DIFFERENT METHODS TO OBTAIN THE *I-V* CURVE OF PV MODULES: A REVIEW

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ABSTRACT

In order to characterize photovoltaic devices a procedure to measure *I-V* curves is required. The main methods used to perform this task are reviewed. It is shown that at least six distinct methods have been reported in the literature with many variations in implementation. A detailed comparison taking into account typical parameters for measuring systems is accomplished**.** This paper could be used as a reference for future work on photovoltaic module characterization.

Keywords: Photovoltaic module measurements, *I-V* curve tracers.

INTRODUCTION

The efficiency of a photovoltaic device is defined as the maximum power generated P_m divided by the product of the input irradiance and its area. This conversion efficiency depends on many factors, such as irradiation and temperature. The manufacture processes usually cause differences in electrical parameters, even in cells of the same type. Moreover, if the losses due to cell connections in a module are taken into account, it is difficult to find two identical photovoltaic modules. Therefore, only the experimental measurement of the *I-V* curve allows us to know with precision the electrical parameters of a photovoltaic device. This measure provides very relevant information for the design, installation and maintenance of PV systems. Given the large number of methods for *I-V* measurement, a survey of them would be very beneficial to researchers in PV systems. We compiled over 26 papers reporting a categorization. The paper concludes with a discussion of the different methods based on their flexibility, fidelity and costs. A table that summarizes the major characteristics of the methods is also provided.

DIFFERENT METHODS

The basic principle to measure the *I-V* curve is based on the control of the current supplied by the photovoltaic module between the zero current point (V_{oc}) to the short circuit point (I_{sc}). There are different methods to perform this task.

A. Variable resistor.

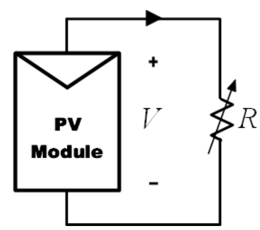

Fig. 1. Variable resistor scheme.

The simplest way to measure the *I-V* curve of a module is to use a variable resistor *R* as it is shown in Fig. 1. The value of *R* will be varied in steps from zero to infinity in order to capture the points of the *I-V* curve from short circuit to open circuit, by measuring the voltage and the current in each step. This method is only applicable to low-power modules since resistors for higher power are hardly available. Load resistors are not recommended for photovoltaic module characterization because I_{sc} is never exactly reached and the reverse bias characteristics cannot be determined. However, the use of load resistors to evaluate the performance of a solar module can provide an inexpensive way of approximating its performance. In [1], the load resistor is increased manually in steps. In each step, the voltage and the current (actually the voltage across a shunt resistor) are sensed using a pair of handed digital multimeter. It is reported in [2] that manual change of the load resistor makes the process very slow, so solar radiation and thermal conditions could be changed during the measurement. The system presented in [3] and [4] employs a set of resistors as load. An array of relays, controlled by a computer card, is used to select the combination of resistors to achieve a specific resistive load. The resistors are chosen to obtain a good spread of points around the "knee" of the curve. Two A/D channels of the computer card are used in order to measure each *I-V* pair. With this approach, manual operation over the resistor is avoided and the acquisition time is improved.

B. Capacitive load.

The second measuring method is based on biasing the module by a large capacitor; which is charged while the former moves from short circuit to open circuit. A schematic circuit using this principle is shown is Fig. 2.

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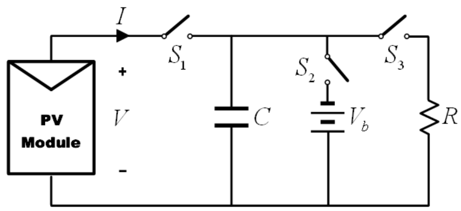

Fig. 2. Capacitive load scheme.

