International Journal of Scientific & Engineering Research, Volume 8, Issue 5, May 2017
ISSN 2229-5518

A Novel Mathematical Model for Photovoltaic Module

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Abstract— The analysis of photovoltaic systems starts by the modeling and the analysis of the photovoltaic generator. This study introduces a novel mathematical model for photovoltaic module based on its manufacturing datasheet and the recorded ambient temperature and solar irradiation. Where, this novel mathematical model is obtained using the electrical equivalent circuit of photovoltaic module and bond graph methodology. In this study, all the parameters of the photovoltaic module will be given as a function of the recorded ambient temperature and solar irradiation. To prove the accuracy of the proposed model comparisons are done under standard test conditions.

Index Terms— PV module model, I-V curve, P-V curve, circuit simulator, bond graph modeling, PV generator modeling, five-parameters of PV module.

1 Introduction

THE analysis of photovoltaic (PV) system starts by the modeling and the analysis of the PV generator. The modeling of the PV generator is based on its equivalent electrical circuit. Studies had been done on one and two–diodes models of PV generator. Recently, studies have been done on three-diode model of PV generator.

The performance of photovoltaic cells is normally evaluated under the standard test condition (STC). To satisfy the requirement of temperature and insolation in STC, the test usually needs specified environment and some special testing equipment, such as an expensive solar simulator. Where, simple experiments may not be sufficient to reproduce accurately the solar cell electrical characteristics [25]. Studies had been done on PV generator to extract its five parameters using numerous methods [1] others used several simplifications or approximations or using graphical imprecise data [2–5, 8–11, 13–23, 27–28] while others used artificial neural network [6] and others used LabView graphical programming language [12] or software packages as MATLAB/Simulink [7, 19, 31] and PV*SOL 3.0 [29].This study introduces a simple model of PV module based on its manufacturing datasheet and the recorded ambient temperature and solar irradiation. Where, the mathematical model of PV module is obtained using its electrical equivalent circuit and bond graph methodology, than we propose new equations for the five-parameters of the PV module as a function of both the recorded ambient temperature and the solar irradiation. To prove the accuracy of the proposed mathematical model comparisons are done under standard test conditions.

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2 Circuit Model of Photovoltaic Module

A set of connected PV cells form a panel which is generally composed of series cells in order to obtain large output voltages. Panels with large output currents are achieved by increasing the surface area of the cells or by connecting cells in parallel. A general mathematical description of I-V output characteristics for a PV cell has been studied for over the past four decades. Such an equivalent circuit-based model is mainly used for the MPPT technologies [7].Usually the equivalent electrical circuit of the PV cell consists of a photovoltaic current source (known as the current generated by the photosensitive diode) I_{ph} in parallel with a sensitive diode to the light (D) and shunt resistance (R_{sh}) expressing a leakage current and a series resistance (R_s) describing internal resistance to the current flow. This circuit can be used either for an individual cell, for a module consisting of several cells, or for an array consisting of several modules [8].The mathematical equation of the PV cell using its electrical equivalent circuit is applicable for the PV modules and generators. Depending on the case, parameters, voltages and currents must be according to the number of cells, modules, etc., in series and/or parallel [15].

The bond graph representation of the photocurrent source (I_{ph}) is a source flow Sf, while the shunt and series resistances both are represented by a resistance R. the diode (D) is represented by a resistance R, too. Since a typical PV cell produces less than 3 watts at approximately 0.5 volt dc, cells must be connected in series or/and in parallel configurations to produce enough power for high-power applications [4, 7]. And therefore, for a module consisting of N_s photovoltaic cells in series and N_p photovoltaic cells in parallel, the relationship between the previous parameters of the PV module equivalent electrical circuit and the parameters of the PV cell equivalent electrical circuit is given by the following equations:

$$I_{PhM} = N_P \, I_{Ph} \quad (1)$$

$$Isat_M = N_P \, Isat \quad (2)$$

$$n_M = N_s \, n \quad (3)$$

$$R_{SM} = (N_S / N_P) \, R_S \quad (4)$$

$R_{ShM} = (N_S / N_P)\, R_{Sh}$ (5)

