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ORIGINAL PAPER

Study of a Low-Cost PV Emulator for Testing MPPT Algorithm Under Fast Irradiation and Temperature Change

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Abstract

This paper presents a study of a low-cost photovoltaic (PV) emulator to test the real implementation of maximum power point tracking (MPPT) algorithm. This PV emulator is composed of a variable DC supply in series with a variable resistor; it is based on the maximum power transfer theorem in order to provide a curve that exhibits a peak which can be tracked by an MPPT algorithm. Moreover, this emulator can be used to test the performance of the MPPT algorithm under fast variation of the solar irradiance and temperature. For this reason, the P&O MPPT algorithm with a boost DC-DC converter is used in order to validate the functionality of the PV emulator. Finally, the experimental results show that our PV emulator can provide a simple, efficient and low-cost way for users (researchers, engineers, students, etc.) to test and validate their MPPT algorithms.

Keywords DC supply · Low cost · PV emulator · MPPT · Photovoltaic

Introduction

Today, solar energy has taken a large part of the market due to the continued development of PV system technology and its lower prices [1]. Therefore, several reseachers are working on the optimization of this source of energy in order to extract power with high reliability, low cost, and improve energy efficiency [2].

The energy production of PV panels is dramatically affected by climatic conditions in terms of solar irradiance and temperature [3, 4]. Besides, the power provided by the PV panels is maximum only when the latter operates at its maximum power point (MPP). Therefore, the MPPT controller is used to track the MPP. In this context, a large number of MPPT methods have been developed in the literature, such as: Perturb & Observe (P&O) [5, 6], incremental conductance (INC) [7–9], fractional open circuit voltage [10], fractional short-circuit current [5], fuzzy logic control [11], and neural network [12], etc.

On the other hand, to validate the performance of such MPPT algorithm, it is required to test it under different values of temperature and irradiance. However, it is difficult to realize the desired test case because we cannot control the climatic conditions [13].

Therefore, different solutions have been used in the literature that can be classified into two categories: commercial ones and proposed ones in science research. Among the most used commercial solutions, we find:

- Artificial lights [14, 15].
- The Agilent Solar Simulator [16].
- PV emulators based on DC power programmable [17, 18].

Firstly, the solution presented in [14, 15] is based on using spotlights served as a light source to produce the light on the PV panel surface. Then by controlling the light intensity, it is possible to make the desired test case to emulate the irradiance change. But, the inconvenient of this solution is that the spotlights increase dramatically the PV panel temperature. Moreover, several PV emulators commercial have been used in [16–18], they are considered as the best devices to emulate the P-V and I-V curves of the PV panel under desired climatic conditions. However, these solutions

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are very expensive and not always available in all research laboratories.

On another hand, many solutions have been proposed in the literature especially the following ones:

- PV emulator based on DC power supply and DC-DC buck-boost DC/DC converter controlled by micro-controller [19].
- PV emulator based on DC power supply and PV panel [20].
- PV emulator based on DC power supply and series resistor [21].

The PV emulator presented in [19] is based on a DC power supply and a buck-boost DC/DC converter which is controlled by a microcontroller. This PV emulator is complex and expensive because of using several devices to build it such as buck-boost and its components and the microcontroller. Secondly, work proposed in [20] presents a PV emulator that is constructed by the parallel connection of PV panel and a DC power supply. This PV emulator can simulate a variety of I–V curves under different solar irradiations, but it is not giving the way to emulate the temperature variation. Thus, a low-cost PV emulator is proposed in [21] which is based on a variable voltage analog DC power supply with a resistor. Nevertheless, this PV emulator was not well investigated.

For that, this work aims to study a low-cost PV emulator to provide a simple and low-cost way to test the real implementation of MPPT algorithms. This PV emulator is composed of a variable DC supply in series with a variable resistor.

This paper is organized as follows. The next section presents operating configuration which describes: maximum power transfer theorem, sizing of PV emulator, and PV emulator for testing the fast variation of Solar irradiance and temperature. Next, the Experimental and validation are presented in "Experimental and Validation". And the conclusion is given in "Conclusion".

Operating Configuration

Maximum Power Transfer Theorem

PV emulator must give a power curve as this of PV panel that exhibits a peak. Therefore, a simple DC supply in series with a variable resistor can be used, because based on 'maximum power transfer theorem' this DC supply can provide its maximum power when load resistor equals to the series resistor. The PV emulator basic schematic is presented in Fig. 1.

