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A detailed modeling of photovoltaic module using MATLAB

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KEYWORDS

Irradiance;
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$I(V)$/$P(V)$ characteristic;
MATLAB/Simulink

Abstract The PV module is the interface which converts light into electricity. Modeling this device, necessarily requires taking weather data (irradiance and temperature) as input variables. The output can be current, voltage, power or other. However, trace the characteristics $I(V)$ or $P(V)$ needs of these three variables. Any change in the entries immediately implies changes in outputs. That is why, it is important to use an accurate model for the PV module. This paper presents a detailed modeling of the effect of irradiance and temperature on the parameters of the PV module. The chosen model is the single diode model with both series and parallel resistors for greater accuracy. The detailed modeling is then simulated step by step using MATLAB/Simulink software due to its frequent use and its effectiveness.

1. Introduction

The number of unknown parameters increases when the equivalent circuit of the chosen model becomes more convenient and far from being the ideal form. But most of the manufacturers' data sheets do not give enough information about the parameters which depend on weather conditions (irradiance and temperature). So, some assumptions with respect to the physical nature of the cell behavior are necessary to establish a mathematical model of the PV cell and the PV module, in addition of course, to the use of that information given by the constructors. The objective of this paper is to present useful work to those who want to focus their attention on the PV module or array as one device in a complex ‘‘electro-energetic system’’. So, the goal is to obtain at any time, the maximum power but also the more precise, therefore, the closest to the experimental value.

The characteristic $I(V)$ is a non-linear equation with multiple parameters classified as follows: those provided by constructors, those known as constants and the ones which must be computed. Sometimes, searchers develop simplified methods where, some unknown parameters cannot be calculated. They are thus assumed constant. For example, in Walker and Geoff (2001) the series resistance R_S was included, but not the parallel resistance for a model of moderate complexity. The same assumption is adopted in Benmessaoud et al. (2010),

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Atlas and Sharaf (1992), Beckman et al. (xxxx), Bryan (1999), Bouzid et al. (2005), by considering the parallel resistance very large. Other authors neglect both parallel and series resistances; the former due to being very large, the latter being very small. On the other hand, there are in the literature other papers, in which, these two internal characteristics of the PV module are very important and have to be determined more accurately as in Townsend (1989), Alsayid and Jallad (2011), Kashif Ishaque and Syafaruddin (2011), Gazoli et al. (2009), De Soto (2006) and Chouder et al. (2012). In addition to the series and parallel resistances and according to the authors, two or three other parameters are to be determined; the photo current (I_{ph}), the saturation current (I_0) and the ideality factor (A).

2. Presentation and modeling of PV module

2.1. In the Fig. 1a

The model does not take into account the internal losses of the current. A diode is connected in anti-parallel with the light generated current source. The output current I is obtained by Kirchhoff law:

$$I = I_{ph} - I_d \tag{1}$$

I_{ph} is the photocurrent, I_d is the diode current which is proportional to the saturation current and is given by the equation (13):

$$I_d = I_0\left[\exp\left(\frac{V}{A.N_s.V_T}\right) - 1\right] \tag{2}$$

V is the voltage imposed on the diode.

$$V_T = k \cdot T_c/q \tag{3}$$

I_0 is the reverse saturation or leakage current of the diode (A), $V_{Tc} = 26\,\text{mV}$ at 300 K for silisium cell, T_c is the actual cell temperature (K), k Boltzmann constant 1.381×10^{-23} J/K, q is electron charge (1.602×10^{-19} C).

V_T is called the thermal voltage because of its exclusive dependence of temperature (Anne and Michel, 2006; Sheik Mohammed, 2011).

Ns: is the number of PV cells connected in series. A is the ideality factor. It depends on PV cell technology and can be chosen in Table 1. It is necessary to underline that A is a constant which depends on PV cell technology.

All the terms by which, V is divided in equation (2) under exponential function are inversely proportional to cell temperature and so, vary with varying conditions. In this work, this term is designed by 'a' and called the thermal voltage (V), the ideality factor, is considered constant and is chosen in Table 1 according to technology of the PV cell. The thermal voltage "a" is presented by equation (4)

Table 1 Ideality factor (A) Huan-Liang et al., 2008, [16].

Technology	Ideality factor
Si-mono	1.2
Si-poly	1.3
a-Si-H	1.8
a-Si-H tandem	3.3
a-Si-H triple	5
cdTe	1.5
CTs	1.5
AsGa	1.3

$$a = \frac{N_S \cdot A \cdot k \cdot T_C}{q} = N_S \cdot A \cdot V_T \tag{4}$$

In Chouder et al. (2012)), 'a' is called "the modified ideality factor" and is considered as a parameter to determine, while A is the diode ideality (See Table 2).

2.2. In the (Fig. 1b)

In reality, it is impossible to neglect the series resistance Rs and the parallel resistance R_P because of their impact on the efficiency of the PV cell and the PV module. When R_S is taken into consideration, equation (2) should take the next form:

$$I_d = I_0\left[\exp\left(\frac{V + I \cdot R_S}{a}\right) - 1\right] \tag{5}$$

Of course, Fig. 1b is a simplified form, easy to implement in simulators. But Fig. 1c is the most representative of the PV cell.

2.3. In the (Fig. 1c)

By applying Kirchhoff law, current will be obtained by the equation:

$$I = I_{ph} - I_d - I_p \tag{6}$$

I_P, is the current leak in parallel resistor.

