ISESCO JOURNAL of Science and Technology

Volume 11 - Number 19 - May 2015 (66-71)

Practical Identification of Photovoltaic Module Parameters

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Abstract

The amount of energy radiated to the earth by the sun exceeds the annual energy requirement of the world population. Making use of this inexhaustible energy source for our everyday electricity requirement is the great challenge of the present and the future. The generation of electric energy from the sun via photovoltaic (PV) generation is one of the most eligible candidates in this regard. For PV applications, the accurate simulation of the PV module performance, which is an important point in the accurate design of these systems, depends mainly on the electrical parameters of the PV module (series resistance, reverse saturation current, short circuit current temperature coefficient, and ideality factor). Also, knowledge of the effect of ageing on the PV module's performance after a certain period requires an accurate identification of these parameters. This paper presents accurate methods to obtain the PV module electrical parameters through practical measurements for its current-voltage (I-V) characteristics under different operating conditions (different solar radiation intensity and module temperature) using an accurate data acquisition system. The paper then compares the theoretical performance of the PV module using the identified parameters with the measured curves to work out the accurate determination of the PV module parameters.

Keywords: *PV module Parameters, PV Measurements, Photovoltaic Simulation.*

1. Introduction

The strong demand for alternatives to fossil fuel-based energy sources and growing environmental concerns have boosted interest in solar (photovoltaic, PV) cells as a long-term, exhaustless, environmentally friendly and reliable energy technology. Continuous efforts to develop various types of solar cells are being made in order to produce solar cells with improved efficiencies at a lower cost, thereby taking advantage of the vast amounts of free energy available from the sun. Due to the rising costs of conventional energy and its limited supply, PV energy has become a promising energy for the future in the world [1]. The PV system is a generating system using the photoelectric effect which changes the light energy into electric energy. And the performance of the PV system is dependent upon radiation and temperature [2].

Most solar cell parameters can be obtained from simple current-voltage (I-V) measurements. ***Figure 1*** shows the I-V characteristics of a typical solar cell under forward bias and illumination. The short circuit current (I_{sc}) is the current through the solar cell when the voltage across the solar cell is zero. The open circuit voltage (V_{oc}) is the voltage across the solar cell when the current through the solar cell is zero and it is the maximum voltage available from the solar cell. The

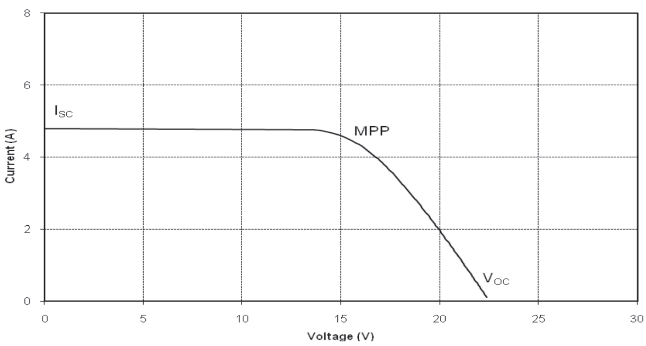

Figure 1. *I-V characteristics of a typical solar cell.*

maximum power point (MPP) is the condition under which the solar cell generates its maximum power (P_{max}); the current and voltage in this condition are defined as I_{max} and V_{max}, respectively. The fill factor (FF) and the conversion efficiency (η) are metrics used to characterize the performance of the solar cell. The fill factor is defined as the ratio of P_{max} divided by the product of V_{oc} and I_{sc}. The conversion efficiency is defined as the ratio of P_{max} to the product of the input light irradiance and the solar cell surface area. Therefore, it is of prime importance to measure the I–V characteristics with high accuracy under natural environmental conditions [3].

The equivalent circuit used to model the DC behavior of a typical solar cell is shown in ***Figure 2***. The equivalent circuit, which describes the static behavior of the solar cell, is commonly composed of a current source, a pn junction diode and a shunt resistor (R_{sh}) in parallel along with a series resistor (R_s). The current source models electron injection from light. R_s is the total Ohmic

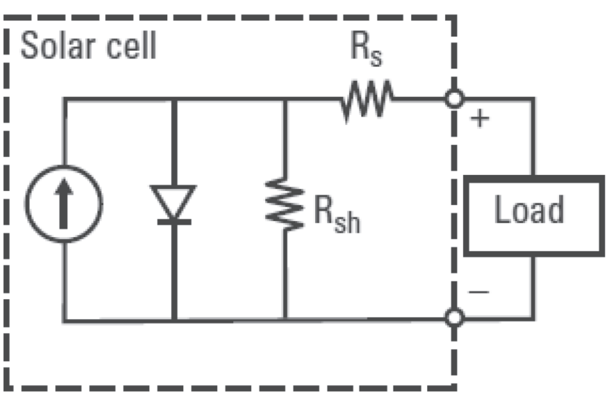

Figure 2. *Equivalent circuit of a typical solar cell.*

resistance of the solar cell, which is essentially the bulk resistance. Smaller R_s values equate to increased solar cell efficiencies. R_{sh} accounts for stray currents such as recombination currents and leakage currents around the edge of the devices. In this case a larger Rsh value equates to increased solar cell efficiency since it means that the stray currents are reduced.

