Design of the Control Algorithms for Photovoltaic Grid-Connected Renewable Agents using the Hardware-in-the-loop Simulation Technique

N. F. Guerrero-Rodríguez, A. B. Rey-Boué, S. de Pablo-Gómez

Abstract-- **The purpose in this paper is to design the vector control algorithm for a voltage source inverter (VSI) that will be used as a power conditioner and link between the Photovoltaic (PV) agent as the primary renewable energy source and the low voltage 3-phase utility grid. The vector control algorithm must be able to regulate the instantaneous active and reactive power when disturbances (harmonic and unbalances) in the low voltage 3-phase utility grid occur, allowing an unitary power factor operation of the inverter-grid connection with high power quality.**

A design procedure will be shown in this paper for developing a vector control algorithm of the voltage source inverter working in the grid-connection mode. In order to validate the performance of the control algorithms for the Photovoltaic Generator, some simulations using MATLAB/SIMULINK from The MathWorks, Inc. will be shown firstly, and secondly, some real-time measurements using the hardware-in-the-loop simulation technique will be carried out. A real platform for the control subsystem will be used, whereas the power subsystem will be run in a real-time digital simulator platform. In both steps, the dynamic of the system and its robustness will be tested by introducing some disturbances, such as harmonic contamination and unbalances in the 3-phase utility grid.

***Keywords*: Photovoltaic Agent, 3-phase grid-connected Voltage Source Inverter, d-q control, hardware-in-the-loop simulation.**

I. INTRODUCTION

Traditional primary energy resources have the following drawbacks: the eminent depletion of these sources is coming soon, whereas its pollutant effects cannot be denied. So, new clean and infinite renewable energy resources such as Photovoltaic, Wind, as well as Fuel Cells for energy storage, etc., have been arisen as an alternative to traditional ones, being necessary to connect them efficiently to the low-voltage 3-phase utility grid with good power quality according to certain standards [1], as a collaborative effort towards the mitigation of the greenhouse effect. The connection of renewable agents to the utility grid must be properly controlled according to the expected operating conditions of the primary energy source such as different values of irradiance, temperature variation, as well as to the utility grid normative such as the control of the power factor connection (synchronization module), islanding protections, etc.

To deal with the aforementioned facts, new control algorithms have been designed focusing on improving the performance of the connection of primary renewable energy agents to the low-voltage 3-phase utility. Photovoltaic modules produces DC electric energy and a power conditioning system is needed to convert the DC quantities into AC quantities, as well as to balance the power flow between the renewable agent and the utility grid; this task can be done in the DC or AC stage of the system [2]. For a grid-connected photovoltaic agent, it is usual to do a current source control [3].

Renewable agents are very expensive systems, some of them could be delicate, and so, it is difficult to test new control algorithms used by the inverter controller in a real operative renewable agent. It is also possible that the first algorithm versions are not fully debugged which could lead to cause faults in the renewable installation, or damage it at all in the worst case. In addition, too many laboratories are not able to do tests with a real 3-phase utility grid due to the lack of space or resources, or even do not have a grid connection platform fed by a renewable agent. A good solution to these kind of problems is the application of the hardware-in-the-loop simulation technique in which the plant (renewable agents + inverter + LCL filter + the low-voltage 3-phase utility grid) could be modeled and implemented in real time [4],[5], whereas the controller is a real device such as a DSP or a FPGA.

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II. PHOTOVOLTAIC SYSTEMS (PV)

Photovoltaic cell is an electric device that produces electric energy when it is exposed to direct sunlight and connected to a load [6]. A simple equivalent circuit for a photovoltaic cell is a current source connected in parallel with a diode [3],[7]. The equivalent circuit for a photovoltaic cell is shown in Fig. 1. The sun irradiance is represented by the current source, the diode represent the P-N junction, R_S is connected in series and represent the losses due the contacts connection and R_{Sh} represent the leakage current in a diode [3],[8]. By a general form the output current (I) of the photovoltaic cell is given in (1).

$$I = I_{ph} - I_0 \left[\exp^{\frac{q(V+IR_S)}{nkT}} - 1 \right] - \frac{V + IR_S}{R_{Sh}} \tag{1}$$

where I_{ph} is the photocurrent of the PV module, I_O is the reverse saturation current, q is the electron charge, k is the Boltzmann's constant, n is the diode factor, T is the solar array panel temperature and V is the output voltage of a solar cell [1],[3],[7].

