Prototype for the Characterization of Photovoltaic Panels based on a SEPIC Converter

José J. Chacón, Reynaldo A. Ortiz, John E. Archila, María A. Mantilla, Mónica A. Botero, Johann F. Petit.
Grupo de Investigación en Sistemas de Energía Eléctrica (GISEL)
Universidad Industrial de Santander
Bucaramanga, Santander, Colombia
jose.chacon@correo.uis.edu.co, reynaldo.ortiz@correo.uis.edu.co, john.archila@correo.uis.edu.co, marialem@uis.edu.co, mabotero@uis.edu.co, jfpetit@uis.edu.co

***Abstract*—This paper presents the design and implementation of a prototype based on a SEPIC (Single-Ended Primary Inductance Converter) used to measure the characteristic curves of photovoltaic (PV) panels. The SEPIC is controlled to emulate a variable resistance at the output of the PV panel in order to obtain a set of values (voltages and currents) for different operating points at the output of the panel. The set of voltages and currents are stored and sent to a computer in order to display the characteristic curves in real-time. The performance of the prototype is firstly evaluated though simulations in PSIM and subsequently by experimental results. The results show the outstanding performance of the SEPIC converter and its suitable use for this kind of applications due to its low input current ripple and its operation as a buck-boost converter. The resulting prototype allows the characterization of PV panels up to 500 W.**

Keywords—DC-DC converters, photovoltaic systems, characteristic curves, Single-Ended Primary Inductance Converter (SEPIC).

I. Introduction

Nowadays, photovoltaic (PV) systems are a solution for reducing the contamination due to traditional energy sources. Solar PV has grown hugely in recent years reaching a total global capacity of about 227 GW in 2015. Even more, PV systems are currently an economically competitive source of energy in several locations [1].

Solar panels are the fundamental component of a PV system. These devices allows the generation of electricity from the sun radiation by means of the photovoltaic effect. The electrical operation of a solar panel is described by its characteristic curves: current vs. voltage (I-V) and power vs. voltage (P-V) curves. An example of a P-V curve is presented in Fig. 1.

Manufacturers of PV panels present in the datasheet the characteristic curves of the panels under certain uniform conditions of irradiance and temperature. However, meteorological conditions change along the planet, which can generate uncertainties in the characteristic curves according to the place of installation. Furthermore, the characteristic curves of the PV panels vary according to possible partial shading conditions in its surface; however, this behavior is not described in the datasheet. In this way, it is of interest to know the electric performance of the photovoltaic panels according to the place where they are installed in order to do a reliable and suitable design of the PV system. Furthermore, these curves provides pertinent information for the implementation and maintenance of PV systems.

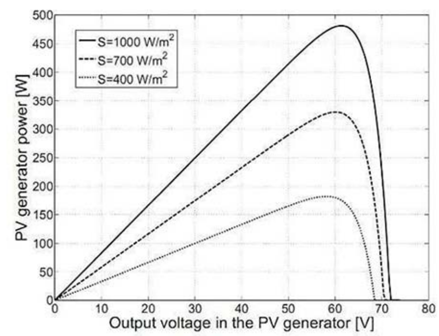

Fig. 1 P-V characteristic curves for difference irradiance (S) conditions [2].

The experimental measurement of the characteristic curves can be achieved by means of variable resistances, capacitive loads, variable electronics loads and DC-DC converters [3-7]. Among these methods, the DC-DC converters present outstanding benefits such as simple structure, easy scalability and automatic measurement of the characteristic curves.

Regarding the DC-DC converters, the SEPIC (Single-Ended Primary Inductance Converter) is one of the most suitable converters for this application due to the following features [8] y [9]:

- Low input ripple and noise due to the input inductor.
- Non-inverted output.
- Their inductors may be coupled on the same core.
- It can be easily obtained a galvanic isolated version of the SEPIC by changing one of its inductors for a high frequency transformer.
- Its buck-boost operation allows a complete sweep of the PV panel characteristic curves.

Accordingly, this paper presents the design and implementation of a prototype for the systematic measurement of the I-V and P-V curves in PV panels. The prototype is based on a SEPIC, which is controlled to emulate a variable resistance at the output of the panel in order to obtain a complete sweep of the PV panel curves. The control algorithm modifies the duty

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cycle of the SEPIC in order to obtain a set of values (voltages and currents) for different operating points at the output of the panel. The set of voltages and currents are stored and sent by serial communication to a computer in order to display the curves in real-time.