From the equivalent circuit of the typical solar cell, we can write the cell current as follows:

$$I_c = I_{ph} - I_d - I_{sh} \tag{1}$$

$$I_{sh} = \frac{V_c + I_c R_s}{R_{sh}} \tag{2}$$

Since the shunt resistance of the PV cell is much greater than its series resistance, the current I_{sh} becomes much smaller compared to the other currents in the cell. Therefore, this current will be neglected as it will not cause a large error in the PV cell simulation model [4]. Then, equation (1) can be written as follows:

$$I_c = I_{ph} - I_d \tag{3}$$

And, I–V characteristics of a PV cell can be expressed in terms of the cell current and voltage as follows [5]:

$$I_c = I_{ph} - I_o \left\{ e^{\left[\frac{q}{AKT}(V_c + I_c R_s)\right]} - 1 \right\} \tag{4}$$

$$V_c = \frac{AKT}{q} \ln\left(\frac{I_{ph} + I_o - I_c}{I_o} \right) - I_c R_s \tag{5}$$

The PV cell photoelectric current and reverse saturation current will be calculated respectively using the following equations [6]:

$$I_{ph} = \left[I_{scr} + K_i (T - 298) \right] \frac{G}{1000} \tag{6}$$

$$I_o = I_{or} \left(\frac{T}{T_r} \right)^3 e^{\left[\frac{qE_{Go}}{AK} \left(\frac{1}{T_r} - \frac{1}{T} \right) \right]} \tag{7}$$

Since the photovoltaic module consists of series of connected solar cells, the I-V characteristics of the whole module can be derived by scaling the characteristics of one cell with a factor equal to the number of cells in series. Then equations (4) and (5) will be modified to the following pattern:

$$I = I_{ph} - I_o \left\{ e^{\left[\frac{q}{n_s AKT}(V + n_s I R_s) \right]} - 1 \right\} \tag{8}$$

$$V = \frac{n_s AKT}{q} \ln\left(\frac{I_{ph} + I_o - I}{I_o} \right) - n_s I R_s \tag{9}$$

Equations (8) and (9) simulate the current-voltage characteristics of the PV module, provided that the PV module parameters such as series resistance, reverse saturation current, short circuit current temperature coefficient and module ideality factor are known.

Several methods for the determination of photovoltaic module parameters are proposed by different authors [7-10]. An accurate knowledge of the photovoltaic module parameters is essential for the design and quality control of solar modules and for simulating their performance. These parameters are often determined using experimental data under a given illumination and temperature [11].

The present paper presents an accurate method to estimate PV module parameters such as module series resistance, reverse saturation current, short circuit current temperature coefficient, and ideality factor based on practical measurements of I-V curves for the PV module under different operating conditions.

2. Practical measurements

Practical measurements of the I-V curves of the PV module depend mainly on the data acquisition system (DAS). DAS is used to record the signals from the different sensors that are used for measuring the different physical parameters of the PV system. These measurements include the incident solar radiation on the surface of the PV module, PV module surface temperature, module voltage, and module current. These parameters can be measured and recorded via a PC driven by AD card [12]. ***Figure 3*** shows the electronic circuit diagram for the proposed data acquisition system.

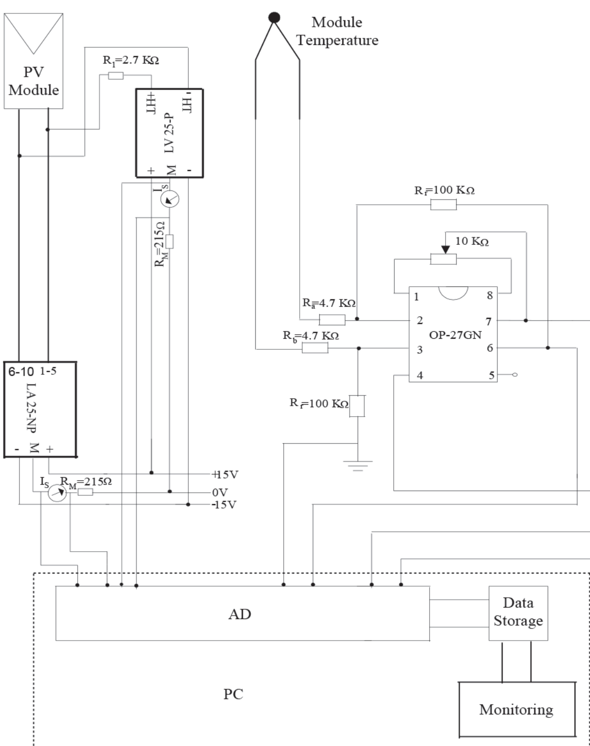

Figure 3. *I-V Electronic circuit diagram for the proposed data acquisition system.*

