COMPARISON OF SINGLE-DIODE MODELS APPLIED TO THIN FILM PV MODULE OPERATING UNDER DIFFERENT ENVIRONMENTAL CONDITIONS

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Abstract: The electrical current-voltage (I-V) characteristic a of photovoltaic (PV) module depends on the environmental conditions under which it operates. The shape of the I-V curve depends on the solar cell technology and changes dynamically in time with irradiance and temperature. A simulation model of the PV module can be used to examine the dynamic behavior of the I-V curve as well as to extract the module parameters from the curves.

This paper presents the results of comparison of two different models based on a single-diode equivalent circuit applied to a thin film module. The Matlab/Simulink simulation studies of I-V characteristic curves in the function of irradiance and temperature were carried out. The results were compared with the experimental data of the I-V curves obtained from outdoor measurements. Relative errors of the simulation and experimental results were analyzed.

Keywords: solar energy, photovoltaics, I-V electrical characteristics, computational modeling

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1. Introduction

The world energy consumption increases continuously. Fossil fuels which are nowadays the most important energy resources are running out and they will become very expensive in the nearest future [1, 2]. Oil and natural gas are finite resources and will run out in 40 and 60 years, respectively. Coal, one of the most widely used energy resources will run out in about 130 years [3]. Governments of many countries are working on alternative solutions of producing energy from coal, petroleum or gas. Many of them focus on environmentally friendly technologies, which allow obtaining clean energy. Among a variety of renewable energy resources, solar energy has a great potential that can be used.

Photovoltaic systems are non-polluting, do not create greenhouse gases, do not create waste that needs storing. Solar modules have no moving parts so they are also far quieter than wind turbines. They require very little maintenance beyond regular cleaning because they do not have any moving parts to break and replace. Almost the total cost of the PV systems is the initial cost of installation [4].

The conversion efficiency of a PV module depends on its technology. It varies from 7% in case of thin film to 19% for monocrystalline silicon modules [5]. Irradiation as well as the operation temperature of PV modules has a significant impact on the conversion efficiency and energy output of the module [6].

In order to standardize the information about the PV module of different technology a current-voltage characteristic is measured under standard test conditions (STC) defined as follows: Irradiance $G^* = 1000\,\mathrm{W/m^2}$, module temperature 25°C, AM 1.5 spectrum. A typical I-V characteristic curve of the solar cell has been shown in Figure 1. As can be seen from the figure, the I-V curve is characterized by the following three points [7, 8]:

- The Maximum Power Point (MPP) is the point on the I-V curve at which the PV module works with maximum power across the load. For this point, the maximum current I_m and maximum voltage V_m can be found;
- The short-circuit current I_{sc} is the current that corresponds to the short circuit condition when voltage is equal to 0;
- The open-circuit voltage V_{oc} is the voltage when the open circuit occurs and there is no current in the cell.

Commercial PV design software uses the information about the I-V curve of the module to calculate the amount of energy produced by the photovoltaic system [9].

Considering the output power of a PV module for cloudy conditions [10], the model has to be fast enough to follow the I-V curves that change dynamically in time. An efficient approach which works well with the silicon crystalline solar cells is the model based on a single diode with series resistance included [11, 4]. The results of the I-V curve modeling for different irradiation and temperature can be found in [12] and [13], respectively. However, many of the researches were verified on crystalline solar modules of the small power in comparison with modules available on the market today [14–17]. The main purpose of this paper was to carry out the Matlab/Simulink simulations to verify the single diode model applied to a thin film module for different irradiance and temperature. Two approaches were taken into consideration. First, the approach presented in the work of [10] and second, the approach described in paper [18]. Both methods were implemented using the Matlab/Simulink software.

The results of calculations were compared with experimental data collected from outdoor measurements for different environmental conditions.

