Enabling End-User for LV Smart Grids

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***Abstract*—In order to increase the rate of transformation of traditional grid to a future Smart Grid, there is a huge necessity for enabling the end-user to become an activity participant. Technological and financial considerations are key driving factors in empowering the end-user. From a technological point of view end-user needs to manage his own load, power generated from renewables and also in providing the services to the grid. A promising and innovative solution to meet these needs of the end user in LV network is the Open UPQC (Open Unified Power Quality Conditioner). This device has been designed to meet different tasks required by an end-user (Power Quality, Demand Response, Ancillary Service, etc.). This paper presents the Shunt Unit of Open UPQC with RES (Renewable Energy Sources) as a solution which can provide all the necessary functionalities required by an end-user in enabling him to become an active participant in electrical grid transformation. The performance of the device is demonstrated using simulation results under online and island operation modes.**

***Index Terms*—End-User, Open UPQC, Renewable Energy, Shunt Unit, Smart Grid.**

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I. INTRODUCTION

Extensive research is ongoing in order to reform the existing electricity network into an intelligent system called Smart Grid [1]. This is to employ the 21st century technologies into the legacy electrical network and change its fundamental operation principle to a deregulated structure increasing its efficiency, reliability and usage of renewable energy resources.

The national agencies are bringing several policies to advance the growth of these Smart Grids, such as Smart Grid European Technology Platform [2] in Europe and Energy Independence and Security Act of 2007 [3] in USA. These policies directed the research to focus on technologies and establish standards for the individual stake holder to participate in Smart Grids.

In this transformation to Smart Grids, the Low Voltage (LV) network is of paramount importance and the end-user emerges as a key stake holder [4] to play an important active role. The recent technological advancements in power electronics [5] and renewable energy resources allow the LV grid end user to produce electricity by using Photovoltaic energy systems [6]. With the integration of Information and Communication Technologies (ICT) [7] the end-user can provide demand response [8] and ancillary services [9] to the utility. These technologies enable the end-user to become an active entity.

Apart from the conceptual designs, in reality the growth of Smart Grids is hindered [10]. One of the major causes is the lack of policies in order to enable to become an active entity. The stringent requirements from the grid codes and standards [11] for the interconnectivity adds up to this issue.

In the literature, several technologies are introduced to make the end-user an active entity. However, these technologies work only for specific applications and needs of end-user. These technologies clearly show a lack of unified approach to engage the end-user into a Smart Grid. For example, UPS systems [12], UPQC [13], etc.

Open-UPQC (Open-Unified Power Quality Conditioner) [14] is a power electronic device developed, designed and field tested under the *SmartDomoGrid* project co-founded by the *Italian Ministry of Economic Development* to enable the interaction between Grid and the end-user for the future Smart Grids. The device consists of a Series unit and several Shunt units which can be installed at the end-users. The Shunt unit [16] is designed to handle the essential functionalities required by the end-user, such as peak shaving, power quality and storage management. Together with the Series unit and other Shunt units it can coordinate to provide functionalities to manage the Utility grid. This device is a potential technological solution in order to enable the end-user with the capabilities required to become an activity entity in a LV Smart Grid.

In this paper, the Shunt unit of the Open-UPQC with Photovoltaic (PV) RES is presented. This is an addition to the existing Shunt unit, which enhances its functional capabilities in providing PV power generation, storage and load management for online and island mode of operation. Hence this work is taken up to design a suitable control for PV in order to integrate it to the Shunt unit of Open UPQC and verify its performance.

The rest of the paper is organized as follows. In section II, the functional requirements of the end-user and Open-UPQC with RES capabilities are discussed. Section III describes the modified Shunt unit configuration of Open UPQC and explains the control strategy adapted for integrating PV. In section IV the experimental prototype realized is described. Section V provides the simulation results to demonstrate the controller performance and device performance in online and island mode of operations. Section VI concludes the paper.