Therefore, the equivalent electric circuit diagram of the PV module is similar to that of the PV cell. It consists of a photocurrent source (I_{phM}), in parallel with a sensitive diode to the light (D_M) which is the equivalent of N_s of diodes connected in series and N_p of diodes connected in parallel. In addition to the parallel and series resistances of the module, respectively (R_{ShM}, R_{SM}), as shown in Fig. 1. (a). The bond graph representation of the photocurrent source is a source flow ($S_f{:}I_{phM}$), while the shunt and series resistances both are represented by a resistance ($R{:}R_{ShM}$,$R{:}R_{SM}$). Since the diode (D) is represented by a resistance ($R : R_D$), the diodes of the module are represented by an equivalent resistance ($R_{DM}=(N_S/N_P)R_D$), as shown in Fig. 1. (b).

Based on the Fig.1, and using the characteristic equations of the junctions in consideration of the causality with the constituting laws of the elements, the final equation of the PV module output voltage is given by the following equation

$$V_M = V_{ThM} \ln\left(\frac{I_{phM} - \frac{V_M}{R_{ShM}} - \frac{R_{SM}}{R_{ShM}} I_M - I_M}{I_{satM}} + 1\right) - R_{SM} I_M \quad (6)$$

with $V_{ThM} = n_M K_b T / q$, is the thermal voltage, n_M is an ideal factor of the diode (D_M), K_b is the Boltzmann's constant ($K_b = 1.38065 * 10^{-23}$ J/K), T is the PV module's working temperature, q is the magnitude of electronic charge, (q=1.602*10^{-19} C), and I_{satM} represents the saturation current of the diode (D_M) which is equivalent to the Ns of diodes connected in series and Np of diodes connected in parallel in the PV module.

From the previous equation the PV module current is given by the following equation

$$I_M = I_{PhM} - I_{satM}\left(\exp\frac{V_M + R_{SM} I_M}{V_{ThM}} - 1\right) - \frac{V_M + R_{SM} I_M}{R_{ShM}} \quad (7)$$

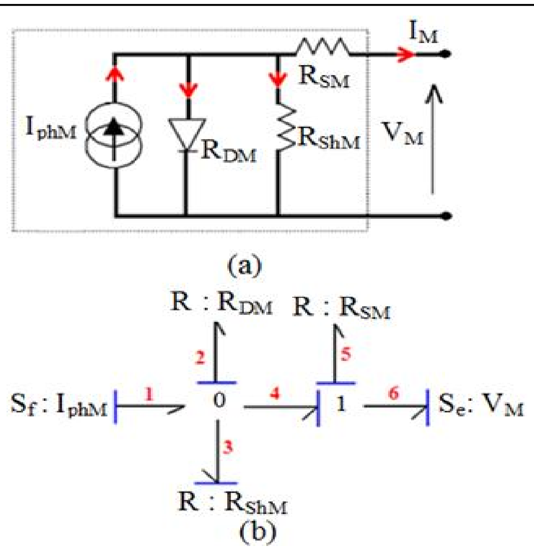

Fig. 1. (a) Equivalent electrical circuit of the PV module and (b) its bond graph model.

The model represented by the two equations (6 and 7) is usually carried out using Kirchhoff's law and Shochley's diode equation. Those equations require the computation of five parameters, namely: I_{PhM},I_{satM},V_{ThM}, R_{SM} and R_{ShM} that produce the best fit to a given PV module operating under certain conditions. Such parameters are in fact related to two environmental parameters that means solar irradiation and temperature [29].

The PV modeling objective is to estimate the model parameters under standard test conditions (STC) and also under varying environmental conditions from datasheet information provided by the manufacturer of the PV module. The PV model parameters are adjusted to consider the effects of changing temperature and irradiance, and then the PV model is used to estimate the maximum power point (MPP) under given environmental conditions [11].

