Modeling and parameter identification of photovoltaic modules

Modelado e identificación de parámetros de módulos fotovoltaicos

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ABSTRACT

This paper proposes and validates an algorithm to determine photovoltaic (PV) modules model parameters using the information provided by the PV module suppliers. The effect of temperature and solar irradiation variations on the parameters are analyzed for three PV models discussed on the literature. Advantages and drawbacks of the models are compared to determine the best adapted to be used in simulation of PV modules for sizing and energy management. The retained model and parameter identification algorithm is validated with the specifications of two different PV modules.

Keywords: Modeling and simulation, photovoltaic modules, parameter identification.

RESUMEN

Este trabajo propone y valida un algoritmo para determinar los parámetros del modelado de módulos fotovoltaicos usando las especificaciones entregadas por los fabricantes. El efecto de la temperatura y de la irradiación es analizado en tres modelos usados en la literatura. Las ventajas y desventajas de cada uno son comparadas para determinar la mejor solución para simular paneles fotovoltaicos para aplicaciones de dimensionado y gestión de energía. El modelo considerado y el algoritmo de identificación de parámetros son validados con las especificaciones de dos diferentes módulos fotovoltaicos.

Palabras clave: Modelado y simulación, módulos fotovoltaicos, identificación de parámetros.

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Nomenclature

STC	Standard test conditions
PV	Photovoltaic
I_{pv}	Photocurrent (A)
$I_{pv,n}$	Photocurrent at STC (A)
$I_{sc,n}$	Short circuit current at STC (A)
I_0	Diode saturation current (A)
V_t	Diode thermal voltage (V)
a	Diode ideality factor (-)
R_s	Series resistance (Ω)
q	Absolute charge on an electron ($1.602\mathrm{x}10^{-19}$C)
V_{oc}	Open circuit voltage (V)
$V_{oc,n}$	Open circuit voltage at STC (V)
G	Solar irradiance (W/m^2)
Gn	Solar irradiance at STC (1000 W/m^2)
T	Cell temperature (K)
Tn	Temperature at STC (25 °C)
K	Boltzmann's constant ($-1.381\mathrm{x}10^{-23}$ J/K)
K_I	Temperature coefficient of short cicuit current(A/K)
K_V	Temperature coefficient of open circuit voltage(V/K)
N_S	Number of cells in series (-)
R_P	Shunt resistance (Ω)
P	Constant (-)

Introduction

Solar PV power systems have been widely commercialized as a renewable and clean energy source with multiple potential benefits. PV modules are typically represented by equivalent electrical circuits, which can vary their topology and number of elements according to the modeling requirements [1]–[3]. The element's parameters are calculated by experiment measurements [4]–[6], especially with the *I-V* characteristic curve, which, in general, are determined by manufactures under Standard Test Conditions (STC). Modeling and parameter identification of photovoltaic models allow improving the simulations and design of PV systems prior to installation

Performance of most type of panels (i.e. multi-crystalline, mono-crystalline, thin-film) is strongly affected by variations of cell temperature and solar irradiation [7]. For this reason, modeling the panel without considering these variations could result inaccurate even for design stages which require simple and low computational-cost models, as energy management and PV systems sizing.

This paper is organized as follows: Section II presents three PV models. Section III proposes and validates an algorithm to identify the parameters of the PV models. Section IV selects one PV model and Section V presents the conclusions of the research.

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Photovoltaic modules modeling

Three widely used models are considered in this section.

One-diode model considering Rs (4-p model)

Figure 1 illustrates the series resistance PV model. In this model, the series resistance represents the internal losses due to current flow and connecting wires [1][2]. Due to its simplicity, this model is widely used to estimate the non-linear *I-V* characteristic curve. This model is also known as four-parameter (4-p) model, these parameters are I_{pv1}, I_0, a and R_s. The following set of equations describes the PV model. Eq. (1) represents the output current and the other equations are used to identify I_{pv1} and I_0:

$$I=I_{pv1}-I_d=I_{pv1}-I_0\left(\exp\left(\frac{V+IR_s}{a*V_t}\right)-1\right) \tag{1}$$

$$I_0=I_{pv1}\left(\exp\left(-\frac{V_{oc}}{a*V_t}\right)\right) \tag{2}$$

$$I_{pv1}=I_{sc,n}\left(\frac{G}{G_n}\right)+K_I(T-T_n) \tag{3}$$

$$V_{oc}=V_{oc,n}+V_t Ln\left(\frac{G}{G_n}\right)+K_V(T-T_n) \tag{4}$$

$$V_t=\frac{N_S KT}{q} \tag{5}$$

One-diode model considering Rs and Rp (5-p model)

