Design and Implementation of a Photovoltaic Emulator Using an Insulated Full Bridge Converter Based Switch Mode Power Supply

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Abstract The study of renewable energies, such as photovoltaic generators, is still relevant until this day. As a result, PV Emulator is highly recommended. It allows to faithfully reproduce the characteristic of a panel, module or any photovoltaic field by taking into consideration the variation of the radiance, temperature and load. The PV Emulator proposed in this paper consists of an isolated switch mode power supply based on a full bridge converter. To force the current tracking the PV characteristic, PI controller and phase shift PWM are implemented via an F28335 platform. To duplicate PV module behavior, two modeling approaches are investigated and compared in simulation and confronted to experimental characteristics. Then, the PV Emulator is implemented using these modeling methods and the designed power supply. Both simulation and experimental results are presented at the end of this paper.

Keywords PV emulator · DC-DC converter · PV systems · SMPS · Phase shift

1 Introduction

With the significant interest in renewable energies a great effort and a lot of investments are devoted to the development and research in renewable energy, specifically

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photovoltaic systems. This has caused a significant demand for different equipment to test these systems [1].

The output of the photovoltaic panels is highly dependent on climatic conditions. Therefore, it is difficult to test the performance of photovoltaic energy conversion systems for different temperature and radiance values. A photovoltaic Emulator, which is essentially a DC Power Supply, offers the possibility of testing various photovoltaic systems (Inverter/MPPT Controller) while controlling through a software the climatic conditions [2].

Generally, the PV Emulator architecture which is widely used for research purpose, is based on the Buck converter [3–5]. However, despite the simplicity of this power topology and its control scheme, it is galvanically not isolated and it remains limited in terms of power that does not exceed a few hundred Watts. However, in this project, the high power and efficiency are the two most deterministic criteria in the choice of the power topology. It is a constraining challenge to realize a controlled supply that can reach 1KW of power and emulates perfectly the actual behavior of PV modules from short circuit to open circuit.

In terms of characteristic generation, several approaches could be used to control the PV Emulator. In this work, two approaches will be investigated: The first approach consists of using a Look-Up-Table containing the data of a PV module and providing in real time the reference signal either for the current loop or the voltage loop [6, 7].

The second approach consists in replacing the Look-Up-Table generator with a mathematical model of the emulated PV panel [8, 9]. In this paper, an implicit model that does not require any identification test or any extra numerical method is presented. The model only uses the characteristics provided by the manufacturer datasheet.

2 Implicit Mathematical Model of PV Module

The current of the photovoltaic module, which will be feed to the current controller, can be generated as an expressed of its voltage by the Eq. (1) [10]:

$$I_{PV} = I_{sc}.\left(1 - C_1.\left(exp\left(\frac{V_{pv}}{C_2.V_{oc}}\right) - 1\right)\right) \tag{1}$$

Where:
I_{pv}, V_{pv}: Current and voltage supplied by module [A]

$$C_1 = \left(1 - \frac{I_{mpp}}{I_{sc}}\right).\left(exp\left(\frac{-V_{mpp}}{C_2.V_{oc}}\right)\right) \tag{2}$$

$$C_2 = \frac{\left(\frac{V_{mpp}}{V_{oc}} - 1\right)}{ln\left(1 - \frac{I_{mpp}}{I_{sc}}\right)} \tag{3}$$

C_1 and C_2 depend on the following module parameters:

I_{sc}: Module short-circuit current [A]
V_{oc}: Module open circuit voltage [V]
I_{mpp}: Module maximum power point current [A]
V_{mpp}: Module maximum power point voltage [V]

These parameters can be expressed as follow:

$$I_{sc}(G, T) = I_{scs}\frac{G}{G_s}(1 + \alpha(T - Ts)) \quad (4)$$

$$V_{oc}(T) = V_{ocs} + \beta(T - T_s) \quad (5)$$

$$I_{mpp}(G, T) = I_{mpps}\frac{G}{G_s}(1 + \alpha(T - Ts)) \quad (6)$$

$$V_{mpp}(T) = V_{mpps} + \beta(T - T_s) \quad (7)$$

Where α and β are respectively the current and the voltage temperature coefficient.

V_{ocs}, I_{scs}, I_{mpps} and V_{mpps} are defined under standard test conditions i.e. Gs = 1000 W/m^2 and Ts = 25 °C.

Compared to the LUT method, the major advantage of this implicit model is that all necessary parameters are provided by the manufacturer technical datasheet of the module. In LUT technique, the effort must be focused hardly on the measurement and implementation of current and voltage values that varies at each meteorological change. In addition, for more precision, it is necessary to collect a large number of data to fill the LUT; which means the need of a large storage space unlike for the model technique.