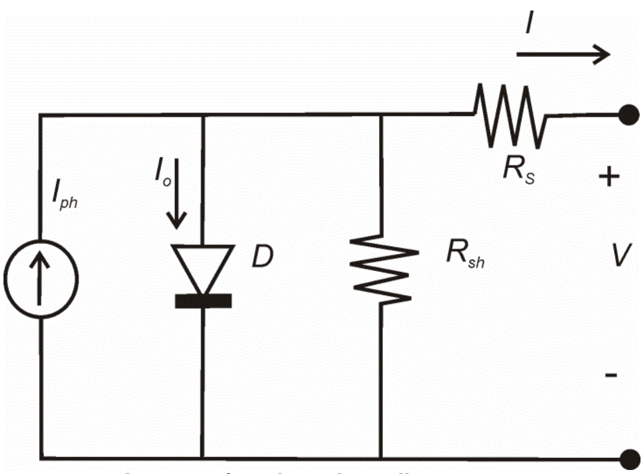

Fig. 1. Equivalent circuit for a photovoltaic cell

III. Grid Connected Photovoltaic System

The main purpose for PV grid-connected systems is to control the power flow between the primary renewable energy source and the utility grid, as well as the power factor of the inverter-grid connection with high power quality [1]. It is necessary that the power conditioner guarantees the maximum efficiency by injecting the maximum available power in the PV module, as well as by controlling the power factor of the inverter-grid connection; the latter makes use of the instantaneous reactive power theory for 3-phase systems which allows the control of the instantaneous active and reactive powers in decoupled d-q axes. The global 3-phase PV grid-connected system can be divided in two subsystems: the power and the control subsystems, whose block diagram is depicted in Fig. 2.

A. Power Subsystem

The power subsystem is formed by:

Photovoltaic modules: PV modules are the main part of a PV system [9]. There are types of PV modules technology with different levels of efficiency. The function of PV modules is to supply the necessary voltage and current for the renewable grid-connected system [7], which will be a function of the available solar energy. The size (arrange of parallel-series PV cells) of the PV module will be a function of the required power of the Photovoltaic system [10],[11].

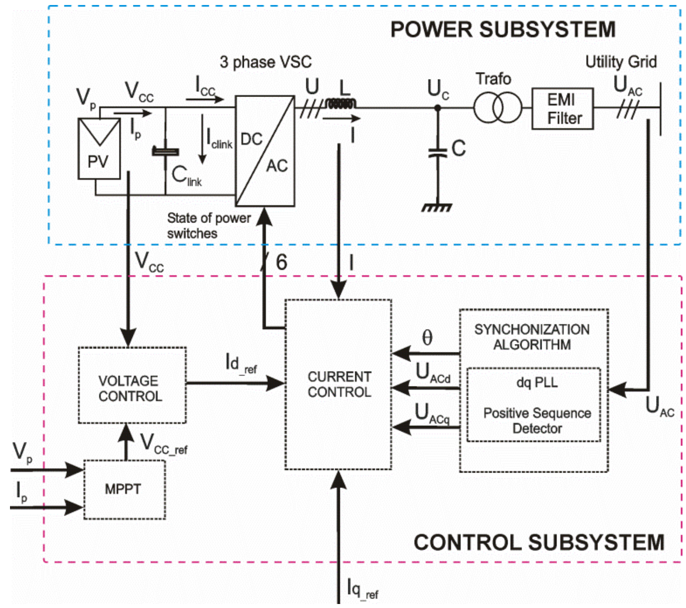

Fig. 2. Block diagram of the Power and Control Subsystems for the PV system connected to the 3-phase grid

