

PV Array Emulator for Testing Commercial PV Inverters

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Abstract—This paper is devoted to the design and construction of a photovoltaic array emulator for high power applications in order to analyze and evaluate all kind of commercial photovoltaic inverters. To validate the proposed photovoltaic emulator experimentally, a rapid prototyping tool based on xPC Target of Matlab/Simulink has been used, providing a real-time testing environment. The proposed emulator has been used to test the performance and maximum power point tracking algorithm efficiency of a commercial photovoltaic inverter by programming the desired conditions of temperature and irradiance.

Index Terms—Photovoltaic systems, inverters, energy efficiency, Matlab.

I. INTRODUCTION

Nowadays, the power electrical system scenario is quite different in comparison with the traditional configuration [1]-[2]. Several factors, such as an electrical consumption increase, the electrical market liberalization, the need to reduce CO₂ emission, and the new technological development are boosting the distributed generation (GD).

Renewable distributed energy resources are becoming more and more popular (wind turbines, photovoltaic (PV) plants, fuel cells, microturbines, etc) [3]. Many of them can only output DC voltage so an inverter interface has to be used.

PV generation plants have increased a lot over the last years, taking an important role towards a sustainable energy system. The performance of PV panels and PV inverters and also their maintenance are keys in the pay-back time and the profitability of grid-connected PV plants.

Several control algorithms are involved in PV inverters, for instance: maximum power point tracker (MPPT) [4], anti-islanding algorithm and reactive power compensation ability. The efficiency of these algorithms must to be assured in order to carry out their roles being essential in the overall performance [5].

Due to the high cost of the solar panels, the maximum power point (MPP) operation is necessary to maximize the output power in different conditions of irradiance (W) and

temperature (T).

This fact obliges that every commercial PV inverter must be tested under different conditions. For high power testing applications a DC power supply is hard to find and certainly a PV array could not be available.

There are some commercial PV array emulators but they present limitations in the output power and also in the number of points of the I-V panel curve reproduction. Several prototypes developed by researchers can be found in the literature [6]-[10]. In [6] a DC power supply is programmed according to a PV model which increases the accuracy of the I-V curve but the same power level limitation level appears when the MPPT efficiency is tested. Other works [7]-[9] use different DC/DC converter topologies to obtain the I-V curves but the influence of temperature and solar irradiance is not taken into account in some of them. In other cases, the used model to emulate the I-V curve requires some parameters which are not provided by manufacturers in the PV panel datasheet being difficult their use [10].

The main goal of this paper is to show a regenerative PV array emulator for high power application in order to test PV inverters. Every kind of PV panels could be emulated by a PV model which only uses parameters provided in datasheets. The power conversion is done by a three-phase synchronous rectifier which allows demanding sinusoidal currents from the grid which are synchronized with the voltage at the point of common coupling (PCC) increasing the power quality. This emulator can be used to evaluate the performance of PV inverters and the efficiency of MPPT algorithms under different conditions of W and T.

II. PV ARRAY EMULATOR TOPOLOGY

In order to achieve PV array emulation, an electronic converter working as a rectifier has been used. AC/DC family of converters constitutes the interface circuit between the electrical grid and the DC loads. With the ever increase of power quality requirements at the point of common coupling (PCC), these converters are nowadays required to achieve different task such as: provide high input power factor, low current distortion [11] and fixed output voltage.

Synchronous rectifier allows demanding sinusoidal currents from the grid which are synchronized with the voltage at the PCC. Fig. 1 shows the topology used in the PV array emulator.

