

**Methodology for Photovoltaic Modules
Characterization and Shading Effects Analysis**

L. A. Hecktheuer

Centro Federal de Educação Tecnológica de Pelotas

Rua General Netto, 171/403

96015-280 Pelotas, RS. Brazil

laheck@vortex.ufrgs.br

A. Krenzinger

PROMEC/UFRGS, Rua Sarmento Leite, 425 90050-170 Porto Alegre - RS

arno@mecanica.ufrgs.br

C. W. M. Prieb

Laboratório de Energia Solar PROMEC/UFRGS

Rua Sarmento Leite, 425

90050-170 Porto Alegre, RS. Brazil

cprieb@ufrgs.br

This work describes the methodology, basic procedures and instrumental employed by the Solar Energy Laboratory at Universidade Federal do Rio Grande do Sul for the determination of current-voltage characteristic curves of photovoltaic modules. According to this methodology, I-V characteristic curves were acquired for several modules under diverse conditions. The main electrical parameters were determined and the temperature and irradiance influence on photovoltaic modules performance was quantified. It was observed that most of the tested modules presented output power values considerably lower than those specified by the manufacturers. The described hardware allows the testing of modules with open-circuit voltage up to 50 V and short-circuit current up to 8 A.

Keywords: Solar energy, I-V curve tracing, photovoltaic modules

Introduction

Nowadays the electric energy is mostly obtained from hydroelectric, fossil or nuclear plants. In the past decades alternative and renewable energy sources have been deserving a growing interest, firstly due to environmental issues. Considering that traditional energy sources are finite (e.g. petroleum), the costs per generated kWh are expected to be continuously increasing. On the other hand, the dissemination of energy generation plants, together with R & D in system components and processes, pulled the generation costs of alternative energy sources to levels in many cases competitive with traditional sources. The photovoltaic solar energy is an outstanding example of this process. Using an abundant primary source, the photovoltaic cells (associated in photovoltaic modules) convert the radiant energy from the Sun directly to electricity. Originally intended for extra-terrestrial use in satellites and spaceships, photovoltaic systems are today largely used in rural electrification and grid connected systems.

The determination of the current versus voltage curves plays a fundamental role in the analysis of photovoltaic modules electrical performance. In this work, the necessary conditions and basic procedures for the I-V curve determination are established and the methodology used at the Solar Energy Laboratory of Universidade Federal do Rio Grande do Sul is described. Also some I-V curves are shown, from which important observations related to the module and bypass diodes operation are discussed.

The Photovoltaic Cell

A photovoltaic cell transforms the radiant energy from the Sun or other source of light into electricity. It is constituted by a semiconductor, usually silicon, purified to a very high degree. For each free electron of the crystal there is an incomplete bond between the atoms. This area with missing electrons is called "hole". If in this semiconductor is introduced a small fraction of atoms with five valence electrons, the semiconductor conductivity will increase drastically. On the other hand, if a same fraction of trivalent atoms is introduced, the number of holes will increase at the same rate.

The region of the semiconductor crystal doped with pentavalent atoms, such as phosphorus, is denominated type N and the region doped with trivalent atoms, such as boron, is called type P. Through the interface there will be a diffusion of electrons from region N to P and a diffusion of holes from region P to N, establishing an electric field in the opposite direction of this natural diffusion. In balance, the current through the interface (junction) is null. When light reaches this PN junction, some electrons absorb the energy of the photons, forming pairs of electrons-holes. The free electrons from area P are dislocated to area N and the holes from area N migrate to area P due to the electric field at the junction. This electrons and holes displacement establishes a difference of potential on the terminals of the device. If the terminals are connected through a conductor, a "photocurrent" will flow as long as the light reaches the junction.

Photovoltaic Cell Electrical Equivalent Circuit

The equivalent circuit of a photovoltaic cell is shown in [Fig. 1](#). The current source represents the photocurrent (I_L), generated at the junction region by the photons with energy enough to produce pairs of electrons-holes; the diode represents the PN junction with reverse saturation current (I_0); Joule losses and leakage currents are represented by the currents through the series resistance (R_S) and the shunt resistance (R_P) respectively.

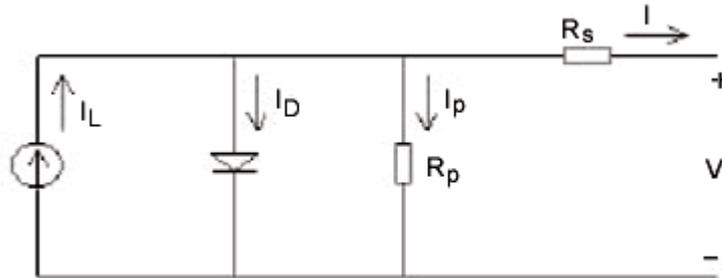


Figure 1. Equivalent circuit of a photovoltaic cell.