The 'maximum power transfer theorem' can be explained as follows [22]:

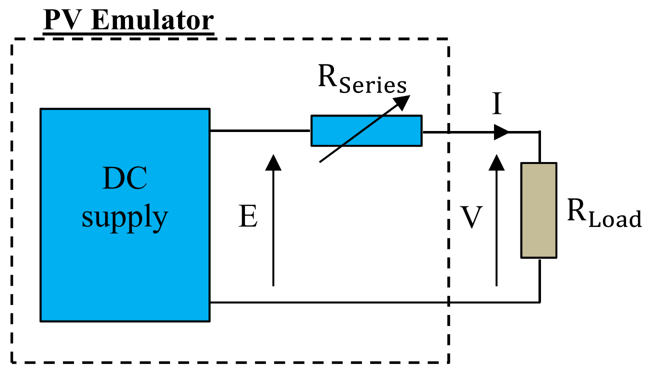


Fig. 1 Basic schematic of the PV emulator

Based on Fig. 1, the following equations can be found:

$$P_{load} = I * V = I^2 * R_{load} \tag{1}$$

$$I = \frac{E}{R_{series} + R_{load}} \tag{2}$$

Replacing Eq. 2 in Eq. 1, Eq. 3 is found:

$$P_{load} = \frac{R_{load}}{(R_{series} + R_{load})^2} * E^2 \tag{3}$$

$$\frac{dP_{load}}{dR_{Load}} = E^2 \frac{R_{series} - R_{load}}{(R_{series} + R_{load})^3} \tag{4}$$

The power is at its maximum when its derivative is equal to zero. Then from Eq. 4, this can be reached when the load resistor is equal to the series resistor as follows:

$$R_{load} = R_{series} \tag{5}$$

Therefore, in this case, maximum power transfer condition (5) will appear when the voltage of the load is half of that generated by the DC supply.

$$V = \frac{E}{2} \tag{6}$$

Sizing of the PV Emulator

As described previously, the PV emulator must reflect the behavior of the PV panel and especially in the P-V curve at MPP. Table 1 presents the characteristics of the PV panel used in this work.

In order to size the PV emulator parameters (The value of DC supply and the series resistor), the values of DC supply (E) and the series resistor can be calculated by the following equations:

$$R_{serie} = R_{mpp} = \frac{V_{mpp}}{I_{mpp}} \tag{7}$$

$$E = 2 * V_{mpp} \tag{8}$$

From Table 1, and Eqs. 7 and 8, the values of DC supply and series resistor at STC are respectively 37.52 V and 17.53 Ω.

Table 1 Characteristics of the PV panel TDC-M20-36 at STC

Characteristics TDC-M20-36	
Maximum power, Pmax	20 W
Voltage at Pmax, Vmp	18.76 V
Current at Pmax, Imp	1.07 A
Short-circuit current, Isc	1.17 A
Open-circuit voltage, Voc	22.70 V
Temperature coefficient of Voc, Kv	−0.35%/°C
Temperature coefficient of Isc, Ki	−0.043%/°C
Number of cells	36

Generally, only one resistor value can lead the PV panel to operate at its MPP [23]. Figure 2 shows a complete schematic view of the PV emulator control. The PV panel is replaced by DC supply and series resistor. So, the MPPT bloc is constituted by the DC-DC converter controlled by an MPPT algorithm in order to operate the PV emulator at MPP, when the equivalent resistor (between PV emulator and load) is equal to the value of the series resistor.

PV Emulator for Testing the Fast Variation of Solar Irradiance and Temperature

MPPT algorithms must be tested for different solar irradiance and temperature values to validate its robustness.

