Chapter 2
Evaluation and Validation of an Electrical Model of Photovoltaic Module Based on Manufacturer Measurement

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Abstract. The analysis of the performance of a photovoltaic (PV) array needs basically the reporting the real working conditions to a reference condition of irradiance and temperature. Normally it is used the Standard Test Conditions (STC). Then the corrected I-V curves can be compared and an analysis of the performances can be carried out. In this context this paper proposes an analytical model to evaluate the energy performance of a PV module. The proposed model is based on some data provided by the manufacturer of the module in STC conditions. The photovoltaic module used as test-bed in the experiments gives the possibility to have the six terminals of the three strings forming the module, that normally are connected in series. This is very useful in the case of shading or disuniform radiation. The model is validated with numerical examples, and tested using both measured and estimated data relative to each single string and their connection in series and parallel. Results show how the parameters extraction depends on the measured value of the maximum power points, if measures are not accurate the analytic model here implemented can not converge to a feasible solution.

1 Introduction

Nowadays there are many efforts to increase the yearly energy production of a PV plant. Mainly it depends on design choices and construction solutions, but on the other hand the initial efficiency must be kept as high as the initial value of the PV plants in order to insure the goodness of the investment. In this context many efforts are focused on developing monitoring tools that, starting from a suitable model of the PV plant, can detect not only a specific difference between the expected efficiency and the measured one, but also a trend over the time that could indicate aging phenomena. These tools are mainly based on proper models of both PV module and PV strings. Actually in literature there are many models but very often they have been developed for PV cells mainly for testing aims. Then these models have been extended to PV modules and a few to PV arrays. The passage of the model from cell to module is critical as the presence of the layers of materials (e.g. Glass, EVA, Tedlar), that forms a PV module, causes some uncertainties, such as the real irradiance that strikes the cells inside a PV module and also the value and distribution of the temperature on the cells. The general approach to assess the electrical performance of a PV system is

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based upon the capability of analytically describing the I–V characteristic of the photovoltaic component for each operative temperature and solar radiation. Traditionally, the analytical models used in the study of these phenomena evaluate the behaviour of the PV cell by assimilating it into an equivalent electrical circuit that includes some non-linear components [13]. These electrical equivalent circuits are based on some unknown parameters, from three to seven depending on the complexity of the model; the most common electric circuit is known in literature as RP-model, which consists of a current generator, a diode, a series resistant and a shunt resistant. The characteristic equation of this equivalent circuit contains five independent parameters, for this reason it is also called "*five parameters model*". This model offers a good compromise between simplicity and accuracy and has been applied widely [3]. The five parameters can be evaluated by means of either numerical methods, that minimize the difference between a measured I-V curve and the one calculated by the model, or just using the technical data provided by that manufacturer of the PV module. However, due to the transcendental nature of the current equation for PV module, significant computation effort is required to obtain all the five model parameters [10]. For example, in [9] they have analyzed the development of a method for the mathematical modeling of PV arrays. In order to improve the accuracy of the method, analytic solutions [2, 6, 7, 8] and intelligence algorithms [4, 11, 12] are applied to deduce the all parameters. Moreover, recently various high accuracy algorithms techniques have been reported, such as particle swarm optimization (PSO) [15], differential evolution (DE) [10], genetic algorithm (GA) [13] and pattern search (PS) [1].

The aim of this paper is to develop a five parameter model that allows to evaluate the I-V curve of a photovoltaic model starting from data provided by the manufacturer relative to STC conditions. This model has been used since it has been successfully applied and it seems to give good approximations of the I-V curve [5, 14]. In this case, a module that allows to have as output the six terminals of the three strings forming the module, that normally are connected in series, is used to test and verify the adopted solution. The manufacturer provides data relative to each single string and their connection in series and parallel. These data are compared with data evaluated using the model here proposed.

2 Five Parameter Model

The five parameter model is relative to the equivalent circuit representative either a PV cell or a PV module, shown in Fig. 1. It is a complete circuit where both the sources of power losses are used, R_S and R_{SH}.