When the first Kirchoff law is applied to one of the nodes of the equivalent circuit, the current supplied by a cell, at a specified temperature, is given by:

$$I = I_L - I_D - I_P = I_L - I_0 \left\{ \exp \left[\frac{e(V + IR_S)}{NmKT_{cel}} \right] - 1 \right\} - \frac{V + IR_S}{R_P} \quad (1)$$

Where

I is the output current

I_L is the photocurrent

I_D is the diode current

I_P is the leakage current

I_0 is the reverse saturation current

N is the number of cells associated in series

m is the diode ideality factor, which lies between 1 and 2 for

monocrystalline silicon

K is the Boltzman constant

T_{cel} is the cell temperature

e is the electron charge

V is the terminal voltage

R_S is the series resistance

R_P is the shunt resistance

If an association of cells (photovoltaic modules) the case, N is the number of cells associated in series. Most of the photovoltaic modules available in the market are constituted by 30 to 36 cells.

Three points of the curve should be highlighted:

- a) open-circuit: this point is obtained when the terminals of the module are disconnected. The module presents a voltage called "open-circuit voltage" V_{OC} ;
- b) short-circuit: the terminals of the module are connected with an ideal conductor, through which flows a current called "short-circuit current" (I_{SC}). In this situation, the voltage between module terminals is zero;
- c) maximum-power: point where the voltage versus current product is maximum.

[Figure 2](#) shows a generic characteristic curve. It can be observed that, from the short circuit, the current presents a slightly descending behavior until it reaches to an "elbow" from where it decreases quickly down to zero.

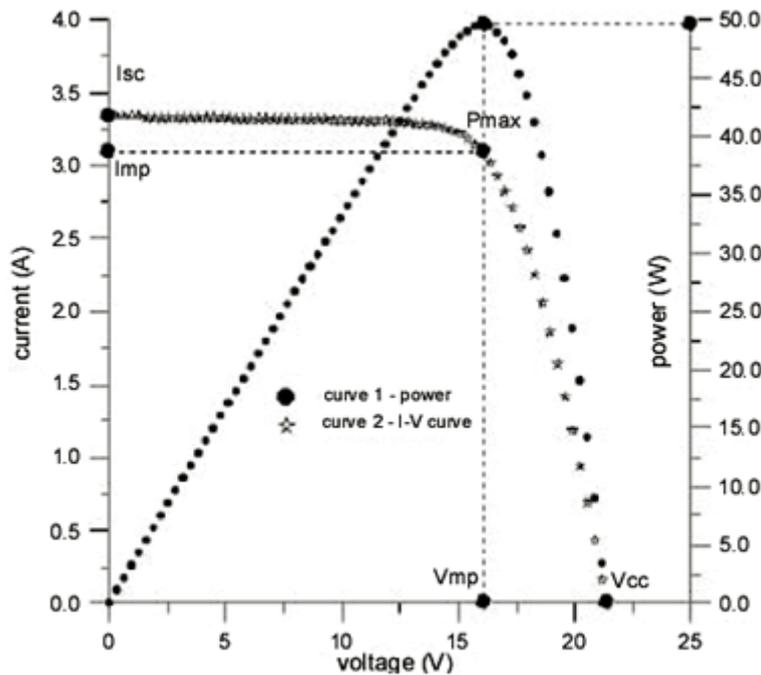


Figure 2. Characteristic curve of a photovoltaic module.

Standard Conditions for the Determination of Photovoltaic Modules I-V Curves

The amount of solar energy transformed into electric energy by a photovoltaic module depends on the irradiance, the spectral distribution and the cells temperature. For

establishing a base of comparison between different modules, the following values were internationally adopted as standard for the I-V curve determination:

Irradiance = 1000 W/m²

Temperature of the cells = 25 °C

Spectral distribution = AM 1.5 (air mass 1.5)

The air mass index is the relative thickness of the atmosphere, i. e., the radiation path length through the atmosphere considering the zenith path at sea level as unity. AM 1.5 is obtained when the angle formed by the zenith and the line of sight to the Sun is about 48°.

Nevertheless, while in operation the modules are normally not under standard condition. So another condition was defined, named "normal operation condition", which presents the following values:

Irradiance = 800 W/m²

Ambient temperature = 20 °C

Wind speed = 1 m/s

Spectral distribution = AM 1.5

In this case the temperature of the photovoltaic cells will depend on the ambient temperature, speed of the wind and the module thermal performance.

Terrestrial spectral distribution tables of irradiance on normal surfaces and surfaces with inclination of 37°, for AM 1.5, are presented in ASTM (1987a) and ASTM (1987b) respectively.

