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A Grid Connected Voltage Controlled Single-Phase Photovoltaic System with Multifunctional Shunt Controller

B.Ajay Krishna

PG Research Scholar
SreeChaitanyaCollege of Engg.

T.Ranjani

H.o.D ,Assoc.Professor
SreeChaitanyaCollege of Engg

***Abstract*— In this paper services provided by photovoltaic (PV) systems in to power systems could facilitate their penetration along with the improvement of power quality by designing a low power PV systems. A repetitive controller used in this paper provides grid voltage support and compensation of harmonic distortion for single-phase photovoltaic system The maximum power provided by the PV panels is tracked based on incremental conductance method of a Maximum Power Point Tracking (MPPT) algorithm specifically modified to control the phase of the PV inverter voltage.**

***Index Terms*—PV system, power quality conditioner, shunt controller, *Incrementanl conductance* MPPT algorithm.**

I. INTRODUCTION

Among the renewable energy sources, a noticeable growth of small PV power plants connected to low-voltage distribution networks is expected in the future, as a consequence, research has been focusing on integration of extra functionalities such as active power filtering into PV inverters operation. Anyway, distribution networks are less robust than transmission network and their reliability, because of the radial configuration, decreases as voltage level decreases. Hence, usually it is recommended to disconnect low-power systems when the voltage is lower than 0.85 pu or higher than 1.1 pu. For this reason PV systems connected to low-voltage grids should be designed to comply with these requirements but can also be designed to enhance the electrical system offering “ancillary services”. Hence they can contribute to reinforce the distribution grid maintaining proper quality of supply which avoids additional investments. However low-voltage distribution lines have a mainly resistive nature and, when a distributed power generation system (DPGS) is connected to a low-voltage grid, the grid frequency and the grid voltage cannot be controlled adjusting active and reactive power independently. This problem together with the need of limiting cost and size of the DPGS, that should remain economically competitive even when ancillary services are added, makes the design problem particularly challenging.

The present paper proposes to solve this issue using a voltage controlled converter that behaves as a shunt controller improving the voltage quality in case of small voltage dips and in presence of nonlinear loads.

Shunt controllers can be used as static var generator for stabilizing and improving voltage profile in power systems and to compensate current harmonics and unbalanced load current.In this paper the PV inverter supplies the power produced by the PV panels but also improves the voltage profile as already pointed out. The presented topology adopts a repetitive controller able to compensate the selected harmonics. Among the most recent MPPT algorithms it has been chosen an algorithm based on incremental conductance method. It has been modified in order to take into account the power oscillations on the PV side and it controls the phase of the PV inverter voltage.

The paper is organized as follows, in § II it is discussed the possible voltage and frequency support provided by a DPGS converter connected to the grid; § III discusses the use of shunt controllers for voltage dips compensation; the PV system improved with shunt controller functionality is proposed in § IV; § V presents the simulation results and § VI shows the experimental results, finally, § VII presents the conclusions.

II. VOLTAGE AND FREQUENCY SUPPORT

The power transfer between two sections of the line connecting a DPGS converter to the grid can be studied using short-line model and complex phasors, as shown in Fig.1.

$$\delta \cong \frac{XP_A}{V_A V_B} \tag{1}$$

$$V_A - V_B \cong \frac{XQ_A}{V_A} \tag{2}$$

When the DPGS is connected to the grid through a mainly inductive line $X >> R$, R may be neglected. If also power angle δ is small **sinδ=δ** and **cos δ=1**;

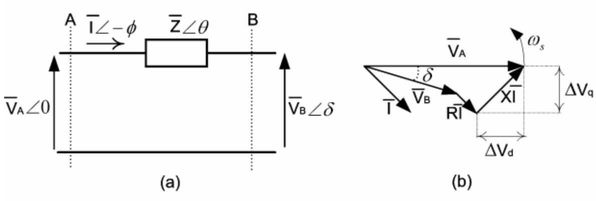


Fig. 1. (a) Power flow through a line; (b) phasor diagram.

where V_A , P_A ,Q_A denote respectively the voltage, the active power and the reactive power in A and V_B is the voltage in the section B, indicated in Fig.1.

For $X>>R$, a small power angle δ and a small difference $V_A - V_B$, equations (1) and (2) show that the power angle depends predominantly on the active power, whereas the voltage difference $V_A - V_B$ depends predominantly on the reactive power. In other words the angle δ can be controlled regulating the active power whereas the inverter voltage V_A is controlled through the reactive power. Thus by adjusting the active power and the reactive power independently, frequency and amplitude of the grid voltage are determined. These conclusions are the basis of the frequency and voltage droop control through respectively active and reactive power. In this paper the relation has been adopted to optimize the power extraction from the PV panels (MPPT).