On the other hand, the voltage in the presented mathematical model depends on the temperature only, which degrades the accuracy for certain PV panel technologies.

3 PV Emulator Power Circuit Description

A PV Emulator consists of a switch mode power supply controlled by current or voltage taking into account climatic conditions and load as shown in Fig. 1.

Different topologies of switch mode power supplies exist. In this work, a Full Bridge based topology is designed, as it can offer high powers of 1 KW order. For isolation, HF transformer is used with magnetizing and demagnetizing cycles under positive and negative voltage alternatively in order to gain two quadrants operation.

Figures 2 and 3 respectively show the power circuit and the synoptic diagram of the emulator. The power part consists mainly of five cascade disposed stages i.e. Low frequency rectifier feeding a Full-Bridge inverter which is built with four MOSFETs to allow high commutation frequency. With such high switching frequency, the

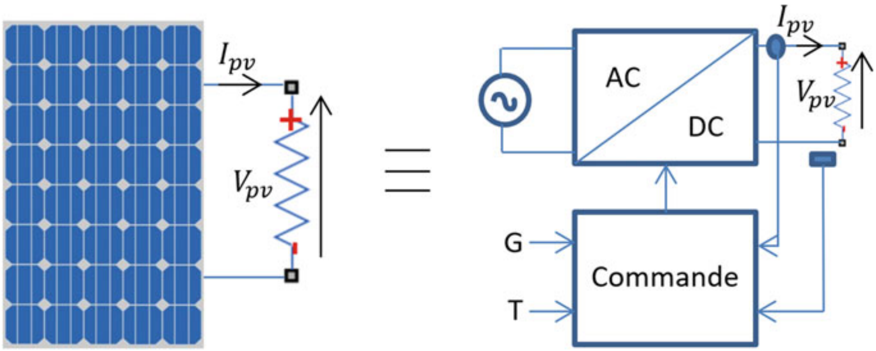

Fig. 1 General architecture of the PV Emulator

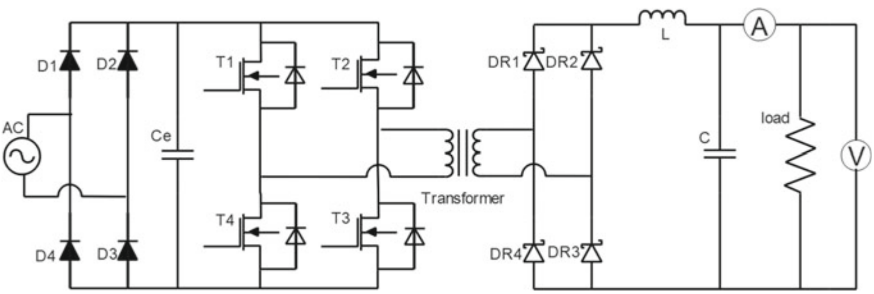

Fig. 2 PV Emulator power circuit

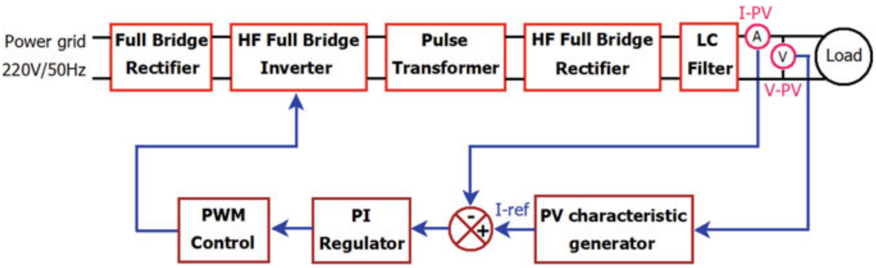

Fig. 3 Synoptic diagram of the proposed PV Emulator

seizing yields to a very small and light pulse transformer. Galvanic isolation is systematically gained as well, with very less cumbersome and low cost magnetic components.

The back-end stages are processing high switching frequency voltage. Consequently, the output rectifier is Schottky diode bridge and the LC filter is HF type filter which is seized according to ripple rate and slew rate requirements.

The control circuit, built around an F28335 DSP Controller, takes in charge the PV characteristic generation using either the implicit model of the PV panel or the I-V data in form of Look-Up-Table. Furthermore, the controller ensures the PV current tracking using a Phase Shift PWM Control technique and PI controller.

The above special design results in high efficiency PV Emulator, which is a very critical design performance requirement.