II. OPEN-UPQC WITH PV RES

An extensive research performed over the years identifies the important functionalities required by end-user as follows:

- the end-user must be able to produce electricity using micro energy generation, use it for meeting his own demand and sell the excess to Utility grid. The Utility must also be able to request the end-user to limit the injected power into the Utility;
- the end-user must provide demand response [8] when requested by the Utility. It can be performed by shifting his peak load demand or by using energy from the storage and/or from the micro generation;
- the end-user must be an ideal load by extracting power at unity power factor and also by not polluting the Utility with harmonics;
- the end-user must participate in Utility grid management by providing ancillary services;
- the end-user must be able to disconnect and work in island mode under uncertain grid conditions and connect back to the grid.

In order to meet these requirements, Open-UPQC is introduced in [14]. The device consists of a Series unit and Shunt units. As described in [15], the series unit provides voltage support to the Utility grid. Each shunt unit is designed to meet the functionalities required by its end-user [16]. The shunt unit is with a central inverter connected to a battery storage system. This device makes the end user an ideal load by compensating the entire reactive power and harmonics absorbed by the load from the Utility grid.

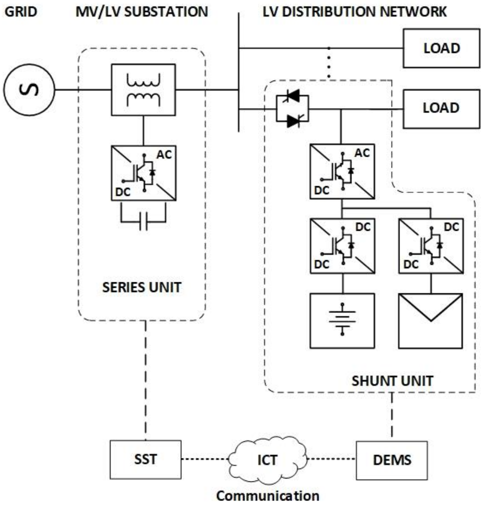


Fig. 1 Block Diagram : Open UPQC (Shunt unit with PV RES)

It provides the functionality of demand response by peak shaving using the energy from the battery storage. Since the shunt unit is equipped with internet-based ICT it allows the end-user to participate in Utility grid management by injecting the reactive power into the grid and for supporting the Series unit [17]. In order to be able to generate electricity from RES and operate in micro generation mode, an additional converter to manage PV RES is integrated into the Shunt unit of the Open-UPQC. The Open-UPQC (Shunt unit with PV RES) block diagram is given in Fig.1. With this integration, Shunt unit with RES gets the functionality of managing RES and can enable the end-user to operate in micro power generation mode meeting his own load demand, managing storage and/or sell excess power to the Grid. Together with all these functionalities, Open UPQC with RES becomes a potential and unique power electronic solution in order to empower the end-user of the Smart Grid.

III. DEVICE CONFIGURATION AND CONTROL

The configuration of the Shunt unit as described in [16] is updated with an additional power electronic converter in order to manage the PV RES. The new modified schematic of the Shunt unit is shown in Fig.2. In brief, the device consists of three power electronic converters. A centralized inverter acts as a grid interface and acts in multimode operation. The other two converters manage PV and Storage respectively. The DC bus acts as common interface between PV, Storage and the centralized inverter. A static switch enables to work in online or island mode of operation.

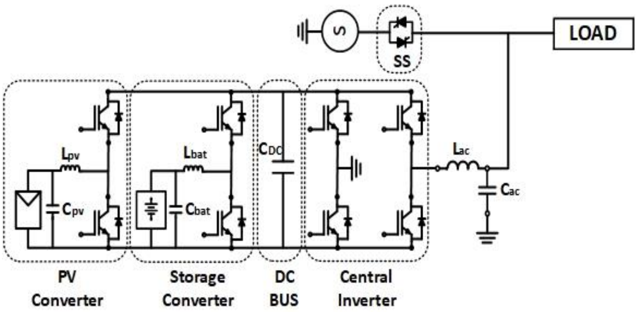


Fig. 2 Schematics: Shunt Unit of Open UPQC with PV RES

As the device has three power electronic converters, it requires a complex control strategy in order to realise the required functionalities. The central inverter plays a key role and has the most complex control algorithm. It works as a current source under online operation mode and as a voltage source under island mode of operation. Under online operation mode using instantaneous power theory [18] reactive power and harmonic currents of the end-user load is compensated. It can respond to the Utility commands for demand response and provide peak shaving. These are passed as reference currents to a model-based controller for the control of the inverter. The storage converter acts as a bidirectional device acting in buck and boost mode of operations for charging and discharging operation respectively, the control in order to control the charging and discharging are realized using simple PI controllers. The detailed modelling of the converter and design of the control for the inverter and the storage converter are described in [19].