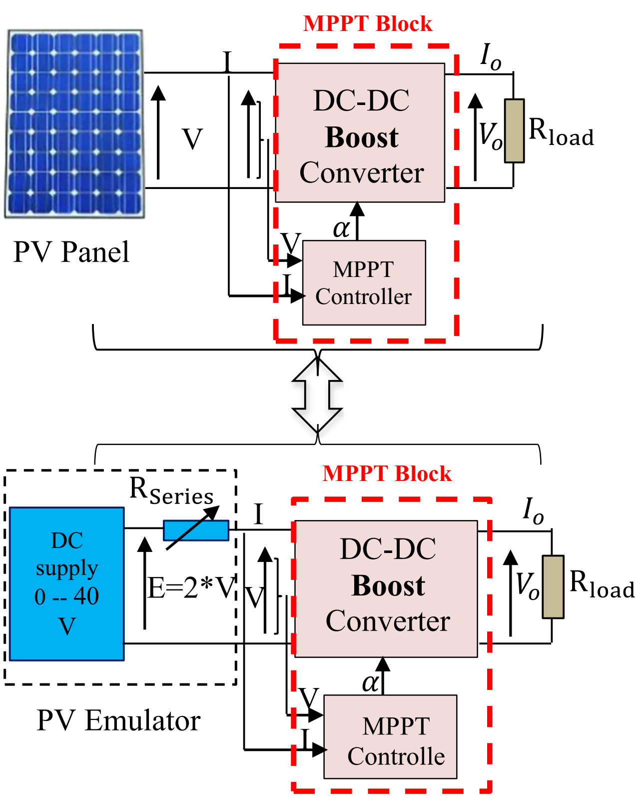


Fig. 2 A complete schematic of the PV emulator system

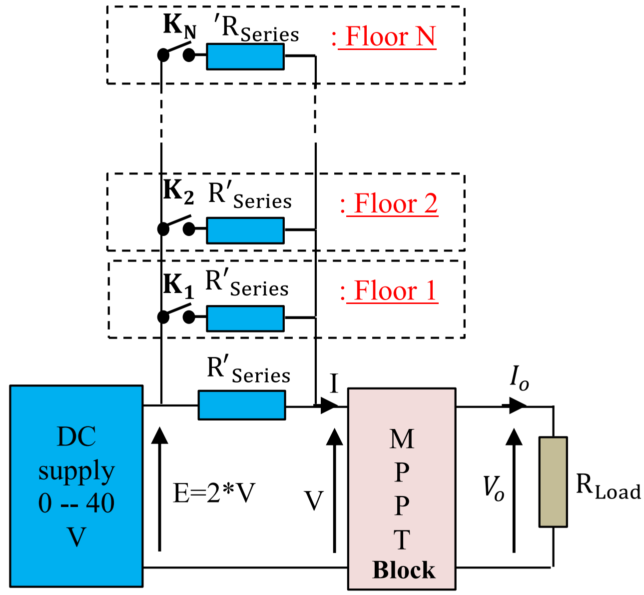


Fig. 3 General design to emulate of the fast variation of the solar irradiance

But as was described previously that is difficult to make such tests in reality. For this reason, a study to emulate several values of these parameters is described in this part.

- Fast variation of the solar irradiance

A simple design based on the PV emulator is developed to emulate different values of the solar irradiance and it is presented in Fig. 3. The number of solar irradiance values depends on the number of floors. To emulate a number N of values of solar irradiance we must add N-1 of floors. Then the value of R'_{series} can be calculated by the following equation:

$$R'_{series} = N \times R_{series} \tag{9}$$

For instance, to emulate five values of solar irradiance, four floors must be used, for that R'_{series} is equal to $5 \times R_{series}$. In Table 2, the solar irradiance values which can be obtained by using 4 floors with 5 combination of the switches are

Table 2 Obtained solar irradiance values according to the switches states by using four floors

	K1	K2	K3	K4
G = 1000 W/m^2	1	1	1	1
G = 800 W/m^2	1	1	1	0
G = 600 W/m^2	1	1	0	0
G = 400 W/m^2	1	0	0	0
G = 200 W/m^2	0	0	0	0

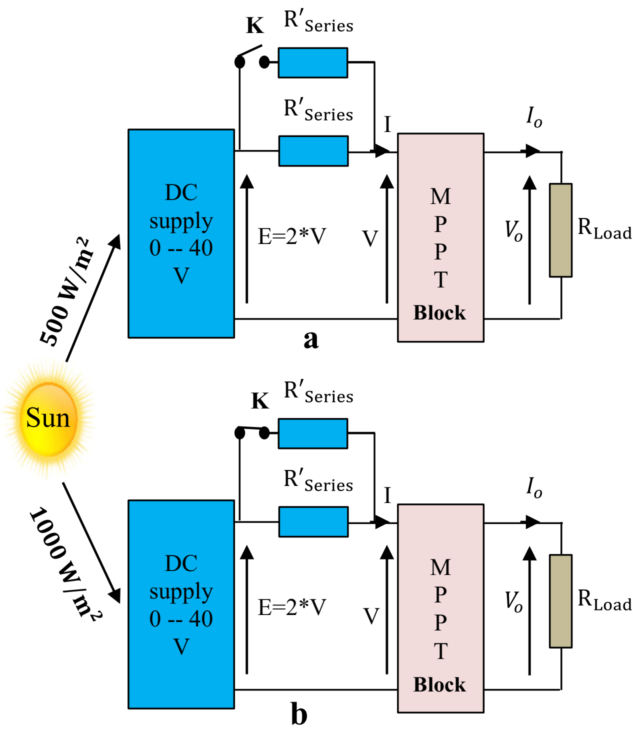


Fig. 4 Example of the fast variation of the solar irradiance

presented. Generally, obtained solar irradiance values can be calculated by using the following equation:

$$G = \frac{(K+1) \times 1000}{N} \quad (10)$$

Where G the value of the solar irradiance level and K is the number of closed switches.

For enriching understanding, an example of a rapid change of the solar irradiance from 500 W/m^2 to 1000 W/m^2 is developed in Fig. 4. In the case of 500 W/m^2 of the

