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A method for modelling photovoltaic modules under non-standard conditions of solar radiation and ambient temperature in Quibdó, Colombia

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ABSTRACT
This work describes a mathematical model developed to estimate the *I–V* and *P–V* curves of photovoltaic modules operating under non-standard conditions of irradiance and temperature in Quibdó, Colombia.

The model was implemented using the Matlab™ software using an equivalent circuit of a diode for a photovoltaic panel. The input parameters of solar radiation and ambient temperature were obtained from a monitoring station installed in the city of Quibdó. The average annual solar radiation was 256.96 W/m^2 while the annual average temperature was 27.59°C in 2015. The model resulted in curves for *I–V* and *P–V*. These were compared with simulated results from the information reported by the manufacturer of a polycrystalline 250 W silicon solar panel (reference AS-6P30), which is part of a photovoltaic system 2 kW interconnected with the grid. This resulted in an average error of 0.5% for the *I–V* curve and 0.3% for the *P–V* curve.

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KEYWORDS
Photovoltaic; solar cells; solar radiation; temperature

1. Introduction

Only a fraction of solar radiation is converted by photovoltaic (PV) systems into electricity, while a large part of the thermal energy is wasted and contributes to the increase of solar (or PV) cell temperature (Spertino et al. 2016). As a consequence, the electrical efficiency drops (Kalogirou and Tripanagnostopoulos 2006; Chow 2010), because the performance of solar cells depends on their ambient conditions. Therefore, the cell operating temperature plays a major role in its performance.

In PV inverters, the maximum power point tracking (MPPT) circuit should be connected to the PV array and the load, as it plays a key role in the efficiency of the PV array. At present, the conventional MPPT control methods are: constant voltage tracking method, perturbation and observation (P&O) method, and incremental conductance method (Zhou, Wu, and Li 2008; Koran, LaBella, and Jih 2014; Zhou and Sun 2015). However, these methods are based on stable irradiation and no shadow.

The core of a PV module modelling process is estimating equivalent circuit DC parameters. In general, these parameters can be estimated using two types of approach: analytical (King, Boyson, and Kratochvil 2004) and numeric (Ma, Yang, and Lu 2014). An analytical approach offers fast and simple parameter calculations (Chan and Phang 1987), but is not as accurate as a numerical approach since the simplifications in the numerical approach model do not reflect real operational conditions.

Many studies have been devoted to developing different non-linear electric models which are used to describe the characteristics of the PV modules and the effect on the module temperature performance, under non-standard conditions of radiation intensity and ambient temperature.

In this paper we present a mathematical procedure to calculate the *I–V* and *P–V* curves of a PV module of 250 W, which is part of a Building Integrated Photovoltaic System (BIPVS) of 2 kW. The system is installed at the Universidad Tecnológica del Chocó, in Quibdó, Colombia. The results are compared with data reported by the manufacturer.

The great contribution of this work is in the field of the characterisation of PV systems operating in climatic conditions of the tropical region of the Department of Chocó in Colombia. This region is the poorest in Colombia. This population has great needs in health, education and work opportunities. They have serious problems accessing electricity. This work will allow us to move forward in offering the community opportunities for access to energy for their daily needs.

2. Theoretical analysis

In general, the equivalent circuit of a solar cell consists of: a current source photogenerated by the action of solar radiation; a diode representing operation in darkness; a resistor in parallel; and a series resistor, which represents the internal resistance of the material to current flow (see Figure 1) (Narvaez et al. 2013; Granda-Gutiérrez et al. 2013).

In Figure 1, series resistor R_s is due to the load resistance of the semiconductor material, the metal contacts and interconnections, and contact resistance between the semiconductor and the metal contacts. Parallel resistor R_p is due to no idealities and impurities near the p–n junction.

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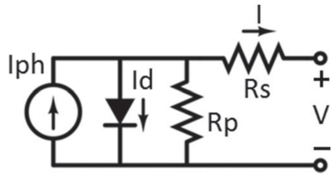

Figure 1. Equivalent circuit diagram of a PV cell (Narvaez et al. 2013).

