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Comparative Energy Analysis of Photovoltaic Module

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Comparative Energy Analysis of Photovoltaic Module

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Abstract. This work introduces a comparative energy analysis of photovoltaic module using its different single diode equivalent electrical circuits (five-parameter model, four-parameter model, and ideal model). These equivalent circuits are used for different purposes according to the objective. The ideal model is still used in many applications particularly power system analysis and water pumping. Three commercially available (SUNTECH) photovoltaic modules (50W, 70W and 130 W) are used in this analysis at standard test conditions. Using those three PV modules; the relative errors of the maximum output power mismatch are highlighted in the three cases. Obtained results show that the five-parameter model gives the most accurate maximum power prediction in comparison to that of manufacturer's data sheet, while the ideal model shows a remarkable relative error at the maximum output power which is up to 8.93013%. This evaluation allows users deciding on the selection of appropriate equivalent circuit to be used in a given application.

1. Introduction

Solar energy has been recognized as one of the alternative solutions to replace fossil based power plants. Its abundance, noiselessness, clean source, free cost, advantages among many others of this source of electric energy. Photovoltaic is one way to convert sunlight energy to electricity. The number of PV modules depends on the power demand, voltage requirement and site's solar radiation availability. The PV generator can be standalone or grid tied system. For the two architectures, analysis, design, optimization, or control, the use of the equivalent circuit of the PV module is required. Different equivalent circuits of PV module are available which differ in the number parameters and the number of diodes used in the modeling. This paper investigates equivalent circuits of single-diode model. Chouder A. *et al.* [1] presented a simulation study and experimental validation of a PV grid connected system with a rated power of 3.2 KW. A PV module, forming part of the whole PV array, is modeled by a single diode five-parameter model and the model has been validated experimentally by carrying out outdoor I–V characteristic measurements. Similarly Elyes*et al.* [2] used the five-parameter model for PV generator when they reported the development of a statistical fault detection approach for monitoring the performances in a grid connected PV system by detecting faults on the DC side and diagnosing the type of detected fault. To simplify analysis and computation, four parameter equivalent circuit is preferred. For instance, Biji*et al.* [3] modeled and simulated the PV pumping system for maximum efficiency using for-parameter model of PV generator. Djeriou *et al.* [4] applied a maximum power point tracker (MPPT) technique for stand-alone photovoltaic water pumping system to improve the overall operating efficiency system. The latter used a four-parameter

single diode model to simulate the whole system. The PV generator of the system is modeled using the four-parameter model. Neglecting PV cell physical phenomena such as contact resistances, the current lost by photocell sides as well as the ageing of cells [5], [6] while introducing the capacitor (C) allows to overcome the problem of causal [7]. The PV generator equivalent to a current source shunted by a junction diode which is known to be the ideal model. This model is employed to analyze photovoltaic system being associated to storage batteries where modeling using bond graph methodology is investigated in [5], [8]. In addition, Siecker*et al.* [9] presented extensive reviews of various cooling techniques used to enhance the performance of a PV system where the PV generator is modeled using the ideal model. Similarly Mezghani *et al.* [6] used the ideal model of PV generator to model the hybrid pumping system using the bond graph approach. Anbarasi Jebaselvi *et al.* [10] provided overviews of the performance analysis of hybrid power systems, control methodologies and modeling techniques so as to get an optimum output power. The latter study is based on the modeling of the PV generator using the ideal equivalent circuit.

Many researchers have focused on the analysis of neglecting model parameters such as series and parallel resistance. Madansure *et al.* [7] presented the PV system behavior modeling using bond graph approach. They introduced different bond graph based model representations of the PV cell using different equivalent electrical circuits namely five-parameter model, diode capacitance representation, Norton representation, Thevenin's representation and Gyrator representations. Besheer*et al.* [11] presented thorough comparative analysis a study for various kinds of single-diode model based photovoltaic power source. The analysis was done for different values of temperature as well as solar irradiation. Ahmad H. Besheer *et al.* [12] presented a comparative analysis study for the PV module based on single diode model representation with various levels of complexity. The analysis is based on four single diode model and the experiment validated data for two different kinds of PV module available in the market. The relative errors between each PV single diode model output and the experimentally validated data are computed at low, medium and high temperature and irradiance level as well as at standard test conditions. The variation of the temperature and the solar irradiation are not done simultaneously which may not reflect the correct corresponding relative error between the dynamic performance of such photovoltaic models and the experimental data from the manufacturer's data sheet under varying atmospheric conditions. Silvano [13] proposed two mathematical models of PV cell, namely: the complete model (five-parameter model) and the simplified model (four-parameter model) where the values of the relative error between the dynamic performance of such photovoltaic models and the experimental data from the manufacturer's data sheet under varying atmospheric conditions are not highlighted.