The organization of the paper is as follows. Section II describes the SEPIC topology and its operation for the systematic measurement of the characteristic curves in PV panels. In section III, the design and the main components of the experimental prototype are exposed. Section V shows the simulation and experimental results. Finally, the main conclusions of the work are presented.

II. Operation of the SEPIC for the Systematic Measurement of the Characteristic Curves

The topology of a SEPIC connected to a PV panel is shown in Fig. 2. This converter provides a non-inverted output voltage and exhibit a buck-boost characteristic.

In continuous conduction mode, the SEPIC operates in two possible states (State A and State B). In state A (Fig. 3), the switch Q_1 is closed during the interval $0 \leq t < DT_s$, where T_s corresponds to the switching period and D is the duty ratio. In this case, the diode D_1 is off and the currents by the inductors (L_{1A} and L_{1B}) increase. Regarding state B (Fig. 3), the switch Q_1 is open during the interval $DT_s \leq t < T_s$ and the diode D_1 is closed. The currents by the inductors (L1A and L1B) decrease.

In the steady state and considering as ideal the components of the SEPIC, the relationship between the input (V) and output voltages (V_{out}) is given by (1) for continuous conduction mode.

$$V_{out} = V\frac{D}{1-D} \tag{1}$$

In this application, the SEPIC is controlled to obtain a complete sweep of the PV panel curves as seen in Fig. 4. Therefore, the SEPIC emulates a variable resistance at the output of the panel by modifying the duty cycle in the interval $0 \leq D < 0.94$.

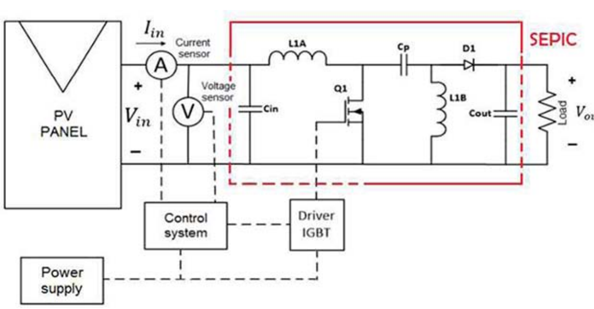

Fig. 2 Topology of a SEPIC

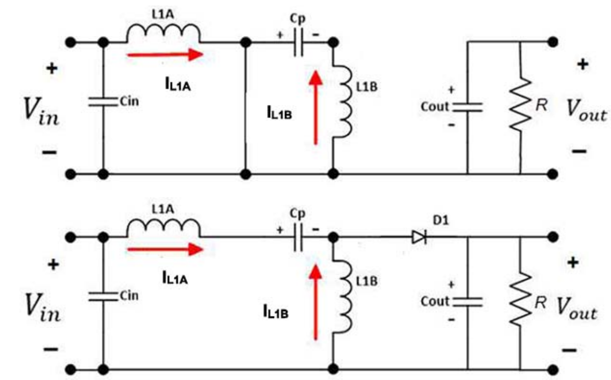

Fig. 3. SEPIC states in continuous conduction mode. State A is in the top of the figure and state B is in the bottom.

The initial duty cycle is set in 0, so the resulting operating point is VOC (Open Circuit Voltage) at the PV panel output as seen in Fig. 4. Then the duty cycle is increased with variable steps from 0 to 0.94 in order to sweep the total curves from the operating point VOC until near the operating point ISC (Short Circuit Current). The values of the voltage and current at the PV panel output are measure for each point in the sweep of the duty cycle.

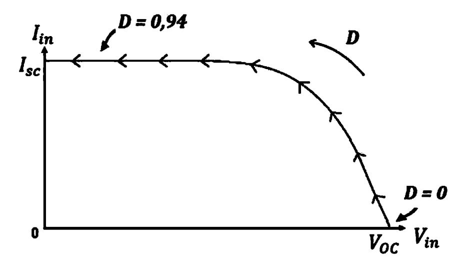

Fig. 4. Sweep of a I-V panel curve

The duty cycle is synthetized by using a Pulse With Modulation (PWM) technique in order to obtain the firing pulses of the switch Q_1.

III. Prototype Design and Experimental Setup

The prototype has five stages as seen in Fig. 2: the DC-DC converter (SEPIC topology), a measurement stage (voltage and current sensors), the control system, the driver for the switching device and the power supply stage.

