Estimation of the Electrical Energy Generation Function of a Photovoltaic Module

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Abstract: ***Knowing the electrical power generation function of a photovoltaic module for a locality is of vital importance in predicting the possible amount of energy to be produced by the module over a period and determining whether or not it covers demand. The objective of this research was to determine the electric power generation function of a photovoltaic module from the measured instantaneous power, and therefore to be able to predict the amount of electrical energy that will be produced in a given time interval. In this paper, there are 9655 measurements of a photovoltaic cell recorded in the months of July, August and September. An application was developed to process the data, so that the instantaneous power could be calculated for each measurement and, with a mathematical assistant, instantaneous power values of the electrical generation function of the module were able to be adjusted. With the function of "sought electrical generation", we proceeded to predict the generation of electrical energy for different days and compared it with the measured results of the generated electrical energy. It was possible to verify the validity of the applied method with an error of 1.7%.***

Keywords: Curve fitting, estimation function, photovoltaic module, power, voltage

1. Introduction

At present, solar cells are nothing more than semiconductors, where electrons can be excited by a photon originating from solar radiation with a certain energetic power, from the valence band to the conduction band forming a hollow pair-electron and allowing the generation of an electrical current [1, 2].

The energy of the photon (E_f) is a function of the propagation frequency (ν) and is given by expression (1) [3]:

$$E_f = h\nu \qquad (1)$$

Where:
h – Planck constant, equals $6.626\text{x}10^{-34} Js$;
ν – Photon propagation frequency.

It is worth highlighting that the energy of a photon that is harnessed in forming a hollow-electron pair causes a heating of the photovoltaic cell, affecting its efficiency.

The current produced in a cell can be calculated by (2) according to [1], or more practically by equation (3), as per [4]:

$$I = I_{sc} - I_0\left(e^{\left(\frac{qV}{K_B T}\right)} - 1\right) \qquad (2)$$

$$I = I_{sc} - I_0\left(e^{(bV)} - 1\right) \qquad (3)$$

Where:
I_0 – Reverse saturation current, which ranges approximately from 4.1 x10^{-5} A;
q – Elementary charge, equal to 1.60 x10^{-19} C;
V – Tension;
b – Coefficient with a value of 0.5;
K_B – Boltzmann constant;
T – Absolute temperature;
I_{SC} – Maximum short-circuit current, calculated by (4), as demonstrated by [1].

$$I_{sc} = \frac{q}{E_g}\eta_u P_s \qquad (4)$$

In that expression:
E_g – Barrier energy, equal to 1.1 ev (1 ev = 1.6x10^{-19} J);
η_u – Ultimate efficiency, equal to 0.44;
P_S – Solar radiation potency received by the solar cell, can be calculated by (5):

$$P_S = \frac{2\pi q^4 (K_B T)^4 f \pi^4}{C^2 h^3 15} \qquad (5)$$

Whereby:
C – Speed of light, equal to 2.998 x 10^8 m/s;
f – Factor defined by the expression 6:

$$f = \left(\frac{r_\odot}{A_\odot}\right)^2 \qquad (6)$$

Therefore:
$r_\odot$ – Radius of the Sun;
$A_\odot$ – Distance between the Sun and the Earth.

The voltage of the open circuit (V_{OC}) is the voltage when the current has a value of 0 and can be calculated by (7) [1]:

$$V_{oc} = \frac{K_B T}{q}\ln\left(\frac{I_{sc}}{I_0} - 1\right) \qquad (7)$$

When placing a load resistance on the cell, the voltage (V) will be less than the open circuit voltage (V_{oc}) and the current (I) will be less than the short circuit current (I_{sc}), so that the maximum power that the cell will deliver is calculated by expression (8):

$$P_{max\,c} = I_{mp} V_{mp} \qquad (8)$$

The filling or quality factor is calculated by expression (9) [5]:

$$\eta_f = \frac{P_{max\,c}}{I_{sc} V_{oc}} \qquad (9)$$

The nominal efficiency of the cell (η_n) can be calculated by expression (10) [1]:

$$\eta_n = \frac{I_{sc} V_{oc}}{P_S} \qquad (10)$$

One of the requirements for the sizing of photovoltaic generators is to know the actual available potential of solar time energy, since the nominal power in Wp of a photovoltaic generator is calculated from the coefficient of irradiance Io = 1kW/m^2, installed in a fixed horizontal position, under a certain radiation spectrum that falls on it and for temperature of cells that are maintained at 25^{0}C [5-10].

