

# Dynamic and Reconfigurable Photovoltaic Emulator Based on FPAA

Francesco Barra, Marco Balato, Luigi Costanzo, Daniele Gallo, Carmine Landi, Mario Luiso, Massimo Vitelli

*Department of Industrial and Information Engineering, Second University of Naples  
Via Roma 29, 81031 Aversa (CE), Italy  
mario.luiso@unina2.it*

**Abstract** – A photovoltaic (PV) emulator is an electronic device which allows, without using real PV modules, to reproduce the current vs. voltage characteristics of PV sources in the desired operating conditions as concerns the values of the irradiance and of the temperature. This is very useful since it is possible to evaluate the performances of the electronic DC/DC or DC/AC converters adopted in PV systems, under perfectly replicable operating conditions. Moreover, it is possible to fairly compare advantages and drawbacks of different MPPT algorithms under perfectly controlled stationary or dynamic atmospheric conditions. In this paper a dynamic and reconfigurable photovoltaic emulator which allows to reproduce the PV current vs. voltage characteristics both in stationary and dynamic environmental conditions, is presented and discussed. It is based on the implementation of the circuitual model of the considered PV module in a Field Programmable Analog Array. The field Programmable Analog Array provides a suitable time varying reference signal to the control circuitry of a step-down DC-DC converter. The output port of such a DC/DC converter emulates the current versus voltage characteristic which is obtained at the terminals of the considered PV module in the desired atmospheric conditions. The main advantages of the proposed PV emulator are represented by the simplicity of programming of the FPAA and by its low cost. The results of numerical simulations and of experimental activities are reported and discussed.

## I. INTRODUCTION

Photovoltaic (PV)  
PhotoVoltaic Emulator (PVE)  
PhotoVoltaic Module (PVM)  
Field Programmable Analog Array (FPAA)  
Distributed Maximum Power Point Tracking (DMPPT)

In the last ten years the interest in renewable energy sources, especially photovoltaic (PV) sources, has led to the exponential growth of PV installations, also thanks to

the reduction of the PV modules costs. The commonly used grid connected PV installations, made of a string of PV modules put in parallel and feeding a central inverter, are not very efficient in mismatching conditions. Such conditions are due to clouds, shadows, dirtiness, manufacturing tolerances, aging, different orientation of sections of the PV field, thermal gradients, etc. In fact, when mismatching conditions occur, the Power versus Voltage (P-V) characteristics of the PV array may exhibit multiple peaks. The presence of multiple peaks may cause in turn the failure of the MPPT algorithms (e.g. the Perturb & Observe algorithm), carried out by the central inverter, thus possibly leading the PV system to work in a suboptimal operating point rather than in the real MPP. Moreover, the absolute maximum power of the mismatched PV field is lower than the sum of the available maximum powers that the mismatched modules are able to provide. On the basis of the above considerations it is clear that the increase of the energetic performances of the PV systems represents an additional element able to boost the interest in PV systems.

For these reasons in the scientific literature, in the last ten years, several papers on control strategies and architectures allowing the increase of the energetic performances of PV systems were published. Some of them focus on the use of quite sophisticated MPPT algorithms [1-2], while the other ones analyze the adoption of advanced static or dynamic PV architectures (e.g. DMPPT applications, array reconfiguration strategies etc.) [3-6].

Whichever the MPPT algorithm or the architecture to validate, it is nearly always unpractical or even impossible to carry out the experimental test activities on real PV modules. In fact the following limitations should be taken into account when using real PV modules:

- 1) The presence of enough solar radiation is not always guaranteed.
- 2) The repeatability of the experimental tests cannot be ensured because the external climatic conditions are not under our control.
- 3) The cost, the dimensions of the PV array and the availability of enough space on the roof for the

installation may represent a problem for Universities or small/medium Companies research laboratories.

- 4) The outdoor installation of the measurement station is not easy, especially in presence of unfriendly environmental conditions.
- 5) The case of PV sources with portion of cells which are damaged or shaded would require destructive testing.