A. DC-DC Converter (SEPIC Topology)

The SEPIC is designed to operate in continuous conduction mode for a rated power of 500 W. It is considered that the voltage and current at the PV panel output can vary between 5V-50V and 0A-10A, respectively.

An important issue for the converter design is the ripple in the inductor currents. A high ripple increases electromagnetic interferences (EMI) and a low ripple can generate an unstable behavior of the system. It is recommended to consider a ripple between 20% and 40% of the inductor average current [10]. In this paper it was considered a ripple of 30%.

The inductors values were calculated considering the upper limit of the voltage at the PV panel output (input for the SEPIC), a duty cycle of 50%, a switching frequency(f_{sw}) of 20 KHz a minimum average current of 0.5 A in the inductors and an efficiency of 90% for the converter. In this way, the resulting current ripple (ΔI_L) and minimum inductors values are given by equations (2) and (3), respectively.

$$\Delta I_L = 30\% \frac{0{,}5}{0{,}9} = 0{,}1667\,A \tag{2}$$

$$L_{1A} = L_{1B} = L_{min} = \frac{V_{in}D}{\Delta I_L f_{sw}} \frac{50(0{,}5)}{0{,}1667(20000)} = 7{,}5\,mH \tag{3}$$

Consequently, each inductor value was established in 10 mH, resulting in a current ripple of 0.125 A. Considering a maximum input current of 10 A, the maximum instantaneous currents by inductors are given by equations (4) and (5) [11], [12].

$$I_{L1A} = \frac{10}{0{,}9} + \frac{0{,}125}{2} = 11{,}174\,A \tag{4}$$

$$iL_{1B} = 10\left(1 + \frac{30\%}{2}\right) = 10(1{,}15) = 11{,}5\,A \tag{5}$$

The resulting maximum instantaneous current by the switch Q_1 is given by 22.674 A (the sum of the maximum instantaneous currents by inductors).

The output capacitor (C_{out}) is calculated for a maximum ripple of 0.5 V as seen in equation (6).

$$C_{out} \geq \frac{I_{out}D}{\Delta V_{rpl} f_{sw}} = \frac{10(0{,}5)}{(0{,}5)20000} = 500\,\mu F \tag{6}$$

The maximum output voltage is 834 V considering a maximum input voltage of 50 V and the maximum duty cycle of 0.94. In this way, the switch Q_1 and the diode D_1 must withstand a maximum voltage of 884 V (Vin+Vout) each one.

Table I presents the resulting components for the SEPIC according to the previous design.

B. Measurement Stage

The measurement of the voltage and current at the PV panel output is performed for each point in the sweep of the duty cycle using the LEM sensors LV25 y LA25, respectively. The sensors provides galvanic isolation between the power and the control stages.

TABLE I. SEPIC COMPONENTS

Component	Name	Value or reference
Inductors	L_{1A}, L_{1B}	10 mH / 10 A
Switching device - IGBT	Q_1	SKM50GB12D for SEMIKRON
Diode	D_1	Four diodes of 650 V / 15 A each one
Input capacitor	C_{in}	2200 µF / 450 V
Coupling capacitor	C_p	2200 µF / 500 V
Output capacitor	C_{out}	560 µF / 400 V
Load resistance	Load	48 Ω / 500 W

The sensors are set to measure voltages between 0-60V and currents between 0-12.5A. The outputs of these sensors correspond to voltages signals between 0-5V, which are the inputs of the control system.

C. Control System

The control system is implemented at Arduino MEGA 2560. This system performs the following tasks:

- Sweep of the duty cycle.
- Generates the PWM signal.
- Acquires the sensors signals by using the Analog to Digital converter (ADC).
- Sends the current and voltage measurements to the computer by serial communication.

The data acquisition is made by using an algorithm in PYTHON. This algorithm is linked with the Arduino code. The algorithm receives the data from the serial port, calculates the operating point of the P-V and I-V curves, graphs the characteristics curves in real-time and generates three files: two images in PNG format that include the P-V and I-V curves and a text file with the information of the operating points (powers, voltages and currents). Furthermore, the user can introduce the irradiance and temperature values for each test.

D. Driver stage

The driver stage is used to provide the suitable levels of voltage and current of the firing pulses for the IGBT (switch Q_1) and the galvanic isolation between the power and control stages. A diagram of this stage is shown in Fig. 5. It is composed of a optocoupler HCPL3120 and the SKYPER 32R form SEMIKRON.