3 Extraction of the Photovoltaic Module Parameters'

All PV module datasheets contain basically the following information under STC of temperature and solar irradiation: the open-circuit voltage (V_{oc}), the short-circuit current (I_{sc}), the voltage at the MPP (V_{pmax}), the current at the MPP (I_{pmax}), the open-circuit voltage temperature coefficient (K_V), the short circuit current temperature coefficient (K_I), and the maximum experimental peak output power (P_{max}). Unfortunately, some of the parameters required for adjusting PV module models cannot be found in the manufacturer's datasheets, such as the photocurrent source (I_{ph}), the series and shunt resistances, the diode ideality factor, the diode reverse saturation current, and the band gap energy of the semiconductor [17, 18]. In this paper the PV module five-parameters' will be extracted using simple mathematical equations built in blocks using MATLAB/Simulink. Highlighting the influence of the ambient temperature and the solar irradiation on the five parameters of the PV module, the current-voltage and the power-voltage characteristics of the PV module will be obtained.

According to the Shockley theory for silicon diodes n should be equal to unity. However, actual diodes are likely to have values greater than unity. For crystalline silicon cells the value of n depends on the calculation method used, with results that sometimes offer large differences. Even for a single device, depending on the conditions or the test data, the n values can vary over a wide range. Normally the proposed model requires an ideality factor between 1 and 1.3 [15, 16]. Though cases have also been observed in which lower values than 1 are needed and higher than 2 [15]. Nevertheless, different studies have shown that n equal unity is adequate for modeling purposes [16]. When the parameters setting method is used ideality factor is always set as 1 or 1.3 [15, 17]. While, the ideality factor n is set at a reasonable level depending on the semiconductor material (n = 1.30 for Si-monocrystalline, n = 1.35 for Si-polycrystalline) [28] yields for our study we used the ideality factor equal to 1.3.

Usually the photovoltaic parameters' are given as a function of the T and G. where, T represents the PV cell's temperature/ the PV module's working temperature in Kelvin and G represents the solar irradiation. But in our proposed model those two parameters represent, respectively, the temperature and the irradiation given by the equations (8 and 9) as a function of the ambient temperature T_a and the solar irradiation G_a. those two equations will affect all the PV module's parameters.

$$T = T_a \left(\frac{T_{STC}}{T_a}\right)^{K_T} \quad (8)$$

$$G = \frac{T_a}{T_{STC}} * \frac{G_{STC}}{G_a} \quad (9)$$

where T_{STC} and G_{STC} are the temperature and the solar irradiation, respectively, at standard test conditions (that means; G_{STC} = 1000 W/m^2 and T_{STC} = 298 K).

Many studies have shown that the shunt resistance impacts the I-V curve near the maximum power point, and the series resistance determines the slope of I-V curve between the open circuit voltage and the maximum power point voltage. A typical approach [14] is to estimate the series and the shunt resistances value by using the slopes at the open circuit voltage and the short circuit current, respectively. While, the expressions of the series and the shunt resistances are still transcendental equations. Several researchers have used the Newtone-Raphson method to solve the expressions of those resistances. However, the Newtone-Raphson method does not always converge [13]. Moreover, unreasonable initial value may cause a large deviation, which even cannot obtain the numerical solution [13]. To avoid this, a new method is proposed [13], which is to match the maximum experimental power point and the calculated maximum power point by interactively increasing the value of the series resistance. Unfortunately, it does not consider the effect influenced by various irradiance and temperature. Using the maximum power point, an analytic solution of the series and the shunt resistances is given [16]. However, it is found that the deviation between the calculated and experimental value is large, especially for PV module. With the consideration of the above methods, a new method was employed.

Villalva and all in [17] found that only the photocurrent source and the saturation current can be calculated analytically, the remaining parameters (V_{ThM}, R_{SM} and R_{ShM}) have to be determined numerically. These normally involve iterative process using numerical methods such as Newton Raphson. Consequently, V_{ThM}, R_{SM} and R_{ShM} cannot be computed simultaneously along with the photocurrent source and the saturation current for a particular environmental condition i.e. temperature and irradiance. The value of R_{SM} and R_{ShM} are iterated simultaneously but a constant value of V_{ThM} has to be used. Different approaches are found in the literature, to jointly determine the values of both R_{SM} and R_{ShM}. However, increasing computational burden, highly complexity levels and lengthy computational time are the main drawbacks of these methods [30]. In our study we assumed that both the series and the shunt resistances are related to both the ambient temperature and the solar irradiation. Where, we proposed new expressions of the series resistance, R_{SM}, and the shunt resistance, R_{ShM}, of the PV module as given by the following equations

$$R_{SM} = \frac{Ns}{Np}\frac{K_S}{G_a}\left(\frac{T_{STC}}{T_a}\right)^{K_T-2} \quad (10)$$

$$R_{ShM} = \frac{Ns}{Np}\frac{K_{Sh}}{G_a}\left(\frac{T_{STC}}{T_a}\right)^{K_T-2} \quad (11)$$

where K_S and K_{Sh} are consternates to be adjusted at standard test conditions. Equations (8-11) are proposed and cannot be proved.