4 Simulation Results

The proposed power topology of the PV Emulator with the Phase Shift PWM Controller was simulated in MATLAB-Simulink environment using the LUT characteristic generation technique and the implicit PV model described in Sect. 2. Sharp module NA-E135L5 is taken as a reference characteristic with a radiance E = 400 W/m^2 and a temperature T = 15 °C. Table 1 shows the parameters of that Sharp module at STC. Realistic component parameters as well as experimental PV characteristic are used in order to predict the physical behavior of the PV Emulator.

Figure 4 shows the reference I-V characteristic together with the characteristic provided by the simulated PV Emulator in both generation technique cases.

It is clear from the results above, that the characteristic provided by the simulated PV Emulator follows almost exactly the reference characteristic.

Specifically, the simulation curves let see two particular zones. i.e. zone (A) where both generation techniques provide characteristics that perfectly merge with the reference. Then, zone B where the LUT based characteristic drift slightly from the reference compared to the model based technique. This is due to the spaced data used in LUT method in conjunction with a first order interpolation (Fig. 4 zoom). At the opposite, the implicit model calculates the (I,V) pairs at each sampling step resulting in better precision.

Table 1 Electrical characteristics of the module Sharp NA-E135L5 at STC

Maximum power	135Wp
Voltage at MPP	47.0 V
Current at MPP	2.88 A
Open circuit voltage	61.3 V
Short circuit current	3.41 A
Temperature Coef - V_{oc}	−0.3%/K
Temperature Coef - Isc	0.07%/K

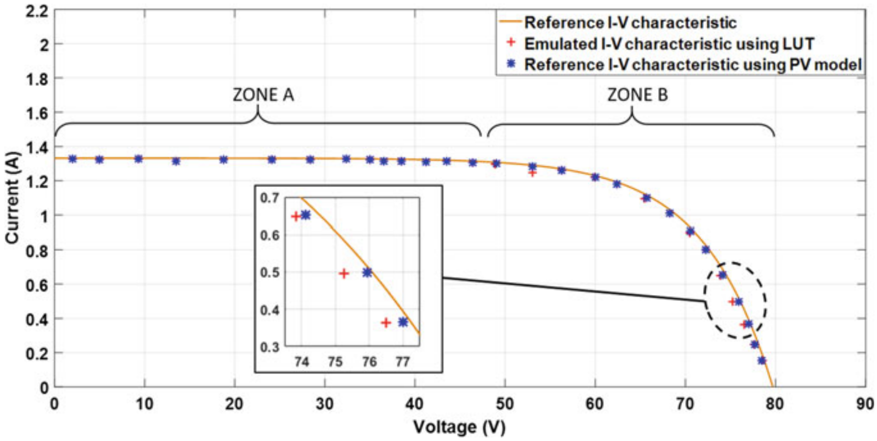

Fig. 4 Reference and emulated I-V characteristics using the LUT and the mathematical model of the PV module

5 Experimental Results

For validation purpose, a PV Emulator (Fig. 5) was built around MOSFETs Full Bridge converter and HF transformer. The switching patterns are generated by Phase Shift PWM Controller following a current regulation. The voltage feedback feed the characteristic generator that is a LUT generator, in the first time, and an implicit model generator in the second time. The control part is implemented using an F28335 board.

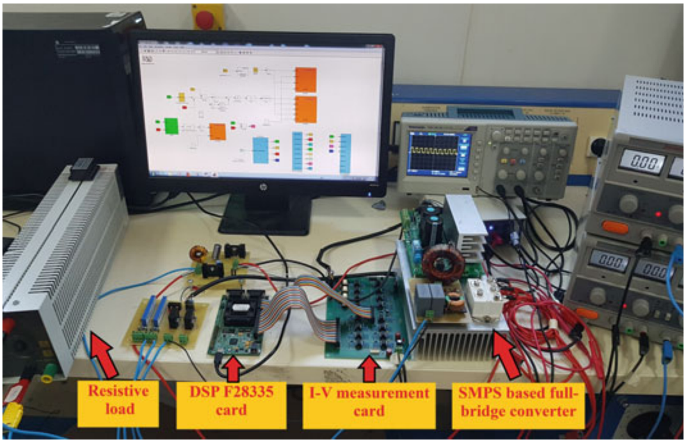

Fig. 5 Photograph of the experimental test bench

To emulate accurately the behavior of real PV modules, the designed switch mode power supply should present a fast dynamic response and a reduced output voltage ripple. In order to ensure these criteria, the LC filter is properly sized first; then special HF materials and components are used to build the prototype. Figure 6 shows the output circuit, which regroups the pulse transformer, the HF diode bridge and the LC filter.

