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Energy Reports

Provided in Cooperation with:

Elsevier

Suggested Citation: Arab, A. Hadj et al. (2020) : Maximum power output performance modeling of solar photovoltaic modules, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, Iss. 1, pp. 680-686,
<https://doi.org/10.1016/j.egy.2019.09.049>

This Version is available at:

<https://hdl.handle.net/10419/243808>

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6th International Conference on Energy and Environment Research, ICEER 2019, 22–25 July,
University of Aveiro, Portugal

Maximum power output performance modeling of solar photovoltaic modules

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Received 29 July 2019; accepted 16 September 2019

Available online 24 September 2019

Abstract

The aim of this work is to present the results of maximum power performance measurements of PV modules of the first grid-connected PV system installed at Centre de Développement des Energies Renouvelables (CDER), working since June 2004. The analysis has shown that all the PV modules are producing power, but less than rated value.

In our case, two mathematical models have been used in order to determine the maximum power output (P_{max}) delivered by the PV module as function of the solar irradiance intensity and the PV-module temperature. Comparison have been made for the two models. Note that PVWATTS model is simpler than the analytical five-parameter model.

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Peer-review under responsibility of the scientific committee of the 6th International Conference on Energy and Environment Research, ICEER 2019.

Keywords: Photovoltaic module; Maximum power; Temperature correction; Performance

1. Introduction

In recent years a decrease in cost of crystalline silicon photovoltaic (PV) modules was observed, this trend leads to a great promise for the future.

One of the efforts of manufacturers of PV modules is to improve their lifetime and performance even under harsh operating conditions.

The PV module shows a non-linear current–voltage characteristic which depends on load demand, solar radiation and cell temperature. Thus, in order to extract maximum power from PV module, an MPPT is required, and the PV inverter integrates the MPPT in DC stage for a grid connected PV system.

The use of models is crucial, in order to predict the performance of PV systems.

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Fig. 1. PV array.

Testing and modeling PV module performance in outdoor environment are influenced by a variety of interactive factors related to the environment and solar cell physics. In order to effectively design, implement, and monitor the PV systems performance, King et al. [1] have proposed a performance model, which was able to separate and quantify the influence of all significant factors.

Rawat et al. [2] have presented several expressions for estimating power generation from solar PV module.

Sandia National Laboratories developed equations and applications dealing with the photovoltaic array performance model developed over a period of twelve years [1]. In addition, the Loss Factors Model can estimate the maximum power point, open-circuit voltage (V_{OC}) and short-circuit current (I_{SC}), analyzing temperature coefficients, performance at STC and low light [3,4]. De Soto et al. [5], gave description of the five-parameter model using data provided by manufacturers, absorbed solar radiation and cell temperature together with semi-empirical equations, to predict the current–voltage curve. The study describes how the parameters of the five-parameter model are determined and compares predicted current–voltage curves with experimental data. Marion [6], tested three models in order to estimate the performance of PV modules when the irradiances and PV cell temperatures are known. A modification to the power temperature coefficient model was also evaluated that provided improved accuracy.

In this study, emphasis will be put on how to estimate the maximum power output delivered by the PV module as functions of the solar irradiance intensity and the PV-module temperature using simple method. Note that in our case, comparison was done for a PV system which is in operation and made of 90 modules. Furthermore, this method will lead us in the future to combine with other work dealing with the prevision of the power produced by any PV plant.

2. Experiment description

The PV array is located at the CDER (Algiers), as shown in Fig. 1. The PV modules are installed on the administration building roof. The station's latitude is 36.8° . The unique tilt angle considered of the PV array is 27° , which favors energy production in summer period to improve ventilation. Algiers is near the sea and is affected by the seasons [7]. In Algeria, peak loads occur on summer afternoons because of the extensive use of air conditioners.