To demonstrate the equation defining the mathematical model of a PV cell, the Kirchhoff equation is used:

$$I = I_{ph} - I_d - I_{sh}, \quad (1)$$

where:

$$I_d = I_0(e^{(V+IRs)/V_t} - 1), \quad (2)$$

$$I_{sh} = \frac{V + IR_s}{R_p}. \quad (3)$$

Substituting in Equation (1):

$$I = I_{ph} - I_0(e^{((V+IR_s)/V_t)} - 1) - \frac{V + IRs}{R_p}, \quad (4)$$

I_{ph} is defined as the photogenerated current which is proportional to the irradiance on the surface of the cell (Equation (7)), I_0 is the saturation current of the diode, V_t is the thermal voltage given by Equation (5), R_s is the series resistor *y* and R_p is the parallel resistor.

$$V_t = \frac{mkT}{q}, \quad (5)$$

V_t is the equation that describes the thermal voltage, k is the Boltzman constant (1.38×10–23 J/K), T is the absolute temperature of the cell, q is the electron charge (1.6 × 10–19 C) and m is the diode ideality factor ($1 < m < 2$). This allows a distinction to be made between a cell behaviour silicon = 2 and germanium = 1, and subsequently the manufacturing technology of the solar cell.

The equation for the current is represented by:

$$I = I_{ph} - I_0(e^{(q(V+IR_s)/mkT)} - 1) - \frac{V + IRs}{R_p}. \quad (6)$$

Some parameters contained in Equation (6) are not provided by the manufacturer, such as (I_{ph}, I_0, R_s and V_t) which shall be determined for the *I*–*V* relationship. Since the above parameters are a function of temperature and solar radiation, this allows the photogenerated current to be calculated.

$$I_{ph} = \frac{S}{S_{Ref}}[I_{ph,\,Ref} + \mu_{ISC}(T_C - T_{C,\,REF})], \quad (7)$$

where S is the solar radiation (W/m^2); S_{Ref} the solar radiation at reference conditions (1000 W/m^2); $I_{ph,Ref}$ the photogenerated current at reference conditions ($I_{ph,Ref} = I_{SC}$); T_C the cell temperature PV (°C); $T_{C,REF}$ the reference temperature (25°C); μ_{ISC} the temperature coefficient of the short circuit current (A/°C). It is important to note that I_{ph} and μ_{ISC} are available on the manufacturer's data sheet.

The saturation current I_0 (Equation (8)) of the diode is an approximation of the transport mechanisms in cell reverse current semiconductor junction.

$$I_0 = I_{0,\,Ref}\left(\frac{T_{C,\,Ref} + 273.15}{T_C + 273.15}\right)^3 \times \exp\left[\frac{e_{gap}N_s}{qV_t}\left(1 - \frac{T_{C,\,Ref} + 273}{T_c + 273}\right)\right], \quad (8)$$

where, for a silicon device, the saturation current density (I_0/ (cell area)) is from 10–12 A/cm^2. In the darkness under zero voltage, the cell current is approximately equal to the saturation current. e_{gap} is the energy range of the band material (1,17 eV for Si) [30].

To calculate the saturation current at reference conditions $I_{0,Ref}$ given in Equation (8), Equation (8a) was used, which takes values provided by the manufacturer, such as $V_{OC,REF}$ (open circuit voltage (V)) of the PV panel (Krismadinataa, Rahima, Pinga, and Selvaraja 2013; Bellia, Youcef, and Fatima 2014).

$$I_{0,\,Ref} = I_{ph,\,Ref}\exp\left(-\frac{V_{oc,\,Ref}}{V_{t,\,Ref}}\right). \quad (8a)$$

The behaviour of the *I*–*V* curve of the PV cell is described by Equations (4), (5) and (8) (Castro, Algarín, and Pabón 2014).