Correction Of I-V Curves in Function of Irradiance and Temperature

When the determination of a module characteristic curve is performed outdoors, most of the times the module is not likely to be under standard conditions. Therefore, the test is taken under any condition that satisfies the standards minimum requirements and the collected points of the I-V curve are mathematically translated to the standard conditions.

The short-circuit current of monocrystalline silicon modules is proportional to the solar irradiance and increases slightly with increasing the photovoltaic cell temperature. The open-circuit voltage increases logarithmically with increasing the solar irradiance and decreases linearly with increasing cell temperature. The following equations allow the correction of the short-circuit current, open-circuit voltage and all pairs of current and voltage between the points of short-circuit and open-circuit, according to ASTM (1985) and ABNT (1991).

The correction of the short-circuit current to the standard condition is made through Eq. (2):

$$I_{SC(STD)} = \frac{G_{STD}}{G} I_{SC(measured)} + \alpha(T_{STD} - T_{cel}) \quad (2)$$

where

$I_{SC(STD)}$ it is the short-circuit current of the module at the standard condition

G_{STD} is the standard irradiance = 1000 W/m²

G is the solar irradiance on the surface of the module

$I_{SC(measured)}$ is the measured short-circuit current of the module

T_{STD} is the standard cell temperature = 25 °C

α is the temperature coefficient of the short-circuit current of a PV cell ($6 \times 10^{-5} \times I_{SC}/^{\circ}\text{C}$ typical for crystalline silicon cells).

The correction of the open-circuit voltage is performed according to Eq. (3):

$$V_{OC(STD)} = V_{OC(measured)} + N\beta(T_{STD} - T_{cel}) + N \frac{mKT_{cel}}{e} \ln\left(\frac{G_{STD}}{G}\right) \quad (3)$$

where

$V_{OC(STD)}$ is the open-circuit voltage of the module in the standard condition

$V_{OC(measured)}$ is the measured open-circuit voltage of the module

β is the temperature coefficient of the open-circuit voltage of a PV cell (-2.3 mV/°C typical for crystalline silicon cells).

In order to estimate the efficiency of photovoltaic modules, besides the short-circuit current and open-circuit voltage at the standard condition, also the values of the current and voltage pairs close to the point of maximum-power must be known. The points along the characteristic curve are corrected to the standard condition through Eq. (4) and Eq. (5), again in accordance with ASTM (1985) and ABNT (1991).

$$I_{(STD)} = I_{(measured)} + I_{SC(measured)} \left(\frac{G_{STD}}{G} - 1 \right) + \alpha(T_{STD} - T_{cel}) \quad (4)$$

where

$I_{(STD)}$ is the current of the module at standard condition

$I_{(measured)}$ is the measured module current

and

$$V_{(STD)} = V_{(measured)} + \beta(T_{STD} - T_{cel}) - F_{CC}I_{(STD)}(T_{STD} - T_{cel}) - R_S(I_{(STD)} - I_{(measured)}) \quad (5)$$

where

$V_{(STD)}$ is the voltage of the module in the standard condition

$V_{(measured)}$ is the measured voltage of the module

F_{CC} is the curve correction factor

R_S is the series resistance of the module.

Equation (5) corrects the voltage and introduces a term that takes into account the module series resistance. The "curve correction factor" (F_{CC}), was also inserted and affects more the points in the region of maximum-power. A typical value of F_{CC} for monocrystalline silicon cells is $1.25 \text{ m}\Omega / ^\circ\text{C}$.

Test Standards and Required Accuracy of the Instrumental for I-V Curve Tracing

The I-V curve determination of photovoltaic modules is regulated by a number of standards, which establish the minimum conditions for their electrical performance evaluation, allowing the comparison between different modules.

The module under test and the reference cell used to sense the irradiance must have similar spectral responses and must be on the same plane (with a maximum deviation of $\pm 2^\circ$). The incident radiation must be normal to the module surface, with a maximum deviation of $\pm 10^\circ$.

The irradiance, measured from the reference cell short-circuit current, must remain higher than 700 W/m^2 during the five minutes that precede the test and not vary more than 1 % while the test is being performed. The reference cell current must be measured with an accuracy better than $\pm 0.5 \%$ of its short-circuit current at 1000 W/m^2 .

The reference cell and the module must be at the same temperature and in thermal equilibrium. During the I-V curve tracing the module temperature must not vary more than $\pm 2^\circ\text{C}$ and must be measured with an accuracy of $\pm 1^\circ\text{C}$.

The module voltage and current measurement must be independent, with separated wires for voltage and current, in order to avoid errors due to voltage drops. Voltage and current must be measured with maximum errors of $\pm 0.1 \%$ and $\pm 0.5 \%$ respectively.

