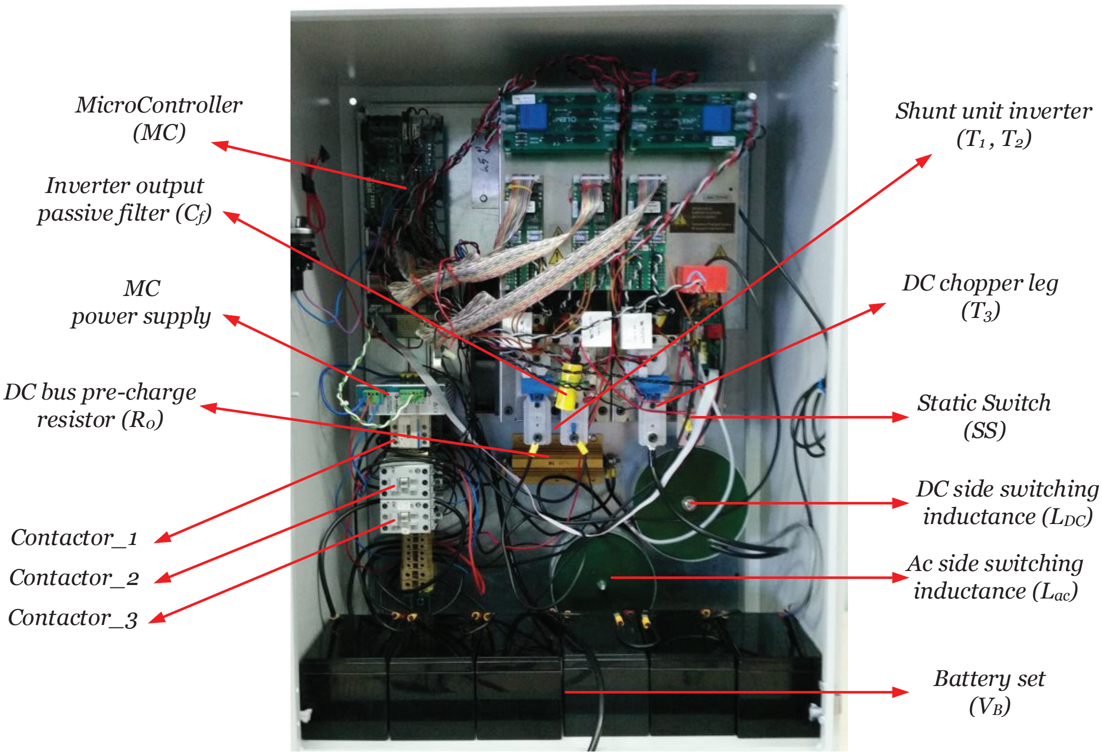

Figure 5.26: *Open UPQC Shunt unit single phase realized unit.*

In the case of the shunt unit, the heavy and bulky components are Battery set, ac and DC side switching inductances and the inverter itself. In Figure 5.26 the inverter module includes its capacitors, heatsink and cooling fans, one for inverter and another one for DC chopper leg. The module is designed to work below 50° and the heatsink needs to be designed keeping the switches temperature below this threshold. Heatsink calculation is beyond focus of this study and it can be found in literature like [52], Chapter 29. To keep the shunt unit within working temperature, it needs either a big heatsink or alternatively it could be equipped with cooling fans as it has been realized. The fans are controlled by unit MC. Switching modules temperatures are measured by temperature sensors and unit MC is programmed to start the fans if the sensed temperature goes above 50°. It will turn off the fans once the temperature falls below 40°.

It can be concluded that in order to decrease system size, it is crucial to carefully design inverter IGBT modules, heatsink and cooling system, switching inductances in term of current and value and finally the DC bus capacitor size.

CHAPTER 6

Simulation and Experimental Results

This chapter presents simulation and experimental results on Open UPQC series and shunt units. The Simulation study has been performed by MATLAB software. Series unit and shunt unit inverters are designed with four IGBT modules of SimPowerSystem toolbox. The simulation has been carried out with discrete fixed step solver so, the implemented control method could be easily adopted to digital microprocessor in experimental setup. Experimental prototype data is reported in Chapter 5 and the same data is used to create the Simulation model in order to compare simulation and experimental results and eventually to find well agreement between simulation and experimental results.

Most of the reported results are belong to Laboratory tests although single phase series unit and five shunt units are installed in field in a real LV network. Here the results are reported to verify proper operation of the devices. The results on proposed MBC are reported in Chapter 3 in order to show the controller performance which is used for both series and shunt units. Instead this Chapter reports simulation and experimental test results on series and shunt units functionalities and performance. Although, simulations have been carried out before hardware design and prototype realization to verify designed controller effectiveness, here all the results are reported together to enable comparison between simulation and experimental.

6.1 Series Unit

Figure 6.1 shows the circuit configuration of the series unit which both simulation and experimental tests are run. Series unit is connected in series to the line by means of a coupling transformer. The transformer turn ratio and nominal power are selected according the analysis has been addressed in Chapter 5. The system is simulated according the design parameters those are reported in Chapter 5 and the system functionalities is verified by simulation prior to experimental prototype setup.

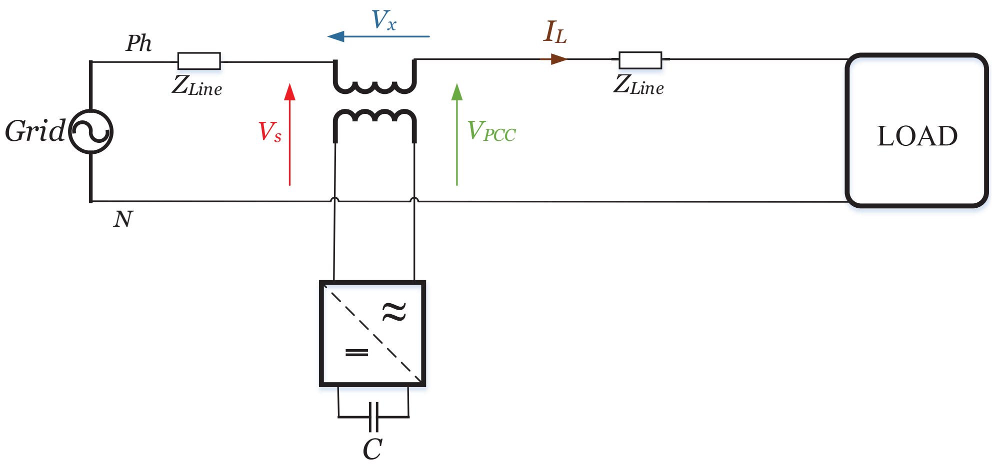

Figure 6.1: *Simulation and Experimental schema - series unit configuration.*

Open UPQC series unit is responsible to improve voltage power quality at its output (PCC) by injecting required compensation voltage V_x. Several phenomena can be considered however as it was discussed, the most important and prevailing issues are fast voltage sags/swells and also voltage rms drift in term of under and over voltages. Flickers and voltage harmonic compensation is not considered in Open UPQC single phase series unit. These functionalities can be added to the final three phase schema. Here the simulation and experimental laboratory test results are reported on single phase series unit to compensate over voltage and under voltage phenomena. Also in order to guarantee series unit continuous operation, its behavior under load variation and also operation limits and V_{ref} update algorithm performance are illustrated.

6.1.1 Over Voltage - Compensation

Open UPQC series unit performance to deal with swell and over voltage phenomena at grid side voltage (V_s) has been tested both in MATLAB based simulation and laboratory experimental setup.

Simulation

The Simulation circuit is built to show series unit performance to deal with 10% over voltage at grid side. The simulation has been performed for a system with constant load, about 4.5kW + 2kVar. Simulation starts with no over or under voltage at grid side till t=2s. Between t=[2-3]s 10% over voltage has been simulated at grid side. The series unit works to keep voltage at PCC (V_{PCC}) constant at nominal value (230 V) regardless to the over voltage at grid side. Figure 6.2 shows the transient response of the series unit. The over voltage at V_s starts at t=2s, the V_{PCC} sees negligible transient over voltage for about half cycle but series unit effectively restores the voltage deviation and keep voltage at PCC unaffected. As it is explained in Chapter 2, due to the reactive power compensation strategy (injected voltage is perpendicular to the current) the PCC voltage experiences a transient frequency deviation which is present in Figure 6.2 as well however, the phase change is pretty small and it is difficult to visually be detected in Figure 6.2.

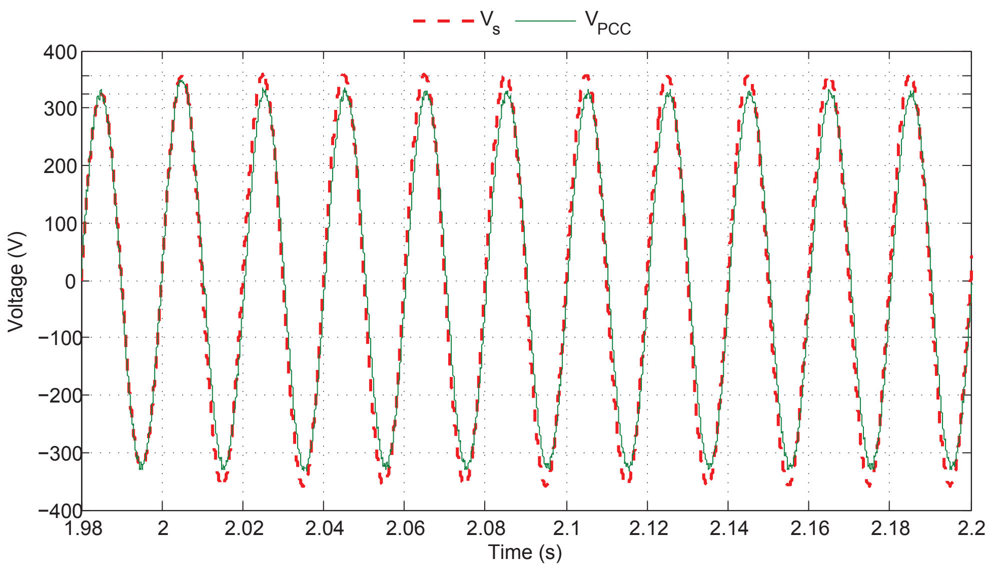

Figure 6.2: *Simulation - series unit over voltage compensation, transient during starting of 10% over voltage event.*

Figure 6.3 reports the V_{PCC}, V_s and series unit injected voltage (V_x) RMS values during the 10% over voltage event for one second. It can be noticed that outside the period [2-3]s the series unit injects about 5 V which is meant to compensate the losses due to the coupling Transformer and series unit inverter switching losses in order to keep series unit inverter DC bus voltage regulated. Once the over voltage starts, PCC voltage sees a slight increase but it is restored in half cycle to the set nominal value and it is kept constant during all the event. The series unit manages to keep the V_{PCC}

constant by injecting the required voltage V_x about 25V, as it is shown in Figure 6.3 (b) within the period [2-3]s.

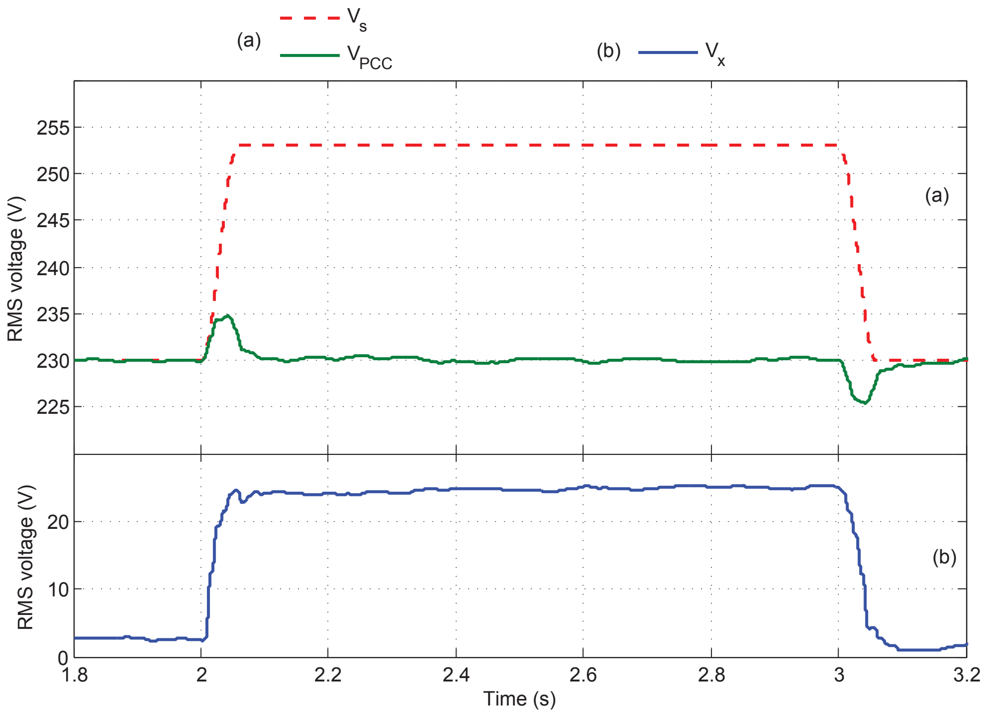

Figure 6.3: *Simulation - series unit over voltage compensation, long term (a) grid side and PCC voltages, (b) series unit injected voltage.*

Figure 6.4 illustrates the DC bus response of the series unit during the same event. Before t=2s the DC bus is constant and system was working in steady state. By starting the over voltage event, the series unit DC bus increases in order to store extra power due to the 10% over voltage at grid side. After the transient event, when the over voltage is removed, the series unit restores the DC bus voltage to its set value within less than 1s. This transition can be faster however, series unit DC bus voltage controller is designed to be slow and flexible in order not to affect the main PCC voltage control task of the series unit. The main responsibility of the series unit is to keep V_{PCC} voltage constant, and DC bus control is considered as second priority controller and it has been designed to be slower than the main controller.

Finally Figure 6.5 shows the active and reactive power exchange of the series unit during the over voltage event. As it can be seen, outside the period [2-3]s the active and reactive power exchange is close to the zero and as it was explained those have been meant to compensate system losses and keep DC bus voltage constant. Within the period [2-3]s the system starts to compensate over voltage event with pure reactive power injection principle so, the series unit reactive power during the event is increased to about 650Var while the active power exchange is always stays around

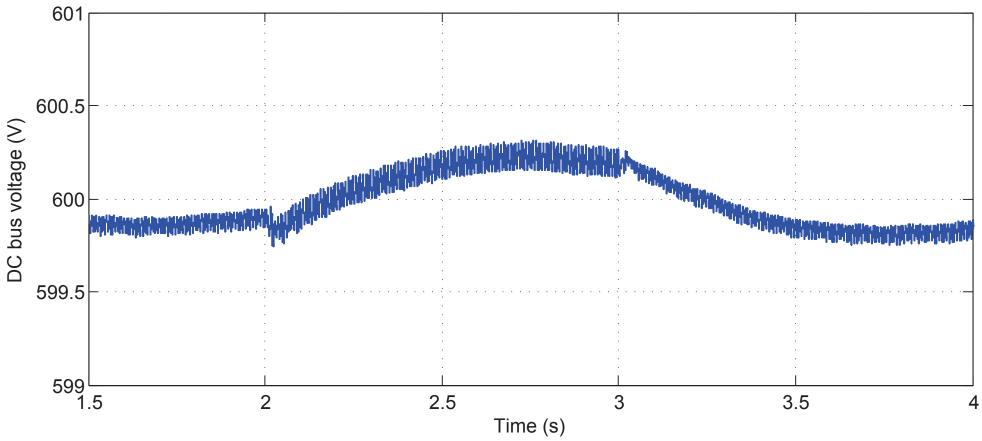

Figure 6.4: *Simulation - series unit over voltage compensation, DC bus voltage response to 10% over voltage event.*

zero except during the transient when the over voltage starts at t=2s or it has been removed at t=3s. During this transients, for about half period the series unit absorbs/injects active power due to the phase variation on injected voltage.

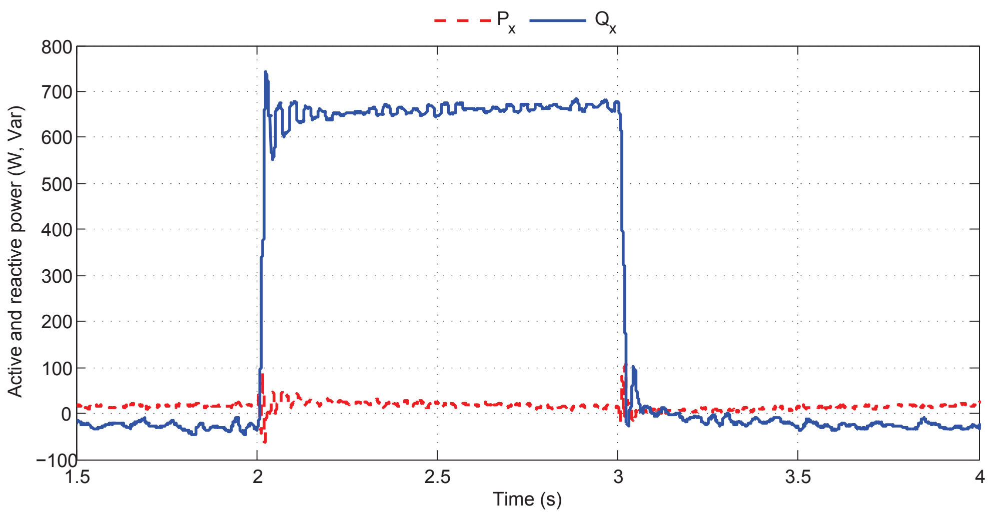

Figure 6.5: *Simulation - series unit over voltage compensation, series unit active and reactive power exchange during 10% over voltage event.*

Experiment

For laboratory test the over voltage event has been stimulated with available instruments in Politecnico di Milano, Energy Department, Power Quality laboratory. The over voltage is simulated by means of *Variac*. The prepared prototype has been connected at the output of the Variac and Variac output voltage has been set to 90% of the input value. Inside the series unit all the control logic has been modified and the reference voltage has been set to this 90% value which at the time of experiment was about 195 V. So, during experiment test, inside the controller for the series unit, this 195V is defined as nominal value and by moving the Variac output to its 100% it is possible to create 10% over voltage event. Figure 6.6 shows the experimental results. Constant 1kW + 800Var load is supplied during laboratory test. The device was working in steady state and at the time t=0.1s shown in Figure 6.6, the Variac output has been increased to 100% abruptly for about 0.6s and returned to the initial value at the end of the event. As it can be noticed from Figure 6.6 V_{PCC} and V_s are equal before the event, once the over voltage is triggered, the series unit is managed to keep voltage at PCC constant by injecting required compensation voltage (V_x) perpendicular to the current (reactive injection). Figure 6.6 shows the instantaneous voltages of V_{PCC} and V_s.

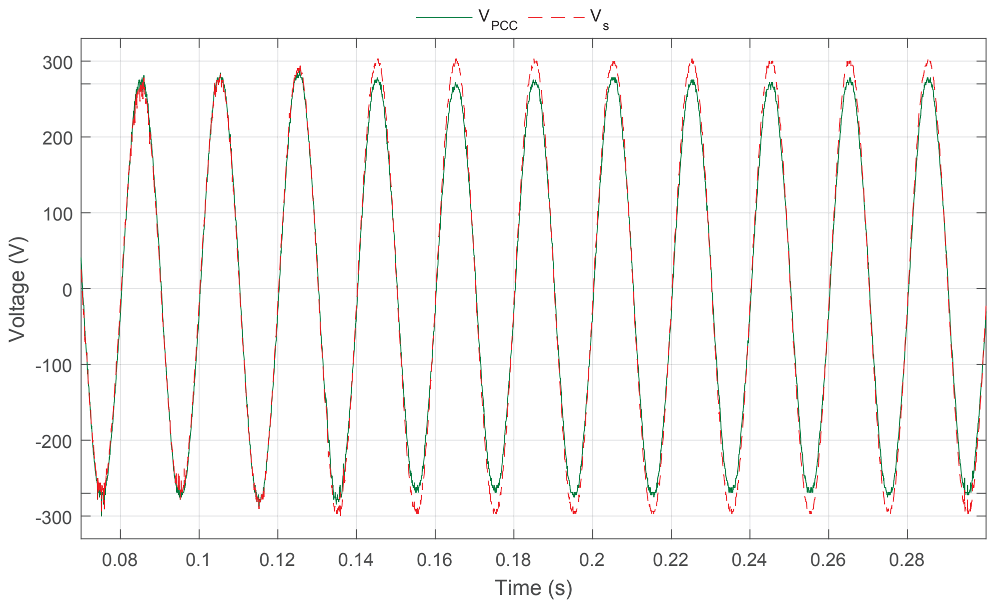

Figure 6.6: *Experimental - series unit over voltage compensation, transient during starting of 10% over voltage event.*

Figure 6.7 (a) shows the V_{PCC} and V_s RMS values before, during and after the explained over voltage experiment on laboratory prototype. At Figure 6.7 (a) V_{PCC} and V_s RMS values see a transient at starting of the figure, those are due to the initialization stage of how the recorded experimental data are managed where the data for one cycle (0.02s) are not trust-able. During the experiment over voltage (swell) event, the series unit keeps the voltage at PCC unaffected by menas of injected voltage which is shown in Figure 6.7 (b) while the voltage at grid side is increased about 10%. The results in Figure 6.7 (b) verifies the simulation study, while before and after the over voltage event series unit injects about 5 V which is meant to compensate system losses and keep its DC bus voltage constant at set value. During the over voltage event, series unit injects about 25 V to compensate the event and keep V_{PCC} regulated.

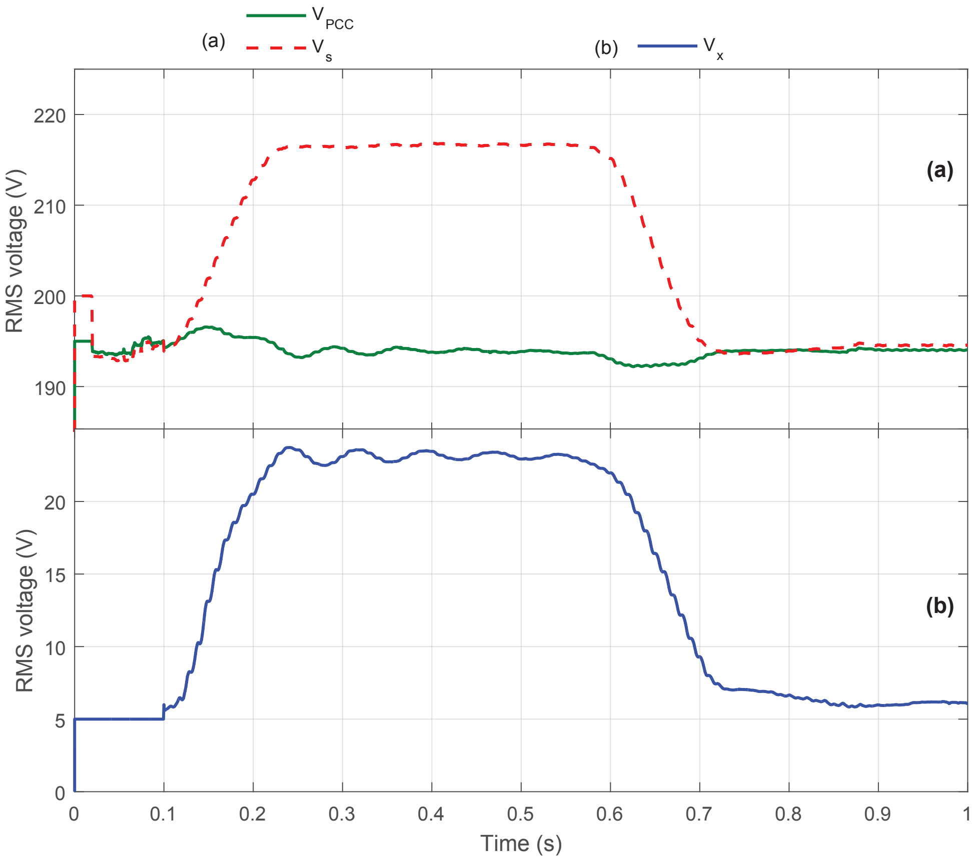

Figure 6.7: *Experimental - series unit over voltage compensation, long term, (a) grid side and PCC voltages, (b) series unit injected voltage.*

Figure 6.8 shows the series unit DC bus voltage controller response for the similar test event but not the same test. Similar test has been repeated and DC bus voltage response has been recorded for the 10% over voltage at grid side. As it is shown in Figure 6.8, the event has been started at about t=0.9s and last 0.7s till 2.6s and the series unit DC bus increased during the event. After the described over voltaeg event, the series unit started to restore its DC bus voltage to the set value slowly. In experiment, the DC bus management has been programmed slower than what it was set in simulation and for the experimental setup it took about 6s for series unit inverter to restore the DC bus voltage to its set value.