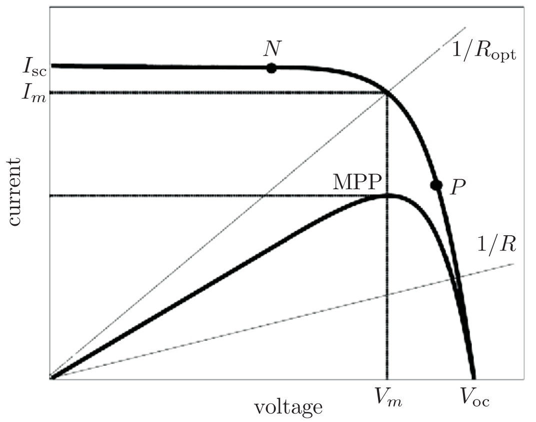

Figure 1. Current-voltage and power-voltage characteristic of PV module

2. PV module modeling

The I-V electrical characteristic curves under various environmental conditions were modeled with the use of a one-diode model following the studies developed by [10]. This model has been tested before [14, 15] on silicon crystalline modules with low output power. According to the model, the net current of the PV cell can be calculated as a difference between photocurrent I_L and the normal diode current:

$$I = I_L - I_0 \left(e^{\frac{q(V+IR_s)}{nkT}} - 1 \right) \tag{1}$$

where

I_0 – the saturation current of the diode,
q – the electron charge $1.6 \cdot 10^{-19}$ C,
k – the Boltzmann constant $1.381 \cdot 10^{-23}$ J/K.
T – the temperature of the cell
R_s – the series resistance of the cell
n – the ideality factor (shape factor)

Photocurrent I_L depends on the solar irradiance G and temperature T of the cell. It can be calculated from the expression:

$$I_L = I_{sc}^* \frac{G}{G^*} + \mu_{isc}(T - T^*) \tag{2}$$

where

G, G^* – the actual irradiance and irradiance at the reference conditions
T^* – the cell temperature at the reference conditions in Kelvins
μ_{isc} – the temperature coefficient of the short circuit current

The saturation current of the diode I_0 depends on the temperature only. It can be expressed by the equation:

$$I_0 = I_0(T^*) \left(\frac{T}{T^*} \right)^{\frac{3}{n}} e^{\frac{qV_g}{nk\left(\frac{1}{T} - \frac{1}{T^*}\right)}} \tag{3}$$

where V_g – the material bandgap energy (1.12 eV for crystalline Si, 1.75 eV a-Si).

$$I_0(T^*) = \frac{I_{\mathrm{sc}}(T^*)}{e^{\frac{qV_{\mathrm{oc}}(T^*)}{nkT^*}} - 1} \tag{4}$$

The ideality factor n usually takes a value between 1 and 2 in dependence of the technology of the module. An estimation has to be done to obtain the best curve match. Values of n factors for different module technologies can be found in [15].

The set of Equations (1)–(4) was solved numerically with the use of the iterative Newton-Raphson method, which is the most familiar, root finding procedure for finding solutions in the PV modeling area. A set of I-V characteristics points was obtained as an output for a given irradiance and temperature of the module. The results of the simulation with use of the approach described above are discussed in the next sections of this paper.

As regards the second approach of applying a single-diode model to thin a film module, the value of n factor is determined using the method described in [18]. This method forces the I-V curve to move around three main points of the characteristic, i.e. the current at short circuit I_{sc}, the voltage at open circuit V_{oc}, voltage V_m and current I_m at a maximum power point. Including the relationship between voltage and current in these points a set of equations can be obtained:

$$I_{\mathrm{sc}}^* = I_L^* - I_0^* \left(\exp\left(\frac{qI_{\mathrm{sc}}^* R_s}{nkT^*} \right) - 1 \right) \tag{5}$$

$$0 = I_L^* - I_0^* \left(\exp\left(\frac{qV_{\mathrm{oc}}^*}{nkT^*} \right) - 1 \right) \tag{6}$$

$$I_m^* = I_L^* - I_0^* \left(\exp\left(\frac{q(V_m^* + I_m^* R_s)}{nkT^*} \right) - 1 \right) \tag{7}$$

Due to the fact that the reverse saturation current I_0 for any diode is a very small quantity, the impact of the exponential part of equation (5) is minimized. It leads to the assumption that the photocurrent at this condition is equal to the short-circuit current. Another simplification concerns the first term of equations (6)-(7). The exponential term is much greater than the first term, that can be neglected. Taking these assumptions into consideration equation (7) can be written as follows:

$$I_m^* = I_{\mathrm{sc}}^* - I_0^* \exp\left(\frac{q(V_m^* + I_m^* R_s)}{nkT^*} \right) \tag{8}$$

