A SINGLE-PHASE VOLTAGE-CONTROLLED GRID-CONNECTED PHOTOVOLTAIC SYSTEM WITH POWER QUALITY CONDITIONER FUNCTIONALITY

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***Abstract*:-**This 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 the presence of nonlinear loads. Shunt controllers can be used as a static var generator for stabilizing and improving the voltage profile in power systems and to compensate current harmonics and unbalanced load current. This paper presents a single-phase PV system that provides grid voltage support and compensation of harmonic distortion at the point of common coupling thanks to a repetitive controller. In this paper, the PV inverter not only supplies the power produced by the PV panels but also improves the voltage profile. The presented topology adopts a repetitive controller that is able to compensate the selected harmonics. Among the most recent Maximum Power Point Tracking (MPPT) algorithms, an algorithm based on the incremental conductance method has been chosen. It has been modified in order to take into account power oscillations on the PV side, and it controls the phase of the PV inverter voltage. The designed PV system provides grid voltage support at fundamental frequency and compensation of harmonic distortion at the point of common coupling. An inductance is added on the grid side in order to make the grid mainly inductive.

Keywords- Maximum Power Point Tracking (MPPT), Distributed power generation system (DPGS), phase-locked loop (PLL).

I.INTRODUCTION:-

Among the renewable energy sources, a noticeable growth of small photovoltaic (PV) power plants connected to low-voltage distribution networks is expected in the future [1]. As a consequence, research has been focusing on the integration of extra functionalities such as active power filtering into the PV inverter operation [2]. Distribution networks are less robust than transmission networks, and their reliability, because of the radial configuration, decreases as the 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 [3].

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" [4]. Hence, they can contribute to reinforce the distribution grid, maintaining proper quality of supply that 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 grid voltage cannot be controlled by independently adjusting the active and reactive powers [5]–[6]. This problem, together with the need of limiting the cost and size of DPGS, which should remain economically competitive even when ancillary services are added, makes the design problem particularly challenging.

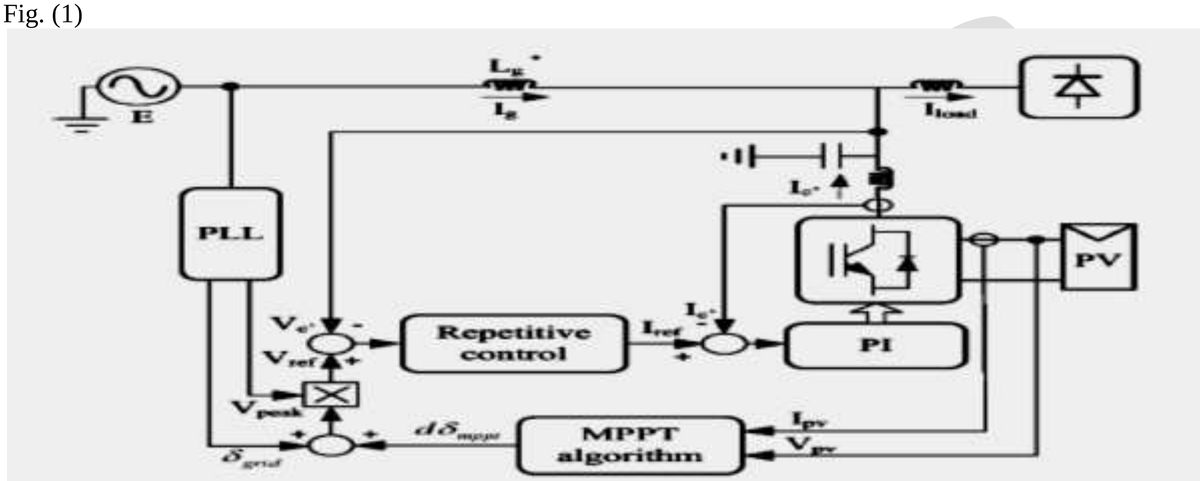
This paper proposes to solve this issue using a voltage controlled converter that behaves as a shunt controller, improving the voltage quality in case of small voltage dips and in the presence of nonlinear loads. Shunt controllers can be used as a static var generator for stabilizing and improving the voltage profile in power systems and to compensate current harmonics and unbalanced load current [7]–[11].

