Series connected photovoltaic cells-modelling and analysis

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Series Connected Photovoltaic Cells—Modelling and Analysis

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Abstract: As solar energy costs continue to drop, the number of large-scale deployment projects increases, and the need for different analysis models for photovoltaic (PV) modules in both academia and industry rises. This paper proposes a modified equivalent-circuit model for PV modules. A PV module comprises several series-connected PV cells, to generate more electrical power, where each PV cell has an internal shunt resistance. Our proposed model simplifies the standard one-diode equivalent-circuit (SEC) model by removing the shunt resistance and including its effect on the diode part of the circuit, while retaining the original model accuracy. Our proposed equivalent circuit, called here a modified SEC (MSEC), has less number of circuit elements. All of the PV cells are assumed operating under the same ambient conditions where they share the same electric voltage and current values. To ensure the simplification did not come at a reduction in the accuracy of the SEC model, we validate our MSEC model by simulating both under the same conditions, calculate, and compare their current/voltage (I/V) characteristics. Our results validate the accuracy of our model with the difference between the two models falling below 1%. Therefore, the proposed model can be adopted as an alternative representation of the equivalent circuit for PV cells and modules.

Keywords: photovoltaic module; equivalent-circuit; current/voltage characteristics

1. Introduction

Photovoltaic (PV) cells absorb light of appropriate photon energy as it strikes its surface, leading to energy-carrying electrons to be released to circulate in a closed loop circuit through an external load to supply it with energy. The resulting electric current continues as long as the light continues to strike the surface of the PV cell. The load has to have an optimum value where the generated electric power of the PV cell is the maximum [1,2]. A PV module comprises a number of series-connected PV cells in order to amass more energy than that which is converted by a single PV cell. Researchers and manufacturers of PV modules alike strive to achieve the highest possible electrical efficiency by characterizing and optimizing the fabrication parameters of the PV cells. One of the most important characterization methods applied for PV cells is the current/voltage (I/V) characteristic, which is a key in deriving important electrical parameters of the PV modules [3,4]. For example, these parameters include the module's current (I_{m}), voltage (V_{m}) at maximum-power point, open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), fill factor (FF), and efficiency (η). Figure 1 shows the current/voltage (I/V) characteristics of a PV module whose electrical parameters are depicted on the same figure.

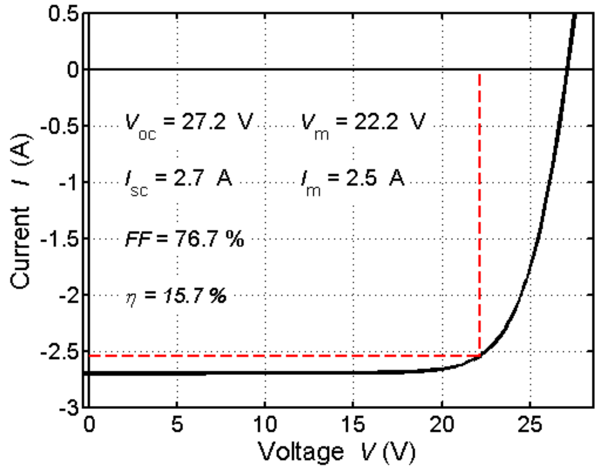

Figure 1. Current/voltage (I/V) characteristics of a PV module highlighting the key electrical parameters.

Several works in the past investigated different models for PV cells [5–13]. The interest of the researchers and manufacturers is driven by a need to optimize new technologies and to study their behavior in different contexts and under varying conditions. Additionally, accurate and simplified models for PV modules are cornerstones for the development of reliable and robust simulation technology to aid in design and manufacturing. Recent advances in simulation methodologies, availability of software, and technical developments have made simulation one of the most widely used and accepted tools in systems analysis and operations research. The work of Romero et al. [14] presented, for the first time, an exact analytical solution for the two-diode circuit of PV cells based on the Lambert W-functions. Additionally, Pozo et al. [15] solved the two-diode circuit model that has a transcendental equation system by numerical techniques. A novel simplifying method was investigated by Ding et al. [16] to simulate the behavior of the I/V characteristic of PV modules by applying three parameters using MATLAB Simulink blocks, while other researchers built a one-diode model using blocks from the Simulink library [17–20]. Santos et al. presented an accurate model based on the Shockley equation for simulating photovoltaic modules. This modeling tool allows the analysis of the behavior of electrical characteristics in accordance with environmental changes, such as temperature and irradiance [21]. Wang et al. proposed a new piecewise linear circuit model for PV cells and modules based on a series-structure equivalent circuit. This proposed model is different from the parallel-structure circuit model that has been extensively used in PV system analysis and simulation for a few years [22].