6.1.2 Under Voltage - Compensation

Similar to the analysis that have been performed for over voltage compensation case, capability of the series unit to deal with under voltage event has been evaluated both

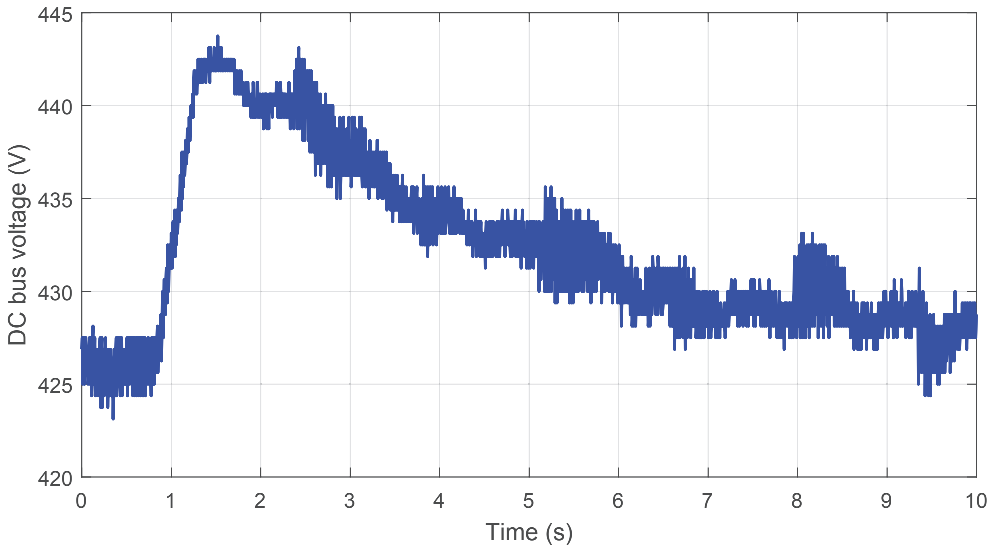

Figure 6.8: *Experimental - series unit over voltage compensation, DC bus voltage response during 10% over voltage event.*

by simulation study and also on experimental laboratory prototype. Identical scenarios have been defined for simulation and experimental tests, in this case for 10% under voltage event, and the results have been reported in the following.

Simulation

The Simulation circuit is created to show series unit performance during 10% under voltage at grid side and it has been performed for a system with constant load, 4.5kW + 2kVar. The simulation has been started with no over or under voltage at grid side till t=2s. Between t=[2-3]s, 10% under voltage has been simulated at grid side. The series unit works to keep voltage at PCC (V_{PCC}) constant at nominal value (230 V) regardless to the under voltage event at grid voltage. Figure 6.9 shows the transient response of the series unit. The under voltage at V_s starts at t=2s, the V_{PCC} sees negligible transient under voltage for about half cycle but series unit effectively restores the voltage deviation and keep voltage at PCC unaffected. As it is explained for over voltage case and also in Chapter 2, due to the reactive power compensation strategy, the PCC voltage experiences a transient frequency deviation which is present in Figure 6.9 as well however the phase change is pretty small and it is not possible to visually be detected in Figure 6.9.

Figure 6.10 shows the V_{PCC}, V_s and V_x RMS voltages for the described under voltage event. Before t=2s the system working with no under voltage so the series unit injects small amount of V_x, Figure 6.10 (b), to compensate system losses and keep DC bus voltage regulated. At t=2s, 10% voltage drop is simulated till t=3s. As it can be seen

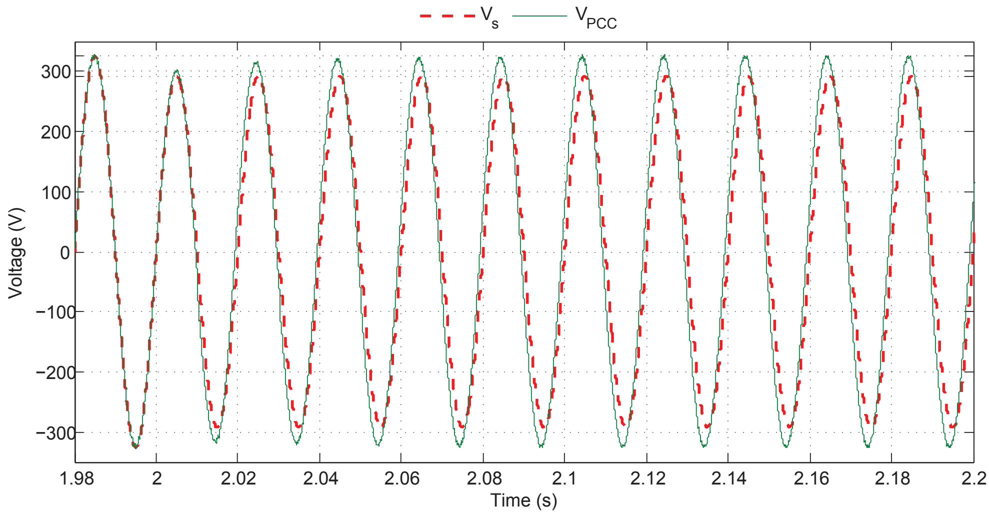

Figure 6.9: *Simulation - series unit under voltage compensation, transient during starting of 10% under voltage event.*

from Figure 6.10 (a), regardless the voltage drop at grid side, the V_{PCC} is kept constant by means of series unit although around t=2s and t=3s for short period the V_{PCC} sees slight deviation from set value. Figure 6.10 (b) shows the series unit injected voltage. In this case the series unit injects about 40 V to compensate 10% voltage drop.

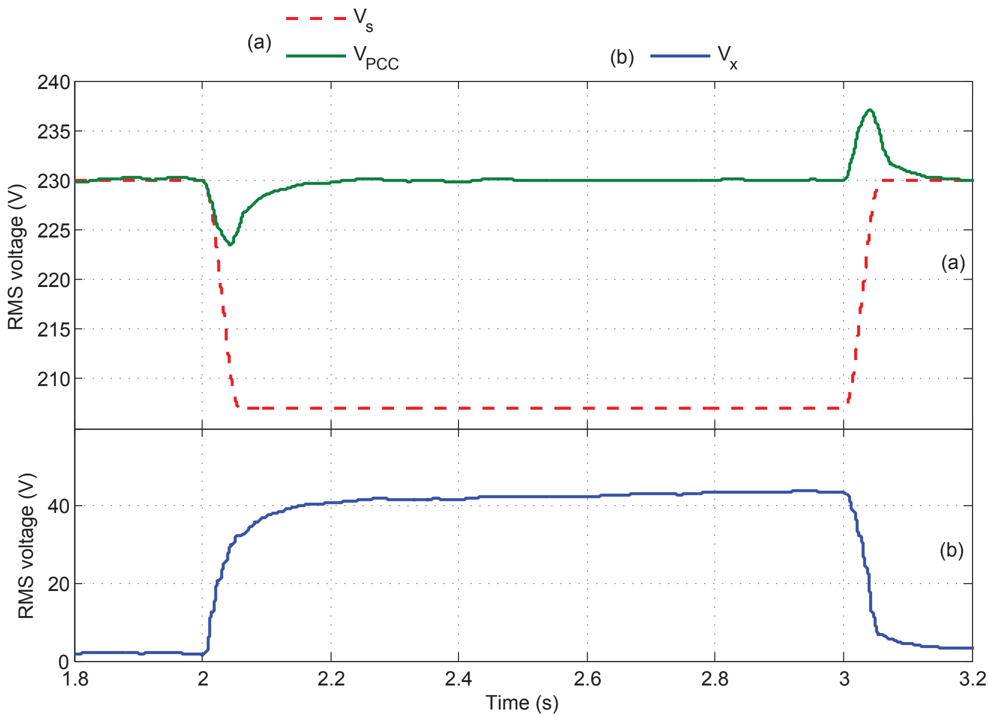

Figure 6.10: *Simulation - series unit under voltage compensation, long term, (a) grid side and PCC voltages, (b) series unit injected voltage.*

The DC bus voltage response is shown in Figure 6.11. The DC bus was constant about set value before the voltage drop starts at t=2s. Conversely to the over voltage case, during under voltage event, the DC bus voltage experiences slight drop because the series unit discharge the DC bus during transient in order to support V_{PCC} control logic. At the end of the event t=3s, the series unit starts to restore the DC bus voltage to its set value and it takes about 1s for the simulated schema to recover the DC bus voltage to its initial set value.

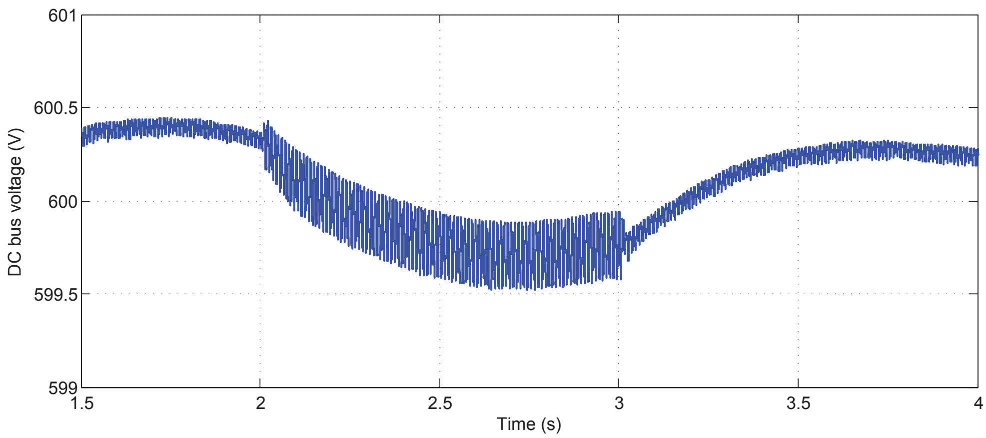

Figure 6.11: *Simulation - series unit under voltage compensation, DC bus voltage response during 10% under voltage event.*

Figure 6.12 shows the active and reactive power exchange of the series unit for 10% voltage drop test. Contradictory to the over voltage case, series unit produce negative reactive power to deal with under voltage event. The amount of the active power exchange is almost the same as it was for over voltage case in Figure 6.5 because the active power is meant to compensate the device losses in order to keep DC bus voltage constant and it is not affected by over or under voltage event. Instead, the injected voltage magnitude and its direction are different for over voltage and under voltage cases and these differences can be noticed comparing Figures 6.5 and 6.12.

Experimental

Similar but not exactly the same scenario has been tested on experimental setup at laboratory for about 10% voltage drop at grid side voltage. Realized series unit and associated control method performance to deal with this event is reported. Similar to the over voltage case, a Variac has been used in laboratory to simulate the voltage drop. The series unit is supplied at secondary of the Variac and the output voltage was fixed to the 100% initially and the reference voltage inside control method has been updated to the grid measured value which during the test was about 217 V. An

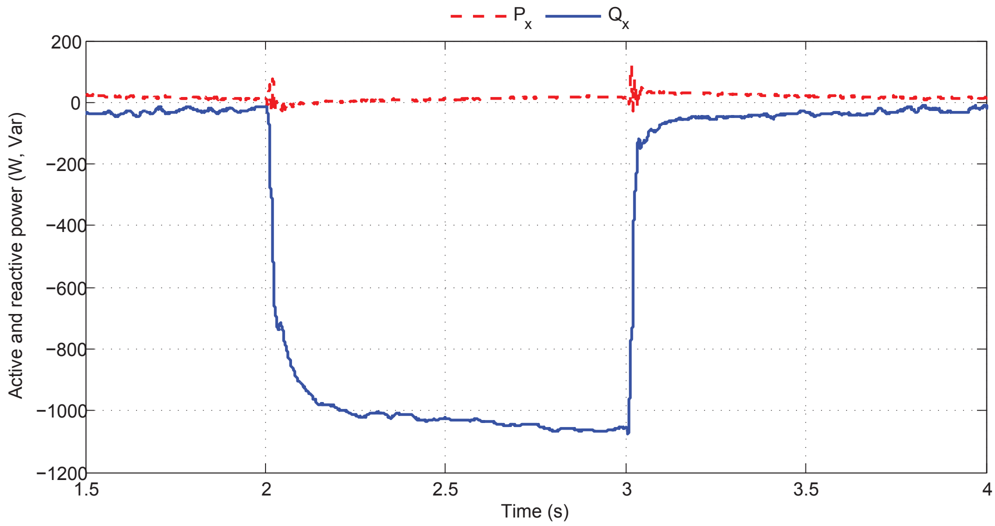

Figure 6.12: *Simulation - series unit under voltage compensation, series unit active and reactive power exchange during 10% under voltage event.*

abrupt 10% voltage drop has been simulated by means of Variac. Figure 6.13 shows the transient response of the series unit to this event. Before t=0.1s the V_{PCC} and V_s were completely match to each other. At t=0.1s the voltage drop is triggered and as it can be noticed, this distortion is restored by series unit in less than half cycle (about 10ms) and the voltage at V_{PCC} is kept unaffected to this distortion. There is small amount of the phase difference between V_{PCC} and V_s due to the reactive V_x injection however, it is not possible to visually see it at Figure 6.13.

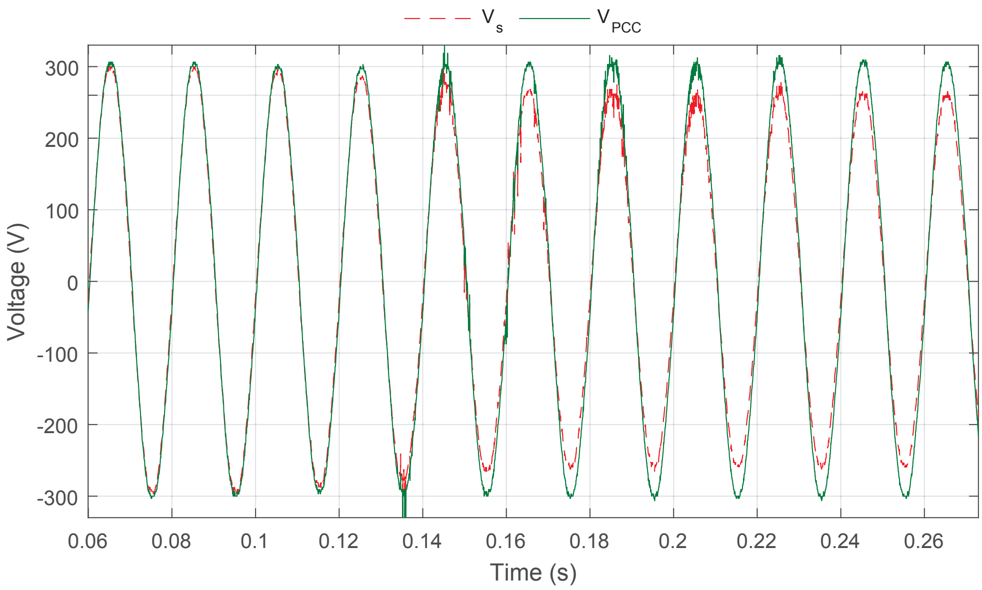

Figure 6.13: *Experimental - series unit under voltage compensation, transient during starting of 10% under voltage event.*

Figure 6.14 shows experimentally recorded V_{PCC}, V_s and V_x RMS voltage values for the explained under voltage event laboratory test. Similar to the over voltage case, before the under voltage event (t=0.1s), the voltage at PCC and grid side voltage are equal and the series unit injects about 5 V in order to compensate system losses to keep DC bus voltage regulated, Figure 6.14 (b). The voltage drop (around 10%) is triggered at t=0.1s and it lasts about 0.8s. As it can be seen from Figure 6.14 (a), the PCC voltage is kept constant regardless to the voltage drop at grid side. The series unit injects about 25 V to compensate voltage drop at grid side and regulate voltage at PCC by means of pure reactive power compensation strategy, Figure 6.14 (b).

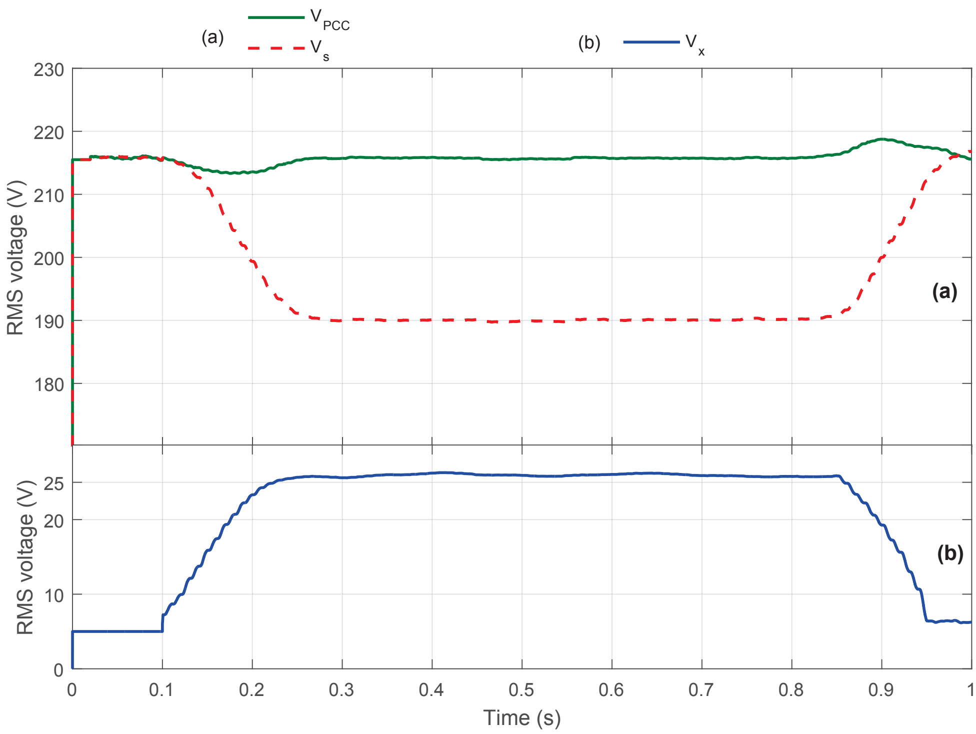

Figure 6.14: *Experimental - series unit under voltage compensation, long term, (a) grid side and PCC voltages, (b) series unit injected voltage.*

The experimental under voltage test is repeated and the series unit inverter DC bus voltage variation is recorded as it is reported in Figure 6.15. The system was in steady state till t=0.4s and DC bus voltage was regulated to its set value. At t=0.4s for about 0.7s, 10% under voltage at grid side is applied to the series unit by means of Variac. Contradictory to the over voltage case and same as it was depicted by simulation study, the DC bus voltage decreased during the voltage drop. After the event, the series unit starts to recover the DC bus to its set value slowly where in the experimental test it takes about 4s to reach its set value.

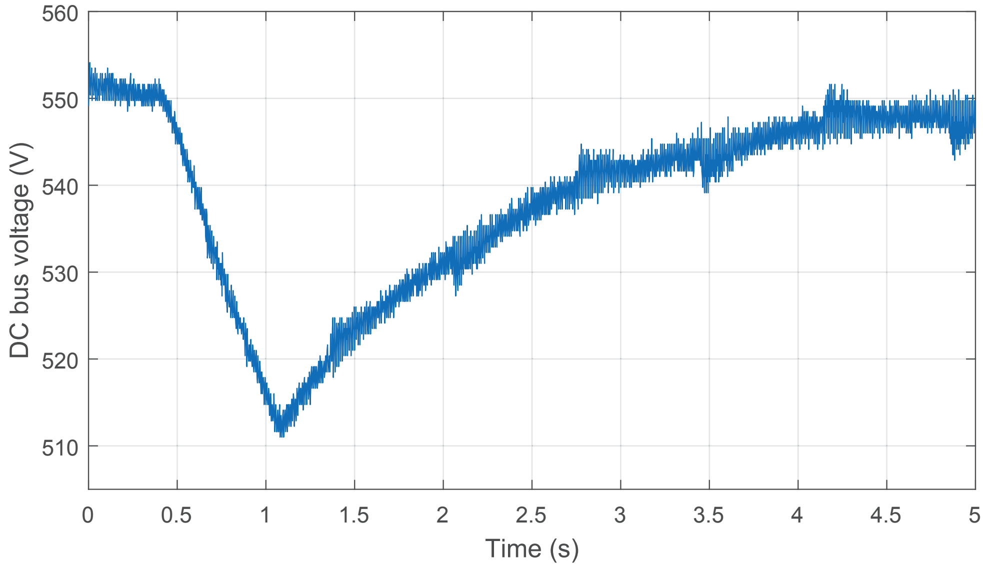

Figure 6.15: *Experimental - series unit under voltage compensation, DC bus voltage response during 10% under voltage event.*

6.1.3 Load Variation

Common application for a series connected PQ conditioner is to stay off-line most of the time and only if there is any disturbance in the network, it starts doing compensation. Mostly the device has been managed by a detection algorithm in order to detect the disturbance in the grid voltage which triggers the unit to react and compensate the events. However, Open UPQC series unit is a continuous operating PQ conditioner and despite common application, it will be online all the time giving PQ services to the connected area. So it will carry always the total load current and it need be able to operate under fast load variation. Here the simulation and experimental studies have been carried out to observe series unit performance under fast and large variation on load.

The simulation study has been done to examine the device performance dealing with voltage drops and over voltages under considerable load variations however due to the laboratory setup restrictions, performing exactly the same tests in laboratory was not possible and experimental prototype performance only in one situation is examined and results are reported.

Simulation - Over Voltage

The schema shown in Figure 6.1 is simulated with MATLAB and same as previous cases the simulation has been carried out with discrete, fixed step solver, so the implemented control method performance in simulation is very similar to the experimental results by digital microprocessor implementation.

In order to examine the system response to load variation with over voltage compensation, the simulation is done for 10% over voltage at grid side case, by adding a certain load and removing the same load. The system at starting condition works with 10 kW + 12 kVAr load to compensate grid voltage drops or over voltages. Then at t =3s, 10 kW is added to the load. Power Factor (P.F.) is changed from 0.65 to 0.85 and current is increased from 66A to 100A RMS. Transient behavior of the device is reported in the following. Then at t=5s the 10 kW load is removed from the load and system transient starts and the system comes back to the starting condition with 10 kW + 12 kVAr load, but with 10% over voltage at grid side. Grid side voltage (V_s) has constant 10% over voltage during this simulation study which is not shown in reported results.

At Figure 6.16 before t=3s, the series unit is working under constant load to compensate the voltage deviation and set PCC voltage to nominal value. Then the load variation is applied to the system. Series unit response to the added load is shown in Figure 6.16. Till t =3s the system is working under constant initial conditions explained before and compensating 10% over voltage. At t =3s the load increment has been applied to the system. As it can be seen, the system is able to manage this critical load change. Figure 6.16 (a) shows that V_{PCC} is not affected by this change. Series unit injected voltage is shown in Figure 6.16 (b) which as it can be noticed, experiences phase and magnitude variation during transient event. Figure 6.16 (c) shows line current which changes with no inrush or over/under shoot during load variation. Simulation results proofs that, series unit and its controller is able to manage large load variation with minimum effect on PCC voltage.

Series unit response to remove the same 10 kW load during over voltage compensation is presented too. Figure 6.17 shows the results where the series unit was compensating 10% over voltage with 20 kW + 12 kVAr load till t=5s and system response to remove 10 kW load is depicted. At t=5s, the load is removed and system comes back to the starting condition. As it can be seen in Figure 6.17 (a), PCC voltage is not affected with this critical load change. Figure 6.17 (b) shows that, by changing the load current, the injected voltage magnitude and phase have been changed accordingly. Current waveform is shown at Figure 6.17 (c) and it smoothly changes without any over or under shoot.

