PERGAMON

Renewable Energy 25 (2002) 371–380

RENEWABLE ENERGY

www.elsevier.nl/locate/renene

Selecting a suitable model for characterizing photovoltaic devices

M.A. de Blas *, J.L. Torres, E. Prieto, A. García

Departamento de Proyectos e Ingeniería Rural, Universidad Pública de Navarra, Campus Arrosadía, 31006 Pamplona, Spain

Received 30 November 2000; accepted 15 January 2001

Abstract

The aim of this work is to evaluate a simple analytical method for extracting parameters involved in the photovoltaic module behaviour equation. Based on a series of experimental voltage–intensity curves obtained under various temperature and irradiance conditions, values are obtained to extract the model parameters, giving rise to adjustment errors at data points (short circuit current, open circuit voltage and voltage at maximum power point) and in the entire curve that are less than 1%. It has also been confirmed that assigning suitable values for series and parallel resistance avoids having to know beforehand the slope value of the characteristic curve, which is not normally indicated in the solar module specifications; this gives rise to good adjustment results between the experimental curves and the theoretical model, even when the theoretical parameters are adapted to other temperature and irradiance conditions. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Photovoltaic model; *V–I* characteristics

1. Introduction

The behaviour of a solar cell, module or array can be explained with an equivalent electric circuit that is similar to the device that is to be characterized. There are a number of more or less complex models in the bibliography for simulating the behaviour of a photovoltaic device (operating curve or intensity–voltage) for specific irradiance and temperature conditions.

* Fax: +34-948-169148.
E-mail address: mblas@unavarra.es (M.A. de Blas).

PII: S0960-1481(01)00056-8

Nomenclature

I	electric current (A)
I_0	diode saturation current (A)
I_{sc}	short circuit current (A)
I_m	current at maximum power point (A)
I_L	photocurent (A)
K	Boltzmann's constant (1.381×10^{-23})
n	diode quality factor
P_m	maximum power (W)
q	electronic charge (1.602×10^{-19} C)
R_p	lumped shunt resistance (Ω)
R_s	lumped series resistance (Ω)
R_{sho}	reciprocal of slope at short circuit point
R_{so}	reciprocal of slope at open circuit point
T	temperature of the photovoltaic device (K)
V	voltage (V)
V_m	voltage at maximum power point (V)
V_{oc}	open circuit voltage (V)
V_T	thermal voltage ($V_T=(k\cdot T)/q$)

The degree of complexity of the model will determine which of the methods is most suitable in extracting the parameters that are involved in the mathematical expression of the model. In general, these methods can be broken down into two groups: numerical methods that require powerful mathematical tools and iterative methods to solve the implicit non-linear equation associated with the photovoltaic device and analytical methods that introduce a series of simplifications and approximations and lead to a simpler solution without introducing significant errors into the model.

The model for the photovoltaic device that is studied in this article is an equivalent circuit with a single diode (single exponential), which is amply described in the bibliography. In spite of offering a closer representation of the solar cell [1], the double-diode model (double exponential) is rejected in this case because the recombination that is incurred by the second diode dominates at low voltage [2] and low irradiance [3], which are operation conditions that are discarded if the object that is simulated is a solar module that is to be used as a power source.

Therefore, one of the aims of this work is to define a method to extract, in a simple manner and with a sufficient degree of precision, the parameters related to the model for the solar module under study, to define a model with which, based on certain experimentally known values, such as short circuit current, open circuit voltage and current and voltage at maximum power point, it is possible to characterize the behaviour of the solar module. The values of said points are usually included in the technical specifications issued by the manufacturer of the certified solar module, at least for standard temperature and irradiance conditions. The model should also characterize the operation of the device within the temperature and irradiance range of interest.