2. Modified Standard Equivalent-Circuit (MSEC)

In this work, we derive our simplified model from the standard equivalent-circuit (SEC), shown in Figure 2a, of one PV cell [23]. The model comprises a current source, a diode, and parasitic resistors. The parallel (or shunt) resistance (R_{p}) reflects the leakage occurrence through the PN-junction of the PV cell [24], whereas R_{s} represents the electrical losses of the cell's surface and bulk. The current/voltage (I/V) characteristics can then be written as given in Equation (1) [25–27]:

$$\begin{aligned} I &= I_D + \frac{V-IR_s}{R_p} - I_{ph}, \\ &= I_S\left(\exp\left[\frac{V-IR_s}{nV_t}\right] - 1\right) + \frac{V-IR_s}{R_p} - I_{ph}, \end{aligned} \tag{1}$$

where I_D is the diode's (PN-junction) current, I_s is the reverse-saturation current, V_t is the thermal voltage [28] (equal to 25.9 mV at 300 K), n is the ideality factor [29] that depends on the exact recombination mechanism, and I_{ph} is the maximum generated current (short-circuit current) from the

PV cell. Figure 2b shows the standard equivalent model (SEC) of N identical series-connected PV cells operating under the same ambient conditions.

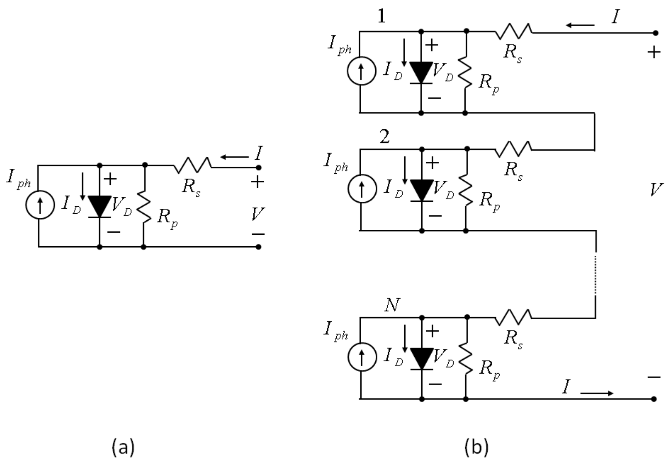

Figure 2. Standard equivalent-circuit (SEC) of (**a**) one PV cell and (**b**) N series-connected PV cells.

Our ultimate objective in this work is to further simplify the SEC of N series-connected PV cells to increase its utility. To integrate the circuit elements of each PV cell, we propose to modify the SEC of the PV cell as shown in Figure 3 which directly simplifies each PV cell where the current/voltage (I/V) equation resulting from Figure 2 should be kept identical to that of the circuit shown in Figure 3. The resulting series resistance R_{sx} shown in Figure 3a is not linear since it depends on the current, as will be shown in the upcoming systems of equations.

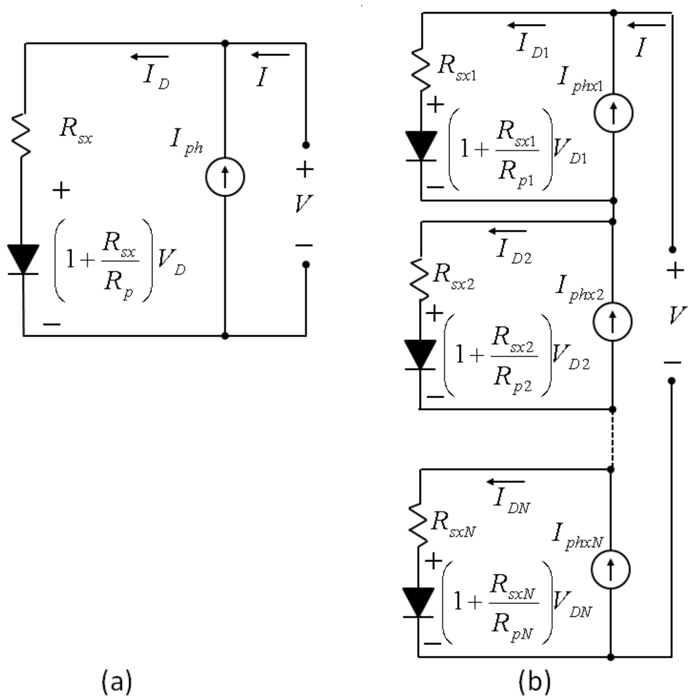

Figure 3. Modified standard equivalent-circuit models of (**a**) one PV cell and (**b**) N-series connected PV cells.