In this paper, the PV inverter not only supplies the power produced by the PV panels but also improves the voltage profile, as already pointed out [12]. The presented topology adopts a repetitive controller [13]–[17] that is able to compensate the selected harmonics. Among the most recent Maximum Power Point Tracking (MPPT) algorithms [18]–[20], an algorithm based on the incremental conductance method has been chosen [21]–[22]. It has been modified in order to take into account power oscillations on the PV side, and it controls the phase of the PV inverter voltage.

This paper is organized as follows. Section II discusses the possible voltage and frequency support provided by a DPGS converter connected to the grid. Section III discusses the simulation results. Section IV discusses the experimental results. Section V discusses the conclusion. Section VI refers to the reference papers

II. PV SYSTEM WITH SHUNT-CONNECTED MULTIFUNCTIONAL CONVERTER

In case of low-power applications, it can be advantageous to use the converter that 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 by supplying active and reactive powers when the sun is available. At low irradiation, the PV converter only operates as a harmonic and reactive power compensator. As explained in Section III, it is difficult to improve the voltage quality with a shunt controller since it cannot provide simultaneous control of the output voltage and current. In addition, 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 Lg of 0.1 pu, as shown in Fig. (1)



Fig(1).Grid-connected PV system with shunt controller functionality.

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

A. Control of 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, current injection is indirectly controlled. The amplitude of the current depends on the difference between the grid voltage and the voltage on the ac capacitor Vc . 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 injected 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 dδmppt. Moreover, the inverter has its inner proportional integral (PI)-based current control loop and overcurrent protections. A phase-locked loop (PLL) detects the amplitude Vpeak and phase δgrid of the grid voltage. Then, the phase displacement dδmppt is provided by the MPPT algorithm described in Section IV-B. The voltage error between Vref and Vc is preprocessed 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 fifth ones are compensated (Fig)(2)

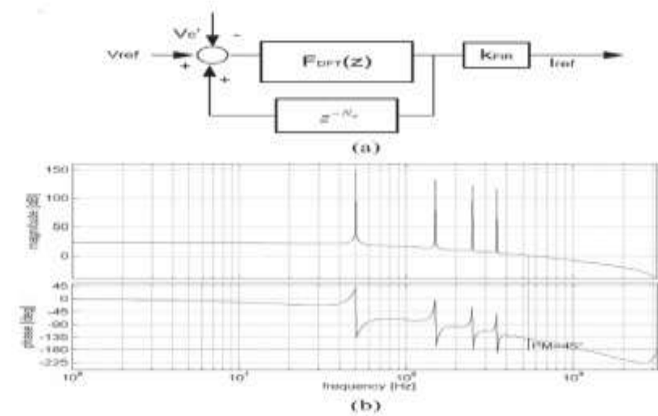


Fig2. Proposed repetitive-based controller. (a) Control scheme. (b) Open loop Bode diagram of the system obtained using *k*FIR = 1, *Na* = 0, and *Nh* = {1; 3; 5}.

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

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

where N is the number of samples within one fundamental period, Nh is the set of selected harmonic frequencies, and Na is the number of leading steps determined to exactly track the reference. The repetitive controller ensures a precise tracking of the selected harmonics, and it provides the reference for the inner loop. In it, a PI controller improves the stability of the system, offering a low-pass filter function. The PI controller Gc

$$G_c(s) = k_p + \frac{k_i}{s}$$

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 (b): stability is guaranteed since the phase margin is about 45◦.

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 only acts as a shunt controller, eliminating the harmonics. Controlling the voltage Vc , the PV converter is improved with the function of voltage dip compensation. In the presence of a voltage dip, the grid current Ig is forced by the controller to have a sinusoidal waveform that is phase shifted by 90◦ with respect to the corresponding grid voltage.