2. Method

The selected model responds to the following expression:

$$I=I_L-I_0\left[\exp\left(\frac{V+I\cdot R_s}{n\cdot V_T}\right)-1\right]-\frac{V+I\cdot R_s}{R_p}. \tag{1}$$

As indicated, this implicit non-linear equation can be solved with numerical iterative methods, such as the Levenberg–Marquardt algorithm [4], although these systems, as well as requiring powerful mathematical tools also require a close approximation of initial parameter values to attain convergence. In order to simplify the process, the parameters are extracted by means of analytical methods.

Eq. (1) and its derivative are evaluated at the short circuit, open circuit and maximum power points. The parameters are extracted based on the obtained expressions with a series of simplifications (Table 1). The resolution of the equations of Table 1 requires that we estimate the initial R_s value, based on R_p itself [Eq. (4)]

Table 1
Equations for the analytical extraction of the parameters with the single exponential model

R_{so} (experimental)	R_{sho} (experimental)	R_p
$-\frac{dV}{dI_{(V=V_{oc})}}$ (2)	$-\frac{dV}{dI_{(I=I_{SC})}}$ (3)	$R_{sho}-R_s$ (4)
R_s	n	
$\dfrac{R_{so}\left(\frac{V_{oc}}{V_T\cdot n}-1\right)+R_{sho}\left(1-\frac{I_{sc}R_{so}}{V_T\cdot n}\right)}{\frac{V_{oc}-I_{sc}R_{sho}}{V_T\cdot n}}$ (5)	$\dfrac{V_m+I_mR_s-V_{oc}}{V_T\ln\left[\dfrac{(I_{sc}-I_m\left(1+\frac{R_s}{R_p}\right)-\frac{V_m}{R_p}}{I_{sc}\left(1+\frac{R_s}{R_p}\right)-\frac{V_{oc}}{R_p}}\right]}$ (6)	
I_{ph}	I_0	
$I_0\left[\exp\left(\frac{V_{oc}}{n\cdot V_T}\right)-1\right]+\frac{V_{oc}}{R_p}$ (7)	$\dfrac{I_{sc}\left(1+\frac{R_s}{R_p}\right)-\frac{V_{oc}}{R_p}}{\exp(V_{oc}/n\cdot V_T)}$ (8)	

and n [Eq. (6)]. The R_s value [Eq. (5)] is then recalculated to obtain the correct value with rapid convergence.

Following this line of reasoning, but introducing different simplifications, Phang et al. [5] deduced other known expressions for the analytical extraction of parameters. As well as the short circuit current, open circuit voltage and the voltage and current at maximum power point, the previous analytical expressions require that we know the reciprocal of slope for the characteristic curve at points I_{sc} and V_{oc} (R_{sho} and R_{so} values).

The precise determination of the slope of the voltage–intensity curve at said points requires experimentation under certain temperature and irradiance conditions to obtain enough pairs of voltage–intensity values near the points of intersection of the characteristic curve and the intensity and voltage axes, both for positive and negative voltage values (evaluation in I_{sc}) and intensity values (evaluation in V_{oc}). The need to measure these points and to obtain a precise slope value makes it necessary to avail of a system that is apt for determining characteristic curves that, as well, permit operation with negative voltage and current values. In addition, the habitual incorporation of protection diodes in solar modules makes it impossible to subject them to negative voltage, since the purpose of said diodes is to prevent inverse polarization.

Given the difficulty in determining the slope and since the goal is a model that is simple but with a sufficient degree of precision, it is convenient to fix the R_s and R_p values and extract the rest of the parameters with the corresponding analytical expressions. In this way, the two parameters are assigned fixed values for normal module operating temperature and irradiance.

In order to adapt solar module behavior to different conditions of temperature and irradiance, it is possible to apply the procedure described in the International Standards IEC 891 [6] or the one collected in Alonso [7]. At any rate, the method followed in this case to validate the model involves recording the short circuit current and open circuit voltage under specific temperature and irradiance conditions in order to avoid uncertainty in these data points when a corrective method is applied.