This work presents a comparative energy analysis of commercial (SUNTECH) photovoltaic module of 50, 70 and 130W using three different representations of equivalent electrical circuits (five-parameter model, four-parameter model, and ideal model).Analyses are done at standard test conditions in order to provide comparisons between the obtained results using the three representations and the values given in manufacturing data sheet. The remaining of the paper is organized as follows: Section 2 provides the modeling of PV module based on bond graph methodology and three different equivalent electrical circuits of PV module. Section 3 shows the obtained results using the three representations at STC. Finally, a conclusion is drawn to end up the paper.

2. Modeling of photovoltaic module

Bond graphs actually indicate the structure through which energy is exchanged [14]. It represents the power transfer within a system by using a series of connections called power bonds [15], [16]. It utilizes nine basic elements or building blocks which may represent physical subsystems, components or phenomena in every energy domain. The elements are classified in three categories, the passive elements and the active elements and the elements of the junction. These elements in addition to the detectors are used to represent the phenomenon that connects the generalized variables. Since this technique is based on the electrical circuit of the system. In this paper the modeling of PV modules is done based on its equivalent electrical circuit and using bond graph methodology.

The equivalent electrical circuit of the photovoltaic (PV) module consists of a photovoltaic current source I_{phM} in parallel with a diode (D_M) and shunt resistance (R_{ShM}) expressing a leakage current and

a series resistance (R_{SM}) describing internal resistance to the current flow, as shown in Figure 1. (a). The bond graph representation of this later is shown in Figure 1. (b). Where; 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 ($R: R_{ShM}$, $R: R_{SM}$). The diode (D_M) is represented by a resistance ($R: R_{DM}$) with considering the Shochley's diode equation.

Based on Figure 1, and using the characteristic equations of the junctions in consideration of the causality, the resulting expression of the PV module's output voltage, $V_1(e_6)$, is given by the following equation [14]

$$V_1 = V_{ThM} \ln\left(\frac{I_{phM} - \frac{V_M}{R_{ShM}} - \frac{R_{SM}}{R_{ShM}}I_1 - I_1}{I_{satM}} + 1\right) - R_{SM}I_1 \qquad (1)$$

From the previous equation one can deduce that the PV module current equation, $I_1(f_6)$, can be deduced as follows

$$I_1 = I_{PhM} - I_{satM}\left(exp^{\frac{V_1 + R_{SM}I_1}{V_{ThM}}} - 1\right) - \frac{V_1 + R_{SM}I_1}{R_{ShM}} \qquad (2)$$

The model represented by equations **(1)–(2)** is usually carried out using Kirchhoff's laws and Shochley'sdiode equation. Multiplying the PV module current, given by the above equation by its output voltage yields the output power of the used PV module, as given in the following equation

$$P_1 = I_1 * V_1 \qquad (3)$$

Since the shunt resistance is very large it can be removed from the equivalent electrical circuit of the PV module shown in Figure 1. Thus, a simplified equivalent electrical circuit of PV module is obtained as shown in Figure 2.

Based on Figure 2, this latest figure and using the characteristic equations of the junctions in consideration of the causality, the PV module current, I_2, equation is obtained as a function of the PV module output voltage, V_2, as given in the following equation
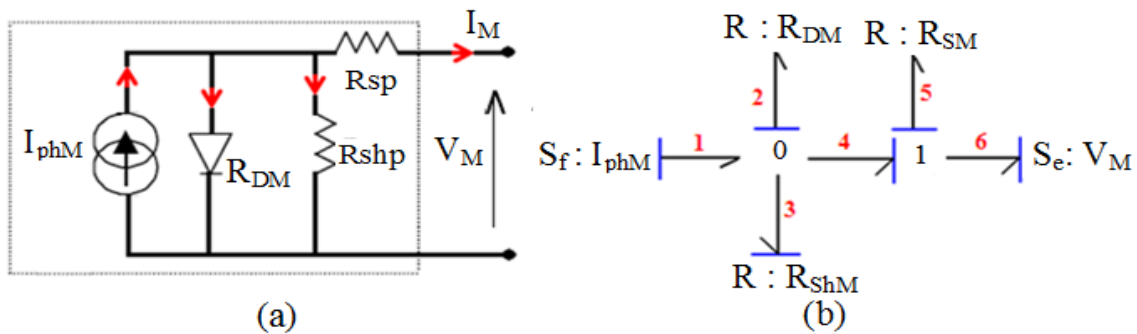