Modules are paid for based on the peak power (W_p). However, under the actual operating conditions of the generator it is very unlikely that the calculation parameters will be reached, so that its operating power will be less than the rated power and the fluctuation of the irradiance throughout the day will cause instability in the system.

It is known that the average density of solar radiation reaching the upper part of the atmosphere is 1366 W/m^2 [1], called the solar constant. Nevertheless, due to the phenomena of reflection, absorption and atmospheric transmittance and under reasonably good conditions of clear sky, the maximum irradiance value obtained at the Earth's surface is I_o = 1kW/m^2, taken as the unit of measurement of one Sun.

For the purposes of the energy potential of a region, the parameter to be determined is the irradiation as the amount of energy radiated over a period of time and this is calculated by the expression $H = \int_{t_1}^{t_2} I(t)dt$, which can be used to make hourly, daily, monthly or annual calculations, where $I(t)$ is the irradiance function.

The irradiance $I(t)$ that reaches the Earth's surface at each instant of time is variable and depends on the geographic coordinates, the climatological situation and the moment of measurement, making the electric energy production of a photovoltaic panel variable. In [11] it is argued that photovoltaic panels are not competitive, with one of the causes being the variability of production, fundamentally related to climate changes. The experimental results of [12] show that the performances of photovoltaic systems are affected by the change of variables as: the spectral components, the weather conditions, the installation type, etc.; consequently the impact on the energetic production must be evaluated.

The increase in temperature in the cell and its yield drop is 0.5%/^{0}C, due to factors such as: temperature of the environment, variation of irradiance, wind and others [13]; it also reduces open-circuit voltage (V_{OC}).However, the increase in cell temperature could be used in a hybrid photovoltaic solar dryer developed in [14]. For crystalline silicon cells the relation (12) is commonly used [8]:

$$\frac{dV_{oc}}{dT_c} = -k_v \frac{mV}{{}^oC} \qquad (11)$$

Where:
k_V = 0.0023 V/^{0}C – Coefficient of voltage drop due to an increase of one degree of temperature.

For a photovoltaic module, its maximum power (P_{max}) is calculated by expression (13) [5]:

$$P_{max} = A_T \eta_A I(t) \qquad (12)$$

Where:
A_T – Total area of the photovoltaic module;
η_A – Efficiency of the total area of the module;
$I(t)$ = 1kW/m^2 for the maximum power.

In this research paper, what is meant by 'instant power function' $F_P(T(t), I(t))$ is a continuous mathematical function that allows the calculation of the power delivered by the photovoltaic module for any instant of time, when keeping the load constant. Therefore, the variation of the output power would be given by the variation of the working temperature of the cell $T_C(t)$ and the solar irradiance $I(t)$ received by the cell at each instant of time.

If we integrate the expression 11, we can have a formula for the voltage drop (ΔV_{T_c}) in a module due to the effect of the temperature, given by the expression (13):

$$\Delta V_{T_c} = k_v(T_c(t) - 25)n \qquad (13)$$

Where:
n – Number of cells in the module.

Taking into account the definitions given in 9 and 10, and also considering the constant resistance in the circuit, the instantaneous power of the module can be calculated by expression 14:

$$F_P(T_c(t), I(t)) = A_T \eta_A I(t) - \frac{nk_v^2(T_c(t)-25)^2}{R} \qquad (14)$$

Where:
R – Resistance.