The PV array is made of 90 PV modules of $106 W_p$ (monocrystalline technology). The short-circuit current, the current at maximum power point, the open circuit voltage and the voltage at maximum power point of the PV module are respectively: 6.54 A, 6.1 A, 21.6 V and 17.4 V. Three sub-arrays of 30 modules each, form the PV array. The sub-array configuration is 15 series by two in parallel. For each sub-array a 3 kVA inverter is used (see Fig. 2) [8]. Data acquisition system based on the PVPM2540C device connected with sensors box (reference cell and temperature sensors). In order to measure the I–V curve of PV module and small string up to 250 V and 40 A. Two I–V measurements for each PV module were performed (see Fig. 3).

3. Modeling of PV module

In this study, two mathematical models have been used in order to determine the maximum power output delivered by the PV module testing at different irradiance and temperature conditions.



Fig. 2. Technical room.

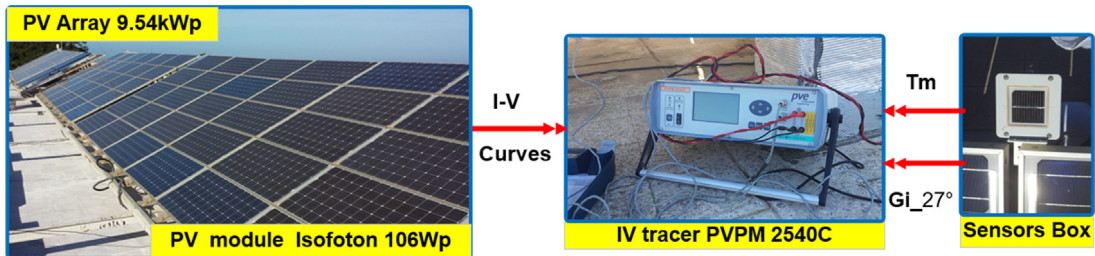


Fig. 3. Synoptic scheme for I–V measurement of 90 PV modules.

3.1. PVWatts model

PVWatts model, developed by the National Renewable Energy Laboratory (NREL), was used in our case. The model deals with PV performance modeling application [9]. We can notice the simplicity of equations where two variables are used as input: Effective irradiance, PV cell temperature.

PVWatts relates these two parameters to the maximum power point (P_M) with the Eq. (1) depending on the solar radiation. For high solar radiation $> 125 \text{ W/m}^2$:

$$P_M = \frac{G}{G_0} P_{M0} (1 + \gamma (T_C - T_0)) \quad (1)$$

where

P_M : Maximum power point

P_{M0} : Maximum power point at reference solar radiation (1000 W/m^2) and reference temperature ($25 \text{ }^\circ\text{C}$)

G : solar radiation received on module plane (W/m^2)

G_0 : reference solar radiation (1000 W/m^2)

γ : temperature correction for maximum power ($^\circ\text{C}$).

T_c : cell/module operating temperature ($^\circ\text{C}$)

T_0 : reference temperature ($25 \text{ }^\circ\text{C}$)

3.2. Analytical five-parameter model

The relation linking the current–voltage at a given irradiance and temperature, is expressed by:

$$I = I_{ph} - I_s \left[\exp \frac{V + IR_s}{mV_t} - 1 \right] - \frac{V + IR_s}{R_{sh}} \quad (2)$$

where $V_t = \frac{k.T}{e}$

I_{ph} is the photocurrent, I_s the saturation current, R_s the series resistance, m the diode quality factor, R_{sh} the shunt resistance, k the Boltzmann’s constant, T the temperature of the solar cell ($^{\circ}K$) and e the charge of the electron.

The analytical five-parameter method has been used to perform the PV array at different irradiance and temperature conditions [10].

At a particular temperature and irradiance, the five parameters I_{ph} , I_s , R_s , R_{sh} and m can be calculated from the open-circuit voltage (V_{OC}), the short-circuit current (I_{sc}), the voltage and current at maximum power point (V_m , I_m), R_{s0} and R_{sh0} .