(a)   (b)

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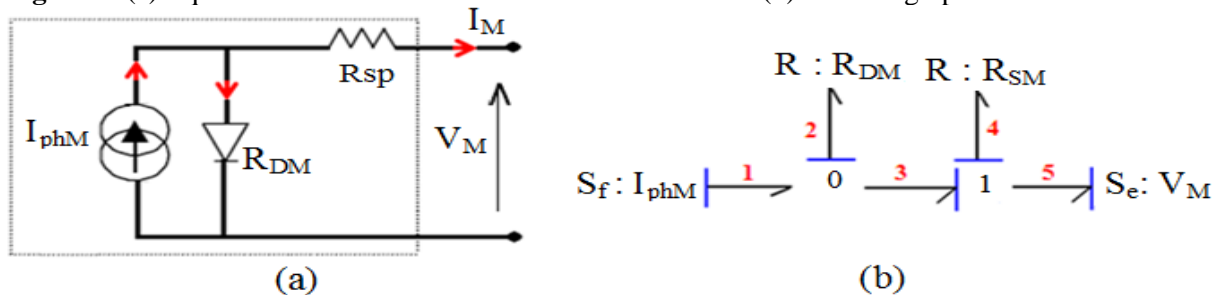

(a)   (b)

Figure 2. (a) Equivalent electrical circuit of the PV module and (b) its bond graph model with neglecting the shunt resistance.

$$I_2 = I_{PhM} - I_{satM}\left(exp^{\frac{V_2 + R_{SM}I_2}{V_{ThM}}} - 1\right) \tag{4}$$

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

$$P_2 = I_2 * V_2 \tag{5}$$

Further simplification can be done in the equivalent electrical circuit of the photovoltaic cell by neglecting the serial resistance Rs as it is very small. And therefore, in the equivalent electrical circuit of the photovoltaic module the series resistance can be neglected. This model is shown in Figure 3. (a). Based on this latter and using the characteristic equations of the junctions in consideration of the causality, the PV module current, I_3, equation is obtained as a function of the PV module output voltage, V_3, as given in the following equation.

$$I_3 = I_{PhM} - I_{satM}\left(exp^{\frac{V_3}{V_{ThM}}} - 1\right) \tag{6}$$

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

$$P_3 = I_3 * V_3 \tag{7}$$

3. Results and discussion

In this section, a commercially available (SUNTECH) photovoltaic module of 50, 70 and 130 W is analyzed at standard test conditions for the three cases. For each PV module the I-V curves and the P-V curves are plotted for the three cases where the differences in maximum power points are highlighted (see Figure 4-Figure 6). The curves plotted in Figure 4-Figure 6 show that the five-parameter and four-parameter models are very close to each other while the ideal model is far from them with remarkable higher maximum power prediction.

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

$$E\% = \frac{|E_{simulated} - E_{measured}|}{E_{measured}} * 100 \tag{8}$$

Where, $\Delta E_1\%$, $\Delta E_2\%$, and $\Delta E_3\%$ represent the absolute relative errors between the manufacturer datasheet and the calculated data for case 1, case 2 and case3, respectively.

Obtained results are reported in Table 1-Table 3. From those tables, it is clear that the obtained maximum power using the five-parameter model is very close to that given in the manufacturing data sheet of the PV module. In other words, the absolute relative error of the maximum power is 0.01176% for PV module of 50W, 0.01109% for PV module of 70W and 0.001607% for PV module of 130W.
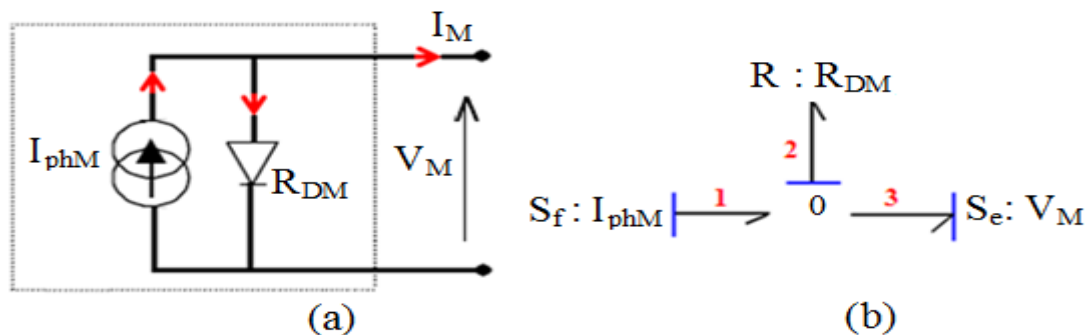