As shown in ***Figure 3***, using the data acquisition system, the PV module voltage can be measured accurately by using an LV 25-P voltage transducer with galvanic isolation between the primary circuit (high voltage) and the secondary circuit (low voltage), while a current transducer LA 25-NP is used to measure the PV module current. A thermopile pyranometer, mounted on the PV module structure and parallel to the module of type Kipp and Zonen (model CM5-774035) is used to measure the solar radiation intensity. A type K thermocouple is used to measure the PV module surface temperature.

3. PV module

The PV module is a thin film triple junction silicon solar cell technology with a maximum output of 64 W (at STC 25 °C ambient temperature and 1000 W/m^2 global radiation). The complete specifications of the PV module are listed in ***Table 1***.

TABLE 1. PV module characteristics at STC.

Maximum power	64 W
Operating temperature	47°c
Open circuit voltage	27.1 V
Short circuit current	4.8 A
Dimensions in cm^3	137 cm x 74.1 cm x 3.2 cm
Weight	9.17 Kg

4. Determination of the PV module parameters

The PV module parameters that needed to be determined are the module series resistance (R_s), reverse saturation current (I_o), short circuit current temperature coefficient (K_i), and ideality factor (A). The next sections describe the methods of detecting these parameters.

4.1. PV module series resistance

The series resistance modifies slightly the shape of the I-V characteristics of the PV module. It causes a reduction in the slope of the I-V characteristics in the region of the peak power point. For more efficient PV modules, its series resistance must be very low [13].

To obtain more accurate estimates of R_s, a series of forward biased I-V measurements are made using different values of input light irradiance (please see ***Figure 4***). First, a forward-biased I-V measurement under an arbitrary light irradiance is made and a value V1 that is slightly higher than V_{max} (as shown in ***Figure 4***) is selected. Next, a value of ΔI is calculated where $\Delta I = I_{sc1}(0) - I_{sc1}(V_1)$. This process is then repeated more times using lower values of light irradiance as shown in ***Figure 4***. Finally, R_s is estimated by averaging R_1, R_2 and R_3, as shown below [13]. ***Figure 5*** shows the group of practical measured I-V curves used in these calculations.

$$R_s = \frac{R_1 + R_2 + R_3}{3} \tag{10}$$

Where

$$R_1 = \frac{V_2 - V_1}{I_{sc1}(V_1) - I_{sc2}(V_2)}, \quad R_2 = \frac{V_3 - V_2}{I_{sc2}(V_2) - I_{sc3}(V_3)},$$

$$R_3 = \frac{V_3 - V_1}{I_{sc3}(V_3) - I_{sc1}(V_1)} \tag{11}$$

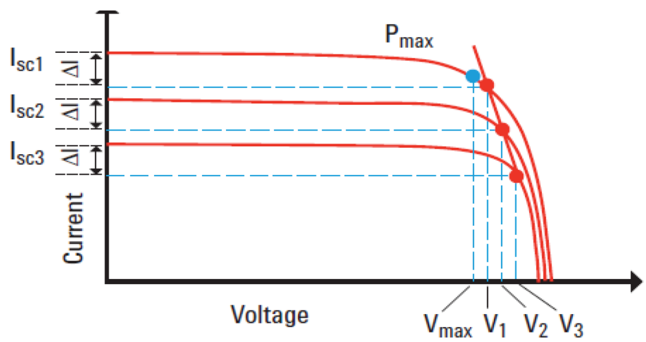

Figure 4. *Determination of the PV module series resistance.*

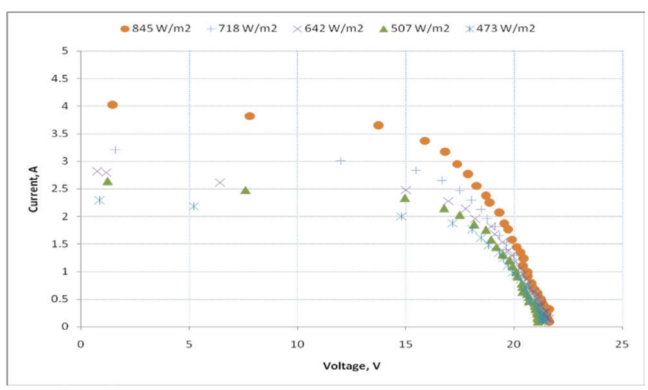

Figure 5. *Measured I-V curves of the PV module at different radiation levels (Temp. 45 °C).*