Using the same equations for the PV module parameters' as used in [2, 3, 17, 19, 26] with applying the equations (8 and 9) yields new equations for PV module parameters' as given in the following equations. Therefore, the affects of both the ambient temperature and the solar irradiation on the PV module parameters' are highlighted in this subsection.

The short-circuit current of the photovoltaic module is given by the following equation

$$I_{SCM}(G,T) = I_{SatM}(T)\,\frac{T_a}{T_{STC}\,G_a} \quad (12)$$

The photocurrent source of the PV module is given by the following equation

$$I_{PhM}(G,T) = \left[I_{SatM}(T)\left(exp^{\frac{V_{OCM}(T)}{V_{ThM}}} - 1\right) + \frac{V_{OCM}(T)}{R_{ShM}}\right]\frac{T_a}{T_{STC}G_a} \quad (13)$$

Introducing a new expression of the open circuit voltage of PV module as a function of both the ambient temperature and the solar irradiation as given by the following equation

$$V_{OCM}(G,T) = V_{ThM}\ln\left(\frac{I_{PhM}(G,T) - \frac{1}{R_{ShM}}V_{OCM}(G,T)}{I_{SatM}(T)} + 1\right) \quad (14)$$

the saturation current, $I_{SatM}(G,T)$, is given by the following equation [3]

$$I_{SatM}(G,T) = exp^{\frac{-V_{OCM}(G,T)}{V_{ThM}}} * \left(I_{SCM}(G,T) - \frac{V_{OCM}(G,T) - I_{SCM}(G,T)R_{SM}}{R_{ShM}}\right) \quad (15)$$

Equations (10-11 and 12–15) represent the change in PV module parameters' with respect to both the ambient temperature and the solar irradiation.

A PV module is analytically described by means of the following one-diode equation that will be used to obtain the current-voltage I-V characteristic of the used PV module.

$$I_M(G,T) = I_{PhM}(G,T) - I_{SatM}(G,T)\left(exp^{\frac{V_M(G,T)+R_{SM}I_M(G,T)}{V_{ThM}}} - 1\right) - \frac{V_M(G,T)+R_{SM}I_M(G,T)}{R_{ShM}} \quad (16)$$

this equation shows the complete behavior of a single diode model of PV module that is described by the five parameters (I_{PhM}, I_{SatM}, R_{SM}, R_{ShM}, V_{ThM}) which are representative of a physical PV module.

Multiplying the photovoltaic module current, given by equation (16), by its output voltage yields the output power of the used photovoltaic module, as given in the following equation

$$P_M(G,T) = I_M(G,T) * V_M(G,T) \quad (17)$$

4 RESULTS AND DISCUSSION

In this section the I–V and P–V curves will be plotted under standard test conditions. These curves are plotted for two types PV module, namely SUNTECH PV module of 50W and Q.PRO-G2C photovoltaic module of 230W (see Figs. 2-3).

The absolute relative error of the PV module parameters ($\Delta E\%$) was calculated to reflect the accuracy of the estimated parameters using equation (19).

$$\Delta E\,\% = \frac{|E_{simulated} - E_{measured}|}{E_{measured}} * 100 \quad (19)$$

A basic factor, which describes the quality of the I–V curve, is the fill factor (FF) which is calculated using equation (20).

$$FF = \frac{P_{Mmax}}{V_{OCM} I_{SCM}} \quad (20)$$

For the two PV modules, comparisons between results obtained using the proposed PV module model and Villalva algorithm with the data given in the manufacturing datasheet are given in Tables 1-3. Where $\Delta E_1\%$ represents the absolute relative error between the proposed model and the manufacturer datasheet. And $\Delta E_2\%$ represents the absolute relative error between Villalva algorithm and the manufacturer datasheet.