Figure 3. (a) Equivalent electrical circuit of the PV module and (b) its bond graph model with neglecting both the shunt and the series resistances.

Four-parameter model introduces an additional maximum power with respect to the five-parameter model appears in the values of the absolute relative error of the maximum power which is 0.00684% for PV module of 50W, 0.00501% for PV module of 70W and 0.001331% for PV module of 130W. Neglecting series and shunt resistances in the the PV module's equivalent circuit results in a considerable value of the absolute relative error. In other words, the absolute error of the maximum power is computed as 6.27636% for PV module of 50W, 6.81198% for PV module of 70W and 8.927192% for PV module of 130W with respect to the four-parameter. In addition, the absolute relative error of the maximum power is 6.2832% for PV module of 50W, 6.81699% for PV module of 70W and 8.928523% for PV module of 130W with respect to the five-parameter. Therefore; it is important to mention that neglecting one the equivalent circuit resistances results in mistaken estimation of the available maximum power. In other words, the absolute relative error of the maximum output power of PV generator will have an additional value more than 6% of that given in its data sheet. And therefore; the corresponding absolute relative error of the fill factor is higher by more than 6% with respect to the corresponding value of datasheet.

Table 1. SUNTECH photovoltaic module of 50 W at STC

SUNTECH PV module 50W	V_{Pmax} (V)	I_{Pmax} (A)	P_{Mmax} (W)	FF	R_{SM} (Ω)	R_{ShM} (KΩ)
Case1	17.5	2.9136	50.988	0.7472	0.3733	79.2
Case 2	17.5	2.9138	50.9915	0.7473	0.3733	
Case 3	18.45	2.9372	54.1913	0.7941		
Data sheet	17.4	2.93	50.982	0.7471		
ΔE_1 %	0.5747	0.5597	0.01176	0.0133		
ΔE_2 %	0.5747	0.5529	0.0186	0.0267		
ΔE_3 %	6.03448	0.24573	6.29496	6.2909		

Figure 4. SUNTECH photovoltaic module of 50 W at STC: (a) I-V curves and (b) P-V curves.