The one-diode PV model considering R_s and R_P is shown in Figure 2. In this model, the shunt resistance is considered in order to improve the accuracy of the modeling. This resistance represents the leakage current of the p-n junction [1] [5]. In literature, this model is the so-called five-parameter (5-p) model as the model requires the determination of five parameters values, i.e. a, R_s, R_P, I_{pv2} and I_0. The 5-p model is characterized by its Eq.(6) and the other ones to find I_{pv} and I_0 :

$$I=I_{pv2}-I_d-I_p=I_{pv2}-I_0*\left(\exp\left(\frac{V+R_sI}{V_t*a}\right)-1\right)-\frac{V+R_sI}{R_P} \tag{6}$$

$$I_{pv2}=(I_{pv2,n}+K_I*\Delta_T)\frac{G}{G_n} \tag{7}$$

$$I_{pv2,n}=\left(\frac{R_s+R_P}{R_P}\right)*I_{sc,n} \tag{8}$$

$$\Delta_T=T-T_n \tag{9}$$

$$I_0=\frac{I_{sc,n}+K_I*\Delta_T}{\exp(V_{oc,n}+K_V*\Delta_T/V_t*a)-1} \tag{10}$$

Two-diode model

In a real solar cell, the recombination losses in the diode depletion region are significant, especially at low voltage levels [4], for this reason, this model adds another diode to the equivalent circuit, as is shown in Figure 3. This allows improving the non-linear *I-V* curve characteristics as it is fitted to the specifications. This model is more accurate for polycrystalline cells [6]. The following set of equations represents the *I-V* relationship of the PV panel:

$$I=I_{pv2}-I_{d1}-I_{d2}-I_p=I_{pv2}-I_{01}*\left(\exp\left(\frac{V+R_s*I}{V_t*a1}\right)-1\right)-I_{02}*\left(\exp\left(\frac{V+R_s*I}{V_t*a2}\right)-1\right)-\frac{V+R_s*I}{R_P} \tag{11}$$

$$I_{01}=I_{02}=I_2=\frac{I_{sc,n}+K_I*\Delta_T}{\exp(V_{oc,n}+K_V*\Delta_T/V_t*({a1+a2}/p))-1} \tag{12}$$

I_{01} and I_{02} represent reverse saturation currents for each diode, while $a1$ and $a2$ represent ideality factors. Equation (11) can be simplified considering the expression $(a1+a2)/p=1$, where $a1=1$ and the variable p can be chosen to be ≥ 2.2 [4]. According to this, Equation (11) can be rewritten as Equation (13).

$$I=I_{pv2}-I_2*\left(\exp\left(\frac{V+R_s*I}{V_t}\right)+\exp\left(\frac{V+R_s*I}{V_t*(P-1)}\right)-2\right)-\frac{V+R_s*I}{R_P} \tag{13}$$

Model parameters determination and validation

PV modules specifications or datasheets does not provide model parameters; nevertheless these specifications provide *I-V* curves. Those curves are generally presented for different irradiances at constant temperatures and for different temperatures at constant irradiances. The aim of this section is to propose and validate a procedure to determine PV model parameters (e.g. R_s , R_P or a) using the information provided by the PV module supplier.

The algorithm illustrated in Figure 4 is proposed to determine the set of parameters which minimizes the difference between the data provided by the supplier and simulation results. In this paper the algorithm is implemented in Matlab using the Fmincon function (Find minimum of constrained nonlinear multivariable function), however the algorithm could be implemented using techniques such as genetic algorithms or simulated annealing.