To calculate the thermal reference voltage $V_{t,Ref}$, Equation (8a) takes into account Equation (9) (Bellia, Youcef, and Fatima 2014).

$$V_{t,\,Ref} = \frac{2V_{mp,\,Ref} - V_{oc,\,Ref}}{\frac{I_{sc,\,Ref}}{I_{sc,\,Ref} - I_{mp,\,Ref}} + \ln\left(1 - \frac{I_{mp,\,Ref}}{I_{sc,\,Ref}}\right)}, \quad (9)$$

where $V_{mp,Ref}$ is the maximum power point voltage (V) at reference conditions; $I_{mp,Ref}$ the maximum power point current (A) at reference conditions; $I_{sc,Ref}$ the short circuit current (A) at reference conditions.

Furthermore, the thermal voltage V_t in function of temperature is expressed as:

$$V_t = \frac{T_c + 273}{T_{c,\,Ref} + 273}V_{t,\,Ref}. \quad (10)$$

Finally, the equation for computing the series resistance (R_s), if the value is not provided by the manufacturer, is (Bellia, Youcef, and Fatima 2014):

$$R_s = \frac{V_{Ref}\ln\left(1 - \frac{I_{mp,\,Ref}}{I_{sc,\,Ref}}\right) + V_{oc,\,Ref} - V_{mp,\,Ref}}{I_{mp,\,Ref}}. \quad (11)$$

The model described above was implemented in Matlab™ through iterative loops, resulting in the performance curves of the 250 W (AS-6P30) PV panel for different levels of solar radiation and ambient temperature. The time records of solar radiation and ambient temperature were used, and were measured by an automatic weather station located in the city of Quibdó (5.45°N, 76.39°W) installed at the Universidad Tecnológica del Chocó, at an altitude of 53 m above sea level and approximately 85 km from the Pacific Ocean.

Table 1 shows the averages of solar radiation and ambient temperature for every month of 2015. These were used as input parameters of the model developed in Matlab™.

Table 1. Monthly average of solar irradiance and temperature measured at the weather station of Universidad Tecnológica del Chocó, 2015.

Month	Temperature (°C)	Irradiance (W/m^2)
January	26.92	212.41
February	26.82	215.96
March	26.83	218.90
April	27.50	263.75
May	27.81	265.67
June	28.50	283.03
July	27.70	262.90
August	27.85	277.73
September	27.96	287.49
October	27.63	263.21
November	27.61	271.22
December	27.91	213.30
Annual average	27.59	252.96

Table 2. Data sheet reported by the manufacturer of the solar panel AS-6P30.

Electrical parameters at STC	AS-6P30
Nominal power (*P*max)	250 W
Open circuit voltage (V_{OC})	38.0 V
Short circuit current (I_{SC})	8.75 A
Voltage at nominal power (V_{mp})	30.3 V
Current at nominal power (I_{mp})	8.26 A
Module efficiency (%)	15.37
Number of cells in series (*N*s)	60
Number of cells in parallel (*N*p)	1

Table 2 shows the data sheet of the 250 W polycrystalline solar panel at reference conditions (STC, solar radiation = 1000 W/m^2, cell temperature = 25°C, AM = 1.5), which consists of 60 solar cells.

3. Results and discussion

For the model in Matlab™, radiation and temperature data were analysed in the installation site of the solar panel for the purpose of modelling *I*–*V* and *P*–*V* curves under non-standard conditions. Table 1 shows that 2015 had an annual average solar radiation of 252.9 W/m^2 and an annual average temperature of 27.6°C.