For the integration of the PV converter, a single leg IGBT converter is considered, the top switch acts as a diode and it operates in the boost mode by controlling the bottom switch, this converter is coupled to the Shunt unit through the DC bus.

The control is designed to extract maximum power from PV panels using Perturb & Observe (P&O)

Maximum Power Point Tracking (MPPT) algorithm. This algorithm provided the reference voltage, which is filtered and fed through a PI regulator to generate a current reference, which in turn fed to a model-based controller to generate the duty for the PV converter.

Fig.3 shows the block diagram of the control implemented for the PV converter. The step for voltage is taken as 0.1V for the P&O MPPT and it provides V_{MPPT}. The $V_{optimal}$ is calculated as 0.6 times the previous reference value and 0.4 time the V_{MPPT}. Then a reference values V_{REF} is generated from Filter block and is passed through a comparator to generate V_{Error} for the PI controller. The PI generates a Current reference $I_{REF.}$ This is used to generate the I_{Error} for the Model Based Controller (MBC) which works on the PV inductor (L_{pv}) current to generate the duty cycle.

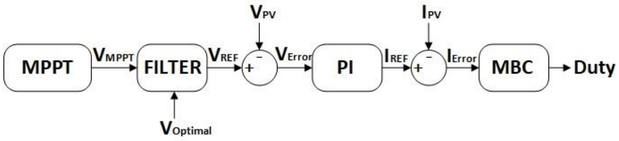


Fig. 3 Control scheme for PV Converter

Notice that the input voltage control loop works quite differently compared to conventional feedback used in output voltage control. Under this control scheme, when the PV array voltage (V_{pv}) tends to go higher than the reference panel voltage (V_{ref}) set by the MPPT algorithm, the control loop increases the panel current command (I_{ref}) and, thereby, controls the panel voltage at its reference level (V_{ref}). When the panel voltage tends to go lower than the reference, the control loop reduces the panel current command in order to reestablish the panel voltage to its reference level.

IV. HARDWARE PROTOTYPE

The existing Shunt unit prototype is upgraded in order to integrate a new PV converter leg, its associated switching inductor and the filter capacitor. The complete prototype is shown in Fig.4. The brief description of the prototype is as follows in clock wise direction of the housing.

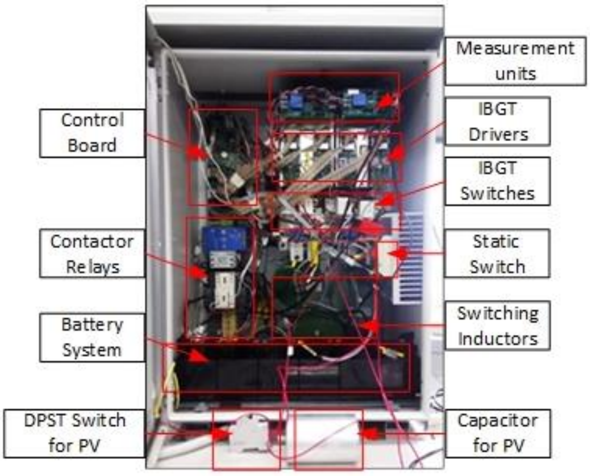


Fig. 4 Shunt unit with PV RES: Harware Prototype

The voltage measurement units are places on the top right of the housing. Just under these, the driver circuits for the IGBTs are installed. The converter switches are realized using IGBTs and are mounted on heat sinks. Under these the switching inductors are mounted. The lead-acid battery storage units are placed on the lower side of the housing as shown in the Fig 4. The contactors and resistors for the pre-start of the device are installed on bottom left of the housing. A DSP control board mounted on the top left corner. The static switch is mounted on a heat sink and attached to the left side wall.