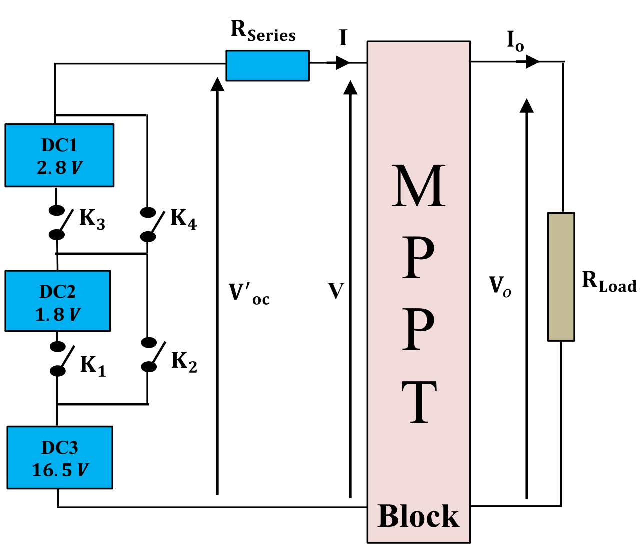


Fig. 5 Example of the fast variation of the solar irradiance

Table 3 Different temperature values according to the switches states

	K1	K2	K3	K4
T3 ($V'_{oc} = 16.5\ V$)	0	1	0	1
T2 ($V'_{oc} = 18.3\ V$)	1	0	0	1
T1 ($V'_{oc} = 21.1\ V$)	1	0	1	0

solar irradiance (Fig. 4a), the switch K1 must be opened so that the value of the equivalent resistor is equal to 35.16 Ω (**2** × **R**$_{\mathbf{series}}$). And if we close the switch K1 (Fig. 4b), the value of the equivalent resistor will be equal to 17.53 Ω which correspond to R_{series}. In this case, the value of the solar irradiance occurs 1000 W/m^2 . Then to emulate the fast change of the solar irradiance of 500 W/m^2 to 1000 W/m^2 it is necessary to permute the state of the switch K1 from 0 to 1.

- Fast variation of temperature

Figure 5 describes a simple method to emulate 3 values of temperature. The idea is that by replacing the DC supply of PV emulator by 3 DC supply in series so that the sum of their voltages must be equal to the desired maximum value of V'_{oc}. This value corresponds to the desired minimum temperature value. If we want to emulate at least a temperature of 25 °C, which corresponds to the MPP at STC, the V'_{oc} must be equal to 2 × V_{mpp}. In Table 3, the temperature values (with T1 < T2 < T3) which can be obtained by using 3 DC supply with four switches are presented. Then to emulate a fast change of the temperature it is necessary to permute the state of the switches as shown in Table 3.

Experimental and Validation

PV Emulator Validation

The circuit model and the experimental setup of the developed system are presented in Figs. 6 and 7 respectively in order to validate the performance of used PV emulator.

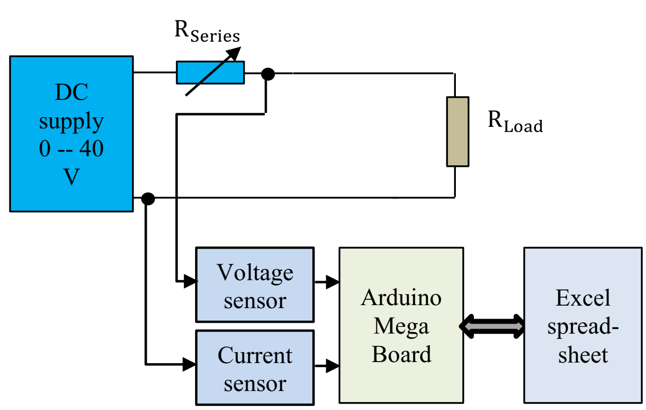


Fig. 6 Circuit model of the developed PV emulator

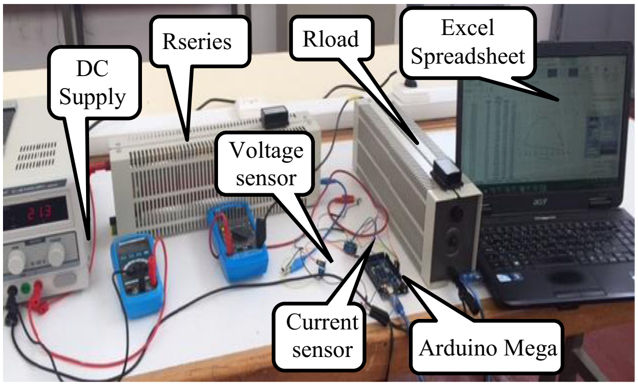


Fig. 7 Experimental setup of used PV emulator system

The output power obtained by voltage and current sensors is transmitted and plotted directly in real-time in Excel by using PLX-DAQ data acquisition Macro, which allows communication between the microcontroller of the Arduino Mega and an Excel spreadsheet through serial communication [24]. Figure 8 presents the experiment P-V and I-V curves characteristics of the PV emulator. As shown in Fig. 8, the peak in the power curve occurs when the output voltage of the PV emulator is half of the Dc power supply voltage.

Effect of the Solar Irradiance Variation

Figure 9 presents the experimental P-V curves for a fixed V'_{oc} and various series resistances. This situation is similar to variation of the solar irradiance in case of PV panel.

Figure 10 shows the experimental I-V curves for different series resistors at fixed V'_{oc}. According to this figure, the short-circuit current of PV emulator decreases when the value of R_{series} increases. It is noticed that when the series resistor varies in the PV emulator, the current varies linearly and do not reflect the actual I-V characteristic of a PV panel. Nevertheless, we are interested in the P-V characteristic which presents a peak in the power curve that can be followed by the MPPT algorithm to be tested.