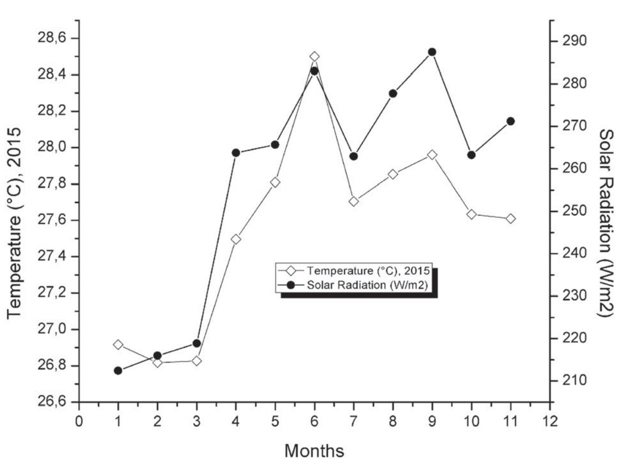

Figure 2. Average solar radiation and ambient temperature in Quibdó, Colombia, 2015.

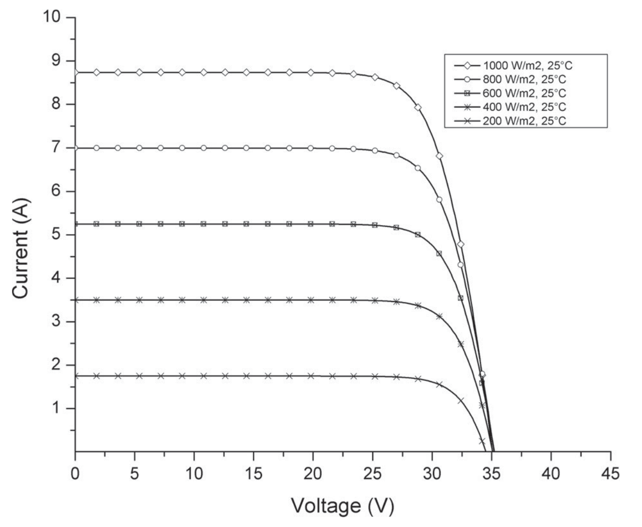

Figure 3. Variation of the *I*–*V* curves of the PV module for different values of solar radiation and 25°C.

Figure 2 shows the average solar radiation and ambient temperature for 2015 in Quibdó.

September 2015 presented the highest radiation month (283.03 W/m^2), while the minimum average irradiance occurred in January 2015 (212.41 W/m^2). June had the highest average temperature (29°C), while February and March 2015 had lowest average temperatures (26.82°C and 26.83°C, respectively).

Figure 3 shows *I*–*V* curves generated by the model for different values of solar radiation and constant temperature. The irradiance varied between 200 W/m^2 and 1000 W/m^2, with a temperature of 25°C.

For 800 W/m^2, the current recorded was 7 A with an open circuit voltage of 35 V. For standard solar radiation of 1000 W/m^2, the current obtained was 8.70 A and an open circuit voltage of 35 V. For the same level of solar radiation, the solar panel manufacturer reported a short-circuit current of 8.75 A and open circuit voltage of 38 V (Table 2). This difference represents an error of 0.5% between the data generated by the model developed in Matlab™ and data reported by the manufacturer.

Figure 4 shows the *P*–*V* curves generated by the model for different irradiance values and with a constant temperature of 25°C.

- For a solar radiation level of 200 W/m^2 and 25°C of temperature, the open circuit voltage was 34.8 V and 48 W of DC power.
- For a solar radiation level of 1000 W/m^2 and 25°C of temperature, open circuit voltage was 35 V and 246 W of DC power.
- The percentage error between the maximum power point of the solar module, reported by the manufacturer and delivered by the model with 1000 W/m^2 and 25°C, was 1.5%.

Figure 5 shows the *I*–*V* curves generated by the model for temperatures between −25°C and 75°C and a constant radiation of 1000 W/m^2.

It can be observed that the performance of the panel is greater with a temperature of −25°C and 1000 W/m^2 of solar radiation.