V. SIMULATION RESULTS

To evaluate the functionalities and performance of the designed controller and the device, simulations are performed in MATLAB environment. Three conditions are considered important to test the device. Firstly, the performance of the controller is tested for varying irradiance and secondly, the device functionality in online mode for injecting the PV power is tested. Lastly, the device performance under variation of load in island mode are tested. The PV converter parameters used for the simulation are given in Table 1.

TABLE I

PV CONVERTER PARAMETERS OF SHUNT UNIT

#	Component	Value
1	PV Inductor (L_{pv})	1.5mH
2	PV Capacitor (C_{pv})	6800uF
3	PV Switching Frequency	20kHz
4	PI controller values	K_p=4, K_i=0.001

A. Controller Performance

In this test the performance of the controller is evaluated by varying the irradiance from 1000W/m^2 to 200W/m^2 in steps of 200W/m^2. The IV and PV characteristic of the PV array used are given in Fig.5.

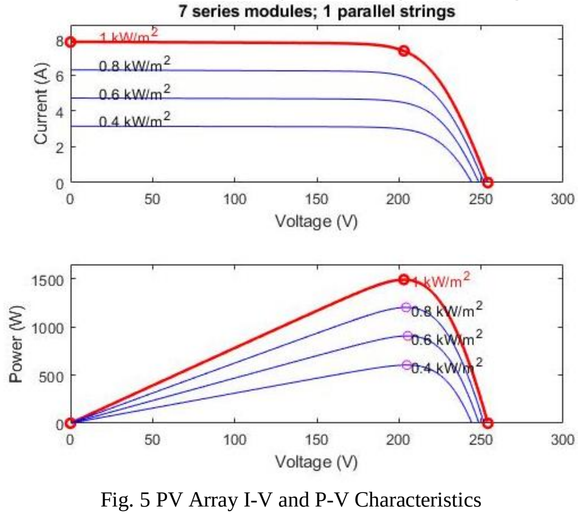
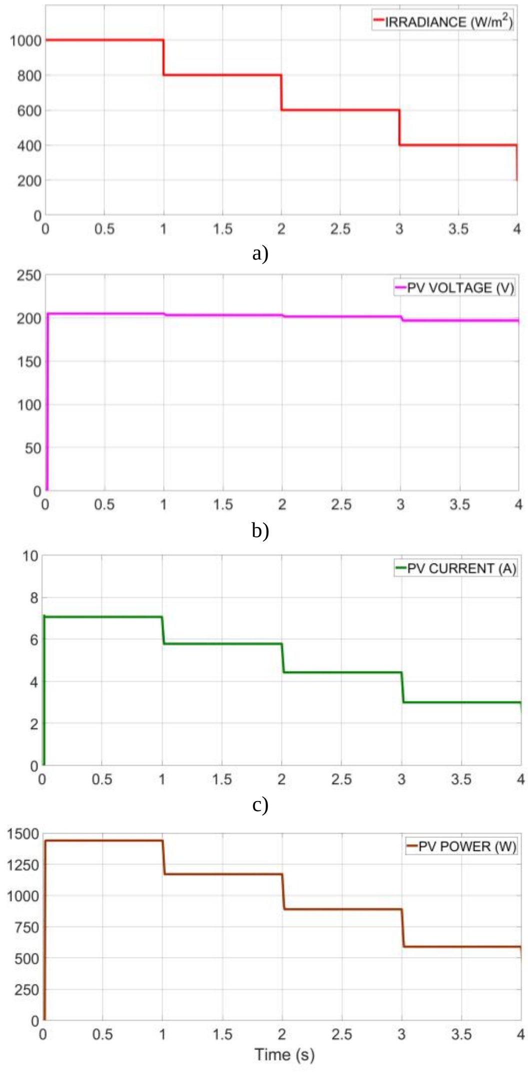