If the instantaneous power $P(t)$ is measured and recorded, then the instantaneous irradiance $I(t)$ can be calculated by expression (15), and the irradiation for a period of time by (16):

$$I(t) = \frac{RP(t)+nk_v^2(T_c(t)-25)^2}{RA_T\eta_A} \qquad (15)$$

$$H(\Delta t) = \int_{t_1}^{t_2} I(t)dt \qquad (16)$$

The objective of this research was to determine the electrical power generation function of a photovoltaic module based on the measured instantaneous power, allowing for a prediction to be made of the amount of electrical energy that will be produced in a time interval (be it a day, month or year), in a given geographical location.

2. Materials and Methods

2.1 Equipment and applications

a) Photovoltaic cell array, controlled by an electronic circuit, which allowed the real time measurement of voltage and currents.

The characteristics of the small module are:
- Poly-crystallinesiliconcells.
- EfficiencyηA– 7%
- Dimensions of 12x12 cm, A_T = 0.0144 m^2
- Voltage– 12 V
- Ratedpower– 1WP
- Resistance– 144 Ω
- Number of cells in module – 1

b) Spreadsheet to store the recorded data.
c) Database, for debugging, processing and data analysis.
d) Mathematical Assistant MATLAB, to determine the instantaneous power function and calculate the electrical energy that the module can produce, as well as the irradiation for a desired time interval.

2.2 Methodology

The methodology for measurements and calculations consisted of the following steps:

1) The cell was placed in a horizontal position, controlled by a level, in a geographical point of the city of Tunja, located at 5.533 degrees North Latitude, and 73.367 degrees West Longitude.
2) Eight (8) days of the months of July, August and September were chosen to carry out the measurements, from 6:00 a.m. to 5:00 p.m., the values of voltage and current being recorded in the spreadsheet.
3) For the analysis and processing of the data, a database was created, to import the data needed to calculate the instantaneous output power of the module.
4) The processed data was taken to the curve fitting assistant of the MATLAB application, in order to determine the electrical generation function of the module.
5) For the calculation of the energy generated by the module each day, this research made use of the electrical generation function determined in step 4 and its integration in the desired interval with the MATLAB assistant.
6) The results obtained were plotted and presented in tables, which allowed for their analysis and discussion.

3. Results and Discussion

Table 1 shows some values of the measurements made, observing that the greatest instantaneous power is at around noon, at which time the highest values of the irradiance are obtained. It is important to emphasize that the power of the module is of 1W, and according to the measurements registered, only on 8 occasions did values appear above 0.95 W. The average values of the 9665 measurements are also shown.

Table 1: Sample of 24 Records of the 9655 Performed Measurements

Date	Voltage (V)	Power (W)	Irradiance (W/m^2)
28/07/2016 09:26	8.9	0.56	551.2
28/07/2016 12:03	11.2	0.87	866.8
28/07/2016 15:30	8.9	0.55	545.7
06/08/2016 09:26	10.9	0.83	822.1
06/08/2016 12:03	9.9	0.68	674.9
06/08/2016 15:30	8.3	0.47	469.5
07/08/2016 09:26	9.6	0.63	629.7
07/08/2016 12:03	9.8	0.66	657.0
07/08/2016 15:30	10.1	0.71	705.2
06/09/2016 09:26	8.9	0.55	545.7
06/09/2016 12:03	11.3	0.89	878.2
06/09/2016 15:30	9.2	0.59	582.3
07/09/2016 09:26	9.1	0.57	569.4
07/09/2016 12:03	8.9	0.56	551.2
07/09/2016 15:30	8.8	0.53	527.9
08/09/2016 09:26	9.4	0.62	610.5
08/09/2016 12:03	9.6	0.64	637.4
08/09/2016 15:30	9.0	0.56	556.6
09/09/2016 09:26	9.4	0.61	602.9
09/09/2016 12:03	11.7	0.94	936.1
09/09/2016 15:30	9.2	0.59	587.9
11/09/2016 09:26	9.0	0.57	562.0
11/09/2016 12:03	10.3	0.74	729.9
11/09/2016 15:30	11.0	0.84	831.0
Mean Values	9.3	0.60	594.3

The electrical generation function of each of the days studied was determined by making a curve fit for each day's measurements. Figure 1 shows the data for September 6 along with the adjustment curve. It can be seen that the values of the axis of the abscissa take the consecutive value in minutes of the day, starting at 6 in the morning. For example, the value 10 means 6:10 am, and the value 400 means 12:40 pm of September 6. It can be observed that the power values of the module increase from morning to midday, with high values remaining until around 4:30 in the afternoon.