Based on Table 1&3 and Fig. 2, although Villalva algorithm shows a better coincidence than the proposed model for the voltage and the current corresponding to the maximum power point but the advantage at this point is the proposed model. In addition, the proposed model shows a better coincidence than Villalva algorithm concerning the fill factor. Concerning the shunt resistances: we notice that the value of the shunt resistance using Villalva algorithm is not very high to be removed from the equivalent electrical circuit (its value is 85.498294Ω up to 564.459461Ω), while its value using the proposed model is very high (it is 79.2 KΩ) that can be accepted to be removed from the equivalent electrical circuit of the used PV module for simplification purposes. (ii) Using Q.PRO-G2C photovoltaic module of 230 W, based on Table 2&3 and Fig. 3, Villalva algorithm shows a better coincidence than the proposed model concerning both the maximum power point and the fill factor. Concerning the shunt resistances: we notice, here also, that the value of the shunt resistance using Villalva algorithm is not very high to be removed from the equivalent electrical circuit (its value is 44.717689 Ω up to 162.424882Ω), while its value using the proposed model is very high (it is 132 KΩ) that can be accepted to be removed from the equivalent electrical circuit of the used PV module for simplification purposes.

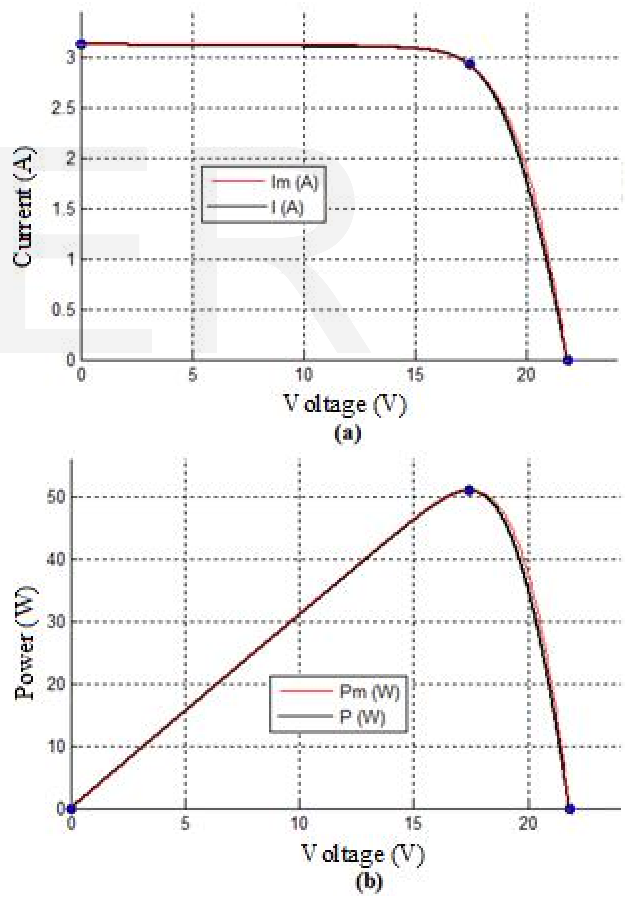

Fig. 2. SUNTECH photovoltaic module of 50 W at STC: (a) I-V curve, and (b) P-V curve. (Im, Pm were obtaned using the proposed model and I, P were obtained using Villalva model).