Where R_{s0} and R_{sh0} are reciprocal of slope at open circuit point and reciprocal of slope at short circuit point respectively. The obtained equations are:

$$m = \frac{V_m + I_m R_{s0} - V_{OC}}{V_t \left[\ln \left(I_{SC} - \frac{V_m}{R_{sh}} - I_m \right) - \ln \left(I_{SC} - \frac{V_{OC}}{R_{sh}} \right) + \left(\frac{I_m}{I_{SC} - \frac{V_{OC}}{R_{sh0}}} \right) \right]} \tag{3}$$

$$I_s = \left(I_{SC} - \frac{V_{OC}}{R_{sh}} \right) \exp \left(- \frac{V_{OC}}{m V_t} \right) \tag{4}$$

$$R_s = R_{s0} - \frac{m V_t}{I_s} \exp \left(- \frac{V_{OC}}{m V_t} \right) \tag{5}$$

$$I_{ph} = I_{SC} \left(1 + \frac{R_s}{R_{sh}} \right) + I_s \left(\exp \frac{I_{SC} R_s}{m V_t} - 1 \right) \tag{6}$$

$$R_{sh} = R_{sh0} \tag{7}$$

Eqs. (3) to (7) have been used to determine the five parameters I_{ph} , I_s , R_s , R_{sh} and m that are necessary to apply Eq. (1).

In order to check the accuracy of the model, measured current–voltage curves for a silicon module are compared with modeled curves. The measured and simulated curves are plotted in Fig. 4 for comparison. The model fits measured curves very well.

The curve of Eq. (1) is only applicable at one particular irradiance (G_1) and temperature (T_1). A model [10] is used to translate this curve to other irradiance (G_2) and temperature (T_2) according to Eqs. (8) To (13):

$$I_{SC2} (G_2, T_2) = I_{SC1} (G_1, T_1) \cdot \frac{G_2}{G_1} + \alpha (T_2 - T_1) \tag{8}$$

$$V_{OC2} (G_2, T_2) = V_{OC1} (G_1, T_1) + m V_t \cdot \ln \left(\frac{G_2}{G_1} \right) + \beta (T_2 - T_1) . \tag{9}$$

$$I_2 = I_1 + \Delta I_{SC} \tag{10}$$

$$V_2 = V_1 + \Delta V_{OC} \tag{11}$$

where

$$\Delta I_{SC} = I_{SC2} - I_{SC1} \tag{12}$$

$$\Delta V_{OC} = V_{OC2} - V_{OC1} \tag{13}$$

To evaluate this model, we have compared measured I–V curves at different ambient conditions, with the curves defined by Eq. (1) through (12). A good fit between the measurement and simulation is obtained.

4. Results and discussions

In order to quantify the relative error (RE) of the maximum power output (Pmax) of the PV modules; measured standardized values are compared to the reference ones given by the manufacturer’s data of PV module. The

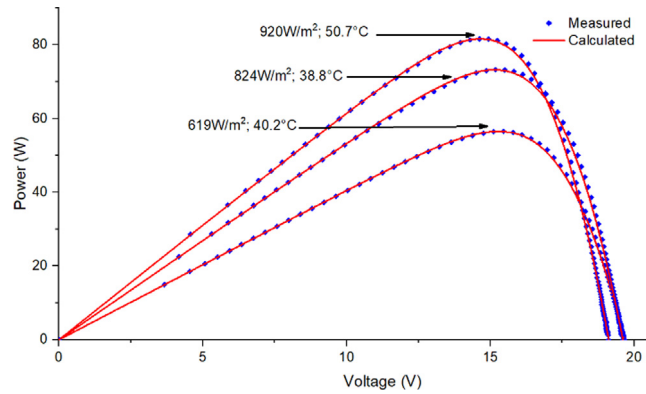


Fig. 4. P-V curve comparison between measurement and simulation.

Table 1. RMSE for measured and estimated of maximum power for the three sub-arrays.