Figures 7 and 8 demonstrate respectively the ripple for an output voltage of 15 V and the response time of the voltage across the load.

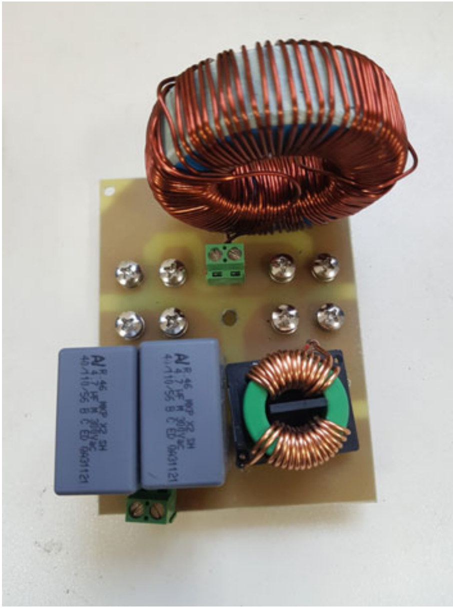

Fig. 6 Transformer, rectifier and LC filter

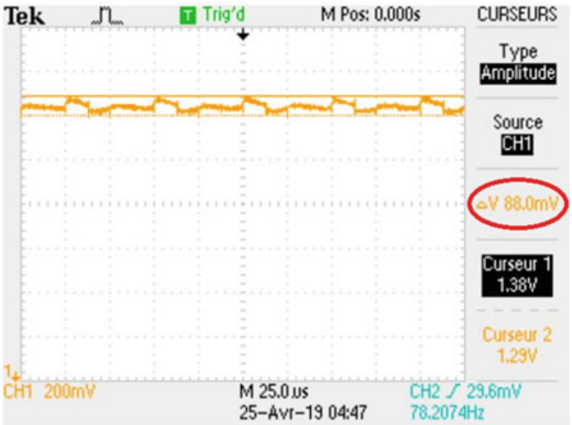

Fig. 7 Ripple of the voltage across the load at 15 V

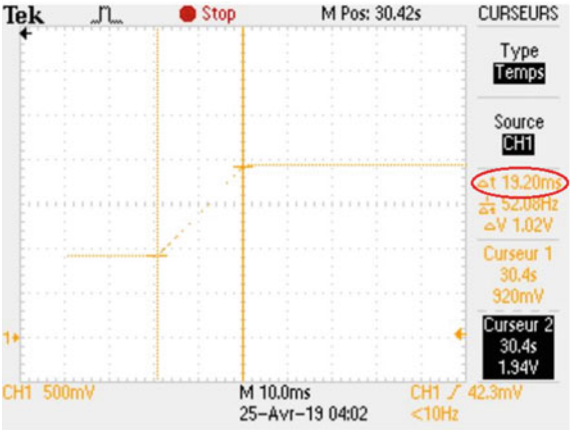

Fig. 8 Dynamic response time of the voltage across the load

According to these results the ripple rate is equal to 0.58% and the response time is 19.20 ms. These performances are within the range order of ripple rate and slew rate of a real PV module.

The experimental results below (Figs. 9 to 12) represent the current and the power versus voltage characteristics provided by the PV Emulator when, successively, implicit PV model and LUT techniques are used.

The PV Emulator is tested for two different reference PV modules presenting different Fill Factors 0.7 and 0.12 respectively.

Figures 9 and 10 are associated with the implicit PV model method, while Figs. 11 and 12 are associated with the LUT method.