The concept of PV emulator (PVE) came up as a result of the above factors. Only two commercial PVEs are available on the market: Agilent E4360 Modular Solar Array Simulators [7] or Magna-Power photovoltaic-power-profile-emulation [8]. The main problem, which makes the commercial PVEs unusable in nearly all the University laboratories or in small/medium Companies research laboratories is their prohibitive cost. It should be taken into account the fact that one or two of these devices are not sufficient at all in order to emulate even a small PV plant (e.g. 3kWp) due to their limited voltage and current ratings [7-8]. For such reasons, many researchers have been trying to develop low cost PVEs [9-11]. In all these papers, the PVE consists of a DC/DC power converter, which is controlled by means of a FPGA or DSP-based unit using the pulse width modulation (PWM) principle.

The only paper dealing with an analog implementation of the control circuitry of a PVE is [12].

In this paper, a novel dynamic and reconfigurable PVE based on the use of Field Programmable Analog Arrays (FPAA) [13], is presented and discussed. The FPAA provides a suitable time varying reference signal to the control circuitry of a step-down DC-DC converter. The output port of such a DC/DC converter emulates the PV current versus voltage characteristic. The main advantage of the proposed solution is represented by the simplicity of programming of FPAA with respect to FPGA or DSP based implementations. The paper is organized as follows: Section 2 describes the operation principle of the proposed PVE. Section 3 reports the experimental results of a PVE which emulates a Solar World SW225 PV module [14]. In section 4 the conclusions are reported.

## II. EMULATOR DESIGN

The general scheme of the realized PVE is shown in Fig. 1: a device that, supplied at the input with characteristic quantities of a desired PVM to be emulated, has an electrical output characteristic similar to desired PVM. A block diagram of the proposed emulator is shown in Fig. 2. It consists of a power stage whose output current is regulated, through a controller, by the FPAA. The topology used for the power stage is a Buck DC-DC converter supplied by a DC power source, for example an AC-DC power supply. When the input parameters are set, the FPAA generates the emulated PV curve; the load voltage and current are sensed by the FPAA and it generates a signal that represents the PV output current,

which is sent to the current control loop as reference signal. So the controller regulates the duty cycle of the Buck converter in order to follow the current reference.

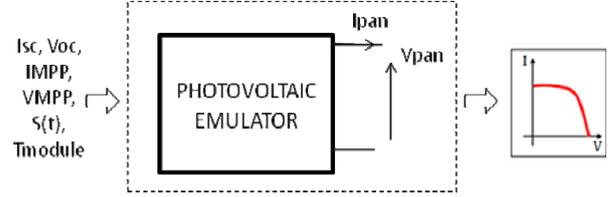


Fig. 1 General scheme of the photovoltaic emulator

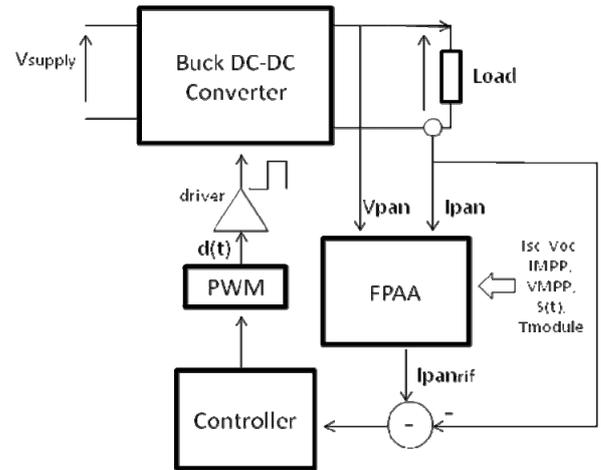


Fig. 2 Block diagram of the proposed emulator

### A. The model of the PV module

A PVM is identified by some quantities typically provided by photovoltaic panel constructors; they are: Open Circuit Voltage ( $V_{oc}$ ), Short Circuit Current ( $I_{sc}$ ), Maximum Power Point Voltage and Current ( $V_{MPP}$  and  $I_{MPP}$ ), Voltage and Current Temperature Variation Coefficient ( $\alpha_V$  and  $\alpha_I$ ). Once these quantities are assigned, the operation of the PVM depends on module temperature, solar irradiance and electrical load.