It is known that the diode saturation current is proportional to temperature raised to the third power. The equation proposed by Townsend [8] makes it possible to adapt this parameter to other temperature conditions if it is considered a fixed value of the diode quality factor. Therefore, based on the corrected value of I_0 and the R_s and R_p values, the rest of the parameters are extracted with the corresponding analytical equations and the I_{sc} and V_{oc} values under the new conditions. The parameters that are considered variables under temperature and/or irradiance conditions are I_0, I_L and the diode quality factor n.

This last parameter should be considered independent of temperature and thus have a fixed value to be congruent with the above indications, but in adapting the model to new operating conditions for the proposed solar module, it is used as an adjustment parameter so that the relationship between parameter values yields an adequate correspondence between the theoretical model and the experimental characteristic curve of the device under specific temperature and irradiance conditions. The importance of the relationship between the values of model parameters and their individual values in obtaining suitable adjustments is described by Krezinger et al. [9].

In order to quantify the degree of approximation of the model to the experimental characteristic curve, for specific temperature and irradiance conditions, the deviations of the values calculated with the model should be calculated with respect to the experimental values, at the data points of interest (short circuit intensity, open circuit voltage and maximum power point). As well as these points, it is also necessary to determine the global adjustment error of the experimental curve of the model, using the relative value of the area contained within the experimental and theoretical curves, with respect to the area of the experimental curve, a method which has certain advantages over the standard deviation method [10].

3. Experimental procedure

In order to validate the diode model for solar module, a series of experimental curves are used under different irradiance and temperature conditions with natural sunlight on clear days. The curves are measured using a bipolar power supply that acts as a charge on the solar module under study, the voltage of which is uniformly increased. The voltage and current of the solar module is recorded at each operating point with two high precision digital meters. The temperature and irradiance of the module are recorded at the beginning and end of each experiment, rejecting curves in which these magnitudes vary.

The solar module under study is made up of 36 mono-crystalline silicon cells connected in series. The nominal values of the characteristic points, as indicated by the manufacturer for conditions of 1000 W m^{-2}, spectrum A.M. 1.5 and a temperature of 25°C are as follows: I_{sc}=7.7 A; V_{oc}=21 V; I_m=7.1 A; V_m=16.9 V; P_m=119.99 W.

Based on the data points of interest and the slope values of the experimental characteristic curves at the points corresponding to short circuit current and open circuit voltage (Table 2), the model parameters are determined for a diode (Table 3), using the expressions proposed in Table 1 and the expressions corresponding to Phang et al. [5], in order to first evaluate these two analytical adjustment methods.

In order to determine which are the values of parameters for series and parallel resistance that give rise to an improved adjustment to the theoretical model, the series resistance values that are considered are between 0.30 and 0.33 Ω; i.e. the lower and upper limits obtained by analytically determining the value of this parameter based on the slope of the experimental curves. Similarly, the parallel resistance is considered between 50 and 170 Ω. The ample variation with this second parameter, in addition to the excessive low values that it presents in comparison to other results shown in the bibliography for similar modules, is due to the uncertainty of the slopes of the analysed experimental curves, since there are not enough voltage–intensity points in the segment of interest, mainly, due to the lack of negative voltage values that results from the limitations of the system employed in the experimental determination of the characteristic curves. A comparison is made between the adjustment

Table 2
Values of the points of interest corresponding to experiments with the solar module under study

Curve	Irradiance (W m^{-2})	Temperature (°C)	I_{sc} (A)	V_{oc} (V)	I_m (A)	V_m(V)	R_{so}	R_{sho}
1	918	39	6.5812	20.0589	5.7313	14.6120	0.572	116.279
2	832	22.7	5.9659	21.1263	5.3949	15.8107	0.577	166.667
3	994	23.5	7.0707	21.2218	6.2604	15.6675	0.522	63.291
4	649	31	4.7481	20.232	4.0809	15.4583	0.67	51.282