At the beginning of the measurement the capacitor is short-circuited and when the S_3 switch is opened and the S_1 is closed its loading starts. As the charge of the capacitor increases, current drops and voltage rises. When the charge is completed, the current supplied by the module becomes zero and the open circuit condition is achieved. Instead of beginning in short circuit, we could start with S_2 closed, so the capacitor would be initially charged to negative voltage and the *I-V* curve would cross the current axis in order to get I_{sc}. To obtain a reliable *I-V* curve with the capacitor method, high quality capacitors (low Equivalent Series Resistance) with small losses are required. In addition, the three switches must be activated with the appropriate sequence, and the prior discharge of the capacitor is needed to start a new measurement. As the *I-V* curve reproduction is not cyclic, a direct visualization or a partial reproduction of the curve is not possible. In [5], the voltage and current are monitored by means of a computer card. The measurement starts when the card sends a trigger signal to the switch that connects the capacitor to the cell. The authors of [6] describe a portable capacitive load based on insulated gate bipolar transistors (IGBTs), for PV arrays under real operating conditions. The switches are implemented using IGBTs and the capacitor is performed with a parallel arrangement of capacitors and resistors. The author of [2] reports that the capacitor size must be directly proportional to the I_{sc} and indirectly proportional to V_{oc}. Furthermore, the higher the speed of the measuring system, the smaller will be the size of the required capacitor. Accordingly, the paper presents a capacitance calculation chart, which enables selecting the correct capacitance for measuring the *I-V* characteristics by a computerized data acquisition system.

C. Electronic load.

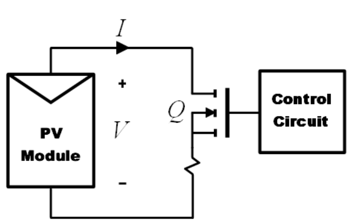

Fig. 3. Electronic load scheme.

The electronic load method (Fig. 3) uses a transistor (usually a MOSFET) as load; the resistance between drain and source is modulated through the gate-source voltage, and consequently the flow of current supplied by the module. When this method is used to trace the *I-V* curve of the module, the MOSFET must operate in its three modes of operation (cut-off, active and ohmic region). As a result, most of the power delivered by the module will have to be dissipated by this device, which limits its application to medium power. In [7], a simple electronic load based on a MOSFET is proposed to achieve the *I-V* curve of panels by quickly scanning the load. Its advantage is the fast variation of the equivalent load resistance of the MOSFET. The linear MOSFET is driven by a low frequency scan signal with a large enough amplitude to cover the complete range of panel characteristic. Several MOSFETs can be operated in parallel to handle higher output current from an array with several PV panels. The output voltage and current are sensed using a potential divider and a sensing resistor respectively. The outputs are fed to an oscilloscope for displaying the curve. I_{sc} and V_{oc} are obtained using two peak detectors and voltage and current signals are multiplied using a multiplier to get the instantaneous power, thus a third peak detector can be used to capture the P_m value. The authors of [8] introduce a system for monitoring the performance of PV solar plants, including *I-V* curves, which are obtained in a short time to prevent cloud interference during outdoor measurements. The electronic load is constituted by several transistors in cascade. By reducing gradually the transistor base current, the PV generator moves from the short-circuit point to the open-circuit voltage status. A data acquisition card with high-speed A/D converter is used for measuring the current and voltage, while the operating point changes. The innovation of this circuit is that the scan of the *I-V* curve is controlled through a current ramp, instead of using a voltage ramp. In [9] is presented a circuit to measure *I-V* curves of PV multi-junction cells (those that have more that one junction in order to capture more photons). An n-channel MOSFET transistor and an operational amplifier are combined to create the voltage controlled current sink. For each current setting a differential amplifier is used to read the voltage across the solar cell, sweeping this one through several points along its characteristic curve. Data gathered for each curve includes solar cell temperature, solar angle and time.

D. Bipolar Power Amplifier.

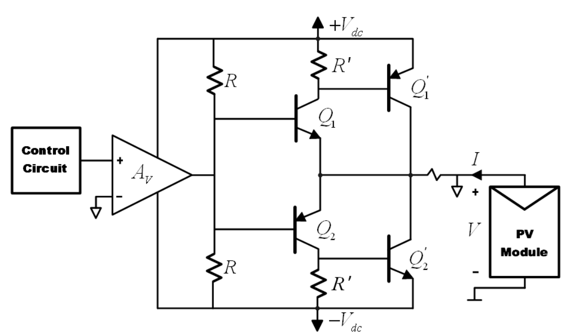

Fig. 4. Bipolar power amplifier scheme.