The iterative algorithm requires defining a set of initialization parameters which define the convergence of the algorithm. Considering typical values found on literature, the following initialization values are considered: the series resistance range is defined as $0.3 < R_s < 1$, the shunt resistance is defined as $R_p > 10$ and the diode ideality factor range is defined $1 < a < 1.6$.

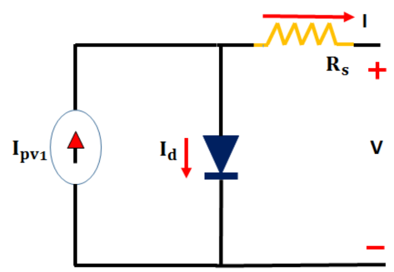


Figure 1. One-diode model considering Rs (4-p model).

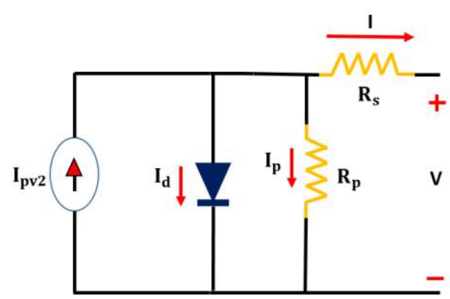


Figure 2. One-diode model considering Rs and Rp (5-p model).

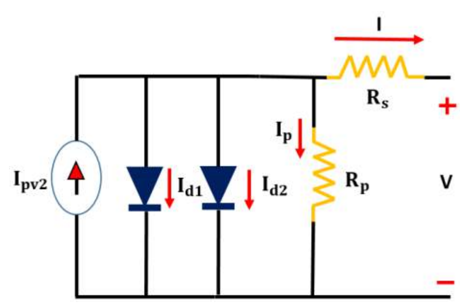


Figure 3. Two-diode model.

The proposed algorithm is used to determine the model parameters using the information provided in the specifications of the Shell SM55 Photovoltaic Solar Module and to determine set of parameters for the three PV models presented in this paper.

One-diode model considering series resistance (4-p model)

This model requires defining a set of two parameters, the series resistance *Rs* and the diode ideality factor a. The algorithm can be used to simultaneously determine both parameters, however as simplicity is preferred, the algorithm is implemented to find one of the parameters while the second is fixed.

The *I-V* curve with constant temperature is used to determine the value of R_s and a in 5 values of irradiance. Figure 5 illustrates the obtained relationship between R_s and G, for a fixed value of the ideality factor a. Figure 6 presents the relationship between a and G, for a fixed value of the series resistance.

The *I-V* curve with constant irradiance is used to determine the value of R_s and a in 5 values of temperature. Figures 7 and 8 show the obtained relationship between *a, Rs* with *T,* respectively. The results show that the value of R_s is not dependent of the PV temperature. Similar results are found for the dependence of a and T. This result is useful as it facilitates the implementation of the model.

This subsection verified that the R_s model provides accurate simulation results for operation at irradiances and temperatures provided by the supplier. It can be noted that R_s and a are monotonic decreasing functions with the irradiance. This is useful because the relationships can be represented by exponential or linear functions. This is presented on next Section.

One-diode model considering series and shunt resistance (5-p model)

This model requires defining a set of three parameters, the series resistance R_s , the shunt resistance R_p and the diode ideality factor a. The algorithm can be used to simultaneously determine all the parameters, to determine two parameters when the third is let constant (3 possibilities) or to determine only one parameter with two constant (3 possibilities).

The algorithm is performed to define the parameters in the different possibilities but results are only presented when the algorithm is used to simultaneously determine all the parameters. Figures 9, 10 and 11 illustrate the results of the algorithm to determine the relationship between a, R_s, R_p with *G.* Figures 12, 13 and 14 illustrate the results of the algorithm to determine the relationship between R_s, R_p and a with T.

The results obtained in this subsection show that the R_s and R_p model provides accurate simulation results for operation at irradiances and temperature provided by the supplier. However, it is difficult to identify monotonic relationships between the model parameters (R_s ,R_p and a) with the model inputs (G and T).

Two-diode model

As in the two resistances model, this model requires three parameters, the series resistance R_s, the shunt resistance R_p and the diode ideality factor a. The algorithm is performed to define the parameters in the different possibilities but results are only presented when the algorithm is used to simultaneously determine R_s and R_p with the ideality factor is set constant. Figures 15 and 16 illustrate the results of the algorithm to determine the relationship between R_s, R_p and a with G. Figures 17 and 18 show the relationship between R_s, R_p and a with T.