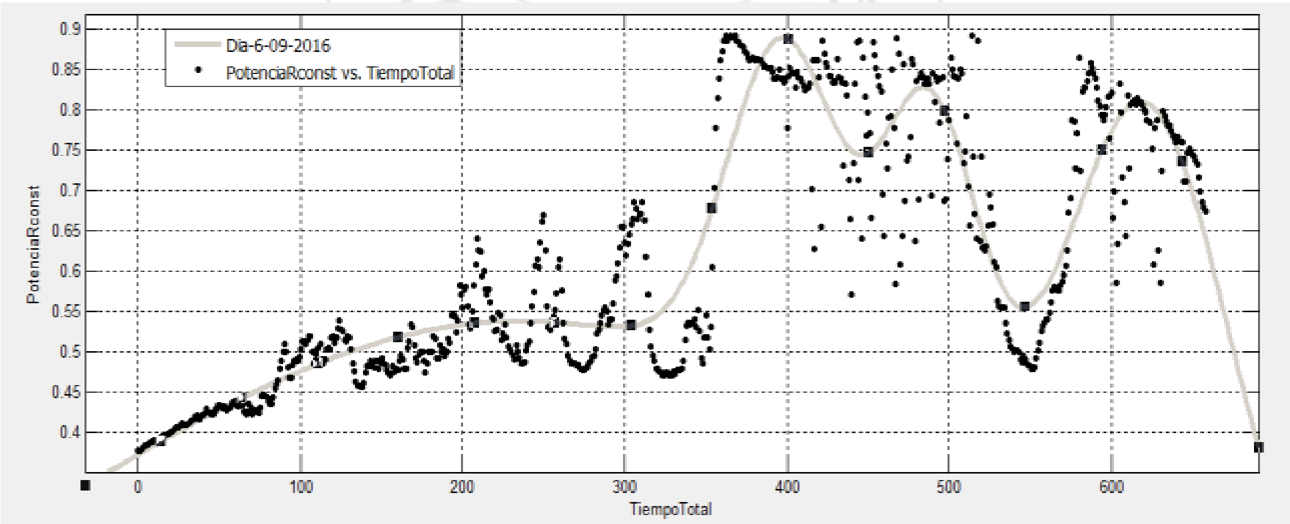

Figure 1: Power Generation Function of the Photovoltaic Module on September 6, 2016, Power over Time

It should also be noted that the power generated fluctuates at all hours of the day, without changing the load, which is due to the variation of irradiance throughout the day.

The adjustment of the given values was carried out with a Gaussian function of 4 terms, given by the expression (17)

$$f(x) = a_1 e^{-\left(\frac{(x-b_1)}{c_1}\right)^2} + a_2 e^{-\left(\frac{(x-b_2)}{c_2}\right)^2} + a_3 e^{-\left(\frac{(x-b_3)}{c_3}\right)^2} + a_4 e^{-\left(\frac{(x-b_4)}{c_4}\right)^2} \quad (17)$$

Coefficients values are as follows:

a_1 = 0.4404, b_1 = 488.3, c_1 = 43.81;
a_2 = 0.5373, b_2 = 235.4, c_2 = 388.4;
a_3 = 0.608, b_3 = 622.6, c_3 = 71.45;
a_4 = 0.4314, b_4 = 398.5, c_4 = 48.96.

Figure 2 shows the power fluctuation of the module between the hours 13 and 14.