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This method involves a simple circuit that allows the current and voltage in the module can be reversed, and therefore it is possible to measure the dark *I-V* curves of the module. Its scheme is based on a traditional class-*B* power amplifier (Fig. 4). It uses two BJTs transistors as load, for forward and reverse current respectively. The bipolar transistors must operate in its three modes of operation (cut-off, active and saturation region). As a result, most of the power delivered by the module will have to be dissipated by those devices, which limits its application to medium power. In [10], a PC controlled test setup is presented. It is orientated to measure the *I-V* characteristics of large-area solar cells under an artificial light source, which simulates the solar radiation. The measurement is done in an automated way by employing standard GPIB instruments interfaced to a PC. High test current needed by the large area solar cell is provided by a bipolar power amplifier driven by a function generator, which performs a stepped voltage at its output. An application controls the function generator to start from a minimum bias voltage and step up in increments, until the maximum bias or a maximum safe current value is reached. The voltage and current at each step are sensed taking advantage of the separate voltmeter and ammeter inputs of a digital multimeter. In [5] (also referenced in section II.B), a very similar circuit is presented to bias voltage of a cell, but instead of using a function generator, a D/A card plays the role of control circuit.

E. Four-quadrant power supply.

A four-quadrant power supply is a system capable of delivering as well as dissipating power; in other words, it can source or sink current with bipolar (positive or negative) voltage. It can be used as an adjustable load for other power supplies or other equipment. For a photovoltaic module the main interest is to get the *I-V* curve in the first quadrant. But, the exploration of the points lying in the second and fourth quadrant may be an important diagnostic tool in order to detect possible mismatching in PV module operation; as one or more partially shadowed cell when they are connected in series.

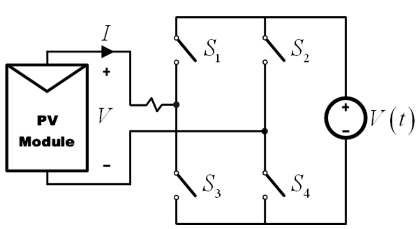

Fig. 5. Four-Quadrant power supply scheme.

A four-quadrant power supply can be seen as a power supply *V(t),* which output can be varied by a reference input signal or programmed to sweep a range of values. The circuit shown in Fig. 5 is a functional view of the four-quadrant power supply. A schematic circuit for a four-quadrant power supply is more complex and is beyond the scope of this review.

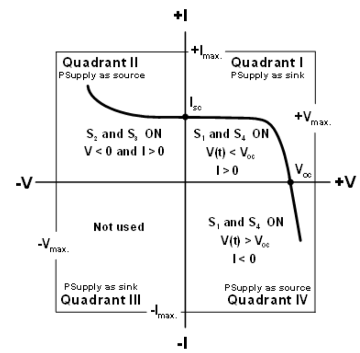

Fig. 6. *I-V* characteristic in 1st, 2nd and 4th quadrant.

With S_1 and S_4 closed and *V(t)* higher than the open circuit voltage of PV module under test, the PV operating point is shifted into the fourth quadrant. With S_1 and S_4 closed and *V(t)* minor than V_{oc}, the PV operating point is shifted into the first quadrant. Finally, if S_2 and S_3 are closed, the PV voltage *V* is forced to *-V(t)* and the PV operating point is shifted into the second quadrant. It is shown in Fig. 6. This type of load is intrinsically expensive. Furthermore, four-quadrant power supplies that work over 1 kW. are hardly available, so this method is not applicable to measure a whole PV generator. In [1], a system to measure *I-V* curves using variable bipolar operational power supply with four-quadrant capability is presented (this paper is also referenced in section II.A) The procedure consists in varying the voltage on the power supply manually in steps. The voltage across the solar cell is measured using a digital multimeter and with another one current is sensed (with the help of a shunt resistor). Also the reverse bias characteristics can be determined. A variable power supply is also useful in rapidly measuring the short-circuit current or the current at a given voltage. The authors of [11] describe a methodology for the determination of *I-V* characteristic curves of photovoltaic modules under diverse conditions. But, in this case, the voltage sweep of the power supply is controlled automatically by a computer. The voltage and current are measured simultaneously by two digital multimeters connected to a computer via GPIB. The computer retrieves the acquired data, and the main electrical parameters are determined. In [12], a concentration photovoltaic cell characterization facility is described. The PV cells are illuminated with a solar parabolic concentrator and a set of shutters allows control the PV cell exposition time obtaining a train of flashes over the cell but using solar radiation. Synchronized with the shutters is a set of instruments that measures the *I-V* curves so all the points of the curve can be found in successive radiation flashes. The sweep is controlled by a waveform generator that is able to generate a pre-programmed analogue voltage ramp that is amplified by the power supply. Two channels (current and voltage) of a power analyzer are used as a high speed and simultaneous data acquisition of the curve. In [13] the curves are also measured using the same principle. The temperature and irradiance of the module are recorded at the beginning and end of each experiment, rejecting curves in which these magnitudes vary significantly. In [14] the voltage of the power supply is controlled by a D/A converter of a computer card. Current is measured as a voltage drop on one of the set of seven resistors, each using separate input of the A/D of the same computer card. The resistors are changed automatically using binary output signals of the card, in function of the current range of the module to measure.