B. MPPT Algorithm

The power supplied from a PV array mostly depends on the present atmospheric conditions (irradiation and temperature); therefore, in order to collect the maximum available power, the operating point needs to continuously be tracked using an MPPT algorithm [28]. To find the maximum power point (MPP) for all conditions, an MPPT control method based on the incremental conductance method [32], [34], which can tell on which side of the PV characteristic the current operating point is, has been used. The MPPT algorithm modifies the phase displacement between the grid voltage and the converter voltage, providing the voltage reference Vref . Furthermore, there is an extra feature added to this algorithm that monitors the maximum and minimum values of power oscillations on the PV side. In case of single-phase systems, the instant power oscillates with twice the line frequency. This oscillation in power on the grid side leads to a 100-Hz ripple in voltage and 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 [33]. 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 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., explaining how the angle of the reference voltage is modified in order to keep the operating point as close to MPP as possible. The MPP can be tracked by comparing the instantaneous conductance Ipvk/Vpv_k to the incremental conductance dIpv/dVpv, as 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 side of the MPP, dδmppt has to decrease. This decrement is indicated in Fig. with side = −1. Moreover, operating in the area on the right side of the MPP, dδmppt 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 that is denoted with incr in Fig.(3)

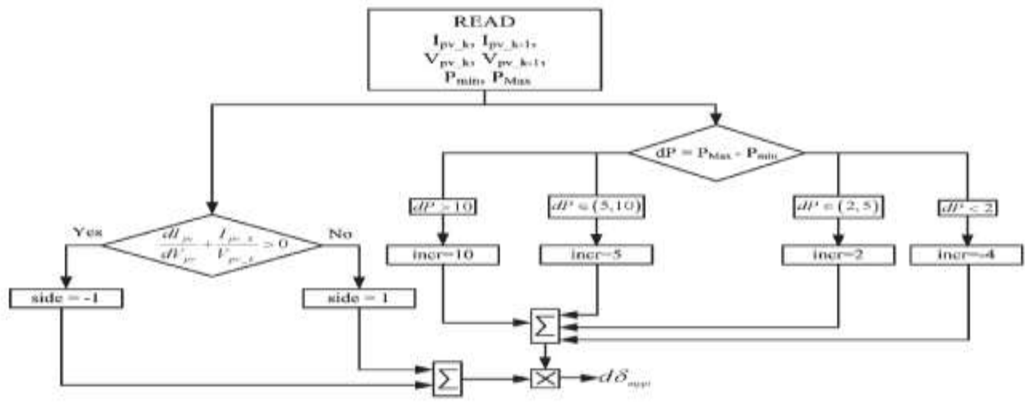


Fig3. Flowchart of the modified MPPT algorithm.

III. SIMULATION RESULTS

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

The control has been validated in the 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 a controlled inverter in order to collect the maximum available power (i.e.,2 kW).

The controller parameters are kFIR = 0.3, N = 128 (sampling frequency = 6400 Hz), Na = 0, kp = 4.5, and ki = 48. The set of test aims to demonstrate the behavior of the system during a voltage sag and the interaction of the voltage control algorithm with the MPPT algorithm.

The simulation results, shown in Figs , are obtained in case of a voltage dip of 0.15 pu.