The results obtained in this subsection show that the two diodes model provides accurate simulation results for operation at irradiances and temperature provided by the supplier. However, it is difficult to identify monotonic relationships between the model parameters (R_s, R_p and a) with the model inputs (G and T). Table 1 shows a summary of features of the identified PV models.

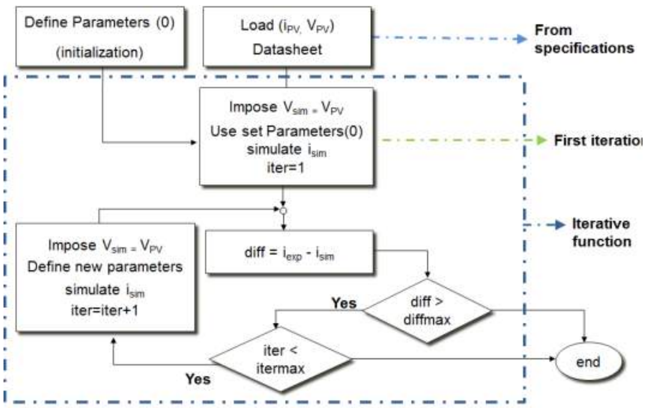


Figure 4. PV module parameter identification flowchart.

Table 1. Features of the identified PVP models.

Features	4-p model	5-p model	Two-diode model
Provides accurate simulations at irradiances and temperatures provided by the PV module supplier.	✓	✓	✓
Parameters are easy to identify.	✓	✓	✓
The relationships between parameters and irradiance can be modeled by monotonic functions.	✓	✗	✗
Parameters do not depend of the PV temperature.	✓	✗	✗

Table 2. Algorithm results between parameters and irradiance for the three identified PV models.

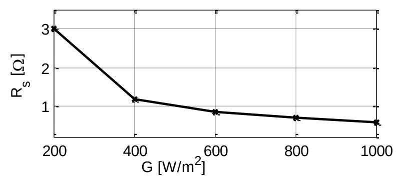
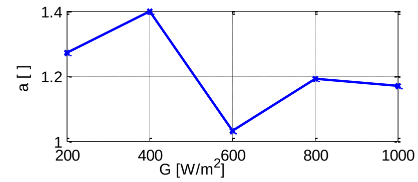
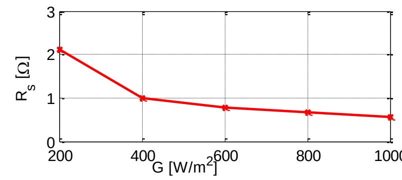
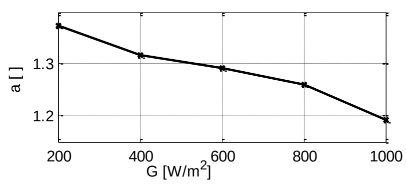
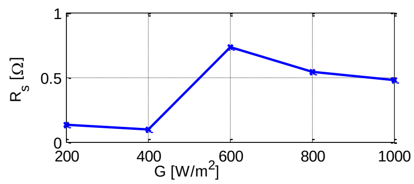
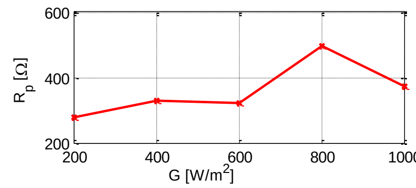
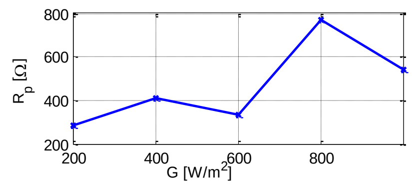
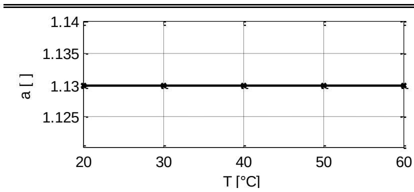
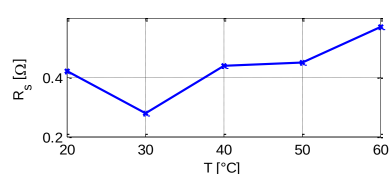
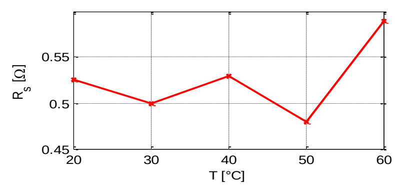
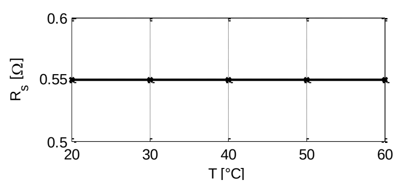
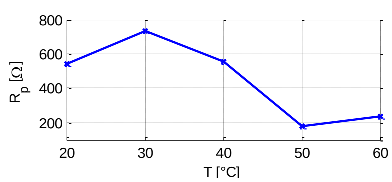
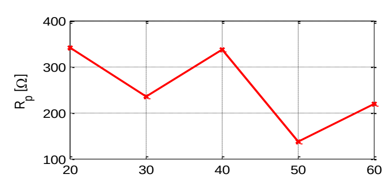
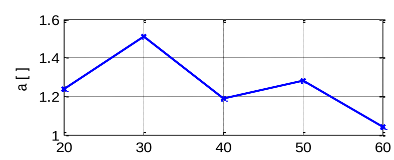
4-p model	5-p model	Two-diode model
 Figure 5. SM55 PV module - Rs Vs G. a=1; T=25°C.	 Figure 9. SM55 PV module- a Vs G T=25 °C.	 Figure 15. SM55 PV module- Rs Vs G: a1=1; a2=1.3; p=2.3; T=25 °C.
 Figure 6.SM55 PV module a Vs G. Rs=0.5 [Ω]; T=25°C.	 Figure 10. SM55 PV module - Rs Vs G ; T=25 °C.	 Figure 16. SM55 PV module-Rp Vs G: a1=1; a2=1.3; p=2.3; T=25 °C.
	 Figure 11. SM55 PV module- Rp Vs G ; T=25 °C.	