	Sub-array G1	Sub-array G2	Sub-array G3
γ_i (%)	-0.63	-0.44	-0.54
RMSE (γ) (%)	2.45	0.67	1.47
RMSE (γ_i) (%)	1.07	0.35	0.69
RMSE (Pc5) (%)	0.06	0.05	0.07

difference in percentage represents the reduction of the parameter. The relative error of power is given respectively by the following equation:

$$RE(\%) = \left(\frac{P_{\max_C} - P_{\max}}{P_{\max_C}} \right) \times 100 \quad (14)$$

where P_{\max_C} and P_{\max} are respectively maximum calculated power and maximum measured power.

4.1. Temperature correction coefficient for maximum power

The temperature of the solar cell has direct influence on the power output of a solar PV module. When the temperature goes up the maximum output power decreases.

The manufacturer gave the value of temperature correction for maximum power (γ) as 0.0044. For the case of improved values of gamma (γ_i), the corrections are -0.631 for sub-array 1, -0.435 for sub-array 2 and -0.537 for sub-array 3. In our case, root mean square error was calculated in order to compare measured and estimated of maximum power for the three sub-arrays, using data given by the manufacturer and temperature correction.

Table 1 summarizes the Root Mean Square Error (RMSE) of the maximum power output P_{\max} delivered by all PV modules of the three sub-arrays of the grid connected PV system.

In Table 2, is given a detailed estimation of modules relative error for the three sub-arrays.

4.2. Models confrontation

A confrontation of PVWatts model and Five parameters to measured values model was achieved. Figs. 5–7 represent maximum power obtained by PVWatts model (P_{cw}) and analytical five parameters model (P_{c5}), plotted with the measured values (P_m), respectively for the subarray G1, G2 and G3. Looking at the curves, we can notice that the values given by the models fit well with measured ones. Nevertheless, the model based on five parameters fits the best (see Table 2).

5. Conclusion

The maximum power performance of the PV module is highly influenced by the solar irradiance and the PV module temperature.

Table 2. Relative error for PV modules for three sub-arrays.

Module	Sub-array G1				Sub-array G2				Sub-array G3			
	String 1		String 2		String 1		String 2		String 1		String 2	
	γ	γ_i	γ	γ_i	γ	γ_i	γ	γ_i	γ	γ_i	γ	γ_i
M1	1.27	3.79	3.65	0.11	0.30	0.41	0.08	0.01	0.63	2.68	4.48	3.34
M2	0.80	4.33	1.46	2.27	1.29	1.41	0.77	0.66	0.14	3.06	4.44	3.24
M3	0.53	4.75	5.22	1.79	0.48	0.36	0.55	0.43	0.74	2.41	1.64	0.33
M4	1.08	4.00	4.36	0.86	1.09	1.21	0.58	0.47	0.72	2.50	1.06	0.36
M5	1.07	4.04	5.26	1.92	0.12	0.24	1.02	0.89	0.25	3.01	1.75	0.44
M6	0.87	3.93	0.98	2.40	0.08	0.22	1.13	0.99	1.66	1.48	0.71	0.70
M7	1.61	3.13	5.01	1.74	0.85	0.98	0.80	0.66	1.61	1.48	2.27	0.83
M8	2.58	2.07	5.43	2.08	0.36	0.48	0.76	0.62	0.86	2.14	2.63	1.17
M9	0.34	4.27	6.27	2.93	1.40	1.27	1.44	1.30	0.83	2.15	2.27	0.86
M10	1.77	2.80	5.37	2.07	0.46	0.34	1.01	0.87	2.34	0.42	1.93	0.51
M11	2.70	1.33	3.70	0.48	1.35	1.23	0.84	0.71	2.41	0.19	1.76	0.16
M12	5.18	1.98	3.14	0.16	0.27	0.14	1.11	0.98	1.39	1.14	1.09	0.61
M13	3.51	0.11	7.98	5.07	0.13	0.26	1.16	1.02	3.07	0.76	1.25	0.42
M14	3.44	0.14	8.92	6.03	0.36	0.48	0.62	0.48	2.81	0.61	2.82	1.11
M15	4.33	0.89	5.30	2.45	1.22	1.09	1.18	1.03	1.19	1.09	1.52	0.22