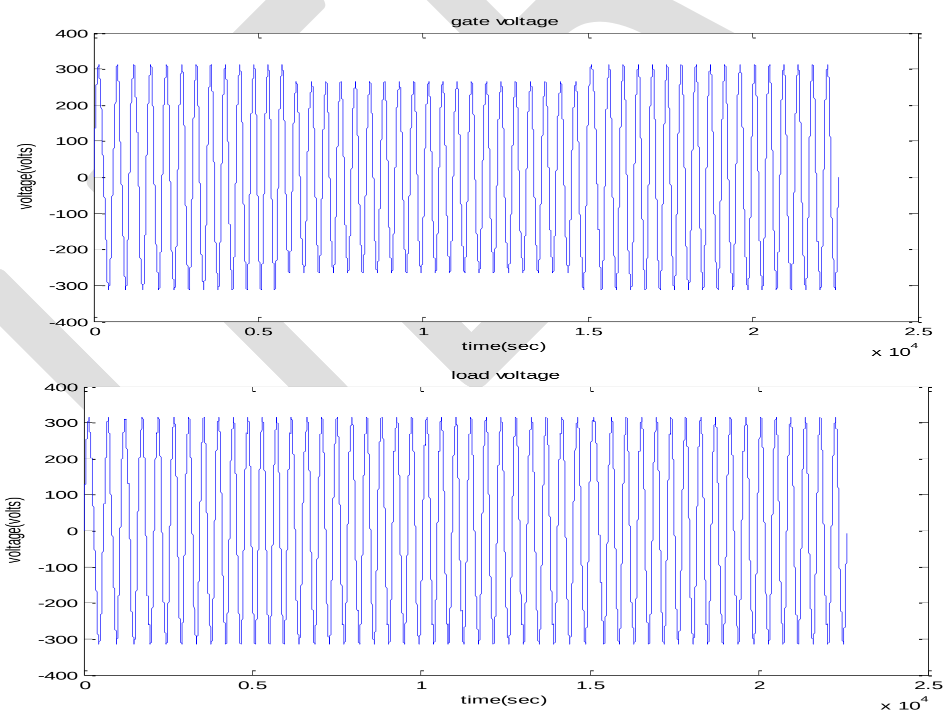


Fig4. Performance of the voltage-controlled shunt converter with MPPT algorithm: grid voltage *E* and load voltage *V*load.