F. DC-DC Converter.

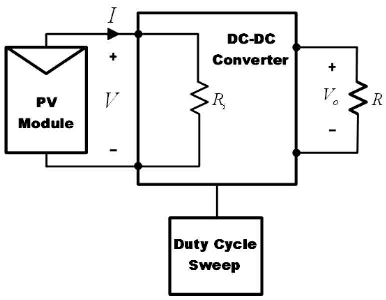

Fig. 7. DC-DC converter scheme.

The ability of DC-DC converters to emulate a resistor has been studied and analyzed in several applications. This property of the DC-DC converters of acting as resistor emulators has been applied to obtain *I-V* curves of solar modules. The three basic converter configurations (Buck converter, Boost converter and Buck-Boost converter) are similar to a DC transformer both in Continuous Conduction Mode (CCM) and in Discontinuous Conduction Mode (DCM). In a dc transformer the relationship of transformation can be controlled electronically by changing the duty cycle of the converter in the range [0,1]. Fig. 7 shows the scheme to characterize a module by means of a DC-DC converter with duty cycle sweep, R_i is the emulated resistor on the terminals of the module. Based on this scheme, in [15]-[16], an automatic system to trace *I-V* curves is proposed. Its methodology, based on the use of different DC-DC converters is presented. In [17], different topologies of DC-DC converters oriented to the measuring of *I-V* curves have been analyzed. Theory demonstrates that Buck-Boost-Derived structures are the only ones that allow a complete sweep of the curve. Buck structures do not allow tracing the points of the curve that are close to I_{sc}, whereas Boost structures cannot reach the points near to V_{oc}. When SEPIC (Single-Ended Primary Inductance Converter) and Cuk structures are used, the reproduction of the *I-V* curve is achieved with less ripple. Experimental results show that these topologies are optimal for this application. A drawback of DC-DC converters is the current ripple by the inductor due to the switching technique (this problem is not present in other methods). Nevertheless, some techniques have been developed to reduce the ripple, such as: coupled inductors [18] and interleaved DC-DC converters [19]. Both papers discuss the use of such techniques to obtain the *I-V* curve of solar modules. In [20], this methodology, which can carry out the complete sweep of the voltage and the current, is applied to analyze and monitor failures in photovoltaic modules. The system proposed is based in automatic generation of *I-V* curves using a System Acquisition Data used also in order to sense temperature and irradiance. Meteorological measurements are very useful in order to analyze the performance of the modules and to detect any failure or anomaly in their operation. In [21], a circuit model to emulate the *I-V* behaviour of a PV field is described. This circuit model is based on a DC-DC Buck converter. The DC-DC converter, suitably driven, can accurately describe the current-voltage characteristic of a PV array. A new solar cell power supply system is presented in [22], in which the Boost type bidirectional DC-DC converter and the simple control circuit are employed with a small monitor solar cell. Also, a power efficiency comparison between the new solar cell power supply system and a conventional one is made theoretically and experimentally. In [23]-[25], a Boost bidirectional DC-DC converter is used in order to measure the actual evolution of the *I-V* characteristic curves of photovoltaic generators. These *I-V* curves are used later to emulate these generators to test photovoltaic inverters. A 15-kW prototype is designed and built. With the proposed device, the optimal configuration and performance of photovoltaic modules and generators, as well as the operation of photovoltaic inverters can be thoroughly analyzed under real atmospheric conditions. A high-performance controllable DC load based in Buck converter with input filter is introduced in [26]. The load features simple structure, low cost and fast response. The load can be used to test and evaluate single fuel cells, fuel cell stacks or solar arrays. The load can be programmed to produce the complete polarization curve of fuel cells and fuel cell stacks, as well as *I-V* characteristic of solar arrays. The programmable dc load can be used to emulate a variable-resistor, variable-current load or variable-power load. The load can also be used to emulate an arbitrary dc load profile. The performance of the proposed controllable dc load has been analyzed and simulated. The limitation of the proposed controllable dc load lies in its inability to emulate active dc loads featuring power reversal, such as variable-speed drives capable of regenerative braking.