The inverter: The inverter transforms the generated DC voltage into suitable AC currents to be fed into the 3-phase low-voltage utility grid [12]. The inverter is mainly made by semi-conductor electronic devices (IGBTs and Diodes) commonly called "power switches". Pulse-width modulation (PMW) and space vector modulation (SVM) [13] techniques are used to control the trigger of the power switches according to the averages of the voltages and currents references. According to Fig. 2, the DC side of the inverter can be described as follows:

$$i_p = i_{clink} + i_{cc} \tag{2}$$

$$i_{cc} = S_u i_u + S_v i_v + S_w i_w \tag{3}$$

$$i_{clink} = C_{link} \frac{dv_{cc}}{d_t} \tag{4}$$

$$P_{PV} = v_p i_p \tag{5}$$

where v_p and i_p are the output voltage and current in the PV generator, P_{PV} is the power in the PV generator for a specific irradiance, v_{cc} is the dc bus voltage, i_{clink} is the current across the link capacitor (C_{link}) and i_{cc} is the current that will be injected into the inverter [1].

Taking into account that the voltage in the capacitor is nearly the same that the voltages in the three phase utility grid [1], the dynamic in the AC side of the inverter expressed in a vector way is as follows:

$$\mathbf{u} - \mathbf{u}_{AC} = R\mathbf{i} + L\frac{\mathbf{di}}{\mathbf{dt}} = \mathbf{u}_R + \mathbf{u}_L \tag{6}$$

where $\mathbf{u}$, $\mathbf{i}$, $\mathbf{u}_{AC}$ are the inverter voltage, the inverter line current and the utility grid voltage space vectors, respectively, L is the line inductance and R its resistance. Expressing the last vector equation with its d and q components in d-q axes for vector control [1], the instantaneous active power (p) and the instantaneous reactive power (q) can be expressed as follows:

$$p = v_d i_d + v_q i_q \tag{7}$$

$$q = v_q i_d - v_d i_q \tag{8}$$

where v_d, v_q, i_d and i_q are the d-q components of 3-phase voltages and currents allowing a decoupled control if vector $\mathbf{u_{AC}}$ is aligned with the d axis.

LCL Filter: In addition of guaranteeing a constant power delivery to the 3 phase utility grid, grid-connected renewable agents must obey the regulations of power quality. The maximum total harmonic distortion (THD) for the 3-phase currents must be around 5% according to some normative [14], whereas the normative for the low order harmonic distortions is indeed more restrictive. Ripples are created in the output of the inverter due to the high frequency commutations of the IGBTs, meanwhile the low order harmonics are due to its presence in the utility grid voltages, unbalances, dead zone of the semiconductors of the inverters, etc. The low order harmonic distortions of the 3-phase currents must be attenuated to guarantee a good power quality injection to the utility grid. The best solution for correcting these ripples is by using of a LC or a LCL filter in the AC side of the inverter [15].

EMI filter: In a grid-connected Renewable agent, it is necessary to take into account the harmonic pollution due to the Electromagnetic interference (EMI). The EMI interferences in renewable agents are caused by the semi-conductor electronic devices (IGBTs and Diodes) [16] . The PWM technique is usually implemented to reduce the generated harmonics by the high-frequency switching of the IGBTs [17]. An EMI filter is a great help to reduced the electromagnetic interference produced by the IGBTs commutations [1]. There are too many methodologies to design the appropriate EMI filter, some of them are based in trial an error [18]. Novel methodologies are cited in several publications, including [16],[18],[19],[20].

B. Control Subsystem

The control subsystem is made by the following blocks:

Synchronization Algorithm: The Synchronization Algorithm for attaining a controllable power factor in the connection must detect the phase of the 3-phase utility grid voltages with optimal dynamic response. There are several studies which show different structures for synchronization algorithms [21]. The measured signals of the 3 phase low voltage utility grid are contaminated with harmonics, voltage unbalances, and frequency variations [22]; indeed, the used sensors introduce second order harmonics due to accuracy errors. In addition, the dq PLL method for synchronization used in this paper is very sensible to grid voltage unbalances [23], which also produce second order harmonics. A solution for this drawback is to add a positive sequence detector block, which is based in the symmetrical component method or *Fortescue* theorem [24]. By using the *Fortescue* theorem, it is possible to descompose an unbalance 3-phase utility grid voltage system into its positive, negative and zero sequences [25]. In time domain the positive sequence are given by [23]:

$$V_a^+(t) = \frac{1}{3}V_a^f(t) - \frac{1}{6}\left(V_b^f(t)+V_c^f(t)\right) - \frac{1}{2\sqrt{3}}S_{90}\left(V_b^f(t)-V_c^f(t)\right) \tag{9}$$

$$V_b^+(t) = -V_a^+(t) - V_c^+(t) \tag{10}$$

$$V_c^+(t) = \frac{1}{3}V_c^f(t) - \frac{1}{6}\left(V_a^f(t)+V_b^f(t)\right) - \frac{1}{2\sqrt{3}}S_{90}\left(V_a^f(t)-V_b^f(t)\right) \tag{11}$$

Superscript f represents the fundamental component and S90 is a 90-degree phase-shift operator [2] and can be design with the following transfer function:

$$H_{S90}(s) = \frac{1 - \frac{s}{\omega_0}}{1 + \frac{s}{\omega_0}} \tag{12}$$

MPPT (Maximum Power Point Tracking): The Voltage characteristic of a PV module is not lineal and is time-variant due to a series of atmospheric conditions. In grid-connected renewable agents it is necessary to extract the maximum available power to increase the efficiency of the system and an algorithm-module named MPPT is used for this [3]. The MPPT is an essential part of a PV system and several methods for Maximum Power Point Tracking algorithms have been designed [26]. Among them, Perturbation and Observation (P&O), Incremental conductance (Inc Cond.), Ripple Correlation Control (RCC) [3],[26],[27] are the most used.

PI Regulator: The control strategy uses a cascaded control: the inner Current Regulator, and the outer Voltage Regulator. This control has been performed using PI controllers: the outer loop regulator compares the DC bus voltage in the link capacitor with the reference which comes from the MPPT algorithm block, keeping a constant DC voltage and the power flow balance between the PV system and the utility grid, while the inner control loop uses two controllers to regulate the d-q components of the line currents allowing the synchronization of the 3-phase inverter line currents with the 3-phase utility grid voltages. A block diagram of the equivalent small-signal model of the cascaded control for the 3-phase VSI used for PV systems is depicted in Fig. 3.

IV. CASE OF STUDY

To implement the aforementioned facts, a PV grid-connected system of 6kW of nominal power at standard conditions ($1000\,W/m^2$ and 25 °C) will be studied. The parameters of the control and power subsystems are shown in Table I; in this case, the EMI filter will not be considered because no IGBTs high frequency commutations will appear as the inverter model is removed for doing hardware-in-the-loop simulation.