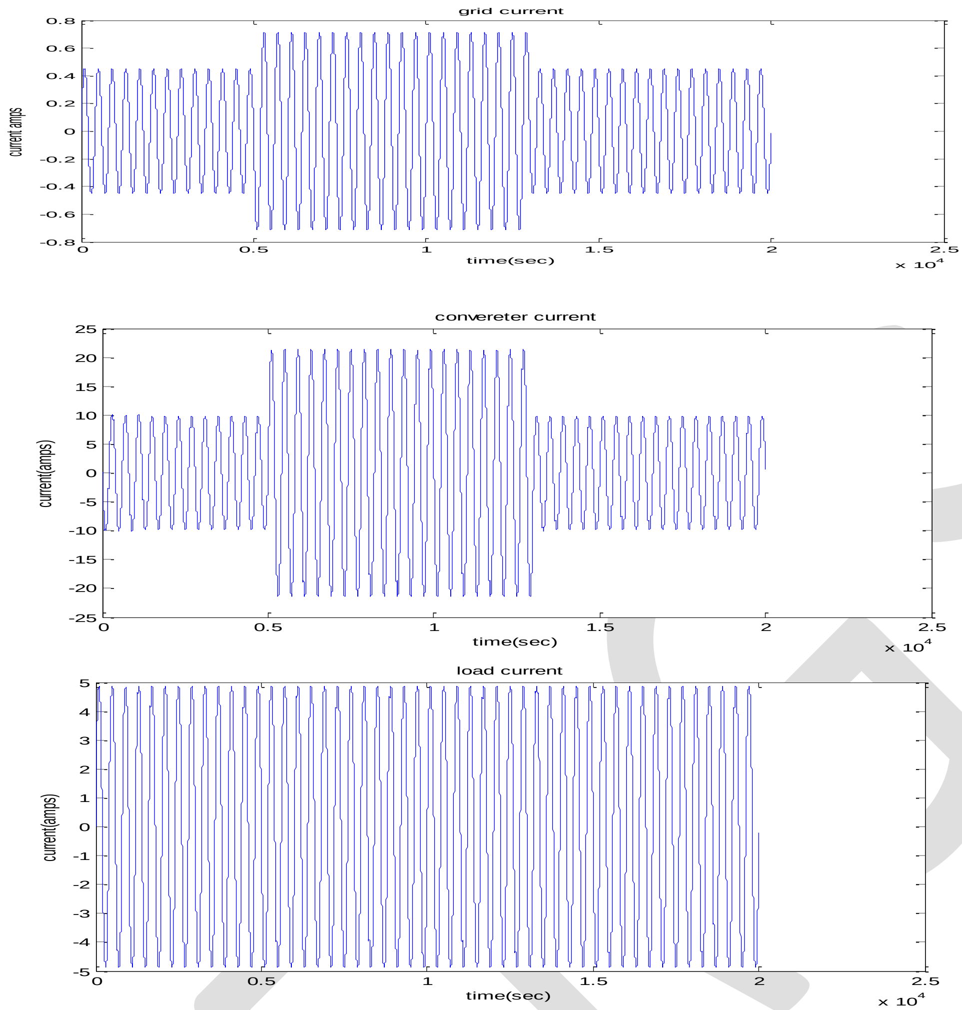


Fig.5 Performance of the voltage-controlled shunt converter with MPPT algorithm: grid current *Ig*, converter current *IC*, and load current *I*load.

During the sag, the inverter sustains the voltage for the local load (Fig.), injecting a mainly reactive current into the grid. The amplitude of the grid current Ig grows from 4.5 to 8.5 A, as shown in Fig, which corresponds to the reactive power injection represented in Fig.

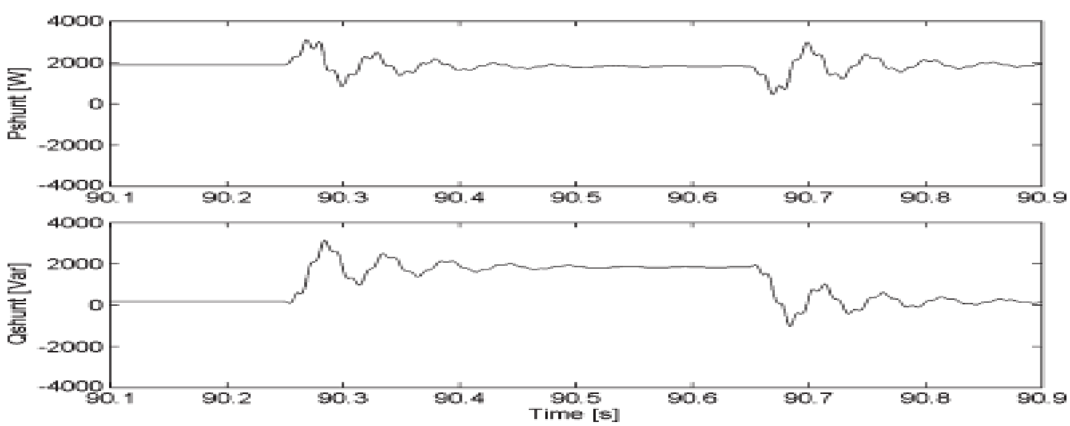


Fig.6 Active and reactive power provided by the shunt-connected multifunctional converter to compensate the voltage sag of 0.15 pu.

The inductance Lg connected in series with the grid impedance limits the current flowing through the grid during the sag. When the voltage sag of 0.15 pu occurs, the converter current grows from 8 to 10.5 A. For this reason, the shunt controller is not a good choice to compensate for deeper dips. Fig. demonstrates the robustness of the presented MPPT algorithm to the voltage dip. In fact, in it are shown the voltage and current on the PV side during the sag. They are not significantly influenced by the dip.