Fig. 5 PV Array I-V and P-V Characteristics

The corresponding PV voltage, PV current and PV power extracted are shown in Fig.6. During the time t=0 to t=1 second, the irradiance is 1000W/m^2 and according to the PV characteristics of the array the voltage and current at the maximum power point of 1492W are 203V and 7.3A. The controller extracts a power of 1428W with a current of 7A at a voltage of 204V. Show that the controller efficiently extracts the PV power. At time t=1 second it can be seen that the simulation it set to introduce a step reduction of irradiance. As it can be noticed the controller is fast in adjusting to the dynamic change in irradiance. The simulation continued for the rest of the time with step changes in irradiance to verify the controller for the irradiance 800W/m^2, 600W/m^2, 400 W/m^2, and 200 W/m^2. The controller performed well as expected by extracting maximum power from the panels which are close to the value from the PV array characteristics and acted fast change in irradiance. These can be verified from the Fig.6.



a)

b)

c)

d)

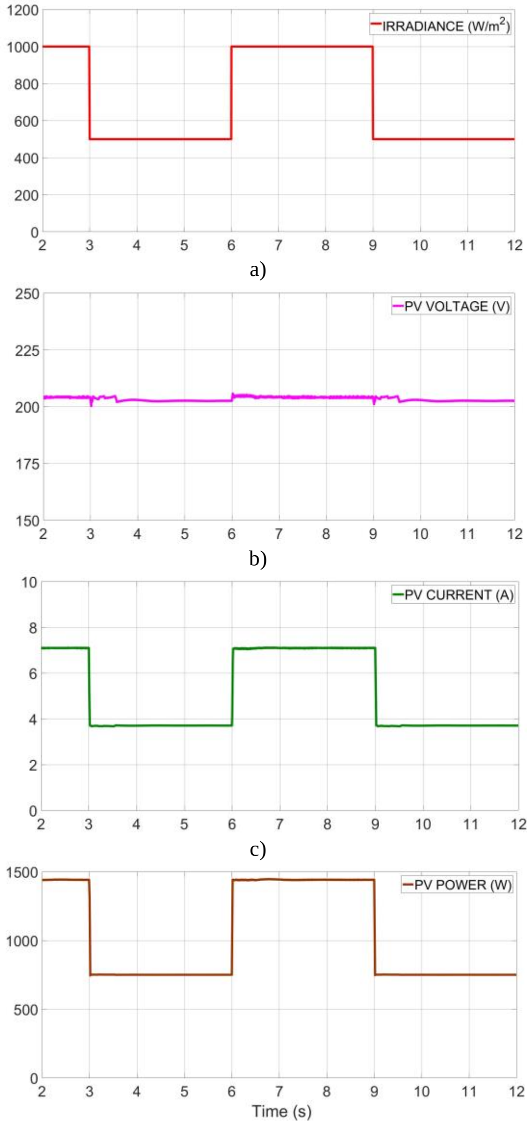
Fig. 6 PV contoller performance: a) Irradiance, b) PV Voltage, c) PV Current, d) PV Power

B. *Online Mode:*

Under this test the functionality of injecting the extracted PV power into the Grid is evaluated. For simplicity the batteries are set in charging mode, it absorbs a constant power of about 200W and load power is assumed to be zero. The Grid Voltage is considered constant with an RMS value of 220V

The test is performed by varying irradiance from 1000 W/m^2 and 500 W/m^2 in two steps, changing at t=3s ,6s and 9s. This is to verify the dynamics of the system while injecting the power into the Grid. Fig.7 shows the irradiance, PV voltage, PV current and PV power extracted from the PV array. Fig.8 shows the grid side parameters RMS Grid Current, Grid Power and the DC bus variation.