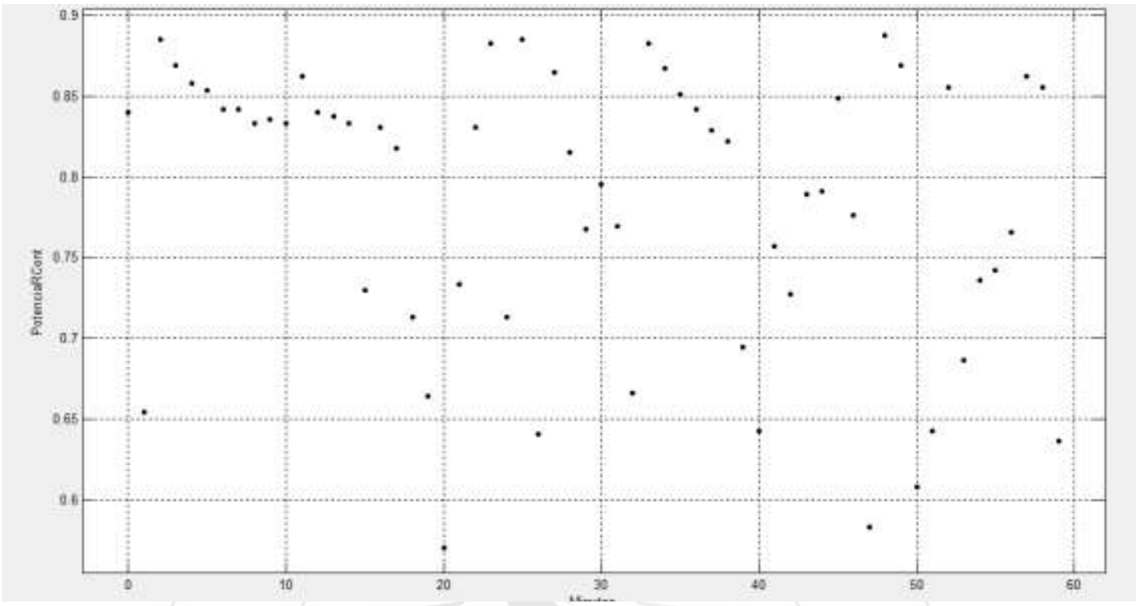

Figure 2: Power of the Photovoltaic Module on September 6, 2016, from 13:00 to 14:00

It is possible to observe how the values fluctuate, a minimum power of 0.57 W was registered at 13:20 and a maximum power of 0.88 W at 13:40, that is to say, in only 28 minutes there was a fluctuation of 0.31 W. This is due to the variation in irradiance, given by a sudden change in cloud cover. Similar rapid changing of the solar irradiation caused by the clouds was reported in Casablanca, Morocco, by [12].

The electrical generation function of the module was determined from the instantaneous powers of all measured days, as per Figure 3.