According to the equation (7), the output current of a module containing N_s cells in series will be:

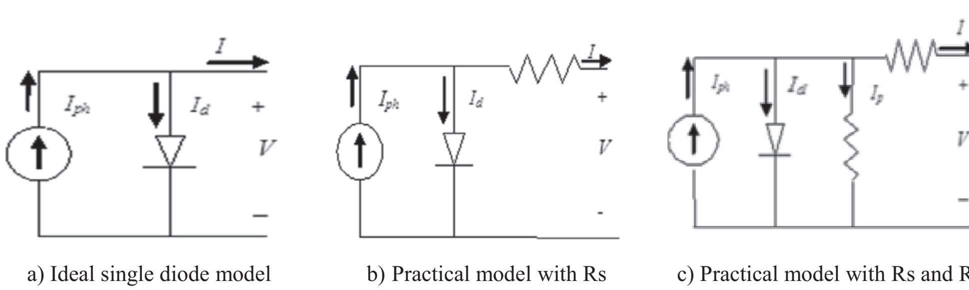

Fig. 1 The equivalent circuit of a solar cell and PV device.

Table 2 PWX 500 PV module (49 W) characteristics.

Parameters	Values
P_{mp} (W)	49
I_{mp} (A)	2.88
V_{mp} (V)	17
I_{sc} (A)	3.11
V_{oc} (V)	21.8
R_S (Ω)	0.55
Noct °C	45
μ_{sc} (K°)	$1.3 \cdot 10^{-3}$
K_d (K°)	$-72.5 \cdot 10^{-3}$
N_S	36

$$I = I_{ph} - I_0\left[\exp\left(\frac{V + I.R_S}{a}\right) - 1\right] - \frac{V + R_s I}{R_p} \tag{7}$$

It is not easy to determine the parameters of this transcendental equation. But this model offers the best match with experimental values.

3. Determination of the parameters

The number of parameters varies depending on the chosen model and on the assumptions adopted by the searchers. For example, in Beckman et al. (xxxx) and De Soto (2006), it is considered that I_{ph}, I_0, R_S, R_P and the factor ideality are five parameters that depend on the incident solar radiation and the cell temperature. While in Bryan (1999), and Townsend (1989), the unknown parameters are I_{ph}, I_0, R_S and γ. Where $\gamma = A \cdot N_S$

In this work the four parameters that have to be evaluated are also I_{ph}, I_0, R_S, R_P.

3.1. Determination of I_{ph}

According to Fig. 1a, the output current at the standard test conditions (STC) is:

$$I = I_{ph,ref} - I_{0,ref}\left[\exp\left(\frac{V}{a_{ref}}\right) - 1\right] \tag{8}$$

This equation allows quantifying $I_{ph,ref}$ which cannot be determined otherwise. When the PV cell is short-circuited:

$$I_{sc,ref} = I_{ph,ref} - I_{0,ref}\left[\exp\left(\frac{0}{a_{ref}}\right) - 1\right] = I_{ph,ref} \tag{9}$$

But this equation is valid only in ideal case. So, the equality is not correct. And then, equation (10) has to be written as:

$$I_{ph,ref} \approx I_{sc,ref} \tag{10}$$

The photocurrent depends on both irradiance and temperature:

$$I_{ph} = \frac{G}{G_{ref}}(I_{ph,ref} + \mu_{sc} \cdot .\Delta T) \tag{11}$$

G: Irradiance (W/m^2), G_{ref} : Irradiance at STC = 1000 W/m^2, $\Delta T = T_c - T_{c,ref}$ (Kelvin), $T_{c,ref}$: Cell temperature at STC = 25 + 273 = 298 K, μ_{SC} : Coefficient temperature of short circuit current (A/K), provided by the manufacturer, $I_{ph,ref}$: Photocurrent (A) at STC.

3.2. Determination of I_0

The shunt resistance R_P is generally regarded as great, so the last term of the relationship (8) should be eliminated for the next approximation. By applying equation (8) at the three most remarkable points at standard test condition: the voltage at open circuit ($I = 0$, $V = V_{oc,ref}$), the current at short circuit ($V = 0$, $I = I_{sc,ref}$), and the voltage ($V_{mp,ref}$) and current ($I_{mp,ref}$) at maximum power, the following equations can be written:

$$I_{sc,ref} = I_{ph,ref} - I_{0,ref}\left[\exp\left(\frac{I_{sc,ref} \cdot R_s}{a_{ref}}\right) - 1\right] \tag{12}$$

$$0 = I_{ph,ref} - I_{0,ref}\left[\exp\left(\frac{V_{oc}}{a_{ref}}\right) - 1\right] \tag{13}$$

$$I_{pm,ref} = I_{ph,ref} - I_{0,ref}\left[\exp\left(\frac{V_{pm,ref} + I_{pm,ref}R_s}{a_{ref}}\right) - 1\right]. \tag{14}$$

The (−1) term has to be neglected because it is very smaller than the exponential term. According to equation (11), and by substituting ($I_{ph,ref}$) in equation (14):

$$0 \approx I_{sc,ref} - I_{0,ref}\exp\left(\frac{V_{oc,ref}}{a_{ref}}\right) \tag{15}$$