Simulation - Under Voltage

Same as over voltage simulation study, equal situation has been simulated for under voltage compensation case. The grid voltage is simulated to have 10% voltage drop. The series unit is working under constant load (10 kW + 12kVar) to compensate

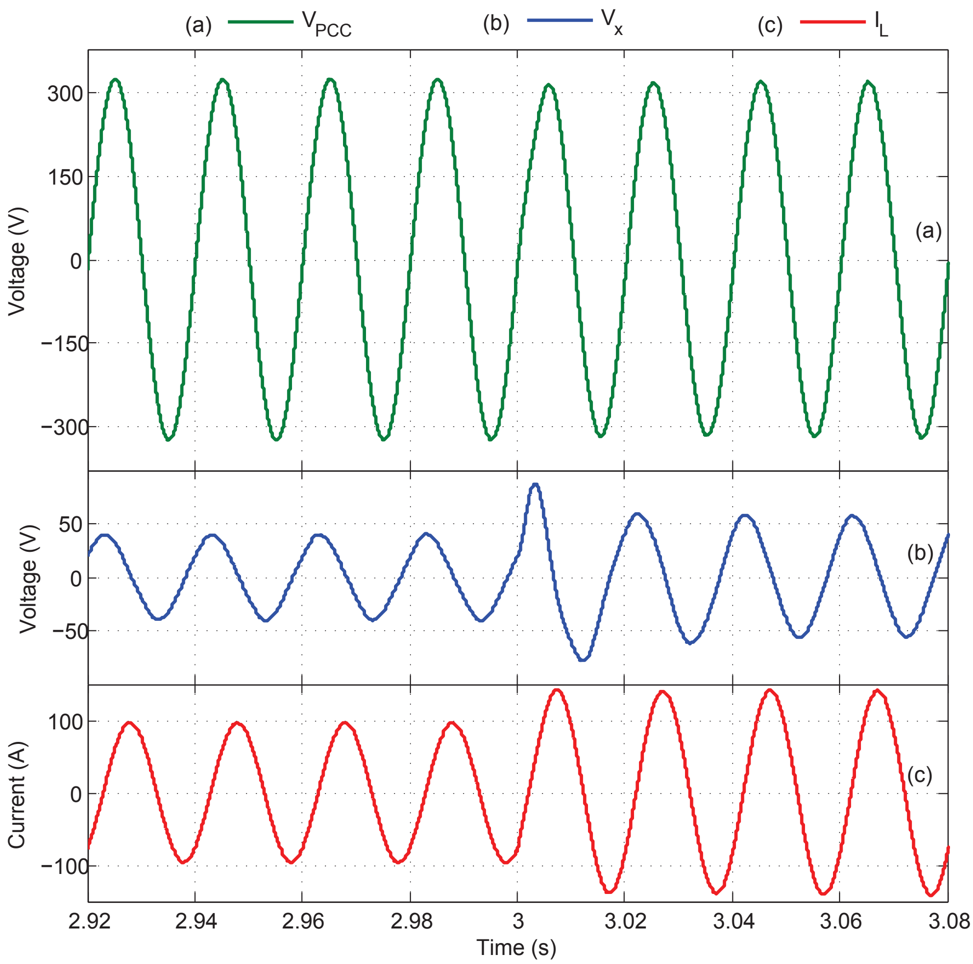

Figure 6.16: *Simulation - series unit response to load variation, over voltage case, adding the load – (a) PCC voltage, (b) series unit injected voltage, (c) load current.*

this voltage drop and set PCC voltage to nominal value. Similar to over voltage case, 10 kW load is added to the system at t=3s and it is removed at t=5s in order to record series unit responses. Figure 6.18 shows series unit response to load increment during voltage drop compensation. As it can be noticed in Figure 6.18, the device is able to deal with this critical change. Voltage drop at grid voltage again is not shown at Figure 6.18. The disturbance in PCC voltage is negligible in Figure 6.18 (a) and thanks to MBC current controller there is not any inrush current through the load. There is a fast change in injected voltage in Figure 6.18 (b) due to the critical change in line current phase. As it is explained in Chapter 2, any change in line current angular frequency affects V_x reference magnitude and phase values. Load current variation is shown in Figure 6.18 (c).

Figure 6.19 shows the series unit response to removing the same load (10 kW) at t=5s under the same 10% voltage drop. So, the series unit was working with 20 kW +

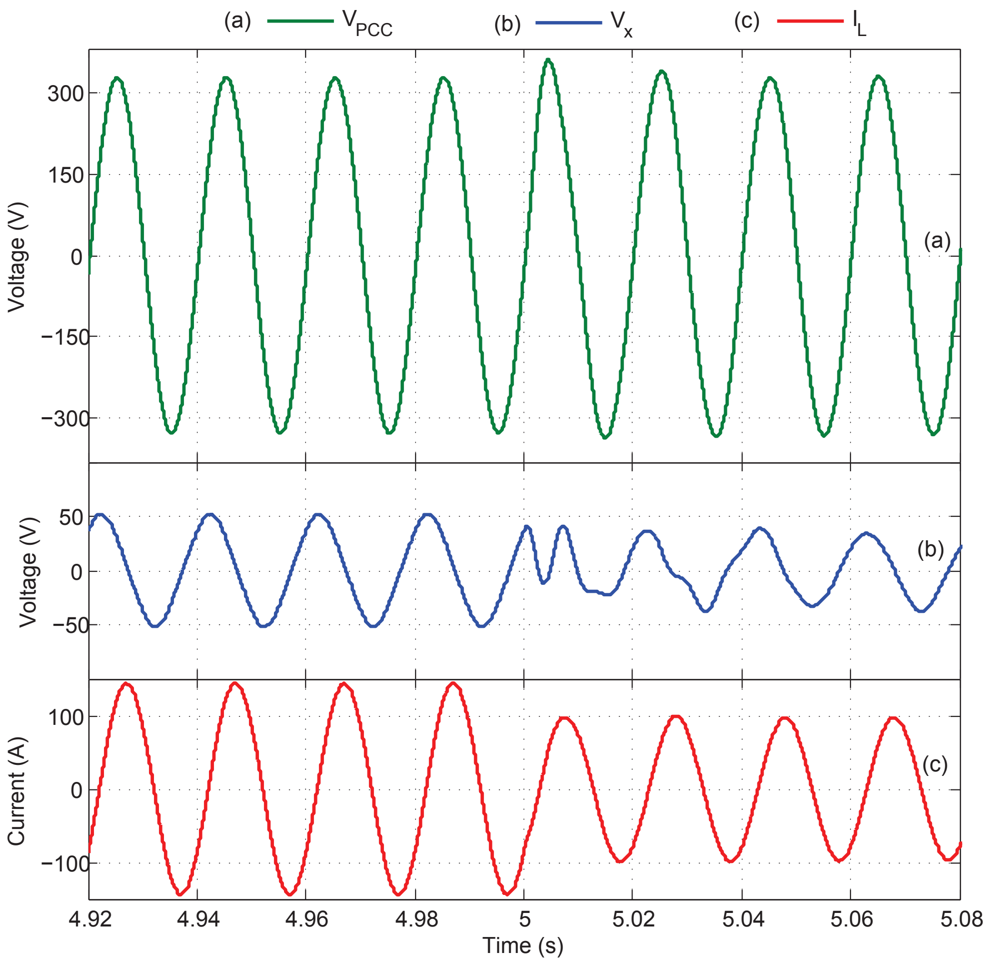

Figure 6.17: *Simulation - series unit response to load variation, over voltage case, removing the load – (a) PCC voltage, (b) series unit injected voltage, (c) load current.*

12 kVAr before t=5s and, removing 10 kW, the system comes back to starting condition. Figure 6.19 (a) depicts the PCC voltage that is not affected with this load change, injected voltage experiences a phase and magnitude change because of the quite critical change of load current phase, as shown in Figure 6.19 (b). The line current is smoothly changes and there is no over or under shoot on it Figure 6.19 (c). By changing the injected voltage phase, there is a small change in V_{PCC} phase too. Although this change is not visible in Figure 6.19 (a), because the injected voltage comparing to the V_{PCC} has a small magnitude, Figure 6.19 (a) and (b) have different voltage scales.

Experimental

Since it was not possible to realize over voltage test in laboratory as it has been done in simulation and also for under voltage test, it was difficult to run similar tests in experiment due to laboratory limits, load variation results are reported for one case

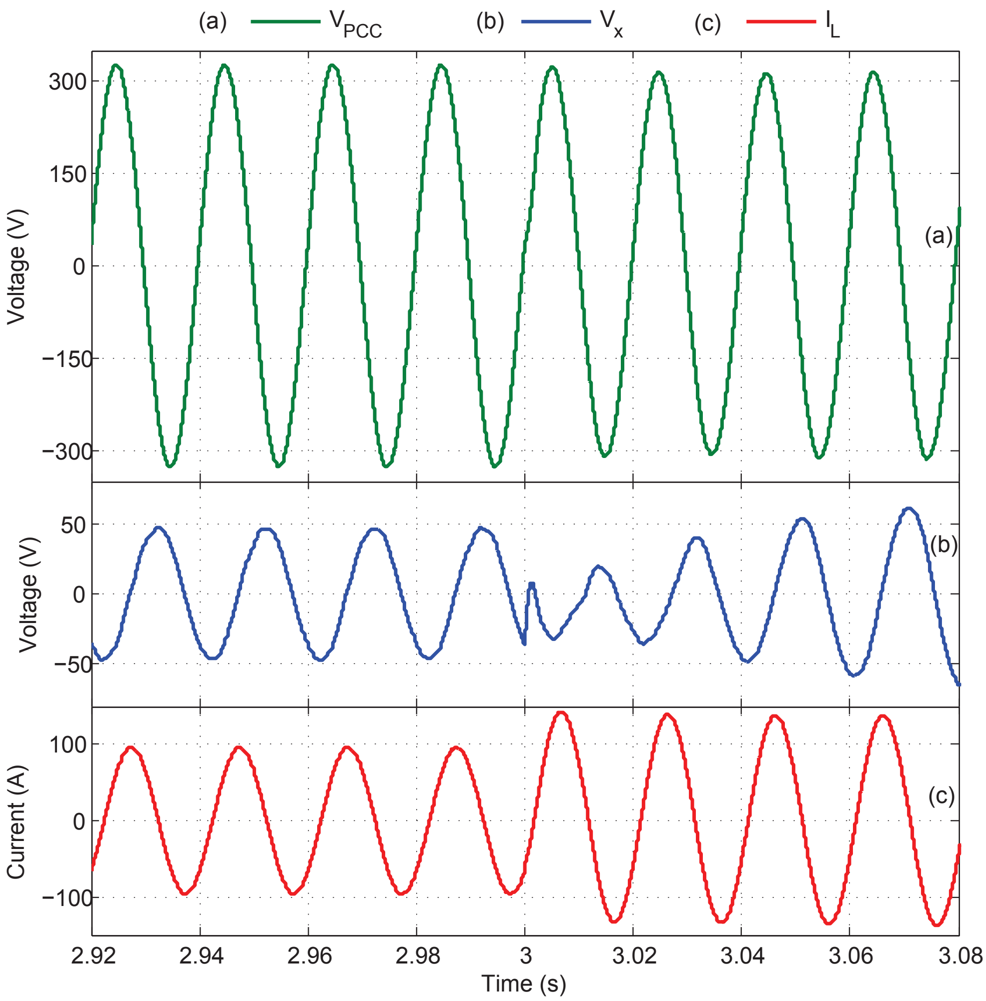

Figure 6.18: *Simulation - series unit response to load variation, under voltage case, adding the load – (a) PCC voltage, (b) series unit injected voltage, (c) load current.*

only with about 220V RMS at grid side and 215V as set value for PCC voltage. 215V is set as PCC voltage reference because with available loads at laboratory, load variation is performed with mostly resistive load, and as it was explained in Chapter 2, when the load power factor is near one, the series unit is working very close to its under voltage compensation limits. So changing the load may causes the series unit to update its reference value according to the load power factor ($cos(\gamma)$) and its operation limits and this would mix device transient response illustration with V_{PCC_ref} update and make the result presentation unclear. Therefore, the PCC reference value is set to a value lower than grid voltage (V_s) and this will give the series unit the possibility to follow the reference value independently than load variation in the interested range.

Initially the connected load was a reactive 850 Var parallel to a resistive 800 W load which the total load became about 1200 VA. Constant resistive 1400 W load is added

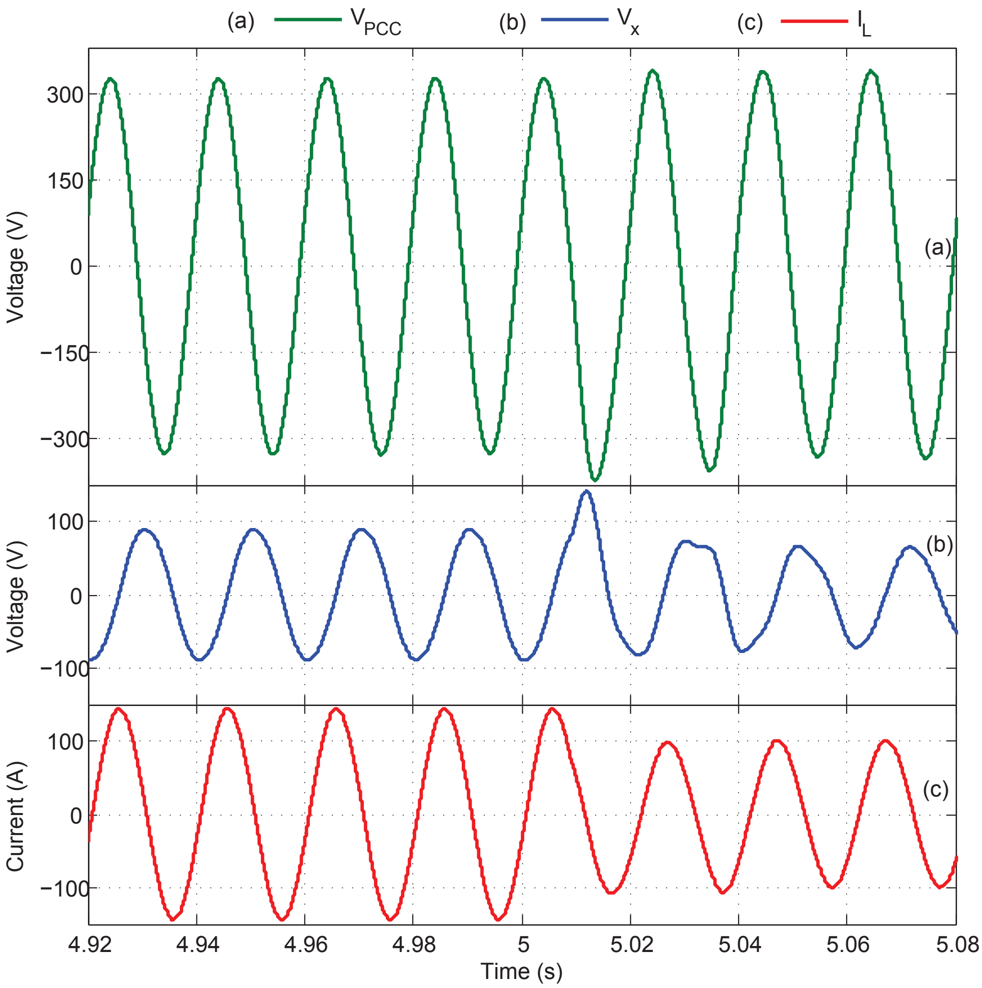

Figure 6.19: *Simulation - series unit response to load variation, under voltage case, removing the load – (a) PCC voltage, (b) series unit injected voltage, (c) load current.*

to the load immediately and series unit response is recorded. The same 1400 W load is removed and gain series unit behavior is recorded.

Figure 6.20 shows the series unit recorded response to adding 1400 W load. Grid voltage (V_s) is not shown since it is constant network voltage with 220V RMS value. Figure 6.20 (a) shows the PCC voltage which at the moment when the load is added to the system, about t=0.085s in Figure 6.20, it experiences very small and negligible disturbance. Figure 6.20 (b) shows the series unit injected voltage which due to the small difference between V_s and PCC reference voltage during all the experiment it has small magnitude however, adding the load causes phase and magnitude change on it as it can be noticed from Figure 6.20 (b). Finally Figure 6.20 (c) shows load current which without any over or under shoot sees a step change after adding the load thanks to the implemented double loop controller and specially MBC as series unit current controller.

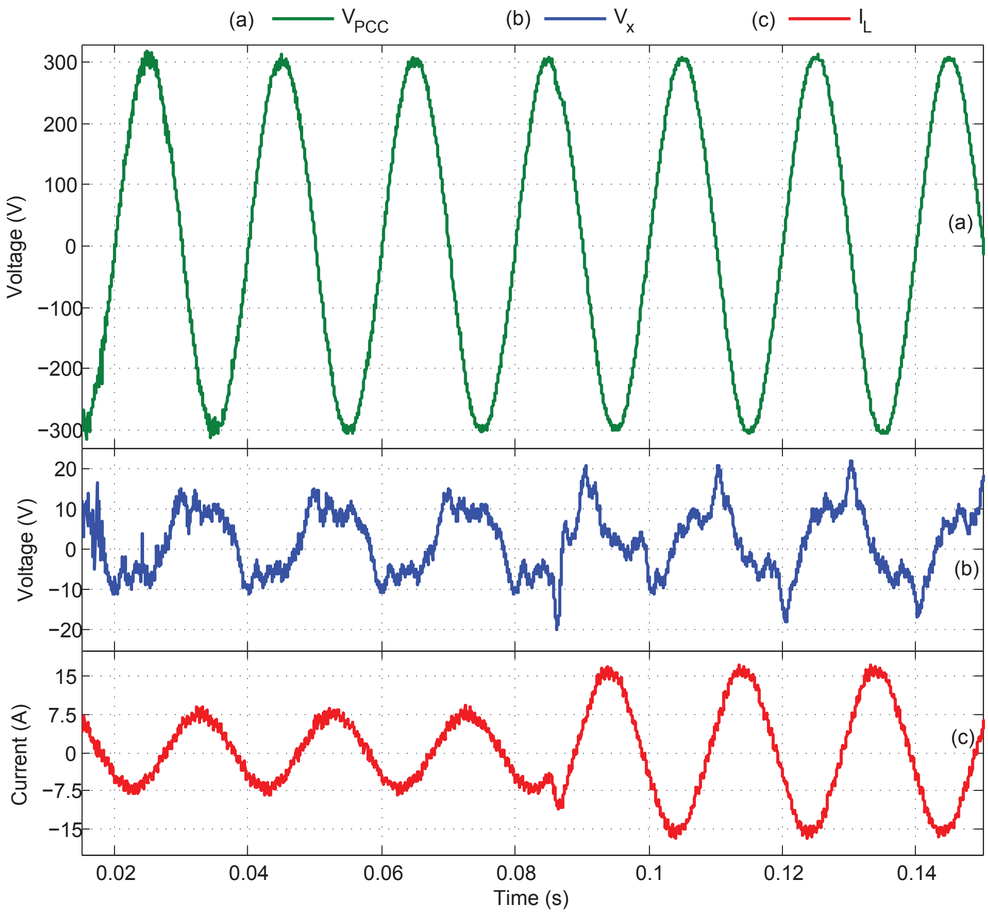

Figure 6.20: *Experimental - series unit response to load variation, adding the load – (a) PCC voltage, (b) series unit injected voltage, (c) load current.*

To verify series unit performance under load step wise decrement, as it was mentioned, same 1400 W resistive load is removed and device performance is recorded as it is depicted in Figure 6.21. In Figure 6.21 the series unit was working with 850 Var + 2200 W constant load, V_s=220V and V_{PCC_ref} =215V then immediately 1400 W load is removed. Grid side voltage (V_s) is not shown. Figure 6.21 (a) shows V_{PCC} profile during this transient. As it can be noticed removing the load has almost no effect on PCC voltage profile. Series unit injected voltage, V_x, sees small phase and magnitude variation as it is shown in Figure 6.21 (b). Same as previous case the injected voltage during the experiment had about 10 V RMS value because the grid side voltage and PCC voltage set values were close to each other. Finally load current variation is illustrated in Figure 6.21 (c) and as it was expected, it experiences a phase shift during transient but again thanks to adopted controller, there is no rapid changes on its magnitude.

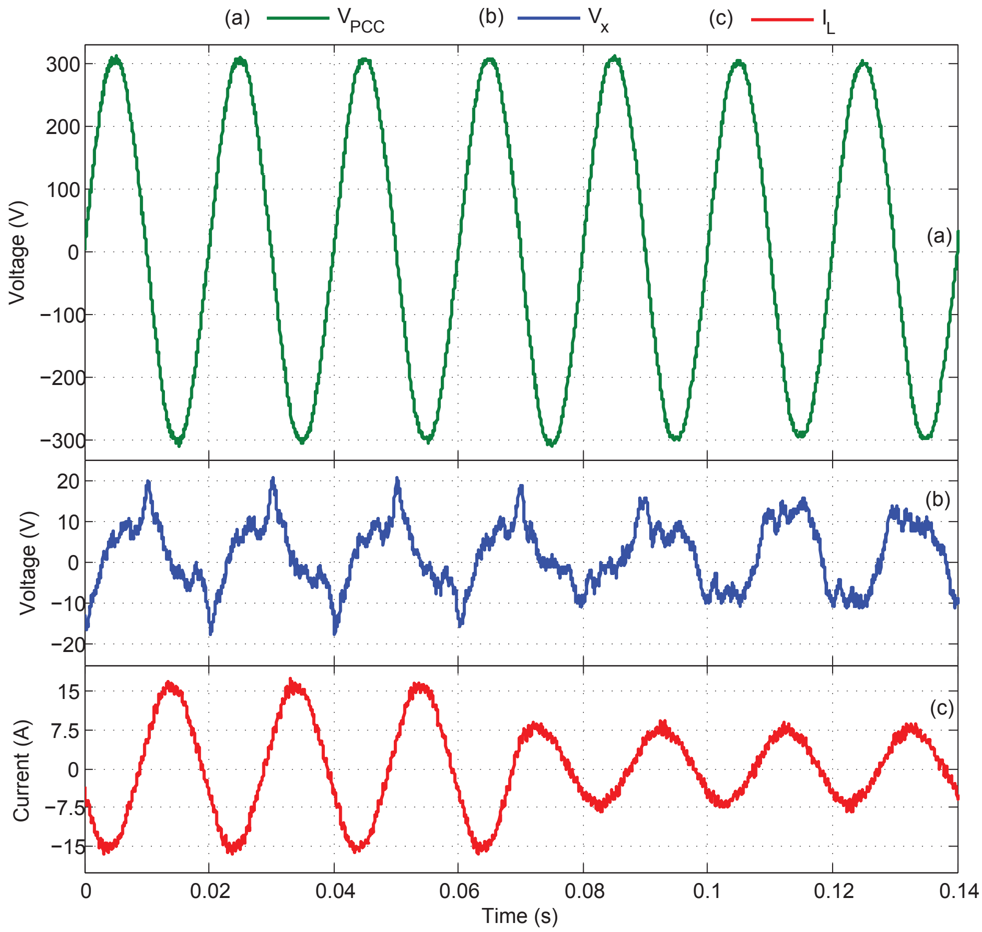

Figure 6.21: *Experimental - series unit response to load variation, removing the load – (a) PCC voltage, (b) series unit injected voltage, (c) load current.*

6.1.4 Operation Limits and V_{ref} Update

Open UPQC series unit needs an autonomous local controller in order to guarantee its continuous operation within standard limits, independent from grid and load variation. As it has been evaluated in detail in Chapter 2, the series unit has over and under voltage compensation operation limits. Those limits has been considered inside its controller design and V_{PCC_ref} update procedure is adopted as well. So, if series unit exceeds its operation limits, the implemented control method will update V_{PCC_ref} inside control loop and set it to optimum achievable value. With new V_{PCC_ref}, series unit would be able to continue its operation avoiding possible failure or instability.

This section reports only simulation results because due to the laboratory restrictions, it was not possible to perform same experimental results at laboratory as those have been created in simulation. Additionally, in order to illustrate operation limits and V_{PCC_ref} update process, grid voltage and load active and reactive power need to be set precisely which was not possible in our laboratory setup so, in this section only MATLAB based simulation results are reported. Similar to limits evaluation, simulations is run for two cases; over voltage and under voltage.