The power supply used to bias the module must be capable to deliver a voltage that runs from V_{OC} to a value negative enough to compensate the voltage drops due to shunt resistor and wires resistance.

One can notice that the standards minimum requirements in terms of accuracy can be considered quite flexible in certain situations. Due to the plenty of high quality

instruments available nowadays, current and voltage can be easily measured with tighter accuracys than those required by standards.

Refrigerated Display Case Used to Control Photovoltaic Modules Temperature

The temperature of the photovoltaic module must be kept constant and uniform during the I-V curve tracing. When the module is exposed to the solar radiation its temperature tends to increase and stabilize, most of the times, at unwanted temperatures.

A refrigerating device, adapted from a refrigerated display case, was developed in order to control the temperature of the module under test. This equipment, provided with a 1/3 HP compressor, has the evaporator located at the back side of the chamber. The deck is slightly downward tilted, favoring the air flow towards the front side. The lateral walls are internally insulated with expanded polystyrene. The front cover is a transparent flat glass and the back side is closed with a plastic curtain.

A removable opaque shield covers the whole display, avoiding the incidence of radiation on the module before the test. This shield is removed just before the I-V curve tracing. Such procedure reduces to a minimum the differences of temperature due to electrical mismatching between module cells. The chamber has room for modules with dimensions up to 1.2 m long and 0.5 m wide.

[Figure 3](#) shows the refrigerated display with a photovoltaic module inside.

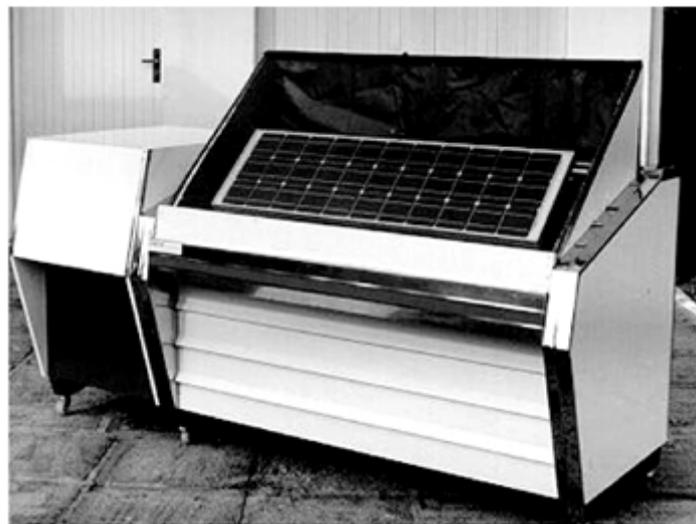


Figure 3. Refrigerated display case used to control the module.

Ten mini fans were installed close to the evaporator, carefully distributed in order to improve the temperature uniformity of the air inside the chamber. In [Fig. 4](#) is shown a detail of these fans.



Figure 4. Fans placed close to the evaporator.

Procedure Used for I-V Curves Tracing

The Solar Energy Laboratory of Universidade Federal do Rio Grande do Sul performs the photovoltaic modules I-V curves determination tests under natural solar radiation. The tests are to be taken in clear sky days in order to get the irradiance and spectral distribution values as close as possible to the standard condition.

The refrigerated display with the module inside is placed outdoors, in a suitable positioning in relation to the sunlight and covered by the opaque shield. If the ambient air is warm to a point that is not possible to have the module at the desired temperature with just ventilation, the refrigerating unit is turned on. The module under test and the reference cell are then slowly cooled until they reach the expected temperature. At this moment the shield is removed and the module is submitted to a voltage sweep controlled by a bipolar power supply, ranging from the short-circuit to the open-circuit while current-voltage pairs, which constitute the points of the curve, are registered.

The module temperature is sensed by a thermocouple. This sensor is attached to the back face of the module in such a way that a good thermal contact is assured. When inside the chamber, the non-uniformity of temperature between module cells, measured with an infrared non-contact thermometer, was observed to be no more than $\pm 2\text{ }^{\circ}\text{C}$.

The Solar Energy Laboratory at UFRGS tested 13 modules and most of them presented maximum power lower than that specified by the manufacturer. [Table 2](#) shows the main electrical parameters obtained from their respective measured I-V curves.

Table 1. Characteristics of a specific photovoltaic module.

	I_{SC} (A)	I_{MP} (A)	V_{OC} (V)	V_{MP} (V)	P_{MAX} (W)	FF (%)	η (%)
Nominal	3.35	3.15	18.0	14.6	46	76.3	12.9
Measured	3.2	2.9	17.4	13.6	39.4	70.8	11.1

Table 2. Measured versus nominal power.