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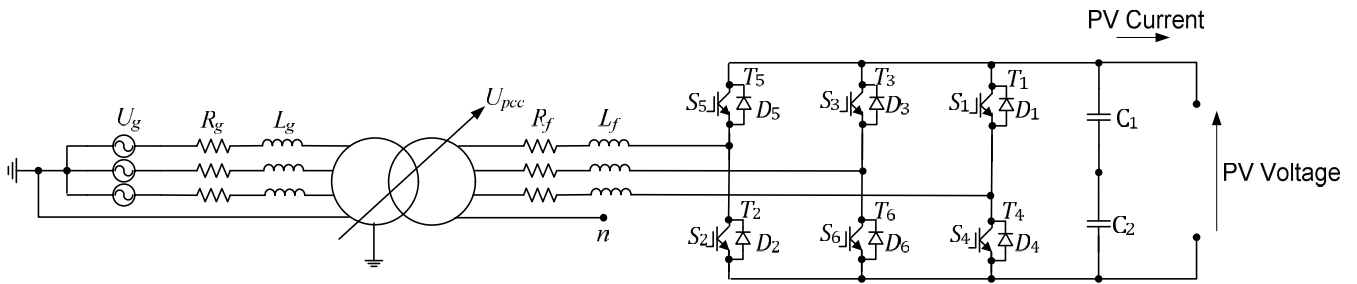


Fig. 1. Photovoltaic array emulator topology.

The electronic converter controlled to emulate the PV array is the Semikron SEMISTACK SKS 230F B8CI 190 V12. The commercial PV inverter to be tested is connected to the DC-link of the PV array emulator.

III. CONTROL STRATEGY. REFERENCE GENERATION

In this section the whole control strategy to generate the references of the PV array emulator are explained. The control strategy block diagram is depicted in Fig. 2.

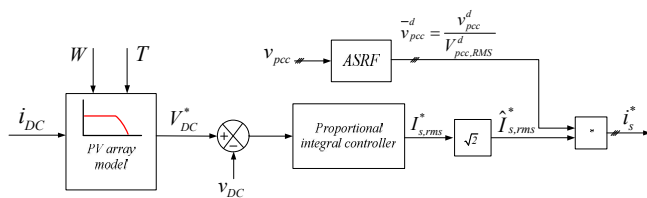


Fig. 2. Control strategy block diagram of the PV array emulator.

A. PV Array Emulator Control Strategy

The measured DC-link current (i_{dc}) is the input of the PV

array model. By this way, the reference DC link voltage (V_{DC}^*) is generated according to the I-V curve.

In order to generate the reference current (i_s^*) to be demanded from the grid by the PV emulator, a proportional-integral (PI) controller calculates the reference RMS current ($I_{s,RMS}^*$) (control variable) depending on the DC voltage error. The peak value of the reference current is multiplied by three unitary waveforms synchronized with the voltage (v_{PCC}) at the PCC. These waveforms are provided by an adjustable synchronous reference frame (ASRF) [12].

B. PV array model

In order to reproduce the typical curve of a PV panel, a PV model has been employed.

This model, explained in detail in [13], is based on the I-V exponential curve defined by the information provided by the manufacturers in datasheets. I-V curves obtained in the simulation of the panel Shell SP 150-P in different conditions of W and T are shown in Fig. 3(a) and Fig. 3(b). The parameters of this commercial panel have been used to emulate the PV array during experimental tests.

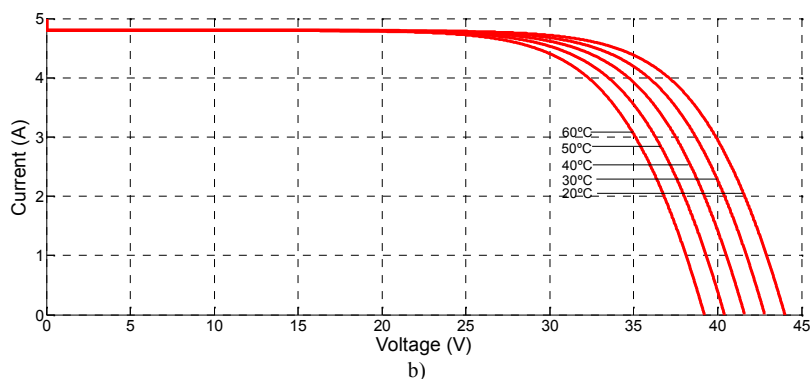
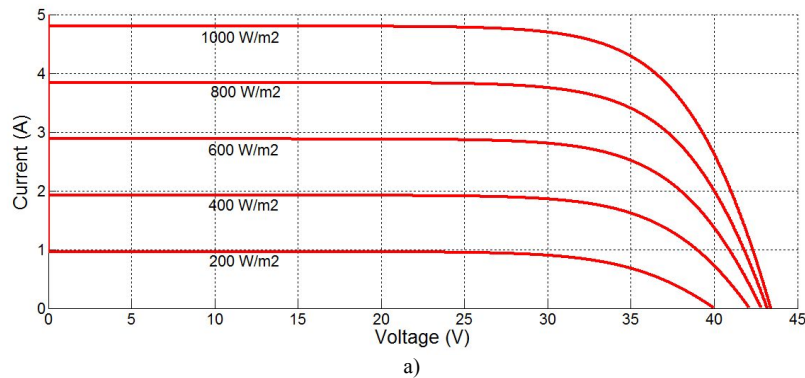