So:

$$I_{0,ref} = I_{sc,ref}\exp\left(\frac{-V_{oc,ref}}{a}\right) \tag{16}$$

The reverse saturation current is defined by:

$$I_0 = DT_C^3\exp\left(\frac{-q\varepsilon_G}{A \cdot k}\right) \tag{17}$$

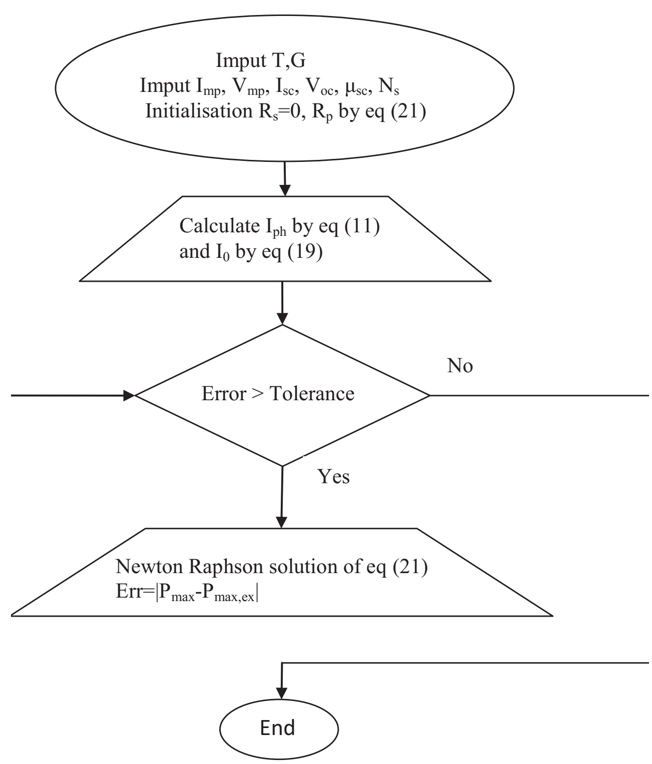

Fig. 2 Iteration flow chart.

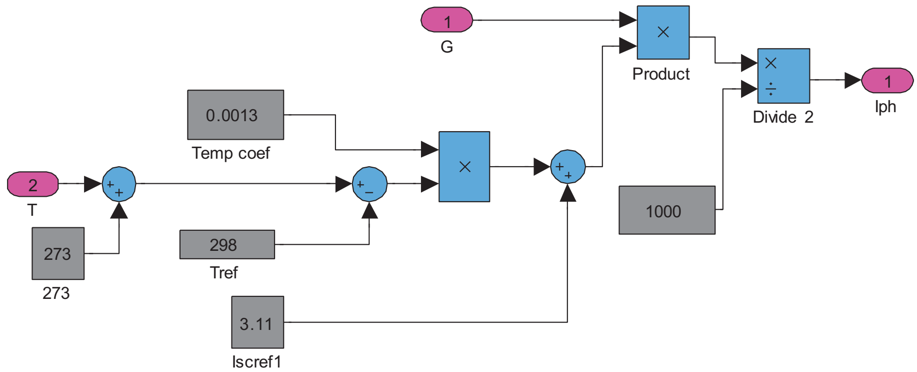

Fig. 3 Detailed I_{ph} implementation.

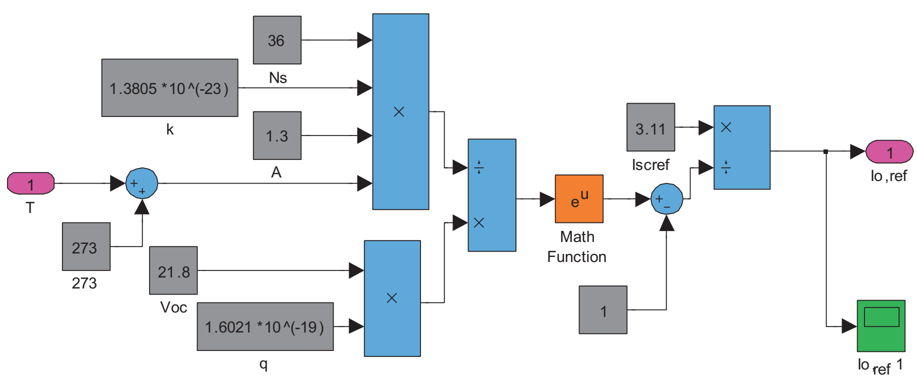

Fig. 4 Detailed $I_{0,\mathrm{ref}}$ implementation.