Through this test dynamics and steady state performance of the device can be observed. From Fig.7 it can be noticed that the PV converter control works effectively and extracts maximum power. From Fig.8 it is evident that this power is injected into the Grid. At time t=3s the irradiance is changed from 1000 W/m^2 to 500 W/m^2. The DC bus goes to transient at t=3s and gets to steady state in about 1.5s. Similarly, DC bus varies for the transient at t=6s and t=9s. This resulted in variation of injected power into the Grid. However, the DC bus voltage is within specified limits and quick in reaching steady state.



a)

b)

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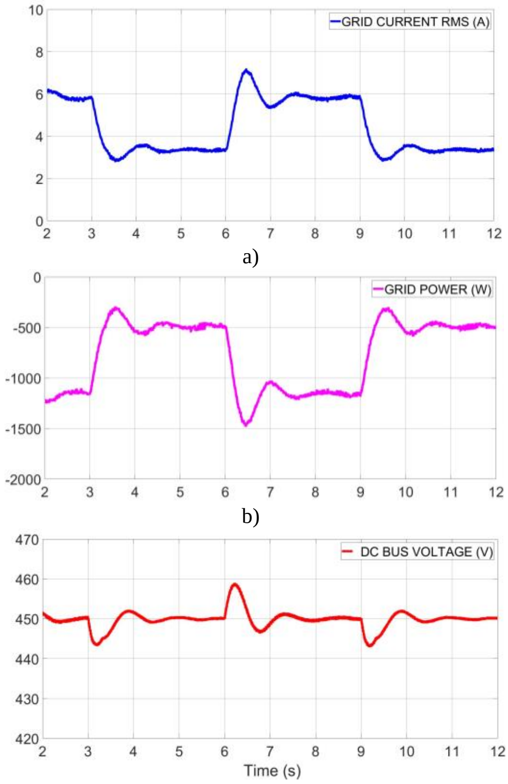
Fig. 7 Online mode: a) Irradiance, b) PV Voltage, c) PV Current, d) PV Power.



a)

b)

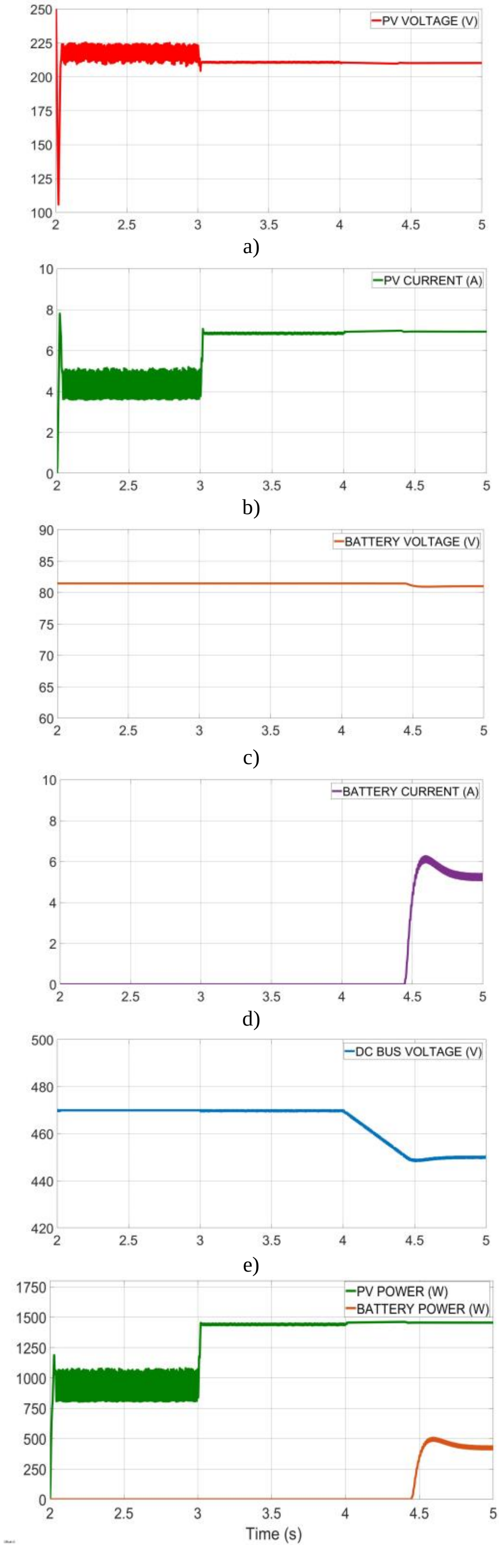
c)