In order to reproduce the operation of the PVM, a model of the PVM is implemented by the FPAA. The utilized FPAA is the AN231E04 by ANADIGM [13]. The model implemented on this device is shown in Fig. 3: it is a circuital model of a PV cell [15].

The quantities of the circuit in Fig. 3 depend on PV characteristic quantities, temperature and solar irradiance according to [16].

Then, the equations that describe the circuit operation are reported in the following:

$$I_{pan} = I_{ph} - I_d - I_r \quad (1)$$

$$I_{ph} = I_{sc} \cdot k(T_{module}) \quad (2)$$

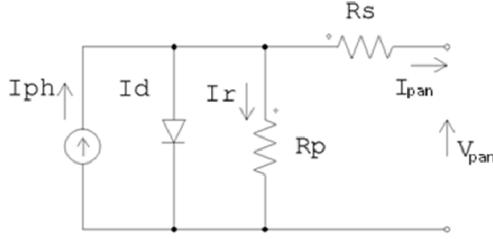


Fig. 3 Circuitual model of PV cell

$$I_d = I_{sat} \cdot \left( e^{\frac{V_{pan} + R_s I_{pan}}{V_T}} - 1 \right) \quad (3)$$

$$I_r = \frac{V_{pan} + R_s I_{pan}}{R_p} \quad (4)$$

where  $I_{sc}$  is the short circuit current given by the equation

$$I_{sc} = I_{scSTC} \cdot \frac{S}{S_{STC}} \quad (5)$$

( $I_{scSTC}$  is the short circuit current in Standard Test Conditions,  $S_{STC}$  is the irradiance in STC);  $k(T_{module})$  is:

$$k(T_{module}) = 1 + \alpha_I \cdot (T_{module} - T_{STC}) \quad (6)$$

( $\alpha_I$  is the current variation temperature coefficient,  $T_{module}$  is the panel temperature,  $T_{STC}$  is the panel temperature in STC);

FPAA can be programmed by the software ANADIGM DESIGNER 2 [13] and a scheme of the implemented PV circuit is shown in figure 4.

The implementation consists in some gains, adders and a Look Up Table (LUT).

Gains are given by the following equations:

$$G1 = \frac{12 \cdot V_{MAX}}{2.8 \cdot Voc}; G2 = \frac{12 \cdot R_s \cdot I_{MAX}}{2.8 \cdot Voc} \quad (7)$$

$$G3 = \frac{V_{MAX}}{R_p \cdot I_{MAX}}; G4 = \frac{R_s}{R_p} \quad (8)$$

$$G5 = k(T_{module}) \cdot \frac{I_{sc}}{I_{MAX}} \quad (9)$$

Where  $V_{MAX}$  and  $I_{MAX}$  are maximum values of the power stage output voltage and current.

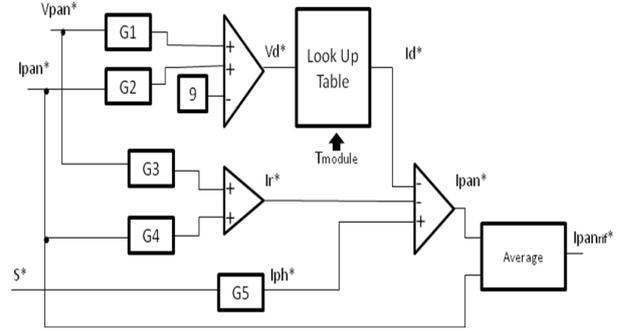


Fig. 4 Scheme of the implemented PV circuit

The LUT represents the diode. The FPAA's LUT can implements a user specified voltage transfer function with 256 quantization steps, given by the user with a ".csv" file. It produces a specified output voltage in response to the value of the sampled input voltage. The PV mathematical model is characterized by having as input the PV current, that is the output. This is achieved by reporting the output current as an input; so, to improve the accuracy, especially in the vertical part of the PV characteristic, we use an average block with a low-pass filter (cut frequency of 10kHz). It is important to note that the irradiance can be entered as a voltage signal, and the model follows its temporal variations; otherwise the temperature is given as a parameter for the creation of the LUT, so if it changes, the LUT have to be reloaded. This is a realistic scenario, because of the strong thermal inertia of photovoltaic panels.