Application of Kirchoff's Current Law on the equivalent circuit results in the current flowing to the load:

$$I = I_{PH} - I_D - I_{SH} \tag{1}$$

If the diode current and the current through the shunt resistance (I_D and I_{SH}, respectively) are expanded, Eq. 2 is obtained.

$$I = I_{PH} - I_o \cdot \left(e^{\frac{V + I \cdot R_S}{\eta \cdot V_t}} - 1 \right) - \frac{V + I \cdot R_S}{R_{SH}} \tag{2}$$

where $V_t = m \cdot k \cdot T/q$, m is the number of cells connected in series, *k* is the Boltzmann's constant, *T* the absolute temperature and *q* the electronic charge.

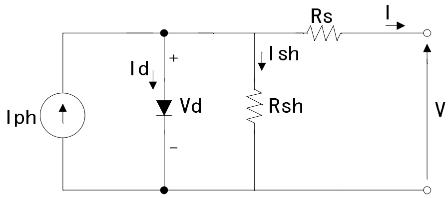


Fig. 1. Equivalent circuit representing the five-parameter model

The characteristic equation of the equivalent circuit contains five parameters: I_{PH} that represents the light current (A), I_0 that represents the diode reverse saturation current, η that represents the ideality factor, R_S that represents the series resistance and finally R_{SH} that represents the shunt resistance. In general, these five parameters are functions of the solar radiation incident on the cell and cell temperature. Reference values of these parameters are determined for a specified operating condition such as STC. Three current–voltage pairs are normally available from the manufacturer at STC: the short circuit current, the open circuit voltage and the current and voltage at the maximum power point. A fourth piece of information results from recognizing that the derivative of the power at the maximum power point is zero. Therefore, to calculate the five parameters, Eq. 1 has to be calculated in the following three points: open circuit "OC" (Eq. 3), short circuit "SC" (Eq. 4) and maximum power point "MP" (Eq. 5).

$$0 = I_{PH} - I_o \cdot \left(e^{\frac{V_{OC}}{\eta \cdot V_t}} - 1 \right) - \frac{V_{OC}}{R_{SH}} \tag{3}$$

$$I_{SC} = I_{PH} - I_o \cdot \left(e^{\frac{I_{SC} \cdot R_S}{\eta \cdot V_t}} - 1 \right) - \frac{I_{SC} \cdot R_S}{R_{SH}} \tag{4}$$

$$I_{MP} = I_{PH} - I_o \cdot \left(e^{\frac{V_{MP} + I_{MP} \cdot R_S}{\eta \cdot V_t}} - 1 \right) - \frac{V_{MP} + I_{MP} \cdot R_S}{R_{SH}} \tag{5}$$

Differentiating Eq. 2 with respect to V gives:

$$\frac{dI}{dV} = -\frac{\frac{I_o}{\eta \cdot V_t} \cdot e^{\frac{V + I \cdot R_S}{\eta \cdot V_t}} + \frac{1}{R_{SH}}}{\frac{I_o \cdot R_S}{\eta \cdot V_t} \cdot e^{\frac{V + I \cdot R_S}{\eta \cdot V_t}} + \frac{R_S}{R_{SH}} + 1} \tag{6}$$

Calculating Eq. 2 at the maximum power point, we have:

$$\frac{dP}{dV} = I + V \cdot \frac{dI}{dV} \tag{7}$$

$$I_{MP} - V_{MP} \cdot \left(\frac{\frac{I_o}{\eta \cdot V_t} \cdot e^{\frac{V_{MP}+I_{MP}\cdot R_S}{\eta \cdot V_t}} + \frac{1}{R_{SH}}}{\frac{I_o \cdot R_S}{\eta \cdot V_t} \cdot e^{\frac{V_{MP}+I_{MP}\cdot R_S}{\eta \cdot V_t}} + \frac{R_S}{R_{SH}} + 1} \right) = 0 \tag{8}$$