Fig. 3. a) I-V curves in different irradiance conditions. b) I-V curves in different temperature conditions.

IV. CURRENT CONTROLLER. REFERENCE TRACKING

A hysteresis band Fig. 4 has been used as current controller in the PV array emulator to track the demanded reference current. This technique compares the reference current with the measured current and depending of the sign of the error the switching signals of the IGBT's are generated.

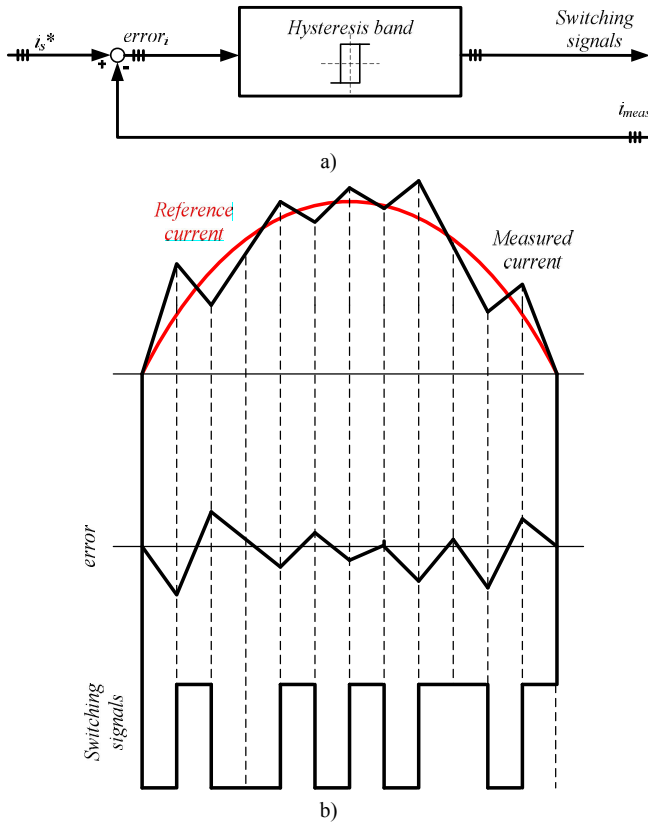


Fig. 4. a) Hysteresis band block diagram. b) Switching signal generation.

V. PV ARRAY EMULATOR EXPERIMENTAL SETUP

A block diagram of the experimental prototype and the

real-time testing environment is depicted in Fig. 5.

The real time environment built for rapid prototyping is based on xPC Target from Matlab/Simulink. The PV model, control strategy and current controller have been implemented on the host PC (which runs Matlab/Simulink, Real-Time Workshop and xPC Target toolbox). xPC Target operates with the code generated by a C compiler from the Simulink models in order to develop the real-time target application. Target application can be executed in real time once it is downloaded in the target PC from the host PC through TCP/IP. The target PC is equipped with data acquisition Cards (DAQ's). The measurements are carried out with hall effect sensors to measure the DC-link current and the demanded current from the grid and voltage sensors to capture the DC-link voltage and voltages at PCC.