From Figures 2 and 3, the PV cell's output voltage and current are expressed according to the SEC (Equation (2)) and MSEC (Equation (3)) models, respectively, as:

$$V = IR_s + \left(I + I_{ph} - I_D\right)R_p \tag{2}$$

where $I = \frac{V - V_D}{R_s}$:

$$V = \left(I + I_{phx}\right)R_{sx} + \left(I + I_{phx} - I_D\right)R_p \tag{3}$$

where $I = \frac{V - V_D}{R_{sx}} - I_{phx}$.

By equating the similar terms of Equations (2) and (3), and assuming that $I_{phx} = I_{ph}$, we find the voltage across the PV cell as:

$$V = I_D R_{sx} + \left(1 + \frac{R_{sx}}{R_p}\right)V_D \tag{4}$$

Figure 3a shows the modified equivalent-circuit (MSEC) of N series-connected PV cells where it has one series resistance $R_{sx} = \frac{I}{(I + I_{phx})}R_s$ while the parallel resistance is included in the equivalent diode's voltage drop $\left(1 + R_{sx}/R_p\right)V_D$.

All of the PV cells are assumed operating under the same conditions and, thus, share the same electric voltage and current values. Therefore, the voltage and the current of the PV module are expressed as:

$$V = NI_D R_{sx} + \left(1 + \frac{R_{sx}}{R_p}\right)NV_D \tag{5}$$

$$I = I_s\left(\exp\left(\frac{V - I_D N R_{sx}}{N\left(1 + \frac{R_{sx}}{R_p}\right)nV_t}\right) - 1\right) - I_{ph} \tag{6}$$

The standard current/voltage equation for a PV module is:

$$I = I_s\left[\exp\left\{\frac{\frac{V}{N} - IR_s}{nV_t}\right\} - 1\right] + \frac{\frac{V}{N} - IR_s}{R_p} - I_{ph} \tag{7}$$

where the saturation current density I_s is temperature dependent and is expressed as:

$$I_s = I_{s0}\left(\frac{T}{300}\right)^3 e^{\left(\left(\frac{T}{300} - 1\right)\frac{E_g}{n\,V_t}\right)} \tag{8}$$

The short-circuit current I_{ph} is also temperature- and illumination-dependent and can be expressed as:

$$I_{ph} = I_{ph0}(1 + \alpha_I(T - T_0))\frac{G}{G_0} \tag{9}$$

where α_I is temperature coefficient of the short-circuit current (assumed 0.0006/K) with I_{ph0} is the short-circuit current at standard test conditions (STC) i.e., T_0 = 25 °C, AM = 1.5, and radiation G_0 = 1000 W/m^2. The band gap E_g also decreases as the temperature increases [30,31] as follows:

$$E_g = 1.16 - 7.02 \times 10^{-4}\left(\frac{T^2}{T - 1108}\right) \tag{10}$$

3. Discussion and Results

To validate our modified model for the PV module equivalent-circuit, we calculate the current/voltage (I/V) characteristics for a PV module by applying both the standard model (Equation (7)) and the modified model (Equation (6)). The parameters of N identical series-connected PV cells used to calculate the I/V characteristics are listed in Table 1. The PV module is assumed to consist of 36 series-connected cells where each cell has an area of 100 cm^2.

Table 1. Parameters of N identical series-connected PV cells used to calculate the I/V characteristics.

	Cells 1-*N*
Number of series-connected cells	36
Absolute operating Temperature (K)	300
Area of a PV cell (cm^2)	10×10
Series resistance Rs (Ω)	0.01
Shunt resistance Rp (Ω)	100
Ideality factor n	1.5
Reverse saturation current I_{s0} (A)	1×10^{-8}
Short-circuit current I_{ph0} (A)	2.7

Figure 4 shows the comparison between the calculated I/V characteristics of a PV module, having the parameters depicted in Table 1, using the standard model and the modified model. The result of our modified model agrees with that of the standard model and is simpler to express.