Considering and manipulating Eq. (3), (4) and (5) it is possible to express the parameters I_{PH}, I_0 and R_{SH} in function of R_S and η:

$$R_{SH} = -R_S + \frac{V_{MP} \cdot \left(e^{\frac{I_{SC}\cdot R_S}{\eta \cdot V_t}} - 1 \right) \cdot \left(e^{\frac{I_{SC}\cdot R_S}{\eta \cdot V_t}} - e^{\frac{V_{OC}}{\eta \cdot V_t}} \right) - V_{OC} \cdot \left(e^{\frac{I_{SC}\cdot R_S}{\eta \cdot V_t}} - e^{\frac{V_{MP}+I_{MP}\cdot R_S}{\eta \cdot V_t}} \right) \cdot \left(e^{\frac{I_{SC}\cdot R_S}{\eta \cdot V_t}} - 1 \right)}{I_{SC} \cdot \left[\left(e^{\frac{V_{MP}+I_{MP}\cdot R_S}{\eta \cdot V_t}} - 1 \right) \cdot \left(e^{\frac{I_{SC}\cdot R_S}{\eta \cdot V_t}} - e^{\frac{V_{OC}}{\eta \cdot V_t}} \right) - \left(e^{\frac{V_{OC}}{\eta \cdot V_t}} - 1 \right) \cdot \left(e^{\frac{I_{SC}\cdot R_S}{\eta \cdot V_t}} - e^{\frac{V_{MP}+I_{MP}\cdot R_S}{\eta \cdot V_t}} \right) \right] - I_{MP} \cdot \left(e^{\frac{I_{SC}\cdot R_S}{\eta \cdot V_t}} - 1 \right) \cdot \left(e^{\frac{I_{SC}\cdot R_S}{\eta \cdot V_t}} - e^{\frac{V_{OC}}{\eta \cdot V_t}} \right)} \tag{9}$$

$$I_{PH} = \frac{V_{OC} \cdot \left(e^{\frac{I_{SC}\cdot R_S}{\eta \cdot V_t}} - 1 \right) - I_{SC} \cdot (R_S + R_{SH}) \cdot \left(e^{\frac{V_{OC}}{\eta \cdot V_t}} - 1 \right)}{R_{SH} \cdot \left(e^{\frac{I_{SC}\cdot R_S}{\eta \cdot V_t}} - e^{\frac{V_{OC}}{\eta \cdot V_t}} \right)} \tag{10}$$

$$I_O = \frac{R_{SH} \cdot (I_{PH} - I_{SC}) - R_S \cdot I_{SC}}{R_{SH} \cdot \left(e^{\frac{I_{SC}\cdot R_S}{\eta \cdot V_t}} - 1 \right)} \tag{11}$$

Substituting these equations in (8) we have an equation in two variables R_S and η. Calculating the absolute minimum of the obtained function, it is possible to find the five parameters. The main point is that this approach has the advantage to use input data that are always provided by the manufacturers such as: V_{OC}, I_{SC}, V_{MP}, I_{MP}, irradiance and the PV cell temperature. In particular these data refer to STC conditions. In this case these parameters are specified with a lowercase "ref ", as follows: I_{PH_ref}, I_{0_ref}, $\eta_{\_ref}$, R_{S_ref} and R_{SH_ref}.

3 Experimental Setup

For the experiments, data relative to the basic PV module SG Mono GF245F, manufactured by SUNEL, has been used. This module is composed by 60 monocrystalline silicium cells. The advantage of using this module is that there is the possibility to have the six terminals of the three strings forming the module, that normally are connected in series. This is very useful in the case of shading or disuniform radiation. Having the outputs of the three strings, in fact, it is possible to obtain three maximum power points, each one relative to each sub-string. Moreover, it is possible to have different configurations connecting the strings in series or in parallel. Moreover, two solutions have been considered: mono junction-box and multi junction-box, shown in Fig. 1 and Fig. 2, respectively. While

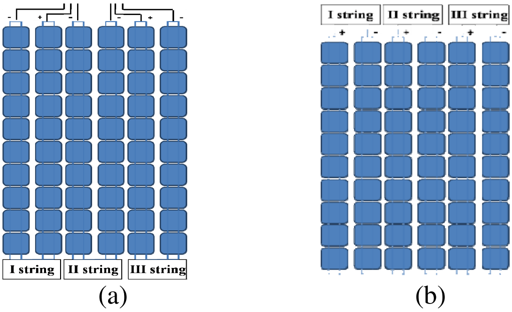


Fig. 2. Connection of PV module "SG Mono GF245F" manufactured by SUNEL; (a) mono junction-box solution; (b) multi junction-box solution