### III. FPAA IMPLEMENTATION

The model shown in fig. 4 has been implemented on the FPAA by loading, through the software ANADIGM DESIGNER 2, the following configuration:

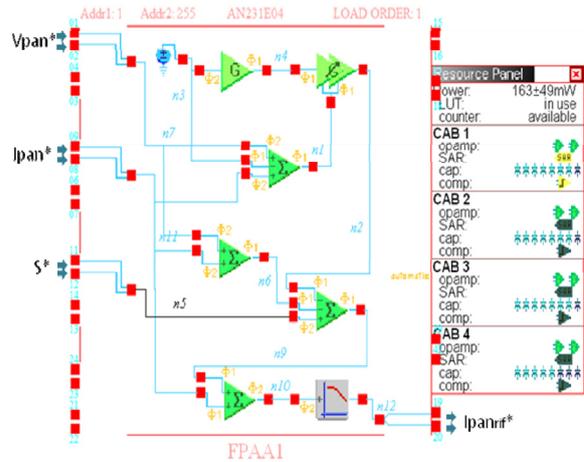


Fig. 5 Implementation of PV model on FPAA

Then, a preliminary testing was performed. The FPAA

was supplied with a positive ramp from 0V to the open circuit voltage with a frequency of 100 Hz. In Fig. 6 there is a screenshot of the oscilloscope display showing the input ramp and the output voltage of the FPAA. Fig. 7 show, instead, a comparison between the emulated PV curve and the desired one. A low deviation can be appreciated.

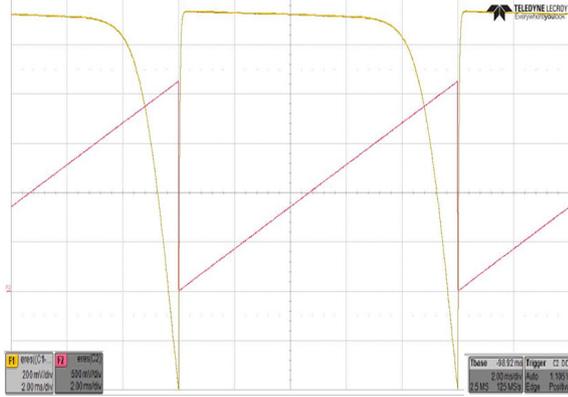


Fig. 6 Emulated PV curve by the FPAA, acquired through an oscilloscope

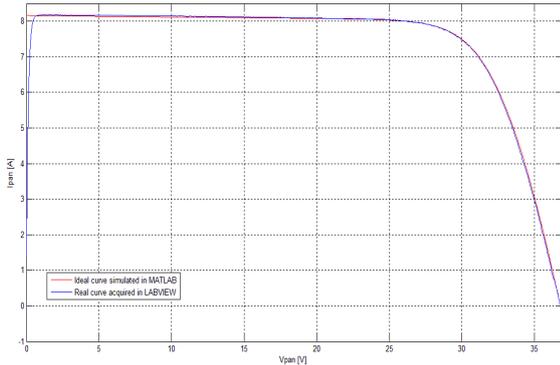


Fig. 7 Comparison between emulated and desired PV curves

#### IV. POWER STAGE IMPLEMENTATION

As shown in Fig. 2, the power stage used in the proposed PV emulator is a Buck converter. A PWM control of this converter is implemented to follow the reference signal generated by the FPAA device. The scheme of a Buck PWM control is shown in Fig. 8, and the corresponding scheme in Laplace domain is shown in Fig. 9. In this scheme the Buck converter is represented by its transfer function from duty cycle  $d(s)$  to output current  $i(s)$  given by the equation:

$$G_{id} = \frac{V}{R \cdot D} \cdot \frac{1}{1 + s \frac{L}{R} + s^2 LC} \quad (10)$$

This is a linearization of the non linear Buck behavior

and so the control scheme was studied in the three points of the PV characteristic shown in Fig. 10.