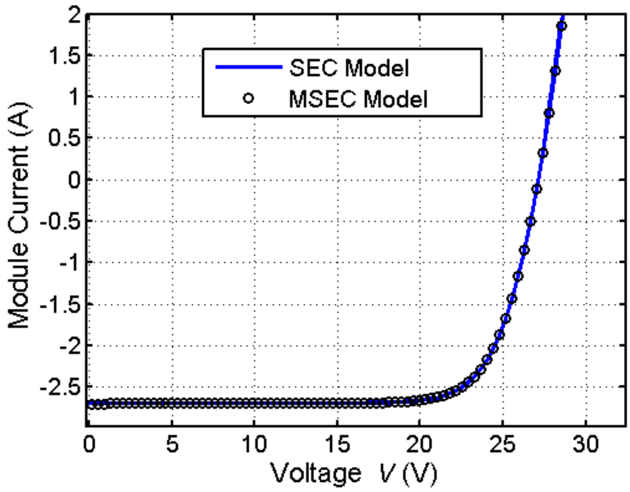

Figure 4. Calculated I/V characteristics of a PV module using the standard model expressed by Equation (7) (circles) and the modified model expressed by (Equation (6)) (line).

To determine the difference between the two methods, a linear line of slope equal to 1 is plotted on the I/V data calculated from both methods. The difference Δ between the calculated I/V data according to both standard, $I_{convtional}$, and modified, $I_{\mathrm{mod}ified}$, models is defined as:

$$\Delta = \sum_{i=1}^{M} \left| \frac{I_{convtional} - I_{\mathrm{mod}ified}}{I_{convtional}} \right| \times 100\ \% \tag{11}$$

where M is the length of the I/V data. According to Figure 5, it equals 0.05% leading to the conclusion that our modified model of the PV cell matches the standard model.

We also measured the I/V characteristics for a mono crystalline PV module consisting of N = 18 cells. This measurement takes place at the labs of Abu Dhabi University where the operating temperature of the setup is T = 300 K and the lamps have an AM = 1.5-like spectrum. The measured data is modeled by the SEC model and the MSEC model by applying the fitting parameters depicted on Figure 6. Each cell of the tested PV module has an area of 5 cm^2. Figure 6 shows the comparison between the calculated I/V characteristics of a PV module using the SEC model (solid line) and the MSEC model (dashed line). Our modified model very well fit the measurement of the I/V characteristics of the tested PV module.

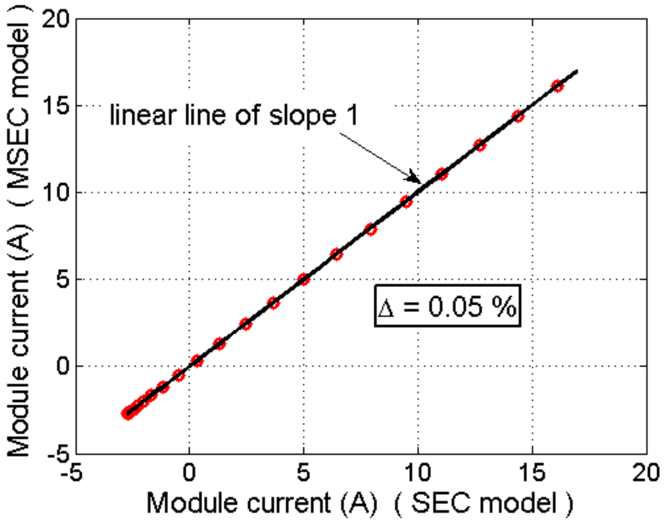

Figure 5. Calculated of I/V characteristics via SEC and MSEC. The difference between the line (slope = 1) and the circles is 0.05%.

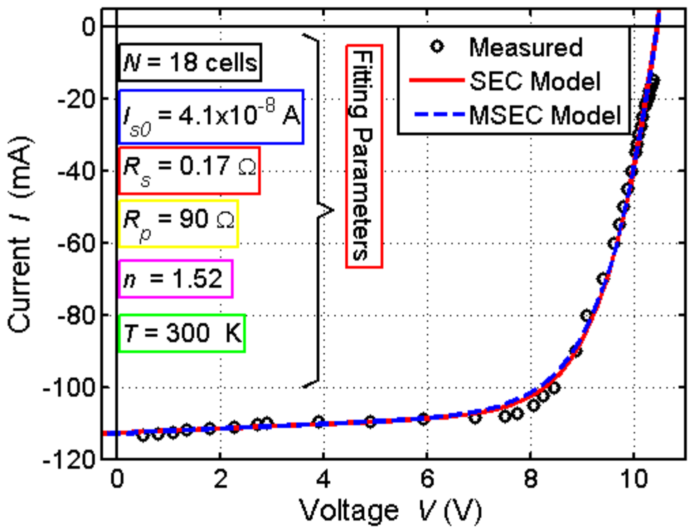

Figure 6. Measured (circles) and modeled I/V characteristics of a PV module using the SEC model (solid line) and the MSEC model (dashed line).