Finally, having applied the assumption, I_0^* can be written as follows:

$$I_0^* = I_{\mathrm{sc}}^* \exp\left(\frac{-qV_{\mathrm{oc}}^*}{nkT^*} \right) \tag{9}$$

Combining equations (8) and (9), the value of n can be calculated from the following equation:

$$n = \frac{q(V_m^* + I_m^* R_s - V_{\mathrm{oc}}^*)}{kT^* \ln\left(1 - \frac{I_m^*}{I_{\mathrm{sc}}^*}\right)} \tag{10}$$

As can be seen from equation (10), the ideality factor n depends on the series resistance of the module and the I-V reference parameters measured under the STC. These values are taken form the manufacturer data sheet.

In order to find the series resistance R_s the iterative search method based on a correlation between the temperature coefficient of the open-circuit voltage μ_{Voc} supplied by the manufacturer and the coefficient value calculated from the analytical equation (11) were used.

$$\mu_{\mathrm{Voc}} = \frac{\partial V_{\mathrm{oc}}^*}{\partial T^*} = \frac{nk}{q}\left[\ln\left(\frac{I_{\mathrm{sc}}^*}{I_0^*}\right) + \frac{T^* \mu_{\mathrm{Isc}}}{I_{\mathrm{sc}}^*} - \left(3 + \frac{qV_g}{nkT^*}\right)\right] \tag{11}$$

The basic idea of the procedure is to use the binominal search routine in order to find new guesses of R_S on the basis of μ_{Voc} calculations compared to the reported value. The bisection method has been chosen to converge on the proper value of μ_{Voc} by making new guesses for R_S. If convergence is good enough, R_S as well as the value of n are determined. On the basis of these parameters and the procedure described by equations (1)-(4) the I-V characteristic can be calculated. The results of simulations carried out on the basis of the two described approaches were compared with outdoor experimental measurements for different environmental conditions.

3. Experimental set-up

Taking into account the restricted conditions that have to be fulfilled during the measurements (high irradiance, approx. constant temperature, low wind speed), the data was measured in the Mediterranean Climate with use of an automatic test and measurement system that was designed and developed by the IDEA Solar Energy Research Group of the University of Jaen. Voltage and current pairs were measured and their I-V characteristic curve was traced every 5 minutes. The effect of the atmospheric conditions on the electrical behavior of the modules was also investigated. For plotting the I-V curve the measurement system was equipped with a capacitive load designed and built up by the IDEA research group [19]. The LabView$^{\mathrm{TM}}$ program controls the weather station and stores the atmospheric parameters in the same file together with the I-V characteristics, *i.e.* relative humidity, ambient temperature, spectral distribution [20].

4. Results and Discussion

The Phoenix thin film module was chosen for the I-V electrical characteristic modeling and experimental measurements. The key specification of the module under STC is shown in Table 1. The parameters were taken from the manufacturer's datasheet.

The computational simulations as well as outdoor measurements were carried out for irradiance ranged from $800\,\mathrm{W/m^2}$ to $1100\,\mathrm{W/m^2}$. The module temperature was varied from 38.6°C to 47.0°C.The response of the photovoltaic module on different irradiance as well as various temperatures have been shown in Figures 2–5. It can be seen that irradiance has a great impact on the short circuit current. A higher value of irradiance leads to an increase in the short circuit current and thus to higher power generation.

Table 1. Specification of the Phoenix module under STC

Parameter	Variable	Value
Peak Power	P_m	121 W
Short-circuit current	I_{sc}	3.34 A
Open-circuit current	V_{oc}	59.2 V
Voltage at MPP	V_m	59.2 V
Current at MPP	I_m	2.69 A
Temp. coefficient of I_{sc}	μ_{Isc}	0.07%/°C
Temp. coefficient of V_{oc}	μ_{Voc}	–0.3%/°C