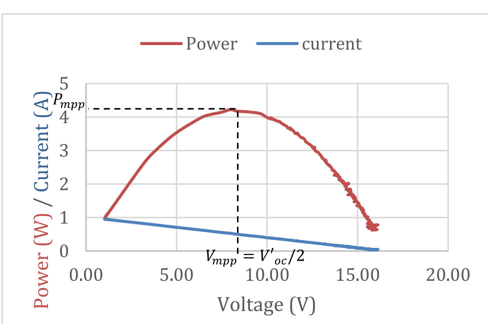


Fig. 8 Experimental P-V and I-V curves characteristics of the PV emulator

Effect of Temperature Variation

Figure 11 presents the experimental P-V curves for a fixed $\boldsymbol{R_{series}}$ and various value of the V'_{oc}. This situation similar to changing temperature conditions in PV panel.

Consequently, we can simulate the effects of the solar irradiance and temperature variations by varying, respectively, the value of the series resistor and the voltage of the DC supply.

Implementation of MPPT Algorithm Using the PV Emulator

MPPT Algorithm

In order to verify the ability of used PV emulator to test the real implementation of an MPPT algorithm, the P&O MPPT algorithm is used as an example in this work. P&O MPPT is a popular control method for PV applications due to its simplicity. The principle operation of the P&O MPPT algorithm is based on the factor $\frac{dP}{dV}$ at the P-V curves. Figure 12 shows the three variation cases of the MPP according to $\frac{dP}{dV}$ factor: 1 ($\frac{dP}{dV} > 0$), 2 ($\frac{dP}{dV} = 0$) and 3 ($\frac{dP}{dV} < 0$). The advantages of this method are its simple structure, less requirement of parameter measurements, and the possibility of its implementation in a low-cost microcontroller. Therefore, the P&O MPPT algorithm is used to validate the good performance of used PV emulator.

The flowchart of the implemented P&O MPPT algorithm is shown in Fig. 13.

The Boost Converter Construction and Parameters

The DC-DC boost converter is inserted between the PV panel and the load. This converter generates an output voltage and current from the current and voltage of the input and the duty cycle α. This duty cycle is calculated by the MPPT algorithm and varies between 0 and 1. The figure below shows the circuit of the DC-DC boost converter [8] (Fig. 14).

The equations of this DC-DC converter are shown below:

$$V_o = \frac{V}{1-\alpha} \tag{11}$$

$$I_o = I(1-\alpha) \tag{12}$$

Where α is the duty cycle, V is the converter input voltage, I is the input current of the Boost converter, V_o is the output voltage and I_o is the output current of the Boost converter.