Table 3
Values of the parameters extracted from analytical expressions

Curve	Parameters derived from equations in Table 1					Parameter derived from equations proposed by Phang et al. [5]				
	R_s	R_p	n	I_0	I_L	R_s	R_p	n	I_0	I_L
1	0.309	116.279	62.728	4.3980×10^{-5}	6.5988	0.311	115.986	62.512	4.2325×10^{-5}	6.5988
2	0.313	166.667	60.478	6.5282×10^{-6}	5.9771	0.314	166.352	60.344	6.3452×10^{-6}	5.9772
3	0.304	63.291	57.525	3.6332×10^{-6}	7.1047	0.307	62.9841	57.244	3.4014×10^{-6}	7.1052
4	0.322	58.480	54.833	3.3806×10^{-6}	4.7743	0.328	58.152	54.452	3.0806×10^{-6}	4.7749

errors of experimental curves under various irradiance and temperature conditions and their corresponding experimentally attained curves, for different R_s and R_p values, to determine which values offer improved adjustment. After this, a check is made to see if these predetermined values maintain the adjustment quality when the rest of the parameters of the theoretical model are adapted to other operating conditions.

4. Analysis of the results

The evaluation of the goodness of fit of the theoretical diode model employing the two groups of expressions to analytically extract the parameters yields satisfactory results (Fig. 1). As can be observed in Fig. 2, the errors at the data points of interest of the curve and the global error are very low, below 1%, which implies that both sets of analytical equations for extracting the parameters allow for a precise adjustment between the experimental curves of the solar module and the single exponential model.

It is important to note that the adjustment results are significantly improved if the value for thermal potential is introduced with a minimum precision of ten-thousandth, since the model is very sensitive to this factor.

In order to determine the values of the series and parallel resistance parameters that yield the best adjustment between the various experimental curves and the theor-

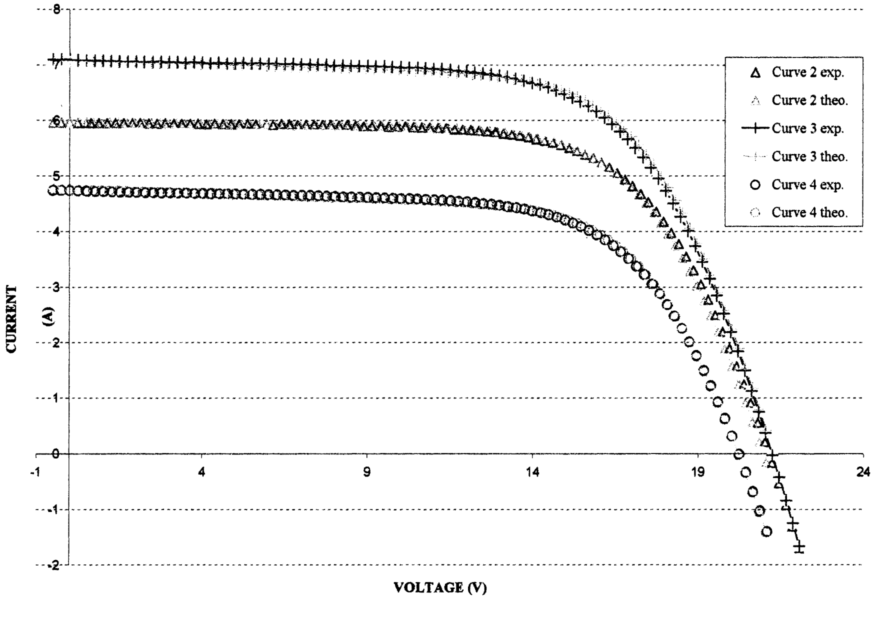

Fig. 1. Characteristic voltage–intensity module curves, experimental value and adjusted to the single exponential model with parameters extracted with the expressions in Table 1.