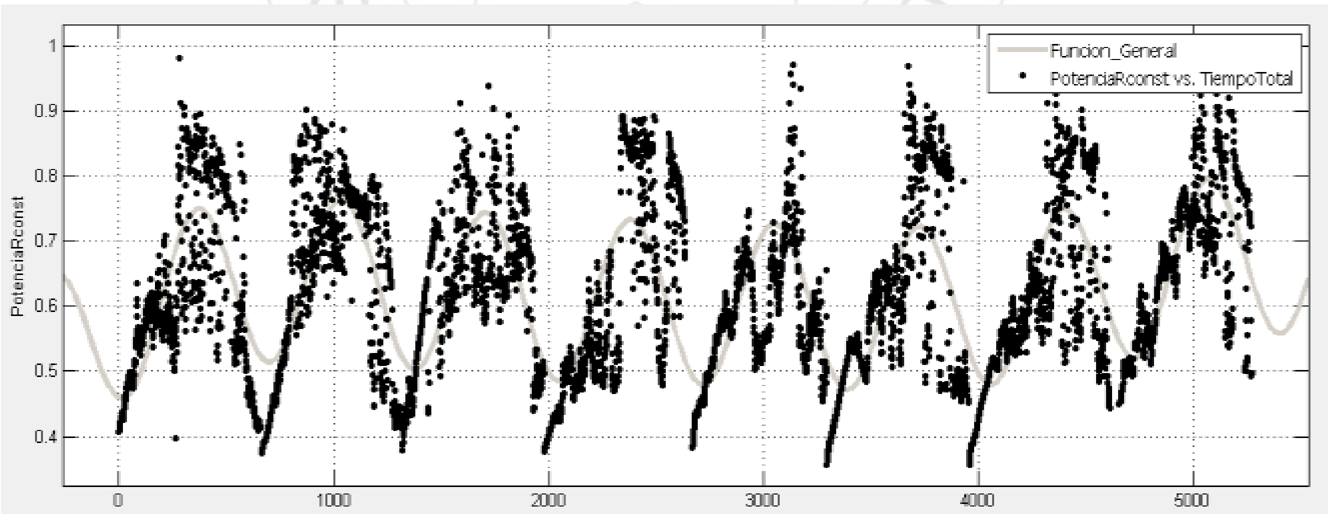

Figure 3: Electric Power Generation of the Photovoltaic Module, Power over Time

The values on the x-axis are given by the cumulative value in minutes from 6 in the morning of the first day until 5 in the afternoon of the last day. The function determined for the adjustment of the values is given by a sinusoidal sum function with 4 terms, whose mathematical expression is given in equation (18):

$$f(x) = a_1 \sin(b_1 x + c_1) + a_2 \sin(b_2 x + c_2) + a_3 \sin(b_3 x + c3 + a4 \sin b4x + c4 \quad (18)$$

The values of the coefficients are:

a_1 = 1.195, b_1 = 0.0004005, c_1 = 0.2286,
a_2 = 0.6012, b_2 = 0.0006361, c_2 = 2.612;
a_3 = 0.1257, b_3 = 0.009351, c_3 = -1.83;

$a_4 = 0.009609, b_4 = 0.002513, c_4 = 0.6181.$

After obtaining the adjustment function for all measurements as shown in expression (18) and called "electric power generation function of the module", this was then integrated for each of the measured days, thereby obtaining the values in Table 2. The values of energy generated were those recorded directly from the measurements, the values of the estimated generation were calculated by integration from the general function of the module's electric generation.

Table 2: Relative Errors between Generated and Estimate Energy

Date	Generated energy (Wh)	Estimated generation (Wh)	Error (%)
28/07/2016	6.84	6.78	0.88
6/08/2016	7.01	6.99	0.29
7/08/2016	6.85	6.83	0.29
6/09/2016	6.75	6.7	0.74
7/09/2016	6.12	6.63	8.33
8/09/2016	6.7	6.57	1.94
9/09/2016	6.67	6.79	1.80
11/09/2016	6.71	7.27	8.35
Total	53.65	54.56	1.70

It can be observed that the largest daily relative errors were on the 7th and 11th of September, with values of 8.33% and 8.35%, whereas the rest of the days feature small deviations. Furthermore, the mean daily production was 6.71 Wh with a standard deviation of 0.26 Wh, a mean estimated production of 6.82 and a standard deviation of 0.22 Wh., the relative error being therefore obtained between the means of 1.7%; this being the same relative error of the production of energy based on 8 days relative to the estimated production of 1.70%.

4. Conclusion

With the voltage of the photovoltaic module measured and recorded, and the subsequent processing and estimation of a mathematical function for the electric power generation of the module, the following conclusions can be reached. The instantaneous power of the photovoltaic module is highly variable, even in small time intervals, due to the fluctuation of the irradiance on the module. It is possible to see that the power of the module increases from the morning time to around noon, where the highest values are reached, beginning to descend at around 4 o'clock in the afternoon.

We sought a mathematical function that allows us to predict, with a margin of error of 1.7%, the production of electrical energy for a given period, this constituting a tool to support decision making in order to know the energy demand and what amount of energy a photovoltaic panel can actually generate.

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