Fig. 9 Experimental P–V curves for many series resistance at fixed V'_{oc}

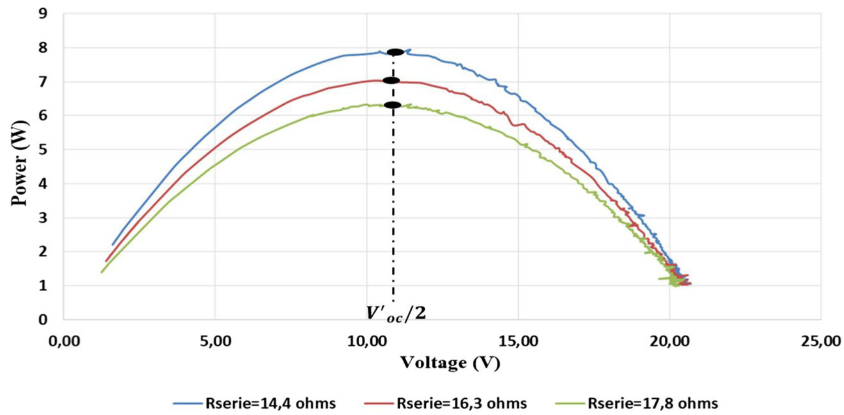


Fig. 10 Experimental I–V curves for different series resistance at fixed V'_{oc}

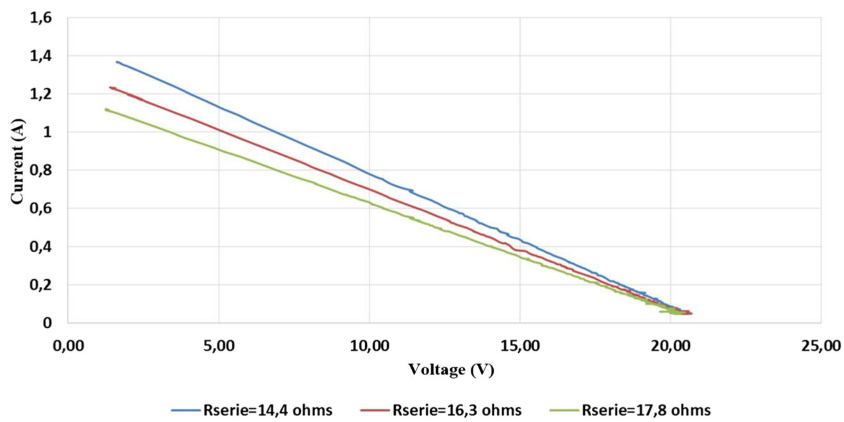
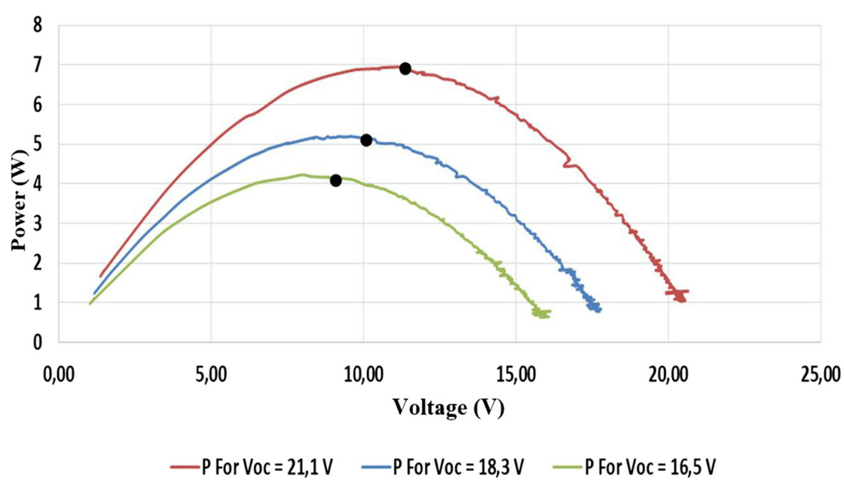


Fig. 11 Experimental P–V curves for different V'_{oc} at fixed R_{series}



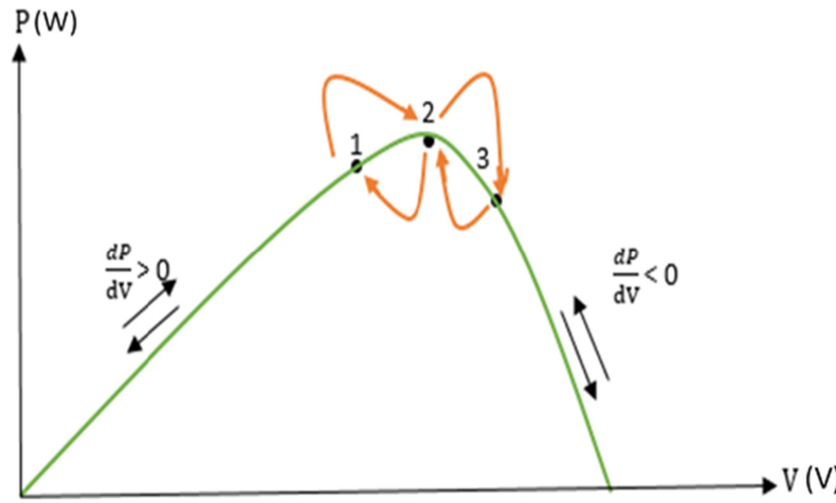


Fig. 12 Slope $\left(\frac{dP}{dV}\right)$ variation and steady state three level operation of P&O MPPT