Module	1	2	3	4	5	6	7	8	9	10	11	12	13
P_{rated} (W)	65	65	50	50	50	50	48	46	46	90	90	57	57
$P_{measured}$ (W)	66.1	62.5	48.6	48.4	48.6	46.3	46.1	41.7	39.4	77.9	80.3	54.6	55.6

The current flowing through the photovoltaic module is measured from the voltage drop across a calibrated shunt resistor. The module voltage is measured directly from its terminals. The module voltage, module and the reference cell shunt resistors voltages are measured simultaneously by three digital multimeters, connected to a computer via GPIB (IEEE-488). The thermocouple voltage is sensed by an internally thermal compensated measuring device. The employed power source has an output ranging from -50 V to $+50$ V and can drain up to 8 A.

[Figure 5](#) presents a schematic diagram of the system used to acquire the I-V curves.

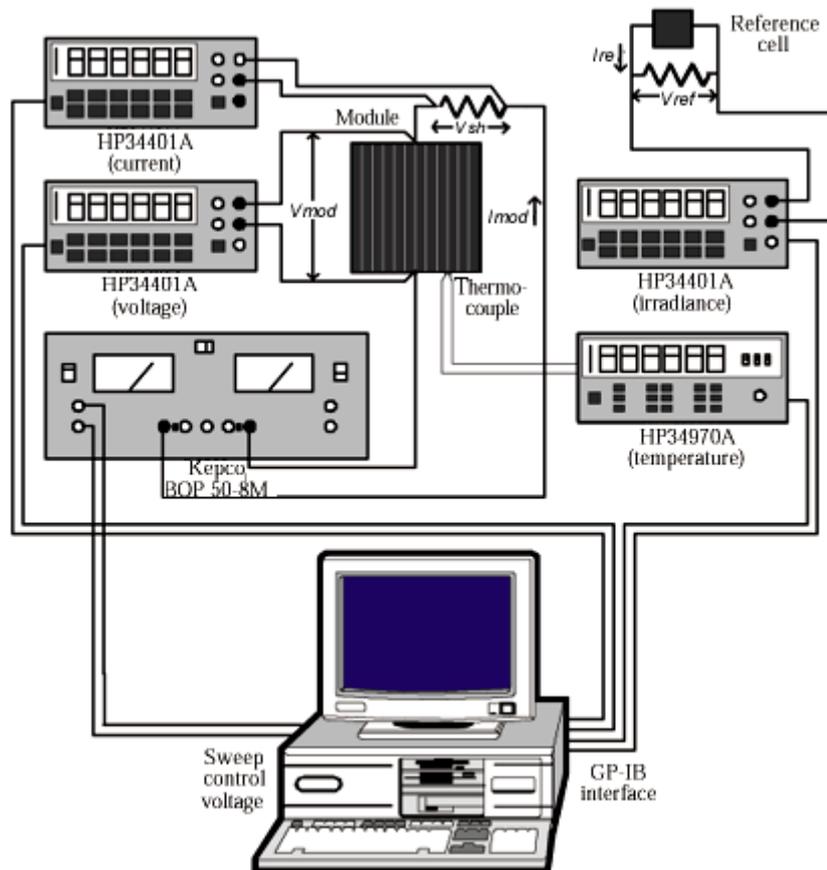


Figure 5. Schematic diagram of the I-V curve tracing system.

The computer, together with a specially developed software, also controls the voltage sweep used to bias the module and stores the acquired data. About 500 points of the I-V curve are registered in a period of 1.8 seconds.

Experimental Results

In order to validate the methodology here described, the I-V curve of a reference module was determined at the Solar Energy Laboratory of Universidade Federal do Rio Grande do Sul. This reference module was previously calibrated at CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Spain). The differences in power found when comparing both curves were smaller than 1 %.

Some results of the behavior of photovoltaic modules will be presented, observed from the characteristic curves measured according to the procedures described before.

In the first row of [Tab. 1](#) are stated the nominal characteristics of a specific module, as specified by the manufacturer. Below are the corresponding experimental results. It can be observed that the measured maximum power is about 85 % of that specified by the manufacturer, not being even in between the limits allowed by the standards (± 10 %).

As mentioned before, the short-circuit current varies proportionally to the incident irradiance, while the open-circuit voltage varies very little for high irradiance values. [Figure 6](#) shows two I-V curves from the same photovoltaic module at different radiation values. The open-circuit voltage remained virtually the same because the curves were traced at the same temperature.