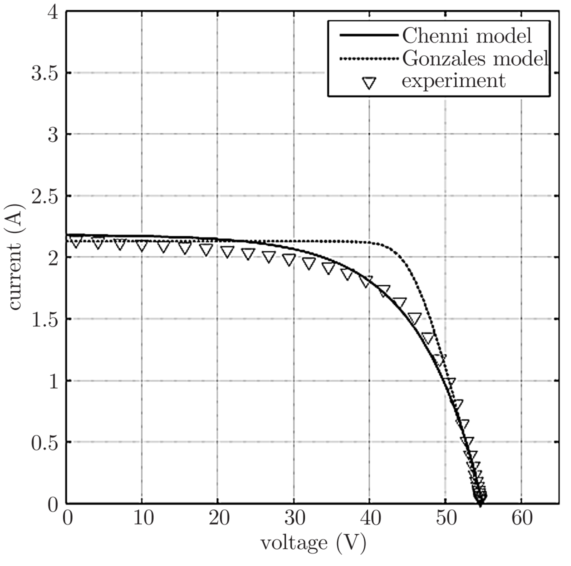

Figure 2. Comparison of calculated and measured I-V characteristic curves for irradiance level equal to 800 W/m^2 and temperature equal to 47°C

Similarly to the irradiance dependency on the I-V curve, changes in the temperature of the module lead to changes in the open circuit voltage. The value of V_{oc} decreases with an increase in temperature what means that the temperature has also a significant impact on the output power generation of the PV module. Tables 2–3 show the comparison between outdoor experimental measurements and simulation results that were carried out on the basis of two models applied to the commercial thin film module. As can be seen from the tables, in case of the short circuit current and the open circuit voltage, both models were characterized by a satisfying accuracy. However, the precision of the maximum power point estimation is high only in terms of the second approach (Table 3).

More detailed calculations of relative errors in comparison between the results of both simulation methods and experimental measurements of the short circuit current, open circuit voltage and maximum power point are also shown in Tables 2–3.

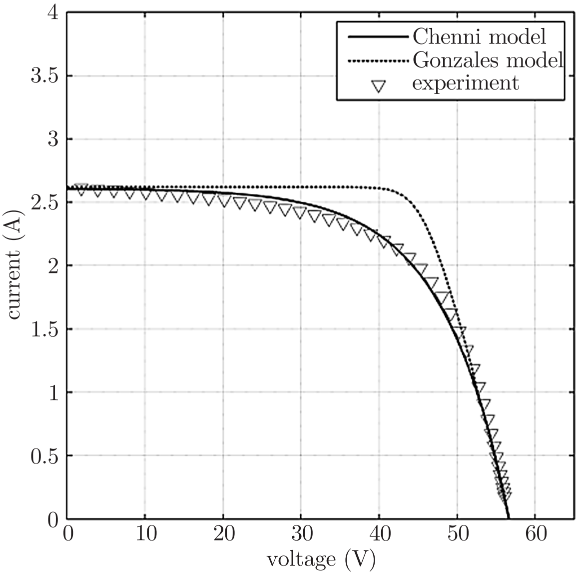

Figure 3. Comparison of calculated and measured I-V characteristic curves for irradiance level equal to 900 W/m^2 and temperature equal to 40.8°C

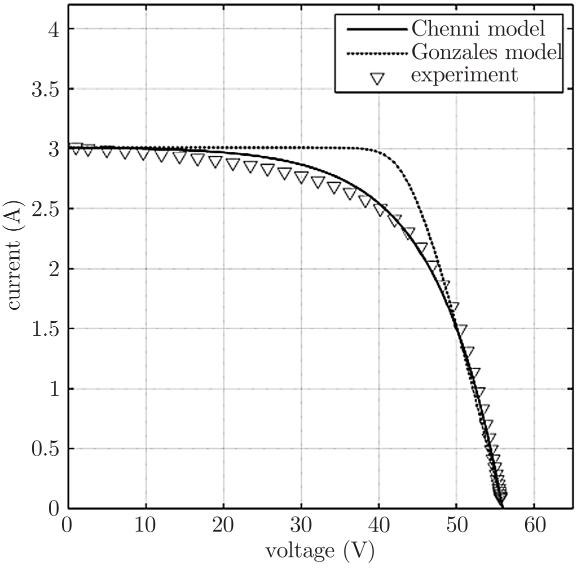

Figure 4. Comparison of calculated and measured I-V characteristic curves for irradiance level equal to 1000 W/m^2 and temperature equals 38.6°C