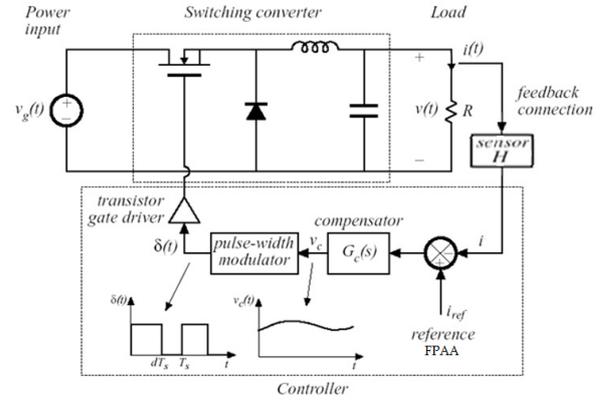


Fig. 8 PWM control of BUCK converter

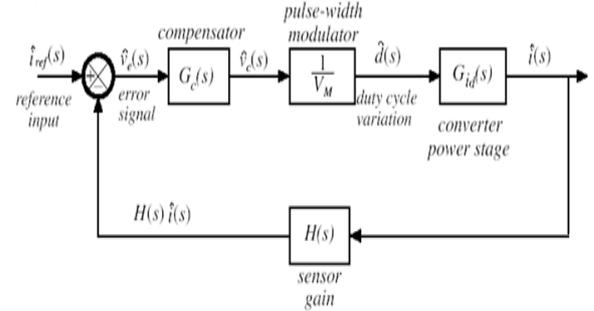
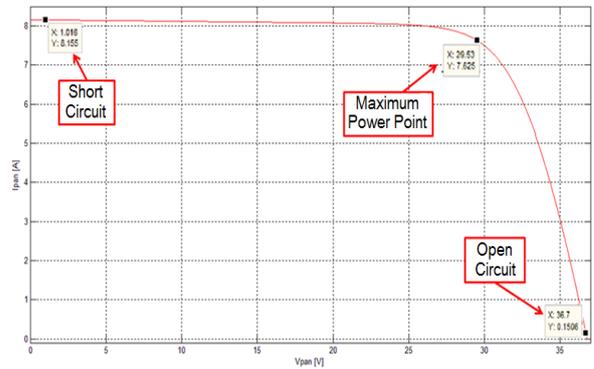


Fig. 9 Control scheme in Laplace domain



$$P_{SC} \equiv (1V; 8.15A) \quad P_{MPP} \equiv (29.5V; 7.63A) \quad P_{OC} \equiv (36.7V; 0.15A)$$

Fig. 10 PV curve's characteristic points

The designed compensator's transfer function is given by the equation:

$$G_c(s) = \frac{0.08s + 200}{10s} \quad (11)$$

The complete control scheme that implements the PV

emulator was simulated in Standard Test Conditions using a circuit simulator (PSIM). The test was performed in some PV curve's points varying the load resistance. The results are shown in Fig.11.

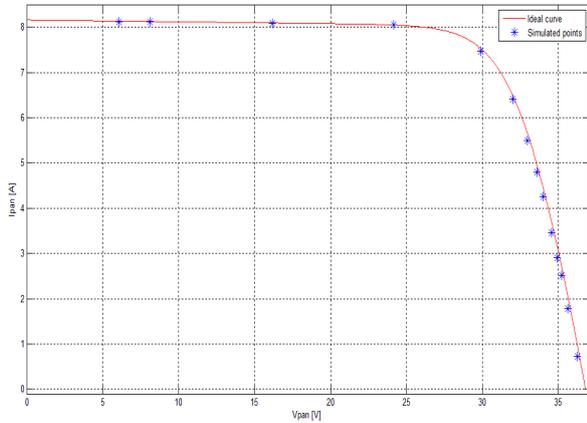


Fig. 11 Comparison between desired photovoltaic curve and simulated points

### V. EXPERIMENTAL RESULTS

The implementation of the designed PV emulator is shown in Fig. 12. It can be observed that two FPAA were used; one to generate the reference signal, and the second to implement the regulator [17]-[22].