Over Voltage

In the case of over voltage the maximum grid voltage that can be compensated with only reactive voltage injection, can be calculated by Equation 6.1 as it was explained in Chapter 2 also.

$$|V_{s,max}| = \sqrt{|V_{x,max} + V_{PCC\_ref}.sin(\gamma)|^2 + |V_{PCC\_ref}.cos(\gamma)|^2} \tag{6.1}$$

The $V_{s,max}$ limit depends on two factors; $V_{x,max}$ which is series unit inverter maximum voltage ratio and γ that is supplied load power angle. To show an example of over voltage case limit exceed and V_{PCC_ref} update process, this situation is simulated as it is explained in following. Series unit inverter maximum voltage, $V_{x,max}$ is fixed to 30V. Constant load with power factor equal to 0.9 is connected at PCC which active and reactive powers are 8000 W and 3875 Var respectively. Nominal voltage value is 230V and V_{PCC_ref} is set to its nominal value accordingly. Replacing these values to Equation 6.1, the maximum grid side voltage that can be compensated by series unit can be computed and it is equal to 244.2V. Therefore with this configuration series unit is able to compensate over voltage events up to 244.2V at grid side but, for voltages over this limit the V_{PCC_ref} need to be updated by using Equation 6.2, in order to avoid active power absorption or series unit instability and failure.

$$V_{PCC\_ref} = -V_{x,max}.sin(\gamma) + \sqrt{(V_{x,max}.sin(\gamma))^2 + V_s^2 - V_{x,max}^2} \tag{6.2}$$

In order to demonstrate this operation limit and V_{PCC_ref} update process, the grid is simulated to initially have 5% voltage increment so, initially the grid voltage is equal to 1.05×230 = 241.5V and while it is inside series unit operation limit, it should be able to do perfect compensation and reach set nominal value at PCC voltage. Figure 6.22 shows the simulation results. As it is shown before t=2s, V_s is below its maximum limit and series unit is able to catch nominal set value (230V) as it can be seen in Figure 6.22 (b). At t=2s till t=3s, an immediate over voltage is simulated at grid side voltage and V_s became equal to 1.1 nominal value (253V) so, as it can be seen from Figure 6.22 (a), this new V_s exceeds the maximum V_s limit and series unit is no longer able to compensate this over voltage by pure reactive power. It either need active power injection to do complete compensation or it can update V_{PCC_ref} value to its minimum according to Equation 6.2. Replacing all the values inside Equation 6.2, new achievable reference for PCC voltage can be computed and it is equal to 238.8V.

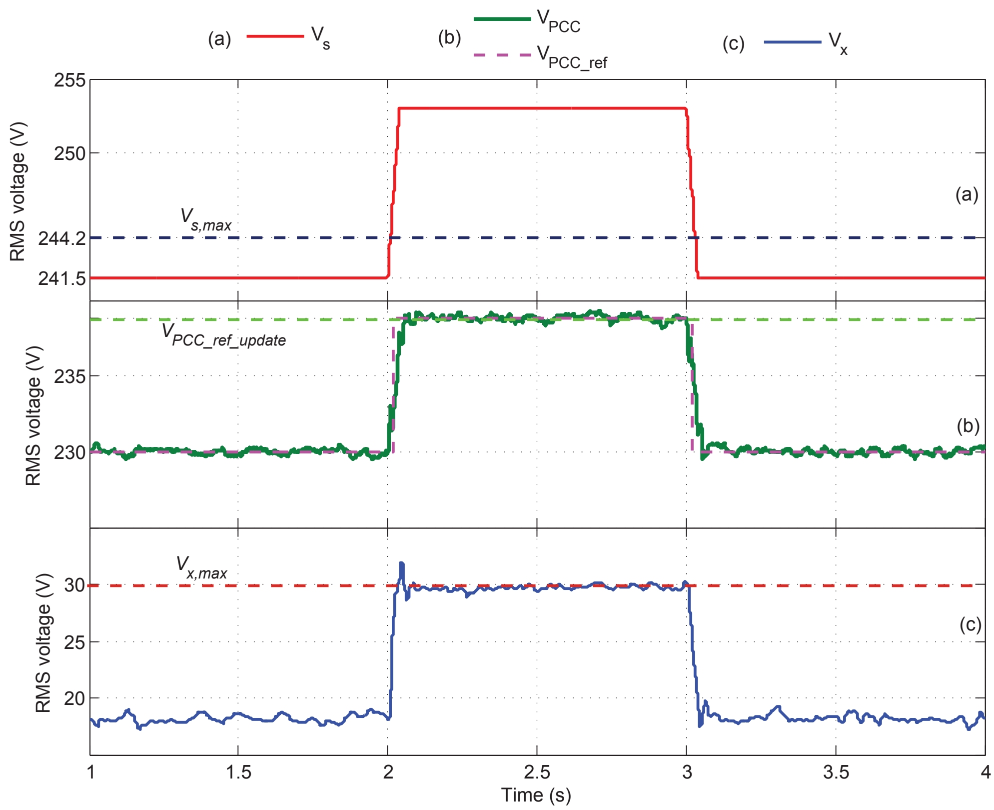

Figure 6.22: *Simulation - series unit operation limit and V_{ref} update demonstration, over voltage case – (a) grid side voltage, (b) PCC voltage and its reference, (c) series unit injected voltage.*

As it can be noticed from Figure 6.22 (a) when V_s exceeds its maximum limit, series unit updates its reference voltage to new value, Figure 6.22 (b) between t=2s till t=3s. With this new reference, although series unit is not able to do complete compensation and set PCC voltage to nominal value (230V) however, it sets V_{PCC_ref} to an upper value in order to perform partial compensation and keep system stable within standard definition.

Figure 6.22 (c) shows series unit injected voltage during this event. Before t=2s series unit injects about 20V, however inside the [2-3]s period, when system works close to its limit, series unit inject about 30V which is the series unit inverter maximum injection capability in this example. This results confirms that within [2-3]s period, series unit works at its operation limit.

After t=3s, system came back to its initial condition. The V_s is below its maximum limit, series unit is able to do perfect compensation setting V_{PCC} to its nominal value, Figure 6.22 (b), and series unit injected voltage is about 20V below series unit inverter maximum limit.

Under Voltage

In the case of under voltage, when the grid side voltage V_s is less than nominal value, the series unit is responsible to compensate this voltage drop and set V_{PCC} to nominal/set value. For this situation, as it has been explained in Chapter 2, the limits can be due to two different reasons; limit due to inverter maximum voltage and limit due to load power factor. Simulations has been performed for each cases and simulation case study results are reported respectively.

a) Limit due to $V_{x,max}$:

The under voltage limits due to inverter maximum voltage, V_x, can be calculated by Equation 6.3.

$$|V_{s,min\_a}| = \sqrt{|V_{PCC\_ref}.sin(\gamma) - V_{x,max}|^2 + |V_{PCC\_ref}.cos(\gamma)|^2} \tag{6.3}$$

With constant load and fixed γ, if the V_s goes below this limits, the series unit is no longer able to compensate voltage drop with reactive power only and it need to update the V_{PCC_ref} to the new value as it is reported in Equation 6.4.

$$V_{PCC\_ref} = V_{x,max}.sin(\gamma) + \sqrt{(V_{x,max}.sin(\gamma))^2 + V_s^2 - V_{x,max}^2} \tag{6.4}$$

In order to show series unit performance with this limit and V_{PCC_ref} update procedure, the series unit inverter maximum voltage is set to 30V, V_{PCC_ref} is set to its nominal value 230V and constant 8000 W + 3875 Var load with 0.9 power factor is connected as load. With this configuration the $V_{x,max}$ is less than $V_{PCC}.sin(\gamma)$ so, the system will touch limits due to $V_{x,max}$ rather than limits due to γ. The grid voltage, V_s is simulated to have 3% voltage drop and it is equal to 0.97$\times$ 230=223.1V till t=2s as it is shown in Figure 6.23. Replacing reported values into Equation 6.3 the minimum grid side voltage can be calculated and it is equal to 219V. Therefore, till t=2s the grid voltage is above this minimum, and series unit is able to perform perfect compensation at PCC following 230V voltage reference by injecting about 20V as V_x voltage.

Keeping the configuration, V_s is simulated to have further 7% voltage drop (total 10%) within t=[2-3]s as it is shown in Figure 6.23 (a). So, the grid side voltage between t=2s and t=3s is equal to 0.9$\times$ 230=207V and it is below system required minimum value as it can be computed from Equation 6.3, 219V. Consequently the series unit is no longer able to set voltage at PCC to its nominal value, and it updates the V_{PCC_ref} to new value according to Equation 6.4. The new achievable reference voltage is equal to 217.8V and as it can be seen from Figure 6.23 (b), within the period [2-3]s the new reference value is used, series unit is doing its best by injected its almost maximum

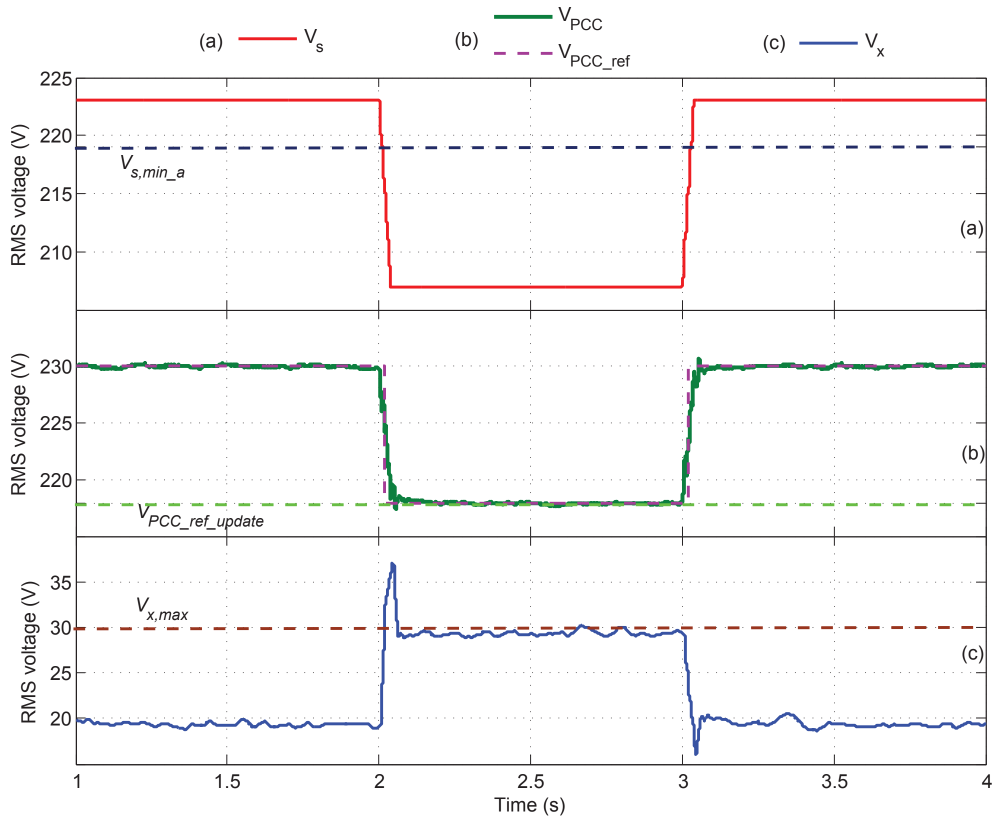

Figure 6.23: *Simulation - series unit operation limit and V_{ref} update demonstration, under voltage case a: limits due to $V_{x,max}$ – (a) grid side voltage, (b) PCC voltage and its reference, (c) series unit injected voltage.*

V_x value (30V) as it can be noted from Figure 6.23 (c). After t=3s, the V_s came back to its initial value (223.1V) and series unit moves to its acceptable operation limits and it is able to set V_{PCC} to its nominal value with reactive power compensation strategy.

b) Limit due to γ :

Series unit under voltage limits due to load power factor, γ, can be calculated using the Equation 6.5.

$$|V_{s,min\_b}| = |V_{PCC\_ref}.cos(\gamma)| \tag{6.5}$$

As it can be noticed from Equation 6.5, this limit can be rejected by load variation so, in contrast to previous cases, to touch under voltage compensation limits due to γ, the load need to be changed since in two previous cases the load was constant and grid side voltage V_s is simulated to have stepwise over voltage or voltage drop. So the simulation is done with constant voltage at grid side V_s = 0.9× 230=207V instead the load is simulated to have power factor equal to 0.9 till t=2s, P=8000W + Q=3875Var. The inverter maximum voltage, $V_{x,max}$, is set to 100V therefore the $V_{x,max}$ is greater than $V_{PCC}.sin(\gamma)$ and Equation 6.5 is valid to find under voltage operation limits rather than Equation 6.3. With cos(γ)=0.9 and using Equation 6.5 the minimum grid side voltage is equal to 207V so till t=2s the series unit is able to compensate 10% voltage drop with reactive power compensation method as it is shown in Figure 6.24.

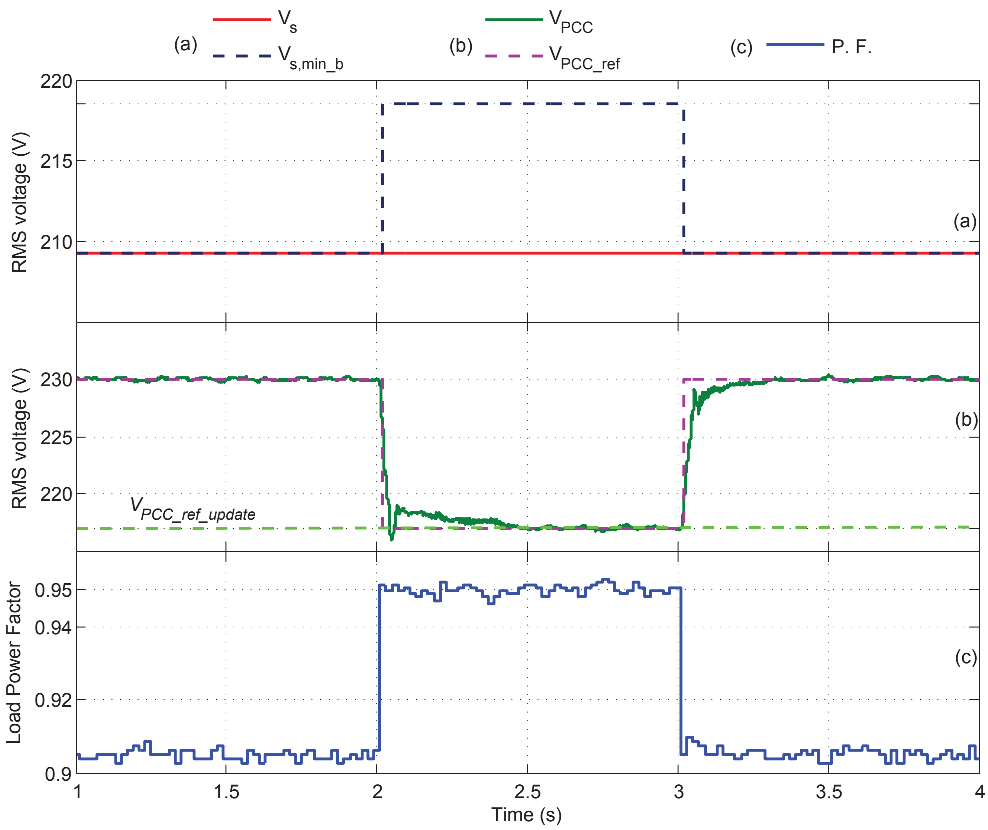

Figure 6.24: *Simulation - series unit operation limit and V_{ref} update demonstration, under voltage case b: limits due to γ – (a) grid side voltage, (b) PCC voltage and its reference, (c) load power factor.*

At t=2s till t=3s the load is simulated to have a step change to 8000W + 2630Var so, the load power factor decreases to 0.95 and new $V_{s,min}$ can be calculated from Equation 6.5 and replacing cos(γ)=0.95 it became 218.5V, as it is shown in Figure 6.24 (a). With this new values, within period [2-3]s the grid side voltage is less than system required minimum value so, within this period the series unit is not able to compensate 10% voltage drop with reactive power only. As it is described in Chapter 2, the reference value can be updated to the maximum achievable PCC reference value which can be found from Equation 6.6. Using Equation 6.6 new reference value can be found and it is equal to 217V and as it is represented in Figure 6.24 (b), between t=2s and t=3s the PCC reference value is updated to 217V in order to avoid series unit instability and continue its operation.

$$V_{PCC\_ref} = \frac{|V_s|}{cos(\gamma)} \tag{6.6}$$

Figure 6.24 (c) shows load side power factor variation. As it can be noticed, after t=3s the load power factor came back to its initial value (0.9) and series unit moved back into its operation limits. The V_{PCC_ref} update is ignored and the reference is set to its nominal value (230V) after t=3s, as it is shown in Figure 6.24 (b).

6.1.5 Field Record - Series Unit

Figure 6.25 shows a field record from series unit which belongs to May 2016. Records show series unit field test for duration more than 2 hours. The data were collected every minutes and as it can be noticed from Figure 6.25(b), during the data record period, grid voltage has about 5V voltage drop from nominal value.

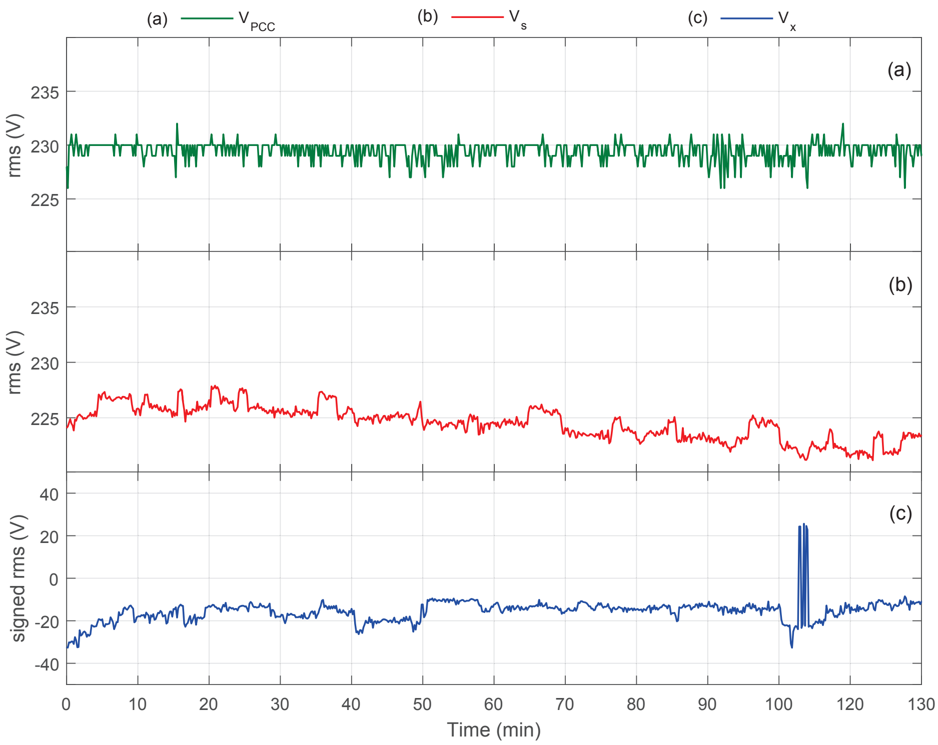

Figure 6.25: *Field Experiment, May 2016 - Series unit (a) PCC voltage, (b) grid voltage, (c) series unit injected voltage.*

Figure 6.25(a) shows that series unit were able to keep voltage at PCC around nominal value. The injected voltage RMS (signed value) is shown in Figure 6.25(c). It shows that series unit were compensating the voltage drop at grid side by injecting about 20V. From Figure 6.25(c), it can be noticed that during some periods the injected voltage change its sign (became positive). This means that series unit change its voltage injection direction. Referring to Chapter 2, the series unit depending on loading condition (inductive or capacitive) can change voltage injection direction. Field test records are shown for long term voltage drift only since during field records no short term voltage sag or swell were occurred on installed line.

6.2 Shunt Unit

Same as the series unit, shunt unit has been simulated in MATLAB based simulation with discrete time fixed step solver and it has been realized according to Chapter 5 hardware design description. Shunt unit performance in order to deliver different services have been reported based on simulation study and also from experimental prototype. The results can be classified into three general conditions; basic and auxiliary services during *Online* operation mode, transition from *Online* to *Island* operation and vice versa and finally *Island* operation mode performance. During *Online* operation mode, simulation and experimental results have been obtained for a system configuration that is depicted in Figure 6.26.

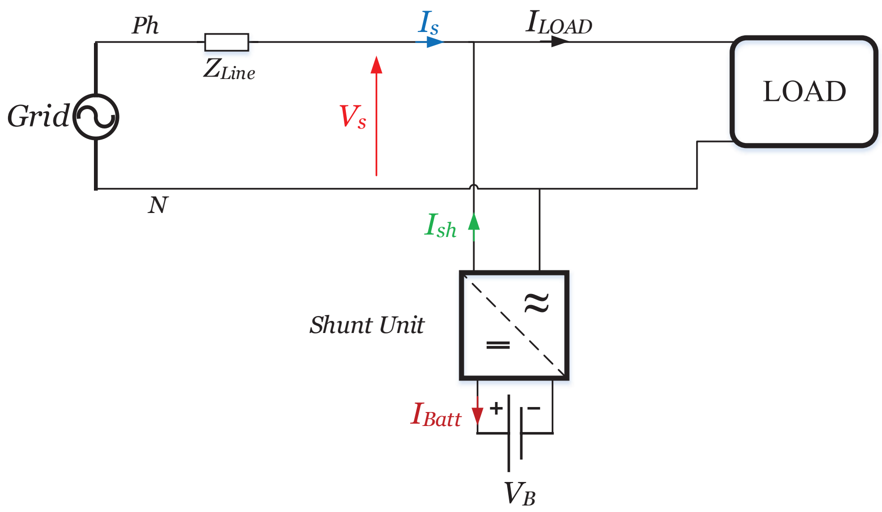

Figure 6.26: *Simulation and Experimental schema - shunt unit Online operation mode.*

Figure 6.26 shows the shunt unit connected in parallel in front end of a load. V_B represents the battery set voltage. I_{Batt} stands for current through/from battery from/to the inverter DC bus. I_{sh} is the shunt unit current which can be composed of different components based on functionalities that shunt unit is performing. V_s is the grid voltage at load connection point, I_s is the grid side current and I_{LOAD} is the load side current and according to KCL, at any moment Equation 6.7 should be respected.

$$I_s = I_{sh} + I_{LOAD} \tag{6.7}$$

MATLAB based simulation is created to verify designed control method prior to laboratory experiment and here simulation results have been reported to show the consistency between simulation and experimental tests, however some functionalities are trivial studies with simulation and only experimental performance of the realized device is addressed.

6.2.1 Online - No load No Charging

Online operation has high importance because the shunt unit mostly will operate in this operation mode. Therefore it is important to understand realized device performance during *Online* operation mode specially from device losses point of view. Figure 6.27 shows shunt unit performance while it is connected parallel to the gird with no load on it. Moreover the battery set charging function is disabled so, device's losses can be evaluated. Figure 6.27 (b) shows the grid side current. Shunt unit absorbs about 55W active power from grid. This active power is meant to compensate shunt unit inverter losses and regulate DC bus voltage.