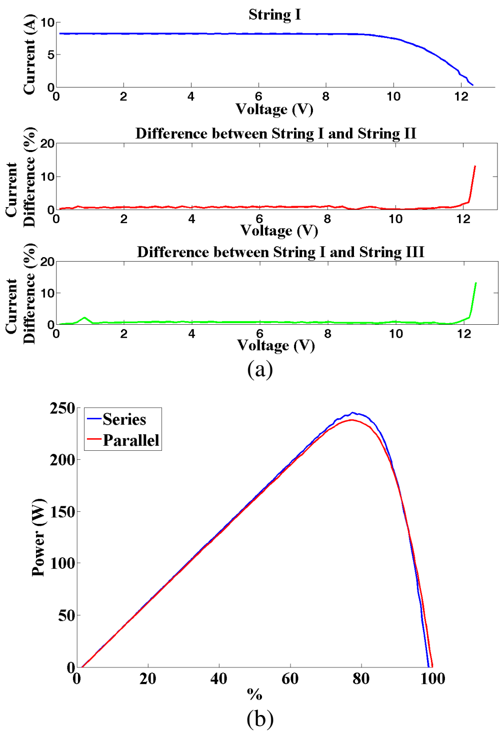
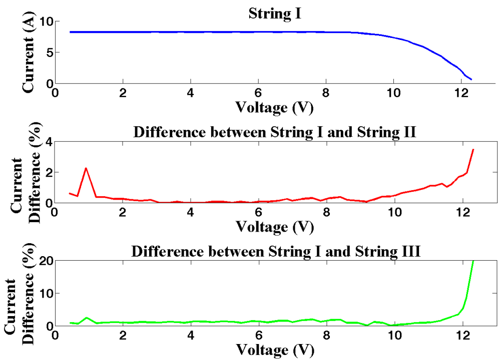
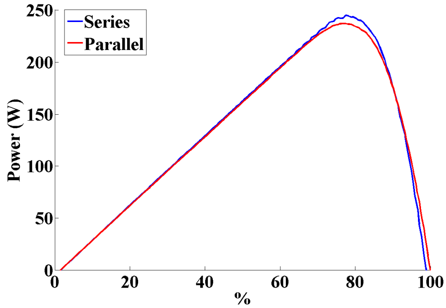


Fig. 3. Characteristics of the module SG Mono GF245F using a mono junction-box; (a) I-V curve of the string I and the difference between the current of string II and string III compared to the current of string I, on equal voltage; (b) Power curve considering series and parallel connections, in the x axis there is the percentage of the voltage relative to V_{OC}

Fig. 3 shows the I-V curve calculated in STC of each of the three strings and their connection in series and in parallel considering the mono junction-box solution, while Fig. 4 shows results obtained using a multi j-box solution. The I-V curves of the three sub-strings are compared, in particular the current of the string II and string III are compared with the current of the string I considering on equal voltage. The power of the series and parallel connections are also compared considering the percentage of the voltage respect to V_{OC}.



(a)



(b)

Fig. 4. Characteristics of the module SG Mono GF245F using a multi junction-box; (a) I-V curve of the string I and the difference between the current of string II and string III compared to the current of string I, on equal voltage; (b) Power curve considering series and parallel connections, in the x axis there is the percentage of the voltage relative to V_{OC}

4 Experimental Results

The five parameter model has been used starting from some data provided by the manufacturer of the module. In particular, the manufacturer provides the values of: V_{OC}, I_{SC}, V_{MP} and I_{MP} in STC relative to each string and the connection in series and parallel of the three strings, for both mono and multi junction-box solutions. These data have been obtained using a Solar Array Simulator PASAN class A. Data used in the model are reported in Table 1.