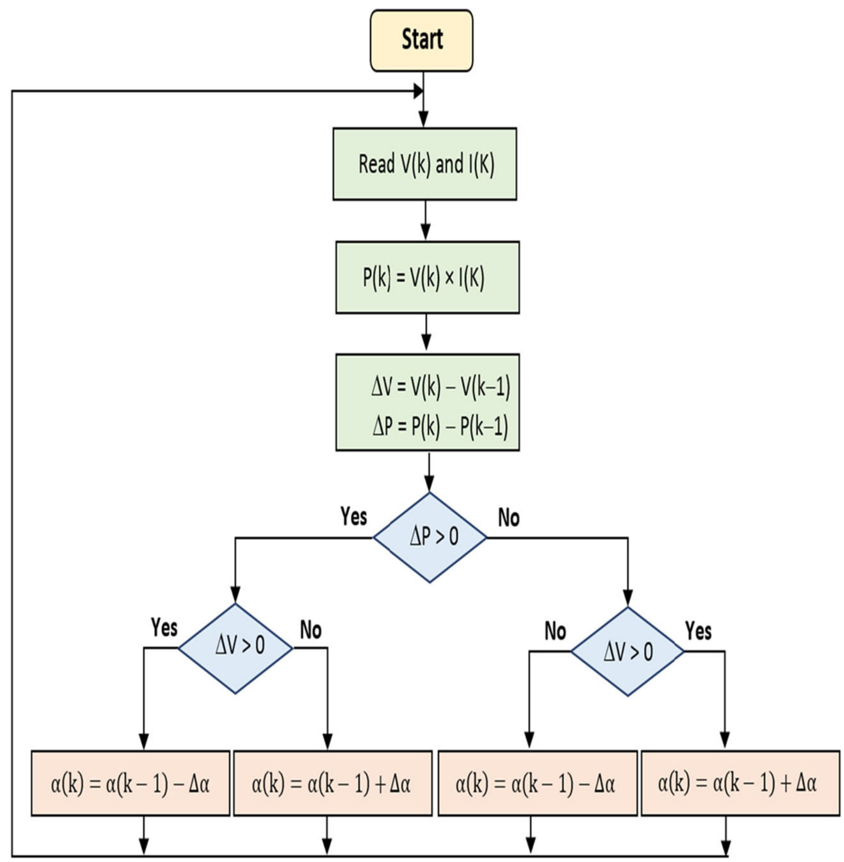


Fig. 13 The flowchart of the implemented P&O MPPT algorithm

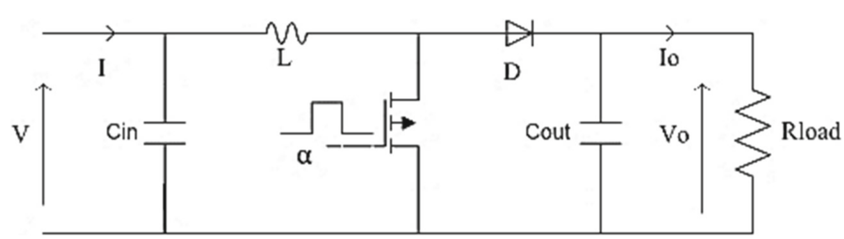


Fig. 14 DC-DC boost converter

Table 4 Parameters of the boost DC/DC converter

Parameters of the boost DC/DC converter	
Inductor (**L**)	20 mH
Input capacitor (C_{in})	220 μF
Output capacitor (C_{out})	470 μF
Switching frequency	1 kHz

The parameters of the elements used in the boost DC/DC converter are given in Table 4.

Test Results

Figure 15 present the experimental setup assembled in the laboratory. The setup consists of used PV emulator, the DC-DC boost converter, load, Arduino Mega board, and a computer to display the experimental results in real-time in Excel. The P&O MPPT algorithm is implemented by the boost converter control with a frequency of 1 kHz.

To validate the functionality and performance of used PV emulator, the P&O MPPT algorithm is tested with a fast change in solar irradiance. At first, the solar irradiance is suddenly decreased by applying a step from 1000 W/m^2 to 500 W/m^2 at t = 1 s, then it is increased by applying a step from 500 W/m2 to 750 W/ m^2 at t = 2 s. The test result is presented in Fig. 16. As shown in Fig. 16, it can be observed that the powers correspond to MPP for the above-mentioned solar irradiance conditions are respectively 20 W, 10 W, and 15 W.

In addition, Fig. 17 present the test result for two steps increase in temperature level, from T1 to T2 at t = 1 s and from T2 to T3 at t = 2 s. It can be observed from results that the powers correspond to MPP for the above-mentioned temperature conditions are respectively 7 W, 5 W and 4 W. These values are in accordance with those obtained in Fig. 11 which shows the experimental P–V curves for different V'_{oc} values.

Consequently, the experimental results validated that the used PV emulator to be a suitable low-cost solution by the performance average compared to the commercial emulator for PV systems.

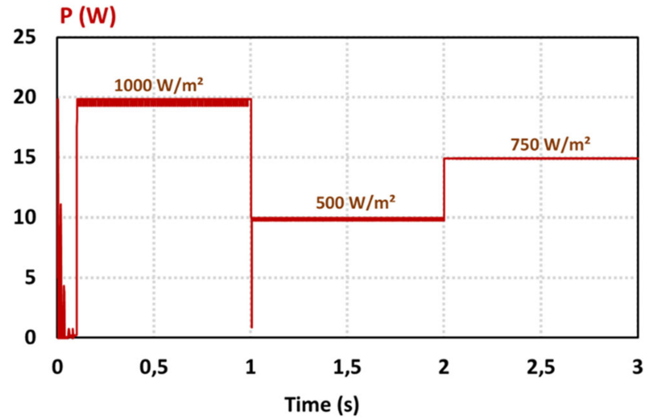


Fig. 16 PV emulator output power with P&O MPPT algorithm at the difference of the solar irradiance

The Used Emulator Comparison with Other Emulators

Table 5 represents a comparison between the used PV emulator and other emulators, based on components, cost, and complexity. The cost of the used emulator is $ 79.99. This price is very low compared with that of other