The current/voltage I/V characteristics, at different radiation levels (G) and operation temperatures (T), for the previous PV cell are calculated using the two models and then error function Δ is calculated. Figure 7 shows the contour plot for the error function Δ at different radiation levels G and operating temperatures T. It can be seen in Figure 6 that the two models match very closely where the maximum value of Δ in is less than 0.053%.

The modified model is again tested for different values of series resistance (R_s), parallel resistance (R_p), ideality factor (n), and reverse saturation current (I_0), as shown in Figure 8. The resulted difference values Δ in Figure 8 are less than 1%.

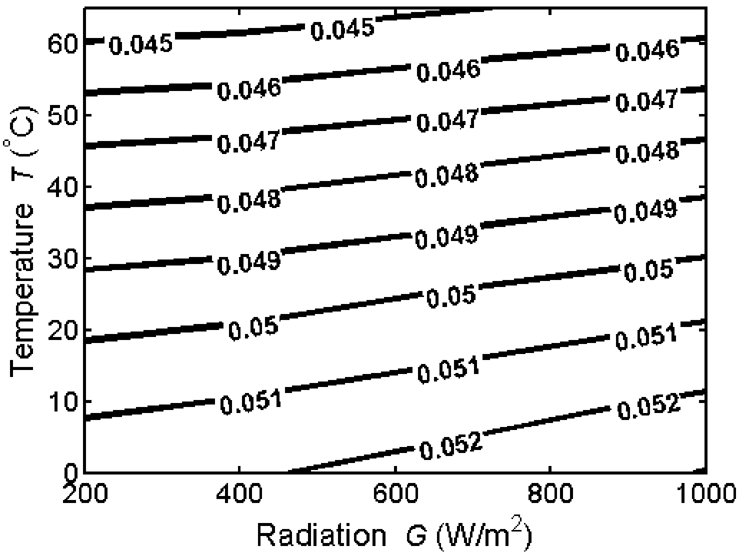

Figure 7. Contour plot of the difference Δ (%) as a function of operating temperature T and radiation levels G.

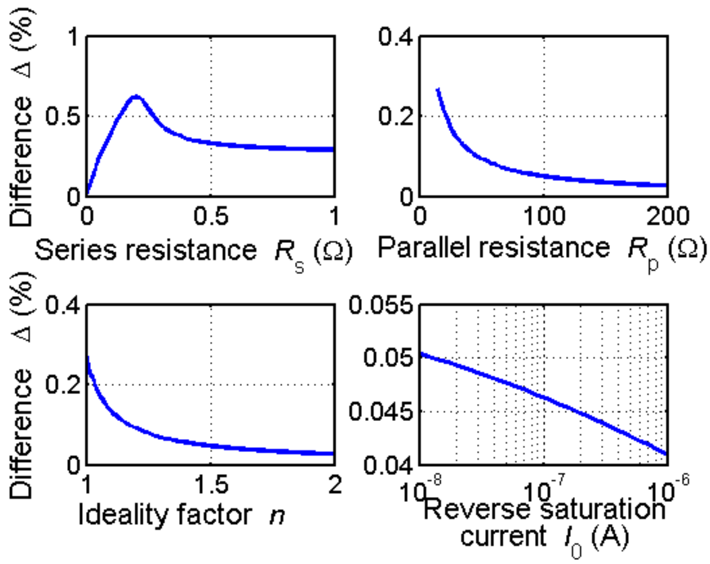

Figure 8. Difference Δ versus series resistance (R_s), parallel resistance (R_p), ideality factor (n), and reverse saturation current (I_0). The resulting difference in all cases is very small.

4. Conclusions

This paper presented a proposed model that modifies the standard equivalent-circuit (SEC) by removing the shunt resistance element from the standard equivalent circuit and including its effect on the diode part of the circuit. Therefore, another equivalent circuit, called here modified SEC (MSEC), results with fewer circuit elements. The current/voltage (I/V) characteristics of a tested PV module were modelled by the two models under the same input variables. The calculations of the current/voltage (I/V) characteristics showed that the difference between the two models is less than 1%. Therefore, our proposed model can be adopted as another representation of the equivalent circuit for PV cells and modules.

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Author Contributions: Anas Al Tarabsheh was the main investigator of this work. Muhammad Akmal and Mohammed Ghazal supported the idea of this work and proposed different techniques to make the model more accurate.

Conflicts of Interest: The authors declare no conflict of interest.

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