Table 3. Algorithm results between parameters and temperature for the three identified PV models.

4-p model	5-p model	Two-diode model
 Figure 7 SM55 PV module - a Vs T. Rs=0.5 [Ω]; G=1000 W/m^2.	 Figure 12. SM55 PV module - Rs Vs T ; G=1000 W/m^2.	 Figure 17. SM55 PV module- Rs Vs T: a1=1; a2=1.3; p=2.3; G=1000 W/m^2.
 Figure 8 SM55 PV module - Rs Vs T. a=1; G=1000 W/m^2.	 Figure 13. SM55 PV module - Rp Vs T ; G=1000 W/m^2.	 Figure 18. SM55 PV module- Rp Vs T: a1=1; a2=1.3; p=2.3; G=1000 W/m^2.
	 Figure 14. SM55 PV module - a Vs T; G=1000 W/m^2.	

To validate the algorithm results, simulations are performed to determine the *I-V* curves using the relationships between parameters and irradiance, temperature from Table 2 and 3 respectively. The three models considered can be used to model PV modules behavior, all of them provide accurate simulation results for operation at irradiances and temperatures values provided by the supplier. Figures 19 and 20 present *I-V* curves using one-diode model considering Rs and Rp.

For a comprehensive comparison, the errors between simulation results from each PVP model considered and the specifications of PV module are calculated. The absolute error is defined as the absolute difference between the datasheet and simulation current values of the *I-V* curves for a given voltage point. These are carried out for the five points of irradiance and temperature as shown in Table 4 and Table 5, respectively. In general, the three PVP models identified exhibit low errors for all environmental conditions (*G* and *T*).

Model selection

Last section showed that PV modules can be accurately modeled with all the considered models. It can be seen that the one-diode one resistance model's parameters are the simplest to calculate. Also, these are not dependent on the temperature and their dependence with the input (G) can be modeled with monotonic functions. For the reasons expressed above, the one-diode one resistance model seems to be the more practical to model PV modules in order to simulate them.