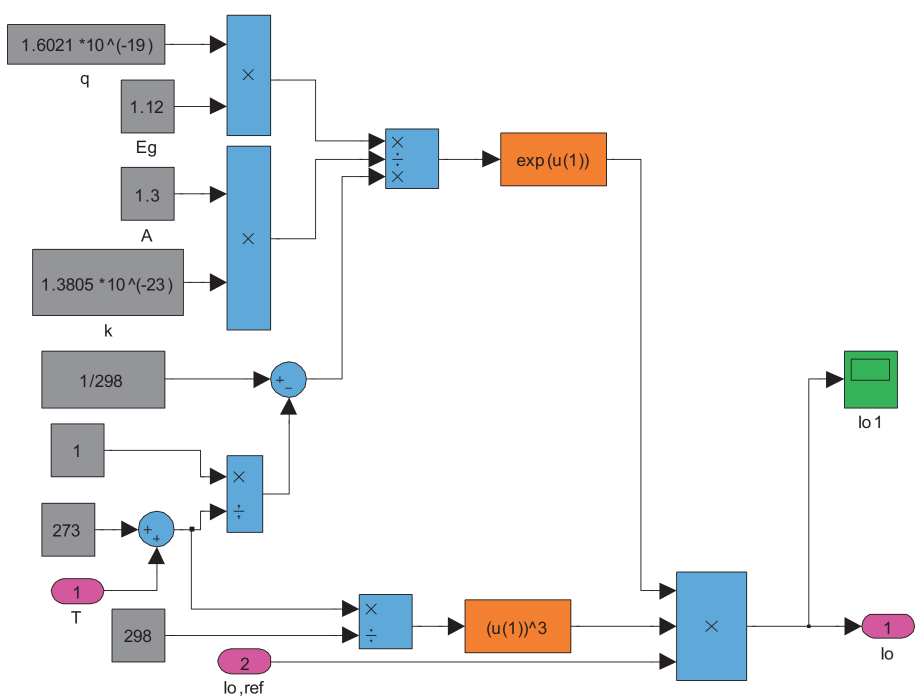

Fig. 5 Detailed I_0 implementation.

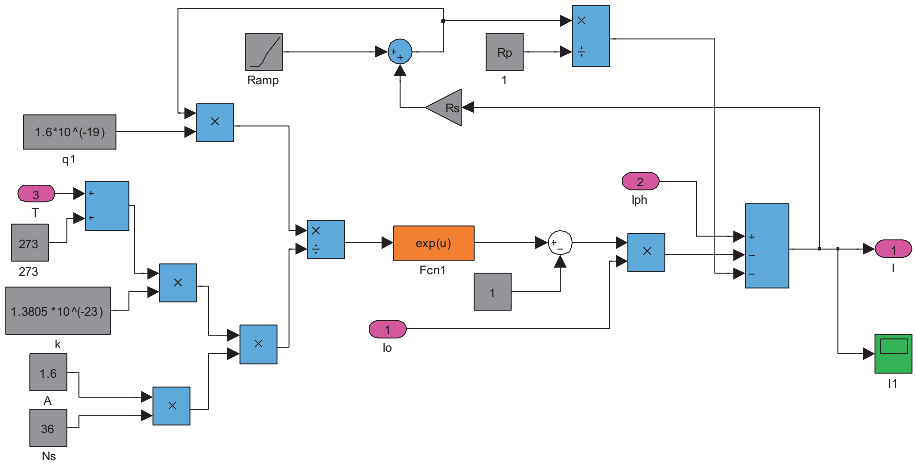

Fig. 6 Detailed model with Rp term.

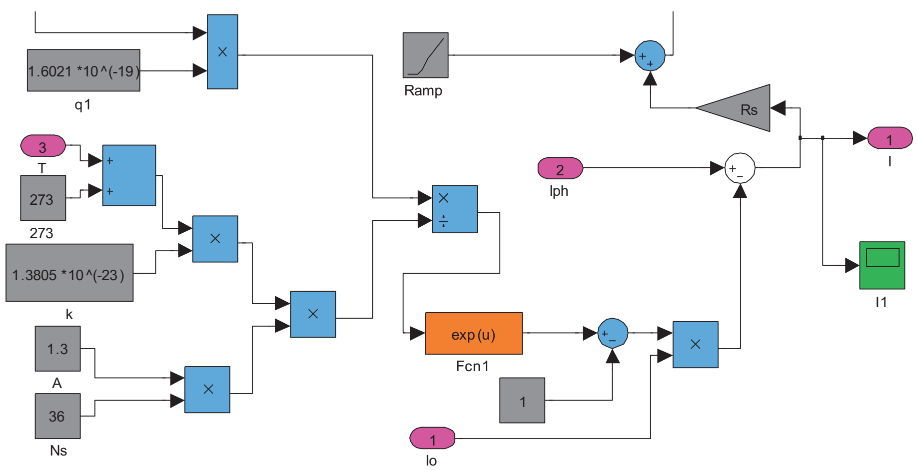

Fig. 7 Detailed model without Rp term.

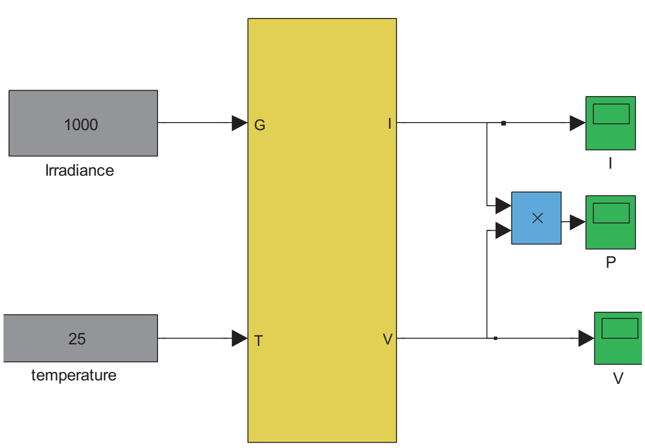

Fig. 8 Presentation of the whole PV model.