As can be seen, the average relative error in terms of I_{sc}, V_{oc} and P_m values was found to be 0.35%, 0.3% and 16.35%, respectively. These results prove that the precision of the model is good enough for the short circuit current and the open circuit voltage estimation under different environmental conditions. However, in terms of the maximum power point the estimation is very poor. For this reason,

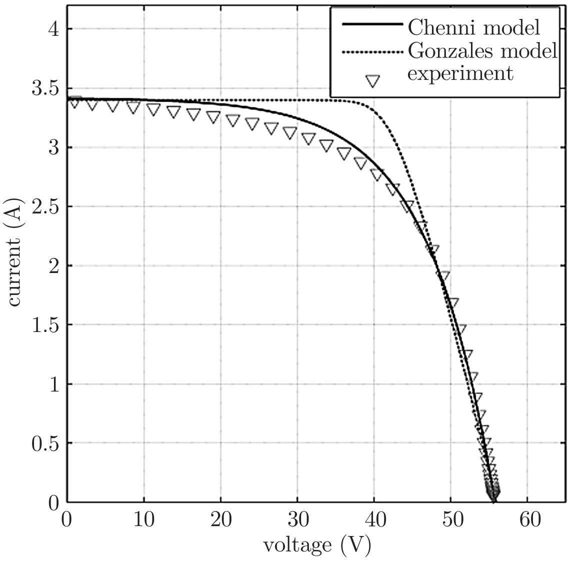

Figure 5. Comparison of calculated and measured I-V characteristic curves for irradiance level equals 1100W/m^2 and temperature equal to 46.3°C

Table 2. Simulation errors on the maximum power point at various irradiance levels (Gonzales approach [10])

G (W/m^2)	T (°C)	Gonzales model			Experiment			Relative error (%)		
		I_{sc}	V_{oc}	P_m	I_{sc}	V_{oc}	P_m	I_{sc}	V_{oc}	P_m
800	47.0	2.2	54.5	86.9	2.2	54.7	72.7	0.5	0.4	19.5
900	40.8	2.6	56.5	102.2	2.6	56.6	90.5	0.0	0.2	12.9
1000	38.6	3.0	55.8	119.0	3.0	56.0	101.4	0.7	0.4	17.4
1100	46.3	3.4	55.6	130.5	3.3	55.7	112.9	0.2	0.2	15.6

Table 3. Simulation errors on the maximum power point at various irradiance levels (Chenni approach [18])

G (W/m^2)	T (°C)	Gonzales model			Experiment			Relative error (%)		
		I_{sc}	V_{oc}	P_m	I_{sc}	V_{oc}	P_m	I_{sc}	V_{oc}	P_m
800	47.0	2.1	54.9	72.2	2.2	54.7	72.7	4.5	0.4	0.7
900	40.8	2.6	56.5	88.8	2.6	56.6	90.5	0.4	0.2	1.9
1000	38.6	3.0	55.8	100.8	3.0	56.0	101.4	0.7	0.4	0.6
1100	46.3	3.3	55.6	113.6	3.3	55.7	112.9	0.6	0.2	0.6

the presented method cannot be used for power production modeling in case of thin film modules. Relative errors of the simulation results in case of the second approach, presented in Table 3, are characterized by similar behavior in terms of the short circuit current and the open circuit voltage. Average values of relative errors were found to be 1.5% and 0.3%, respectively. What is more, the maximum power point estimation results were found to be much better than in the case of the first method. The relative error was found to be 0.95%. It classifies this approach as a fast and simple method that is precise enough for the I-V electrical characteristics modeling of thin film modules.

5. Conclusion

The I-V characteristics of the thin film commercial module were obtained using the Matlab/Simulink simulation studies. The modeling results for various irradiance and temperature of the module were compared to the outdoor measurements results. Two methods of the single-diode model were taken into consideration. It was observed that the results calculated on the basis of both methods showed a good correspondence to the experimental results in terms of the short circuit current and the open circuit voltage with the average relative error varying from 0.3% to 1.5% in dependency of the environmental conditions. However, in the case of the maximum power point estimation, it was only the model presented in [18] that was found to be precise enough (average relative error less than 1%) to map the I-V curve shape in good agreement with the experimental one. It leads to the conclusion that the proposed model can be considered in further research on simulations of energy production by a thin film module.

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