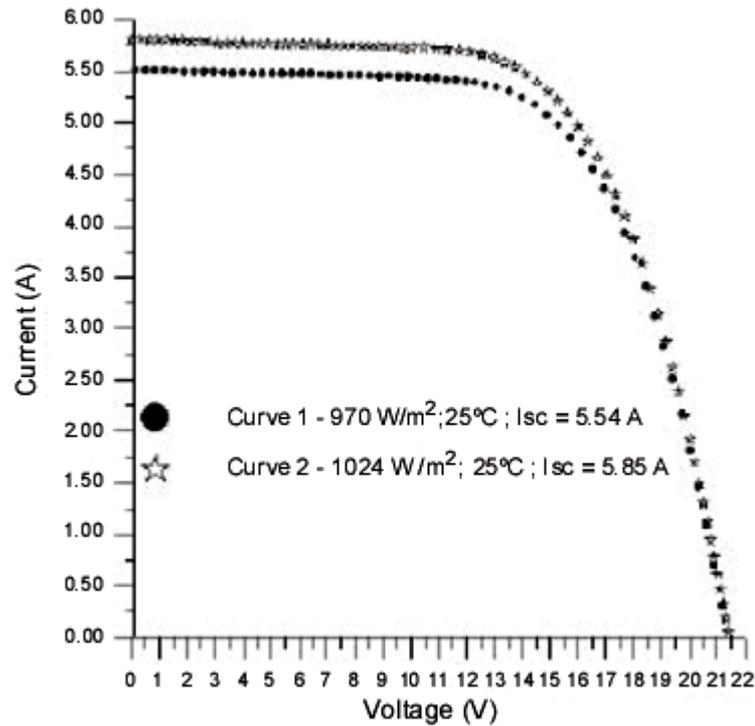


Figure 6. I-V curves of a photovoltaic module at different radiation values and constant temperature.

The variation of the open-circuit voltage in function of the temperature can be observed in [Fig. 7](#), which presents two I V curves of a module at different temperatures and with constant irradiance of 960 W/m². As the temperature raises, the open-circuit voltage decreases with a slight increase of the short-circuit current.

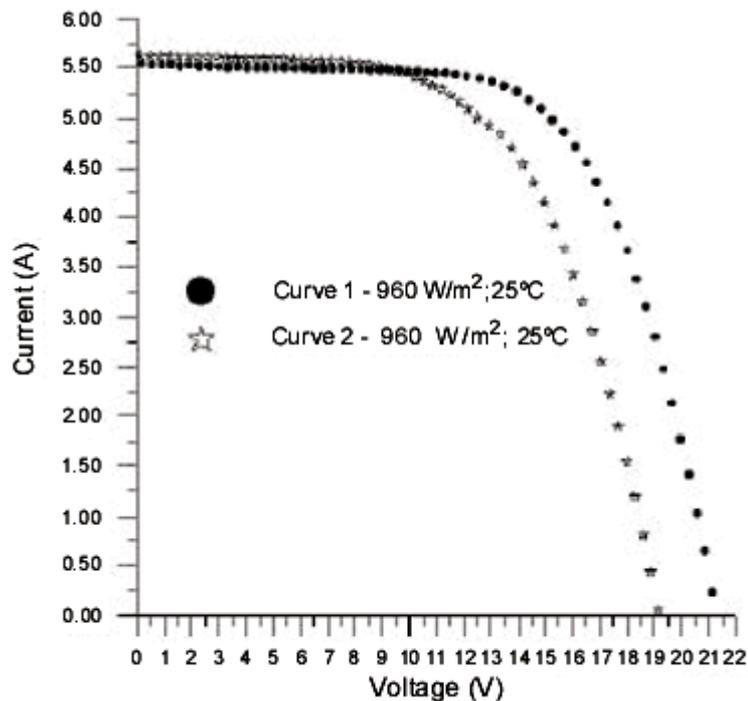


Figure 7. I-V curves of a photovoltaic module at different temperatures and constant radiation.

Shading Effects on Photovoltaic Modules

If all the cells in a module were identical, the resultant I-V curve would be very easy to determine by summing the voltages for serial connected cells and summing the currents for parallel connected cells. Under real situations, if the cells are slightly different from each other or are not uniformly illuminated, the resultant behavior is not easily predictable anymore and depends on a complex combination of the actual electrical behavior of each cell. Several papers presented mathematical models in order to calculate the effect of non identical cells in a module (e.g. Bishof, 1988 and Quashning and Hanitsch, 1996) and the causes of distorted characteristic curves are well known. In this section will be discussed some particularities that occur when photovoltaic modules are partially shaded and how different bypass diodes arrangements affect the I V curves of modules in such conditions, from an experimental point of view.