Fig. 8 Online mode: a) Grid Current RMS, b) Grid Power, c) DC bus Voltage

C. Island Mode:

Through this test the system dynamics and functionality under island mode of operation are tested. For this test the irradiance is set to 1000W/m^2 throughout the simulation and the maximum power that can be extracted from the PV array is 1492W. The batteries are considered to be fully charged. The load is varied considering three cases, in the first case from time t=2s to t=3s the load (789W) is less than the PV power, second case from time t=3s to t=4s the load (1381W) is approximate to the PV power, in the third case from time t=4s to t=5s the load (1820W) is more than the PV power. Fig.9 shows PV voltage, current, Battery voltage, current, PV and battery power used to meet the load, DC bus variation. Fig.10 shows the RMS voltage, current power on load side.

It can be noticed that from t=2s to t=3s the PV controller limits the power extracted from PV, limiting the increment in DC bus voltage and in meeting the load demand. This can be noticed form the variation of the PV current and PV voltage in Fig.9. From t=3s to t=4s the load demand is close to the maximum PV power available, so the controller adjusts itself to extract more or less the maximum power. From t=4s to t=5s the load is more than the maximum PV power available, in this condition the PV extracts the maximum power available, the inverter draws the power from the DC bus, and it starts decreasing, this is seen by the battery storage controller and responds by discharging the batteries to meet the load demand. It can be noticed that there is delay from the load change at t=4s and the start of the battery discharge, this is due to the large DC bus capacitance. A power of about 400W is extracted from the DC bus from t=4s to t=4.4s. This verifies self-regulation of the PV controller



a)

b)

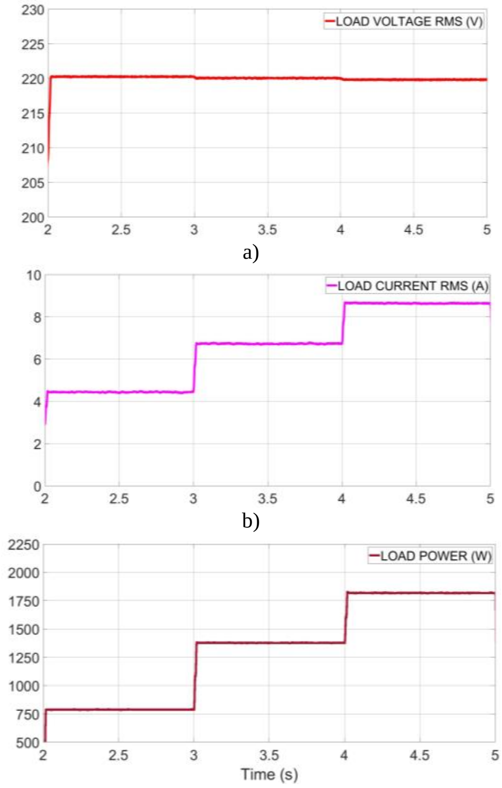
c)

d)

e)

f)

Fig. 9 Island mode: a) PV Voltage, b) PV Current,c) Battery Voltage, c)Battery Current,d) DC Bus Voltage, e) PV Power and f)Battery Power to limit DC Bus voltage raise and coordination with storage system to meet the varying load demand.



a)

b)

c)

Fig. 10 Island mode: a) Load Voltage RMS, b) Load Current RMS, c) Load Power

Fig.10 shows the Load RMS Voltage, RMS Current and the Power absorbed from the Shunt unit. It can be noticed that the Shunt unit provides stiff voltage to the load and meets the power demand in island mode.

VI. CONCLUSION

The end-user being a key stake holder in future Smart Grids, lacks a unique power electronic device which can manage all the functionalities required by him in order to integrate into a Smart Grid, this is also a major contributor in the slow transformation of the existing grid to a Smart Grid. Through this paper the Shunt unit of the Open-UPQC with RES is proposed as a unique power electronic device which can perform renewable energy generation, storage management, power quality, demand response and ancillary service functionalities for the end-user. Simulation results verifies these functionalities device performance under online and island mode of operation. This innovative solution serves as power tool for the end user to become an activity entity and participate in the Grid transformation to an intelligent Smart Grid.

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