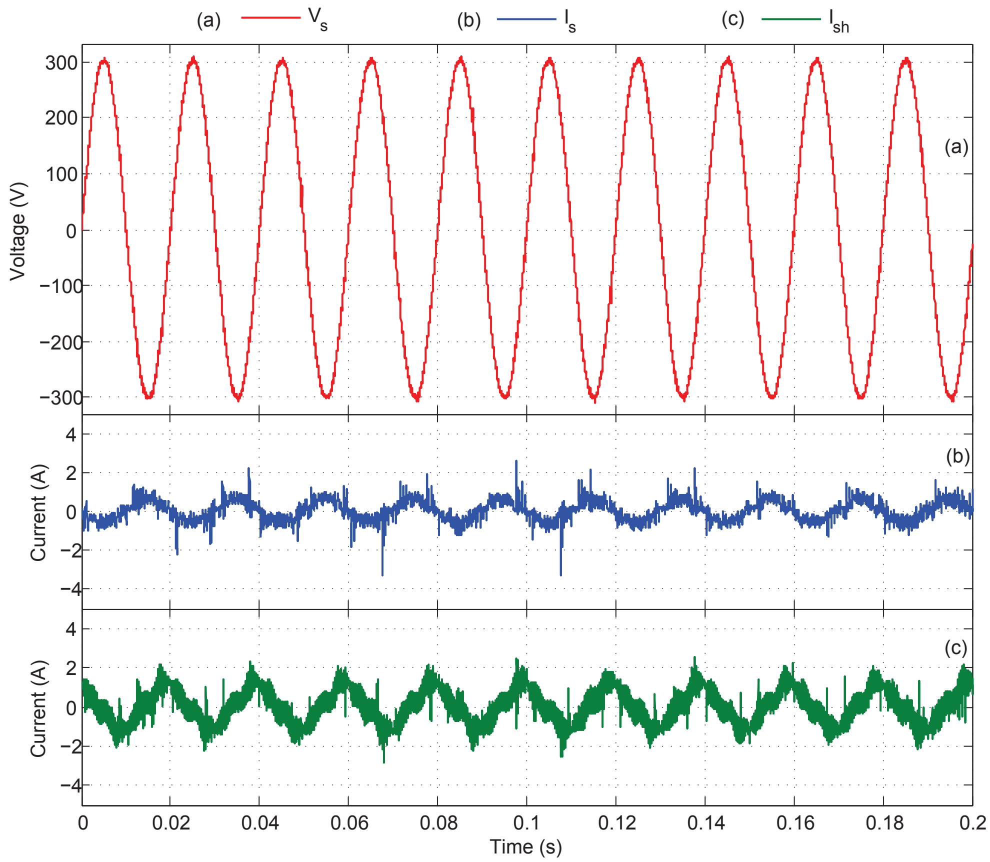

Figure 6.27: *Experimental - shunt unit Online operation mode, No load No charge – (a) grid voltage, (b) grid current. (c) shunt unit current.*

Figure 6.27 (c) shows shunt unit inverter side current. Shunt unit inverter absorbs about 165 VA, 55W + 155Var, from gird. The active part is the same power from grid side instead the reactive part is the reactive power associated to shunt unit inverter side low-pass filter (C_f as it is described in Chapter 5). In the case of shunt unit, this low-pass filter has 10μF capacitor and the required reactive power is equal to about 160Var and experimental result is consistent with theoretical calculation.

The active power (losses) evaluation is more important because the device will be installed in front end of a domestic load and device losses is included in the customer consumption. As it was explained in Chapter 2, the shunt unit can be sent to OFF mode in order to switch off the device and cancel device losses when neither the end user nor DSO are interested on any services from shunt unit.

6.2.2 Online - Charging the Storage

One of the important actions during *Online* operation mode, is to charge the battery set. Due to laboratory limits it was not possible to record all the current and voltages during charging mode at the same time, therefore simulation results is reported as well for this action.

Simulation

The device is connected parallel to a 1kW load and it is simulated to charge the batteries with nominal DC charge current (3A). Figure 6.28 shows the simulation results. Figure 6.28 (a) and (b) show the grid voltage and current. Grid side current is the summation of load and shunt unit current. Shunt unit current has about 2A peak value and again it is composed of shunt unit low-pass filter reactive current and battery charging active power, as it is shown in Figure 6.28 (c). Figure 6.28 (d) shows the battery charging DC current which is set to its nominal current (3A). Battery voltage is about 80V and with 3A, it needs 240W active power so at inverter ac side (230V ac), it requires about RMS 1A current to charge battery with their nominal charge current.

Experiment

Experimental tests have been performed to verify the results from simulation and observe realized shunt unit performance. First the shunt unit is connected parallel to the grid to charge the batteries with no load on it. So, in this configuration the shunt unit acts as a load which is connected parallel to the grid.

Figure 6.29 shows the shunt unit performance during this test. Grid side voltage and current are reported at Figure 6.29 (a) and (b). In this condition the shunt unit

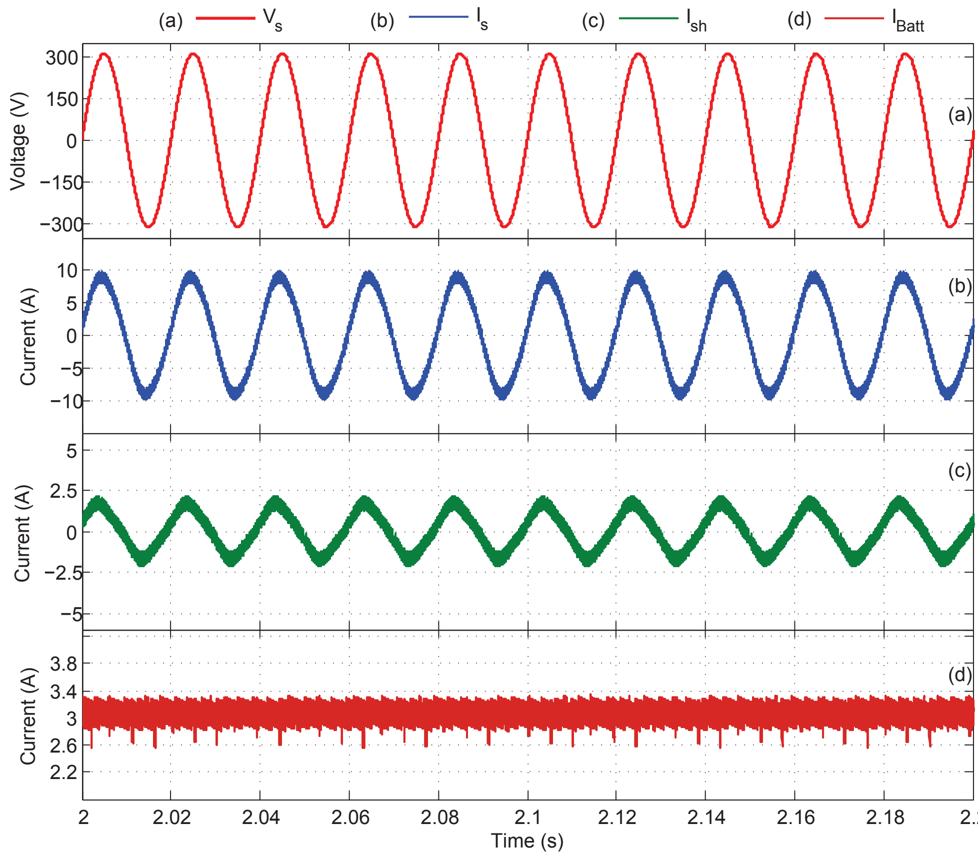

Figure 6.28: *Simulation - shunt unit Online operation mode, battery charge – (a) grid voltage, (b) grid current, (c) shunt unit current, (d) Battery charge current.*

current is the same as grid side current and that is why shunt unit current is not shown in Figure 6.29.

As it can be seen from Figure 6.29(b), grid side absorbs about 2A current which is the summation of battery charge current, inverter losses and also inverter low-pass filter reactive current.

Same as simulation, results with 1 kW load is reported as well. Figure 6.30 shows the shunt unit *Online* operation mode performance while 1 kW constant load is connected and shunt unit charges the batteries with nominal 3A current. Figure 6.30 (b) shows grid side current which is the summation of load current and also shunt unit current that is shown in Figure 6.30 (c). Shunt unit current is almost the same as the current without load condition, as it is shown in Figure 6.29 (b) and it is the summation of the active current to charge the batteries and also reactive power required for inverter side low-pass passive filter (C_f).

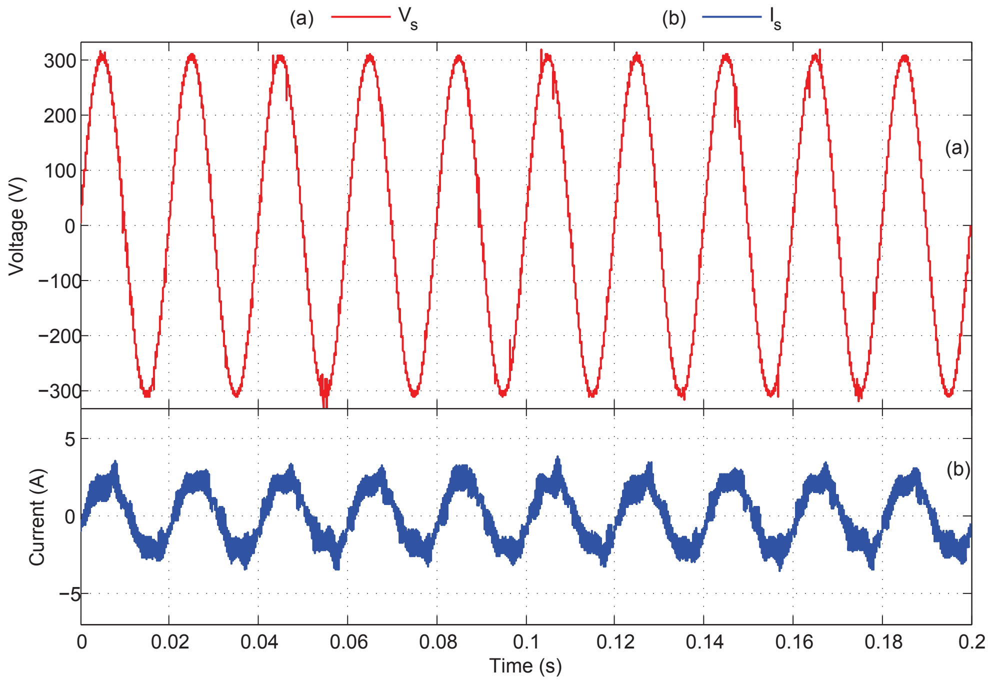

Figure 6.29: *Experiment - shunt unit Online operation mode, battery charge, no load – (a) grid voltage, (b) grid current.*

6.2.3 Online - Peak Shaving

Peak shaving is another important functionality of shunt unit. During peak shaving, shunt unit fixes grid side active power to the requested threshold and supply the exceeded power of the load by means of energy stored inside the battery set. So, as it can be understood, during peak shaving action, shunt unit discharges the battery set and uses energy inside batteries to supply part of the load.

Simulation results on this action is similar to one that is used in Chapter 2 to demonstrate the peak shaving principle so here only experimental result is presented. In order to show shunt unit performance during peak shaving in laboratory set up, shunt unit is connected parallel to a load with about 2.4 kW power. Results are reported in Figure 6.31. Grid voltage is shown in Figure 6.31 (a) and instantaneous grid side and load currents are shown in Figure 6.31 (b) where those current RMS values are shown in Figure 6.31 (c). As it can be seen from Figure 6.31 (c), till t=0.2s the device is working in *Online* operation mode, charging the batteries, because the grid side current is greater than load current (difference between I_s and I_{LOAD} is the battery charging current).

Peak shaving threshold on shunt unit is set to 1.3kW (just to show device performance and there is no reason for that) and at t=0.2s the command is sent to shunt unit. Shunt unit first reaction for peak shaving command is to stop charging the batteries as

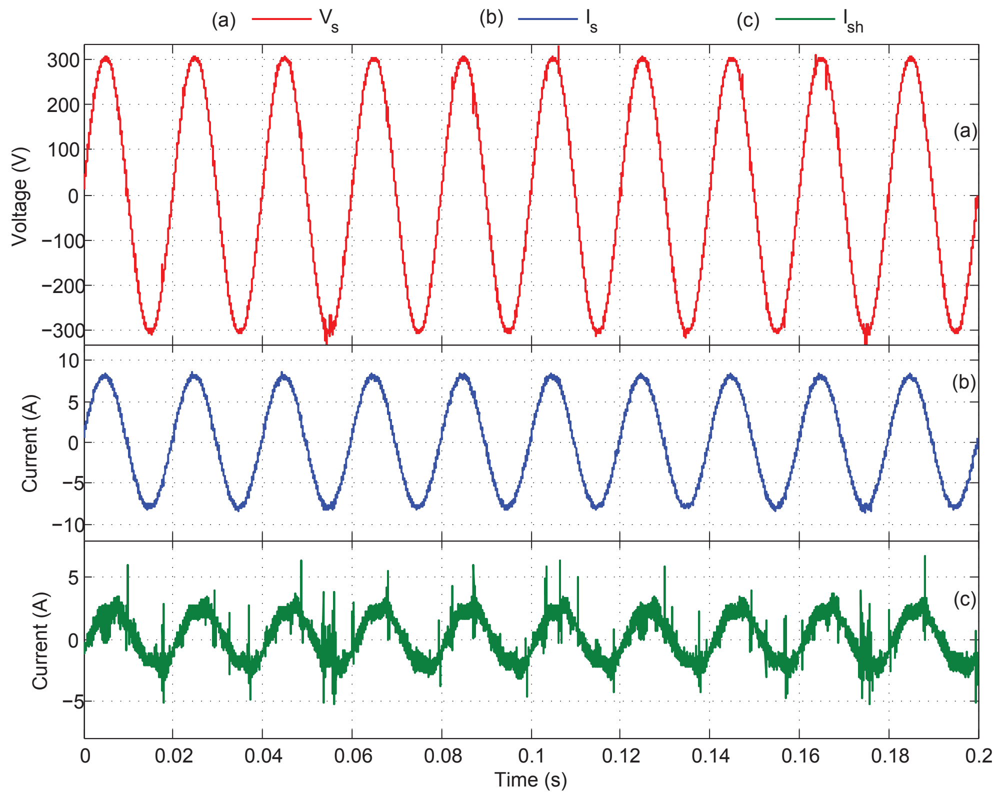

Figure 6.30: *Experiment - shunt unit Online operation mode, battery charge with 1kW load – (a) grid voltage, (b) grid current, (c) shunt unit current.*

it can be noticed form Figure 6.31 (c) where from t=0.2s till t=0.3s the grid side current and load current are the same. Then the grid side current starts to decrease slowly till the grid side current reaches about 6A. The grid side current is fixed to about 6A so, the grid side power is fixed to peak shaving threshold thanks to shunt unit peak shaving action. The difference between grid side current and load current is supported by shunt unit during the experiment always.

6.2.4 Online - Load Reactive Power Compensation

Shunt unit has the capability to compensate load reactive power and set grid side power factor to unity. This functionality is same as STATCOM but shunt unit controller is designed to have smooth and slow response rather than fast and instantaneous compensation. Simulation and experimental results in case of reactive power compensation are quite similar and here only simulation steady state result is shown to demonstrate device operation logic.

Figure 6.32 shows results of a simulation where shunt unit is connected parallel to a load with 2kW + 1.5kVar. So, shunt unit responsibility is to compensate load reactive power and provide unity power factor at grid side. With this functionality,

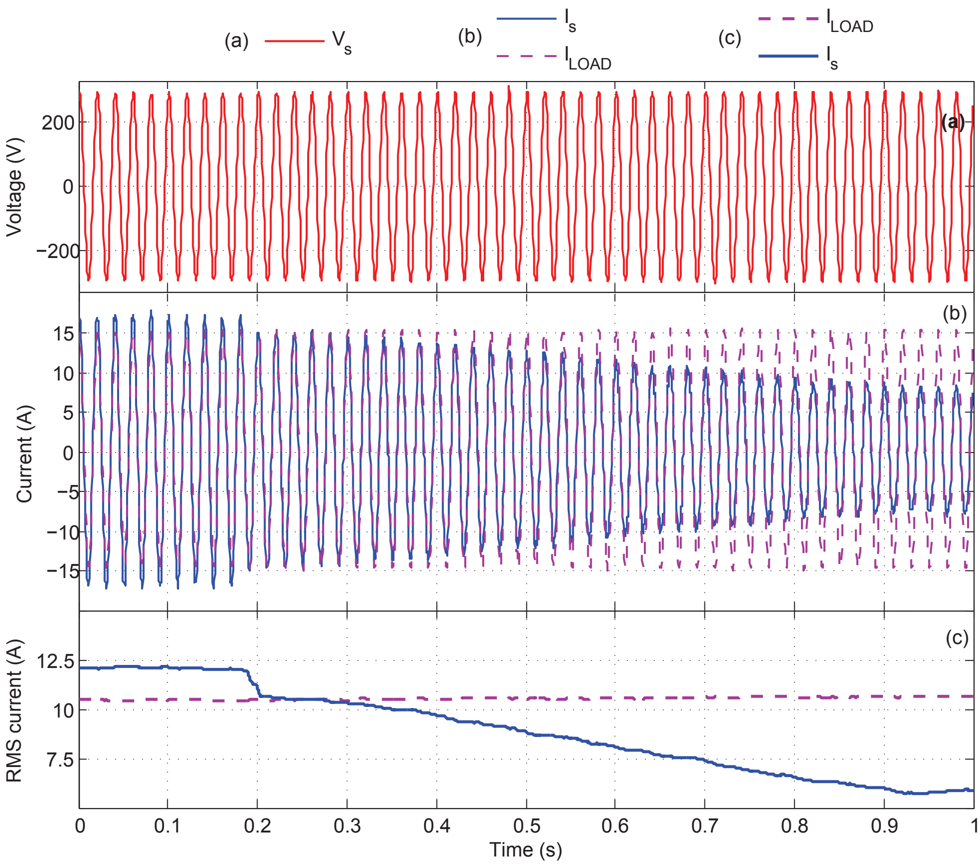

Figure 6.31: *Experiment - shunt unit Online operation mode, peak shaving – (a) grid voltage, (b) grid and load currents, (c) grid and load rms currents.*

grid supplies only active power of the load and load reactive power is supplied by shunt unit.

Figure 6.32 (a) shows grid voltage and in Figure 6.32 (b) load current is depicted. Grid side current (I_s) is shown in Figure 6.32 (c) and as it can be seen, it is in phase with grid voltage and its magnitude also is reduced regarding load current. This grid side current is only active power of the load indeed reactive power of the load is supplied by shunt unit where shunt unit current is shown in Figure 6.32 (d) which is pure reactive power and it is perpendicular to the grid voltage.

6.2.5 Online - Load Harmonic Compensation

Shunt unit has the capability to compensate up to 11th harmonic order of the connected load current. The implemented control method is based on one cycle FFT analysis so, it is not instantaneous and it requires at least one fundamental period (20 ms) in order to detect load's harmonic current and perform compensation action. In order to demonstrate harmonic compensation capability of shunt unit, a load with distorted

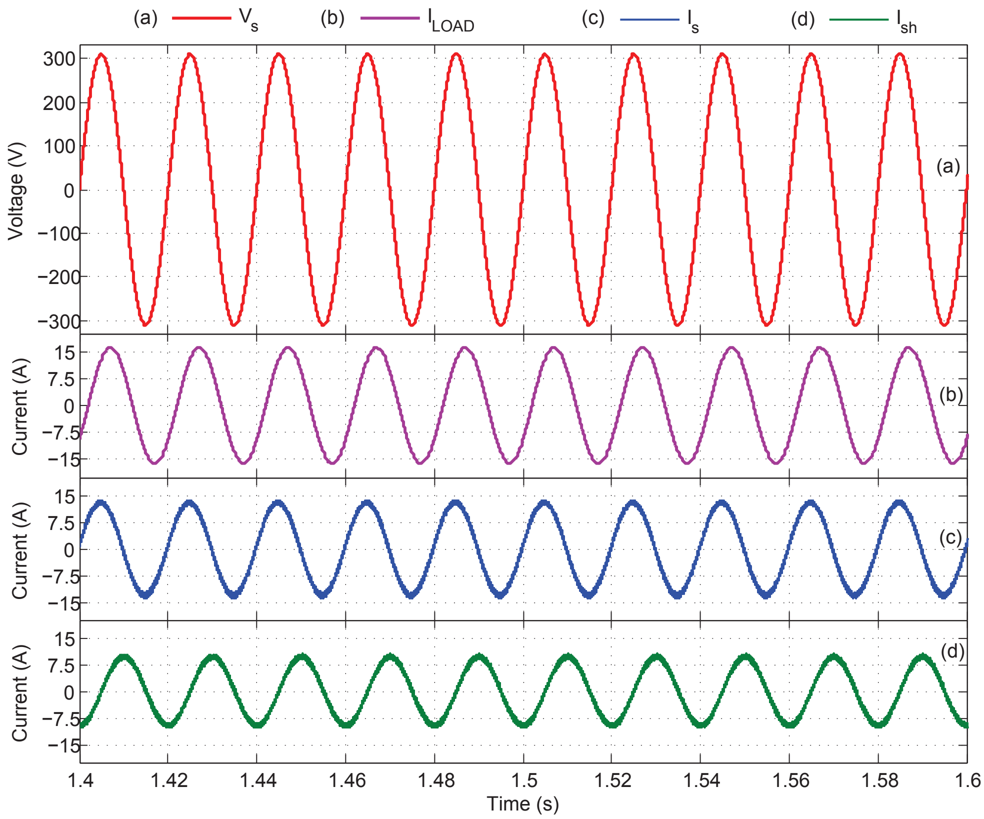

Figure 6.32: *Simulation - shunt unit Online operation mode, load reactive power compensation – (a) grid voltage, (b) load current, (c) grid current, (d) shunt unit current.*

current is required. Open UPQC shunt unit is designed to be connected in front end of domestic load and in domestic LV loads, there is not significant harmonics so it is not easy to illustrate experimental field test results on load harmonics compensation. Therefore here simulation results are shown to demonstrate device harmonic compensation capability. Simulation has been carried out, shunt unit is connected parallel to a load supplied by a diode bridge. The load is connected on DC side of diode bridge and in order to simulate similar situation and quite the same load current ratio as other test cases, RL load is considered equal to 20Ω+0.42H so, the load current is about 10A.

Figure 6.33 shows the simulation results recorded on ac side. The load current, Figure 6.33(b) is highly distorted however thanks to shunt unit harmonic compensation, at grid side the current is perfectly sinusoidal and in phase with grid voltage, Figure 6.33 (c). The compensation is performed by shunt unit, injecting proper harmonic orders as it is shown in Figure 6.33 (d).

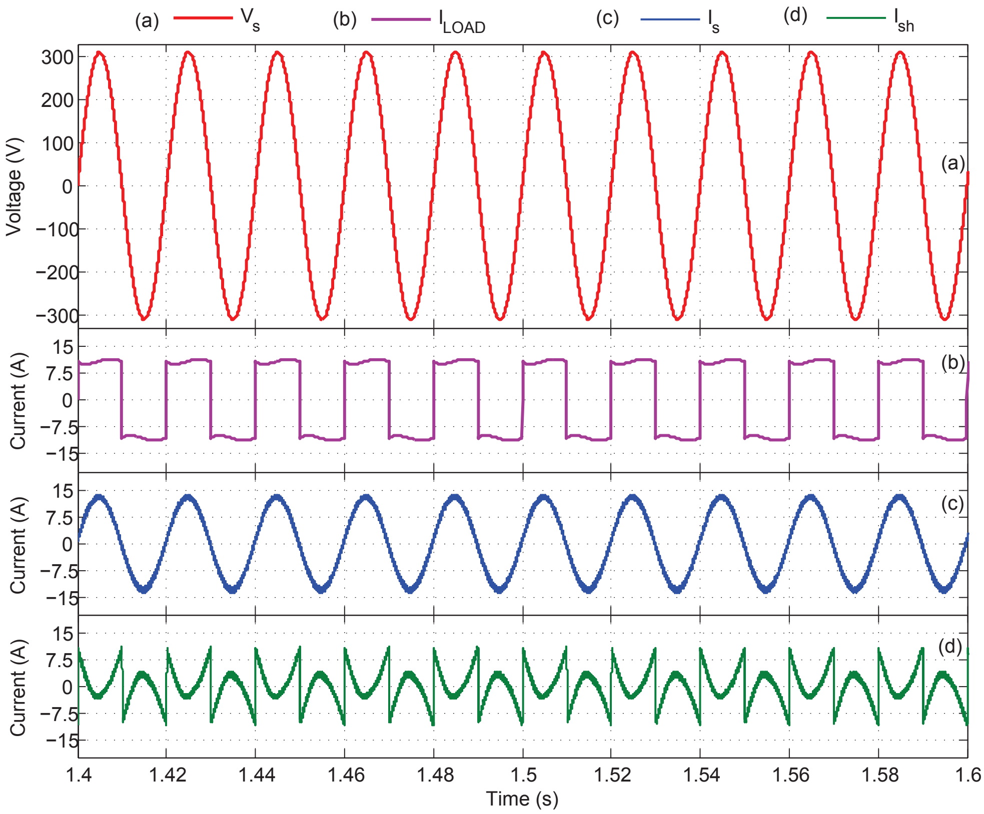

Figure 6.33: *Simulation - shunt unit Online operation mode, load harmonic compensation – (a) grid voltage, (b) load current, (c) grid current, (d) shunt unit current.*

6.2.6 Online - Reactive Power Generation

Shunt unit reactive power generation is an auxiliary service for the grid and DSO. It is fundamental also, to improve series unit performance by means of co-operation. Indeed this function is quite the same as reactive power compensation functionality which the grid side reactive power is set to a constant value rather than zero. Therefore experimental result is reported by setting grid reactive power ($Q_{request}$) to a constant value.