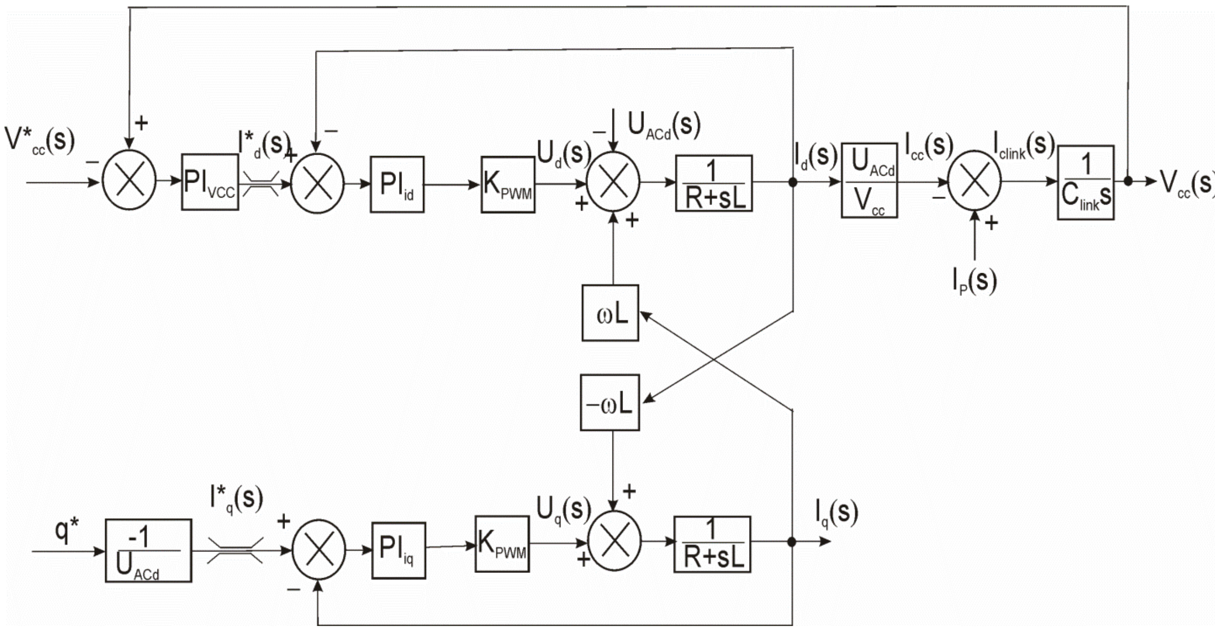

Fig. 3. Block diagram of the continuous equivalent small-signal model of the cascaded control for the 3-phase VSI for PV systems

TABLE I

PARAMETER OF THE POWER AND CONTROL SUBSYSTEMS FOR THE PV AGENT

Parameters	Value
Three-phase inverter	SKS22FB6U+E1CIF+B6 CI,SEMISTACK-IGBT
Outer Filter	M80-3,9-10,from PREMO, L=3.9mh C=1.5μF R=20mH (Y connection)
Distribution transformer	REIM, Dyn11, 50Hz, 308/232V, S_{nom}=6kVA,
3-Phase utility grid	V_{rms}=220V (ph-ph),50Hz
PV generator power	P=6kW
Gain of the inverter	K_{PWM}=233.33
DC bus voltage	V_{cc}= 350V
Switching frequency	F_{sw}=10KHz
Current crossover frequency	f_{cI}=333.4Hz
Link capacitor	Clink=1360μF
Voltage crossover frequency	f_{cV}=10.0Hz
Damping factor of the 2nd order transfer function	$\zeta c=\frac{\sqrt{2}}{2}$
Phase margin	PM= 63.5°

V. SIMULATIONS

Some simulations have been performed with MATLAB/SIMULINK models in order to validate the behavior of the grid-connected PV system. The time evolution of the dc bus voltage is depicted in Fig. 4: a step in irradiance (modelled as a step of 17A) is exerted at 0.15s, and a step in reactive power of 2kVAr is exerted at 0.7s. In both cases, it can be seen the action of the dc bus voltage regulator in the outer loop assuring the system stability.

Also some simulations have been done taking into account the harmonic distortions of the utility grid voltages: the time evolution of the voltage and grid current at phase 1 is depicted in Fig. 5 when a step in reactive power of 2kVAr is exerted at 0.7s and the 5^{th} and 7^{th} harmonics are present in the utility grid voltage with 5% of amplitude. The synchronization is perfectly achieved prior the reactive step and a unitary power factor operation is attained; after the reactive step, there is a lag of the current yielding a decrease of the power factor of the inverter-grid connection. The time evolution of the instantaneous active and reactive powers injected to the 3-phase utility grid is shown in Fig. 6, attained 6kW and 2kVAr, respectively, at steady state.

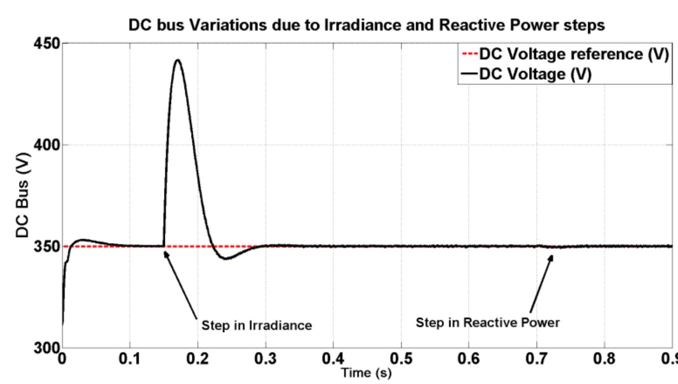

Fig. 4. DC bus variations due to an irradiance modelled as a step of 17 A at 0.15 seconds and a reactive power step of 2kVAr at 0.7 seconds