Table 2.SUNTECH photovoltaic module of 70 W at STC

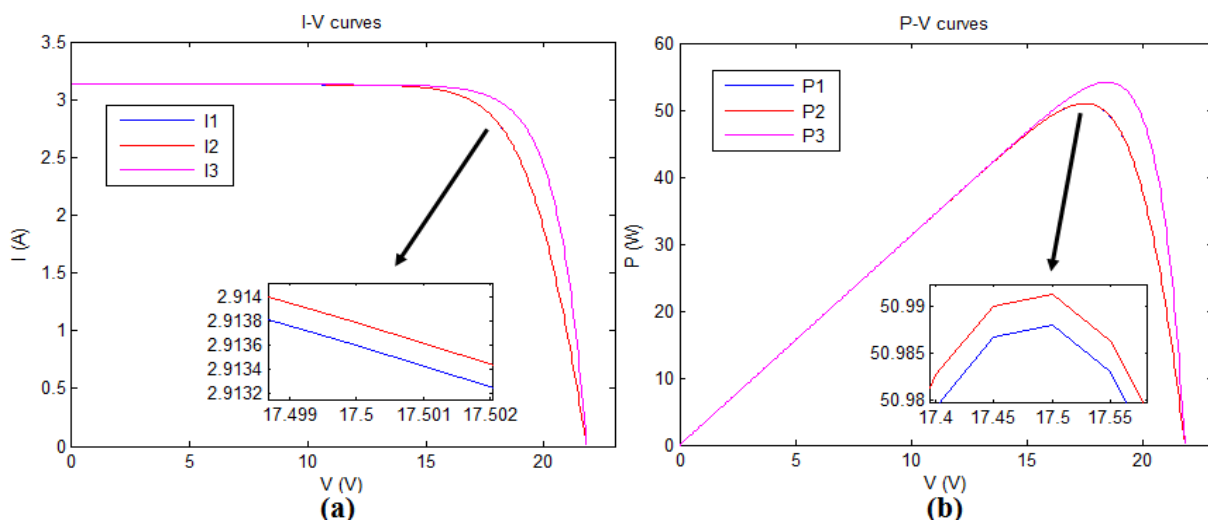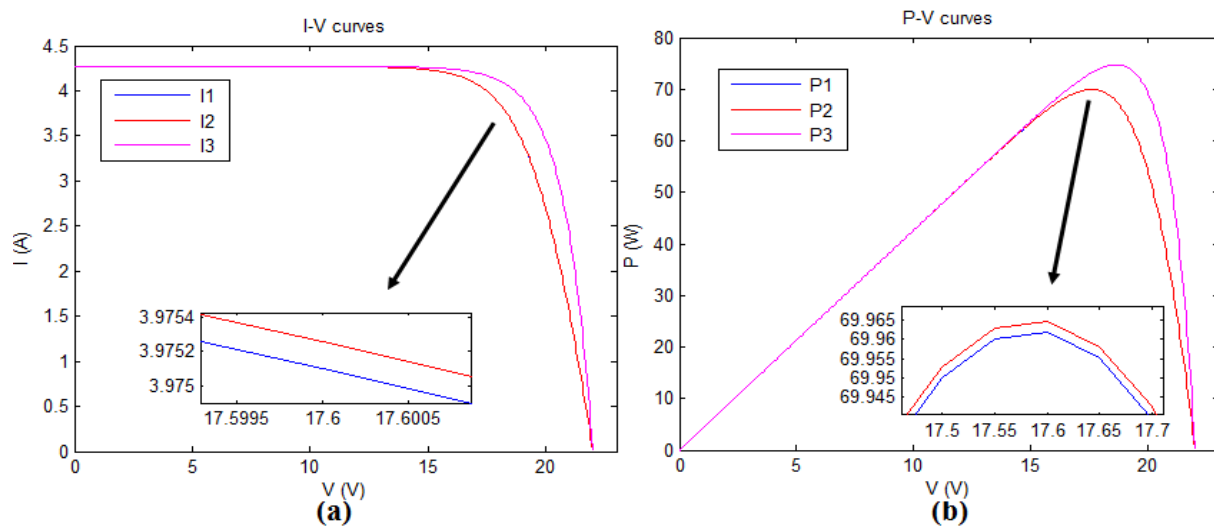| SUNTECH PV module 70 W	V_{Pmax} (V)	I_{Pmax} (A)	P_{Mmax} (W)	FF	R_{SM} (Ω)	R_{ShM} (KΩ)
Case1	17.6	3.9751	69.96176	0.74474	0.2986	96.77
Case 2	17.6	3.9753	69.96528	0.74478	0.2986	
Case 3	18.63	4.0113	74.730519	0.7955		
Data sheet	17.8	3.93	69.954	0.7446		
ΔE_1 %	1.1235	1.1475	0.01109	0.0188		
ΔE_2 %	1.1235	1.1526	0.0161	0.02417		
ΔE_3 %	4.6629	2.0687	6.82808	6.83588		

Figure 5.SUNTECH photovoltaic module of 70 W at STC: (a) I-V curves and (b) P-V curves.