ε_G: Material band gap energy (eV), (1.12 eV for Si)
D = diode diffusion factor

In order to eliminate the diode diffusion factor, equation (18) is computed twice; at T_c and at $T_{c,ref}$. Then, the ratio of the two equations is written in the next expression:

$$I_0 = I_{0,ref}\left(\frac{T_c}{T_{c,ref}}\right)^3 \exp\left[\left(\frac{q\varepsilon_G}{A \cdot K}\right)\left(\frac{1}{T_{c,ref}} - \frac{1}{T_c}\right)\right] \tag{18}$$

$$I_0 = I_{SC,ref} \exp\left(\frac{-V_{oc,ref}}{a}\right)\left(\frac{T_c}{T_{c,ref}}\right)^3 \times \exp\left[\left(\frac{q\varepsilon_G}{A \cdot K}\right)\left(\frac{1}{T_{c,ref}} - \frac{1}{T_c}\right)\right] \tag{19}$$

Equation (20) presents I_0 with some parameters provided by the manufacturers as ($V_{oc,\ ref}$, $T_{c,ref}$), others, related to the technology of the PV cell, as (A, ε_G) and some constants. But "a" and T_c are dependents of actual temperature. That is why; I_0 has to be determined at real time.

3.3. Determination of R_P and R_S

In order to make the proposed model more credible, R_P and R_S are chosen so that the computed max power P_{mp} is equal

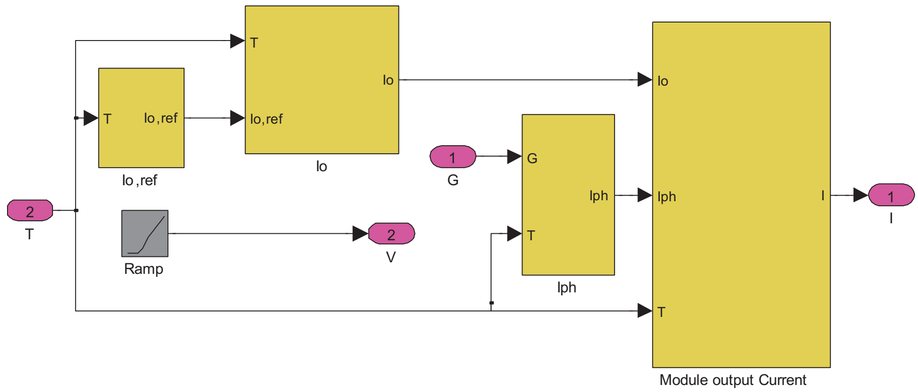

Fig. 9 Grouped subsystems of the PV model.

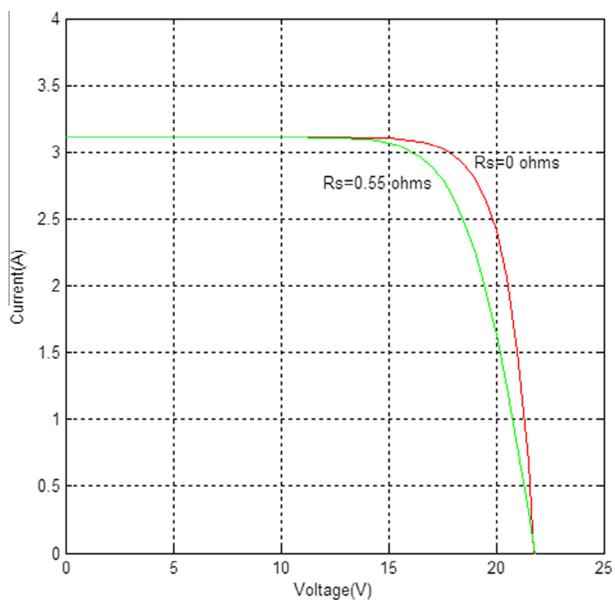

Fig. 10 *I*(*V*) characteristic in Rs model.

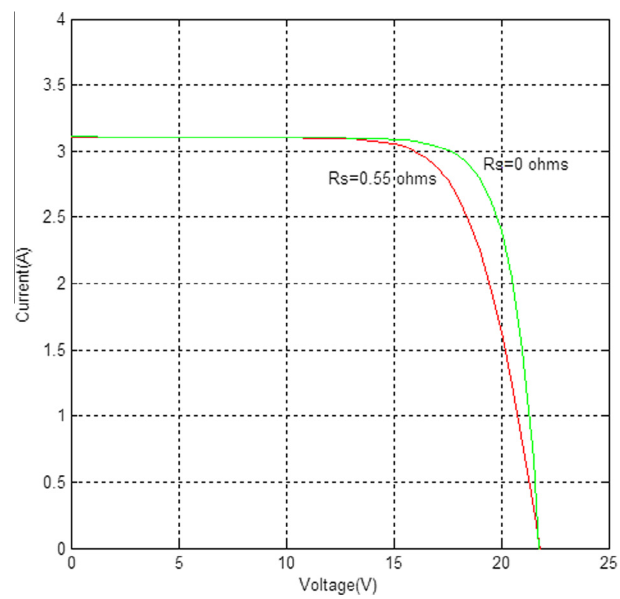

Fig. 11 *I*(*V*) characteristic in Rp model.