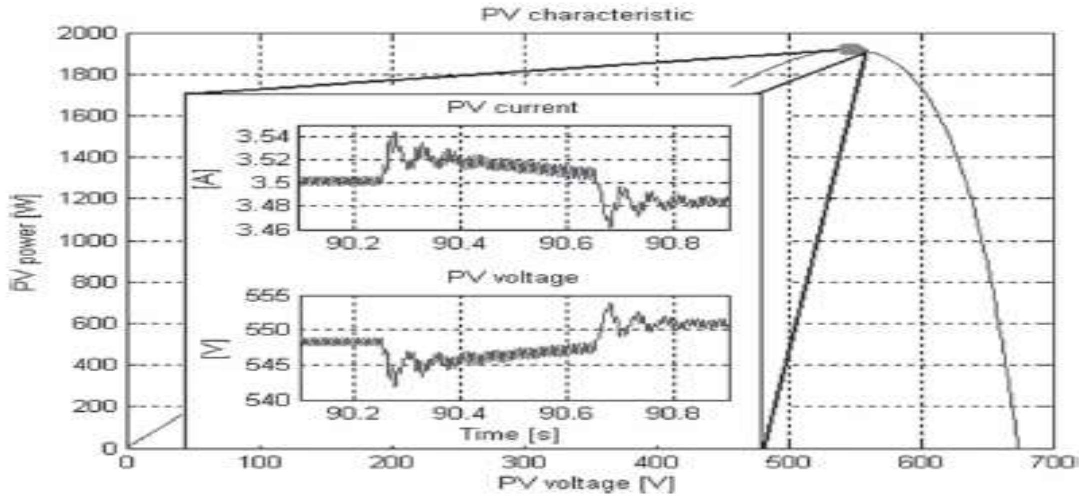


Fig.7 Power–voltage characteristic of the PV array and current and voltage on the PV side in the presence of a grid voltage sag of 0.85 pu.

IV.EXPERIMENTAL RESULTS

In order to verify the previous analysis, some experiments have been carried out on a laboratory setup to test the performance of the PV system with shunt controller functionality. The hardware setup, consists of the following equipment: a Danfoss VLT 5006 7.6-kVA inverter (whose only two legs are used), two series-connected dc voltage sources to simulate the PV panel string, and the dSPACE 1104 system. The PV converter is connected to the grid through an LC filter whose inductance is 1.4 mH, and the capacitance is 2.2 μF in series with a resistance of 1 Ω. In addition, an inductance Lg of 15 mH (0.1 pu) has been added on the grid side of the converter, as explained in the previous sections.

The experimental tests have been made with grid voltage approximate background distortion THD = 1.5%. They have been executed with two different kinds of loads. In the first case, the voltage sag compensation capability has been tested when the system feeds a purely resistive load, absorbing 1200 W. In the second one, the performances of the proposed system in the presence of a highly distorting load have been analyzed.

A. Voltage Sag Compensation

The system has been tested in the following conditions: dc voltage Vdc = 460 V. The results obtained in the simulation in the case of voltage sag of 0.15 pu are experimentally confirmed. During the dip, the load voltage remains constant and equal to the desired voltage. The shunt-connected converter injects a reactive current into the grid in order to compensate the load voltage. The current is mainly capacitive.

B. Voltage Harmonic Compensation in Case of Highly Distorting Load

The performances of the shunt-connected converter have been analyzed in the presence of a distorting load consisting of a single-phase diode bridge connected via a 10-mH inductance to the grid. The bridge feeds a 500-μF capacitor in parallel with a 100-Ω resistor. Before connecting the shunt converter, the load voltage appears highly distorted and the voltage THD is around 17%. When the shunt converter is connected to the grid, it compensates the voltage harmonics introduced in the system by the distorting load where the voltage THD is 2%.

C. Test with Solar Panel Simulator

This section proves the capability of the system to compensate a voltage dip when the inverter is fed by two PV arrays connected in parallel. In fact, the two dc voltage sources used in the laboratory to feed the inverter have been controlled by software that implements the PV voltage–current characteristics as a function of irradiance. The test has been done considering a fixed power level of 700 W and a voltage dip of 0.15 pu occurring for 1.5 s.

V. CONCLUSION

In this paper, a single-phase PV system with shunt controller functionality has been presented. The PV converter is voltage controlled with a repetitive algorithm. An MPPT algorithm has specifically been 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. 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). Experimental results confirm the validity of the proposed solution in case of voltage dips and nonlinear loads.

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