4.2. Other PV module parameters

The PV module light generated current, I_{ph}, equation 6, slightly differs from the practical PV module short circuit current. This difference resulted from the temperature coefficient of the short circuit current, K_i, equations 8 and 9. Also, the I-V characteristics of the PV module presented in equations 8 and 9 is valid only for a certain solar radiation and module temperature. If the solar radiation or the module temperature is changed, then another I-V characteristic for this module can be drawn. Equations 8 and 9 contain two important parameters that are the PV module saturation current, I_o, and module ideality factor, A. These parameters can be calculated by curve fitting for the measured I-V characteristics of the PV module, shown in *Figure 5*, with the theoretical model in equations 8 and 9, based on the least square method.

5. Test the estimated PV module parameters

The obtained parameters of the PV module from the previous sections are listed in *Table 2*. These parameters will be used in the simulation of the PV module characteristics at different temperature and radiation levels.

TABLE 2. Calculated PV module parameters.

Series resistance, R_s	1.055 Ω
Reverse saturation current, I_o	1.9955×10^{-9} A
Short circuit current temperature coefficient, K_i	0.0014 A/°C
Ideality factor, A	1.48

Figures 6 and *7* show the measured and calculated I-V curves of the PV module at different operating conditions. From these figures, it is clear that there is good agreement between the calculated and the measured values of the PV module characteristics, which indicates the accuracy of the method used to get the PV module parameters based on practical measurements.

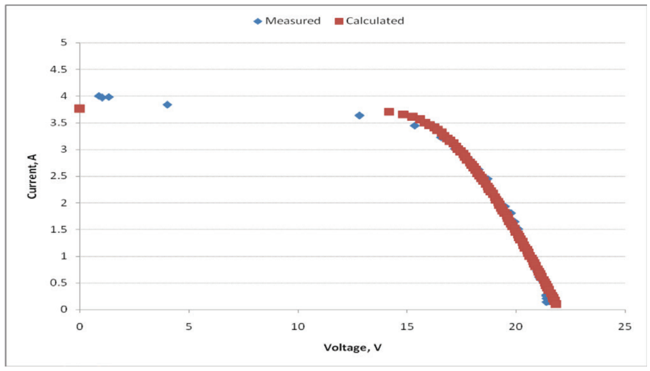

Figure 6. Measured and calculated I-V curves of the PV module at 778 W/m², 45 °C.

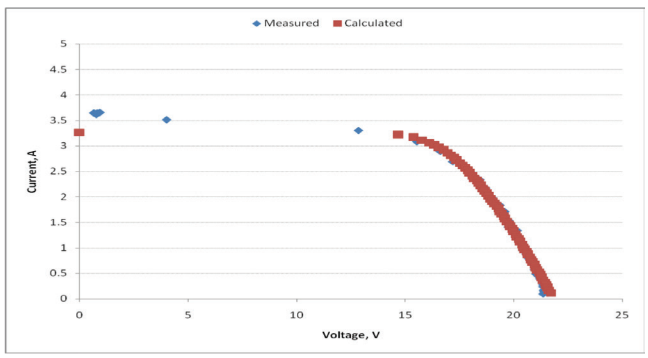

Figure 7. Measured and calculated I-V curves of the PV module at 676 W/m², 45 °C.

Conclusion

The present paper introduces an effective method used for determining PV module series resistance, reverse saturation current, short circuit current temperature coefficient, and ideality factor based on practical measurement of I-V curves for the PV module under different operating conditions. The determination process depends mainly on the accurate measurement of the module characteristics and calculation of the module parameters via the slope of the I-V curve and curve fitting with least square method. The agreement between the measured and the calculated I-V curves of the PV module explains the quality of the method used to get the module parameters.

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Nomenclature

A	Ideality factor.
E_{Go}	Band gap for silicon (1.1 ev).
G	Solar radiation on the PV cell surface (W/m^2).
I_d	Diode current (A).
I_o	PV cell reverse saturation current (A).
I_{or}	PV cell reverse saturation current at reference temperature, T_r (A).
I_{ph}	PV cell light generated current (A).
I_{scr}	PV cell short circuit current at STC (A).
I_{sh}	Shunt current (A).
K	Boltzman's constant (1.38x10^{-23} Nm/°K).
K_i	PV short circuit current temperature coefficient (A/°C).
n_s	The number of cells in series in the PV module (22).
q	Electron charge (1.6x10^{-19} C).
R_s	PV module series resistance (Ω)
R_{sh}	PV module shunt resistance (Ω)
T	PV module surface temperature (K).
T_r	Reference temperature (298 K).