A test of the implemented circuit was performed. The load resistance was changed to make it work in different points of the PV curve. Fig. 13 shows a comparison between the desired PV curve and both the simulated and acquired points. A little deviation can be appreciated.

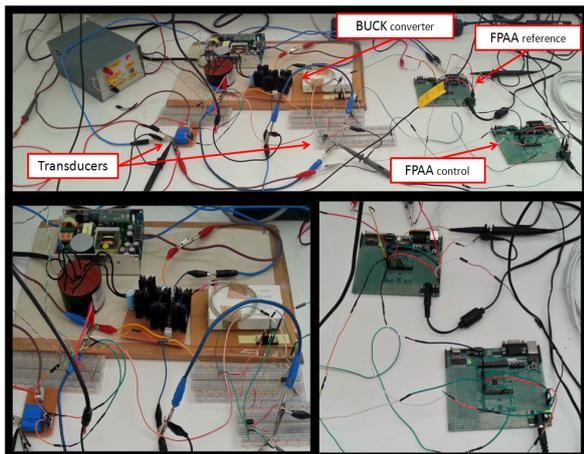


Fig. 12 PV emulator implementation

Then a testing of the PV emulator's dynamic behavior was performed. It was given as irradiance signal a square wave signal between the levels 200W/m<sup>2</sup> and 1000W/m<sup>2</sup>, in order to perform instantaneous irradiance variation. In

Fig. 14 there is a screenshot of the oscilloscope display showing the input square irradiance signal and the load current of the PV emulator. It can be observed that the load current follow the irradiance variation with very good performance.

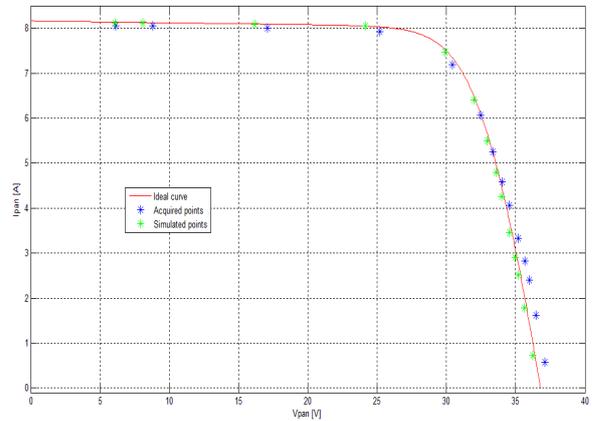


Fig. 13 Comparison between desired photovoltaic curve and both simulated and acquired points

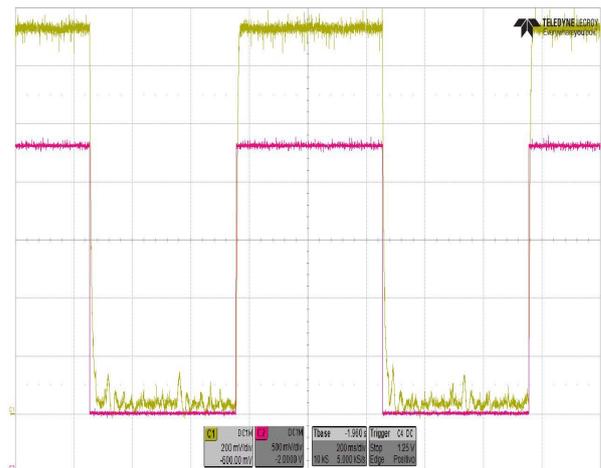


Fig. 14 Test of the PV emulator's dynamic behavior, acquired through an oscilloscope

### CONCLUSION

In this paper a dynamic and reconfigurable photovoltaic emulator which allows to reproduce the PV current vs. voltage characteristics both in stationary and dynamic environmental conditions, is presented and discussed. It is based on the implementation of the circuitual model of the considered PV module in a Field Programmable Analog Array. The Field Programmable Analog Array provides a suitable time varying reference signal to the control circuitry of a step-down DC-DC converter. The output port of such a DC/DC converter emulates the current versus voltage characteristic which is obtained at the terminals of the considered PV module in the desired atmospheric conditions. The main

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