Most photovoltaic modules comes with bypass diodes connected according to [Fig. 8](#), with the purpose of protecting the module from high reverse voltages that could produce hot spots and consequent deterioration of the module. In addition to this, the diodes help to avoid a significant decrease of the curve factor when the module is a partially shaded. With interlaced diodes, the maximum reverse voltage is approximately 1/3 of the voltage of the module plus 1.4 V and with non-interlaced diodes is about 1.4 V.

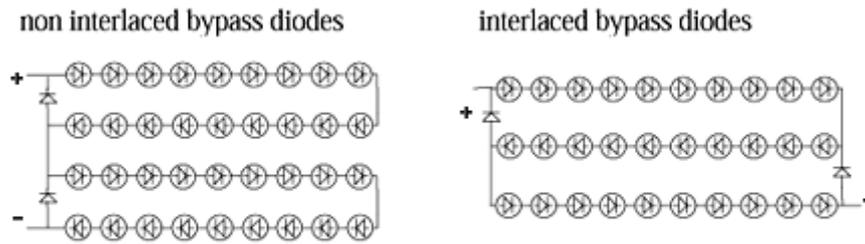


Figure 8. Bypass diodes connection schemes.

Modules with 30 or 33 cells (three columns of cells connected in series) normally have interlaced bypass diodes, while modules with 36 cells (four columns of cells connected in series) present non interlaced diodes. In these modules voltages of 12 V or 6 V are available. In modules with interlaced bypass diodes only one voltage, usually 12 V, is available.

In [Fig. 9](#) is represented the I-V curve of a module with non interlaced diodes, under different conditions of shading, while [Fig. 10](#) presents a curve of a module with interlaced diodes.

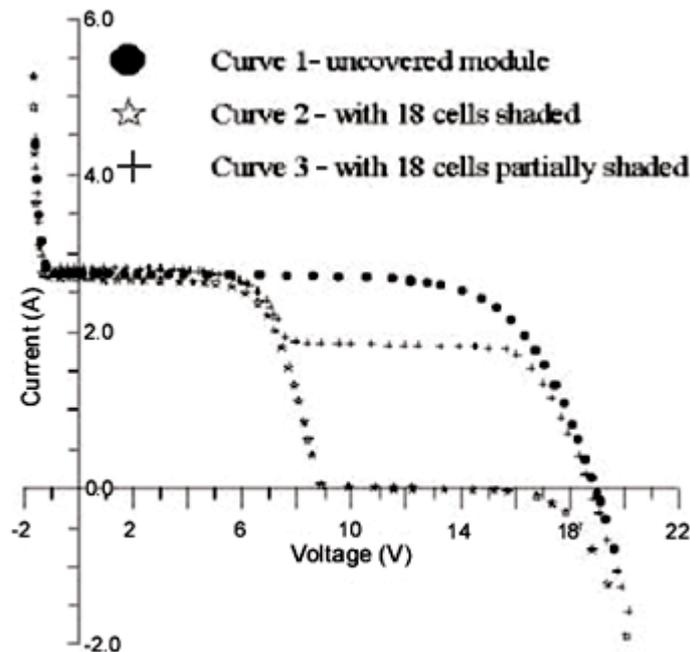


Figure 9. I-V curve of a photovoltaic module with non interlaced bypass diodes.

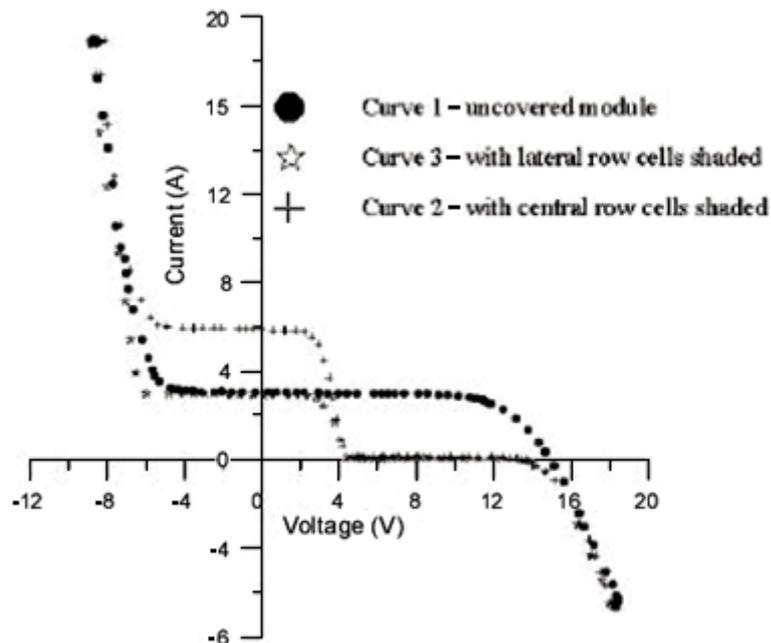


Figure 10. I-V curves of a photovoltaic module with interlaced bypass diodes for an irradiance of 930 W/m² and constant temperature of 67.4 °C.