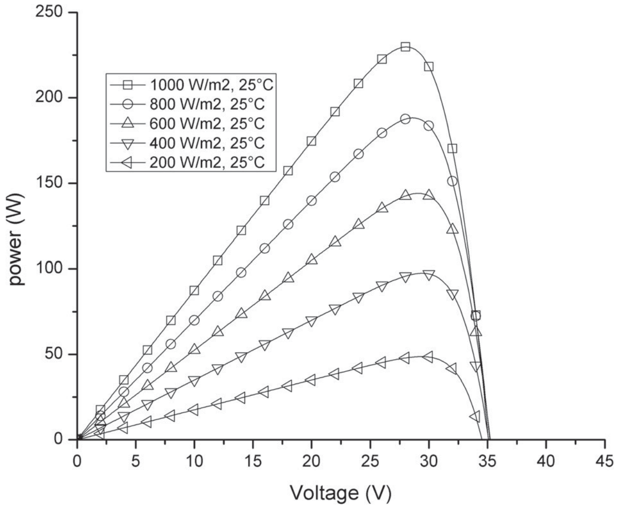

Figure 4. Variation of the *P–V* curves of the solar module for different values of solar radiation and 25°C.

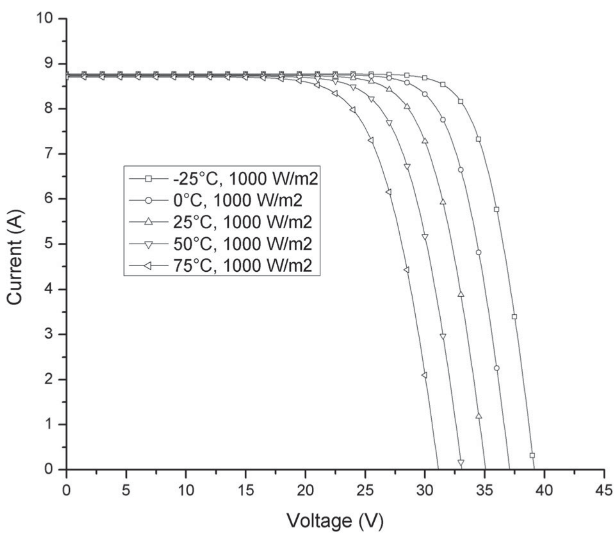

Figure 5. Variation of the *I–V* curves of the solar module for different values of temperature and 1000 W/m^2.

For −25°C, the current calculated was 8.70 A with 38 V of open circuit voltage. For a standard temperature of 25°C, the current obtained was 8.70 A and 35 V of open circuit voltage. For the same level of solar radiation, the manufacturer reported a short-circuit current of 8.75 A and 38 V of open circuit voltage (Table 2). This difference represents an error of 0.05% between the data produced by the model developed in Matlab™ and data reported by the manufacturer.

Figure 6 shows the *P–V* curves generated by the model for different values of temperature and 1000 W/m^2 of solar radiation.

- For a temperature level of 75°C and 1000 W/m^2, the open circuit voltage was 32 V and 185 W of DC power.
- For a temperature level of −25°C and 1000 W/m^2, the open circuit voltage was 38 V and 275 W of DC power.

In addition, the results for *I–V* and *P–V* curves are presented (Figures 7 and 8), with data of radiation and temperature measured at the site of installation during 2015 (Table 1). The

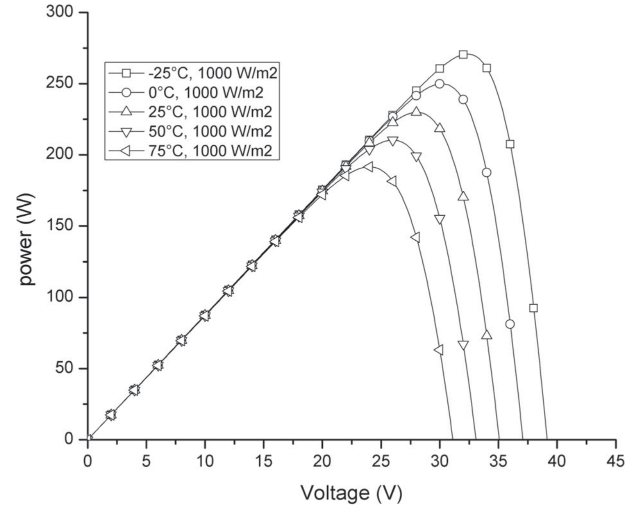

Figure 6. Variation of the *P–V* curves of the solar module for different values of temperature and 1000 W/m^2.