III. Shunt Controllers for Voltage Dips Mitigation

Shunt devices are usually adopted to compensate small voltage variations which can be controlled by reactive power injection. The ability to control the fundamental voltage at a certain point depends on the grid impedance and the power factor of the load. The compensation of a voltage dip by current injection is difficult to achieve, because the grid impedance is usually low and the injected current has to be very high to increase the load voltage. The shunt controller can be current or voltage controlled. When the converter is current controlled it can be represented as a grid-feeding component (Fig. 2(a)) that supports the grid voltage by adjusting its reactive output power according to the grid voltage variations. When the converter is voltage controlled it can be represented as a grid-supporting component (Fig. 2(b)) which controls its output voltage. However also in this second case the control action results in injecting reactive power in order to stabilize the voltage. The vector diagrams of a shunt controller designed to provide only reactive power are reported in Fig. 3. When the grid voltage is 1 pu the converter supplies the reactive power absorbed by the load and the vector diagram of the current or voltage controlled converter is the same, in the first case it is controlled the compensating current I_C , in the second one it is controlled the load voltage as underlined in Fig. 3(a) and Fig. 3(b).

When a voltage sag occurs, the converter provides reactive power in order to support the load voltage and the grid current I_g has a dominant reactive component

$$\dot{I}g + \dot{I}c = -\dot{I}load \quad (3)$$

The amplitude of the grid current depends on the value of the grid impedance since

$$\dot{I}g = \frac{\dot{V}_{Lg}}{j\omega L_g} \quad (4)$$

Where $\dot{V}_{Lg}$ is the inductance voltage drop shown in Fig. 3(c). If the shunt controller supplies the load with all the requested active and reactive power, in normal conditions it provides a compensating current $\dot{I}c = -\dot{I}load$, hence, the system operates as in island mode and $\dot{I}g = 0$.

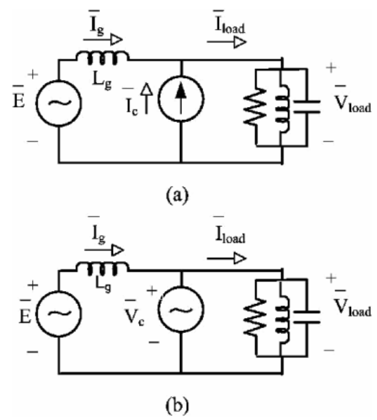


Fig. 2. a)Use of a shunt controller for voltage dips compensation simplified power circuit of the current controlled shunt controller;
Fig 2b)Use of a shunt controller for voltage dips compensation simplified power circuit of the voltage controlled shunt controller.

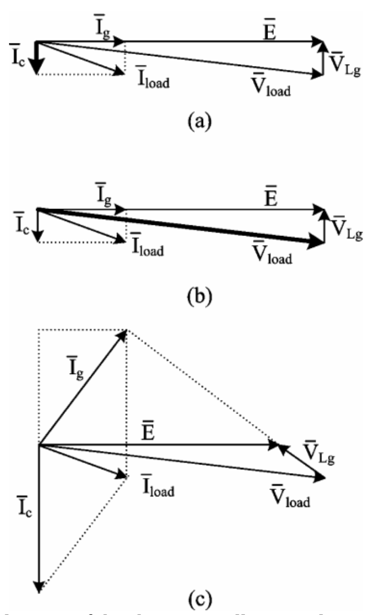


Fig. 3. Vector diagram of the shunt controller providing only reactive power: (a) current controlled converter in normal conditions; (b) voltage controlled converter in normal condition; (c) vector diagram for compensation of a voltage dip of O.15 pu.

In case of a voltage dip, the converter has to provide the active power required by the load and it has to inject the reactive power needed to stabilize the load voltage as shown in Fig. 4(b). The grid current in this case is reactive. It can be seen that

$$\dot{V}_{load} = \dot{E} + \dot{V}_{Lg} \tag{5}$$

hence, during a voltage sag, the amount of reactive current needed to maintain the load voltage at the desired value is inversely proportional to ωL_g. This means that a large inductance will help in mitigating voltage sags, although it is not desirable during normal operation.