Table 3.SUNTECH photovoltaic module of 130 W at STC

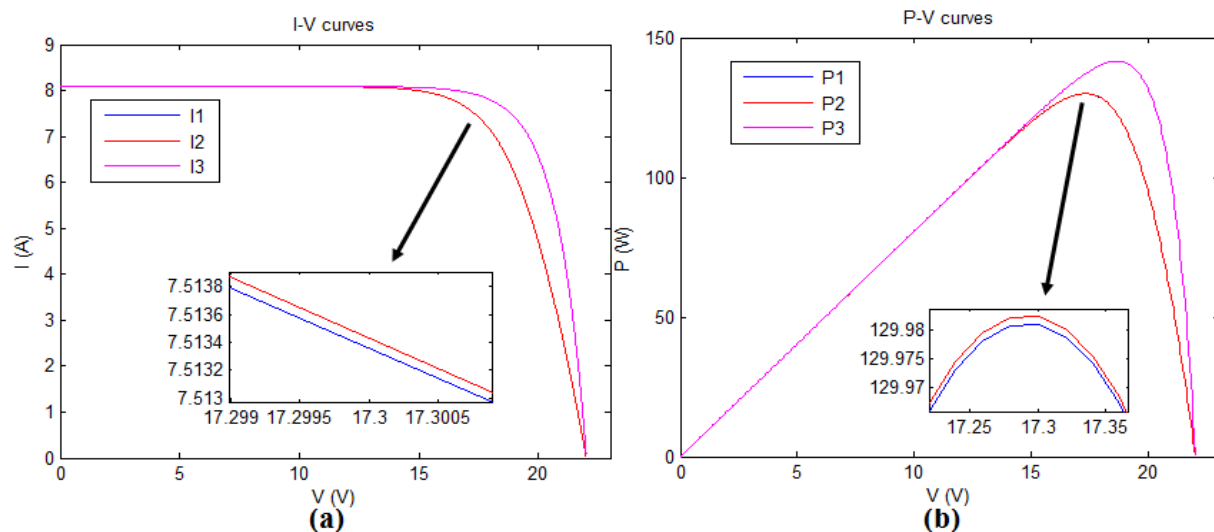| SUNTECH PV module 130W	V_{Pmax} (V)	I_{Pmax} (A)	P_{Mmax} (W)	FF	R_{SM} (Ω)	R_{ShM} (KΩ)
Case1	17.3	7.5133	129.98009	0.730307	0.203	189.1
Case 2	17.3	7.5134	129.98182	0.730317	0.203	
Case 3	18.65	7.5917	141.585205	0.795511		
Data sheet	17.4	7.47	129.978	0.730295		
ΔE_1 %	0.5747	0.57965	0.001607	0.001643		
ΔE_2 %	0.5747	0.58809	0.002938	0.003024		
ΔE_3 %	7.1839	1.62918	8.93013	8.930089		

Figure 6. SUNTECH photovoltaic module of 130 W at STC: (a) I-V curves and (b) P-V curves.

4. Conclusion

In the present paper, a comparative energy analysis of three PV modules is done at standard test conditions based on different equivalent electrical circuits which are five-parameter model, four-parameter model, and ideal model. These equivalent circuits are the most encountered in published studies on the analysis, optimization, design and control of photovoltaic systems.

It has been found that decreasing the number of equivalent circuit parameters decreases the accuracy maximum power prediction. Even though it simplifies the computation but neglecting this effect is not without consequences on the analysis. The selection of equivalent circuit for some application where computation is burden becomes a compromise. As prediction of the PV generator's maximum power is a part of the computation, therefore using simplified PV model becomes an advantage. However, power predictions mismatch may affect the accuracy of analysis or simulation. This study quantifies the amount of error that can be introduced by using simplified models with respect to the accurate one.

5. References

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Nomenclatures:

Symbol	Definition
D_M	Sensitive diode to the light in PV module;
FF	PV module fill factor;
I	PV module current, (A);
I_{Pmax}	PV module current at the MPP, (A);
I_{phM}	Photocurrent produced by PV module, (A);
I_{satM}	Reverse saturation current of diode in PV module l, (A);
K_b	Boltzmann's constant ($K_b = 1.38065*10^{-23} J/K$) ;
P_{Mmax}	Maximum experimental peak output power of PV module, MPP, (W);
R	Bond graph representation of resistance, (Ω);
R_{DM}	Bond graph representation of the diode DM in PV module, (Ω);
R_{ShM}	Parallel (shunt) resistance of PV module, (Ω);
R_{SM}	Series resistance of PV module, (Ω);
S_f	Bond graph representation of current source, source flow; (A);
STC	Standard test conditions ($G_{STC} = \frac{1000W}{m^2}$; $T_{STC} = 25°C$);
T	PV module's working temperature, (K);
V	Output voltage of the PV module, (V);
V_{Pmax}	Voltage at the MPP of PV module, (V);
V_{ThM}	Thermal voltage and it is equal to $\frac{n_M K_b T}{q}$, (V);
e	Bond graph representation of voltage; (V);
f	Bond graph representation of current; (A);
n_M	Quality factor of the diode (D_M);
q	Magnitude of electronic charge, (q=1.602*10−19 C);
$\Delta E\%$	Absolute relative error of the PV module parameters;