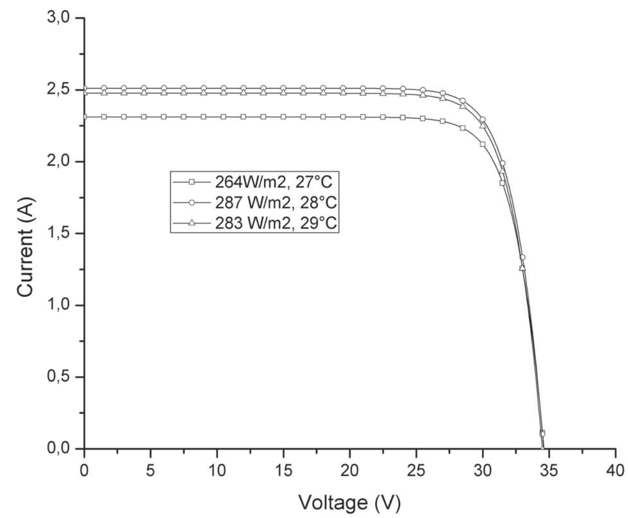

Figure 7. *I–V* curve of the solar module with solar radiation and temperature non-standard.

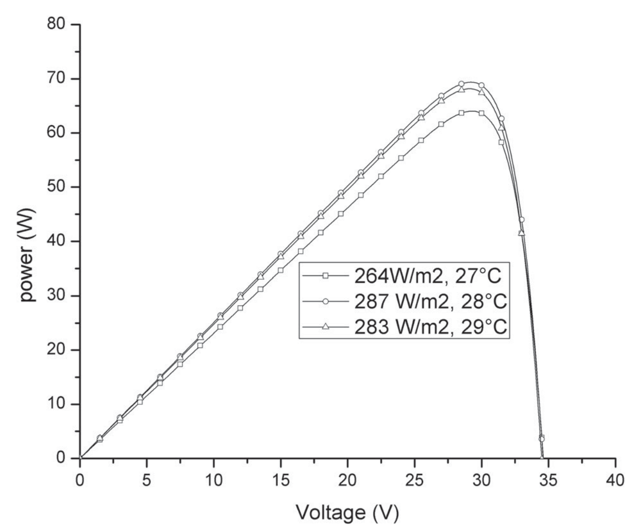

Figure 8. *P–V* curve of the solar module with solar radiation and temperature non-standard.

model was run for the months of April, June and September, since these exhibited different average temperatures (Figure 2).

These results indicated current between 2.3 A and 2.5 A and the average maximum power point registers an approximate value of 65 W using the same model. This shows that the solar module only provides 26% of the nominal power reported by the manufacturer (250 W). However, it should be noted that the solar radiation in this analysis represents the monthly and daily averages, while the nominal power of 250 W is reported for continuous values of standard solar radiation (1000 W/m^2) and ambient temperature (25°C).

4. Conclusions

This paper has presented a descriptive analysis of solar radiation and ambient temperature for Quibdó, Colombia.

Solar radiation exhibits periodic behaviour because of the climatic conditions of the region, which are themselves typical of the tropics.

The results of the simulations obtained by the model developed in Matlab™ enabled the energetic behaviour of the PV modules to be modelled accurately.

The model of the PV modules results in absolute and relative errors of 0.5% for the curves *I–V* and *P–V* in the MPP between the theoretical and the simulated curve of the information provided by the manufacturer. This accuracy is achieved by adjusting the model for each set of modules, because the data supplied by the manufacturer do not include all the information, which would allow greater accuracy in the simulation.

Disclosure statement

No potential conflict of interest was reported by the authors.

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