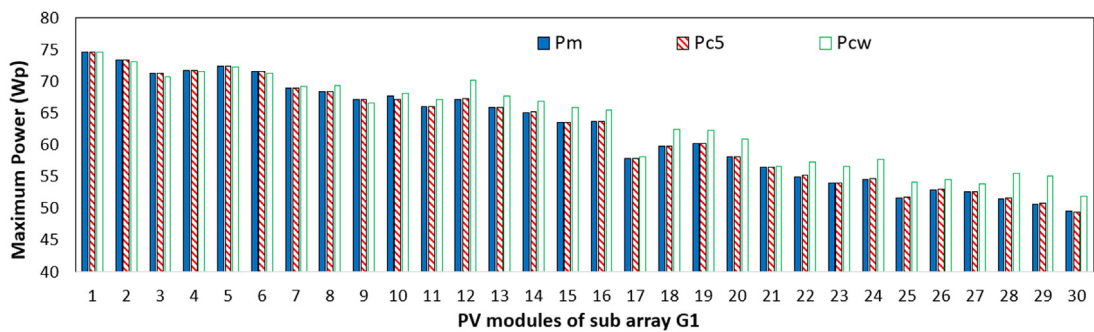


Fig. 5. Maximum power comparison of PV modules of first sub-array G1.

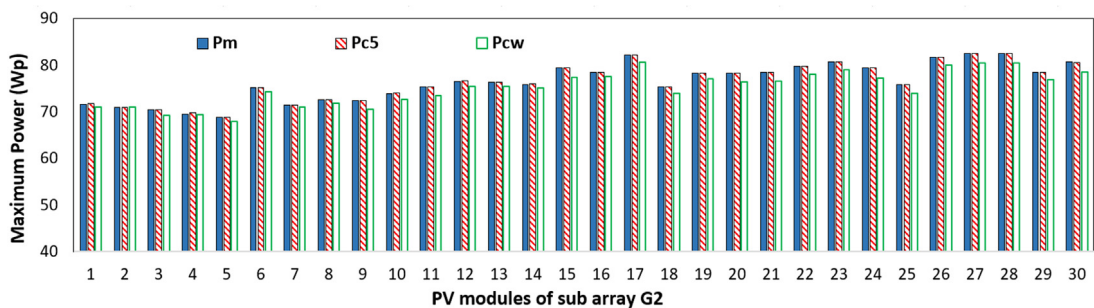


Fig. 6. Maximum power comparison of PV modules of second sub-array G2.

The work presented in this paper comprises a comparison between two mathematical models we have used in our case, in order to determine the maximum power output of PV module. The used models are PVWatts model and Analytical five-parameter model.

Despite, improving the temperature correction for maximum power, five parameters model gives better results in our case. However, using PVWatts model is much simpler than five parameters model.

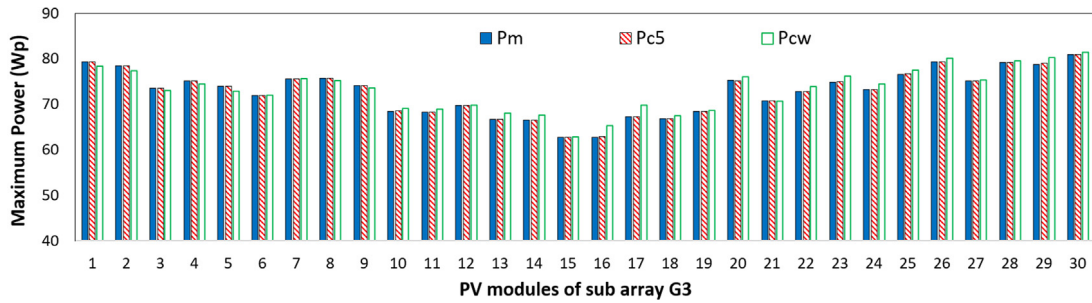


Fig. 7. Maximum power comparison of PV modules of third sub-array G3.

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