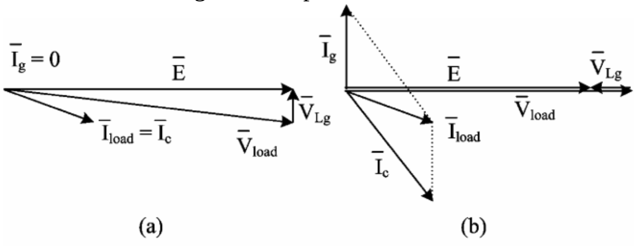


Fig. 4. Vector diagram of the shunt controller providing both active and reactive power: (a) normal conditions; (b) vector diagram for compensation of a voltage dip of 0.15 pu.

IV. PV SYSTEM WITH SHUNT-CONNECTED MULTIFUNCTIONAL CONVERTER

In case of low power applications it can be advantageous to use the converter which is parallel connected to the grid for the compensation of small voltage sags. This feature can be viewed as an ancillary service that the system can provide to its local loads. The proposed PV converter operates supplying active and reactive power when the sun is available. At low irradiation, the PV converter operates only as harmonic and reactive power compensator. As explained in Section III, it is difficult to improve voltage quality with a shunt controller since it cannot provide simultaneously control of the output voltage and the output current. Besides, a large-rated converter is necessary in order to compensate voltage sags. However this topology is acceptable in PV applications since the PV shunt converter must be rated for the peak power produced by the panels. In the proposed system the PV converter operates as a shunt controller; it is connected to the load through an LC filter and to the grid through an extra inductance L_g^* of 0.1 pu as shown in Fig. 5.

Usually in case of low power applications, the systems are connected to low voltage distribution lines whose impedance is mainly resistive, but, in the proposed topology, the grid can be considered mainly inductive as a consequence of L_g^* addition on the grid side. However, since the voltage regulation is directly affected by the voltage drop on the inductance L_g^*, it is not convenient choosing an inductance L_g^* of high value in order to limit the voltage drop during grid normal conditions. It represents the main drawback of the proposed topology.

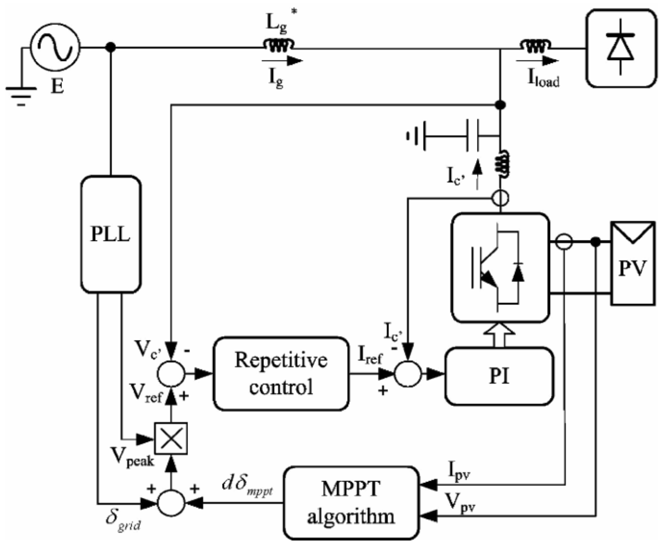


Fig. 5. Grid-connected PV system with shunt controller functionality.

A. Control of the converter

The proposed converter is voltage controlled with a repetitive algorithm. An MPPT algorithm modifies the phase displacement between the grid voltage and the ac voltage produced by the converter in order to force it to inject the maximum available power in the given atmospheric conditions. Hence the current injection is controlled indirectly. The amplitude of the current depends on the difference between the grid voltage and the voltage on the ac capacitor V_{c}'. The phase displacement between these two voltages determines the injected active power (decided by the MPPT algorithm) and the voltage amplitude difference determines the reactive power exchange with the grid. The requested reactive power is limited by the fact that a voltage dip higher than 15 % will force the PV system to disconnect (as requested by standards). The active power is limited by the PV system rating and leads to a limit on the maximum displacement angle $d\delta_{mppt}$. Moreover the inverter has its inner PI-based current control loop and overcurrent protections.

A phase-locked-loop (PLL) detects the amplitude V_{peak} and phase δ_{grid} of the grid voltage. Then the phase displacement $d\delta_{mppt}$ is provided by the MPPT algorithm described in Section B. The voltage error between V_{ref} and $V_{c'}$ is pre-processed by the repetitive controller which is the periodic signal generator of the fundamental component and of the selected harmonics: in this case the third and the fifth ones are compensated (Fig.6).