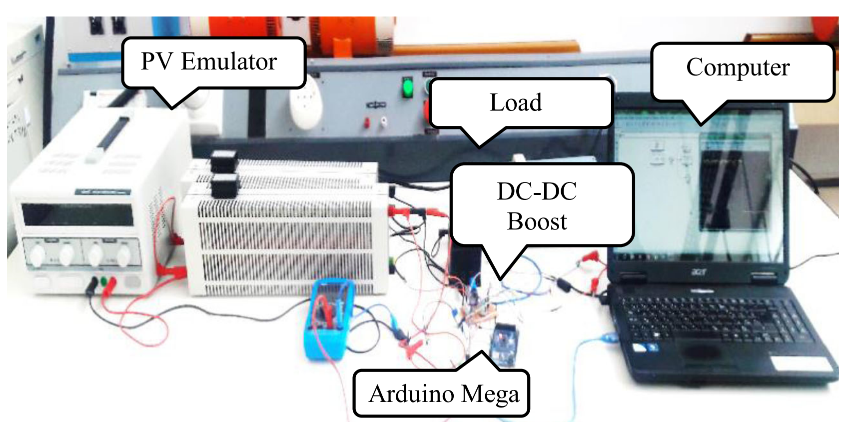


Fig. 15 Experimental setup of the developed PV system

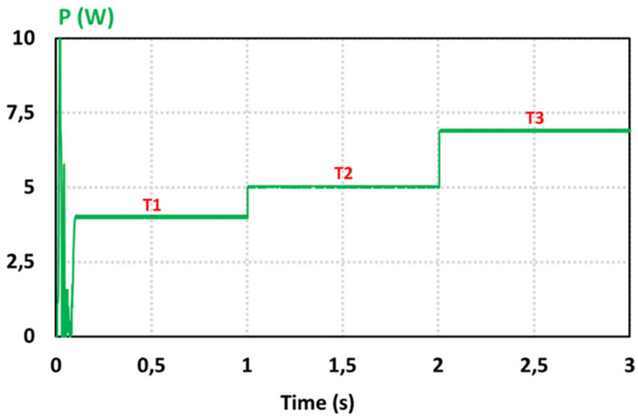


Fig. 17 PV emulator output power with P&O MPPT algorithm at the difference of temperature levels

emulators, for example, the emulator shown in [16] costs 3500.00 $ and the emulator shown in [17] costs 2800.00 $. Thus, the used PV emulator is not complex, easy to build and use it in the laboratory.

Conclusion

The high cost of commercial PV emulators requires finding new solutions for building low-cost system having similar behavior of PV panel. Therefore, this paper describes a low-cost PV emulator by which we replace a PV panel to test the real implementation of MPPT algorithms for PV applications. In this work, the results of experiments test are shown that our PV emulator can provide a P-V curve that it presents a power peak, which can be followed by the MPPT algorithm. In addition, an explication of the PV emulator to simulate a fast variation of the solar irradiance and the temperature in case of PV systems is presented in this work. Moreover, the P&O MPPT algorithm with a boost DC-DC converter is used in order to validate the functionality of used PV emulator. Finally, the results of the rapid change of irradiance and temperature on the PV emulator confirmed the effectiveness of the PV emulator system and show that our solution has several advantages over existing such as low cost, less complexity, and can provide a simple way for users (researchers, engineers, students, etc.) to test and verify their MPPT algorithms.

As perspective, two prospects for improvement can be done: (i) find a general method to calculate the emulated values of temperature as we did for irradiance. (ii) Improve the present PV emulator design to be suitable for testing shading conditions.

Nomenclatures E, DC supply output voltage [V]; I, PV emulator output current [A]; I_0, the output current of the Boost converter [A]; I_{mpp}, Panel output maximum power point current [A]; G, Solar irradiance level [W/m2]; P_{load}, Load power [W]; R_{load}, Load resistance [Ω]; R_{Series}, Series resistance [Ω]; R_{mpp}, Resistor value at MPP [Ω]; T, Temperature [°C]; V, PV emulator output voltage [V]; V_{mpp}, Voltage at MPP [V]; V_0, Boost output voltage [V]; V'_{oc}, PV emulator open-circuit voltage [V]; V_{oc}, Panel open-circuit voltage [V].

Greek Letters α, Duty cycle.

Abbreviations CV, Constant Voltage; DC, Direct Current; INC, Incremental Conductance; MPP, Maximum Power Point; MPPT, Maximum Power Point Tracking; PV, Photovoltaic; P & O, Perturb and Observe.

Table 5 Comparison between the used emulator and other emulators

Work, year	Material used	Cost	Complexity
[17], 2012	- Programmable DC Power Supply (TDK Lambda GEN300-11) - dSPACE DS1104	2800.00$ http://www.ebayshopkorea.com/main/viewsitemID=381850543196	High
[16], 2014	- PV Solar Array Simulator (Agilent E4360A)	3500.00$ http://www.ebayshopkorea.com/main/viewsitemID=253064937146	High
Our work	- DC regulated power supply - variable resistor 320 W 100 Ω	64.99$ www.ebayshopkorea.com /itm/10A-30V-DC-Power-Supply–Adjustable-Dual-Digital-/251705177148 15.00$ http://catalog.efcmd.ma/produit/rheostat-320-w-100/	Less

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