to the experimental one $P_{mp,ex}$ at STC conditions. So it is possible to write the next equation:

$$\begin{aligned} I_{mp,ref} &= P_{mp,ref}/V_{mp,ref} = P_{mp,ex}/V_{mp,ref} \\ &= I_{ph,ref} - I_{0,ref}\left[\exp\left(\frac{V_{mp,ref} + I_{mp,ref}\cdot R_S}{a}\right) - 1\right] \\ &\quad - \frac{V_{mp,ref} + R_s I_{mp,ref}}{R_p} \end{aligned} \tag{20}$$

$$R_P = \frac{V_{mp,ref} + I_{mp,ref} R_S}{I_{sc,ref} - I_{sc,ref}\left\{\exp\left[\frac{V_{mp,ref} + R_S I_{mp,ref} - V_{oc,ref}}{a}\right]\right\} + I_{sc,ref}\left\{\exp\left(-V_{oc,ref}/a\right)\right\} - \left(P_{max,ex}/V_{mp,ref}\right)} \tag{21}$$

The iteration starts at $R_S = 0$ which must increase in order to move the modeled Maximum Power Point until it matches with the experimental Maximum Power Point. The corresponding R_P is then computed. There is only one pair (R_P, R_S) that satisfies this condition.

The implementation presented in Fig. 6. was used to simulate the proposed model by incrementing R_S until matching

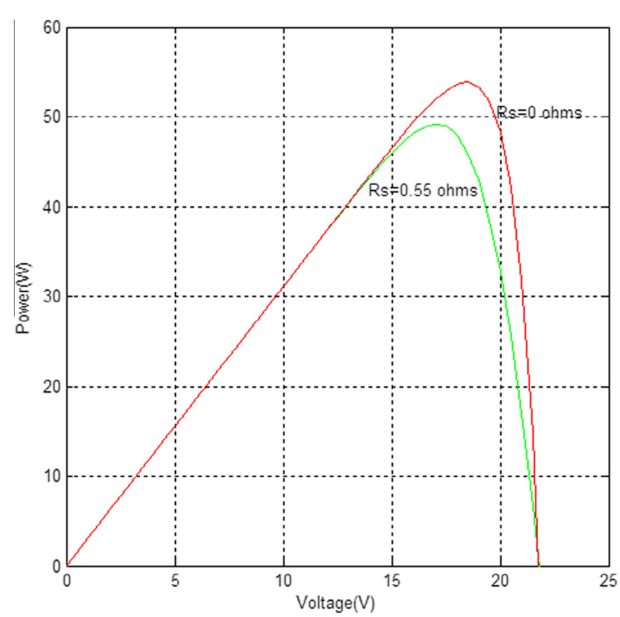

Fig. 12 *I*(*V*) characteristic in RS.

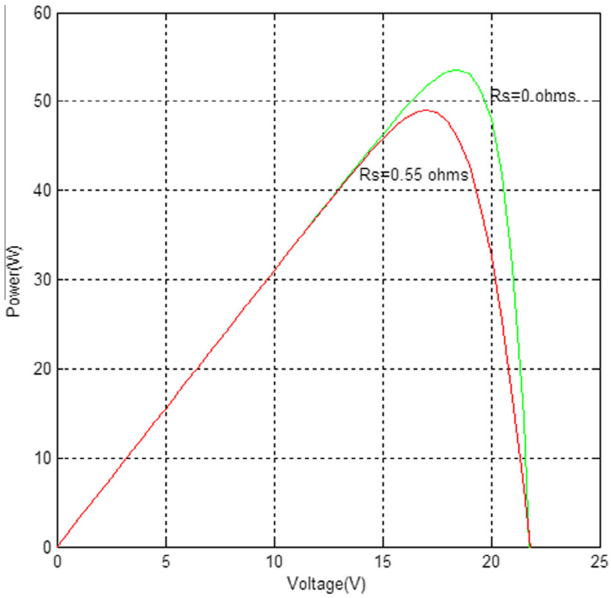

Fig. 13 $I(V)$ characteristic in RP model.

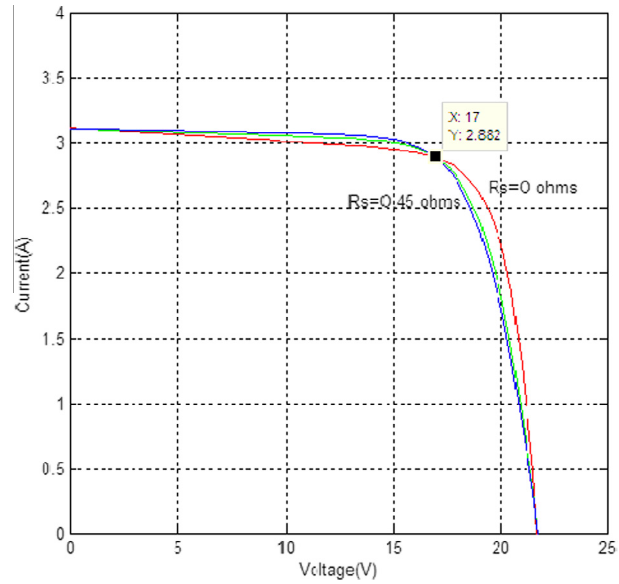

Fig. 15 $I(V)$ characteristic for different RS.