To evaluate the performance of a commercial PV inverter, the power quality analyzer Fluke 435 Series II has been connected to the power stage, which allows measuring the PV inverter performance.

VI. MPPT STATIC EVALUATION

In order to evaluate commercial PV inverter efficiency, the MPPT algorithm must be evaluated. The efficiency of this algorithm and it proper operation are essentials to inject the maximum amount of energy produced by the PV panels.

The MPPT efficiency is calculated as follows (1)

$$\eta_{MPPT} = \frac{P_{pv}}{P_{MPP}} \cdot 100, \quad (1)$$

where P_{pv} and P_{MPP} are the theoretical power of the PV array and the power at the MPP respectively determined it by the commercial PV inverter.

To analyze the static efficiency of a commercial inverter, an experimental test has been carried out. The different parameters used during experimental tests are shown in Table I.

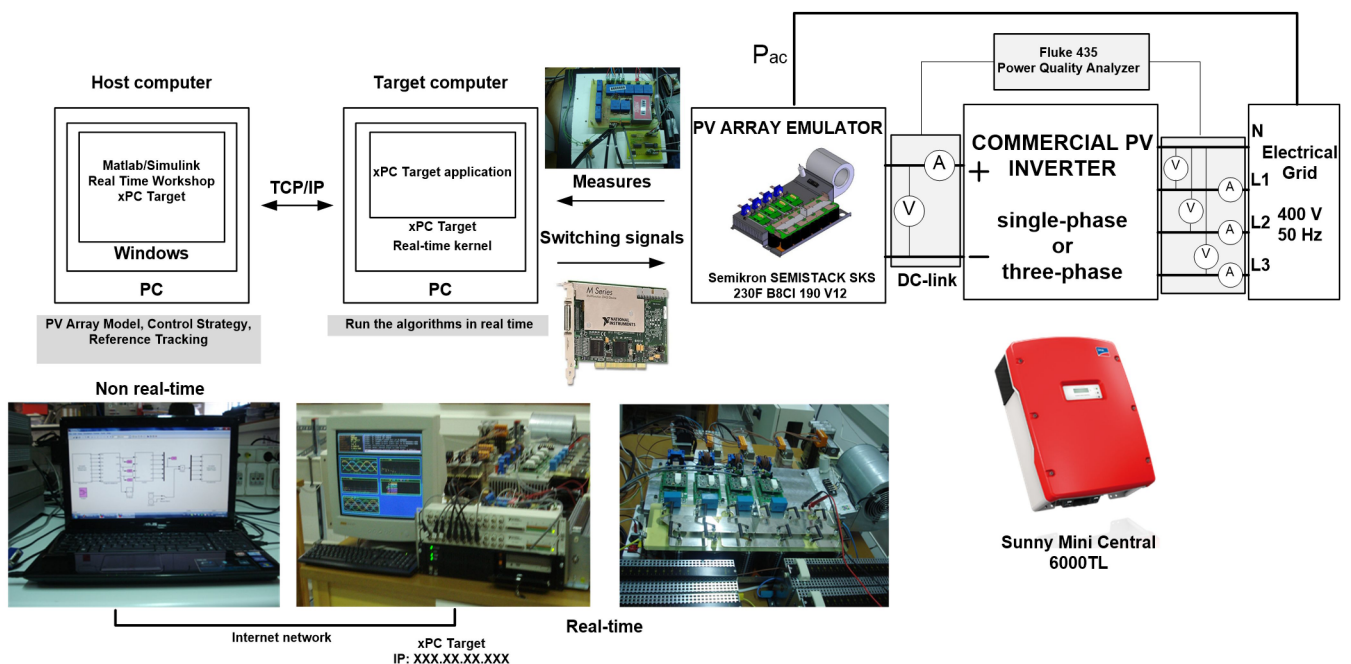


Fig. 5. Block diagram of the experimental test setup.

TABLE I. USED PARAMETERS IN EXPERIMENTAL TESTS.