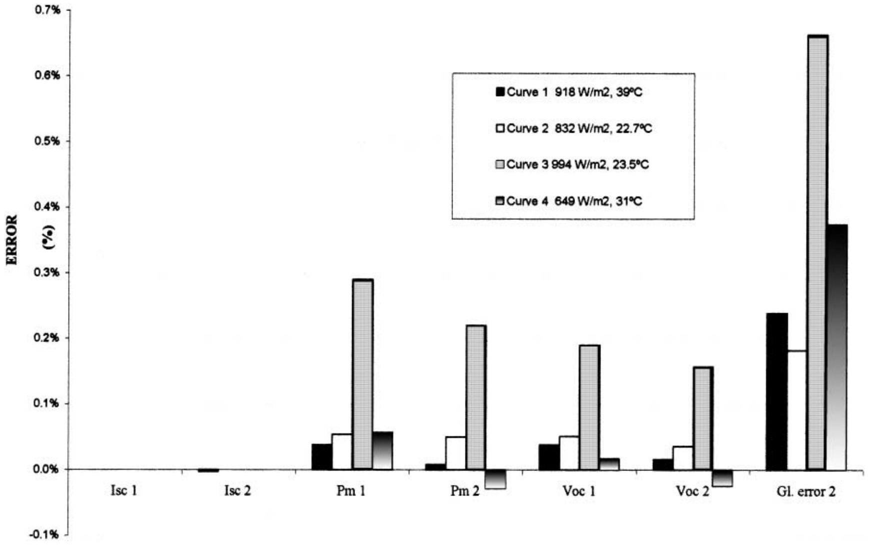

Fig. 2. Adjustment errors between the experimental characteristic curves and the curves obtained with the theoretical model at the data points of interest. (1) Phang et al. (2) Table 1.

etical model, the analytical expressions for calculating the parameters corresponding to Table 1 are used and the resistance values are varied. The series resistance value that offers the best adjustment is 0.315 Ω. In the case of the parallel resistance, however, the value to be used is not clearly determined. A value of 90 Ω can be considered appropriate, although it did not yield optimum adjustment in all of the characteristic curves that were analysed. Nevertheless, the value of 90 Ω was used for parallel resistance since it is a considerable magnitude, which would not justify the exclusion of this parameter in the theoretical model that is used. The significant negative slope of the characteristic voltage–intensity curve in the experimental curves of the solar module is also indicative of a relatively small value for the parallel resistance [11]. In addition, the indicated parallel resistance maintains the adjustment quality between the experimental curve and the theoretical model when the latter is adapted to other conditions of temperature and irradiance, as can be observed in Fig. 3.

It can also be affirmed that the sensibility of the model to the parallel resistance value is minor and that at any rate, both the errors at the points of interest and the global error are less than 1%, if we consider parallel resistance values between 70 and 130 Ω.

If an arbitrary higher parallel resistance (500 Ω) or an infinite parallel resistance value is considered, adjustment results worsens in the studied curves, although it must be recognized that typical values of this parameter for modules are much higher than the ones considered in the present work.