DISCUSSION

In order to emphasize the properties of the different methods presented, a detailed comparison is accomplished. The comparison is carried out with the following fundamental parameters for measuring systems:

A. Flexibility.

The flexibility is an important factor of comparison and plays an important role in order to select one the methods. As a result, DC-DC converter allows configuring the speed and direction of the sweep. By modifying the duty cycle, specific zones of the *I-V* curve can be partially reached. It can be operated continuously around the maximum power point of the photovoltaic module under test. With a four-quadrant power supply, a partial reproduction of the *I-V* curve also is possible, but requires a complex programming of *v(t)* signal. The methods based on electronic load also show high flexibility, but the reproduction of points around the MPP requires excessive power dissipation, especially with high-power generators, since the transistors operate in their linear zone. In the capacitive load method, the *I-V* curve reproduction is not cyclic, so a direct visualization or a partial reproduction of the *I-V* curve is not possible.

B. Modularity.

It is very important to allow several configurations. The method based in DC-DC converter allows making an expansion of the system by just connecting DC-DC converter in parallel. Both the capacitive load and the electronic load methods present difficulties when the power of array under test increases. The principal design concern is speed for the first one and power dissipation for the second. In the case of four-quadrant power supply, modularity only is possible with some manufacturers, which provides a way to combine several supplies allowing their control like it would be one supply, meaning a great increase in costs.

C. Fidelity.

It is hard to evaluate which method is more reliable because this feature is largely dependent on the data acquisition system. However, with method based in DC-DC converter, high fidelity is achieved even for a high speed sweep. An exhaustive analysis of the reviewed methods reveals that it is difficult to reproduce the exact point of zero voltage (I_{sc}). Four-quadrant power supply method only needs an interpolation around zero volts. In capacitor method also interpolation can be applied, but only if a prior negative charge is imposed. With variable resistor method and electronic load method only an extrapolation is possible.

D. Fast Response.

A fast response is particularly interesting because it ensures that all points of the curve have been obtained with the same climatic conditions. It is also important the possibility to configure the sweep speed, since that increases the flexibility and reliability of the system.

E. Direct Display.

The direct display provides the opportunity for a quickly first test of the module. But not all methods allow a direct display. *I-V* curve reproduction is not cyclic for variable resistor and capacitive load methods, and therefore, a direct display or a partial reproduction of a curve is not possible.

F. Cost.

Usually a good cost evaluation can be made by knowing what includes the data acquisition system, the analog or digital technique used, whether it requires software and programming, and the number of sensors. Eliminating current and voltage sensors the costs drop considerably. The capacitive load method requires speed of acquisition and memory storage within the instrument, resulting in high cost. Perhaps, the best way to evaluate all methods in terms of cost is taking into account all the previous features as a complete set. Thus, method based in DC-DC converter is less expensive because it is flexible, modular and reliable. Furthermore, it provides high-power density and allows a direct display of the *I-V* curve. Table 1 summarizes the properties for each method. Note that the method based on DC-DC converter exhibits features that makes it preferable in order to measure the *I-V* curve of photovoltaic modules.

CONCLUSIONS

In this paper, several methods to obtain the *I-V* of photovoltaic modules reported in the literature are discussed and analyzed. The results of the discussion and the comparative table should serve as a useful guide to select the most convenient method for a specific PV system.

ACKNOLEDGEMENTS

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	Flexibility	Modularity	Fidelity	Fast Response	Direct Display	Cost
Variable Resistor	Medium	Medium	Medium	Low	No	Low
Capacitive Load	Low	Low	Medium	Low	No	High
Electronic Load	High	High	Medium	Medium	Yes	High
Bipolar Power Amplifier	High	High	High	Medium	Yes	High
4-Quadrant Power Supply	Low	Low	High	High	Yes	High
DC-DC Converter	High	High	High	High	Yes	Low

Table 1. Characteristics of the different methods.

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