To run the Experimental test, shunt unit is connected parallel to a load with 800W and $Q_{request}$ is set to 500Var. Therefore, shunt unit responsibility is to fix grid side reactive power to 500Var. Figure 6.34 shows laboratory experiment results on this test. Figure 6.34 (a) and (b) show grid side voltage and current respectively. At grid side the active and reactive power are equal to 1175W and 500Var respectively. As it can be noticed the grid side reactive power is set to requested value. Grid side active power is the summation of load active power and about 325W active power which shunt unit absorbs to charge the batteries. Shunt unit active and reactive powers are also recorded during the test. Shunt unit absorbs 325W active power and it produces

565Var reactive power. Shunt unit reactive power is equal to load reactive power plus requested reactive power so, shunt unit need to produce summation of requested reactive power and also load reactive power (considering sign also) in order to set grid side reactive power to the set value.

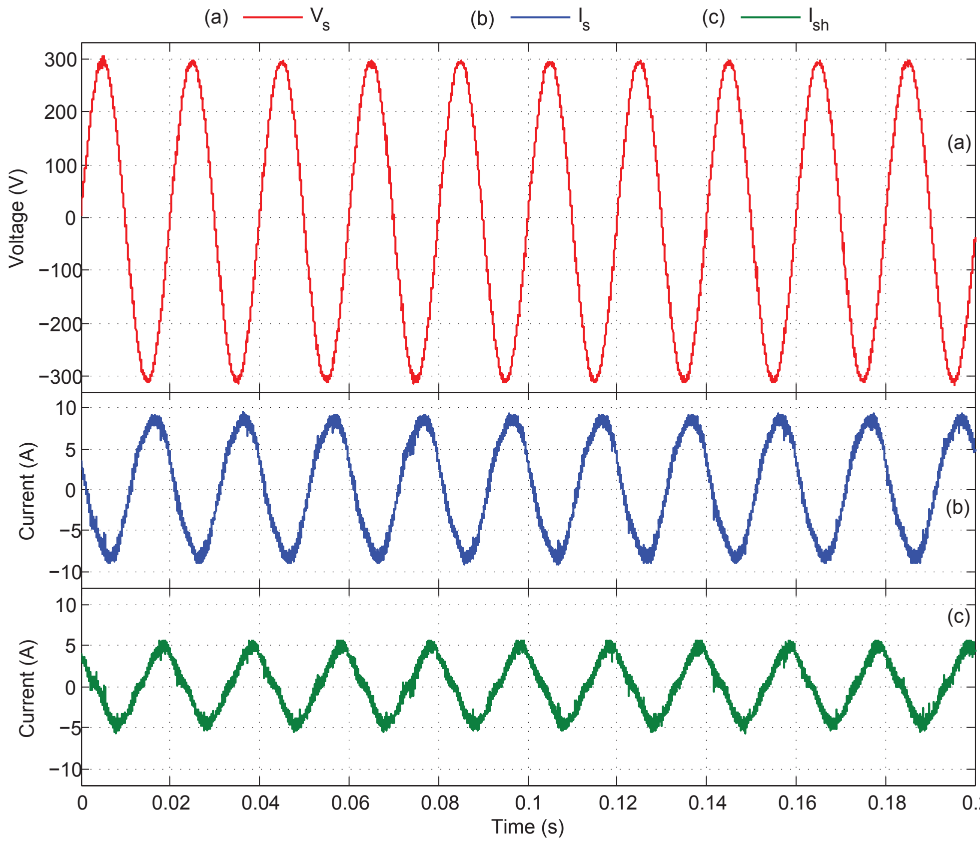

Figure 6.34: *Experiment - shunt unit Online operation mode, reactive power injection – (a) grid voltage, (b) grid current, (c) shunt unit current.*

6.2.7 Transition - *Online* to *Island*

Transitions from *Online* to *Island* operation mode and vice versa, are two important actions that shunt unit should be able to deal with minimum impact on load (customer) voltage and current profile. The implemented control strategy is explained in Chapter 2 with some simulation demonstrations on its performance. However, it is important to verify those results by experiment.

Figure 6.35 shows two operation modes where the difference between two modes can be understood. During *Online* operation mode, Figure 6.35 (a), most of the load power is supplied from grid. Shunt unit can absorb active power to charge the batteries or inject active power to do peak shaving action. Instead during *Island* operation mode, Figure 6.35 (b), the load is decoupled from grid by means of SS and all the active and reactive powers of the load need to be provided by shunt unit, energy coming from battery set.

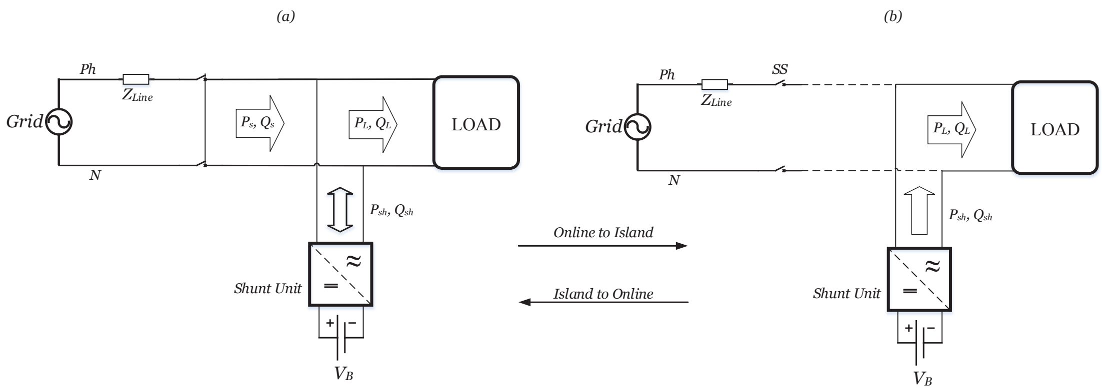

Figure 6.35: *Shunt unit transition from Online to Island and vice versa, (a) Online, (b) Island.*

Experiment results are illustrated for both transitions. Figure 6.36 shows *Online* to *Island* mode transition. The shunt unit was connected parallel to a load about 1kW and it was working in *Online* mode till around t=0.035s where a sudden interruption is happen at grid side voltage and shunt unit reacted immediately and take over the load with less than quarter a cycle (5ms), where Figure 6.36 (a) shows load voltage profile which before transition is grid voltage (V_s) and after transition it is shunt unit ac terminal voltage. Figure 6.36 (b) shows the load current which follows the voltage profile and shunt unit current is depicted in Figure 6.36 (c). The shunt unit current before grid interruption was a small current to charge the battery set but, immediately after grid interruption, shunt unit starts to supply the load so, shunt unit current is same as load current. As it can be noticed from Figure 6.36, the interruption is happen close to voltage peak, and shunt unit was able to detect the interruption and react to restore the load voltage profile in less than 5ms.

6.2.8 Transition - *Island* to *Online*

Reverse transition from *Island* to *Online* operation mode is important in order to reconnect the load to the grid with minimum stress on shunt unit components specially the SS. Because, during *Island* operation mode the shunt unit voltage is no longer synchronized to the grid voltage and it may have big phase difference regarding grid voltage. So, if the reconnection is made without resynchronization, the voltage stress can damage shunt unit components and it also affects load voltage profile.

The synchronization step is described in Chapter 2 and here experimental results of realized shunt unit with implemented control algorithm is reported. Figure 6.37 shows the *Island* to *Online* transition experimental response. The figure shows reconnection

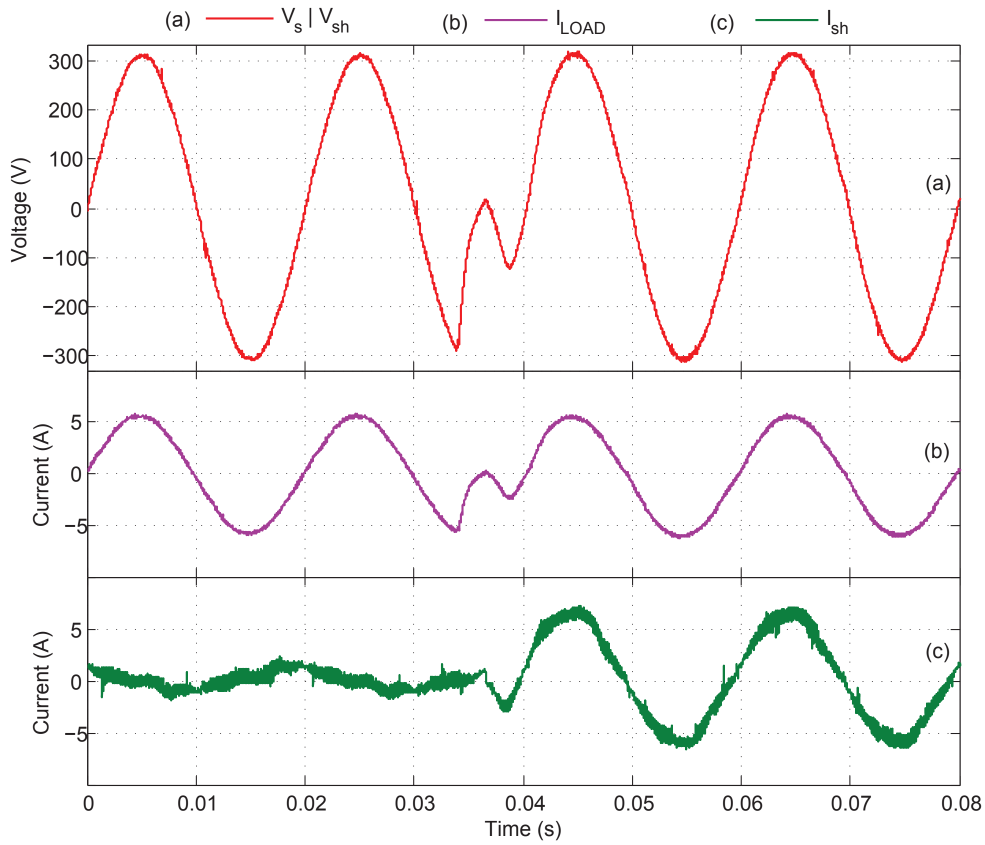

Figure 6.36: *Experiment - shunt unit transition, Online to Island – (a) grid/shunt unit voltage, (b) load current, (c) shunt unit current.*

moment while synchronization has been done before.

The system was in *Island* operation mode. Grid voltage came back to its acceptable range and shunt unit has detected that grid voltage is within standard voltage range. Shunt unit has started synchronization and when the shunt unit ac terminal voltage is in phase with grid voltage and magnitudes match each others, shunt unit waits for next zero crossing to reconnect the load to the grid and change its operation mode from *Island* to *Online*.

Figure 6.37 (a) shows the shunt unit (grid) voltage where the reconnection has been made not exactly at the moment of zero crossing but with some delay (about t=0.041s) due to hardware and also delays inside implemented software. The load current follows its voltage profile Figure 6.37 (b) and shunt unit current as it is shown in Figure 6.37 (c) is equal to load current before reconnecting to the grid and after going to *Online* operation mode the shunt unit current became zero.

After *Island* to *Online* transition, shunt unit follows zero as current reference and for a short period it does nothing and it evaluates the battery SoC and other system data before completely moving to *Online* operation mode.

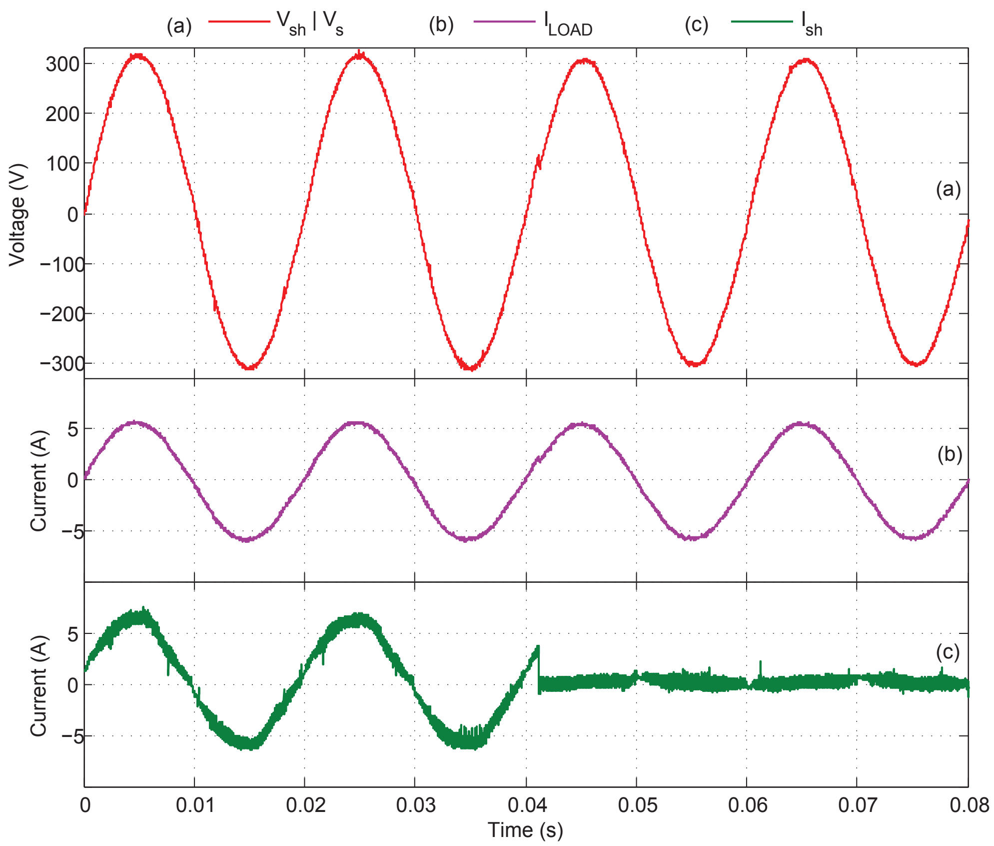

Figure 6.37: *Experiment - shunt unit transition, Island to Online – (a) shunt unit/grid voltage, (b) load current, (c) shunt unit current.*

6.2.9 Island - Noload

Open UPQC shutn unit *Island* operation mode is like a single phase inverter supplying a load by means of energy from a battery set. The configuration is shown in Figure 6.35 (b) and here simulation and experimental results are reported on its performance and transients.

Figure 6.38 shows the shunt unit experimental performance working in *Island* operation mode with no load at its terminals. Figure 6.38 experimentally verifies that shunt unit is able to work as sinusoidal constant voltage source in order to supply the load.

6.2.10 Island - Under Load

Instead Figure 6.39 shows the shunt unit steady state performance during *Island* operation mode supplying 1kW load. Figure 6.39 (a) shows the voltage at shunt unit output (load) terminals and it can be seen that shunt unit is able to provide sinusoidal voltage to supply the load and Figure 6.39 (b) shows the shunt unit current which is the same

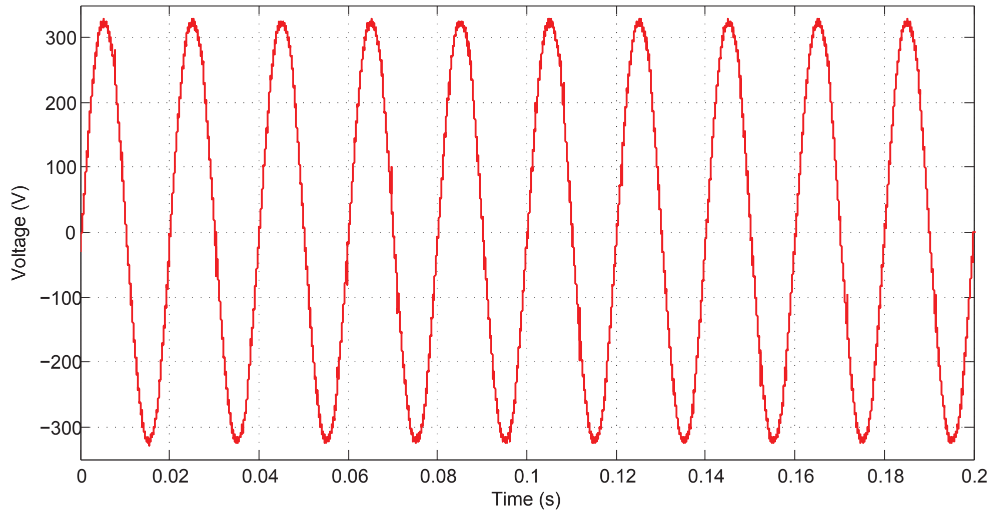

Figure 6.38: *Experiment - shunt unit Island operation mode, no load.*

as load current in this operation mode.

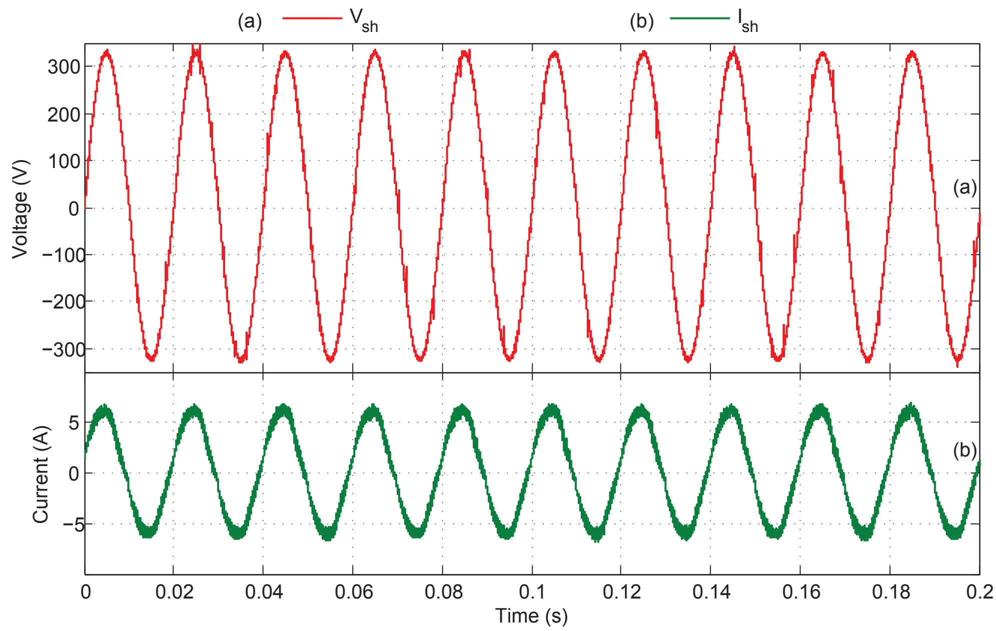

Figure 6.39: *Experiment - shunt unit Island operation mode, 1kW load – (a) shunt unit voltage, (b) shunt unit current.*

6.2.11 Island - Load Variation

Beside steady state response of shunt unit during *Island* operation mode, its transient behavior also taken into account for quite large load step change. Device response for adding the load is considered which has considerable effect on load voltage profile and also shunt unit DC bus control. Removing the load has negligible effect on shunt unit so here simulation and experimental results are reported for adding 1.5kW load during *Island* operation mode.

Simulation

Simulation has been conducted for the shunt unit working in *Island* operation mode with no load and suddenly 1.5kW load is connected as load and system transient behavior is reported in Figure 6.40. Shunt unit ac terminal (Load) voltage profile experience a disturbance connecting the 1.5kW load at t=3.006s. The load is connected at t=3.006s in order to simulated similar condition which the experimental results is recorded, as it is reported later. The load is connected around voltage peak and this transient has high impact on shunt unit performance and load profile because load requires big step on current. If the connection has been done at zero crossing, the load current will be started from zero which will decrease transient effects on load current.

Figure 6.40 (b) and (c) show load and shunt unit current profiles during the transient load step change. Load current follow its voltage profile and since the system is in *Island* operation mode, shunt unit current is the same as load current.

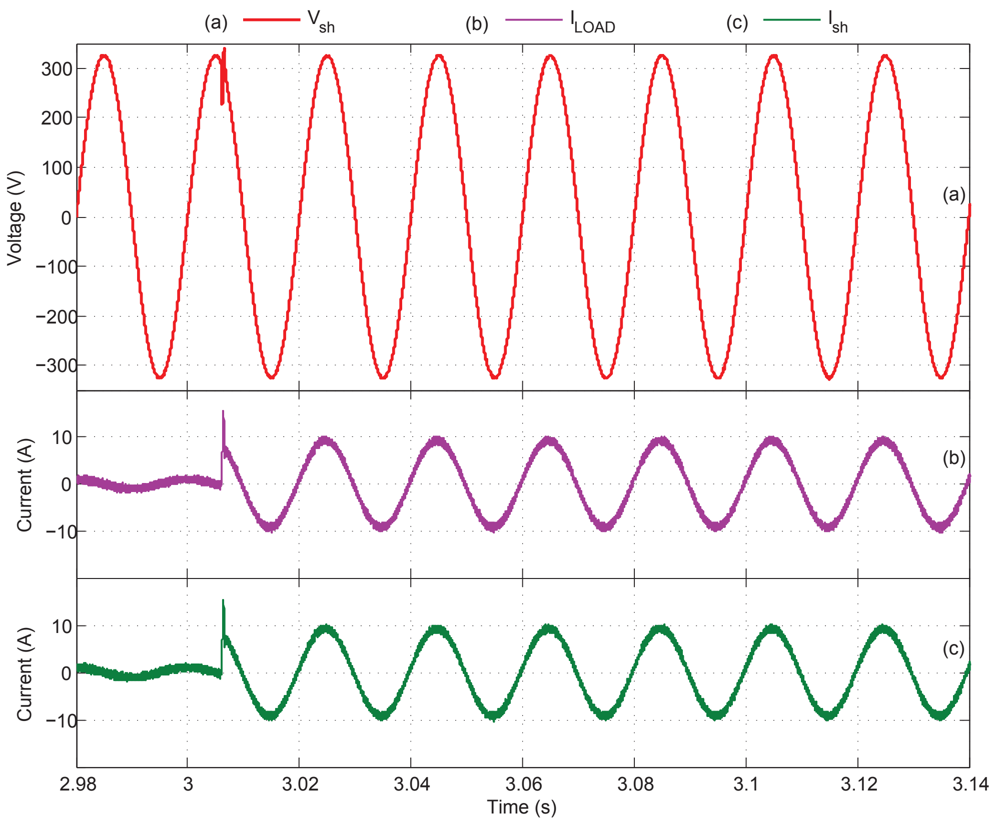

Figure 6.40: *Simulation - shunt unit Island operation mode, 1.5kW step load change – (a) shunt unit voltage, (b) load current, (c) shunt unit current.*

Figure 6.41 shows the shunt unit DC bus voltage response for the same event but longer shot is shown for DC bus response. During *Island* operation mode, DC bus voltage is controlled by means of chopper leg using energy inside the batteries. The energy inside the batteries is managed to keep DC bus voltage constant for shunt unit inverter proper functioning. Records in Figure 6.41 prove that connecting 1.5kW load, DC bus experience a slight voltage drop and then a transient over shoot. However the shunt unit controller is able to stabilize DC bus voltage in less than half second.

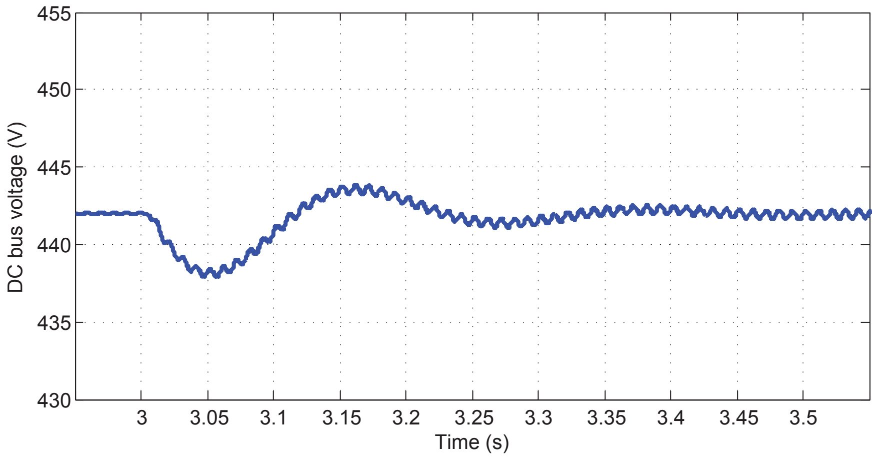

Figure 6.41: *Simulation - shunt unit Island operation mode, DC bus voltage response on 1.5kW step load change.*

Experiment

In order to verify the system performance in practice, experiment test has been performed in laboratory and results are reported. Similar to the study that has been done for simulation, initially shunt unit was working in *Island* operation without any load at its terminal and suddenly 1.5kW load is connected to its output terminal. Figure 6.42 reports the device's response.