Using the five parameter model proposed in this paper, the parameter R_{S_ref} and $\eta_{\_ref}$ can be calculated and then the values of I_{PH_ref}, I_{0_ref} and R_{SH_ref} can calculated using Eq. 9, Eq. 10 and Eq. 11, starting from the values of V_{OC}, I_{SC}, V_{MP} and I_{MP}.

The model has been validated using numerical example. Fixing the values of the five parameters and starting from Eq. 3, Eq. 4 and Eq. 5, the values of V_{OC}, I_{SC}, V_{MP} and I_{MP} have been calculated and then the obtained values have been used to calculate I_{PH_ref}, I_{0_ref}, $\eta_{\_ref}$, R_{S_ref} and R_{SH_ref} using the method here implemented. Table 2 shows the obtained results, that demonstrate that the method here implemented can calculate the five parameter with a good approximation.

Applying the method here presented to the data obtained using the Solar Array Simulator relative to the "SG Mono GF245F" manufactured by SUNEL, we have noted that calculating the five parameters, their values depends on Maximum Power Point, and therefore the algorithm cannot converge if the values of V_{MP} and I_{MP} are not accurate. Therefore, an analysis of the I-V curves obtained starting from different values of V_{MP} and I_{MP} has been done. These values have been calculated varying the measured values of V_{MP} and I_{MP} (Table 3) of ±0.05 with a step of 0.0025, obtaining 1681 combinations of V_{MP} and I_{MP} values. Using these values the five parameters have been evaluated and the I-V curve has been estimated.

Table 1. Parameters of the PV module used in the numerical simulations, in STC (irradiation = 1kW/m2, temperature = 25°C)

		$V_{OC,ref}$	$I_{SC,ref}$	$V_{MP,ref}$	$I_{MP,ref}$
		(V)	(A)	(V)	(A)
Mono Junction-box	I String	12.3047	8.1934	9.6191	7.6953
	II String	12.3535	8.1494	9.6191	7.7246
	III String	12.3047	8.1152	9.6191	7.7637
	Series	37.2070	8.1445	29.1504	7.8857
	Paral.	12.4512	24.2725	9.6680	22.9980
Multi Junction-box	I String	12.3535	8.1982	9.4238	7.9395
	II String	12.3535	8.2129	9.7656	7.6563
	III String	12.3535	8.1982	10.0586	7.4707
	Series	37.1582	8.1933	29.1015	7.9003
	Paral.	12.5098	24.3164	9.6826	23.0420

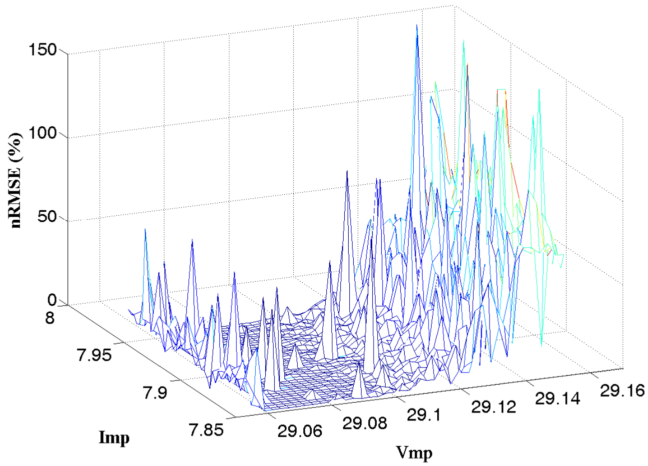
Table 2. Numerical example of the implemented method: T = 48.3°C, V_{OC} (V) = 18.7, I_{SC} (A) = 3.22, V_{MP}(V) = 14.6 and I_{MP}(A) = 2.91

	I_{PH_ref}	I_{0_ref}	$m\cdot\eta_{\_ref}$	R_{S_ref}	R_{SH_ref}
Starting value	3.2205	5.7782·10-7	46	0.3597	972.6
Estimated value	3.2208	3.9426e-007	42.4677	0.4201	905.5186