In this section fit functions are used to model the dependence of R_s and a with G. This can be useful to interpolate *I-V* values for values of irradiance when no information is given by the supplier. Figures 21 and 22 respectively illustrate the obtained relationship between R_s and G, and a and G obtained with the parameter identification algorithm and the fit function. R_s Vs *G* is fitted using an inverse curve and the ideality diode factor is fitted by a linear curve. The results obtained with constant series resistance and variable ideality factor is shown in Figure 23. Similar results are obtained by using the inverse fit function.

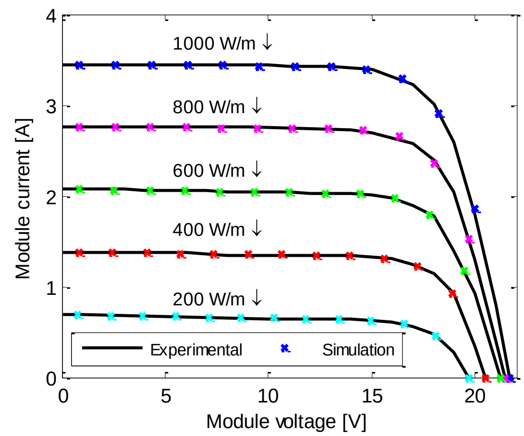
The parameter identification algorithm is applied to determine the model parameters for a Shell ST40 photovoltaic solar module and the results are presented below. Figure 24 illustrates the relationship between the series resistance and the irradiance. Figure 25 presents the relationship a Vs *G*. Figure 26 shows the results obtained by using the parameters interpolated in the fit linear function. Similar results are found by using the fit inverse function.

Table 4. Absolute percentage errors for different irradiation levels.

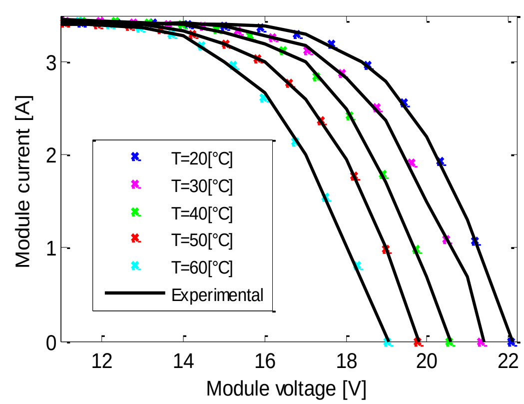
Irradiation (W/m²)	4-p model	5-p model	Two-diode model
200	2.859	0.3248	0.2688
400	1.1645	0.2236	0.1479
600	0.7494	0.09829	0.0982
800	0.2806	0.1385	0.2111
1000	0.1828	0.2036	0.2613

Table 5. Absolute percentage errors for different temperature levels.

T(°C)	4-p model	5-p model	Two-diode model
20	0.3628	0.1168	0.1028
30	0.7612	0.7211	0.7101
40	0.3632	0.1835	0.1315
50	1.3196	0.5258	0.3288
60	0.3609	0.2054	0.1014



. Figure 19. SM55 PV module- I VS V; T=25 °C.



. Figure 20. SM55 PV module -I VS V; G=1000 W/m^2.

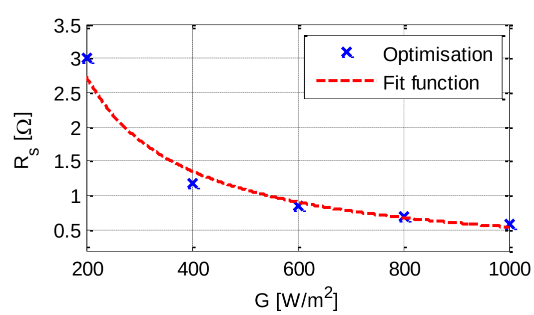


Figure 21. SM55 PV module- Rs VS G; a=1; T=25 °C.
Fit function: Rs=562.37G^ (-1.005). R^2=0.9778.