Figure 6.42 (a), (b) and (c) show load voltage, load current and shunt unit current respectively. It shows that system was working without load till about t=0.03s so as it can be noticed before adding the load, load current is equal to zero however shunt unit produces a small amount of current and it is due to shunt unit inverter output low-pass filter which is working as load for shunt unit in this condition.

By connecting the load at around t=0.03s, the load voltage and current see a transient which is much severe than simulation study one because of the practical limits that the realized unit has. As it can be noticed from Figure 6.42 (c), connecting the load, shunt unit current experience a pretty large over shoot and due to inverter and switching inductance limits the current is saturated at around 25A peak value. This

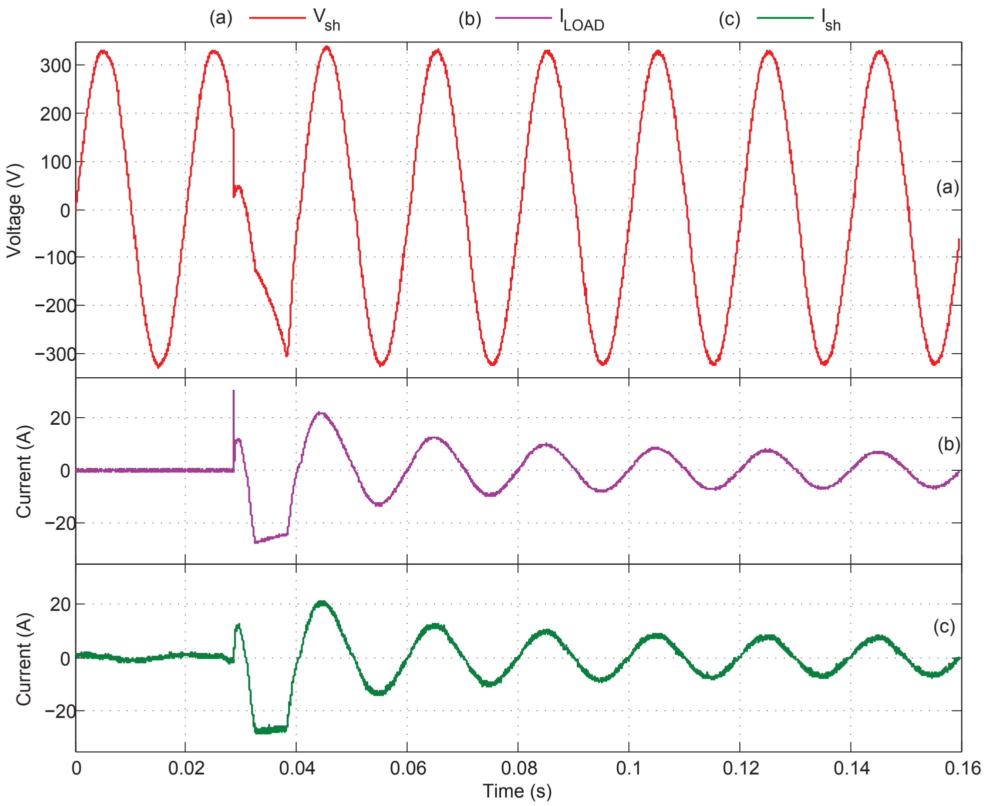

Figure 6.42: *Experiment - shunt unit Island operation mode, 1.5kW step load change – (a) shunt unit voltage, (b) load current, (c) shunt unit current.*

saturation is affected load current and consequently load voltage profile as it is depicted in Figure 6.42 (a) and (b). This transient distortion lasts less than half period and after this short transition, load voltage and current are stabilized at their steady state values.

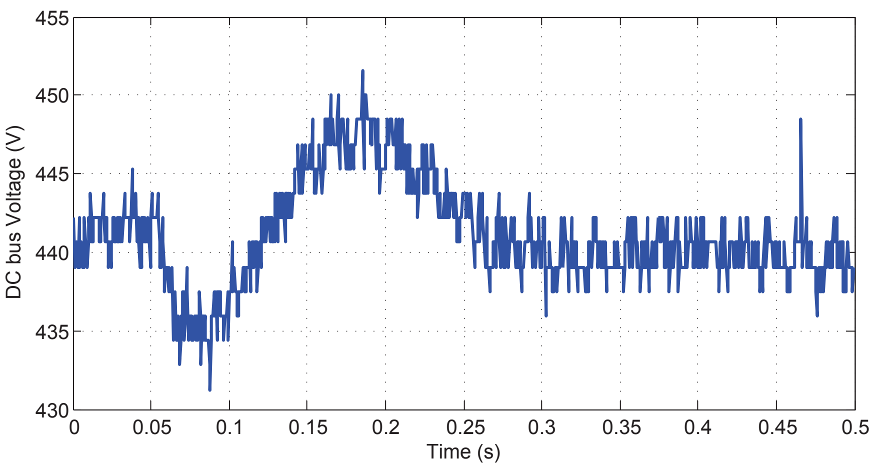

Figure 6.43: *Experiment - shunt unit Island operation mode, DC bus voltage response on 1.5kW step load change.*

Shunt unit inverter DC bus voltage response is recorded for the same event and it is reported in Figure 6.43 for a wider period in order to depict long term behavior of the DC bus voltage control. Shunt unit inverter DC bus control during *Island* operation mode is performed by chopper leg controller and as it can be seen from Figure 6.43, connecting 1.5kW load the DC bus voltage drops about 5V for 2-3 cycles, then chopper leg controller restores it with around 5V overshoot. During experiment test, DC bus transient last less than half second which is consistent with simulation results.

6.2.12 Field Record - Shunt Unit

Figure 6.44 shows a long term field record on active power, reactive power and the storage SoC of a shunt unit from February 2015. Figure 6.44(a) illustrates how the observed shunt unit active power changes during the record. It can be seen that device start and stop storage charging action several times. Instead during the record period no islanding is occurred. During *Island* operation mode, shunt unit supples all the load and its active power sign would change to positive.

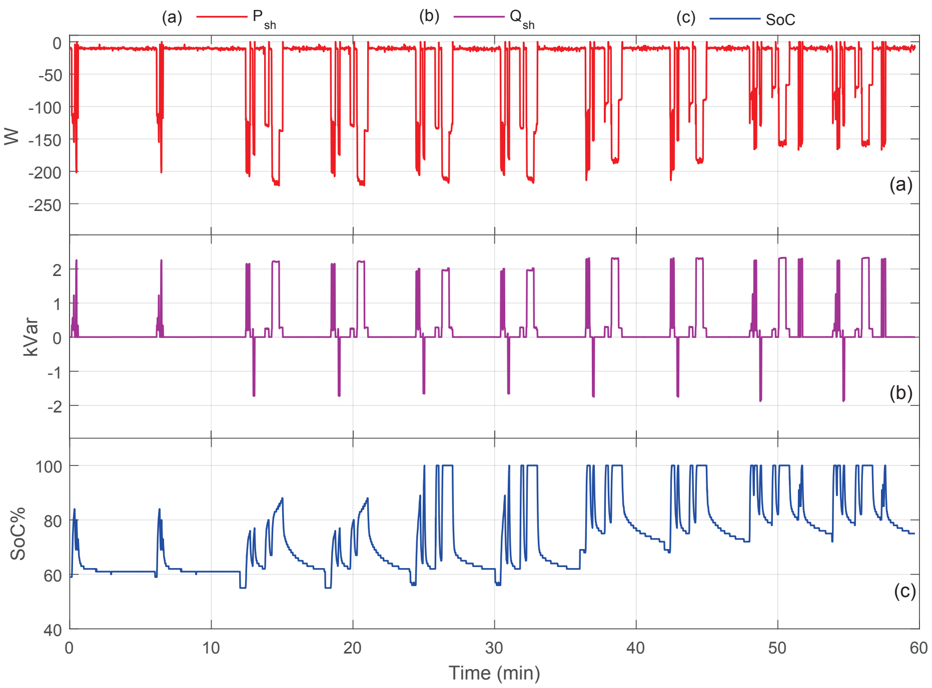

Figure 6.44: *Field Experiment, Feb. 2015 - shunt unit (a) active power, (b) reactive power, (c) storage State of Charge (SoC).*

Figure 6.44(b) shows the recorded shunt unit reactive power during the monitored period. It can be noticed that shunt unit starts to inject about ±2kVar reactive power at some intervals. Finally Figure 6.44(c) shows how the SoC of the storage system changes during the monitoring period. It can be seen that how the SoC increases when the device charges the batteries. Instead when the device stop charging, the SoC estimator evaluates storage system SoC and as it can be noticed stopping the charging action leads SoC decrement. This could be due to SoC estimator error because during charging action batteries internal resistance causes voltage increment at its terminal and this can affect the SoC estimator evaluation and insert some errors.

6.3 Co-operation

Open UPQC series and shun units can work independently but as it was explained in earlier chapters, during SDG project those have been placed within a ICT based coordinated system to be able to co-operate with each other and give better services to the grid. The co-operation is meant for two purposes;

- Decrease feeder losses
- Improve series unit performance by increasing its compensation limit

In order to illustrate the co-operation concept, the test field as it is explained in Chapter 4, is simulated by MATLAB software and some scenarios are investigated. The simulated network is a simplified version of the real test field as it is shown in Figure 6.45. The test phase (B) of the feeder with 15 customers is simulated. The customers are supplied form three busbars where each busbar corresponds to a distribution cabin in real field. Z_1, Z_2 and Z_3 are distribution line impedances between the substation, where series unit is installed, and distribution cabins. V_1, V_2 and V_3 are voltages at distribution cabins as those are depicted in Figure 6.45. As those have been shown, the loads with and without shunt units are simulated in aggregated quantity in order to simplify the simulation. The distribution lines are simulated with $50mm^2$ cables for each phase as it is in real field and the distances are set about 500m for each section.

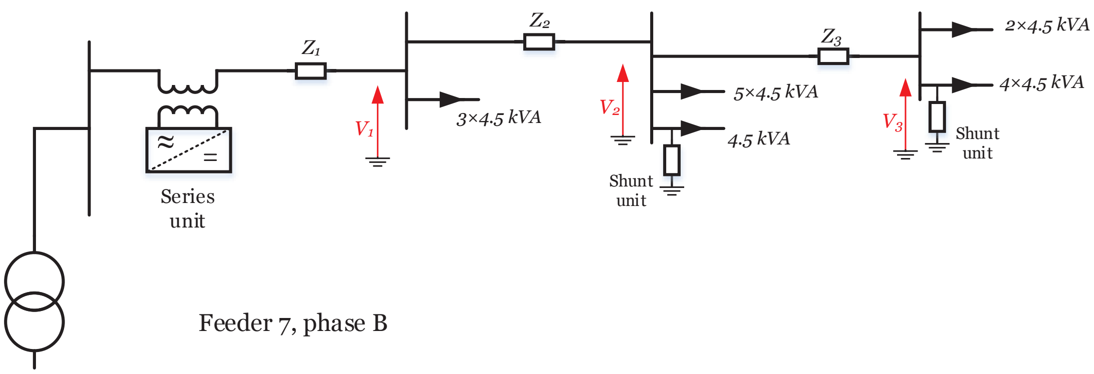

Figure 6.45: *Simplified field demonstration - Feeder 7, Phase B schema where Open UPQC series and shunt units are installed.*

In the following, three different cases, according to the concepts have been introduced in Chapter 2, will be evaluated.

6.3.1 Decrease Feeder Losses

In order to decrease installed feeder losses by means of co-operation between Open UPQC series and shunt units, the series unit can calculated the total reactive power supplied by the installed phase of the feeder, and send the reactive power request to the available shunt units. Shunt units can compensate all the reactive power of the connected loads therefore, the grid will supply the active power of the loads only and this can decrease the magnitude of the current on distribution lines and consequently active power losses on the feeder can be reduced.

The nominal power on the test feeder is about 67.5kVA (15 customers with contractual 4.5kVA power). There are five shunt units with nominal 3kVA power therefore total shunt units power is 15kVA which makes 22.22% of total peak load and this means shunt units can compensate up to 22.22% of total load nominal reactive power in the installed feeder. By calculation it can be found that this can change the feeder power factor about 0.03.

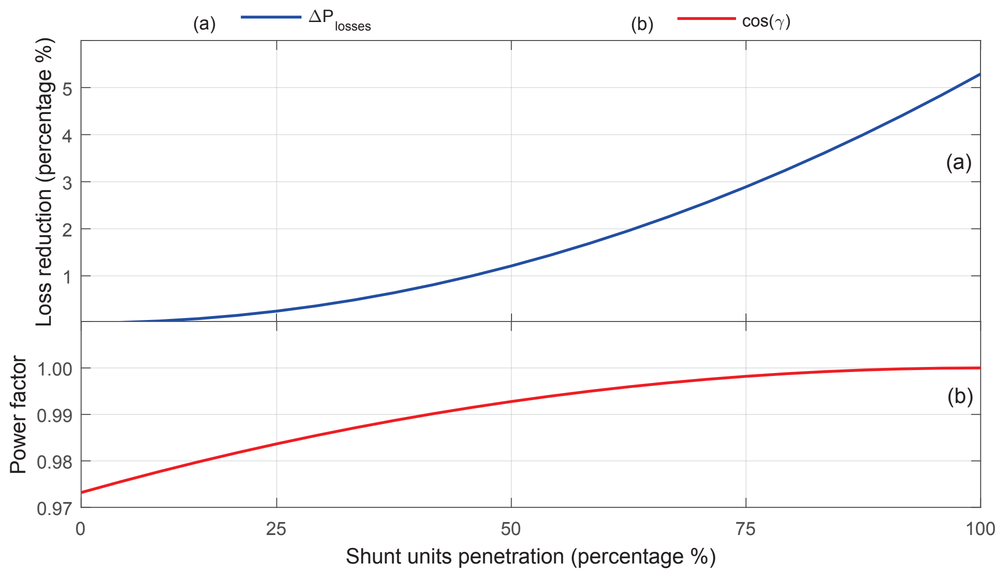

Figure 6.46: *Simulation - Open UPQC series and shunt units co-operation, installed feeder loss reduction demonstration – (a) loss reduction, (b) power factor.*

Considering this variation and since the line losses are proportional to square current, the contribution of this co-operation means can be evaluated as it is reported in Figure 6.46. A system with nominal peak power and total power factor about 0.97 is simulated. Shunt units can compensate up to all reactive power of the total load as it is shown in Figure 6.46 (b) where with 100% shunt units penetration the total power factor of the feeder became unity. With this co-operation action and thanks to shunt units participation, as it can be seen from Figure 6.46 (a), about 5% of loss reduction can be achieved. ΔP_{losses} represents the distribution line loss variation versus shunt units participation percentage.

It is worth to mention that, all the evaluations have been done considering nominal load peak power which rarely happens in power system and also contemporaneity coefficient, *k* (it is introduced in Chapter 5) is not considered in this evaluation as well. Considering contemporaneity coefficient *k*=0.75, the shunt unit share became 30% of total load and following the same procedure, up to 9% loss reduction can be reached in installed feeder.

6.3.2 Increase Series unit Over Voltage Compensation Limits

Open UPQC series and shunt unit co-operation can improve its series unit performance by increasing series unit operation limit region. The co-operation can improve series unit over voltage compensation as it is reported in previous chapters. Series unit maximum grid side over voltage capacity according to Equation 6.8 is function of $V_{x,max}$, series unit inverter nominal voltage and γ, load power angle. As it was reported in Chapter 2, the $V_{x,max}$ is set to 200V during hardware design procedure so, the limits can be evaluated by fixing $V_{x,max}$ where the only leaving variable would be load power angle γ and it can be managed by shunt units during co-operation.

$$|V_{s,max}| = \sqrt{|V_{x,max} + V_{PCC\_ref}.sin(\gamma)|^2 + |V_{PCC\_ref}.cos(\gamma)|^2} \qquad (6.8)$$

Equation 6.8 with $cos(\gamma)$ equal to one (pure resistive load) and $V_{x,max}$ = 200V gives up to 32% over voltage compensation limits for series unit, which is quite large compensation window considering power quality evaluation that is performed in the installed field and also within now a days power system. However, shunt units by injecting reactive power can increase this compensation limit even further. Figure 6.47 shows the shunt units reactive power injection effect on series unit over voltage compensation limit. As it has been evaluated, five shunt units with nominal 3kVA rating power can move total power factor of the feeder about 0.03 and in Figure 6.47 (b) as it is evidence, the total power factor is varied from unity (starting condition) till about 0.97 which is maximum capability of installed five shunt units in the field. Over voltage compensation capability is reported in Figure 6.47 (a) where with pure resistive load it is about 32% and with 100% installed shunt units participation it reaches to more than 45% over voltage compensation capability. ΔV_{max} stands for over voltage compensation window.

Same as system losses evaluation, this analysis has been performed considering

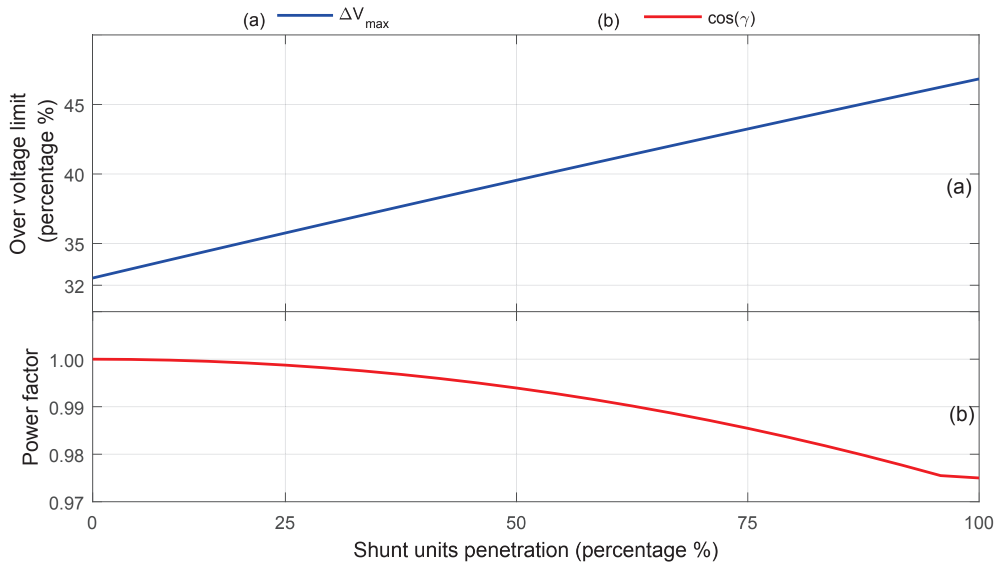

Figure 6.47: *Simulation - Open UPQC series and shunt units co-operation, over voltage compensation limit increment by means of co-operation – (a) over voltage compensation percentage, (b) power factor.*

nominal peak load power without taking into account contemporaneity coefficient (k) where considering k=0.75 could increase shunt unit effect. Following the same procedure with k=0.75, the series unit over voltage compensation limit can be improved to over 50% compensation capability with all shunt units penetration. In practical solution, even 32% over voltage compensation limit with power factor equal to one, and without shunt units co-operation is more than enough in order to cover 99% of over voltage events on under investigation LV network.

6.3.3 Increase Series Unit Under Voltage Compensation Limits

After voltage interruption, under voltage and voltage sags are most common power quality problems in power distribution systems. One of major responsibilities of Open UPQC series unit is to deal with under voltage and voltage sag events. As it was addressed in Chapter 2, the under voltage compensation limits were computed considering two different limits; limits due to $V_{x,max}$ and limits due to γ. Since the $V_{x,max}$ is set to 200V during hardware design procedure, the under voltage evaluation limits can be limited to Equation 6.9 because as it was evaluated, if $V_{x,max}$ was greater than $V_{PCC} \cdot sin(\gamma)$, the effective under voltage limit is the one computed with Equation 6.9 because with $V_{x,max}$ equal to 200V and V_{PCC} about nominal value (230V), till $cos(\gamma)$ equal to 0.5, the $V_{x,max}$ will be greater than $V_{PCC} \cdot sin(\gamma)$ and Equation 6.9 should be used to find series unit under voltage compensation limit.

$$|V_{s,min\_b}| = |V_{PCC\_ref}.cos(\gamma)| \tag{6.9}$$

According to Equation 6.9, in this case the minimum grid voltage that series unit can compensate, is function of γ only and the variation is narrow comparing with over voltage case.

Despite over voltage case, with pure resistive load, series unit has no capability to compensate any under voltage and under voltage compensation margin is zero. Shunt units can introduce reactive power to the load side in order to enlarge series unit operation limit. Without taking into account k factor, with initial pure resistive load, 100% of shunt unit contribution can add about 3% under voltage margin to the series unit. Instead, considering k =0.75 this contribution can be improved. Figure 6.48 starting from pure active load, shows shunt unit contribution to improve series unit under voltage compensation limits by means of co-operation. It can be noticed that with pure active load (power factor = 1) the compensation limit is zero. Adding the reactive power by means of shunt units participation, this ΔV_{min} increases up to 4.5% under voltage compensation capability with all shunt units capacity. ΔV_{min} stands for under voltage compensation window.

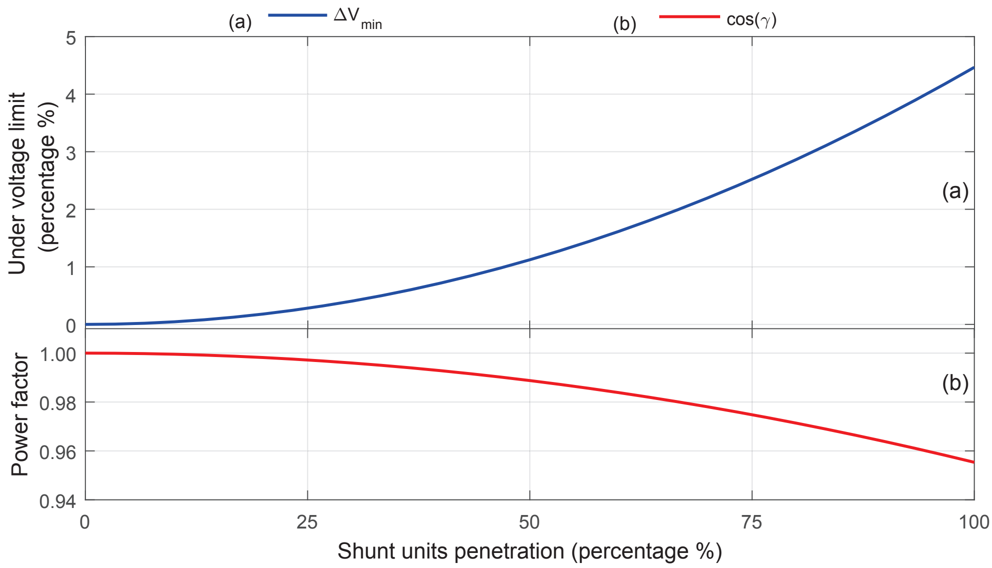

Figure 6.48: *Simulation - Open UPQC series and shunt units co-operation, under voltage compensation limit increment by means of co-operation – (a) under voltage compensation percentage, (b) power factor.*

These evaluation has been carried out under nominal load condition however a power system, especially with domestic loads, not always works with nominal load power. Here in order to demonstrate Open UPQC co-operation effect on series unit under voltage compensation performance, an example scenario is simulated with about 50% of feeder peak load. The system is simulated with total load equal to 25kW + 8kVar. The load is shared between connection points. At first connection point 5kW+1.6kVar and at second and third connection points each 10kW+3.2kVar load is connected. The total load power factor became 0.95 and following the calculation of Equation 6.9 the minimum under voltage that series unit can compensate in this condition is about 5% and $V_{s,min}$ can be found from Equation 6.9 and it is 220V. So, for the grid side voltage above 220V the series unit is able to fix voltage at PCC to its nominal value (230V) however, if the grid side voltage goes under 220V, the series unit is no longer able to do perfect compensation and it need new reference value in order to do its best.