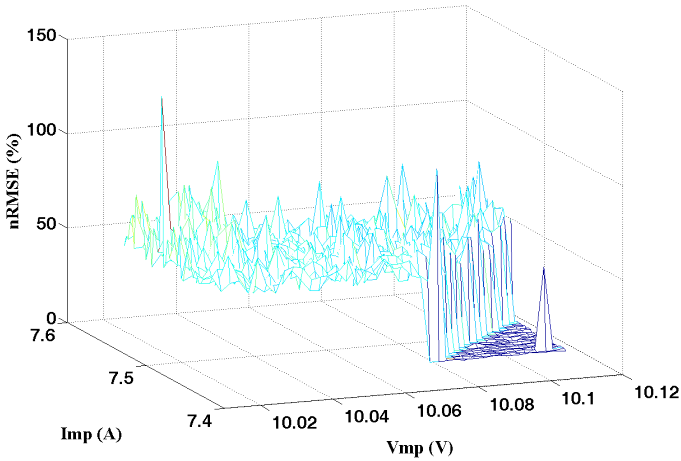
Then the error between the measured I-V curve and the estimated one has been evaluated using the normalized Root Mean Square Error (nRMSE) as main measure. The normalized Root Mean Square Error (nRMSE) is a non-dimensional form of the error:

$$nRMSE = \frac{\sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (y_i - x_i)^2}}{\sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (x_i)^2}} \tag{12}$$

where N is the number of data, the variable y_i represents the estimated value, while x_i represents the measured one.



(a)



(b)

Fig. 5. Error between the measured I-V curve and the estimated one considering different combinations of V_{MP} and I_{MP} values. Results are referred to (a) the series connection of the multi-junction solution; (b) the string III of the multi-junction solution.

Fig. 5 shows two example of the error between the measured I-V curve and the estimated one, considering different combinations of V_{MP} and I_{MP} values. Results are referred to the series connection of the multi-junction solution (Fig. 5.a) and the string III of the multi-junction solution (Fig. 5.b). As it possible to note, the values of nRMSE obtained using the five parameters calculated for each combination of V_{MP} and I_{MP} decrease in some areas of the graphics. That means that the correct Maximum Power Point is situated in that area.

Therefore, it is possible to assert that the measured I-V curve is coherent: if the values of voltage and current in the case of open circuit voltage, short circuit current and maximum power point satisfy the implemented model: if I_{PH_ref}, I_{0_ref}, and $R_{SH\_ref.}$ satisfy the analytical equations; and if exists a numerical solution of $\eta_{\_ref}$ and R_{S_ref} that is coherent with the physic significance of these parameters.

5 Conclusion and Future Works

In this context, an analytical model to evaluate the energy performance of an I-V characteristic of a photovoltaic module is proposed. The model is based on some data provided by the manufacturer of the module. It has been validated using numerical examples, and results show how it is used to estimate the I-V curve of a photovoltaic module with a good precision. The photovoltaic module used during the experiments gives the possibility to have six output terminals, relative to each of the three sub-strings forming the module. Therefore, the manufacturer provided us data relative to the three remarkable points of the I–V curve of the practical array: open circuit, maximum power, and short circuit in STC relative to each string and the connection in series and parallel of the three sub-strings, measured using a Solar Array Simulator. These data have been used to evaluate the I-V curves relative to each case and then these results have been compared with the measured ones and the errors have been calculated using the Root Mean Square Error (nRMSE) as main measure, and tested using both measured and estimated data relative to each single string and their connection in series and parallel. Results show how the parameters extraction depends on the measured value of the maximum power points, if measures are not accurate the analytic model here implemented cannot converge to a feasible solution. Therefore, it is possible to assume that the values of voltage and current in the case of open circuit voltage, short circuit current and maximum power point satisfy the implemented model: if I_{PH_ref}, I_{0_ref} and $R_{SH\_ref.}$ satisfy the analytical equations and if exists a numerical solution of $\eta_{\_ref}$ and R_{S_ref} that is coherent with the physic significance of these parameters.

The I-V curve varies with irradiance and cell temperature so, as matter of fact, an analysis of dependence of the parameters on operating conditions is needed.

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