Parameter	Description	Value	Stage
n_p	Number of panel in parallel	1	Array configuration
n_s	Number of panel in series	12	
I_{sc}	Short-circuit current (A)	4.8	PV panel parameters. Shell SP 150-P
V_{oc}	Open circuit voltage (V)	43.4	
V_{mpp}	Voltage at MPP (V)	34	
I_{mpp}	Current at MPP (A)	4.41	
T	Temperature (°C)	25	Conditions
W	Irradiance (W/m ²)	1000	
V_s	RMS voltage at PCC	400	Electrical grid
L_f	Filter inductance (mH)	6.2	Passive elements
C_1, C_2	DC-link capacitors (mF)	28.2	
f_w	Switching frequency (kHz)	12	

The commercial PV inverter that has been studied is the SMA Sunny Mini Central 6000TL. Figure 6 shows the voltage at the PCC and the demanded current (phase A) by the PV emulator and the proper synchronization in phase

between current and voltage is demonstrated. In Fig. 7 we can see DC-link voltage and current when the MPP is achieved by the commercial inverter.

According to the theoretical parameters of the PV panel Shell SP 150-P provided by manufacturers at MPP and the PV array configuration, the MPP static efficiency is 98 %.

VII. MPPT DYNAMIC EVALUATION

In order to analyze the dynamic MPPT efficiency and the required time to reach the MPP in variable conditions of irradiance, different irradiance profiles have been implemented.

First of all, the time since the MPP algorithm start to work when the commercial inverter is connected to the electrical grid till the MPP is reached has been analyzed. This evolution is shown in Fig. 8. The time that the commercial inverter requires to achieve the MPP is 9 seconds.

Also, a step in the irradiance from 1000 W/m² to 700 W/m² and to 1000 W/m² again has been done. The response of the MPPT algorithm is depicted in Fig. 9. The time to reach the new MPP is 150 ms.

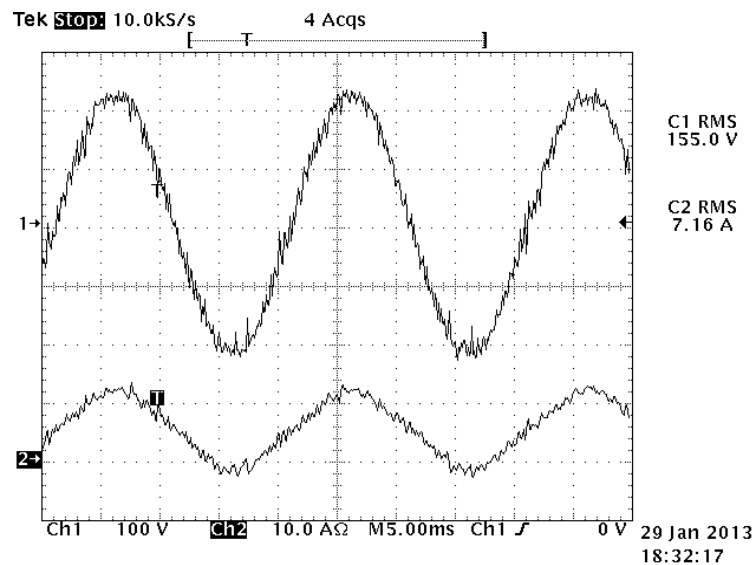


Fig. 6. Voltage at PCC and demanded current (phase A).