Without Co-operation

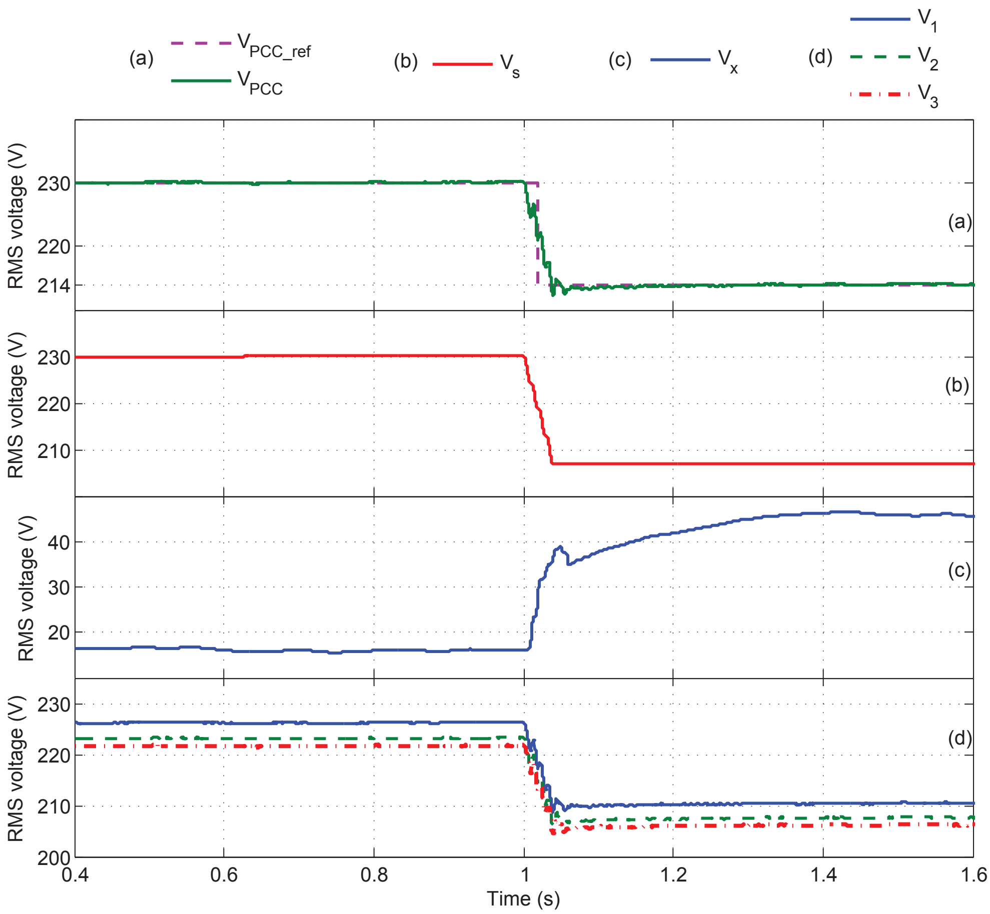

Figure 6.49: *Simulation - series unit under voltage compensation performance without co-operation – (a) PCC voltage, (b) grid voltage, (c) series unit injected voltage, (d) load voltages.*

The network as it was explained is simulated and at t=1s 10% under voltage is simulated to occur at grid side voltage. Figure 6.49 shows the series unit and other load connection points voltage profile without co-operation means. Before t=1s there was no under voltage, series unit follows the reference voltage and as it is shown in Figure 6.49 (c) it injects about 10V which is meant to compensate system losses and keep inverter DC bus voltage constant. The load voltages at connection points, V_1, V_2 and V_3 are shown in Figure 6.49 (d) and those see a voltage drop on distribution lines but in the worse case (V_3) the load voltage is above 220V.

At t=1s, 10% voltage drop is simulated at grid side, Figure 6.49 (b). Series unit touches its compensation limit and according to evaluation that is done in Chapter 2, the new achievable reference voltage can be computed and with above mentioned network situation it is about 214V. As it is shown in Figure 6.49 (a) also, the V_{PCC_ref} value is updated to this new value and series unit is following this new reference value. Figure 6.49 (c) shows the series unit injected voltage and from Figure 6.49 (d) load voltages can be seen. It is obvious that load voltages are below standard definition.

With Co-operation

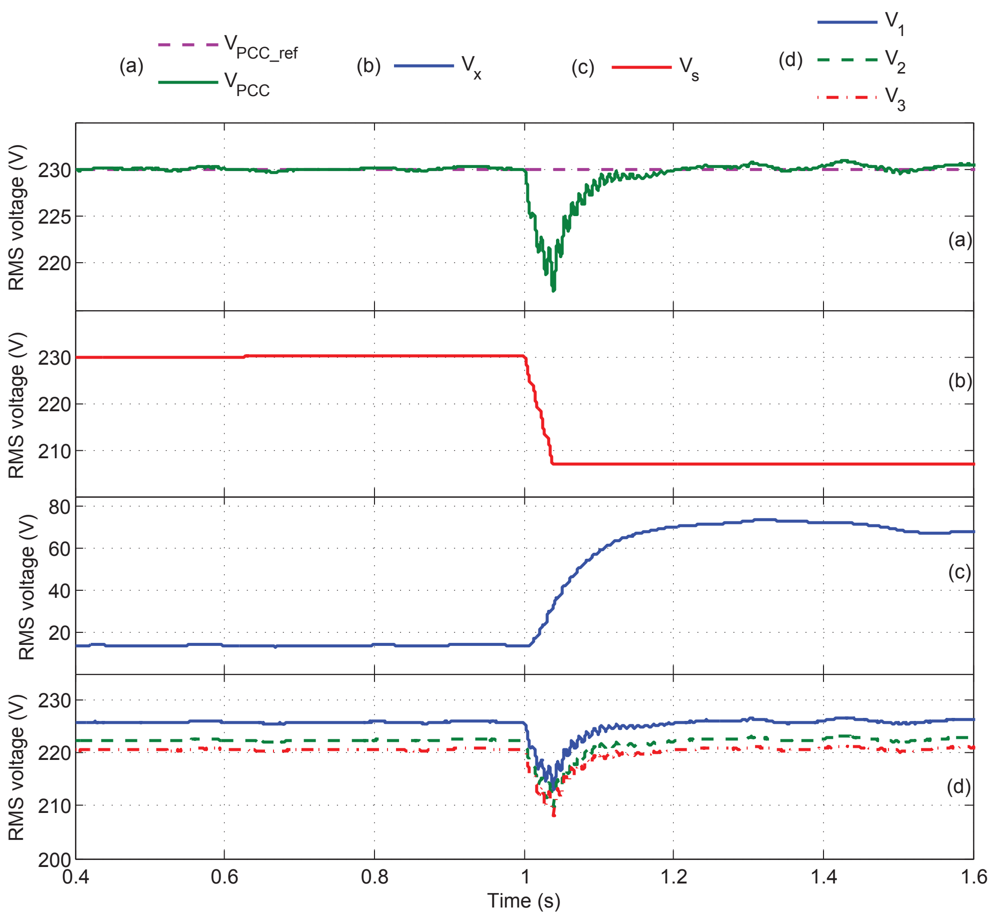

Figure 6.50: *Simulation - series unit under voltage compensation performance with co-operation – (a) PCC voltage, (b) grid voltage, (c) series unit injected voltage, (d) load voltages.*

The same scenario is simulated another time with co-operation between Open UPQC series and shunt units. Till t=1s the situation is similar to the previous representation. With 10% voltage drop, series unit need about 5kVar more reactive power at load side in order to be able to compensate voltage drop perfectly. In this scenario, some of shunt units are simulated to inject reactive power. Shunt unit connected to second busbar produces 2kVar reactive power and two of shunt units connected in third busbar produce 2kVar and 1.5kVar per each units. Therefore, by means of co-operation, total 5.5kVar reactive power is added to the load side. With this extra reactive load, the line current increases about 10A.

Figure 6.50 shows the simulation results. It can be noticed that with this co-operation means and thanks to shunt unit reactive power penetration, the PCC reference voltage is always set to its nominal value (230V) thanks to series unit, Figure 6.50 (a). After t=1s, series unit compensates 10% voltage drop by injecting about 80V as it is depicted in Figure 6.50 (c) and Figure 6.50 (d) shows voltages at load connection points where with this co-operation, load voltages are more stable and within standard limits.

It is worth to notice that, this co-operation is performed by adding reactive power to the network which although improves series unit voltage compensation capability, but in other hand by increasing load current magnitude it can introduce losses to the system. In the above scenario, the voltage compensation capability is improved in the cost of about 5% loss increment at the system. This loss increment need to be evaluated considering voltage drop effects on load power consumption as well [28]. Load behavior and power consumption evaluation is beyond this thesis focus.

CHAPTER 7

Discussions and Conclusions

The thesis has analyzed PQ and *Custom Power* as two somehow related and in some aspects contrary subjects and it has introduced a solution to answer both PQ and *Custom Power* requirements of a grid and supplied customers. PQ standard, PQ conditioners and *Custom Power* devices some times follow the same path and this was the initial trigger for the idea. Several solutions have been introduced by researchers in literature to deal with PQ problems or in order to customized power for the special users however, this common interest was rarely investigated.

The idea of this work was started in 2006 by [22] and the first proposal was submitted to an international journal at 2009, [14]. Later on the proposal was developed more and it has been funded as a wide research project which this research PhD work was a part of it between 2013-2016.

The expectations of this research PhD work were to:

- Theoretically analyze the proposal, considering practical implementation restricts and test field criteria;
- Realize the proposed PQ and *Custom Power* conditioner device in order to evaluate their practical performance;
- Install the realized devices in field and evaluate the system performance.

The series unit as main PQ conditioner part was analyzed and its operation limits and performance is evaluated theoretically and practically. It has the capability to deal with both fast and short term voltage deviations (sags/swells) and also slow and long term voltage drifts. In particular it can deal with fast and short voltage problems working with both active power (coming form DC bus capacitors) and non-active power. Instead since the system has not any storage to support its DC bus voltage, for long term operation it is designed to operate with only non-active power compensation strategy. From this point of view, it is not a new idea, but as a continuous operating series connected PQ conditioner, it is an exclusive solution and design which was not yet analyzed in literatures.

Series unit initially was designed as three single phase solution but three phase performance did not tested and this could be one important future research following up the work. Indeed, three single phase implementation is more compatible with LV network where there are lots of single phase costumers, because it permits to be flexible within the project. By installing single phase series unit it can give to DSO the possibility to shift all the problematic single phase loads on the phase of a specific feeder where the Open UPQC is installed, splitting the investment cost on time.

In other hand shunt unit, as it is designed and realized, is an UPS like PQ and *Custom Power* device and it is installed close to the end user at front end of their property. A storage system is integrated into shunt unit so this make it an attractive device within distribution network since the device can improve the end users network performance supporting end load during any interruptions of the grid. It is able to give several ancillary services to the installed LV network area.

Modern power system is moving toward Smart Grid systems where communication between different elements and actors play important rule within the system. Open UPQC and proposed solution needs ICT infrastructure to enable co-operation between series and shunt units. The communication is established through Internet and different parts within the project are communicating to each other. This communication structure turns Open UPQC to a solution for modern distribution power and Smart Grid systems.

Considering series and shunt units together, Open UPQC, it has been proved that it is possible to find common interest between PQ standard and *Custom Power* requirements and develop a solution to give PQ services to the installed distribution grid and *Custom Power* services to specific or interested end users. The system performance verifies 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 (shunt unit) available at their property.

Original and innovative contributions of the thesis can be listed as below:

1. Common interest and unique solution to answer both PQ and *Custom Power* is-

sues are investigated.

2. Open UPQC as a unique and innovative distributed solution is proposed to be implemented in distribution LV Smart Grid.
3. Working principle is analyzed in detail and especially series unit operation limits is formulated.
4. Series unit (DVR) continuous operation is verified by simulation and experimental tests.
5. First and only worldwide available prototype of Open UPQC has been realized and tested.
6. PQ and *Custom Power* improvement in real LV distribution system is investigated experimentally.

CHAPTER 8

Future Works and Studies

The thesis presented a possible solution for PQ and Custom Power improvement within a LV distribution network. Of course the proposed solution is not the optimum and it is not the best and last one. Instead it arises several lines of research which can be pursued in the future. Here, from author point of view, some potential further research themes are introduced.

Although the series unit is designed as three single phase units and those have been designed to be able to work as final three phase system but, three single phase units were not put together to build experimental three phase prototype. Series unit three phase system can be developed and laboratory results can be compared with single phase units performance from different point of views. At the moment for the author it is not clear in LV level which configuration (single or three phase) is more efficient and economic or which configuration can outperform other one.

In order to design single and also three phase series unit control method, Voltage Unbalance Factor (VUF) need to be taken into account and careful consideration need to be applied based on available standard definition [2, 58]. Specially for single phase and pure reactive power compensation strategy, voltage unbalance standard threshold could be violated if proper attention has not been considered inside the control method.

Moreover, new configuration can be introduced for series and shunt units. The current and common solution for series unit is to install the device in series to the distribution line by means of a coupling transformer. A novel and interesting solution can be to integrate series unit inverter at primary or secondary side of MV/LV substation transformer. With this new configuration, first of all the coupling transformer can be removed since the device is integrated inside distribution transformer. Advantages and disadvantages of the new configuration should be analyzed in detail with traditional system.

Shunt unit performance can be improved significantly since it is connected in front end of end user and its performance is very important since its losses is a part of customer electricity bill. Shunt unit's SS is on the way of total load so it is a series component which introduces losses in function of total load current. Also several functionalities can be defined and added to the shunt units as ancillary service to the end user or to the grid and DSO.

Beside shunt units, several other devices in the installed distribution network, can be used to provide reactive power for series unit during co-operation in order to improve series unit performance. Potential devices considering modern distribution LV network can be Electrical Vehicles, Solar inverters inside the area and other renewable types where the reserve capacity of their inverter can be employed to provide reactive power in order to increase series unit operation limits and improve installed network overall PQ.

Series and shunt units are communicating inside SDG project by means of Raspberry Pi embedded PC board. The communication is through Internet and for each command the system needs about one minute to send the command or receive back requested data. Different communication means can be investigated in order to increase communication speed and performance. Broadband over Power Line (BPL) or even indirect co-operation without physical communication can be analyzed and studied.

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APPENDIX A

Publications During PhD Study

(1)

Authors: G. Accetta, G. D'Antona, D. Della Giustina, **H. Hafezi** and R. Faranda
Paper Title: Open UPQC: a possible solution for customer power quality improvement. Shunt unit analysis
Published in: 16th IEEE International Conference on Harmonics and Quality of Power, ICHQP, Bucharest, Romania, 25–28 May 2014, pp. 596–600.
Abstract: The paper represents power electronics device for PQ improvement and introduces Open UPQC as possible solution to improve whole system PQ level with more features for specific end users. It focuses on shunt unit analysis and performance. Realization of prototype and design consideration are analyzed in detail and different operation modes of the system are described.

(2)

Authors: G. D'Antona, R. Faranda, **H. Hafezi**, G. Accetta, D. Della Giustina
Paper Title: Open UPQC: A possible solution for power quality. Series unit analysis
Published in: International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM, 18-20 June 2014, pp. 1104-1109.
Abstract: Power quality in distribution grids is already a concern in many European Countries where there is a strong presence of renewable energy generation. There is therefore a growing interest in new technologies able to improve the power quality level, among them the Open Unified Power Quality Conditioner (Open UPQC). Despite several proposals have been analyzed in literature, there are still few examples of experimentation in real environments. The paper discusses the design and the simula-

tion of the Open UPQC, focusing on its series component. This analysis is the result of the preliminary investigation lead before the physical installation of the system in a real operating distribution grid.

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(3)

Authors: R. Faranda, **H. Hafezi**, S. Leva, M. Mussetta, E. Ogliari

Paper Title: Enegy production estimation for suitable PV Planning

Published in: International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM, 18-20 June 2014, pp. 248-252.

Abstract: Renewable energy penetration has been greatly increasing in these years and photovoltaic (PV) energy seems to be one of the main renewable source, widely and easily available. To valuate with good accuracy PV energy production usually designers need complicate software tools. In this paper a simple method to estimate the PV plant Yearly Energy production is presented. The proposed method employs only the available data of the PV plant (as location and PV nominal power). The analytical method presented here can be a profitable tool for design engineers in planning PV considering different locations.

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(4)

Authors: **H. Hafezi**, E. Akpinar and A. Balikci

Paper Title: Assessment of Two Different Reactive Power Estimation Methods on Single Phase Loads

Published in: 16th International Power Electronics and Motion Control Conference and Exposition, PEMC, 21-24 Sep. 2014, pp. 82-87.

Abstract: In this paper single-phase instantaneous reactive power (p-q) method and non-active current method have been compared. Reactive power and reactive current calculation using these methods have been considered here under distorted voltage and current waveforms. It has been shown that these two methods have some limitations for reactive power compensation. The p-q method with hysteresis current controller and non-active current theory with sinusoidal pulse width modulation (SPWM) controller have been analyzed in Matlab/Simulink. A prototype system has been designed using TMS320F2812 EzDSP in the laboratory and assessment based on simulation and experimental results is given for these methods in this paper.

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(5)

Authors: **H. Hafezi**, E. Akpinar and A. Balikci

Paper Title: Cascade PI Controller for Single-phase STATCOM

Published in: 16th International Power Electronics and Motion Control Conference and Exposition, PEMC, 21-24 Sep. 2014, pp. 88-93.

Abstract: This paper presents state space model of single-phase STATCOM based on continues switching function. Continues switching functions for bipolar voltage source inverter (VSI) have been used to derive the transfer function for complete controller. Two proportional integral (PI) controllers which are a DC PI for DC link voltage control and an AC PI for alternating current control are implemented in cascade topology in reactive power compensation. Proposed control method has been analyzed in simulation by using MATLAB. Root locus technique is used to design AC PI controller parameters.

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(6)

Authors: R. Faranda, **H. Hafezi**, S. Leva, M. Mussetta, E. Ogliari

Paper Title: The Optimum PV Plant for a Given Solar DC/AC Converter

Published in: Energies 2015, 8(6), 4853-4870; doi:10.3390/en8064853.

Abstract: In recent years, energy production by renewable sources is becoming very important, and photovoltaic (PV) energy has became one of the main renewable sources that is widely available and easily exploitable. In this context, it is necessary to find correct tools to optimize the energy production by PV plants. In this paper, by analyzing available solar irradiance data, an analytical expression for annual DC power production for some selected places is introduced. A general efficiency curve is extracted for different solar inverter types, and by applying approximated function, a new analytical method is proposed to estimate the optimal size of a grid-connected PV plant linked up to a specific inverter from the energetic point of view. An exploitable energy objective function is derived, and several simulations for different locations have been provided. The derived analytical expression contains only the available data of the inverter (such as efficiency, nominal power, etc.) and the PV plant characteristics (such as location and PV nominal power).

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(7)

Authors: G. D'Antona, R. Faranda, **H. Hafezi**, M. Bugliesi

Paper Title: Experiment on bidirectional single phase converter applying simple model predictive control

Published in: IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC) 2015, pp. 1019–1024.

Abstract: Bidirectional converter that is able to manage storage, is a basic power electronics device and it is a major component of renewable energy sources, micro grid and also smart grid concept. In this paper single phase bidirectional converter topology is discussed. State space model has been derived and a simple model based predictive current controller has been utilized to derive the inverter. Control block diagrams has been designed and tested with MATLAB Simulation. Experimental results presented and give credibility to the derived model and control method.

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(8)

Authors: G. D'Antona, D. Della Giustina, R. Faranda, **H. Hafezi**

Paper Title: Open UPQC Power Quality Manager within Distributed Generation Systems

Published in: 10th IEEE International Symposium on Diagnostics for Electric Machines, Power electronics and Drives (SEDMPED), Guarda, Portugal, September 1-4, 2015, pp. 501-507.

Abstract: Power quality in distribution networks is already a concern in many European Countries where there is a strong presence of renewable energy generation. There is therefore a growing interest in new technologies able to improve the power quality level. Among them, the Open Unified Power Quality Conditioner (Open UPQC) is a possible solution. The system consists of a main three-phase AC/DC power converter in the MV/LV substation, and some single-phase or three-phase AC/DC power converter installed at customer's premises. The paper discusses design, simulation, implementation of an Open UPQC installed in real distribution grid in the city of Brescia (north of Italy) within Smart Domo Grid, a project co-funded by the Italian Ministry of Economic Development. Some experimental results are also reported.

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(9)

Authors: G. D'Antona, R. Faranda, **H. Hafezi**, M. Bugliesi

Paper Title: Experiment on Bidirectional Single Phase Converter Applying Model Predictive Current Controller

Published in: Energies 2016, 9(4), 233; doi:10.3390/en9040233.

Abstract: A bidirectional converter able to manage storage is a basic power electronics device, and it is a major component of renewable energy sources, micro grid and also the smart grid concept. In this paper, single-phase bidirectional converter topology is discussed. The state space model has been derived, and a simple model based predictive current controller has been utilized to control the inverter. Control block diagrams have been designed with MATLAB and simulation results are presented and compared with experimental ones, giving credibility to the derived model and the designed control method.

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(10)

Authors: M. C. Falvo, M. Manganelli, R. Faranda, and **H. Hafezi**

Paper Title: Smart n-grid Energy Management with an Open UPQC

Published in: IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC) 2016, 7-10 June Florence, Italy.

Abstract: In the last years, in the new smart grid framework, the need of enabling and managing the

interaction between final users and the main grid has become mandatory. The effective level of interaction depends on the real flexibility of the consumer power demand with respect to the main grid and this level can be increased in case of nano-grids (n-grids), like those of LV domestic customers, via the application of special devices, like the Open Unified Power Quality Conditioner (Open UPQC). Even if this device has been designed for different tasks (PQ, back-up, etc.), the paper is focused on its application in domestic n-grids, with the chief functions of peak-shaving and load-levelling, aimed mainly to reduce the costs of electricity delivery for LV domestic customers. As a consequence, it becomes a tool to support the interaction with the main grid. To assess the advantage of its application, a wide survey on domestic appliances included in a real w-grid has been made, to know the effective power profile, the real peak and average value, basing on which the contractual power is chosen. The analysis of monitoring data shows the potentiality of the application.

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(11)

Authors: R. Faranda, **H. Hafezi**, Z. Shafizadeh, A. Fontana

Paper Title: Load Management by Voltage Optimization

Experimental Investigation of Voltage Variation Effect on Lighting Loads

Published in: IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC) 2016 7-10 June Florence, Italy

Abstract: Load power demand management is important both for final users and for Distributed System Operators (DSOs) in order to manage their network load profile. So several strategies were adopted to get this result, but nowadays the new technologies in electrical loads as lighting systems are changing the electrical loads behaviour. Therefore, it is necessary to reconsider techniques of voltage optimization and their validation. The paper investigates voltage variation effects on several lighting loads. Effect of voltage variation on both Active and Reactive power consumption are taken into account and results are reported in the work.

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(12)

Authors: **H. Hafezi**, R. Faranda, and M. C. Falvo

Paper Title: Single-phase Dynamic Voltage Conditioner control under load variation

Published in: 17th International Conference on Harmonics and Quality of Power (ICHQP), 2016, Belo Horizonte, Brazil, pp. 563-568.

Abstract: Voltage regulation is an important issue for Low Voltage (LV) distribution networks. The voltage in the point of delivery to the end users should be kept within standard limits. The paper deals with a single-phase Dynamic Voltage Conditioner (DVC) able to keep the output voltage at a set value under load variations. A double loop control method, with outer voltage and inner current controller, has been used in order to have a better control on current transient. Proposed control method has been designed with MATLAB and several simulations are presented to verify its performance. The device can be interesting for Distribution System Operators (DSOs) and also within smart grid and micro-grid applications.

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(13)

Authors: **H. Hafezi**, G. D'Antona, A. Dedè, D. D. Giustina, R. Faranda, and G. Massa

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

Published in: IEEE Transactions on Smart Grid, vol. 8, no. 1, pp. 418-427, Jan. 2017.

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.