The proposed repetitive controller is based on a finite-impulse response (FIR) digital filter [20]; it is a "moving" or "running" filter, with a window equal to one fundamental period,defined as

$$F_{DFT(z)} = \frac{2}{N}\sum_{i=0}^{N-1}\left(\sum_{h\in N_h}\cos\left[\frac{2\pi}{N}h(i+N_a)\right]\right).z^{-i} \tag{6}$$

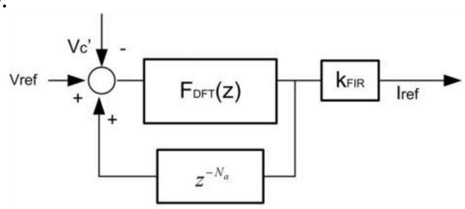
where N is the number of samples within one fundamental period, N_h is the set of selected harmonic frequencies and N_a is the number of leading steps determined to track the reference exactly.

The repetitive controller ensures a precise tracking of the selected harmonics and it provides the reference for the inner loop. In it a proportional-integral (PI) controller improves the stability of the system offering low-pass filter function. The PI controller G_c

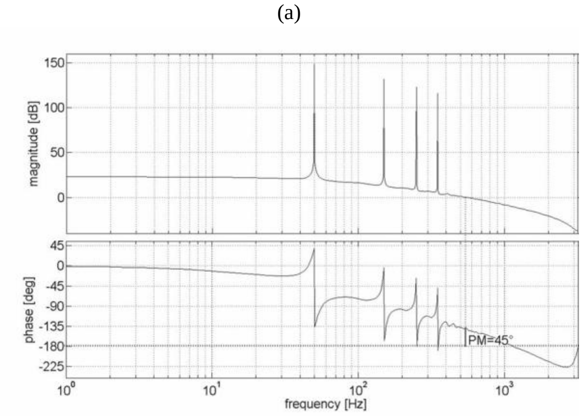
$$G_c(s) = K_p + \frac{k_i}{s} \quad (7)$$

is designed to ensure that the low frequency poles have a damping factor of 0.707. The open-loop Bode diagram of the system is shown in Fig. 6(b): the stability is guaranteed since the phase margin is about 45 degrees.

In normal operation mode the shunt-connected converter injects the surplus of active power in the utility grid and, at the same time, it is controlled in order to cancel the harmonics of the load voltage. At low irradiation, the PV inverter acts only as a shunt controller eliminating the harmonics. Controlling the voltage V_c' the PV converter is improved with the function of voltage dips compensation. In presence of a voltage dip, the grid current I_g is forced by the controller to have a sinusoidal waveform which is phase shifted by 90° with respect to the corresponding grid voltage.



(a)



(b)

Fig. 6. Proposed repetitive-based controller: (a) control scheme; (b) Open–loop Bode diagram of the system obtained using k_{FIR}=1, N_a=0 and N_h={1;3;5}.

B. MPPT algorithm

Power supplied from a PV array depends mostly on present atmospheric conditions (irradiation and temperature), therefore in order to collect the maximum available power the operating point needs to be tracked continuously using a Maximum Power Point Tracker algorithm . To find the maximum power point (MPP) for all conditions, it has been used an MPPT control method based on the Incremental Conductance Method which can tell on which side of the PV characteristic the current operating point is.

The MPPT algorithm modifies the phase displacement between the grid voltage and the converter voltage providing the voltage reference V_{ref}, furthermore, there is an extra feature added to this algorithm, which monitors the maximum and minimum values of the power oscillations on the PV side. In case of single-phase systems, the instant power oscillates with twice the line frequency. This oscillation in the power on the grid side leads to a 100 Hz ripple in the voltage and in the power on the PV side.

If the system operates in the area around the MPP the ripple of the power on the PV side is minimized. This feature can be used to detect in which part of the power-voltage characteristics the system operates. It happens in the proposed control scheme where the information about the power oscillation can be used to find out how close the current operating point is to the MPP, thereby slowing down the increment of the reference, in order not to cross the MPP.