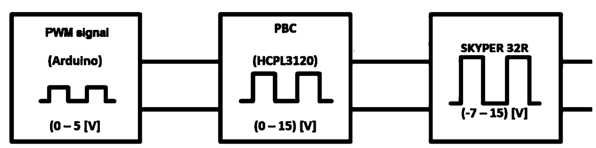

Fig. 5. Driver

E. Power supply

This stage provides the supply signals for the measurement stage, the control system and the driver stage. The supply signals are isolated from the grid by using a transformer with three outputs. This stage is composed by three regulated power supply used to obtain the following output voltages: +15 V, -15 V y +5 V.

IV. ANALYSIS AND RESULTS

The prototype performance was evaluated by simulations in the software PSIM and subsequently by experimental results for the designed and implemented prototype. The results are presented below.

A. *Simulation Results*

The SEPIC topology presented in Fig. 2 was implemented in PSIM taking into account the components shown in Table I. It was considered a KYOCERA KD240GH-2PB solar panel as the input of the prototype. The electrical characteristics for the panel are presented in Table II under standard test conditions (STC): irradiation of 1000 W/m2, AM 1.5 and cell temperature of 25°C.

TABLE II. PV PANEL ELECTRICAL CHARACTERISTICS

Component	Name	Value
Maximum Power	P_{MPP}	240 W
Voltage at the maximum power point	V_{MPP}	29.8 V
Current at the maximum power point	I_{MPP}	8.06 A
Open circuit voltage	V_{OC}	36.9 V
Short circuit current	I_{SC}	8.59 A

The simulation parameters for the IGBT (Semikron SKM50GB12D) are presented in table III.

TABLE III. IGBT SIMULATION PARAMETERS

Variable	Value
Saturation voltage	3.7 V
Transistor resistance	20 mΩ
Diode threshold voltage	2.2 V
Diode resistance	22 mΩ

Simulation results are presented in Fig. 6 to Fig. 9. The characteristic curves, current vs. voltage (I-V) and power vs. voltage (P-V), for an irradiance level of 250 W/m^2 and temperature of 25°C are shown in Fig. 6 and Fig. 7. Uniform irradiance and temperature conditions were assumed in the solar panel surface.

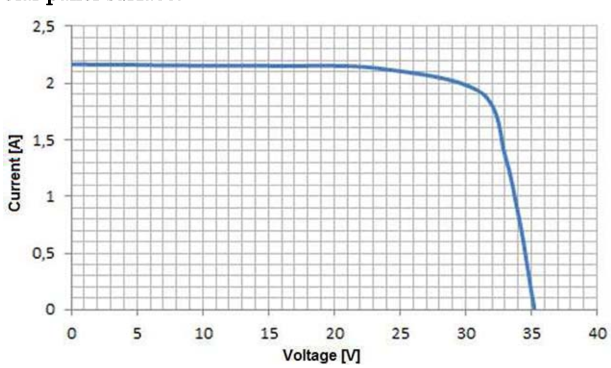

Fig. 6 I vs V curve at 250 W/m^2 and 25°C considering the KYOCERA KD240GH-2PB solar panel

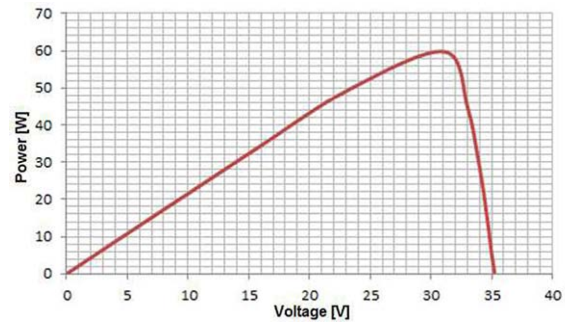

Fig. 7 P vs V curve at 250 W/m^2 and 25°C considering the KYOCERA KD240GH-2PB solar panel

The characteristic curves for an irradiance level of 800 W/m^2 and temperature of 25°C are shown in Fig. 8 and Fig. 9.