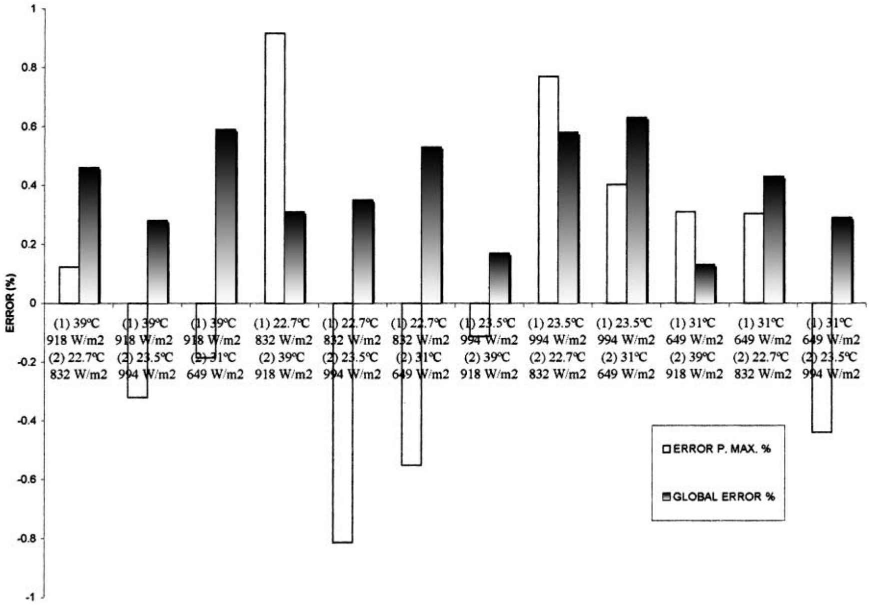

Fig. 3. Adjustment errors at the maximum power point and global error considered in the theoretical model R_s=0.315 Ω and R_p=0.90 Ω. (1) Initial temperature and irradiance conditions. (2) Final conditions. The value of the parameters is adapted to different operating conditions.

5. Conclusions

The use of analytical methods in determining the parameters that intervene in a diode model makes it possible to characterize, with a sufficient degree of precision and in a simple manner, the operation of a solar module under conditions of high irradiance.

The difficulty involved in availing of a sufficient number of data points that are near the points of intersection with the axes, to obtain the slope, as required for the analytical calculation of the parameters, is underplayed by assigning fixed values for series and parallel resistance. If said values are properly selected, the adjustment errors between experimental curves under different temperature and irradiance conditions and the theoretical model, adapted in each case to said conditions, is less than 1%.

It is observed that the sensibility of the model to the value of parallel resistance is minor, as a result of which the designation of an arbitrary fixed value does not affect the quality of adjustment. Nevertheless, the model is particularly sensitive to thermal potential value, and a decrease is observed in the errors that affect the goodness of fit if this term is introduced with a precision of ten-thousandths.

References

[1] Wolf M, Noel GJ, Stirn RJ. Investigation of the double exponential in the current–voltage characteristics of silicon solar cells. IEEE Trans Electron Devices 1977;24:419–28.
[2] Overstraeten RJ, Mertens RP. Characterisation and testing of solar cells and modules. Physics, techonology and use of photovoltaic. Bristol: Hilger, 1986.
[3] Chan DSH, Phang JCH. Analytical method for the extraction of solar cell single and double-diode model parameters from *I–V* characteristics. IEEE Trans Electron Devices 1987;34(2):286–93.
[4] Press WH, Flannery WT, Teukolsky SA, Vetterling BP. Numerical recipes in C. New York: Cambridge University Press, 1992.
[5] Phang JCH, Chan DSH, Phillips JR. Accurate analytical method for the extraction of solar cell model parameters. Electron Lett 1984;20(10):406–8.
[6] International Electrotechnical Commission, IEC 891, 1989.
[7] Alonso MC. Modelado de componentes de sistemas fotovoltaicos autónomos. In: Fundamentos, dimensionado y aplicaciones de la energía solar fotovoltaica. Madrid: CIEMAT, 1999:17–20.
[8] Townsend TU. A method for estimating the long-term perfomance of direct-coupled photovoltaic systems. MS thesis, Mechanical Engineering, University of Wisconsin–Madison, 1989.
[9] Krezinger A, Wagner JA, Chenlo F, Copetti JB. Computer simulation of stand alone PV systems for developing countries. In: Proceedings of the 11th E.C. Photovoltaic Solar Energy Conference, 1992, p. 1411–1414.
[10] Chan DSH, Phillips JR, Phang JCH. A comparative study of extraction methods for solar cell model parameters. Solid-St Electron 1986;29(3):329–37.
[11] Duffie JA, Beckman WA. Solar engineering of thermal processes. 2nd ed. New York: Wiley, 1991.