A flowchart of the MPPT algorithm is shown in Fig. 7 explaining how the angle of the reference voltage is modified, in order to keep the operating point as close to the MPP as possible. The MMP can be tracked by comparing the instantaneous conductance I_{pv_k}/V_{pv_k} to the incremental Conductance dI_{PV}/dv_{pv} shown in the flowchart. Considering the power-voltage characteristic of a PV array, it can be observed that operating in the area on the left hand sideof the MPP $d\delta_{mppt}$ has to decreaseThis decrement is indicated in Fig.7 with *side* = −1, moreover, operating in the area on the right side of the MPP $d\delta_{mppt}$ has to increase and it is indicated with *side* =+1. The increment size determines how fast the MPP is tracked. The measure of the power oscillations on the PV side is used to quantify the increment which is denoted with *incr* in Fig. 7.

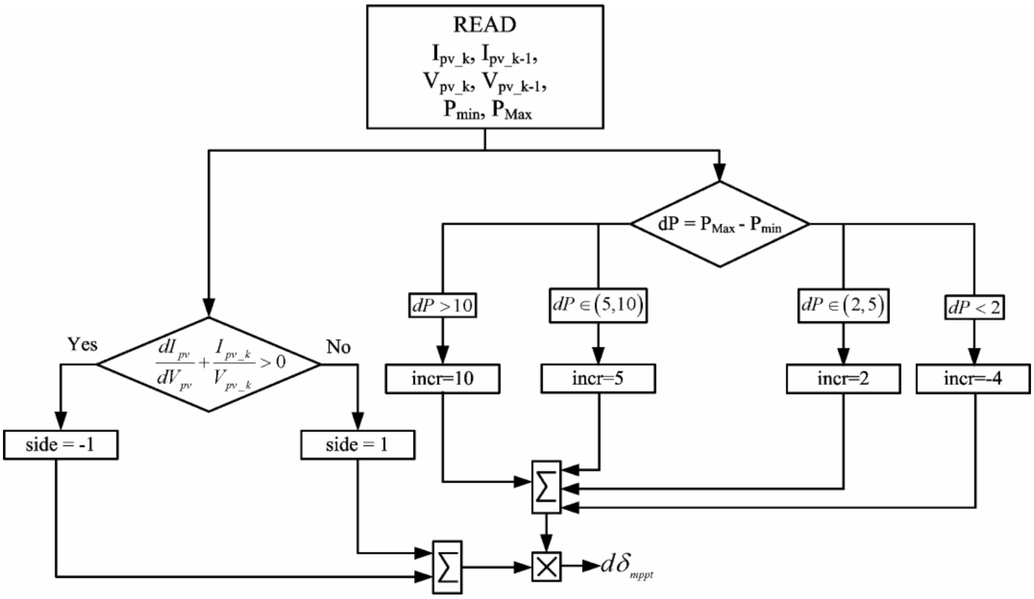


Fig. 7. Flowchart of modified MPPT algorithm.

V. Simulation Results

The PV system with power quality conditioner functionality has been tested in simulation with the following system parameters: LC filter made by 1.4 mH inductance and 2.2 µF capacitance and 1 Ω damping resistance; an inductance L_g^* of 0.1 pu; an 1 kW load.

The control has been validated in presence of sudden changes of the PV power caused, for example, by irradiation variations. The reported tests show the behavior of the MPPT for a voltage sag. The results refer to the case of inverter controlled in order to collect the maximum available power: 2 kW.

The controller parameters are k_{FIR}= 0.3, N=128 (sampling frequency = 6400 Hz) N_a = 0, k_p = 4.5, k_i = 48. The set of test aims to demonstrate the behaviour of the system during a voltage sag and the interaction of the voltage control algorithm with the MPPT algorithm.

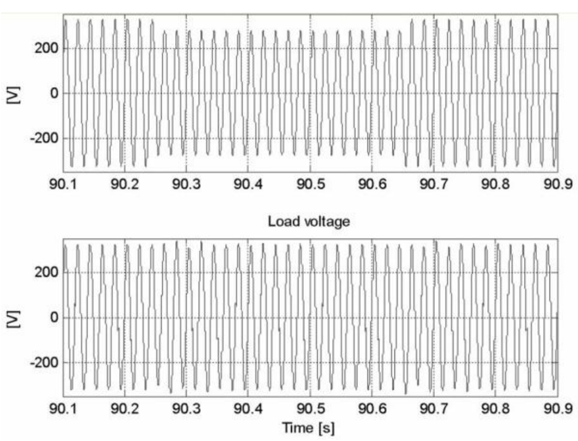


Fig. 8. Performance of the voltage controlled shunt converter with MPPT algorithm: grid voltage E, load voltage V_{load}.