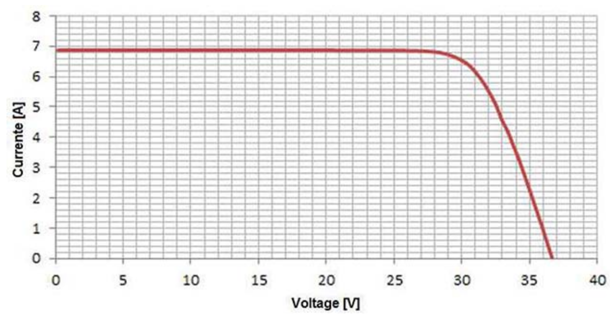

Fig.8 I vs V curve at 800 W/m^2 and 25°C considering the KYOCERA KD240GH-2PB solar panel

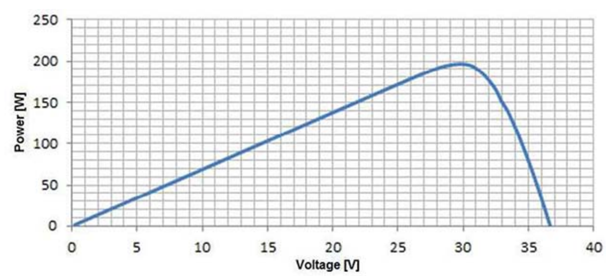

Fig.9 P vs V curve at 800 W/m^2 and 25°C considering the KYOCERA KD240GH-2PB solar panel

As shown in Fig. 6 to Fig. 9, the control strategy and the proposed methodology achieve the goals for different irradiance levels. The variation of the duty cycle in the range from 0 to 0.94 allows the photovoltaic panel to operate in the full range of voltages and currents required to perform the characteristic curves from the operating point VOC (Open Circuit Voltage) until near the operating point ISC (Short Circuit Current).

B. *Experimental Results*

The resulting prototype is presented in Fig. 10. As mention before, it allows the characterization of PV panels up to 500 W.

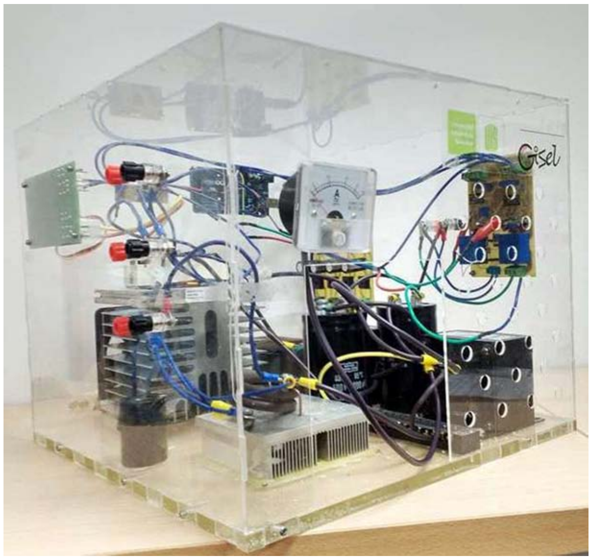

Fig. 10 Experimental prototype.

Experimental test were perform for two types of solar panels, a 240 W KYOCERA KD240GH-2PB solar panel and a 50 W SP50M solar panel. The tests were performed in sunny days with low cloudiness and the duration of each test was about 2 minutes, so the irradiance and temperature levels did not change significantly and it was possible to consider these variables constant.

Fig. 11 and Fig. 12 show the experimental results considering the KYOCERA KD240GH-2PB solar panel. The characteristic curves presented in Fig. 11 were obtained under an irradiance level of around 248 W/m^2 and an environmental temperature of 30°C.

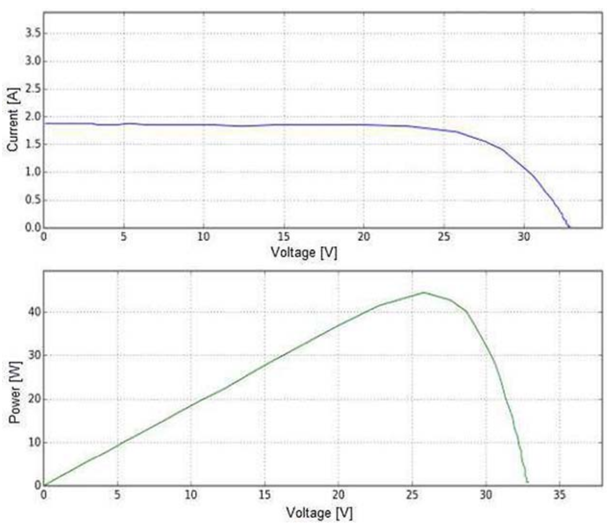

Fig. 11 I vs V and P vs V curves for the KYOCERA panel under 248 W/m^2 and 30°C.