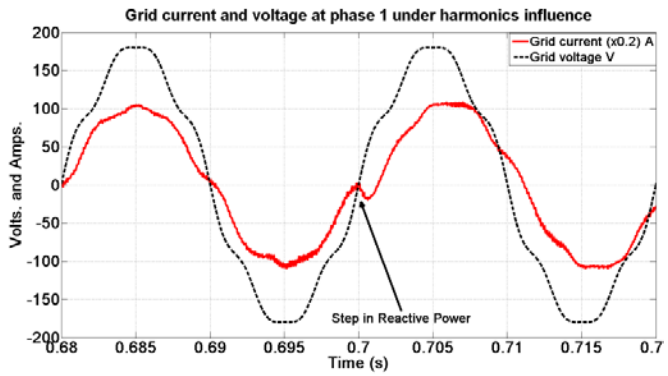

Fig. 5. Simulation of voltage and current behavior of the phase 1 due to an Reactive power step of 2kVAr at 0.7 seconds and under 5% of 5^{th} and 7^{th} harmonics disturbances (THD_I=6.6%)

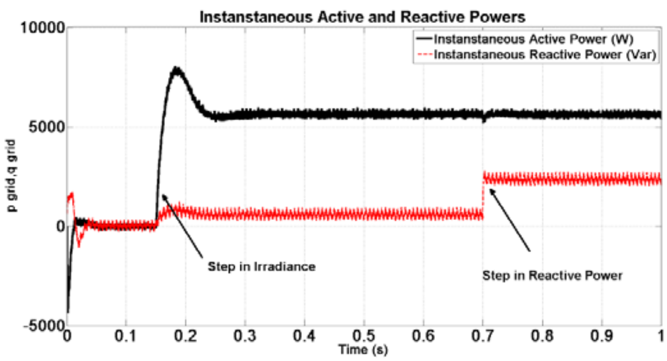

Fig. 6. Instantaneous active and reactive power delivered to the 3-phase utility grid

For an unbalanced 3-phase utility grid voltages, as the one depicted in the upper zone of Fig. 7, a Positive Sequence Detector (PSD) must be used. The PSD allows the generation of the positive sequence of the 3-phase utility grid currents (with successfully balanced condition), as shown in the botton zone of Fig. 7.

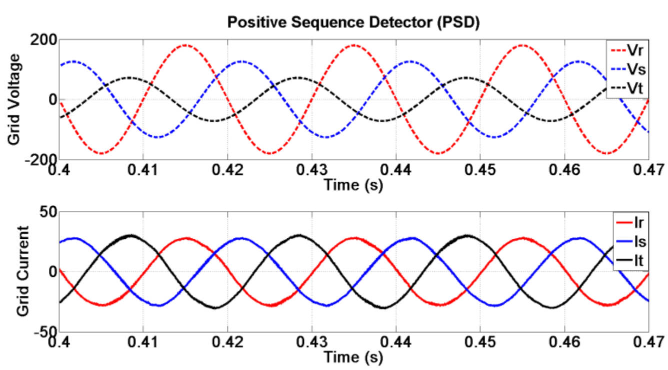

Fig. 7. Positive Sequence Detector effect in the unbalanced 3-phase grid voltages (Vr, Vs, Vt =179Vpeak, 125Vpeak and 71Vpeak, respectively) results in 3-phase balanced grid currents

VI. EXPERIMENTS

The real time experiments will be carried out using a DS1006 DSPACE platform with several I/O and DAC blocks. The model blocks of the control and power subsystems are built in MATLAB/SIMULINK, the C-code is generated with *Real Time Workshop* from SIMULINK and downloaded into the DSPACE platform. The i_d and i_q reference currents have been put in an open loop configuration to test the controllability of the power factor connection.