The simulation results, shown in Fig. 8-9, are obtained in case of a voltage dip of 0.15 pu. During the sag the inverter sustains the voltage for the local load (Fig. 8) injecting a mainly reactive current into the grid. The amplitude of the grid current I_g grows from 4.5 A to 8.5 A, as shown in Fig. 9, which corresponds to the reactive power injection represented in Fig.10. The inductance L_g^* connected in series with the grid impedance limits the current flowing through the grid during the sag.

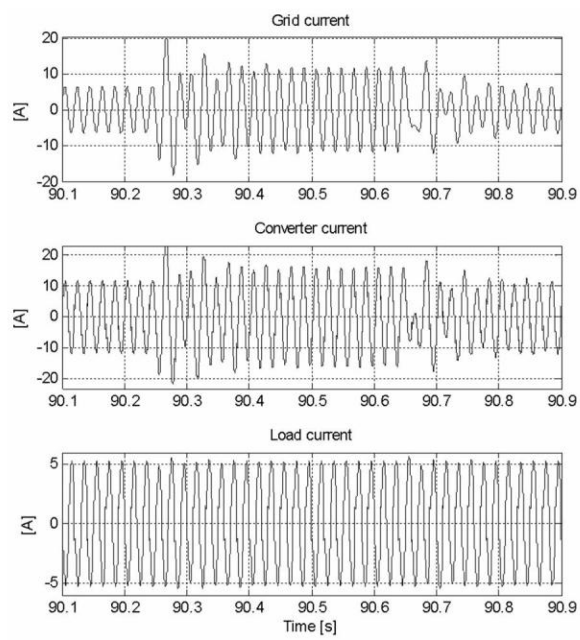


Fig. 9. Performance of the voltage controlled shunt converter with MPPT algorithm: grid current I_g, converter current $I_{c'}$, load current I_{load}.

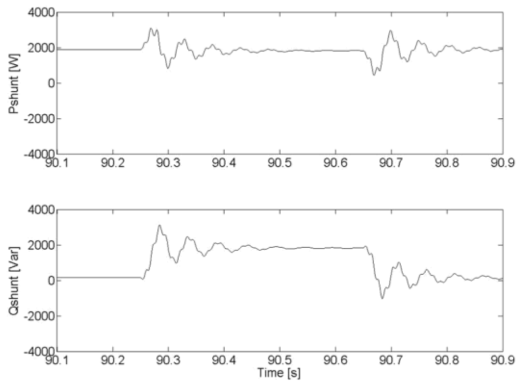


Fig. 10. Active and reactive power provided by the shunt-connected multifunctional converter to compensate the voltage sag of 0.15 pu.

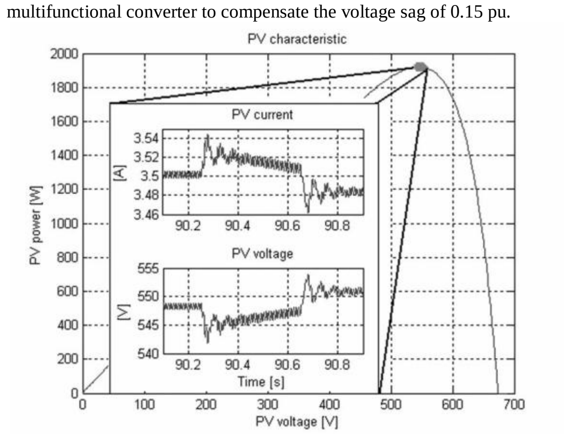


Fig. 11. Power-voltage characteristic of the PV array and current and voltage on the PV side in presence of a grid voltage sag to 0.85 pu.

When the voltage sag of 0.15 pu occurs the converter current grows from 8 A to 10.5 A, for this reason the shunt controller is not a good choice to compensate deeper dips. Fig. 11 demonstrates the robustness of the presented MPPT algorithm to the voltage dip, in fact in it there are shown the voltage and the current on the PV side during the sag. They are not significantly influenced by the dip.

VII. CONCLUSION

In this paper a single-phase photovoltaic system with shunt controller functionality has been presented. The PV converter is voltage controlled with a repetitive algorithm. An MPPT algorithm has been specifically designed for the proposed voltage controlled converter. It is based on the incremental conductance method and it has been modified to change the phase displacement between the grid voltage and the converter voltage maximizing the power extraction from the PV panels. The designed PV system provides grid voltage support at fundamental frequency and compensation of harmonic distortion at the point of common coupling (PCC). An inductance is added on the grid side in order to make the grid mainly inductive, it may represent the main drawback of the proposed system.

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