The characteristic curves for an irradiance level of 838 W/m^2 and an environmental temperature of 30°C.

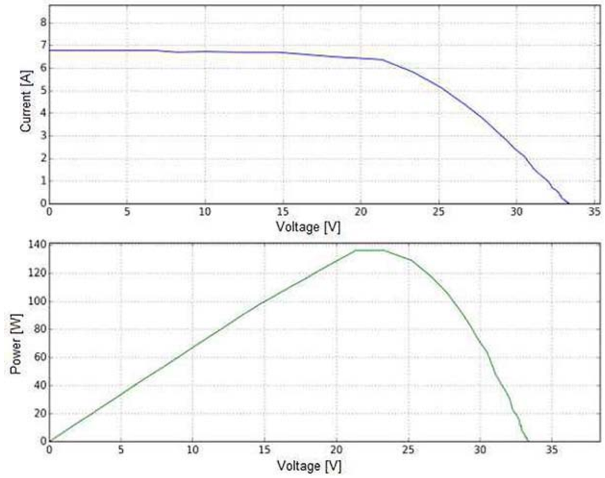

Fig. 12 I vs V and P vs V curves for the KYOCERA panel under 838 W/m^2 and 30°C.

As seen in Fig. 11 and Fig. 12, the short circuit current increases from around 2 A for an irradiance level of 248 W/m^2 to 7 A for an irradiance level of 838 W/m^2. However, the open circuit voltage presents only a little change when the irradiance increases.

Analyzing simulation and experimental results, the short circuit current is similar for both cases when the solar panel is exposed to similar irradiance conditions (results around 250 W/m^2 for Fig. 6, Fig. 7 and Fig. 11 and results around 800 W/m^2 for Fig. 8, Fig. 9 and Fig. 12). However, the open circuit voltage has a drop with a value around 3 V in the experimental results for high irradiance levels. This voltage drop is due to two factors:

- The operation temperature of the solar panel is bigger in the experimental tests.
- Losses in the conductors between the prototype and the place where the PV panels are installed, since the distance between them is approximately 50 m.

The voltage drop reduces the power delivered by the solar panel in the experimental results.

The experimental results for the 50 W SP50M solar panel are presented in Fig 13 for an irradiance level of 814 W/m^2 and environmental temperature of 30 ºC. In this case, the maximum power delivered by the panel is 41.291 W, which corresponds to the power that it should be deliver under the given meteorological conditions.

The experimental results shows the good performance of the prototype for the characterization of solar panel of different rated powers.

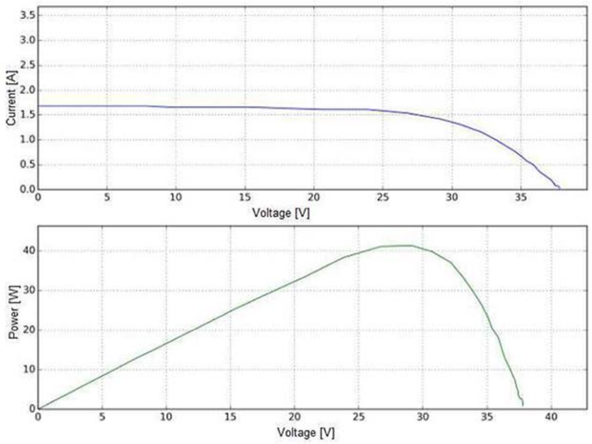

Fig. 132 I vs V and P vs V curves for the SP50M solar panel under 814 W/m^2 and 30°C.

V. Conclusions

This paper presented the design and implementation of a prototype used to obtain the characteristic curves of PV panels. The prototype was built considering a controlled DC-DC SEPIC as its fundamental stage. The buck-boost operation of the SEPIC allows a complete sweep of the PV panel characteristic curves by controlling its duty cycle.

Simulation and experimental results showed the outstanding performance of the prototype for different types of solar panels under various irradiance levels.

It can be highlighted that the resulting prototype graphs the characteristics curves in real-time on a computer and generates three files: two images in PNG format that include the P-V and I-V curves and a text file with the information of the operating points (powers, voltages and currents).

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