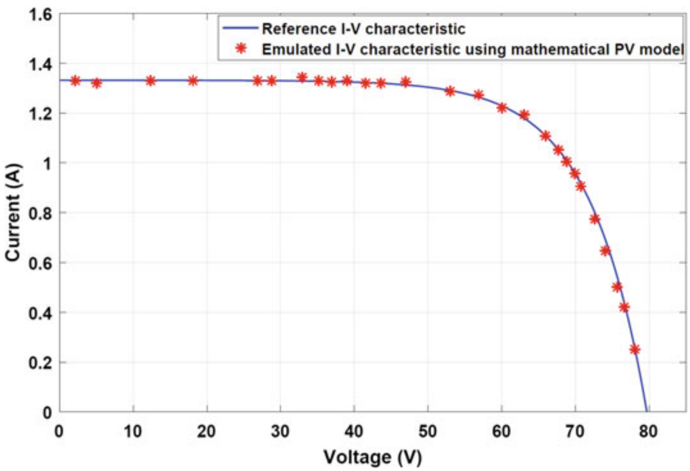

Fig. 9 Reference and emulated I-V characteristic using implicit PV model

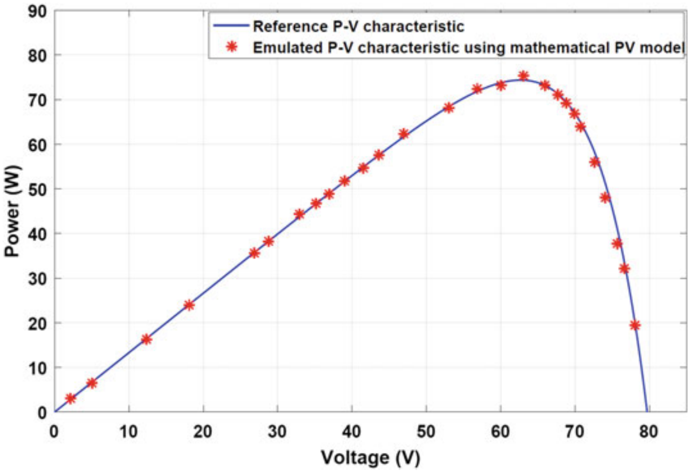

Fig. 10 Reference and emulated P-V characteristic using implicit PV model

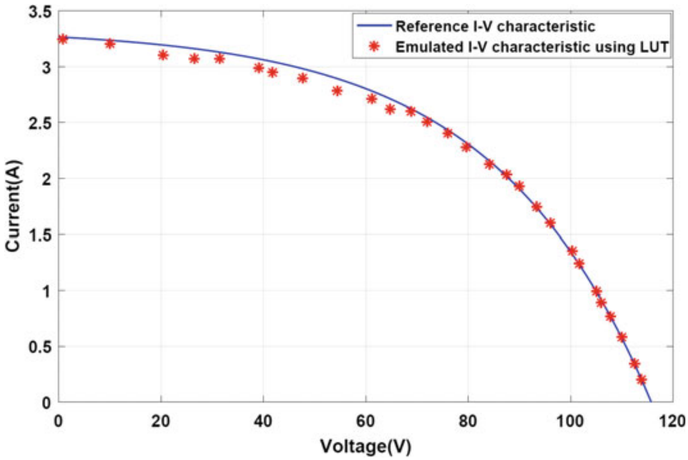

Fig. 11 Reference and emulated I-V characteristic using LUT

With both PV characteristic generation technics, the PV Emulator is able to reproduce accurately the reference characteristics and so to play the role of a real PV module. Particularly, the implicit model method demonstrates a perfect precision compared to the LUT method which confirm the simulation conclusion.

However, the LUT method performances could be improved, at the price of large storage space, if large number of measurement points are used as reference characteristic.

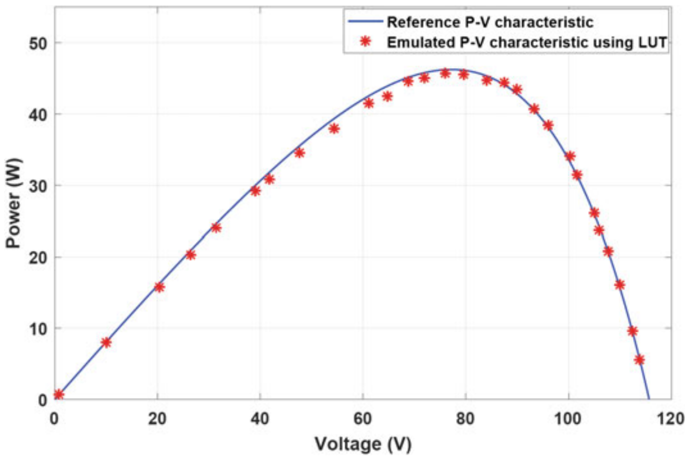

Fig. 12 Reference and emulated P-V characteristic using LUT

6 Conclusion

In this paper, a photovoltaic module emulator capable of reaching considerable power level has been proposed. The power circuit in this PV Emulator includes an isolated switch mode power supply built around a Full Bridge converter and a pulse transformer. Phase Shift PWM technique is used in conjunction with PI controller for the current loop. For the PV characteristic generation, a LUT technique is compared to an implicit model based technique. First, simulation study was carried out, in order to design the control scheme; then experimental tests have been conducted for validation purpose.

For both techniques, within the power rang investigated so far, the PV Emulator demonstrates very good accuracy in reproducing real PV panel behavior. However, the model based method exhibits much better precision thanks to its fast sample real time update.

In perspective, the power rang of the PV Emulator will be extended to cover large PV panels and advanced control techniques will be introduced to improve the performance.

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