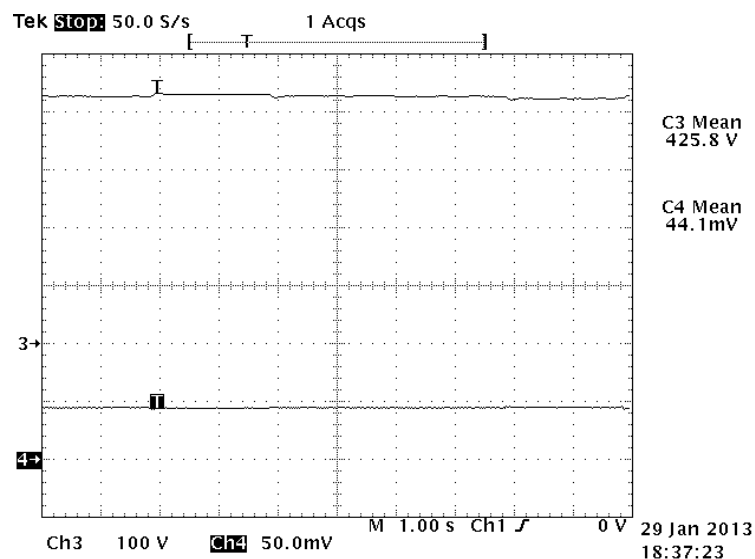


Fig. 7. PV voltage and PV current.

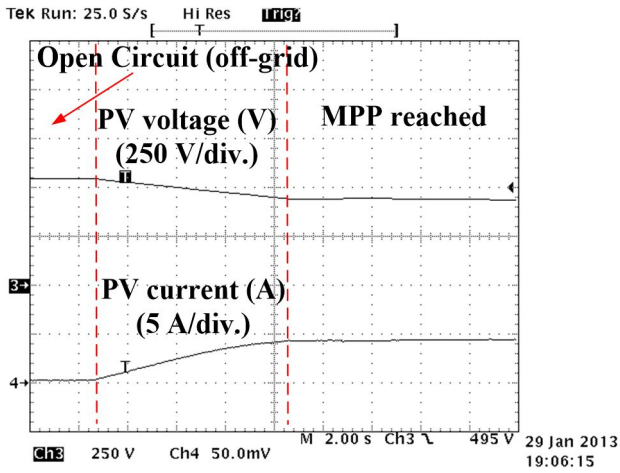


Fig. 8. PV voltage and PV current evolution when the commercial inverter searches the MPP.

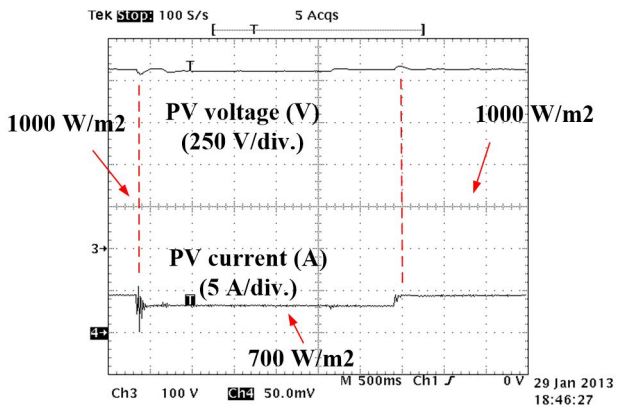


Fig. 9. PV voltage and PV current during irradiance steps.

VIII. PERFORMANCE EVALUATION

To calculate the performance of the energy conversion on the DC-link power and the AC output power the power quality analyzer Fluke 435 Series II has been connected to the power stage. This equipment has the capability of evaluating the power inverter performance. It simultaneously measure AC output power and DC input power for power electronics system.

The obtained performance at rated power of the inverter SMA Sunny Mini Central 6000TL is 92.87 % as Fig. 10 shows.

EFICIENCIA DE INVERSORES			
0:00:30			
kW out	4.588		
kW in	4.941		
Eff %	92.87		
U out	237.9	234.9	240.7
14/02/13 14:33:50 230V 50HzPIE EH50160			

Fig. 10. Calculated performance by the power quality analyzer Fluke 435 Series II of the tested commercial inverter.

IX. CONCLUSIONS

A PV array emulator has been proposed and validated in this paper. It reproduces any PV panel and array association with a high level of accuracy by only using the information provided by manufacturers of PV panels in datasheet.

It device is suitable for testing commercial PV inverter at high power level. Also, it is possible to program any irradiance and temperature profiles which allow evaluating MPP tracking algorithm efficiency and power energy conversion performances.

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