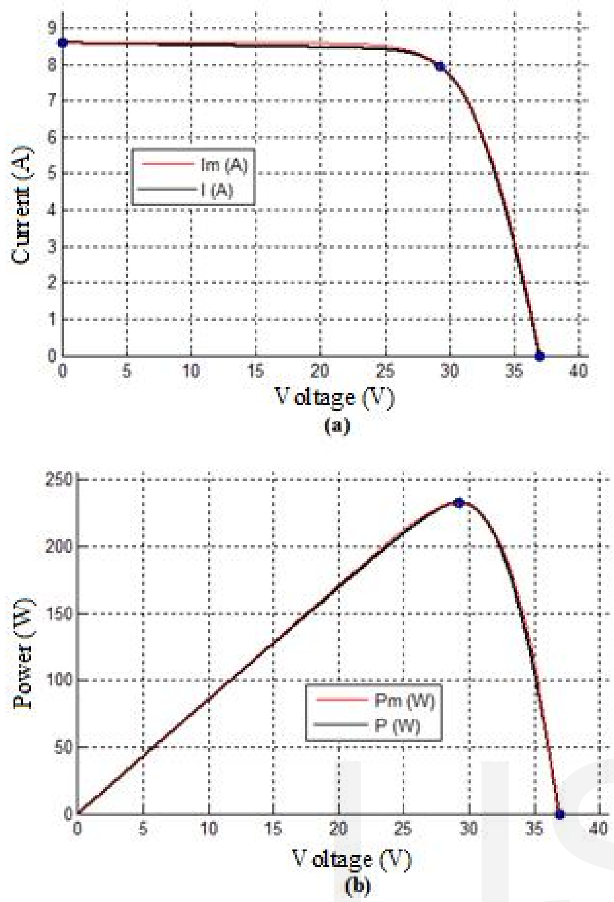

Fig. 3..PRO-G2C photovoltaic module of 230W at STC: (a) I-V curve, and (b) P-V curve. (Im, Pm were obtaned using the proposed model and I, P were obtained using Villalva model).

TABLE 1
PARAMETERS OF SUNTECH PHOTOVOLTAIC MODULE OF 50 W AT STC

	Proposed model	Villalva Algorithm	Datasheet
V_{Pmax} (V)	17.5	17.4	17.4
I_{Pmax} (A)	2.9136	2.9306	2.93
P_{Pmax} (W)	50.988	50.99244	50.982
V_{OC} (V)	21.8	21.8	21.8
I_{SC} (A)	3.13	3.13	3.13
FF	0.7472	0.7473	0.7471
R_{SM} (Ω)	0.3733	0.573-1.501706	
R_{ShM} (Ω)	79.2*10³	85.498294-564.459461	

5 Conclusion

We have presented a novel modeling and parameters extraction method for photovoltaic module. The proposed model uses only the datasheet information provided by the manufacturer to predict the module I-V and P-V curves. The PV module parameters' are given as a function of both recooreded ambient temperature and solar irradiation.

TABLE 2
PARAMETERS OF Q.PRO-G2C PHOTOVOLTAIC MODULE OF 230W AT STC

	Proposed model	Villalva Algorithm	Datasheet
V_{Pmax} (V)	29.1	29.23	29.24
I_{Pmax} (A)	7.9903	7.9534	7.95
P_{Pmax} (W)	232.51773	232.477882	232.4580
V_{OC} (V))	36.95	36.95	36.95
I_{SC} (A)	8.59	8.59	8.59
FF	0.7325	0.7324	0.7323
R_{SM} (Ω)	0.315	0.405 – 0.969811	
R_{ShM} (Ω)	132*10³	44.717689 – 162.424882	

TABLE 3
ABSOLUT RELATVE ERROR OF PHOTOVOLTAIC MODULE AT STC

	SUNTECH photovoltaic module		Q.PRO-G2C photovoltaic module	
	ΔE_1 %	ΔE_2 %	ΔE_1 %	ΔE_2 %
V_{Pmax} (V)	0.5747	0	0.4787	0.0341
I_{Pmax} (A)	0.5597	0.0204	0.5069	0.0427
P_{Pmax} (W)	0.01176	0.02047	0.02569	0.00855
V_{OC} (V))	0	0	0	0
I_{SC} (A)	0	0	0	0
FF	0.0133	0.0267	0.0273	0.0136

Comparisons at standard test conditions between the manufacturer datasheet with both the proposed photovoltaic module model and Villalva algorithm are done. Where, in all the analyzed cases in this study the results showed a negligible error (less than 0.03 % in the surrounding of maximum power point).

This study introduces a simple mathematical model of PV module that can be used to study the PV systems without without having difficulties in the algorithms to calculate the PV generator parameters'.

Acknowledgment

The authors wish to thank the head of Research laboratory Energy and Electrical Systems and Electronics, and the head of team 4 in the same laboratory, faculty of the sciences and the applied sciences at the university Akli Mohand Oulhadj of Bouira-Algeria, for their helpful.

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