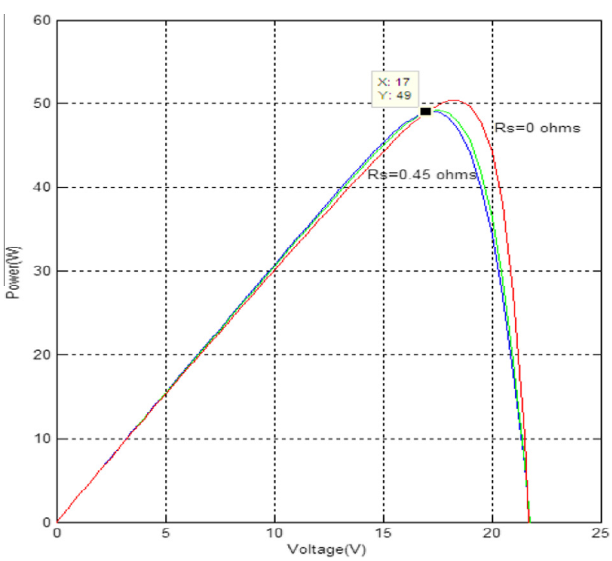

Fig. 14 $P(V)$ characteristic for different RS.

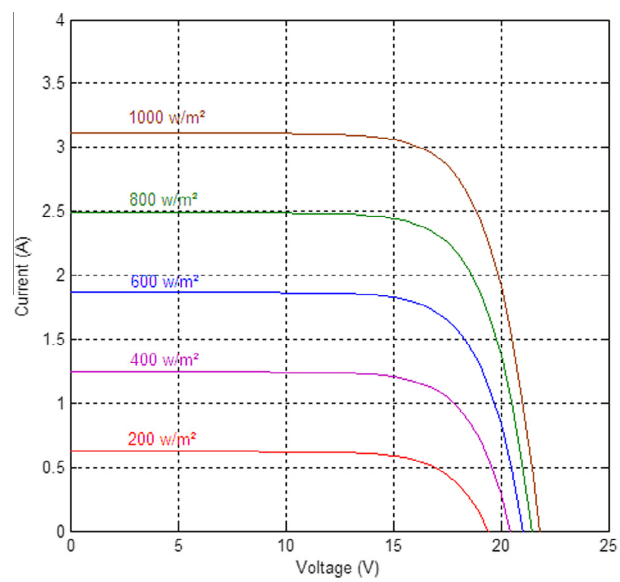

Fig. 16 $I(V)$ characteristics by varying irradiance.

P_{mp} with $P_{mp,ex}$. Three curves for three different values of R_s are presented in Fig. 14. The experimental value of maximum power at STC, provided by the manufacturer of PWX 500 PV module (49 W) was used in equation (22). The iterative method to compute the pair (R_S, R_P) gave $R_S = 0.45\,\Omega$, $R_P = 310.0248\,\Omega$. These two values make the proposed model the most representative of the chosen PV module.

In order to simulate another PV module, its respective experimental maximum power is introduced in the equation (22) and then, the iterative method is used again to determine the appropriate pair (R_S, R_P) which makes this same model the most representative. Now, the R_P model can be used to simulate the given module at different temperatures and irradiances (See Fig. 2).

4. Simulation of the PV model

- First, equation (11) is substituted in equation (12) which gives the photocurrent and then, equation (12) is implemented in MATLAB/Simulink environment. The result is represented in Fig. 3
- The reverse saturation current at STC $I_{0,ref}$ is implemented too, according to equation (17). It is represented in Fig. 4.
- This allows the simulation of I_0 which is represented in Fig. 5. It is a schematic form of equation (20).
- Equation (8) is represented in two different forms; with and without the third term containing the parallel resistance R_P. The both forms of equation (8) are simulated and represented respectively in Fig. 6 and 7.

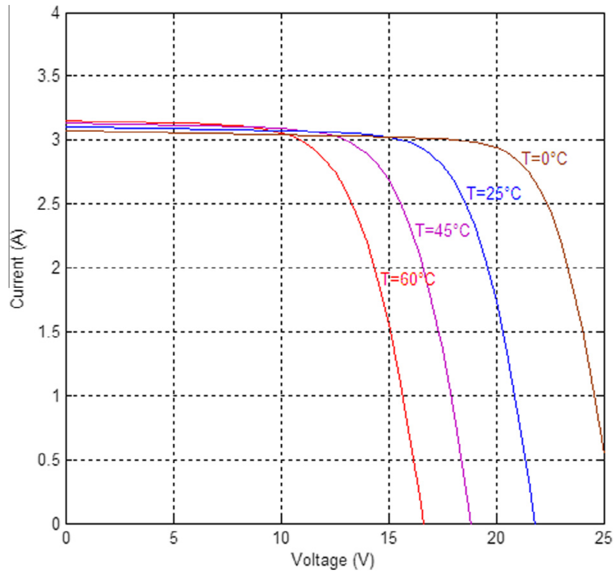

Fig. 17 $I(V)$ characteristic by varying temperature.