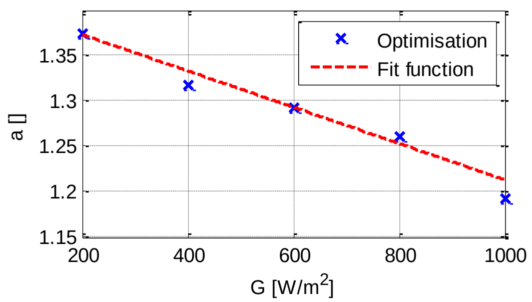


Figure 22. SM55 PV module- a VS G; Rs=0.5 [Ω]; T=25 °C;
Fit function: a=-0.0002G+1.4135. R^2=0.9733.

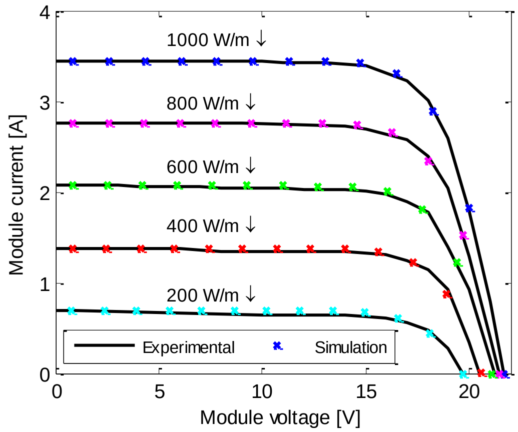


Figure 23. SM55 PV module - I VS V; Rs=0.5[Ω]; T=25 °C.

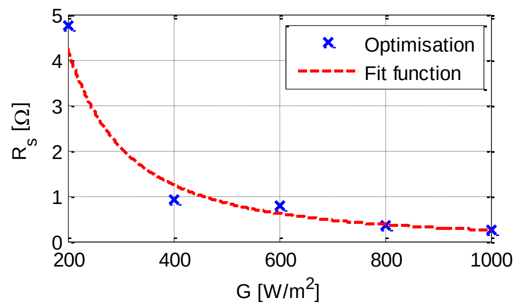


Figure 24. ST40 PV module -Rs VS G; a=1; T=25 °C
Fit function: Rs=48777G^ (-1.764). R^2=0.9644.

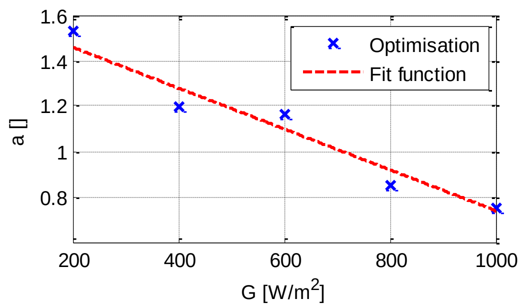


Figure 25. ST40 PV module -a VS G; Rs=0.5[Ω]; T=25 °C
Fit function: a=-0.00096G+1.6399. R^2=0.9488.

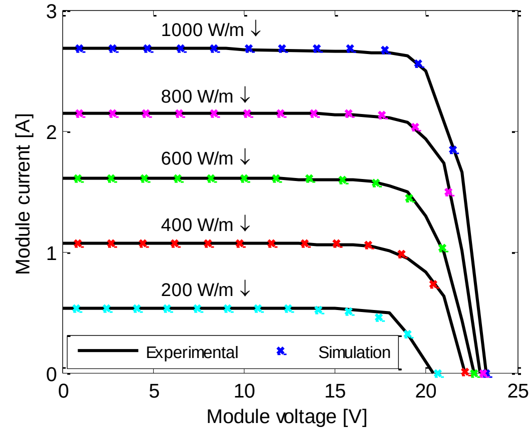


Figure 26. ST40 PV module -I VS V; Rs=0.5[Ω]; T=25 °C.

Conclusions

This paper proposes and validates an algorithm to determine photovoltaic (PV) modules model parameters using the information provided by the PV module suppliers. The effect of temperature and solar irradiation variations on the parameters are analyzed for three PV models on the literature. The retained model and parameter identification algorithm is validated with the specifications of two different PV modules.

The paper showed that PV modules can be modeled with accuracy with all of the considered models at least in the conditions presented in the supplier specifications. The one-diode one resistance model seems to be the more adapted to model PV modules in order to simulate them.

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