The connection of the bypass diodes in a conventional way (non interlaced), where each diode is connected in parallel with only a group of cells, limits the operating reverse voltage of the module, not allowing the cells to individually dissipate excessive amounts of power.

When a cell (or group of cells) of a module is partially shaded, a fraction of the current will circulate through the group of the shaded cell(s), proportionally to the extent of shading, and the rest of the current will flow through the bypass diode. Thus through the group of non shaded cells circulates the sum of the two currents above mentioned. In the case of total shadowing of a cell, the total current that circulates through the remaining cells will also circulate through the bypass diode, causing a voltage drop of approximately 0.7 V.

In the case of modules with interlaced diodes, where each diode is connected in parallel with two groups of cells connected in series, the shading of a cell can lead to two different situations depending on to which column belongs the shaded cell. When a central column cell is totally shaded, the module behaves as if it had two groups of cells connected in parallel. In this situation, the short-circuit current doubles, with a consequent reduction of the open-circuit voltage. That does not occur if the shaded cell is in one of the lateral branches. It is interesting to point out that, when the analysis of systems in operation, the effects of partial shading on the central branch can lead to mistaken power evaluations. An unaware technician who simply read the short-circuit current and open-circuit voltage would not realize that dust or dirt on the module could be modifying the module curve form factor and causing a false current (and power) increment.

With interlaced diodes, when there is a total shading of a cell, the open-circuit voltage is reduced to less than 1/3 of the non-shaded open-circuit voltage (equivalent voltage of a

group of cells in series minus the voltage drop on a bypass diode). Using non-interlaced diodes, this voltage is reduced to almost half of the original non-shaded.

Conclusions

The facilities of the Solar Energy Laboratory at UFRGS are equipped with the sufficient instrumental for the I-V curve determination of photovoltaic modules. Among its features is the described refrigerated display case, which assures a constant and uniform temperature to the module under test. The module is biased by a bipolar voltage source with an automatic voltage sweep, controlled by a computer, which also controls the multimeters and registers the acquired data. The described methodology was validated by comparing the I-V curves of a reference module.

The characteristic curves of the modules were also analyzed under operation in the second quadrant (positive current and negative voltage). The modules with interlaced bypass diodes limited the reverse voltage to approximately 1.4 V plus 1/3 of the voltage of the module, while those with non interlaced bypass diodes presented limit reverse voltage about 1.4 V.

Thirteen photovoltaic modules were characterized with this system under several conditions. From the obtained I-V curves was evaluated the influence of temperature and irradiance in the modules performance. It was also observed that most of tested modules presented maximum power lower than that specified by the manufacturer.

References

American Society for Testing and Materials, 1985, "Standard Methods of Testing Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells: E 1036", Philadelphia, 10 p. [[Links](#)]

American Society for Testing and Materials, 1983, "Standard Practice for Determination of the Spectral Mismatch Parameter Between a Photovoltaic Device and a Photovoltaic Reference Cell: E 973", Philadelphia, 3 p. [[Links](#)]

American Society for Testing and Materials, 1987a, "Standard Tables for Terrestrial Direct Normal Solar Spectral Irradiance for Air Mass 1.5: E 891", Philadelphia, 6 p. [[Links](#)]

American Society for Testing and Materials, 1987b, "Standard Tables for Terrestrial Solar Spectral Irradiance at Air Mass 1.5 for a 37° Tilted Surface: E 892", Philadelphia, 8 p. [[Links](#)]

Associação Brasileira de Normas Técnicas, 1991, "Dispositivos fotovoltaicos – Correção das curvas características corrente versus tensão (IxV), em função da temperatura e radiação: NB-1386", Rio de Janeiro, 3 p. [[Links](#)]

Bishop, J. W., 1988, "Computer simulation of the effects of electrical mismatches in photovoltaic cell interconnection circuits", Solar Cells, Vol. 25, pp. 73-89. [[Links](#)]

Quashning V. and Hanitsch R Solar Energy, 1996, "Numerical simulation of current-voltage characteristics of photovoltaic systems with shaded solar cells", Solar Energy, Vol. 56, No 6, pp. 513-520. [[Links](#)]

Manuscript received: September 2000, Technical Editor: Atila P. Silva Freire

All the content of the journal, except where otherwise noted, is licensed under a Creative Commons License

ABCM

Av. Rio Branco, 124 - 14. Andar
20040-001 Rio de Janeiro RJ - Brazil
Tel. : (55 21) 2221-0438
Fax.: (55 21) 2509-7128

 e-Mail

abcm@domain.com.br