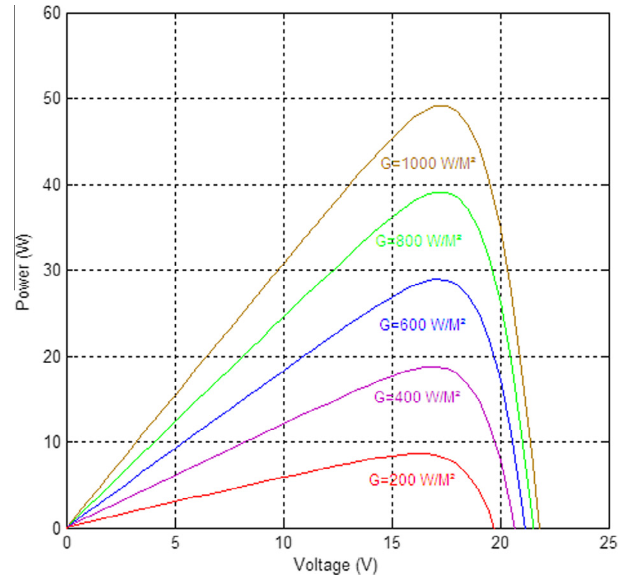

Fig. 19 P(V) characteristics by varying irradiance.

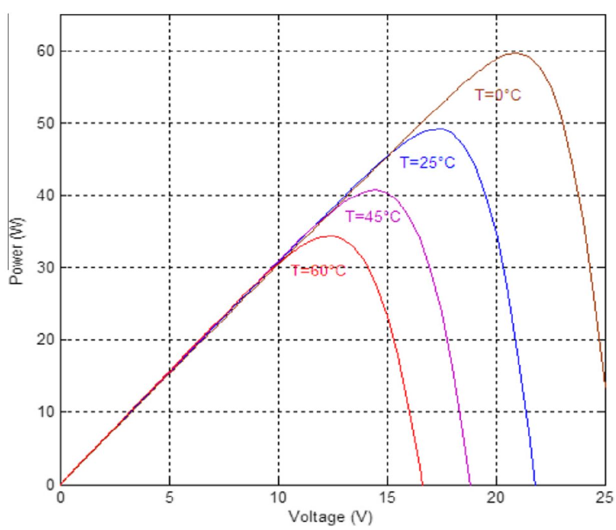

Fig. 18 P(V) characteristic by varying temperature.

- The complete model is presented in Fig. 8. Irradiance and temperature are the inputs while the outputs are current and voltage.
- To make simulation well organized, subsystems are grouped and presented in Fig. 9.

5. Curves and interpretation

First, $I(V)$ characteristic is plotted for R_s equal to zero and $R_s = 0.55\,\Omega$. The last value of the series resistance is provided by manufacturer. It is possible to point out some comments in Figs. 10 and 11; as the fact that neither I_{sc} nor V_{oc} are affected by the change of the series resistance. In spite of this, the shape moves to the rectangular form when R_s decreases. The Maximum Power Point moves to the right, so, P_{mp} is in reverse proportion to the series resistance. This is in accordance with the fill factor relation (Anne and Michel, 2006; Bernard, 2004):

$$FF = \frac{P_{mp}}{V_{oc} \cdot I_{sc}} \tag{22}$$

If I_{sc} and V_{oc} are constant, the fill factor FF changes only according to P_{mp}. which is with respect of both R_s and R_p in equation (21).

As shown in Fig. 12, it is confirmed that the manufacturer did not take into consideration the parallel resistance, because the peak power of the R_s model in this work matches with the experimental peak power given in the data sheet for $R_s = 0.55\,\Omega$. But for the R_p model, the peak power is logically less than the experimental one (See Fig. 13).

The proposed R_p model is more accurate and the most appropriate to simulate PWX 500 PV module (49 W) and any other PV module. For PWX 500 PV module (49 W), all the parameters are available to compute iteratively R_s and R_p. The values were applied in the detailed R_p model presented in Fig. 6. The results are presented in Fig. 14 and 15.

The proposed R_p model is now used to simulate the PV module at different values of irradiance and temperature. The $I(V)$ characteristics are presented in Fig. 16 by varying irradiance from $200\ \text{W/m}^2$ to $1000\ \text{W/m}^2$ and taking The STC temperature. In Fig. 17, the temperature varies from 0 °C to 60 °C at STC irradiance.

P(V) characteristics are then presented in Fig. 18 by varying temperature from 0 °C to 60 °C at STC under STC irradiance. In Fig. 19 the irradiance varies from $200\ \text{W/m}^2$ to $1000\ \text{W/m}^2$ under STC temperature.

6. Conclusions

The presented work is a detailed modeling and simulation of the PV cell and module. It is implemented under MATLAB/Simulink environment; the most used software by researchers and engineers. This model is first drafted in accordance with the fundamentals of semiconductors and the PV cell technology. In other words, the PV module parameters have been selected according to their variation with illumination and temperature. It means that for any type of PV module, one can use this model and determine all the necessary parameters under any new conditions of irradiance and temperature and then, obtain the $I(V)$ and $P(V)$ characteristics. This model can be considered as a tool which can be used to study all types of PV modules available in markets, especially, their behavior under different weather data of standard test conditions (STC). It is important to compute R_S, even if it is given by a manufacturer because the experimental Maximum Power Point does not match with the computed one. For each iteration, a pair of (R_s, R_P) is obtained. But only one pair satisfies the condition of matching the modeled and the experimental peak power. So, R_s is iteratively increased until satisfying the condition. The proposed R_p model gave ($R_s = 0.45\,\Omega$, $R_p = 310.0248\,\Omega$) instead of ($R_s = 0.55\,\Omega$, and R_p not provided). So it can be estimated to be more accurate in simulating the PV module.

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