Fig. 8 shows the platform setup with a host PC to interact with the MATLAB/SIMULINK models. Some perturbations such as harmonics and unbalances, which are not possible to evaluate in a real situation, will be imposed to the real-time simulation of the 3-phase low voltage utility grid, whereas the signals coming from the DSPACE platform will be displayed in an oscilloscope.

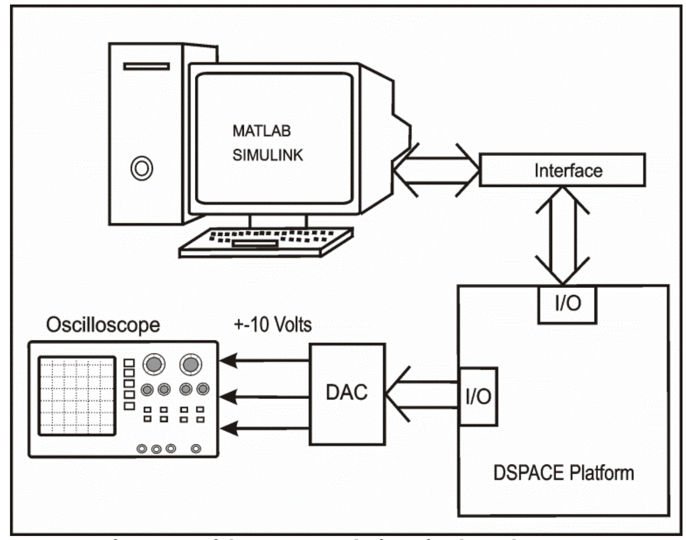

Fig. 8. Configuration of the DSPACE platform for the real time testing using a host PC, a DS1006 DSPACE board with a digital to analog converter interface and an oscilloscope for parameters monitoring

Fig. 9 shows the real time evolution of a 5% in the 5^{th} and 7^{th} harmonics distorted utility grid voltage and the resulting current at phase 1, yielding 6kW of active power when the reference i_d component of the 3-phase grid currents is set to 25A; it can be also observed the reponse of the grid current to a step of reactive power when the reference i_q component is set to -9A. The synchronization in frequency is attained for unitary and non-unitary power factor operation.

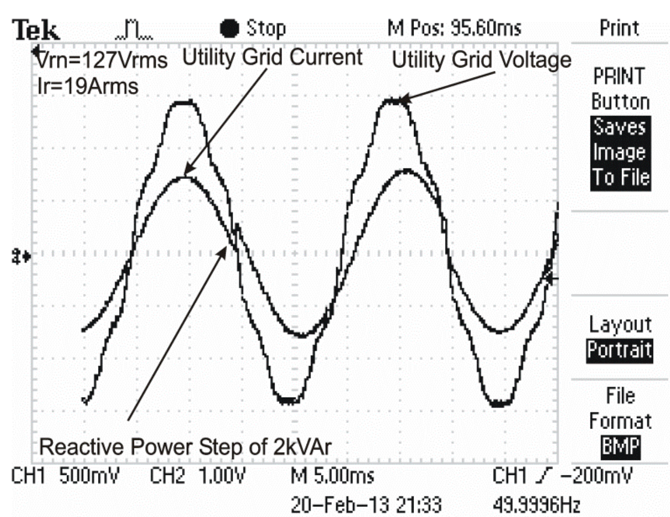

Fig. 9. Real time evolution of voltage and current of phase 1. The grid voltage is under harmonics influence (5th=5% and 7th=5%), and a reactive power step of 2kVAr is exerted

VII. CONCLUSIONS

A summary of grid-connected systems for photovoltaic (PV) used in distributed generation systems is shown in this paper and its main parts are explained.

A current source control based on d-q control of a 6kW grid-connected inverter for a PV system has been analyzed doing simulations with MATLAB/SIMULINK tool from The MathWorks, Inc., under harmonics and unbalanced perturbations in the 3-phase utility grid voltages. Next, the control strategy was implemented in a real-time DSPACE platform, yielding the final validation of the control system for a grid-connected PV system using the hardware-in-the-loop simulation technique, avoiding damages in a real plant during the debugging process for real time control algorithms and assuring the operator safety.

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